

Detection of absorbed neutrons through determination of rhenium content in tungsten with laser induced fast pulse discharge

B.D. Stankov^a, I. Traparić^a, M. Gavrilović Božović^b, M. Ivković^{a,*}

^a Institute of Physics Belgrade, Pregrevica 118, 11080, Belgrade, Serbia

^b Faculty of Engineering, Department of Electrical Engineering and Computer Science, Sestre Janjić 6, 34000, Kragujevac, Serbia

ARTICLE INFO

Keywords:

Laser-induced breakdown spectroscopy (LIBS)
Rhenium detection
Tungsten materials
Neutron absorption
Fast pulse discharge (FPD)
Fusion reactor diagnostics
Material transmutation

ABSTRACT

The diagnostics of the first wall of future fusion reactors provides a major source of information about the state of the machine and the expected lifetime of the first wall components. As the absorption of neutrons can cause induced radioactivity of the first wall tiles and produce significant structural changes to material, it is of the essence to monitor the amount of absorbed neutrons. One possibility to monitor them is via nuclear transmutation reaction where tungsten absorbs neutron and creates rhenium core. Therefore by assessing the amount of rhenium present in the material, information about neutron irradiation conditions can be deduced. Hence in this work, in order to assess the concentration of rhenium, Laser Induced Breakdown Spectroscopy (LIBS) combined with Fast Pulse Discharge (FPD) was used. The main achievement of this work is the amplification of line intensity and signal to noise ratio compared to the classical LIBS setup at reduced pressure which enables detection of Re in samples with less than 0.1% of Re. With synergistic use of LIBS and FPD, ie. Laser Induced Fast Pulse Discharge (LIFPD), significantly enhanced Limit Of Detection (LOD) is obtained compared to the previously reported results. This result is of particular importance since only small amounts of rhenium are expected to be found in the first wall tiles, therefore making this approach suitable for this type of diagnostics.

1. Introduction

The advancement of nuclear fusion technology presents the prospect of a sustainable energy source, but it also imposes significant challenges regarding materials science and engineering. The first wall of fusion reactors, which directly absorbs neutron radiation arising from fusion reactions, plays a critical role in ensuring the reactor's structural integrity and operational efficiency. Tungsten is a leading candidate for future fusion reactors due to its high melting temperature (3422 °C), low sputter yield and high thermal conductivity (~170 W/m/K at room temperature), and low tritium retention [1,2].

Research on tungsten materials, particularly in the context of nuclear fusion, has surged, largely driven by the ITER project, leading to an increase in publications about tungsten's interactions with irradiation and plasma. Extensive studies have been conducted on neutron irradiation-induced defect formation and recovery in tungsten, offering well-characterized data crucial for understanding its properties [3].

While tungsten shows considerable potential as an armor and blanket material, it is predicted to undergo substantial transmutation under fusion neutron irradiation [4–6]. According to [7], W in the first wall

substantially transmutes to Re followed by Os for the water cooled blanket. Noda et al. show a small reduction in W content is seen in the W armor as neutron fluence increases, while concentrations of Re, Ta and Os rise with fluence. In the transmutation processes induced by neutron irradiation, approximately 4% of W transmutes to Re for the W armor of all blankets, irrelevant of the blanket composition, after 10 MWy/m² irradiation. At contrast, there is significant transmutation of W at the first wall position. Rhenium concentration surpasses that of tungsten at approximately 30 MWy/m², as illustrated in [7].

This transformation not only alters the material properties but also impacts the reactor's performance and safety. Precise measurement of Re concentrations is essential to understand the extent of transmutation, which influences the alloying behavior of tungsten and its capacity to maintain structural integrity under extreme conditions. Furthermore, the induced radioactivity associated with rhenium isotopes, particularly ¹⁸⁶Re, necessitates accurate quantification to assess potential safety concerns related to long-term radioactivity in reactor components. Consequently, comprehensive knowledge of Re concentrations in tungsten facilitates enhanced material optimization and ensures the reliability of fusion reactors in both operational and safety contexts [7].

* Corresponding author.

E-mail address: ivke@ipb.ac.rs (M. Ivković).

<https://doi.org/10.1016/j.fusengdes.2025.114943>

Received 25 December 2024; Received in revised form 4 March 2025; Accepted 5 March 2025

Available online 9 March 2025

0920-3796/© 2025 Elsevier B.V. All rights reserved, including those for text and data mining, AI training, and similar technologies.

In addition to rhenium being a product of tungsten transmutation after heavy neutron irradiation, the tungsten-rhenium (W-Re) alloy is very important. Adding rhenium can improve some of the drawbacks of pure tungsten, such as its low ductility at room temperature and low recrystallization temperature, leading to better overall performance as structural material in fusion reactors [8]. With idea of W-Re alloy being PFM, experiments on deuterium permeation and retention were conducted in Bo-Yu Wu et al. [9] using tungsten-rhenium samples with 3% and 25% rhenium to analyze how rhenium affects hydrogen isotope transport in tungsten. The results indicate that adding rhenium increases the D diffusion coefficient but decreases D permeability, with the diffusion coefficients for both W-3 % Re and W-25 % Re being similar, while permeability declines as Re content increases. Therefore, the detection of Re in W is important as W-Re alloy might be used as plasma facing material whose properties are largely influenced by the percentage of Re present in the material. This, on the other hand, can be closely correlated with the neutron irradiation conditions, see e.g. [10] where calculated Re contents for different neutron fluences assigned to different DPA (displacement per atom) levels are given in tabular form. Graph of predicted Re concentration under fusion DPA conditions based on the fission reactor irradiation data on pure W and W-Re alloys can be found in [11].

Detecting small percentages of rhenium in tungsten is critical for several reasons relevant to fusion reactor materials. The addition of just 5% rhenium can reduce thermal conductivity and diffusivity to half that of pure tungsten [8,12]. Furthermore, a drift in the temperature reading of a W-Re thermocouple will occur due to precipitation and compositional changes during irradiation [13]. Therefore, it is important to study the effects of compositional changes due to transmutation on the physical properties of W upon neutron irradiation, which is usually done through complex calculations and numerical simulations [14,15], while experimentally the information about the degree of transmutation could be assessed through accurate and sensitive determination of Re percentage in material. In [10] measurement on solid transmutations with glow discharge optical emission spectroscopy system equipped with dual interferometry system showed an excellent agreement with the results of numerical calculations. On the other hand, the authors state that the GD-OES data collection lasted at least 5 minutes, and they could not be performed in situ, or real time.

Laser Induced Breakdown Spectroscopy (LIBS) technique can provide a fast and reliable estimation of element content in the first wall of fusion reactor. It was already applied in a range of different studies related to the estimation of retained fuel in the first wall and for depth profile analysis of plasma facing components (PFCs) materials or thin film coatings relevant for PFC materials. Maddaluno and collaborators used single pulse LIBS (SP – LIBS) [16], while Colao et al [17] used double pulse LIBS (DP – LIBS) together with Calibration Free LIBS (CF – LIBS) procedure for quantitative assessment of retained fuel. Paris et al [18] studied the fuel retention in different W coatings using SP – LIBS and Nuclear Reaction Analysis (NRA). Bhat et al [19] studied depth profiles of Be coated samples with different percentages of deuterium and seeding gases using SP – LIBS in combination with CF – LIBS to evaluate the impact on fuel retention. Depth profiling using LIBS was also exploited by Feng et al [20], where they estimated lithium penetration depth in Er_2O_3 coatings and its depth concentration by CF – LIBS. The corrosion resistance of Er_2O_3 coating was determined by Li et al [21] using standard LIBS calibration curve technique. Wu et al [22] applied picosecond SP – LIBS in vacuum environment to study the depth distribution of boron in tungsten. Also, Hu et al [23] performed the quantitative analysis with CF – LIBS of deposited impurities on PFCs using a custom developed hand-held portable LIBS device. Van der Meiden et al. [24] demonstrated LIBS as a reliable method for in-situ monitoring of tritium retention and impurity deposition on tungsten plasma-facing components in fusion devices, providing quantitative depth-resolved analysis with high sensitivity. In particular, picosecond LIBS (ps-LIBS) has shown significant advantages for highly

depth-resolved characterization of tungsten PFCs, achieving minimal thermal effects and an ablation rate below 40 nm per pulse, making it well-suited for diagnostic applications [25].

The lowest detection limit regarding Re detection by LIBS, that the authors are aware of, is reported by Ibano et al [26], who used a CF-LIBS to assess the concentration of Re in W-Re alloy. The authors state that relatively weak signal of Re I at 488.9 nm is observed at the right shoulder of a W-I line at 488.7 nm. In their experiment a line of Ar II is also present at 488.9 nm and according to the authors its influence on the line of Re cannot be ignored in cases of Re concentrations lower than 0.5 at.%. The authors confirm that the CF-LIBS results align closely with the nominal manufacturer concentration down to 0.5 at.%. However, after 12 years of full DT operation, the tungsten wall in ITER is expected to produce only about 0.18 at.% of Re [27]. Therefore, developing a more sensitive method based on the LIBS in the non-argon atmosphere is essential.

In this work, we investigate the potential enhancement of LIBS sensitivity through its integration with Fast Pulse Discharge (FPD) in a helium atmosphere, termed Laser Induced Fast Pulse Discharge (LIFPD). This approach is anticipated to significantly amplify the resultant spectral signals [28], thereby improving the limit of detection (LOD) for rhenium in predominantly tungsten targets, which is important for assessing absorbed neutron doses and consequent structural changes both in the pure and Re-alloyed tungsten.

In the following Section 2, we discuss the experimental setup of the LIFPD method. Main results of this work are presented and discussed in Section 3 which is organised as follows: Section 3.1 gives thorough description of the optimisation procedure to achieve highest analytical signal, while the achieved signal amplification with the proposed LIFPD setup is discussed in the Section 3.2. Procedure for detection limit determination of trace Re in W is presented in Section 3.3. Finally, our findings are summarized in Section 4 Conclusion. .

2. Experimental setup

The experimental setup of proposed LIFPD method is shown in the Fig. 1.

Laser beam (Nd:YAG Quantel 450, $\lambda = 532$ nm, pulse duration 6 ns, $E = 50$ mJ, 1 Hz) was focused via lens ($f = 12.5$ cm) onto the target that was placed inside the vacuum chamber. Target was rotated to expose the fresh surface on the target for each measurement. After the laser shot, laser induced plasma enters central part of the cross shaped vacuum vessel, where two electrodes were placed and connected to the capacitor battery ($C = 330$ nF). The experiment was optimized in a way that the laser produced plasma triggers the fast pulsed discharge, meaning that the HV level was carefully adjusted to be close to the breakdown voltage in order that the plasma can ignite the discharge. Targets investigated were 95 % W with 5% of Re, 90 % W with 10% of Re and 75 % W with 25% of Re. Thickness of the targets was measured to be 0.6 mm. Light emitted from LIBS plasma, as well as from the fast pulsed discharge, was collected with the collimator and guided through the fiber cable onto the entrance slit of the SOLinstruments MS7504i spectrometer equipped with Andor iStar ICCD camera (model DH734 – 18F – 63, 1024×1024 pixels, 18 mm sensor size). Camera was triggered and gated with the external digital delay generator (DDG) unit (Stanford Research SRS535), which on the other hand was triggered with signal from photodiode that monitors the LIBS plasma. HV was measured with high voltage probe that was attached to the Tektronix TDS2024C digital storage oscilloscope. Current intensity in pulsed arc was measured with Rogowski coil mounted around the current supply cable. The experiment was performed under controlled atmosphere of He gas, with the pressure adjusted in the range from 3 mbar up to 25 mbar. Each spectrum is obtained as accumulation over 10 laser pulses.

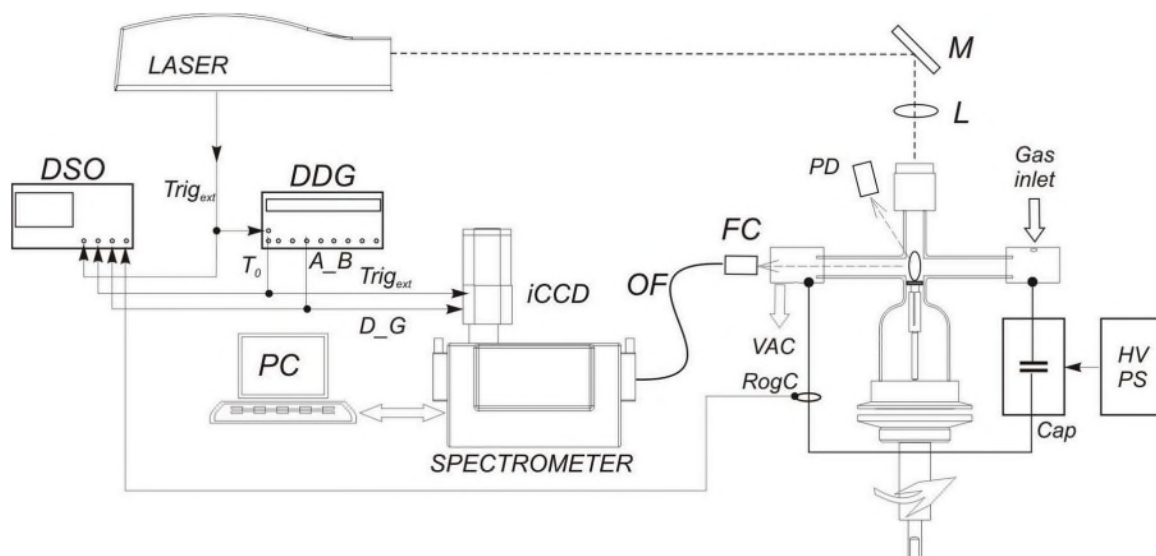


Fig. 1. Experimental setup with interaction chamber for proposed integrated LIFPD. High voltage electrodes are positioned orthogonally to the laser beam propagation direction and charged to the level that fast discharge is formed after laser pulse interaction with the sample.

3. Results and discussion

3.1. Optimization of the experiment

Experimental parameters that were optimized are working pressure inside the discharge tube, discharge voltage, the delay time and gate width of spectra recording with respect to the laser pulse. The optimisation is performed on the target sample consisting of 5 % of Re and 95 % of W.

The influence of ambient gas on the measurements was also carefully evaluated. While argon is noted for its effective performance as an infusing gas in LIBS [26,29], in the case of Rhenium detection it also imposes certain problems due to the spectral lines of Ar overlap the Re lines of interest. Our findings suggest that clear differentiation of the Re I line from tungsten can be obtained in He atmosphere under the optimized conditions within our LIFPD setup, thus avoiding any potential spectral overlaps, which led to the choice of helium as a background gas instead of argon.

For pressures of Helium gas lower than 10 mbar, the temporal reproducibility of the discharge current with respect to the laser pulse was worse than 5 μ s, meaning that the appearance of LIFPD plasma was not temporally reproducible, implying that the experiment must be done at greater pressures. For pressures above 10 mbar, temporal reproducibility was 2 μ s which is acceptable for the application of interest in this paper. In other words, plasma generated by the additional discharge appears with a delay relative to the laser impulse, with a reproducibility of approximately 2 μ s.

The pressure dependence of line intensities belonging to target material is shown in Fig. 2, in the pressure range of 11 mbar to 25 mbar. As can be seen, higher pressure values were preferred to ensure the increase in the intensity of the spectral lines, as well as for temporal reproducibility of the LIFPD. However, pressures exceeding 24 mbar were excluded due to instability in the discharge, which did not occur consistently following each laser pulse, possibly due to the irregular supply of target material particles which propagate at slower speed at increased pressure and experience higher number of collisions moving them out of the LIFPD interaction zone. Consequently, all subsequent measurements were conducted in an atmosphere of 24 mbar of helium, which ensures highest signal enhancement with stable and reproducible LIFPD event.

It is noteworthy that the fast pulse discharge plasma emerges after the LIBS plasma, allowing to assess separately the effects of this

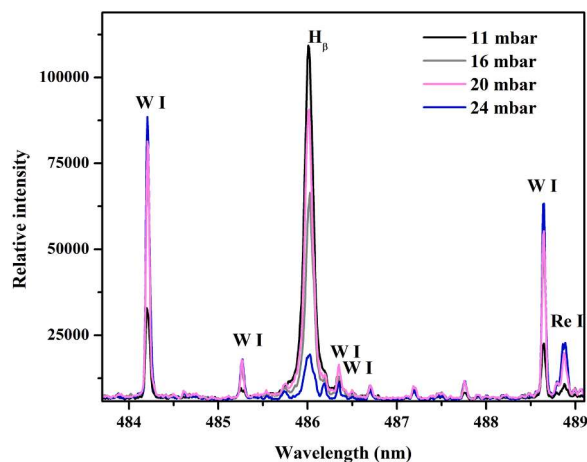


Fig. 2. Pressure optimisation for LIFPD plasma.

additional discharge. This sequence of events was assured with the proper combination of discharge voltage and gas pressure. It is concluded that the voltage of 420 V in combination with the pressure of 24 mbar leads to appearance of LIFPD plasma 7 μ s after the ending of LIBS plasma. Spectra recorded from LIBS plasma for different delay time and gate width are represented in Fig. 3. From Fig. 3 it can be concluded that the LIBS plasma does not persist longer than 20 μ s.

In the present study, the main task was to achieve a stable and reproducible FPD event triggered by the LIBS plasma. All working parameters, including laser energy, spot size, pressure etc were adjusted in that respect. The critical parameter to achieve this reproducibility was laser fluence achieved on the target in combination with suitable working pressure. Namely, laser fluence needed to be sufficiently high to ablate enough sample material to induce LIFPD event and create strong spectral emission of the elements of interest, but on the other hand sufficiently low to avoid explosive boiling of tungsten. Considering previous works regarding tungsten irradiation with Nd:YAG lasers [30, 31], to achieve this with the fixed laser energy of 50 mJ used here, the optimal spot size was determined to be 1 mm. The ablation rate was not studied since the target was constantly rotated, potentially creating overlapping spots which may hamper accurate profilometry measurements.

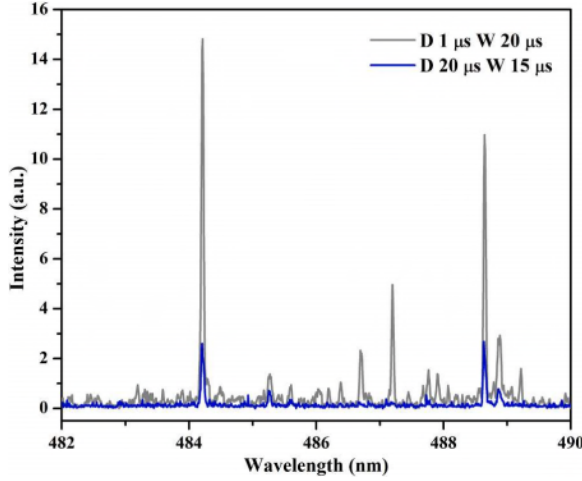


Fig. 3. Typical LIBS spectra obtained from different stages of plasma temporal evolution. Respective delays and gate widths are shown in the figure.

For the LIFPD plasma signal recordings, two options were considered: the first one was to trigger the camera at the maximum of the current signal, and the second is to trigger the camera 2 μ s before the current signal. As the illustration of triggering scheme, oscilloscope signals are shown in Fig. 4.

The signal enhancement for lines of Re in the case of triggering on the current maximum is almost negligible. When the camera is triggered 2 microseconds before the current signal (Fig. 4), the amplification of the signal in the resultant spectra (Fig. 5) is almost 5 times for the tungsten line and almost 10 times for the Re I 488.91 nm line compared to the LIBS signal. Based on these significant analytical signal enhancements, this gating scheme was adopted as optimal and used in all subsequent measurements. Two current maximums are appearing (see Fig. 4) because the pulsed plasma source is not critically damped, i.e. plasma impedance and external circuit impedance are not matched.

After the selection of the pressure, voltage, and the delay time, the gate width was adjusted accordingly. The gate width for the recording of FPD was set to compensate the temporal irregularity of FPD plasma appearance by $\pm 2\mu$ s. The gate width was therefore chosen as the duration of LIFPD current signal plus additional 4 μ s. For that reason the gate width was set to be 23 μ s. Temporal evolution of LIBS and LIFPD plasma is presented in Fig. 5.

To summarize the optimization process, it was determined that the optimal gas for the experiment is helium, with a pressure of 24 mbar. Optimal voltage is 420 V. At this pressure and voltage, the ideal

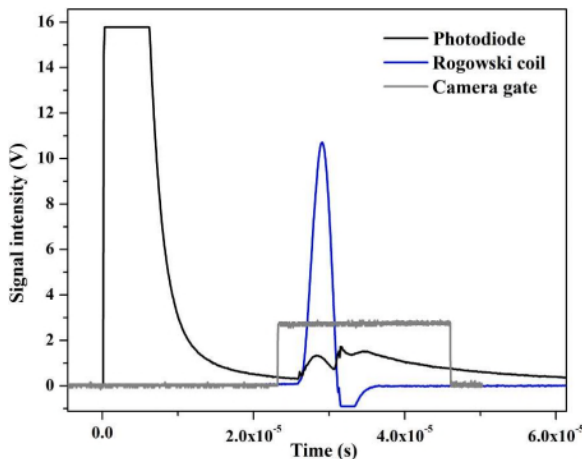


Fig. 4. Triggering and gating of the iCCD camera.

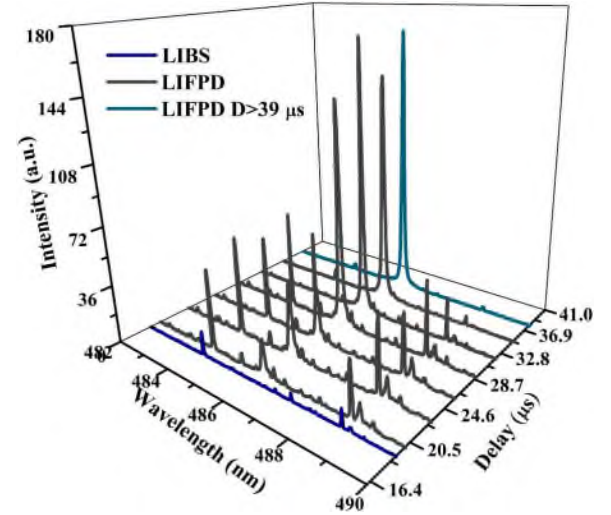


Fig. 5. Temporal evolution of LIBS and LIFPD.

triggering scheme involves initiating camera recording 2 μ s prior to the current signal. The gate width is configured to match the duration of the current pulse, with an additional 4 microseconds added to accommodate the temporal irregularities associated with the discharge plasma's appearance, leading to gate width of 23 μ s.

Electron temperature in LIFPD was estimated from the ratio of intensities of W I 484.381 nm and W I 488.689 nm lines, using the formula:

$$\frac{I_1}{I_2} = \frac{g_1 A_1 \lambda_2}{g_2 A_2 \lambda_1} e^{\frac{E_2 - E_1}{k_B T_e}}$$

Measured relative intensity ratio corresponds to the excitation temperature of 12 000 K. Having this estimation in mind, we determined of electron density. For this purpose, the hydrogen H_β line was used. As a first step, the FWHM was measured to be 0.133 nm. Instrumental width was measured to be 0.025 nm and from Doppler broadening was determined from the formula:

$$\Delta\lambda = 7.16 \times 10^{-7} \cdot \lambda_0 \cdot \sqrt{\frac{T}{M}}$$

to be 0.036 nm. The deconvolution formula [32,33] was used to determine the Stark component from the total FWHM:

$$w_s = \left(w_m^{1.4} - w_{D,I}^{1.4} \right)^{1/1.4}$$

When calculated, Stark width is estimated to be 0.11 nm. Finally, using the formula [32,34]:

$$\log N_e = 22.578 + 1.478 \times \log w_s - 0.144 \times (\log w_s)^2 - 0.1265 \times \log T_e$$

The electron density was estimated to be $3.2 \times 10^{14} \text{ cm}^{-3}$. Since the electron density is estimated to be $3.2 \times 10^{14} \text{ cm}^{-3}$, Stark broadening of the spectral lines is negligible. Furthermore, as this work was performed at low pressures, van der Waals broadening is also negligible.

3.2. Comparison of analytical capabilities of LIBS vs LIFPD

The main objective of this work was to obtain signal amplification with application of LIFPD compared to conventional LIBS. This predicted line intensity amplification is reasonable assumption since LIFPD is much stronger spectral light source than LIBS plasma.

The achieved results regarding signal amplification are shown in the Fig. 6. Optimal camera delay to capture the LIFPD signal with the best intensity is 23 μ s after LIBS plasma, where the highest SNR was achieved. This SNR is three times higher than the one obtained with the pure LIBS, while the line intensity itself is almost 5 times increased. This

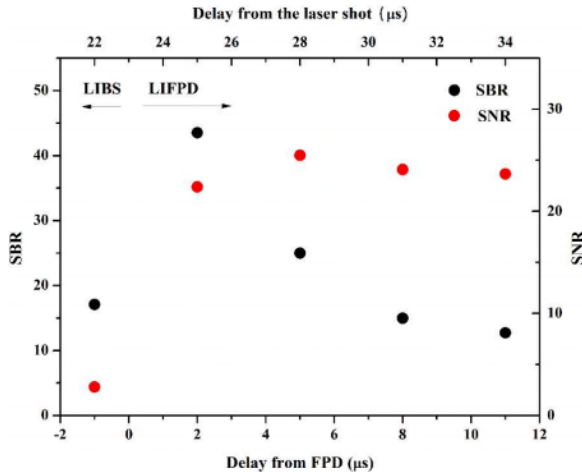


Fig. 6. SBR (Signal to Background Ratio) and SNR (Signal to Noise Ratio) for LIBS and LIFPD plasma as a function of camera delay. The trigger of the camera set 2 μ s before the current pulse is regarded as 0 μ s.

result bears significant importance for the analysis of the first wall of fusion reactors in terms of absorbed neutrons, since predicted concentrations of material of interest, i.e. Re, are expected to be quite low.

The possibility of target ablation via the discharge and its subsequent influence on the intensity of rhenium lines in the spectrum was also examined, as illustrated in the Fig. 7. The discharge was operated in pulsed mode, employing a sequence of 10 accumulated pulses, with the voltage set at 600 V to facilitate a pulsed discharge without the requirement for laser initiation. In the absence of the initial LIBS plasma, no spectral lines from the target material were detected in the pure FPD spectrum; the dominant feature observed was the H_{β} line. However, upon activation of the laser, well-resolved lines corresponding to the target material emerged, exhibiting significantly stronger intensities compared to the pure LIBS signal. This indicates that the primary source of material in the discharge is laser ablation, with contributions from sputtering and ablation due to FPD being negligible in this context. In the absence of the initial LIBS plasma, no spectral lines from the target material were detected in the pure FPD spectrum; instead, the dominant feature was the H_{β} line. This H_{β} line appears as an impurity since hydrogen is absent from both the working gas and the target material. Its presence is attributed to traces of water vapor on the walls of the discharge tube. Notably, the LIBS plasma, due to its significantly smaller size, does not induce moisture evaporation from the tube walls between the electrodes, thereby there are no hydrogen lines in the spectra.

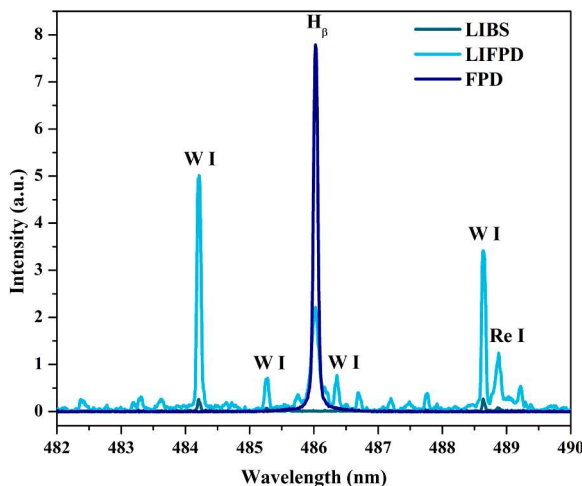


Fig. 7. LIBS, LIFPD and FPD spectra compared.

3.3. Detection threshold of trace Re in W

In this section, we present the calculation of the detection limit (LOD) as the smallest quantity of analyte that can be confidently identified in a sample, along with the quantification limit (LOQ), defined as the smallest quantity that can be reliably quantified, both with the proposed LIFPD approach and standard LIBS setup. The calculations were performed using the formulas: $LOD = 3 \times \sigma / S$ and $LOQ = 10 \times \sigma / S$, where S represents the slope of the calibration curve and σ denotes the standard deviation of the spectral recordings.

The spectra were recorded using the LIFPD setup described in the experimental section, with an optimized set of parameters: pulse energy of 50 mJ, a spot diameter of 1 mm, 10 accumulations per recording, and a gain of 100. The delay time was set to 23 μ s, accompanied by a gate time width of 23 μ s.

Integral intensities of the Re I lines were determined by approximating them with Lorentzian functions, which is appropriate given the negligible contribution of Doppler broadening at temperatures around 10,000. Specifically, the Doppler broadening was calculated to be 1.54 pm for Re I at 488.91 nm and 1.5 pm for W I at 488.69 nm. The Lorentzian profile effectively captures the predominant collisional and natural broadening in this temperature range. The selected line is well-suited for the range of Re concentrations considered in this study.

To evaluate the minimum measurable concentration of rhenium (Re) in relation to experimental error, we employed the Re I line at 488.9 nm recorded from three samples with known concentrations, Fig. 8.

The intensity of this spectral line was plotted against the known concentration of Re to generate a calibration curve, as depicted in Fig. 9. The standard deviation was determined as the average of eight measurements from a target mixture composed of 95% tungsten (W) and 5% rhenium (Re), yielding a value of 308.34.

A linear relationship was established between the intensities of the Re I line at 488.91 nm and the Re concentration, as illustrated in Fig. 9. This finding indicates that the intensity ratio can serve as a reliable indicator of Re concentration in the analyzed samples. The calibration curve's prediction error, calculated as the Root Mean Square Error (RMSE), was found to be 11,354, with a normalized RMSE value of 5.68%. These results demonstrate the robustness of the calibration curve and its potential for accurately quantifying Re concentrations in various applications.

The calculated values for LOD and LOQ were found to be 0.068% (680 ppm or 0.067% at.) and 0.23% (or 2300 ppm or 0.227% at.), respectively. These results represent a significant improvement over previous reports, which indicated a detection limit of approximately 0.5 at.% [26]. This enhancement in sensitivity is crucial for applications requiring precise quantification of trace amounts of rhenium, potentially

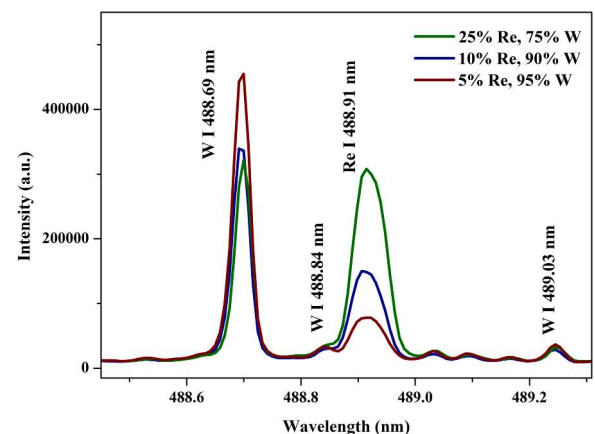


Fig. 8. W I and Re I lines recorded from LIFPD from three samples with known concentrations.

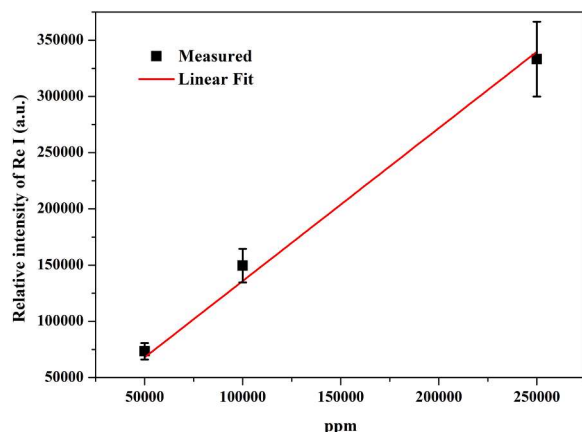


Fig. 9. Calibration curve for determination of LOD for Rhenium in LIFPD.

expanding its applicability in various fields such as materials science and analytical chemistry.

The spectra were also recorded using the standard LIBS setup, with an optimized set of parameters: pulse energy of 50 mJ, a spot diameter of 1 mm, 10 accumulations per recording, and a gain of 150. The delay time was set to 1 μ s, accompanied by a gate time width of 15 μ s.

This is done in order to compare the two methods. For LIBS analysis the standard deviation was calculated to be 260, and the Slope of calibration curve was 0.3701, leading to the value of LOD of 2106 ppm or 0.21%, which is again fairly good result. However, it must be noted that the quality of the fitting is not nearly as good as is in the case of the results obtained with the LIFPD setup. The possible reason is that for the standard LIBS setup, spectra obtained with only 10 accumulations are usually not good enough in terms of reproducibility due to the changes in the amount of ablated material per shot, plasma target shielding for subsequent pulses, more pronounced background in the spectra etc. In addition, the calibration curve in the Fig. 10 is not passing through the coordinate origin as it should, so this additionally speaks in the favour of better reproducibility and higher accuracy of concentration determination with the LIFPD approach.

4. Conclusion

This investigation successfully demonstrates the feasibility of utilizing Laser Induced Breakdown Spectroscopy (LIBS) in conjunction with Fast Pulse Discharge (FPD) to detect low concentrations of rhenium in tungsten samples. Our findings reveal that the proposed method significantly amplifies the spectral signal, achieving a threefold increase in the signal-to-noise ratio and nearly five times greater intensity compared to the conventional LIBS techniques. This amplification is particularly crucial given the anticipated low levels of rhenium resulting from neutron transmutation reactions within the first wall of fusion reactors.

Our experimental approach involved analysis of various tungsten-rhenium alloy specimens, leading to a threshold detection limit of 0.067 at. %. This marks a substantial improvement over previous studies, which reported a detection limit of approximately 0.5 at. % [26].

Our findings indicate that the optimized conditions within our FPD-enhanced LIBS setup enable clear differentiation of the Re I line from tungsten in Helium, thus circumventing potential spectral overlaps caused by the ambient gas.

The LIFPD approach outlined in this research holds promise for enhanced diagnostics of fusion reactor components, allowing for precise monitoring of absorbed neutron levels through the quantification of rhenium. It provides a valuable tool for assessing the integrity and longevity of structural materials in fusion reactors under operational conditions. Future studies should aim to further refine this methodology

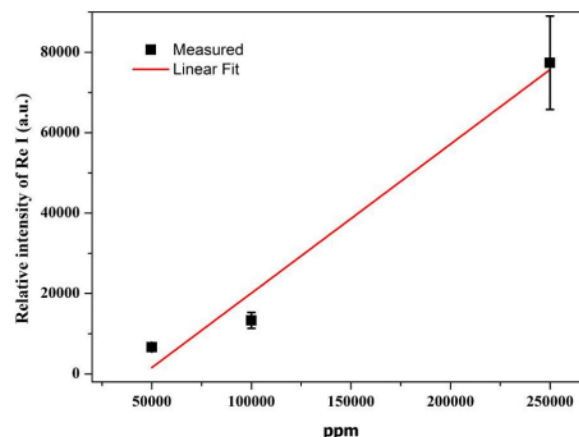


Fig. 10. Calibration curve for determination of LOD for Rhenium in LIBS.

and explore its application in real-time monitoring environments, thereby contributing to the development of safer and more efficient fusion energy systems. This approach is suitable for post-mortem analysis (between experimental campaigns); however, the authors are currently working on a measuring device that will enable the application of this method for real-time in situ measurements (without demounting the components in tokamak).

Additionally, the results of this paper have shown that a standard LIBS setup based on Nd:YAG laser can be successfully applied to quantitative analysis of W/Re composition materials relevant to fusion technology.

Further investigations will focus on optimizing the measurement conditions and exploring the applicability of this method to other analytes, thereby broadening the scope of this analytical technique.

CRediT authorship contribution statement

B.D. Stankov: Investigation, Formal analysis, Writing – original draft. **I. Traparić:** Investigation, Formal analysis, Writing – review & editing. **M. Gavrilović Božović:** Writing – original draft, Formal analysis. **M. Ivković:** Writing – review & editing, Supervision, Conceptualization, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research was funded by the Ministry of Science, Technological Development and Innovations of the Republic of Serbia, Contract numbers: 451-03-68/2022-14/200024, 451-03-66/2024-03/200107 and supported by the Science Fund of the Republic of Serbia, Grant no. 7753287 “NOVA2LIBS4fusion”. The authors thank Stanko Milanovic for technical assistance in preparation and setting up the experiment.

Data availability

Data will be made available on request.

References

- [1] H. Bolt, V. Barabash, W. Krauss, J. Linke, R. Neu, S. Suzuki, N. Yoshida, ASDEX Upgrade Team, Materials for the plasma-facing components of fusion reactors, *J. Nucl. Mater.* 329–333 (2004) 66–73, <https://doi.org/10.1016/j.jnucmat.2004.04.005>.

- [2] V. Philipps, Tungsten as material for plasma-facing components in fusion devices, *J. Nucl. Mater.* 415 (Issue 1) (2011) S2–S9, <https://doi.org/10.1016/j.jnucmat.2011.01.110>. Supplement.
- [3] M. Rieth, R. Doerner, A. Hasegawa, Y. Ueda, M. Wirtz, Behavior of tungsten under irradiation and plasma interaction, *J. Nucl. Mater.* 519 (2019) 334–368, <https://doi.org/10.1016/j.jnucmat.2019.03.035>.
- [4] L.R. Greenwood, F.A. Garner, Transmutation of Mo, re, W, Hf, and V in various irradiation test facilities and STARFIRE, *J. Nucl. Mater.* 212–215 (1994) 635–639, [https://doi.org/10.1016/0022-3115\(94\)90136-8](https://doi.org/10.1016/0022-3115(94)90136-8).
- [5] C.B.A. Forty, G.J. Butterworth, J.-Ch. Sublet, Burnup of some refractory metals in a fusion neutron spectrum, *J. Nucl. Mater.* 212–215 (1994) 640–643, [https://doi.org/10.1016/0022-3115\(94\)90137-6](https://doi.org/10.1016/0022-3115(94)90137-6).
- [6] T. Noda, M. Fujita, Effect of neutron spectra on the transmutation of first wall materials, *J. Nucl. Mater.* 233–237 (1996) 1491–1495, [https://doi.org/10.1016/S0022-3115\(96\)00108-0](https://doi.org/10.1016/S0022-3115(96)00108-0).
- [7] T. Noda, M. Fujita, M. Okada, Transmutation and induced radioactivity of W in the armor and first wall of fusion reactors, *J. Nucl. Mater.* 258–263 (1998) 934–939, [https://doi.org/10.1016/S0022-3115\(98\)00088-9](https://doi.org/10.1016/S0022-3115(98)00088-9). Get rights and content.
- [8] M. Fujitsuka, B. Tsuchiya, I. Mutou, T. Tanabe, T. Shikama, Effect of neutron irradiation on thermal diffusivity of tungsten–rhenium alloys, *J. Nucl. Mater.* 283–287 (2000) 1148, [https://doi.org/10.1016/S0022-3115\(00\)00170-7](https://doi.org/10.1016/S0022-3115(00)00170-7).
- [9] Bo-Yu Wu, Yu-Ping Xu, Yi-Ming Lyu, Xiao-Chun Li, Xiang Geng b, Shou-An Puyang, Xin Shen, Xin-Dong Pan, Hai-Shan Zhou, Guang-Nan Luo, Effects of rhenium content on the deuterium permeation and retention behavior in tungsten, *J. Nucl. Mater.* 565 (2022) 153709, <https://doi.org/10.1016/j.jnucmat.2022.153709>.
- [10] Y. Katoh, L.L. Snead, L.M. Garrison, X. Hu, T. Koyanagi, C.M. Parish, P. D. Edmondson, M. Fukuda, T. Hwang, T. Tanaka, A. Hasegawa, Response of unalloyed tungsten to mixed spectrum neutrons, *J. Nucl. Mater.* 520 (2019) 193–207, <https://doi.org/10.1016/j.jnucmat.2019.03.045>.
- [11] A. Hasegawa, M. Fukuda, S. Nogami, K. Yabuuchi, Neutron irradiation effects on tungsten materials, *Fusion Eng. Des.* 89 (2014) 1568–1572, <https://doi.org/10.1016/j.fusengdes.2014.04.035>.
- [12] T. Tanabe, C. Eamchotchawalit, C. Busabok, S. Taweethavorn, M. Fujitsuka, T. Shikama, Temperature dependence of thermal conductivity in W and W–Re alloys from 300 to 1000 K, *Mater. Lett.* 57 (2003) 2950–2953, [https://doi.org/10.1016/S0167-577X\(02\)01403-9](https://doi.org/10.1016/S0167-577X(02)01403-9).
- [13] R.K. Williams, F.W. Wiffen, J. Bentley, J.O. Stiegler, Irradiation induced precipitation in tungsten based, W–Re alloys, *Metall. Trans. A* 14A (April) (1983) 655–666, <https://doi.org/10.1007/BF02643781>.
- [14] T. Hwang, A. Hasegawa, K. Tomura, N. Ebisawa, T. Toyama, Y. Nagai, M. Fukuda, T. Miyazawa, T. Tanaka, S. Nogami, Effect of neutron irradiation on rhenium cluster formation in tungsten and tungsten–rhenium alloys, *J. Nucl. Mater.* 507 (2018) 78–86, <https://doi.org/10.1016/j.jnucmat.2018.04.031>.
- [15] A. Hasegawa, M. Fukuda, K. Yabuuchi, S. Nogami, K. Imano, D. Nishijima, Y. Ueda, R.P. Doerner, Neutron irradiation effects on the microstructural development of tungsten and tungsten alloys, *J. Nucl. Mater.* 522 (2019) 324–328, <https://doi.org/10.1016/j.jnucmat.2015.10.047>.
- [16] G. Maddaluno, S. Almaviva, L. Caneve, F. Colao, V. Lazic, L. Laguardia, P. Gasior, M. Kubkowska, FTU team, Detection by LIBS of the deuterium retained in the FTU toroidal limiter, *Nucl. Mater. Energy* 18 (2019) 208–211, <https://doi.org/10.1016/j.nme.2018.12.029>.
- [17] F. Colao, et al., LIBS experiments for quantitative detection of retained fuel, *Nucl. Mater. Energy* 12 (2017) 133–138, <https://doi.org/10.1016/j.nme.2017.05.010>.
- [18] P. Paris, I. Jögi, K. Piip, M. Passoni, D. Dellasega, E. Grigore, W.M. Arnoldbik, H. van der Meiden, In-situ LIBS and NRA deuterium retention study in porous W-O and compact W coatings loaded by Magnum-PSI, *Fusion Eng. Des.* 168 (2021) 112403, <https://doi.org/10.1016/j.fusengdes.2021.112403>.
- [19] P.G. Bhat, et al., LIBS depth profiling of Be-containing samples with different gaseous impurity concentrations, *Nucl. Mater. Energy* 37 (2023) 101549, <https://doi.org/10.1016/j.nme.2023.101549>.
- [20] S. Feng, C. Ke, Y. Chen, H. Zhang, Y. He, Y. Zhao, CF-LIBS analysis in depth profile of lithium corrosion resistance of Er₂O₃ coatings prepared by sol-gel method, *Fusion Eng. Des.* 170 (2021) 112506, <https://doi.org/10.1016/j.fusengdes.2021.112506>.
- [21] Y. Li, C. Ke, X. Liu, F. Gou, X. Duan, Y. Zhao, Analysis liquid lithium corrosion resistance of Er₂O₃ coating revealed by LIBS technique, *Fusion Eng. Des.* 136 (2018) 1640–1646, <https://doi.org/10.1016/j.fusengdes.2018.07.001>.
- [22] H. Wu, R. Yi, A. Houben, S. Brezinsek, M. Rasinski, C. Li, G. Sergienko, Y. Liang, T. Dittmar, H. Ding, Study of spectral features and depth distributions of boron layers on tungsten substrates by ps-LIBS in a vacuum environment, *Nucl. Mater. Energy* 41 (2024) 101812, <https://doi.org/10.1016/j.nme.2024.101812>.
- [23] Z. Hu, X. Bai, H. Wu, R. Hai, F. Ding, M. Imran, C. Li, H. Ding, G.N. Luo, Quantitative analysis of impurities deposited on the Plasma-Facing components of EAST tokamak using a portable LIBS device, *Nucl. Mater. Energy* 41 (2024) 101785, <https://doi.org/10.1016/j.nme.2024.101785>.
- [24] H.J. van der Meiden, S. Almaviva, J. Butikova, V. Dwivedi, P. Gasior, W. Gromelski, A. Hakola, X. Jiang, I. Jögi, J. Karhunen, M. Kubkowska, M. Laan, G. Maddaluno, A. Marín-Roldán, P. Paris, K. Piip, M. Písařík, G. Sergienko, M. Veis, P. Veis, S. Brezinsek and the EUROfusion WP PFC, Monitoring of tritium and impurities in the first wall of fusion devices using a LIBS based diagnostic, 61 (2021) 125001 (14pp) doi [10.1088/1741-4326/ac31d6](https://doi.org/10.1088/1741-4326/ac31d6).
- [25] Dongye Zhao, Ding Wu, Jannis Oelmann, Sebastijan Brezinsek, Qingmei Xiao, Rongxing Yi, Laizhong Cai, Hongbin Ding, Highly depth-resolved characterization of fusion-related tungsten material based on picosecond laser-induced breakdown spectroscopy, *J. Anal. At. Spectrom.* 35 (12) (2020) 2867–2879, <https://doi.org/10.1039/D0JA00340A>.
- [26] K. Imano, D. Nishijima, Y. Ueda, R.P. Doerner, LIBS measurement of trace tantalum and rhenium in tungsten for in-situ diagnostic of nuclear transmutation, *J. Nucl. Mater.* 522 (2019) 324–328, <https://doi.org/10.1016/j.jnucmat.2019.05.030>.
- [27] M.R. Gilbert, J.-C. Sublet, Neutron-induced transmutation effects in W and W-alloys in a fusion environment, *Nucl. Fusion* 51 (2011) 043005, <https://doi.org/10.1088/0029-5515/51/4/043005>.
- [28] M. Vinić, M. Ivković, Laser ablation initiated fast discharge for spectrochemical applications, *Hem. Ind.* 68 (3) (2014) 381–388, <https://doi.org/10.2298/HEMIND130314065V>.
- [29] D. Nishijima, Y. Ueda, R.P. Doerner, M.J. Baldwin, K. Imano, Laser-induced breakdown spectroscopy measurement of a small fraction of rhenium in bulk tungsten, *Spectrochim. Acta Part B At. Spectrosc.* 141 (2018) 94–98, <https://doi.org/10.1016/j.sab.2018.01.013>.
- [30] J. Liu, D. Wu, X. Hu, S. Liu, H. Wu, R. Hai, C. Li, H. Ding, Study of spectral intensity of the laser ablated tungsten plasma and ablation mass at various laser spot sizes and laser fluence in vacuum environment, *Spectrochim. Acta Part B At. Spectrosc.* 199 (2023) 106569, <https://doi.org/10.1016/j.sab.2022.106569>.
- [31] M. Ivkovic, J. Savovic, B.D. Stankov, M. Kuzmanovic, I. Traparic, LIBS depth-profile analysis of W/Cu functionally graded material, *Spectrochim. Acta Part B At. Spectrosc.* 213 (2024) 106874, <https://doi.org/10.1016/j.sab.2024.106874>.
- [32] N. Konjević, M. Ivković, N. Sakan, Hydrogen balmer lines for low electron number density plasma diagnostics, *Spectrochim. Acta Part B At. Spectrosc.* 76 (2012) 16–26, <https://doi.org/10.1016/j.sab.2012.06.026>.
- [33] D.E. Kelleher, Stark broadening of visible neutral helium lines in a plasma, *J. Quant. Spectrosc. Radiat. Transf.* 25 (1981) 191–220.
- [34] A. Czernichowski, J. Chapelle, Use of the 447 nm He I line to determine electron concentrations, *J. Quant. Spectrosc. Radiat. Transf.* 33 (1985) 427–436.



PAPER

RECEIVED
27 February 2026

REVISED
25 March 2026

ACCEPTED FOR PUBLICATION
31 March 2026

PUBLISHED
20 April 2026

Functional model of modular measuring head for *in situ* low pressure LIBS on complex surface geometries

M Ivković^{1,*} , N Vujadinović¹ , I Traparić¹ , B D Stankov¹ , M Gavrilović-Božović²,
M Kuzmanović³ and J Savović⁴

¹ Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia

² Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia

³ Faculty of Physical Chemistry, University of Belgrade, 11158 Belgrade, Serbia

⁴ Vinca Institute of Nuclear Sciences, University of Belgrade, 11000 Belgrade, Serbia

* Author to whom any correspondence should be addressed.

E-mail: ivke@ipb.ac.rs

keywords: *in-situ* elemental analysis, modular LIBS measuring head, vacuum sealing, surface adapted spectroscopic diagnostics

Supplementary material for this article is available [online](#)

Abstract

Low-pressure laser-induced breakdown spectroscopy (LP-LIBS) offers improved spectral resolution relative to atmospheric pressure operation due to reduced line broadening and may also improve the signal-to-noise ratio (SNR). However, implementing LP-LIBS for *in-situ* material characterization presents significant technical challenges, particularly in maintaining stable LP conditions during measurements. The aim of this work is to, for the first time, present design, construction, and validation of a modular LIBS measuring head (MH) specifically engineered for *in situ* operation at reduced pressures (1–200 mbar) with adaptable sealing configurations. The system features three distinct vacuum sealing approaches, interchangeable adapters for various surface geometries, and the capability for integration with advanced plasma excitation techniques including high-voltage discharge enhancement. Experimental validation using multiple elastomer materials demonstrates effective sealing across diverse surface conditions, achieving pressures below 1 mbar on smooth surfaces and maintaining stable conditions at 10–20 mbar up to atmospheric pressure during spectroscopic measurements. Spectroscopic characterization confirms the absence of atmospheric contamination and demonstrates analytical performance comparable to conventional vacuum chamber LIBS setups. The modular design enables customization for specific analytical requirements, including spatial confinement, magnetic field application, and discharge-enhanced excitation schemes. Spectroscopic testing also revealed that the achieved SNR in the MH with CCD camera is around 3000, while realized discharge-enhanced excitation scheme caused eightfold increase in Cu I line intensities. This versatile MH addresses critical technical barriers in LP-LIBS implementation and extends the technique's applicability to challenging *in-situ* analysis scenarios across materials science, industrial diagnostics, and specialized applications requiring controlled LP environments including diagnostics of plasma facing components of fusion related reactors.

1. Introduction

Laser-induced breakdown spectroscopy (LIBS) has emerged as a powerful analytical technique for rapid, multi-element material characterization with minimal sample preparation requirements [1–6]. The technique relies on focusing a high-energy laser pulse onto a material surface, creating localized plasma through laser ablation. Spectroscopic analysis of the plasma emission enables qualitative and quantitative determination of elemental composition with high sensitivity and spatial resolution. The application scope of LIBS is vast and diverse, encompassing the analysis of soils [7], organic samples [8–10], explosives detection [11], olive oil classification [12] and many other fields.

Achieving optimal analytical performance in LIBS requires careful control and optimization of the camera recording time as well as the laser parameters (wavelength, energy, and spot size) [13–15]. Besides this, a critical parameter influencing LIBS analytical performance is the ambient gas environment, particularly the pressure at which measurements are conducted. While atmospheric pressure LIBS offers operational simplicity, numerous studies have demonstrated that LP operation (typically 1–100 mbar) provides substantial advantages [16–22]: (1) enhanced signal intensity: reduced gas pressure decreases collisional quenching of excited states, prolonging plasma emission lifetime and substantially increasing spectral line intensities [16, 17]; (2) improved signal-to-noise ratio (SNR): lower background continuum emission at reduced pressures significantly improves detection limits, particularly for trace element analysis [18, 19]; (3) superior spectral resolution: decreased pressure broadening of spectral lines enables better resolution of closely-spaced transitions, critical for isotopic analysis and complex spectral regions [20, 21]; (4) reduced matrix effects: lower pressure conditions can minimize self-absorption effects and improve calibration linearity across wider concentration ranges [22].

Despite these well-documented advantages, practical implementation of LP-LIBS faces significant technical challenges. Conventional approaches typically require placing samples inside vacuum chambers, which severely limits *in-situ* and field applications. This constraint has restricted LP-LIBS primarily to laboratory settings where samples can be transported and analyzed under controlled conditions [19, 23].

Several research groups have attempted to address this limitation through innovative instrumental designs. Portable LIBS systems operating at atmospheric pressure have been extensively developed [24], offering field deployment capabilities but sacrificing the analytical advantages of LP operation. Gas-purging methods, where controlled gas atmospheres are delivered to the measurement point through nozzles or flow cells, represent an intermediate approach [25, 26]. However, these configurations cannot achieve the optimal pressure ranges (10–20 mbar for many applications) where LP-LIBS demonstrates maximum analytical performance.

This work addresses these limitations by presenting a comprehensive solution for versatile LP-LIBS implementation: a modular measuring head (MH) designed specifically for operation at controlled low pressures (1–200 mbar) with adaptable configurations for various analytical requirements and surface geometries. The system features three distinct vacuum-sealing configurations optimized for different surface conditions and pressure requirements and a modular adapter architecture that enables measurements on diverse surface geometries and sample types. In addition, the MH is compatible with both manual operation using telescopic arms and robotic manipulation systems, and includes provisions to prevent sample contamination and memory effects through the use of replaceable protective components.

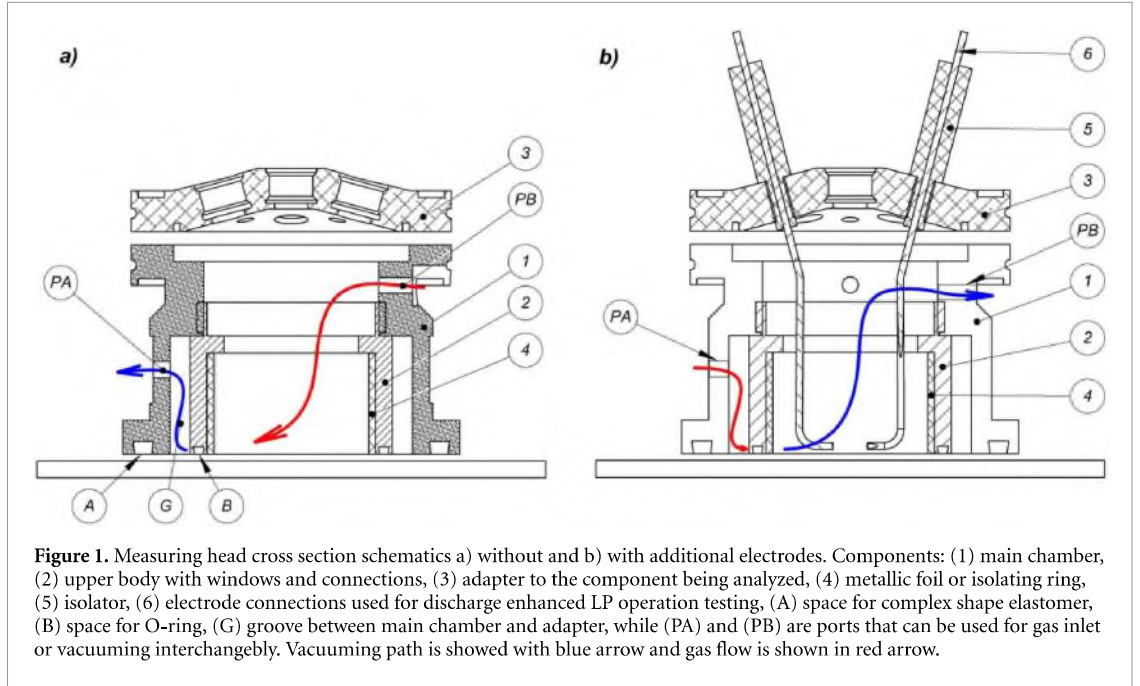
The development approach prioritized practical functionality and experimental validation. Extensive leak rate testing was conducted across various elastomer materials and surface conditions to characterize sealing performance. Spectroscopic validation confirmed the absence of atmospheric contamination under operating conditions and demonstrated analytical capabilities comparable to conventional vacuum chamber LIBS setups.

The modular LP-LIBS instrumentation presented in this work also establishes a framework that can be adapted to specialized techniques for LIBS signal amplification and consequent increase in its analytical performance. The MH architecture readily accommodates modifications for spatially-confined plasma generation [27], magnetic field application for emission enhancement [28], and integration with complementary excitation schemes such as laser-induced fast pulse discharge (LIFPD) [21, 29] or microwave-induced plasma coupling [30].

The remainder of this paper is organized as follows: section 2 describes the complete LIBS system architecture, with detailed focus on the MH design, sealing mechanisms, and system components. Section 3 presents experimental validation results, including leak rate characterization, spectroscopic verification of LP operation, and demonstration of discharge-enhanced LIBS within the MH. Section 4 discusses the implications of this work for LP-LIBS applications and outlines potential extensions of the technology. Section 5 provides concluding remarks on the significance and future directions of this development.

2. LIBS system design

The complete LP-LIBS system comprises three main components: (1) the MH, which creates and maintains the LP environment at the measurement location; (2) the main unit (MU), containing lasers, spectrometers, gas handling equipment, and control electronics; and (3) the remote control system (RC),



enabling operation and monitoring. This modular architecture separates the compact, adaptable MH from the larger equipment components, facilitating flexible deployment strategies.

2.1. MH construction

The MH represents the core innovation of this work, designed specifically to create and maintain stable LP conditions during LIBS measurements without requiring sample placement in a vacuum chamber. The complete assembly consists of three primary components: the main chamber (1), the upper body with optical and connection ports (2) and the surface adapter (3), as illustrated in figure 1(a).

2.1.1. Main chamber design

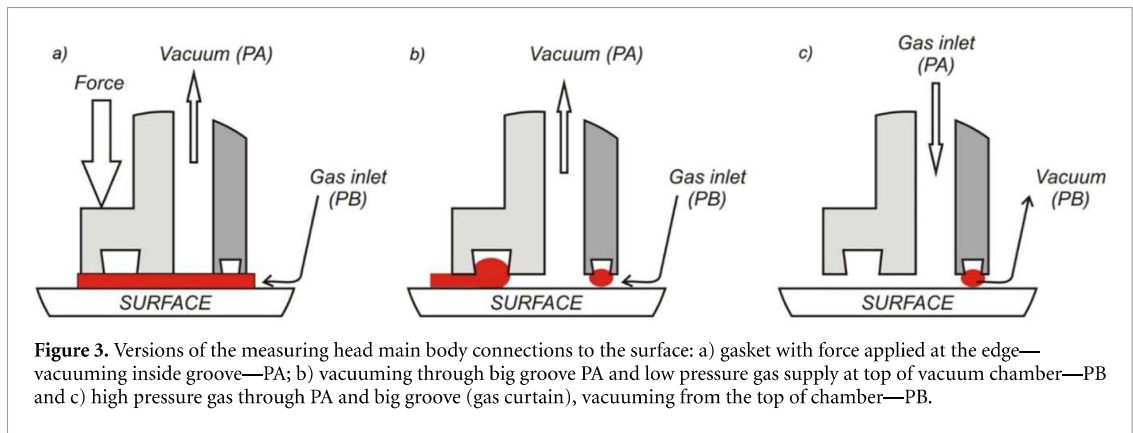
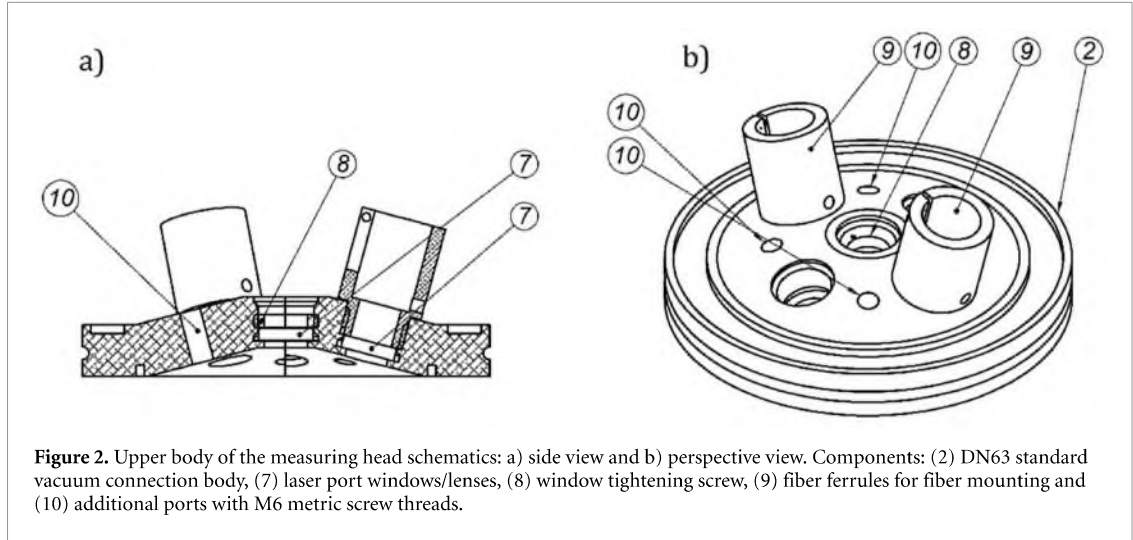
The main chamber establishes the controlled LP volume for plasma generation and spectroscopic observation. In the functional prototype presented here, the internal measurement volume has dimensions of $\phi 5 \text{ cm} \times 4.5 \text{ cm}$, with an outer diameter of 10 cm. This relatively compact design enables operation in confined spaces while providing sufficient volume for plasma evolution without significant wall interactions.

The chamber incorporates several critical design features: (1) protective components: a 5 mm annular rim at the upper adapter interface accommodates easily replaceable metallic foil, glass, or ceramic rings (component 4 in figure 1(a)). These protective elements serve dual purposes: (a) preventing plasma propagation to sealing components at the chamber bottom, and (b) minimizing deposition of ablated material on chamber walls that could cause memory effects and compromise measurement accuracy; (2) vacuum/gas ports: two strategically positioned ports (PA and PB) enable vacuum pumping, controlled gas supply, and pressure monitoring. The specific roles of these ports depend on the selected sealing configuration (detailed in section 2.1.3); (3) sealing grooves: a 30 mm deep, 5 mm wide primary groove (G) between the main chamber and adapter, along with two smaller grooves (A and B) at the chamber bottom, accommodate various elastomer configurations for different sealing strategies and surface conditions.

The modular design philosophy extends to dimensional scalability. For applications requiring analysis of larger or smaller components, the adapter (component 3 in figure 1(a)) can be redesigned while maintaining compatibility with the main chamber. This approach enables a single main chamber/upper body assembly to serve diverse analytical requirements through adapter exchange.

2.1.2. Upper body and optical configuration

The upper body (component 2 in figure 1(a)) is based on a standard DN63 vacuum flange and provides all optical access and auxiliary connections. The design features:



- (1) Optical windows: five ports are distributed across the flange—one central and four radially positioned openings (components 7 in figure 2(a)). The configuration accommodates: two laser beam entry paths (enabling dual-pulse LIBS), one emission collection path, one illumination/observation path for endoscopic monitoring, and one auxiliary path for flexibility. All optical windows utilize double O-ring seals secured with screws, ensuring reliable vacuum sealing while enabling straightforward window replacement for different wavelength ranges or optical configurations.
- (2) Fiber coupling: integrated ferrules (component 9 in figure 2(b)) provide secure mounting for optical fiber cables, both for laser delivery and emission collection.
- (3) Auxiliary ports: four additional M6-threaded ports (components 10 in figure 2) serve multiple functions: vacuum connections, gas supply lines, high-voltage electrical feedthroughs for discharge enhancement, aiming beam entrances, or spare capacity for future modifications.

This standardized flange approach facilitates customization while maintaining compatibility with commercial vacuum components and optical mounts.

2.1.3. Sealing configurations and operating modes

The MHs versatility stems from three distinct sealing configurations, each optimized for specific pressure requirements and surface conditions. All configurations maintain the same main chamber geometry while varying the sealing approach and gas flow patterns.

Configuration A: simple gasket sealing (figure 3(a))

This configuration employs a thin elastomeric gasket (highlighted in red in **figure 3(a)**) with inner diameter exceeding 50 mm and outer diameter up to 100 mm. The gasket directly contacts the component surface, creating a seal sufficient for operation at moderate pressures (10–100 mbar) or when using inert gas atmospheres where minor air infiltration is tolerable. Mechanical pressure applied to the MH

(indicated by arrow in figure 3(a)) compresses the gasket against the surface. Port PB supplies the working gas while port PA connects to vacuum pump. This straightforward approach works well for relatively smooth, non-porous surfaces and applications not requiring ultra-low pressure or high atmospheric purity.

Configuration B: differential pressure sealing (figure 3(b))

This advanced configuration addresses analysis of rough or moderately irregular surfaces while maintaining LP capability. The design utilizes two independent sealing zones with differential pressure control:

- (1) Outer seal (groove A): a specially-shaped elastomer $118 \times 83 \times 8.5$ mm, (see section 2.1.4 and figure 3 in supplementary material for details) prevents atmospheric air ingress and working gas egress. This primary seal accommodates surface irregularities through both material compliance and extended contact length.
- (2) Inner seal (groove B): a standard O-ring limits gas flow from the measurement chamber interior without directly contacting the analyzed surface. This configuration maintains a pressure gradient: atmospheric outside, intermediate in groove G, and controlled low pressure in the measurement chamber.
Continuous evacuation through the primary groove G (via port PA) removes any leaked atmospheric gas before it reaches the measurement volume. Working gas supplied through port PB establishes the desired pressure in the measurement chamber.

This configuration proved essential for irregular surfaces where simple gasket sealing could not achieve adequate vacuum, as demonstrated in section 3.1.

Configuration C: gas Curtain Sealing (figure 3(c))

For applications requiring atmospheric isolation without ultra-low pressure, or when surface contact must be minimized, this configuration employs controlled gas overpressure.

Gas supplied through port PA at pressure slightly exceeding atmospheric creates an outward flow that prevents air ingress while the inner O-ring (groove B) limits gas flow into the measurement chamber. The mass flow controller-manometer feedback loop maintains constant chamber pressure despite continuous gas consumption.

This approach minimizes contact with the analyzed surface and enables operation on delicate or contamination-sensitive materials. The configuration is particularly suitable for applications requiring inert atmospheres at moderate pressures (10–200 mbar) rather than high vacuum conditions.

The insertion of the working gas can be realized through additional ports of the upper body of the MH (components 10 in figure 2(b)).

Adapter customization

For components with geometries incompatible with the standard MH interface, custom adapters (component 3 in figure 1(a)) can be fabricated. The modular design enables adapter shapes conforming to complex surface geometries, including non-circular cross-sections matching rectangular or irregular component shapes, curved bottom surfaces conforming to cylindrical or complex curvatures, extended or reduced height profiles for optimal positioning relative to optical paths or integrated features for specialized plasma confinement or excitation schemes.

The adapter's upper portion maintains standardized threading for attachment to the main chamber, while the lower section is customized for the specific application. This approach provides maximum flexibility without requiring multiple complete MH assemblies.

2.1.4. elastomer requirements and selection

Effective vacuum sealing across diverse surface conditions requires careful elastomer material selection and geometric optimization. The performance of LP-LIBS measurements depends critically on achieving and maintaining the target pressure range, making seal quality a dominant factor in system capability.

Material selection must balance multiple factors such as operating temperature range (room temperature to ~ 100 °C for LIBS applications), pressure differential capabilities (1–1000 mbar differential), chemical compatibility with working gases and potential contaminants, surface conformability and recovery properties, long-term stability and compression set resistance, as well as assembly and maintenance requirements.

Elastomer geometries

Two distinct geometries serve different sealing functions:

- (1) Inner seal (groove B): standard O-rings (in this implementation) provide reliable restriction of gas flow into the measurement volume. The circular cross-section offers excellent sealing with minimal contact force, reducing potential for surface damage or contamination.
- (2) Outer seal (groove A): a custom complex profile (detailed design in supplementary material) optimizes two critical functions: adequate filling of the groove depth to establish primary containment, and extended ‘tail’ section providing prolonged surface contact to enhance sealing capacity despite surface irregularities.

This specialized geometry cannot be produced from standard O-ring stock. A custom manufacturing tool was developed to fabricate these seals from various elastomer materials, enabling systematic testing and optimization.

Elastomer materials

Four elastomer materials were evaluated for sealing performance:

- Silicone rubber (Q): 40 Shore A hardness—excellent flexibility and recovery
- Natural rubber (NR): 45 and 55 Shore A hardness—good general-purpose properties
- Nitrile butadiene rubber (NBR): 70 Shore A hardness—superior chemical resistance

Comprehensive leak rate testing (section 3.1) revealed that hardness is a dominant parameter for rough surface applications, with the 70 Shore NBR providing optimal performance. For porous surfaces, the softer 40 Shore silicone demonstrated advantages through enhanced conformability. All sealing components use the same $118 \times 83 \times 8.5$ mm dimensions for consistency.

Detailed drawings, photographs of manufactured seals, and the fabrication tool design are provided in the supplementary material.

2.2. MU and system integration for *in-situ* operation

While the MH constitutes the primary innovation, the complete LP-LIBS system for *in-situ* operation will require integrated support equipment for operation. MU should house all components except the MH itself, enabling either centralized operation from a control room or field deployment on a mobile cart.

2.2.1. Essential equipment components

Essential equipment encompasses:

Laser System: One or two Q-switched Nd:YAG lasers (for single or dual-pulse LIBS) with power supplies, beam conditioning optics, and fiber coupling assemblies. The optical train includes beam expanders, spatial filters, and precision alignment mechanisms for efficient fiber coupling while preventing fiber damage (discussed in section 2.2.2).

Detection system: spectrometer(s) equipped with intensified CCD and/or standard CCD cameras, depending on temporal resolution requirements. For applications requiring high spectral resolution ($R > 20\,000$), echelle spectrometers provide optimal performance. Segmented spectrometers offer advantages for surveys requiring broad spectral coverage.

Fiber optic coupling: F-matcher optics transfer emission from collection fibers to spectrometer entrance slits with appropriate magnification and illumination characteristics.

Gas handling: mass flow controllers, pressure gauges (capacitive manometers for accuracy at low pressure), and control electronics maintain target pressure with feedback regulation. Small gas cylinders (1–2 l) provide sufficient capacity for extended operation given the low flow rates required.

Vacuum system: compact rotary vane pump ($15\text{ m}^3\text{ h}^{-1}$ capacity sufficient for this application) with valves and pressure monitoring.

Power supply systems: AC mains distribution and DC power supplies for all subsystems. Optional high-voltage DC supply and storage capacitors for discharge-enhanced LIBS modes.

Advanced options: microwave generators for coupled laser ablation/microwave-induced plasma techniques [30], additional discharge power supplies for alternative excitation modes.

Data acquisition and control: computer system with camera interfaces, spectrometer control software, data analysis capabilities, and process control for gas handling and safety interlocks.

2.2.2. Fiber optic considerations for laser delivery

Transmitting high-energy laser pulses through optical fibers presents significant technical challenges due to fiber damage thresholds. Published studies demonstrate permanent damage to hard-clad silica and plastic-clad-silica fibers at energies as low as few mJ [31]. For the typical pulse energies required for LIBS (50–200 mJ), two approaches enable safer fiber transmission:

- (1) Low-energy operation: core diameters $\geq 600\text{ }\mu\text{m}$ with careful coupling optics enable transmission of 20–50 mJ pulses suitable for many LIBS applications [32–35].
- (2) Hollow-core fibers: gas-filled hollow waveguides tolerate higher energies through reduced interaction with solid material [36]. Gas circulation through the fiber bore provides cooling and prevents damage accumulation.

All fiber coupling systems incorporate precision x – y – z positioning stages for optimal beam alignment and diverging beam geometry (focus position before fiber entrance) to prevent air breakdown at the coupling interface.

2.2.3. RC and monitoring

The RC system provides wireless communication between the MH location and operator station, essential for applications where direct line-of-sight is unavailable or operator presence near the measurement point is undesirable.

Video monitoring: endoscopic camera system with integrated LED illumination enables real-time observation of the measurement area, target surface, and plasma generation. The compact camera (7 mm diameter) with 5 m light guide provides adequate resolution (640×480 pixels) for targeting and process monitoring.

System status: wireless displays show critical parameters including pressure, gas flow rates, laser energy, and spectral acquisition status.

Safety interlocks: remote emergency shutdown capability and automated safety responses to fault conditions (pressure loss, laser interlock violations, etc).

The complete system architecture enables flexible operation modes: fully automated sequences for routine measurements, manual control for method development and optimization, or hybrid approaches combining automated measurement protocols with operator oversight.

3. Experimental validation

Experimental testing validated three critical aspects of the MH performance: (1) sealing effectiveness across various surface conditions and elastomer materials, (2) spectroscopic verification of LP operation without atmospheric contamination, and (3) analytical capabilities including advanced excitation modes. These evaluations establish the practical functionality of the proposed LP-LIBS configuration.

3.1. Sealing performance and leak rate characterization

Quantitative assessment of sealing performance provides essential data for optimizing elastomer selection and predicting operational capabilities across diverse surface conditions.

The MH was connected to a rotary vane vacuum pump (Alcatel 2012 A, $15\text{ m}^3\text{ h}^{-1}$ pumping speed) through both PA and PB ports (Configurations A, B and C from figure 3). Pressure was monitored with a Leybold Heraeus DV 1000 manometer.

Table 1. Experimental testing of different elastomers leak rates.

Elastomer type	Surface	Time (s)	Leak rate(mbar cm ³ s ⁻¹)
Silicone rubber(Q, 40 Shore A)	Stone	90	9.7
	Rough metal	270	3.2
	Wood varnished	300	2.9
	Polished metal	330	2.6
Nitrile butadiene rubber(NBR, 70 Shore A)	Stone	10	87.0
	Wood varnished	310	2.8
	Rough metal	315	2.8
	Polished metal	330	2.6

Validation testing with a soft rubber gasket in configuration A (figure 3(a)) demonstrated that pressures below 1 mbar were achieved using either port for vacuum pumping, confirming adequate sealing performance. Mechanical pressure was applied initially and was no longer required once low pressure was reached.

In configuration B (figure 3(b)), after evacuating to <0.1 mbar, a needle valve isolated the MH from the pump and pressure evolution was monitored. The time required for pressure to increase from 0.1 to 10 mbar characterized the leak rate for each surface/elastomer combination. Leak rate was calculated as $Q = V \cdot dP/dt$, where V denotes the volume of the MH and dP/dt is the rate of change of pressure (here fixed to 9.9 mbar). Test surfaces included stone (porous, rough), varnished wood (non-porous, smooth), rough machined metal and polished metal.

Table 1 presents leak rates for silicone rubber (Q, 40 Shore A) and nitrile butadiene rubber (NBR, 70 Shore A) used in configuration B (figure 3(b)). The two natural rubber formulations (45 and 55 Shore A) showed performance within experimental uncertainty of these values and are not separately tabulated. Key findings can be summarized as follows:

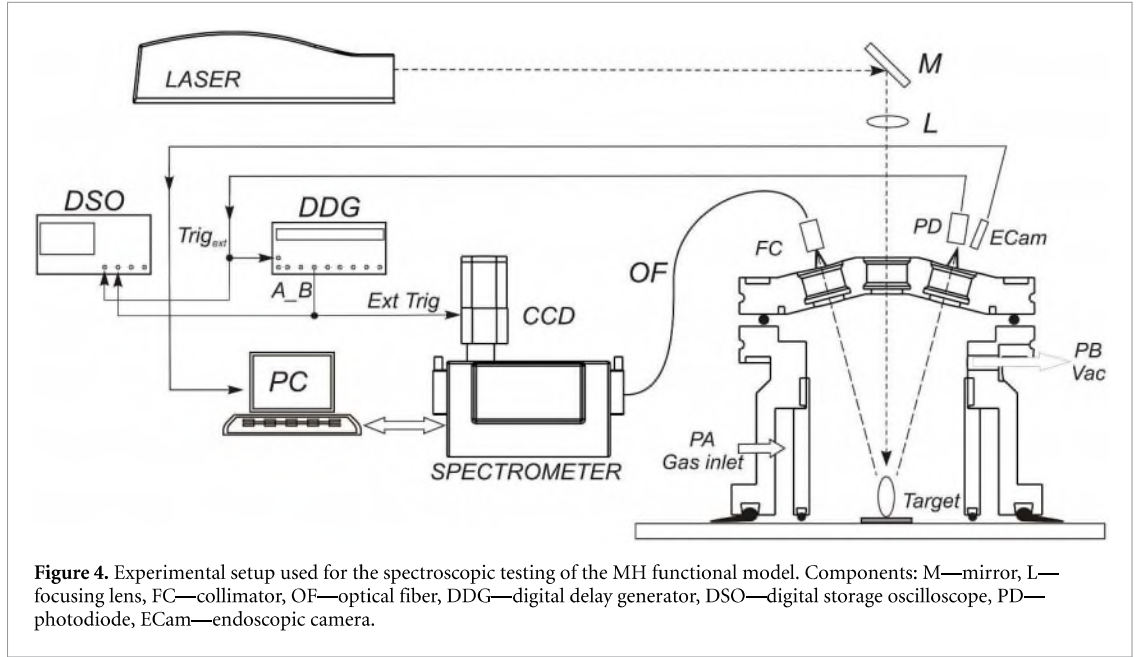
- (1) *Surface hardness dominance:* for rough, non-porous surfaces (rough metal, varnished wood, polished metal), the harder NBR (70 Shore) demonstrated equal or slightly better sealing with leak rates 0.27–0.29 bar cm³ s⁻¹ compared to 0.27–0.33 bar cm³ s⁻¹ for silicone.
- (2) *Porous surface exception:* on porous substrate (stone), the softer silicone rubber (40 Shore) performed markedly better, with leak rates around 10 times lower than NBR. The enhanced conformability of softer elastomers enables penetration into surface porosity for improved sealing.
- (3) *Pump capacity validation:* the measured leak rates confirmed that continuous pumping at 15 m³ h⁻¹ capacity maintains stable LP conditions even on moderately rough surfaces. These results guided subsequent spectroscopic testing, with NBR 70 Shore selected for smooth and rough metal surfaces (most relevant for typical LIBS applications) and silicone 40 Shore reserved for porous materials.

Configuration C (figure 3(c)) was tested to determine whether argon flow through port PA disrupts the pressure established in the vacuum chamber, which is evacuated through port PB. The test surfaces included rough machined metal and stone. The lowest pressures achieved prior to initiating the argon gas curtain were 12 mbar for the rough-machined metal and 14 mbar for the stone surface. After initiation of the argon flow at 25 l min⁻¹, corresponding to an overpressure of 130 mbar above atmospheric pressure, the pressure inside the vacuum chamber remained unchanged for both test surfaces. These results demonstrate that configuration C can achieve and maintain low pressures suitable for LIBS applications while effectively preventing the ingress of ambient gas.

3.2. Spectroscopic verification of LP operation

Beyond mechanical leak rate measurements, spectroscopic analysis provides definitive confirmation that the MH maintains atmospheric isolation during plasma generation and emission collection.

Figure 4 illustrates the complete system used for spectroscopic testing. The laser source was a Quantel QSmart 450 Nd:YAG laser operating at the fundamental wavelength of 1064 nm, with a maximum energy of 450 mJ, pulse duration of 6 ns, repetition rate of 10 Hz, beam diameter of 6 mm, and divergence below 0.5 mrad. The laser beam was focused using a plano-convex lens with a focal length of 100 mm, positioned 90 mm from the target surface, producing an approximately 1 mm diameter focal spot with fluence sufficient for reliable plasma generation on copper targets. Copper samples were mounted on precision positioning stages consisting of computer-controlled XY stepper motors and



a pitch/roll platform, enabling fresh surface exposure for each measurement sequence. The MH was mounted on a flat rough steel plate and evacuated using Configuration B (figure 3(b)), while a continuous helium flow maintained a stable low pressure during measurements. Plasma emission was collected by a collimator (FC) and guided via an round to linear optical fiber (core diameter $\varnothing 400\ \mu\text{m}$, NA 0.22, 99% transmission efficiency in wavelength range of interest) to the entrance slit of the spectrometer. Detection was performed using a SOL Instruments MS7504i imaging spectrometer equipped with a $1200\ \text{l mm}^{-1}$ grating (wavelength resolution $0.03\ \text{nm}$ at blaze wavelength with $20\ \mu\text{m}$ entrance slit and $12\ \mu\text{m}$ pixel size CCD camera) and a Proscan HS 101 H CCD camera (2048×506 , pixel size $12 \times 12\ \mu\text{m}$, Peltier cooling, minimum gate width $1\ \text{ms}$) cooled down to $-10\ ^\circ\text{C}$, with full spectral coverage from 350 to $780\ \text{nm}$ achieved by sequential grating rotation. Real-time monitoring of plasma generation and target surface condition was provided by an endoscopic camera with a resolution of 640×480 pixels, six LED illumination, and a $5\ \text{m}$ light guide.

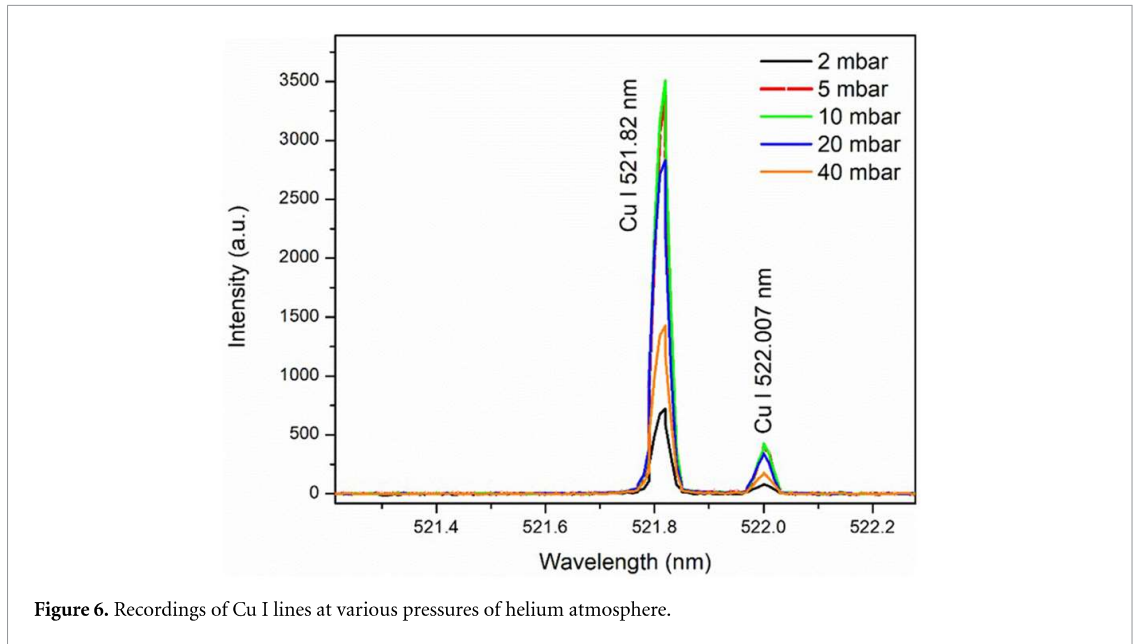
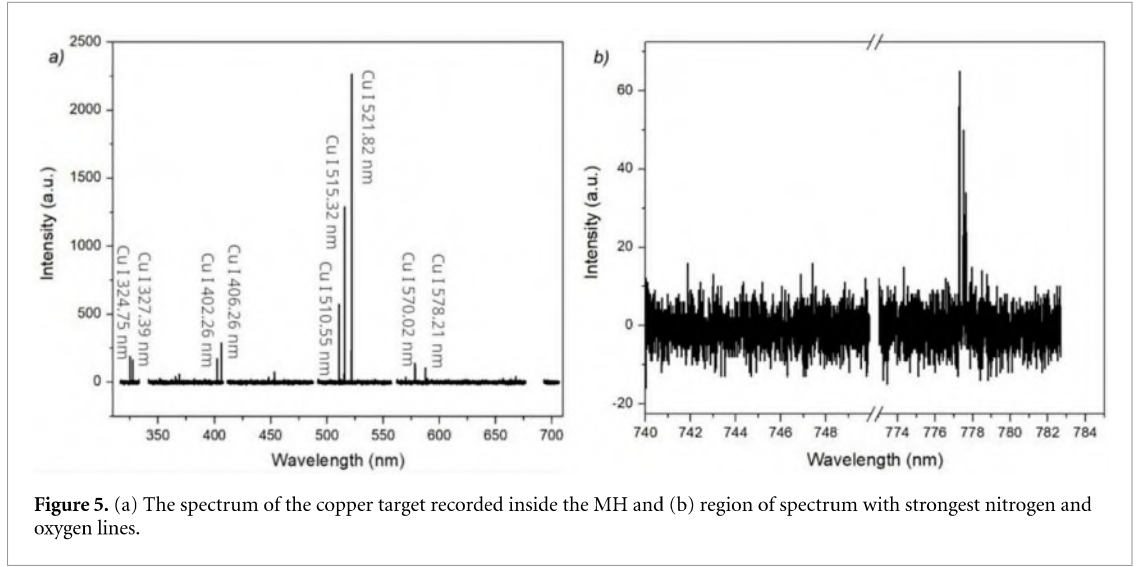
The system was operated at a laser energy of $E = 179 \pm 2\ \text{mJ}$ and wavelength $\lambda = 1064\ \text{nm}$. The spectrometer slit width was set to $50\ \mu\text{m}$. Camera requested a trigger TTL signal of $5\ \text{V}$ amplitude and minimum width of $20\ \mu\text{s}$, hence the triggering was controlled by controlled by a digital delay generator (DDG), while a delay time of $1\ \mu\text{s}$ and a gate width of $1\ \text{ms}$ were set. The helium pressure was $10\ \text{mbar}$ for full spectral measurements, while for pressure-dependence studies it was varied between 2 and $40\ \text{mbar}$.

The recorded complete spectrum (figure 5(a)) exhibits strong copper emission lines throughout the 350 – $700\ \text{nm}$ range, with Cu I multiplets at 510.6 , 515.3 and $521.8\ \text{nm}$ showing highest intensity. The helium working gas is barely detectable (He I line at $587.6\ \text{nm}$ shows intensity more than 20 times weaker than copper lines). Most significantly, hydrogen Balmer lines are completely absent, confirming effective exclusion of atmospheric moisture.

No emission from the aluminum alloy chamber walls was detected, verifying that plasma dimensions and energy remain confined to the target region without wall interactions that could cause contamination or memory effects.

Examination of the 740 – $785\ \text{nm}$ region (figure 5(b)) reveals that the strongest oxygen emission line from the multiplet at around $777\ \text{nm}$ is hardly distinguishable from the noise, while strong nitrogen emission lines around $740\ \text{nm}$ are completely absent and remain below the detection limit. These observations confirm that Configuration B sealing (figure 3(b)) effectively prevents atmospheric ingress even during continuous plasma generation. Any leaked atmospheric gases are removed through the differential pumping groove G before reaching the measurement chamber.

For the pressure-dependence investigation, copper resonance line intensity and profile were measured across the 2 – $40\ \text{mbar}$ pressure range in helium (figure 6). The pressure was controlled with reducing valve and additionally needle valve before the MH. Pressure was monitored also with DV 1000 manometer with overall 15% measurement error. During the measurements, the pressure did not show any significant fluctuations.



The results demonstrate nearly identical analytical characteristics to conventional vacuum chamber LIBS:

- Signal intensity maximizes at 10–20 mbar, consistent with prior studies [19].
- Line shapes and relative intensities match reference chamber measurements.
- Reproducibility (relative standard deviation) <5% across 10-shot averages.

These results validate that the MH introduces no significant analytical artifacts compared to standard vacuum chamber configurations, while enabling in-situ measurement capability.

3.3. Discharge-enhanced LIBS in MH

The modular adapter design enables integration of electrodes for LIFPD, potentially enhancing emission intensity and improving detection limits. This capability was validated by incorporating a custom electrode assembly in adapter component 3 from figure 1(b).

Two electrodes are positioned 4 mm apart, located 6 mm above the target surface. High-voltage connection via auxiliary port on upper body (component d in figure 2). Photographs of the electrode assembly without discharge operation appear in the supplementary material.

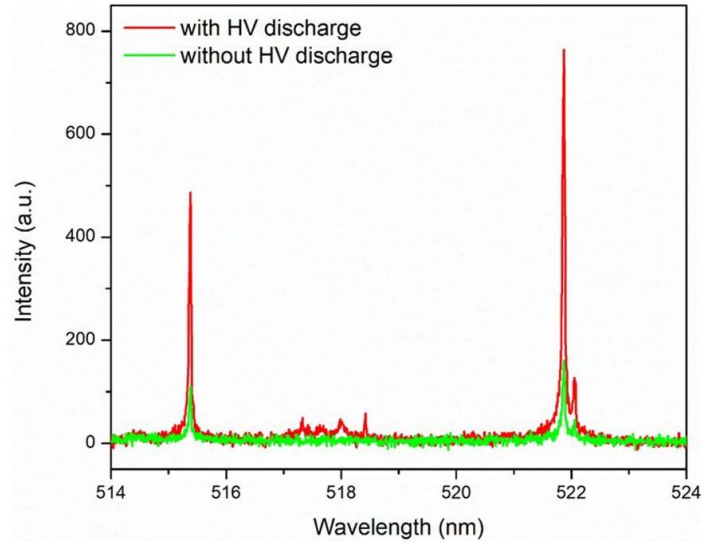


Figure 7. Comparison of intensities of Cu I lines at 515.3 nm and 521.8 nm in air at atmospheric pressure obtained with LIFPD (red) and LIBS (green).

Experimental measurements were performed at atmospheric pressure in air. Capacitors with 100 nF capacitance were charged to 5 kV and discharged through the laser-induced plasma. Comparison of LIBS (laser only) versus LIFPD (laser and discharge) spectra is given in figure 7. An eightfold increase in Cu I line intensities was observed, as well as improved SNR and extended temporal emission window. The additional discharge may introduce local pressure variations within the discharge zone. However, such effects are not of particular importance to the analytical performance of the method, since these variations would not cause significant changes in electron density to broaden the lines of interest and decrease analytical performance compared to atmospheric LIBS or LP-LIBS.

Previous work [29] demonstrated three-fold SNR enhancement and five-fold intensity increase for rhenium detection in tungsten using LIFPD at low pressure. Our MH configuration for the first time enables straightforward implementation of this technique for applications requiring enhanced sensitivity.

The adapter architecture of the MH provides accommodations for other excitation modes such as magnetic field application for Zeeman-based diagnostics, spatial confinement structures for plasma shaping, microwave coupling for laser ablation-microwave induced plasma combination [30] and glow discharge electrodes for alternative ionization schemes. This versatility significantly expands the MH's analytical capabilities beyond conventional LIBS.

4. Discussion

The experimental validation results demonstrate that the proposed MH successfully achieves the primary design objectives: creating and maintaining stable LP environments for LIBS measurements without requiring sample placement in vacuum chambers. This capability addresses a significant limitation that has restricted LP-LIBS predominantly to laboratory settings with transportable samples.

4.1. Analytical performance comparison

The spectroscopic validation (section 3.2) reveals that LIBS plasma generated within the MH exhibits analytical characteristics nearly identical to conventional vacuum chamber configurations. This equivalence confirms that the compact geometry, optical window configuration, and sealing approach do not introduce detrimental artifacts. The MHs demonstrated capabilities include:

- Effective atmospheric isolation (oxygen lines barely distinguishable from the noise, nitrogen below detection limits)
- Pressure-dependent behavior matching reference studies

- Reproducibility comparable to laboratory vacuum systems
- Integration compatibility with advanced excitation modes

For applications where these analytical capabilities meet requirements, the MH enables LP-LIBS measurements previously impractical or impossible.

4.2. Versatility through modular design

The three sealing configurations (section 2.1.3) address diverse measurement scenarios providing cost-effective customization for specialized applications:

- (1) *Configuration A (simple gasket)*: suitable for smooth surfaces and applications tolerating minor atmospheric ingress. Minimal complexity enables rapid deployment and reliable operation.
- (2) *Configuration B (differential pressure)*: optimized for rough or irregular surfaces requiring low pressure and complete atmospheric isolation. Continuous differential pumping removes leaked gases before they reach the measurement volume, enabling reliable operation on challenging surfaces.
- (3) *Configuration C (gas curtain)*: designed for delicate surfaces where mechanical contact must be minimized, or moderate pressure inert atmospheres suffice. Outward gas flow prevents substantial atmospheric ingress while reducing contact forces.

The interchangeable adapter approach (component 3, figure 1) extends versatility to diverse sample geometries without requiring multiple complete MH assemblies. Custom adapters accommodate non-standard cross-sections (rectangular, complex shapes), curved surfaces (matching component curvature), specialized plasma confinement geometries and integration of electrodes, magnets, or other enhancement structures.

4.3. Technical limitations and considerations

While the MH demonstrates substantial capabilities, several limitations and practical considerations merit discussion:

Achievable pressure range: leak rate characterization (table 1) shows that surface condition fundamentally determines the minimum achievable pressure. Smooth, non-porous surfaces enable operation below 1 mbar with simple gasket sealing, while rough surfaces require differential pressure sealing and typically limit operation to 10–50 mbar even with continuous pumping. Applications requiring ultra-high vacuum ($<10^{-3}$ mbar) remain restricted to conventional vacuum chambers.

Surface contact requirements: all demonstrated configurations require some degree of contact between elastomer seals and the analyzed surface. This contact may be unacceptable for certain delicate or contamination-sensitive materials, despite the gas curtain configuration minimizing contact forces.

Measurement volume constraints: the compact chamber geometry ($\phi 5$ cm $\times$ 4.5 cm interior in this implementation) restricts plasma expansion compared to large vacuum chambers. While spectroscopic validation showed no adverse effects for copper target analysis at 10 mbar, applications involving highly energetic plasmas or large ablation craters may encounter wall interactions. Chamber dimensions can be scaled up, but maintaining effective sealing becomes increasingly challenging.

Optical window access: the fixed optical port configuration (two laser entry, one emission collection, one observation, one auxiliary) provides excellent versatility but may constrain specialized geometries requiring, for example, multiple simultaneous emission collection angles or complex beam delivery configurations.

4.4. Applications beyond conventional LIBS

The MH architecture for the first time enables several advanced analytical approaches:

LIFPD: demonstrated intensity enhancement (section 3.3) provides improved detection limits for trace element analysis. Previous studies showed particular advantages for detecting low concentrations in complex matrices [21, 29].

Spatially-confined LIBS: custom adapters incorporating confinement structures can exploit plasma compression effects for emission enhancement [27].

Magnetic field application: integrated magnets enable magnetic field enhanced LIBS [28].

Hybrid techniques: the modular design accommodates combinations of laser ablation with alternative excitation/ionization schemes (microwave-induced plasma [30], glow discharge, arc discharge), potentially expanding analytical capabilities beyond pure LIBS.

These advanced capabilities position the MH as a versatile platform for LP-LIBS research and specialized applications.

4.5. Future development directions

Several extensions of this work could further enhance capabilities:

Automated Positioning: integration with robotic manipulation systems or motorized arms would enable systematic multi-point surveys and automated operation in hazardous or inaccessible environments.

Real-time pressure/composition feedback: incorporating residual gas analysis or optical emission monitoring could provide continuous verification of atmospheric isolation and enable adaptive control for challenging sealing conditions.

Alternative laser wavelengths: the current optical windows accommodate visible and near-IR wavelengths. Substituting ZnSe windows would enable CO₂ laser operation, potentially beneficial for isotopic analysis requiring reduced plasma electron density [20].

Miniaturization studies: investigating scaling limits could determine minimum practical measurement volumes, potentially enabling incorporation into even more constrained geometries.

Field deployment validation: systematic testing in representative application environments (industrial settings, field sites, specialized facilities) would identify practical deployment challenges and opportunities for design refinement.

5. Conclusion

This work presents a comprehensive solution for versatile LP LIBS implementation through a modular MH design specifically engineered for operation at controlled reduced pressures (1–200 mbar) without requiring sample placement in vacuum chambers. The system addresses critical technical barriers that have limited LP-LIBS predominantly to laboratory applications with transportable samples.

The effective sealing across diverse surface conditions was demonstrated, with quantified leak rates guiding the elastomer selection and sealing strategy optimization. Three distinct configurations are introduced to address different pressure requirements and surface challenges.

Spectroscopic testing's confirmed atmospheric isolation and analytical performance comparable to conventional vacuum chamber LIBS. The MH introduced no significant analytical artifacts while enabling *in-situ* measurement capability.

Finally, the integration compatibility with advanced excitation schemes was also shown. Additional fast pulse discharge yielded eightfold analyte emission enhancement within the MH.

The modular architecture based on interchangeable adapters provides cost-effective customization for specialized applications, sample geometries, and analytical requirements. This versatility extends beyond conventional LIBS to encompass hybrid techniques combining laser ablation with alternative excitation/ionization schemes.

By enabling practical implementation of LP-LIBS in diverse application scenarios, this development expands the technique's utility across materials science, industrial process monitoring, field analysis, and specialized applications requiring controlled LP environments for optimal analytical performance. The established design framework provides a foundation for continued advancement of LP-LIBS instrumentation tailored to specific analytical challenges.

Acknowledgments

The research was funded by the Ministry of Science, Technological Development and Innovations of the Republic of Serbia, Contract numbers: 451-03-47/2023-01/200024, 451-03-47/2023-01/200017, 451-03-47/2023-01/200146, 451-03-66/2024-03/200107 and by the Science Fund of the Republic of Serbia through NOVA2LIBS4fusion project Grant No. 7753287 within call IDEAS. This work was carried out

under the project: NIFS21KLPF087. We acknowledge Stanko Milanović, our technical associate, who drew all schematic figures of the measuring head. Artificial intelligence tools were used only to assist with grammar and improve the clarity and flow of the manuscript.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Measuring head photos available at <https://doi.org/10.1088/1361-6501/ae59a6/data1>.

Author contributions

M Ivković  0000-0003-4421-0002

Conceptualization (lead), Funding acquisition (lead), Methodology (lead), Supervision (lead), Writing – original draft (lead)

N Vujadinović  0009-0004-4415-0307

Formal analysis (equal), Investigation (equal), Writing – review & editing (equal)

I Traparić  0000-0001-6492-2360

Formal analysis (equal), Investigation (equal), Visualization (equal), Writing – review & editing (equal)

B D Stankov  0000-0002-6437-4015

Investigation (equal), Writing – review & editing (equal)

M Gavrilović-Božović

Writing – review & editing (equal)

M Kuzmanović  0000-0003-4731-7518

Writing – review & editing (equal)

J Savović

Writing – review & editing (equal)

References

- [1] Miziolek A W, Palleschi V and Schechter I 2006 *Laser Induced Breakdown Spectroscopy* (Cambridge University Press)
- [2] Cremers D A and Radziemski L J 2013 *Handbook of Laser-Induced Breakdown Spectroscopy* (Wiley)
- [3] Noll R 2011 *Laser-Induced Breakdown Spectroscopy, in Laser-Induced Breakdown Spectroscopy: Fundamentals and Applications* (Springer)
- [4] Musazzi S and Perini U 2014 *Laser-induced Breakdown Spectroscopy, Springer Series in Optical Sciences* vol 182 (Springer) p E1
- [5] Singh J P and Thakur S N (eds) 2020 *Laser-Induced Breakdown Spectroscopy* 2nd edn (Elsevier)
- [6] Hahn D W and Omenetto N 2010 Laser-induced breakdown spectroscopy (LIBS), part I: review of basic diagnostics and plasma—particle interactions: still-challenging issues within the analytical plasma community *Appl. Spectrosc.* **64** 335A
- [7] Shirvani-Mahdavi H and Shafiee P 2016 Quantitative analysis of soil calcium by laser-induced breakdown spectroscopy using addition and addition-internal standardizations *Meas. Sci. Technol.* **27** 125502
- [8] Marković M *et al* 2024 Application of laser-induced breakdown spectroscopy for the analysis of pig bones *Meas. Sci. Technol.* **35** 025502
- [9] Tawfik W, Farooq W A and Alahmed Z A 2014 *J Opt. Soc. Korea* **18** 50–54
- [10] Jarota A *et al* 2019 Exploring the ultrafast dynamics of a diarylethene derivative using sub-10 fs laser pulses *Phys. Chem. Chem. Phys.* **21** 192–204
- [11] Kumar Myakalwar A, Spegazzini N, Zhang C, Kumar Anubham S, Dasari R R, Barman I and Kumar Gundawar M 2015 Less is more: avoiding the LIBS dimensionality curse through judicious feature selection for explosive detection *Sci. Rep.* **5** 13169
- [12] Gyftokostas N, Stefan D, Kokkinos V, Bouras C and Couris S 2021 Laser-induced breakdown spectroscopy coupled with machine learning as a tool for olive oil authenticity and geographic discrimination *Sci. Rep.* **11** 5360
- [13] Fikry M, Tawfik W and Omar M M 2021 Controlling the plasma electron number density of copper metal using NIR picosecond laser-induced plasma spectroscopy *Opt. Appl.* **51** 365–74
- [14] Fikry M, Tawfik W and Omar M 2020 Measurement of the electron temperature in a metallic copper using ultrafast laser-induced breakdown spectroscopy *J. Russ. Laser Res* **41** 484–90
- [15] Campos D, Harilal S S and Hassanein A 2010 The effect of laser wavelength on emission and particle dynamics of Sn plasma *J. Appl. Phys.* **108** 113305
- [16] Effenberger J A J and Scott J R 2010 Effect of atmospheric conditions on LIBS spectra *Sensors* **10** 4907
- [17] Ş Y, Tsui Y Y and Fedosejevs R 2004 Pressure dependence of emission intensity in femtosecond laser-induced breakdown spectroscopy *J. Anal. At. Spectrom.* **19** 1295
- [18] Kautz E J, Rönnebro E C, Devaraj A, Senor D J and Harilal S S 2021 Detection of hydrogen isotopes in Zircaloy-4 via femtosecond LIBS *J. Anal. At. Spectrom.* **36** 1217

- [19] Ivkovic M, Savovic J, Stankov B D, Kuzmanovic M and Traparić I 2024 LIBS depth-profile analysis of W/Cu functionally graded material *Spectrochim. Acta B* **213** 106874
- [20] Traparić I, Rankovic D, Stankov B D, Savovic J, Kuzmanovic M and Ivkovic M 2024 Resolving studies of Balmer alpha lines relevant to the LIBS analysis of hydrogen isotope retention *Spectrochim. Acta B At. Spectrosc.* **221** 107050
- [21] Stankov B, Traparić I, Božović M G and Ivković M 2025 Detection of absorbed neutrons through determination of rhenium content in tungsten with laser induced fast pulse discharge *Fusion Eng. Des.* **215** 114943
- [22] Hao Z, Liu L, Shen M, Yang X, Li K, Guo L, Li X, Lu Y and Zeng X 2016 Investigation on self-absorption at reduced air pressure in quantitative analysis using laser-induced breakdown spectroscopy *Opt. Express* **24** 26521
- [23] Palleschi V 2017 If laser-induced breakdown spectroscopy was a brand: some market considerations *Spectrosc. Eur.* **29** 6–9
- [24] Rakovsky J, Čermák P, Musset O and Veis P 2014 A review of the development of portable laser induced breakdown spectroscopy and its applications *Spectrochim. Acta B* **101** 269
- [25] Senesi G S, Harmon R S and Hark R R 2020 *Field-portable and Handheld LIBS Laser-Induced Breakdown Spectroscopy* (Elsevier) pp 537
- [26] Almaguiva S *et al* 2020 LIBS measurements inside the FTU vessel mock-up by using a robotic arm *Fusion Eng. Des.* **157** 111685
- [27] Hao Z, Deng Z, Liu L, Shi J and He X 2022 Spatial confinement effects of laser-induced breakdown spectroscopy at reduced air pressures *Front. Optoelectron.* **15** 17
- [28] Akhtar M, Jabbar A, Mehmood S, Ahmed N, Ahmed R and Baig M 2018 Magnetic field enhanced detection of heavy metals in soil using laser induced breakdown spectroscopy *Spectrochim. Acta B* **148** 143
- [29] Vinić M and Ivković M 2014 Spatial and temporal characteristics of laser ablation combined with fast pulse discharge *IEEE Trans. Plasma Sci.* **42** 2598
- [30] Vujadinovic N, Traparić I, Stankov B D, Rankovic D, Kuzmanovic M and Ivkovic M 2025 Hydrogen isotopes retention studies using laser and microwave induced plasma coupling *Sci. Rep.* **15** 12589
- [31] Allison S, Gillies G, Magnuson D and Pagano T 1985 Pulsed laser damage to optical fibers *Appl. Opt.* **24** 3140
- [32] Dumitrescu C E, Puzinauskas P V and Olcmen S 2008 Movable fiber probe for gas-phase laser-induced breakdown spectroscopy *Appl. Opt.* **47** G88
- [33] Hang Y-H, Qiu Y, Zhou Y, Liu T, Zhu B, Liao K, Shi M-X and Xue F 2022 Effects of pulse energy ratios on plasma characteristics of dual-pulse fiber-optic laser-induced breakdown spectroscopy *Chin. Phys. B* **31** 024212
- [34] Yuan M, Zeng Q, Wang J, Li W, Chen G, Li Z, Liu Y, Guo L, Li X and Yu H 2021 Rapid classification of steel via a modified support vector machine algorithm based on portable fiber-optic laser-induced breakdown spectroscopy *Opt. Eng.* **60** 124114
- [35] Sankhe M L, Favre A, Sirven J-B, Bultel A, L'hermite D, Semerok A, Vartanian S and Grisolia C 2023 Development of fibered LIBS device for tokamak plasma facing components characterization *Fusion Eng. Des.* **197** 114077
- [36] Rajavelu H, Vasa N J and Seshadri S 2022 Hollow-core optical fiber-based laser-induced breakdown spectroscopy technique for the elemental analysis of pulverized coal *Appl. Phys. A* **128** 868



Design of IIR Lowpass Differentiators Using Parallel Allpass Structure

Ivan Krstić¹ · Marijana Gavrilović Božović¹ · Goran Stančić² · Ivana Kostić²

Received: 29 April 2023 / Revised: 11 December 2023 / Accepted: 11 December 2023 /

Published online: 18 January 2024

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2024

Abstract

In this paper, design of infinite impulse response lowpass differentiators that can be realized by parallel connection of two allpass filters whose orders differ by two, where one of the allpass branches is pure delay, is considered. As adopted structure of proposed lowpass differentiators allows formulation of their magnitude and phase responses as functions of allpass filter phase response, a set of nonlinear equations in unknown allpass filter coefficients is derived and iteratively solved in a way that magnitude response approximates the ideal one in weighted Chebyshev sense, in both passband and stopband. On the other hand, passband phase response linearity is shown to be related to the maximum of the magnitude response, which can be directly controlled by an additional design parameter. Design examples reveal that proposed infinite impulse response lowpass differentiators of low order can have very low relative passband magnitude errors and nearly linear phases, while results of comparison with existing lowpass differentiators show that proposed differentiators usually require fewer multiplications.

Marijana Gavrilović Božović, Goran Stančić and Ivana Kostić have contributed equally to this work.

✉ Ivan Krstić
ivan.krstic@kg.ac.rs

Marijana Gavrilović Božović
marijana.gavrilovic@kg.ac.rs

Goran Stančić
goran.stancic@elfak.ni.ac.rs

Ivana Kostić
ivana.kostic@elfak.ni.ac.rs

¹ Department of Electrical Engineering, Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia

² Department of Electronics, Faculty of Electronic Engineering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia

Keywords Digital lowpass differentiator · Parallel allpass structure · Digital allpass filter · Nearly linear phase · Relative magnitude response error minimization

1 Introduction

High-frequency noise filtering along with differentiation at low frequencies is required in various practical applications, among which are physiological signal processing [7, 11, 13, 19], extraction of velocity and acceleration data [16], edge detection in image processing [6] and frequency estimation [14]. The frequency response of an ideal IIR lowpass differentiator having nonzero transition region width can be formulated as:

$$\tilde{H}(e^{j\omega}) = \begin{cases} j\omega e^{-j\omega\tau}, & \omega \leq \omega_p \\ 0, & \omega \geq \omega_s \end{cases}, \quad (1)$$

where τ is the passband group delay, while ω_p and ω_s are passband and stopband edge frequencies, respectively, and it can be approximated by the frequency response of either finite or infinite impulse response (IIR) filter. While a perfectly linear phase cannot be obtained by IIR filter, IIR lowpass differentiators are preferred over finite impulse response ones in applications where some amount of passband phase response nonlinearity can be tolerated, due to significantly lower filter order and lower group delay.

The majority of the IIR lowpass differentiators design methods belong to one of the following four approaches. The conventional approach is to cascade IIR fullband differentiator with the low-order lowpass filter [5, 17], while inversion-based design methods [2, 4, 10] start from the transfer function of IIR lowpass integrator, which is then inverted and stabilized by reflecting the unstable poles inside the unit circle. Methods of the third approach, i.e., the optimal methods [1, 5, 9, 12, 16, 18, 21], formulate the IIR lowpass differentiator design problem of simultaneous minimization of magnitude and phase response as the minimization problem in unknown filter coefficients. In [1, 5, 16], the numerator of the lowpass differentiator is assumed to be the linear phase filter, while denominator coefficients are determined using classical [5] and metaheuristic [1, 16] optimization methods. Method presented in [21] formulates the design problem in quadratic form without frequency sampling, while the method presented in [12] minimizes the group delay deviation with respect to the average group delay under the constraints that the maximum relative passband magnitude error and average squared stopband magnitude response are below prescribed values. Another two optimal methods are presented in [9, 18], where lowpass differentiators based on parallel allpass structure are proposed. Finally, as the maximum-flatness-based methods provide the lowest approximation error at frequencies about some center frequency, methods of the fourth approach [9, 20, 22] consider design of the maximally flat IIR lowpass differentiators.

The assumption, recently introduced by authors in [18], that IIR lowpass differentiator can be realized by parallel connection of two allpass filters of the same order, with a pure delay in one of the allpass branches, has led to the development of a method for design of even-order nearly linear phase allpass-based IIR lowpass differentia-

tors that usually require fewer multiplications compared to differentiators obtained by other design approaches. An additional allpass structure, introduced in [9], suggests that lowpass differentiation can be performed by subtracting the output of the second-order allpass filter from the input signal, i.e., that the design problem of second-order IIR lowpass differentiator can be reduced to the design of the allpass filter of the same order. As discussed in [9], differentiators obtained in such a way are superior to the second-order differentiators from [18] in every aspect except the phase response linearity.

The novelty of this study is generalization of the equiripple design method discussed in [9] to an arbitrary order of the lowpass differentiator that can be realized by parallel connection of two allpass filters whose orders differ by two, where allpass branch of the lower order is a pure delay. This structure allows formulation of the differentiator magnitude and phase responses as functions of the corresponding allpass filter phase response and the value of an additional design parameter, which enables simultaneous minimization of both magnitude and phase response errors. Additionally, aforementioned generalization provides a means of controlling the stopband behavior of lowpass differentiators as the stopband edge frequency becomes one of the design parameters.

The rest of the paper is structured as follows: The problem formulation of the allpass-based nearly linear phase IIR lowpass differentiator with magnitude response approximating the ideal one in weighted Chebyshev sense in both passband and stopband is discussed in Sect. 2. The proposed design method is presented in Sect. 3, while design examples and comparison with the existing lowpass differentiators are given in Sect. 4. Finally, conclusions are drawn in Sect. 5.

2 Problem Formulation

Transfer function of the IIR lowpass differentiators considered in this paper is assumed to be of the following form:

$$H(z) = \frac{\gamma}{2} \left(z^{-(L-2)} - A(z) \right), \quad \gamma > 0, \quad (2)$$

as depicted in Fig. 1, where γ is the maximum of the magnitude response, while $A(z)$ is the L th-order transfer function of the stable allpass filter having distinct poles

$$A(z) = z^{-L} \frac{1 + \sum_{i=1}^L a_i z^i}{1 + \sum_{i=1}^L a_i z^{-i}}, \quad (3)$$

whose phase response is denoted by:

$$\phi(\omega) = \arg \left\{ A(e^{j\omega}) \right\} = -L\omega + 2 \arctan \frac{\sum_{i=1}^L a_i \sin(i\omega)}{1 + \sum_{i=1}^L a_i \cos(i\omega)}. \quad (4)$$

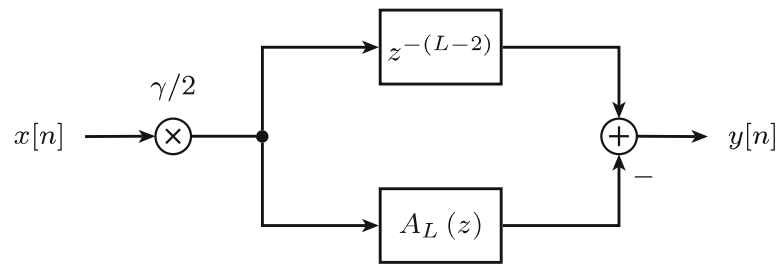


Fig. 1 Proposed realization structure of the IIR lowpass differentiator

Substituting $z = e^{j\omega}$ in (2), phase and magnitude response of the considered IIR lowpass differentiators can be formulated as functions of the corresponding allpass filter's phase response $\phi(\omega) = \arg\{A(e^{j\omega})\}$ as follows

$$\varphi(\omega) = \arg\{H(e^{j\omega})\} = \frac{\phi(\omega) - (L-2)\omega + \pi}{2}, \quad (5)$$

$$|H(e^{j\omega})| = \gamma \left| \sin \frac{\phi(\omega) + (L-2)\omega}{2} \right|. \quad (6)$$

Now, since the phase response of the stable allpass filter $A(z)$ is monotonically decreasing function satisfying $\phi(0) = 0$ and $\phi(\pi) = -L\pi$ [15], from (5) and (6) it follows that $\varphi(0) = \pi/2$ and $|H(e^{j0})| = |H(e^{j\pi})| = 0$, i.e., the frequency response of the proposed IIR lowpass differentiators matches the ideal one at $\omega = 0$ and $\omega = \pi$, note (1). Additionally, as $\phi(\omega) + (L-2)\omega$ equals 0 at $\omega = 0$ and -2π at $\omega = \pi$, there exists frequency point ω^* , $0 < \omega^* < \pi$, where $\phi(\omega^*) + (L-2)\omega^* = -\pi$, that is where maximum of the magnitude response occurs, $|H(e^{j\omega^*})| = \gamma$.

For the magnitude response of the proposed IIR lowpass differentiators given by (6) to approximate the ideal one,

$$|\tilde{H}(e^{j\omega})| = \begin{cases} \omega, & \omega \leq \omega_p \\ 0, & \omega \geq \omega_s \end{cases}, \quad (7)$$

note (1), the phase response $\phi(\omega)$ of the allpass filter $A(z)$ should approximate either $\tilde{\phi}_1(\omega)$ or $\tilde{\phi}_2(\omega)$ defined as

$$\tilde{\phi}_{1,2}(\omega) = \begin{cases} -(L-2)\omega \mp 2 \arcsin \frac{\omega}{\gamma}, & \omega \leq \omega_p \\ -(L-2)\omega - 2\pi, & \omega \geq \omega_s \end{cases}, \quad (8)$$

where parameter γ obviously needs to satisfy $\gamma \geq \omega_p$. Note that $\tilde{\phi}_1(\omega)$ is monotonically decreasing regardless of the value of the parameter γ for $\omega \in (0, \pi)$, while $\tilde{\phi}_2(\omega)$ can be made so by a suitable choice of the parameter γ for $L > 2$.

In this paper, an iterative algorithm for the determination of the allpass filter $A(z)$ coefficients vector

$$\mathbf{a} = [a_1 \ a_2 \ \dots \ a_L]^T, \quad (9)$$

for the predetermined value of the parameter γ is derived, such that the magnitude response of the obtained IIR lowpass differentiator approximates the ideal one in the weighted Chebyshev sense both in passband and stopband, i.e., such that the magnitude response error function

$$\varepsilon(\omega, \mathbf{a}) = W(\omega) \left(\left| H(e^{j\omega}, \mathbf{a}) \right| - \left| \tilde{H}(e^{j\omega}) \right| \right), \quad (10)$$

satisfies

$$|\varepsilon(\hat{\omega}_k, \mathbf{a})| = \delta_p, \quad (11)$$

for $k = 1, 2, \dots, m$, and

$$\varepsilon(\bar{\omega}_k, \mathbf{a}) = \delta_s, \quad (12)$$

for $k = 1, 2, \dots, L - m + 2$, where

$$W(\omega) = \begin{cases} 1/\omega, & \omega \leq \omega_p \\ 1, & \omega \geq \omega_s \end{cases} \quad (13)$$

is weighting function that allows simultaneous minimization of the relative passband and absolute stopband magnitude response errors, $\delta_p = \max_{\omega \leq \omega_p} |\varepsilon(\omega, \mathbf{a})|$ and $\delta_s = \max_{\omega \geq \omega_s} \varepsilon(\omega, \mathbf{a})$ are passband and stopband weighted Chebyshev norms, respectively, and $m \leq L + 1$ is the number of sign-alternating extrema in passband. Frequencies at which sign-alternating extremal values of $\varepsilon(\omega)$ occur in passband and stopband are $\hat{\omega} = [\hat{\omega}_1 \hat{\omega}_2 \dots \hat{\omega}_m]$ and $\bar{\omega} = [\bar{\omega}_1 \bar{\omega}_2 \dots \bar{\omega}_{L-m+2}]$, respectively, while $0 \leq \hat{\omega}_1 < \hat{\omega}_2 < \dots < \hat{\omega}_m \leq \omega_p$ and $\omega_s \leq \bar{\omega}_1 < \bar{\omega}_2 < \dots < \bar{\omega}_{L-m+2} < \pi$. Regarding the choice of the weighting function, note that lowpass differentiators are usually designed with constant relative passband magnitude response error [9, 12].

Since the relative passband magnitude error of the lowpass differentiators is being minimized, to circumvent the magnitude response error function given by (10) to be indeterminate for $\omega = 0$, sine term of the magnitude response is rewritten as

$$\begin{aligned} \sin \frac{\phi(\omega, \mathbf{a}) + (L-2)\omega}{2} &= \omega \lambda(\omega, \mathbf{a}) \\ &= \omega \frac{-\text{sinc } \omega + \sum_{n=2}^L (n-1) a_n \text{sinc } (\omega(n-1))}{\sqrt{\left(1 + \sum_{n=1}^L a_n \cos(n\omega)\right)^2 + \left(\sum_{n=1}^L a_n \sin(n\omega)\right)^2}}, \end{aligned} \quad (14)$$

where

$$\text{sinc } x = \begin{cases} 1, & x = 0 \\ \sin x / x, & x \neq 0 \end{cases}. \quad (15)$$

Note that the transfer function (2) of the proposed IIR lowpass differentiators requires at least $2L - 2$ delays and $L + 1$ or L multiplications depending on the value of the parameter γ . Namely, if γ is expressed as the sum of a few power-of-two terms, required number of multiplications reduces to L .

2.1 Passband Phase Response Linearity Error

If $|H(e^{j\omega})| \approx |\tilde{H}(e^{j\omega})|$, the passband phase response of the IIR lowpass differentiator $\varphi(\omega)$, given by (5), approximates

$$\tilde{\varphi}_{1,2}(\omega) = \frac{\tilde{\phi}_{1,2}(\omega) - (L - 2)\omega + \pi}{2} = \frac{\pi}{2} - (L - 2)\omega \mp \arcsin \frac{\omega}{\gamma}, \quad (16)$$

which is nearly linear function of frequency for $\gamma \gg \omega_p$. On the other hand, to avoid dynamic range problem, the value of the parameter γ should be chosen with great concern. Furthermore, as the maximum of magnitude response, occurring at the frequency $\omega^* \geq \omega_p$, equals γ , γ should be close to ω_p to avoid excessive gain in the transition region or stopband. Therefore, proposed allpass-based IIR lowpass differentiators, i.e., the ones that can be realized by the structure given in Fig. 1, are not capable of providing very low passband phase response linearity errors without increasing the maximum of the magnitude response beyond ω_p .

To quantify the previous claim, let us determine the lower and upper margin functions of the passband phase response linearity function defined as [12, 18]

$$\zeta(\omega) = \varphi(\omega) - \left(\frac{\pi}{2} - \omega\bar{\tau} \right), \quad (17)$$

where $\bar{\tau}$ is the average passband group delay

$$\bar{\tau} = \frac{\varphi(0) - \varphi(\omega_p)}{\omega_p}, \quad (18)$$

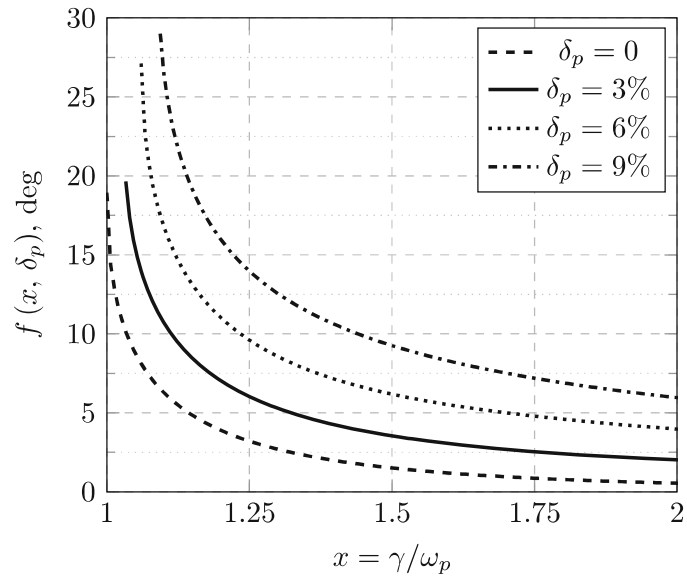
when relative passband magnitude response error is lower than δ_p , i.e., when

$$-\arcsin \frac{\omega(1 + \delta_p)}{\gamma} \leq \frac{\phi(\omega) + (L - 2)\omega}{2} \leq -\arcsin \frac{\omega(1 - \delta_p)}{\gamma}, \quad (19)$$

for $\omega \leq \omega_p$, note (10) and (24). Substituting (5) and (18) in (17), passband phase response linearity function becomes

$$\zeta(\omega) = \frac{\phi(\omega)}{2} - \frac{\omega}{\omega_p} \frac{\phi(\omega_p)}{2}, \quad (20)$$

Fig. 2 Maximum absolute value of lower and upper margin functions for $\omega/\omega_p \leq 1$ as a function of γ/ω_p for four values of δ_p



while its upper and lower margin functions can be determined by means of (19) as

$$\mathcal{U}\left(y = \frac{\omega}{\omega_p}\right) = y \arcsin \frac{1 + \delta_p}{x} - \arcsin \frac{y(1 - \delta_p)}{x}, \quad (21)$$

$$\mathcal{L}(y) = y \arcsin \frac{1 - \delta_p}{x} - \arcsin \frac{y(1 + \delta_p)}{x}, \quad (22)$$

where $x = \gamma/\omega_p$. Plots of

$$f(x, \delta_p) = \frac{180}{\pi} \cdot \max_{y \leq 1} \{|\mathcal{L}(y, x, \delta_p)|, |\mathcal{U}(y, x, \delta_p)|\}, \quad (23)$$

for $\delta_p \in \{0, 3\%, 6\%, 9\%\}$ and $(1 + \delta_p) \leq x \leq 2$ are shown in Fig. 2. Note that maximum passband phase response linearity error $\max_{\omega \leq \omega_p} |\zeta(\omega, \gamma, \delta_p)|$ is lower than $f(x, \delta_p)$, while notations $\zeta(\omega, \gamma, \delta_p)$, $\mathcal{L}(y, x, \delta_p)$ and $\mathcal{U}(y, x, \delta_p)$ are used to emphasize the dependence of $\zeta(\omega)$ on γ and δ_p , and $\mathcal{L}(y)$ and $\mathcal{U}(y)$ on $x = \gamma/\omega_p$ and δ_p . It can be observed from these plots that even in a limiting case, that is for $\delta_p = 0$, if the passband phase response error is to be lower than 1 degree, γ should be higher than $1.5\omega_p$. Furthermore, with increase of maximum relative passband magnitude response error required γ/ω_p ratio increases.

3 Design Method

Mathematical background of the proposed design method depends on whether $\phi(\omega, \mathbf{a})$ is assumed to approximate $\phi_1(\omega)$ or $\phi_2(\omega)$ given by (8). However, as $\phi_2(\omega)$ is not monotonically decreasing function for every L and γ , it is adopted that $\phi(\omega, \mathbf{a})$ needs to approximate $\tilde{\phi}_1(\omega)$. In this case, as $\tilde{\phi}_1(\omega)$ is less than $-(L - 2)\omega$ in passband, and reasonable assumptions that $\phi(\omega, \mathbf{a})$ is also less than $-(L - 2)\omega$ in

passband and that $\phi(\omega, \mathbf{a}) > -(L-2)\omega - 2\pi$ in the transition region are adopted, the magnitude response (6) of the proposed IIR lowpass differentiators can be rewritten as:

$$\left| H(e^{j\omega}, \mathbf{a}) \right| = -\gamma \omega \lambda(\omega, \mathbf{a}), \quad (24)$$

for $\omega \leq \omega_s$. Now, the magnitude response error function (10) at frequencies where its sign-alternating extremal values occur can be rewritten as

$$\varepsilon(\hat{\omega}_k, \mathbf{a}) = -1 - \gamma \lambda(\hat{\omega}_k, \mathbf{a}), \quad (25)$$

for $k = 1, 2, \dots, m$, and

$$\varepsilon(\bar{\omega}_k, \mathbf{a}) = (-1)^{k+1} \bar{\omega}_k \gamma \lambda(\bar{\omega}_k, \mathbf{a}), \quad (26)$$

for $k = 1, 2, \dots, L-m+2$.

Therefore, (11) and (12), which characterize the proposed design method, can be rewritten by means of previous equations as:

$$\lambda(\hat{\omega}_k, \mathbf{a}) + (-1)^{p+k} \frac{\delta_p}{\gamma} = -\frac{1}{\gamma}, \quad k = 1, 2, \dots, m, \quad (27)$$

$$\lambda(\bar{\omega}_k, \mathbf{a}) + (-1)^k \frac{\delta_s}{\gamma \bar{\omega}_k} = 0, \quad k = 1, 2, \dots, L-m+2, \quad (28)$$

where p determines whether the first extremal value of the passband magnitude response error function is maximum ($p = 1$) or minimum ($p = 0$). Evidently, a system of nonlinear equations given by (27) and (28) consists of $L+2$ equations in $L+2$ unknowns. It shows that it can be efficiently solved by following exchange algorithm:

1. Determine $\mathbf{a}'$ such that $\varepsilon(\omega, \mathbf{a}')$ exhibits at least m and $L-m+2$ extremal values in the passband and stopband, respectively. As the following relation can be established between the phase response and coefficients of the allpass filter $A_L(z)$,

$$\sum_{i=1}^L a_i \sin \frac{\phi(\omega) + (L-2i)\omega}{2} = -\sin \frac{\phi(\omega) + L\omega}{2}, \quad (29)$$

note (4), unknown coefficients vector $\mathbf{a}'$ can be determined as a solution to the system of linear equation obtained by setting $\phi(\omega) = \tilde{\phi}_1(\omega)$ at $m-1$ and $L-m+1$ frequency points in passband and stopband, respectively,

$$\omega_k = \begin{cases} (k+2) \frac{\omega_p}{m+2}, & k < m \\ \omega_s + (k-m+1) \frac{\pi - \omega_s}{L-m+2}, & k \geq m \end{cases}, \quad (30)$$

- for $k = 1, 2, \dots, L$.
- Determine frequencies $\hat{\omega}' = [\hat{\omega}'_1 \hat{\omega}'_2 \dots \hat{\omega}'_m]$ and $\bar{\omega}' = [\bar{\omega}'_1 \bar{\omega}'_2 \dots \bar{\omega}'_{L-m+2}]$ where m and $L - m + 2$ sign-alternating extremal values of $\varepsilon(\omega, \mathbf{a}')$ occur in passband and stopband, respectively. It was concluded empirically that $\varepsilon(\omega, \mathbf{a}')$ can have one excess extremum in passband/stopband and that following heuristic approach can be used to select the required number of sign-alternating extremal values:
 - if the first- or last-two extremal values in passband/stopband are of the same sign, then the first or last extrema is not taken into consideration, respectively.
 - if there are $m + 1$ sign-alternating extremal values in the passband, the lower between the first and last extrema is not taken into consideration for $\omega_p < \pi/2$, otherwise, the last extrema is not taken into consideration.
 - if there are $L - m + 2$ sign-alternating extremal values in the stopband, the lower between the first and last extrema is not taken into consideration.
 - Determine coefficient vector $\mathbf{a} = \mathbf{a}' + \Delta\mathbf{a}$ by solving the following system of linear equations

$$\begin{bmatrix} \hat{\Psi}(\mathbf{a}') & \gamma^{-1}\hat{\eta} & \mathbf{0}_{m \times 1} \\ \bar{\Psi}(\mathbf{a}') & \mathbf{0}_{(L-m+2) \times 1} & \gamma^{-1}\bar{\eta} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{a} \\ \delta_p \\ \delta_s \end{bmatrix} = - \begin{bmatrix} \gamma^{-1} \cdot \mathbf{1}_{m \times 1} + \hat{\lambda}(\mathbf{a}') \\ \bar{\lambda}(\mathbf{a}') \end{bmatrix}, \quad (31)$$

obtained by linearization of (27) and (28) about $\mathbf{a}'$ and adopting $\hat{\omega} = \hat{\omega}'$ and $\bar{\omega} = \bar{\omega}'$. In the previous equation, $\hat{\Psi}(\mathbf{a}') = [\hat{\psi}_{ki}(\mathbf{a}')]'$, $\bar{\Psi}(\mathbf{a}') = [\bar{\psi}_{ki}(\mathbf{a}')]'$, $\hat{\lambda}(\mathbf{a}') = [\hat{\lambda}_k(\mathbf{a}')]'$, $\bar{\lambda}(\mathbf{a}') = [\bar{\lambda}_k(\mathbf{a}')]'$, $\hat{\eta} = [\hat{\eta}_k]$ and $\bar{\eta} = [\bar{\eta}_k]$ are $m \times L$, $(L - m + 2) \times L$, $m \times 1$, $(L - m + 2) \times 1$, $m \times 1$ and $(L - m + 2) \times 1$ matrices, respectively, with elements

$$\hat{\psi}_{ki}(\mathbf{a}') = \frac{\partial \lambda(\hat{\omega}'_k, \mathbf{a}')}{\partial a_i}, \quad \bar{\psi}_{ki}(\mathbf{a}') = \frac{\partial \lambda(\bar{\omega}'_k, \mathbf{a}')}{\partial a_i}, \quad (32)$$

$$\hat{\lambda}_k(\mathbf{a}') = \lambda(\hat{\omega}'_k, \mathbf{a}'), \quad \bar{\lambda}_k(\mathbf{a}') = \lambda(\bar{\omega}'_k, \mathbf{a}'), \quad (33)$$

$$\hat{\eta}_k = (-1)^{p+k}, \quad \bar{\eta}_k = \frac{(-1)^k}{\bar{\omega}'_k}. \quad (34)$$

- If $\max |\Delta\mathbf{a}| \leq \Delta_{\text{tol}}$, where $\Delta_{\text{tol}} > 0$ is the prescribed tolerance, the algorithm converged to the solution. Otherwise, set $\mathbf{a}' \leftarrow \mathbf{a}$ and proceed to the step 2.

Note that since only the first m sign-alternating extremal values are considered for $\omega_p > \pi/2$, the utilization of the proposed design method algorithm may not result in a valid transfer function (i.e., the one with relative magnitude response error at the passband edge higher than δ_p). The mentioned limitation will be considered in more detail in the following section.

4 Design Examples and Comparison with the Existing IIR Lowpass Differentiators

In this section, examples of proposed allpass-based IIR lowpass differentiators are given and some conclusions regarding the impact of design parameters L , ω_p , ω_s , γ , and m on the passband phase response linearity and relative passband magnitude response errors are drawn. Δ_{tol} equals 10^{-10} in all examples. Additionally, a comparison with the existing allpass-based IIR lowpass differentiators from [18] and nearly linear phase IIR lowpass differentiators from [5, 12] is presented. Here, it should be noted that second-order IIR lowpass differentiators obtained by the equiripple design method from [9] are the same ones obtained by the proposed design method for $L = 2$ and $m = 3$.

Various lowpass differentiators are compared in terms of the required number of multiplications and delay elements, maximum peak-to-peak passband phase response error in degrees

$$\eta = \frac{180}{\pi} \left[\max_{\omega \leq \omega_p} \zeta(\omega) - \min_{\omega \leq \omega_p} \zeta(\omega) \right], \quad (35)$$

average passband group delay

$$\bar{\tau} = \frac{L-2}{2} - \frac{\phi(\omega_p)}{2\omega_p}, \quad (36)$$

note (18), as well as values of $\delta_p = \max_{\omega \leq \omega_p} |\varepsilon(\omega, \mathbf{a})|$ and $\delta_s = \max_{\omega \geq \omega_s} \varepsilon(\omega, \mathbf{a})$. Additionally, average squared stopband magnitude response

$$P_{sb} = \frac{1}{\pi - \omega_p} \int_{\omega_p}^{\pi} \left| H(e^{j\omega}) \right|^2 d\omega, \quad (37)$$

is used to properly characterize differentiators from [5, 12] in the stopband, as these differentiators do not consider stopband edge frequency as design parameter. Note that proposed allpass-based lowpass differentiators have $\min_{\omega \leq \omega_p} \zeta(\omega)$ equal to zero, as phase response of stable allpass filter is monotonically decreasing function of frequency, note (20).

In the first example, the proposed method is used to design IIR lowpass differentiators with the lowest possible relative passband magnitude response error, i.e., the case when $m = L + 1$ is considered. As a case when $L = 2$ and $m = 3$ are discussed in [9], fourth-order IIR lowpass differentiators ($L = 3$) of various passband edges $\omega_p \in \{0.2\pi(1 + k/13) \mid 0 \leq k \leq 39\}$ and $\gamma/\omega_p \in \{1.02, 1.04, 1.06\}$ are considered here. Note that for $m = L + 1$ (31) reduces to

$$\left[\hat{\Psi}(\mathbf{a}') \gamma^{-1} \hat{\boldsymbol{\eta}} \right] \begin{bmatrix} \Delta \mathbf{a} \\ \delta_p \end{bmatrix} = -\gamma^{-1} \cdot \mathbf{1}_{m \times 1} - \hat{\boldsymbol{\lambda}}(\mathbf{a}'), \quad (38)$$

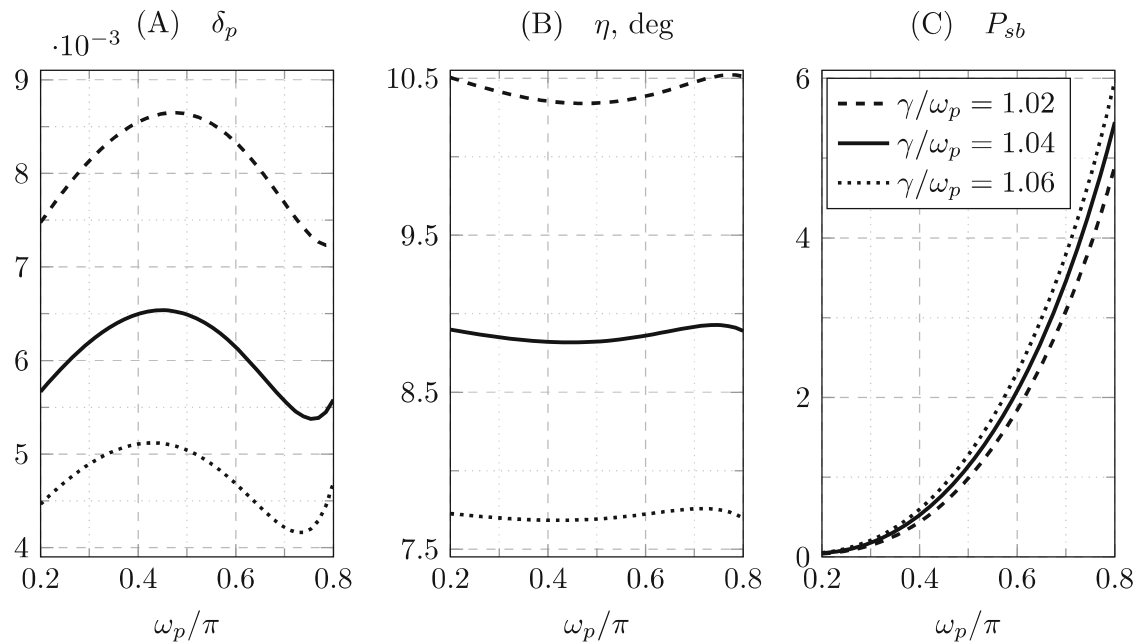


Fig. 3 Proposed fourth-order allpass-based IIR lowpass differentiators. **A** δ_p , **B** η and **C** P_{sb} , as functions of $\omega_p \in [0.2\pi, 0.8\pi]$ for three values of γ/ω_p and $L = 3, m = 4$

as stopband edge frequency is redundant parameter. Plots of δ_p , η and P_{sb} as functions of ω_p , for three values of γ/ω_p are shown in Fig. 3. As can be observed from these plots, with the increase of the parameter γ , maximum relative passband magnitude response error δ_p and maximum passband phase response error η decrease, while average squared stopband magnitude response P_{sb} increases. δ_p is less than 0.86%, 0.65% and 0.51%, while η is less than 10.52 ($f(1.02, 0.86\%) = 14.72$), 8.93 ($f(1.04, 0.65\%) = 10.84$) and 7.76 ($f(1.06, 0.51\%) = 8.96$) degrees, for $0.2\pi \leq \omega_p \leq 0.8\pi$ and γ/ω_p equal to 1.02, 1.04, 1.06, respectively. As expected, the proposed fourth-order IIR lowpass differentiators have lower relative passband magnitude response error compared to the second-order lowpass differentiators [9].

In the second example, the proposed method is used to design sixth-order IIR lowpass differentiators of various passband edges $\omega_p \in \{0.2\pi(1 + 3k/59) \mid 0 \leq k \leq 59\}$, $\omega_s = \omega_p + 0.18\pi$, $\gamma/\omega_p \in \{1.02, 1.04, 1.06\}$ and $m = L = 4$. Plots of δ_p , η and δ_s as functions of ω_p , for three values of γ/ω_p ratio, are shown in Fig. 4. Since only the first m sign-alternating extremal values are considered for $\omega_p > \pi/2$, the utilization of the proposed design method does not result in a valid transfer function (i.e., the relative magnitude response at the passband edge is higher than δ_p obtained by the proposed algorithm) for $\omega_p > 0.7\pi$ ($\gamma/\omega_p = 1.02$), $\omega_p > 0.74\pi$ ($\gamma/\omega_p = 1.04$) and $\omega_p > 0.76\pi$ ($\gamma/\omega_p = 1.06$), $\omega_s = \omega_p + 0.18\pi$, $L = m = 4$. While parameters L, m and the transition region width $\omega_s - \omega_p$ also affect whether relative magnitude response error at the passband edge is higher than δ_p obtained by the algorithm, it is more probable to happen for ω_p closer to Nyquist frequency and γ/ω_p closer to one. From Fig. 4, it can be also concluded that for $L \neq m + 1$, δ_p does not necessarily decrease when γ increases. On the other hand, when γ increases, η decreases, while δ_s increases.

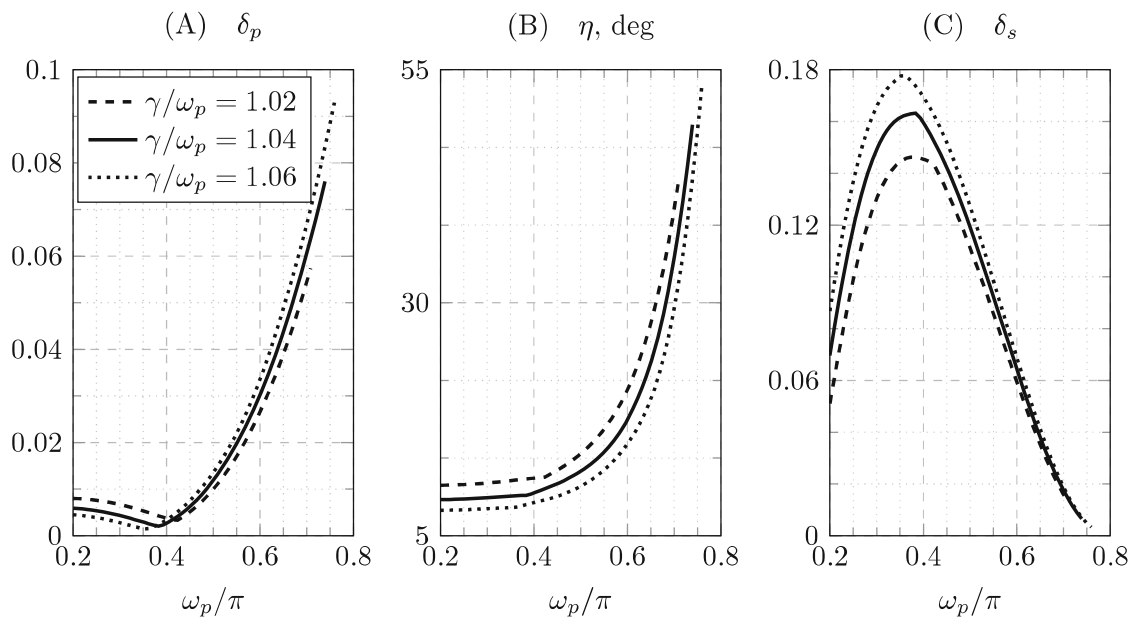


Fig. 4 $L = 4, m = 4, \omega_p \in [0.2\pi, 0.8\pi], \omega_s = \omega_p + 0.18\pi$

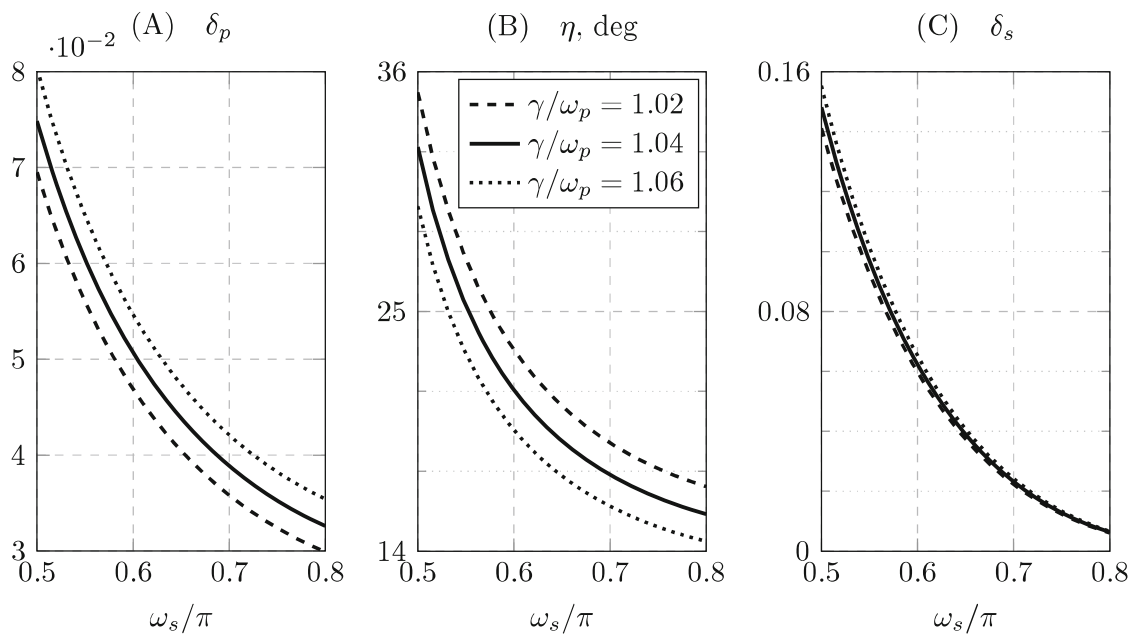


Fig. 5 $L = 3, m = 3, \omega_p = 0.4\pi, \omega_s \in [0.5\pi, 0.8\pi]$

In the third example, fourth-order allpass-based IIR lowpass differentiators of various stopband edges $\omega_s \in \{0.5\pi(1 + 0.6k/19) \mid 0 \leq k \leq 19\}$, $\omega_p = 0.4\pi$, $\gamma/\omega_p \in \{1.02, 1.04, 1.06\}$ and $m = L = 3$ are considered. Plots of δ_p , η and δ_s are shown in Fig. 5. As expected, with the increase of the stopband edge frequency, δ_p , η and δ_s decrease.

Finally, in the fourth example, application of the proposed fourth-order lowpass differentiator with a real input - the electrooculogram (EOG) signal is tested, since its derivative is required for example to detect the direction of eye movements [11]. EOG signal is obtained from [8], and its sampling frequency equals 100Hz. Lowpass

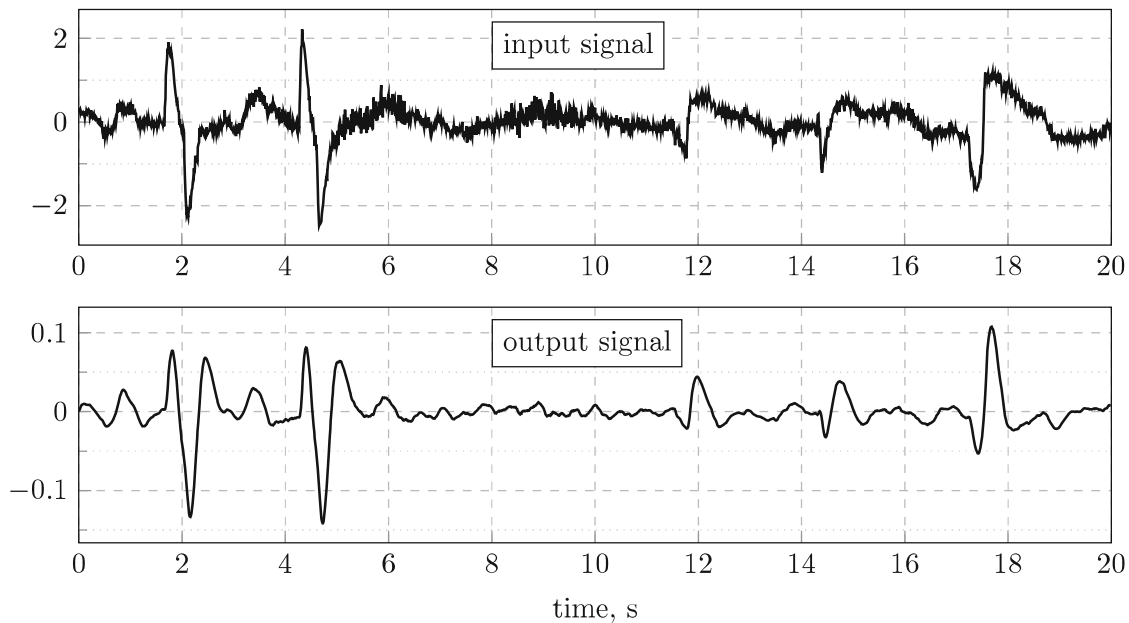


Fig. 6 EOG signal and output of the proposed fourth-order lowpass differentiator

differentiator is designed using $\omega_p = 0.025\pi$, $\omega_s = 0.4\pi$, $L = m = 3$ and $\gamma = \omega_p$. Input and output signals of the lowpass differentiator are shown in Fig. 6. Evidently, lowpass differentiation is required due to existence of high-frequency noise in the input EOG signal.

4.1 Comparison with the Allpass-Based IIR Lowpass Differentiators from [18]

In this subsection, a comparison of the proposed nearly linear phase allpass-based IIR lowpass differentiators with the ones from [18] is presented. These differentiators are also designed by minimizing the weighted Chebyshev norms both in the passband and in the stopband, while their transfer function can be expressed as:

$$H_1(z) = \frac{\gamma_1}{2} \left[A_1(z) - z^{-M} \right], \quad (39)$$

where $A_1(z)$ is the transfer function of M th degree allpass filter.

In the fifth example, the proposed lowpass differentiators are compared to eighth-order ($M = 4$) differentiator from [18] with passband and stopband edge frequencies $\omega_p = 0.3\pi$ and $\omega_s = 0.57\pi$. Three competing differentiators are designed: (a) $L = m = 3$, $\gamma = 1.118$, (b) $L = m = 4$, $\gamma = 1.125$ and (c) $L = 5$, $m = 4$, $\gamma = 2$. The results of comparison are presented in Table 1 and Fig. 7. From these results, it can be observed that eighth-order lowpass differentiator designed using the proposed method outperforms the existing one of the same order from [18] in all terms except the required number of multiplications. On the other hand, proposed fourth- and sixth-order differentiators have the same or smaller values of δ_p , δ_s and $\bar{\tau}$, while passband phase response errors of proposed differentiators are higher compared to differentiator from [18].

Table 1 $\omega_p = 0.3\pi$, $\omega_s = 0.57\pi$

Parameters	Proposed $L = m = 3$, $\gamma = 1.118$	Proposed $L = m = 4$, $\gamma = 1.125$	Proposed $L = 5$, $m = 4$, $\gamma = 2$	[18]
δ_p	2.41%	0.03%	0.33%	2.41%
δ_s	5.64%	11.35%	3.49%	11.94%
$\bar{\tau}$	2.10	3.05	3.52	3.6
η	6.62°	4°	0.49°	0.62°
no. of multiplications	4	4	5	4
no. of delays/filter order	4	6	8	8

Results of comparison of proposed differentiators with lowpass differentiator from [18]

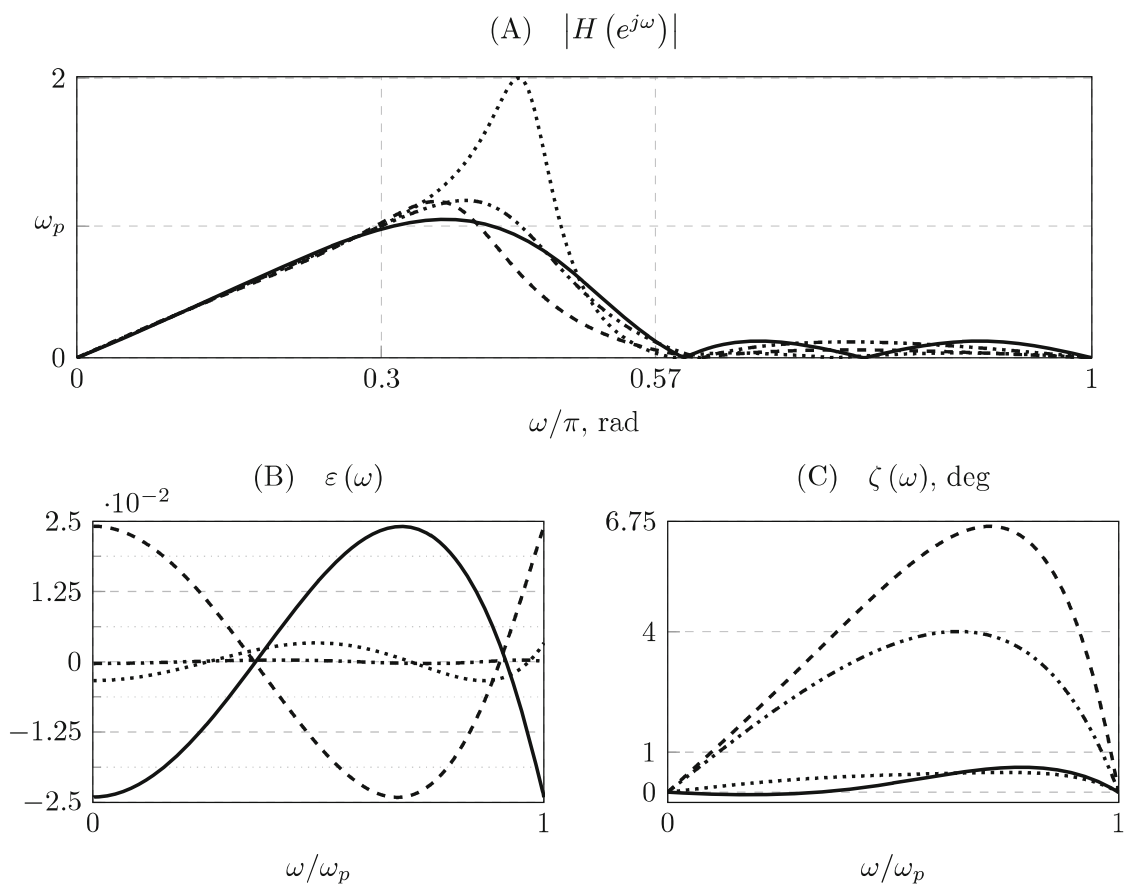


Fig. 7 $\omega_p = 0.3\pi$, $\omega_s = 0.57\pi$. **A** Magnitude responses, **B** relative passband magnitude response errors and **C** passband phase response linearity errors of the IIR lowpass differentiator from [18] (solid line) and the proposed ones (dashed, dash dot dotted, dotted lines correspond to fourth-, sixth- and eighth-order differentiators, respectively)

In the sixth example, proposed lowpass differentiators are compared to the sixth-order ($M = 3$) lowpass differentiator from [18] with the passband and stopband edge frequencies $\omega_p = 0.5\pi$ and $\omega_s = 0.725\pi$. Two competing differentiators of the sixth-order are designed: a) $L = m = 4$, $\gamma = 1.75$ and b) $L = m = 4$, $\gamma = 2.875$. The results of comparison are presented in Table 2. From these results, it can be observed

Table 2 $\omega_p = 0.5\pi$, $\omega_s = 0.725\pi$

Parameters	Proposed $L = m = 4$, $\gamma = 1.75$	Proposed $L = m = 4$ $\gamma = 2.875$	[18]
δ_p	1.31%	1.10%	3.79%
δ_s	8.44%	15.61%	36.3%
$\bar{\tau}$	2.73	2.37	2.45
η	7.22°	1.15°	1.21°
No. of multiplications	4	4	3
No. of delays/filter order	6	6	6

Results of comparison of proposed differentiators with lowpass differentiator from [18]

Table 3 $\omega_p = 0.7\pi$, $\omega_s = 0.825\pi$

Parameters	Proposed $L = m = 6$, $\gamma = 2.25$	Proposed $L = m = 7$, $\gamma = 2.75$	Proposed $L = 10$, $m = 9$, $\gamma = 2.75$	[18]
δ_p	0.72%	0.40%	0.34%	0.84%
δ_s	15%	33.68%	5.06%	10.05%
$\bar{\tau}$	4.63	5.42	8.42	8.52
η	12.41°	3.48°	3.37°	4.61°
No. of multiplications	6	7	10	9
No. of delays/filter order	12	14	18	18

Results of comparison of proposed differentiators with lowpass differentiator from [18]

that both sixth-order lowpass differentiators designed using the proposed method have much smaller maximum passband and stopband magnitude response errors, δ_p and δ_s , compared to existing differentiator of the same order from [18]. On the other hand, only lowpass differentiator having maximum passband magnitude equal to $\gamma = 2.875$ has smaller passband phase response error. In this example, both proposed differentiators require one multiplication more than existing differentiator of the same order.

In the seventh example, the proposed lowpass differentiators are compared to eighteenth-order ($M = 9$) lowpass differentiator from [18] with passband and stopband edge frequencies $\omega_p = 0.7\pi$ and $\omega_s = 0.825\pi$. Three competing differentiators are designed: a) $L = m = 6$, $\gamma = 2.25$, b) $L = m = 7$, $\gamma = 2.75$ and c) $L = 10$, $m = 9$, $\gamma = 2.75$. The results of comparison are presented in Table 3. From these results, it can be concluded that eighteenth lowpass differentiator designed using the proposed method outperforms existing differentiator from [18] of the same order in all terms except the required number of multiplications. Compared to existing differentiator [18], the proposed fourteenth-order differentiator has higher stopband magnitude response error only, while the proposed twelfth-order differentiator has considerable higher passband phase response linearity error and somewhat higher stopband magnitude response error.

Table 4 $\omega_p = 0.3\pi$

Parameters	Proposed $L = m = 3,$ $\omega_s = 0.525\pi,$ $\gamma = 1.25$	Proposed $L = m = 4,$ $\omega_s = 0.45\pi,$ $\gamma = 1.125$	Proposed $L = 5, m = 4,$ $\omega_s = 0.44\pi,$ $\gamma = 1.5$	[12]
δ_p	3.05%	0.21%	0.86%	3.5%
P_{sb}	0.24	0.23	0.24	0.25
$\bar{\tau}$	1.94	3.06	3.73	3.36
η	4.96°	4.10°	1.50°	1.71°
No. of multiplications	3	4	5	6
No. of delays/filter order	4	6	8	3

Results of comparison of proposed differentiators with lowpass differentiator from [12]

The results presented in examples 5, 6 and 7 lead to the conclusion that proposed differentiators compare favorably with existing allpass-based IIR lowpass differentiators [18] of the same order. On the other hand, due to the fact that maximum of the magnitude response of proposed lowpass differentiators equals γ , while higher values of parameter γ are required to obtain nearly linear phase, existing allpass-based lowpass differentiators from [18] have lower maximum of the magnitude response.

4.2 Comparison with the Nearly Linear Phase Lowpass Differentiators from [12]

Comparison of the proposed lowpass differentiators with differentiators from [12] is presented in this subsection. These differentiators are designed by minimizing the group delay deviation subject to constraints on maximum relative passband magnitude response error and average squared stopband magnitude response. Transfer function of lowpass differentiators from [12] can be expressed as:

$$H_2(z) = (1 - z^{-1}) \frac{\sum_{i=0}^{M-1} q_i z^{-i}}{1 + \sum_{i=1}^M p_i z^{-i}}, \quad (40)$$

thus requiring $2M$ multiplications and M delays.

In the eighth example, proposed differentiators are compared to third-order lowpass differentiator from [12] with passband edge frequency $\omega_p = 0.3\pi$. Three differentiators are designed: a) $L = m = 3$, $\omega_s = 0.525\pi$, $\gamma = 1.25$, b) $L = m = 4$, $\omega_s = 0.45\pi$, $\gamma = 1.125$ and c) $L = 5$, $m = 4$, $\omega_s = 0.44\pi$, $\gamma = 1.5$. From the results presented in Table 4, it can be concluded that all differentiators designed using the proposed method outperform existing one in terms of δ_p , P_{sb} and required number of multiplications. On the other hand, the proposed eighth-order differentiator has smaller phase response error, while the fourth- and sixth-order differentiators have somewhat higher value of passband phase response error compared to the existing differentiator from [12].

In the ninth example, two differentiators having the same passband and stopband edge frequencies, $\omega_p = 0.5\pi$, $\omega_s = 0.63\pi$, are designed using the proposed method

Table 5 $\omega_p = 0.5\pi$

Parameters	Proposed $L = m = 4,$ $\omega_s = 0.63\pi,$ $\gamma = 2.3125$	Proposed $L = 6, m = 5,$ $\omega_s = 0.63\pi,$ $\gamma = 2.5$	[12]
δ_p	1.98%	1.4%	6%
P_{sb}	0.87	0.76	0.88
$\bar{\tau}$	2.49	4.44	2.31
η	2.77°	1.7°	1.74°
No. of multiplications	4	6	6
No. of delays/filter order	6	10	3

Results of comparison of proposed differentiators with lowpass differentiator from [12]

Table 6 $\omega_p = 0.7\pi$

Parameters	Proposed $L = m = 6,$ $\omega_s = 0.85\pi,$ $\gamma = 2.25$	Proposed $L = m = 6,$ $\omega_s = 0.815\pi,$ $\gamma = 2.3125$	[12]
δ_p	0.61%	0.96%	1%
P_{sb}	1.18	1.2	1.2
$\bar{\tau}$	4.63	4.58	2.02
η	12.2°	9.69°	11.96°
no. of multiplications	6	6	8
no. of delays/filter order	10	10	4

Results of comparison of proposed differentiators with lowpass differentiator from [12]

with following values: a) $L = m = 4, \gamma = 2.3125$, b) $L = 6, m = 5, \gamma = 2.5$. The results of comparison are presented in Table 5. From these results, it can be concluded that tenth-order proposed lowpass differentiator outperforms existing one in all terms except filter order and average group delay values. On the other hand, proposed sixth-order differentiator requires only four multiplications (compared to 6 multipliers required by the other proposed and existing differentiator) and has lower values of δ_p and P_{sb} , but somewhat higher passband phase error (2.77°) compared to existing differentiator (1.74°).

In the tenth example, two tenth-order ($L = m = 6$) differentiators with passband edge frequency $\omega_p = 0.7\pi$ are designed using the proposed method: a) $\omega_s = 0.85\pi, \gamma = 2.25$ and b) $\omega_s = 0.815\pi, \gamma = 2.3125$, and compared to the lowpass differentiator from [12]. The results of comparison are summarized in Table 6, while magnitude response, relative passband magnitude response and phase linearity errors are given in Fig. 8. Both proposed differentiators have higher group delay/filter order than existing one, while the first proposed differentiator has slightly higher passband phase error (12.2° compared to 11.96°).

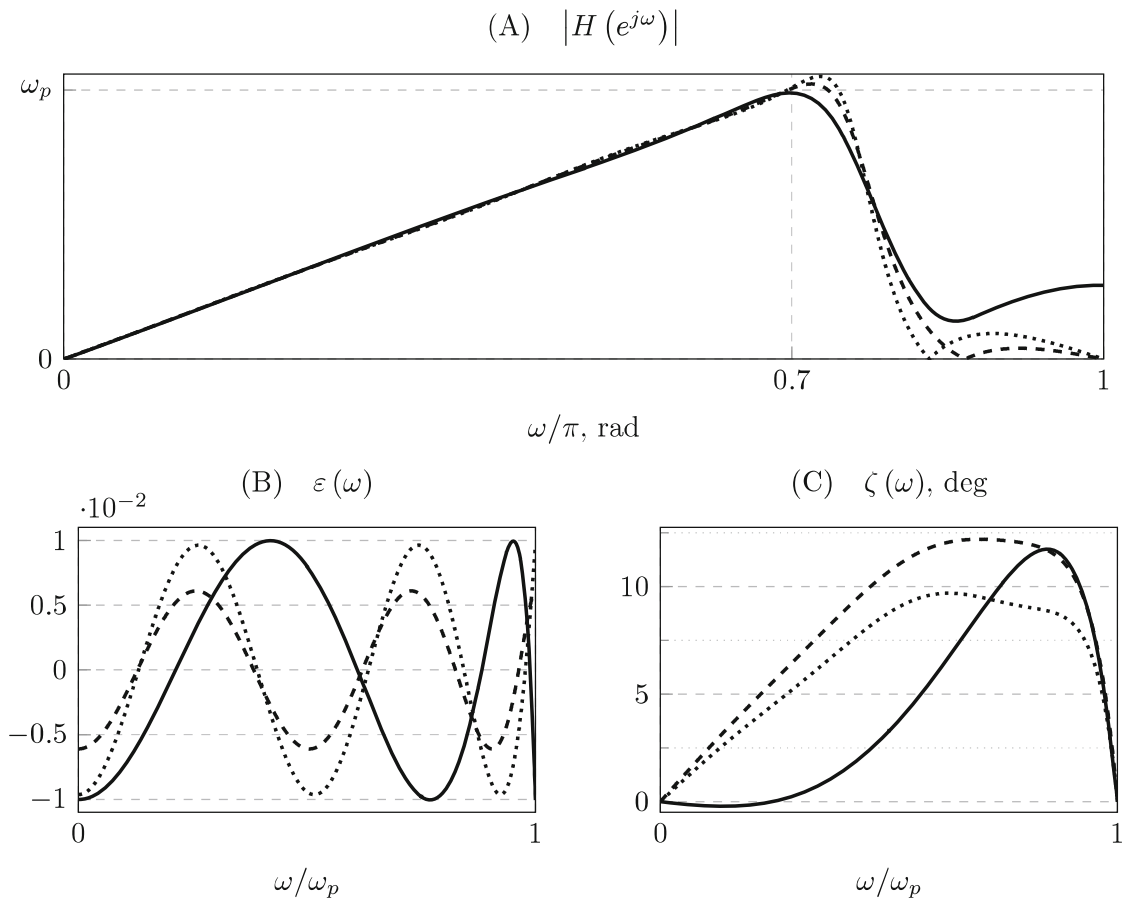


Fig. 8 $\omega_p = 0.7\pi$. **A** Magnitude responses, **B** relative passband magnitude response errors and **C** passband phase response linearity errors of the IIR lowpass differentiator from [12] (solid line) and the proposed ones (dashed and dotted lines correspond to two tenth-order ($\gamma = 2.25$ and $\gamma = 2.1325$) differentiators, respectively)

The results presented in examples 7, 8 and 9 lead to the conclusion that the proposed allpass-based IIR lowpass differentiators, although of the higher order, require less multiplications compared to the existing lowpass differentiators from [12].

4.3 Comparison with the Nearly Linear Phase Lowpass Differentiators from [5]

In this subsection, a comparison of the proposed nearly linear phase IIR lowpass differentiators with the ones from [5] is presented. These differentiators are derived from the lowpass differentiators designed using cascading approach (second-order wideband differentiator [3] is cascaded with the third-order Chebyshev I lowpass filter with 0.1 dB passband ripple value) by altering the denominator coefficients such that magnitude and passband phase response linearity errors are simultaneously minimized. Transfer function of lowpass differentiators from [5] can be expressed as:

$$H_3(z) = \frac{q_0 (1 - z^{-2}) (1 + z^{-1})^3}{1 + p_1 z^{-1} + p_2 z^{-2} + p_3 z^{-3} + p_4 z^{-4} + p_5 z^{-5}}, \quad (41)$$

thus requiring 6 multiplications and 5 delays.

Table 7 $\omega_p = 0.3\pi$

Parameters	Proposed $L = m = 3,$ $\omega_s = 0.625\pi,$ $\gamma = 1.125$	Proposed $L = m = 4$ $\omega_s = 0.55\pi,$ $\gamma = 1.0625$	[5]
δ_p	2.04%	0.10%	2.56%
P_{sb}	0.23	0.22	0.24
$\bar{\tau}$	2.09	3.16	2.34
η	6.05°	5.38°	6.27°
no. of multiplications	3	4	6
no. of delays/filter order	4	6	5

Results of comparison of proposed differentiators with lowpass differentiator from [5]

Table 8 $\omega_p = 0.4\pi$

Parameters	Proposed $L = 3, m = 4,$ $\gamma = 1.2745$	Proposed $L = m = 4$ $\omega_s = 0.6\pi,$ $\gamma = 1.375$	[5]
δ_p	0.93%	0.39%	2.34%
P_{sb}	0.41	0.36	0.41
$\bar{\tau}$	2.08	2.92	1.98
η	10.94°	6.9°	10.58°
No. of multiplications	4	4	6
No. of delays/filter order	4	6	5

Results of comparison of proposed differentiators with lowpass differentiator from [5]

In Examples 10, 11 and 12, proposed lowpass differentiators are compared to fifth-order differentiators from [5] with passband edge frequencies $\omega_p = 0.3\pi$, $\omega_p = 0.4\pi$ and $\omega_p = 0.5\pi$, respectively. The results of comparison are presented in Tables 7, 8 and 9. Magnitude responses, relative passband magnitude response errors and passband phase response linearity errors for $\omega_p = 0.4\pi$ are shown in Fig. 9. From these results, it can be concluded that the proposed fourth-order allpass-based IIR lowpass differentiators have better or comparable performances than existing fifth-order differentiators from [5], while proposed sixth-order differentiators outperform fifth-order differentiators [5] in all terms except filter order and group delay values. Furthermore, proposed fourth- and sixth-order differentiators require significantly less multiplications compared to differentiators from [5].

5 Conclusion

The paper presents the design of nearly linear phase allpass-based IIR lowpass differentiators with the magnitude response approximating the ideal one in weighted

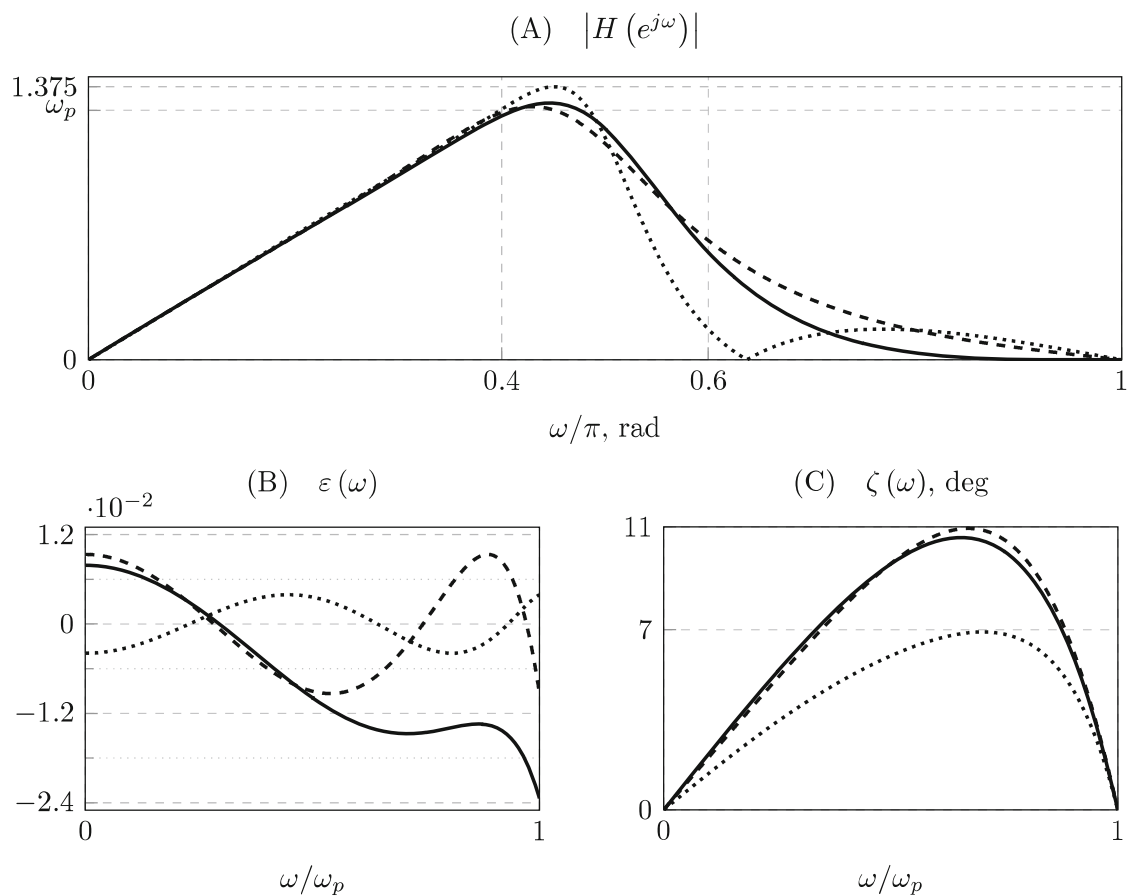


Fig. 9 $\omega_p = 0.4\pi$. **A** Magnitude responses, **B** relative passband magnitude response errors and **C** passband phase response linearity errors of the IIR lowpass differentiator from [5] (solid line) and the proposed ones (dashed and dotted lines correspond to fourth- and sixth-order differentiators, respectively)

Table 9 $\omega_p = 0.5\pi$

Parameters	Proposed $L = 3, m = 4,$ $\gamma = 1.584$	Proposed $L = m = 4$ $\omega_s = 0.7\pi,$ $\gamma = 1.75$	[5]
δ_p	1.04%	1.46%	6.70%
P_{sb}	0.89	0.63	0.89
$\bar{\tau}$	1.88	2.73	1.66
η	11.54°	7.40°	11.77°
No. of multiplications	4	4	6
No. of delays/filter order	4	6	5

Results of comparison of proposed differentiators with lowpass differentiator from [5]

Chebyshev sense both in the passband and the stopband. Employed parallel connection of two allpass filters whose orders differ by two, where allpass branch of lower order is a pure delay, allows formulation of the differentiator magnitude and phase responses as functions of the corresponding allpass filter phase response and maximum of the magnitude response (i.e., the value of the parameter γ). Relation between these two responses is such that the phase response linearity error can be effectively controlled by the maximum of the magnitude response and the maximum of the relative passband magnitude response error. This, if very low phase linearity errors (below few degrees) are required, it leads to considerable magnitude response overshoot in the transition region. Therefore, instead of increasing the maximum of the magnitude response, phase correction of the proposed low-order lowpass differentiators may be a better solution. This will be a matter of future research.

Design examples demonstrate that even fourth-order differentiators (requiring only 3 or 4 multiplications depending on whether γ can be expressed as the sum of a few power-of-two terms or not) can have very low relative magnitude response errors and nearly linear phases. Furthermore, proposed differentiators compare favorably with existing allpass-based IIR lowpass differentiators of the same order, while compared to other existing IIR nearly linear phase lowpass differentiators, proposed differentiators require less multiplications.

Funding The authors received no financial support for the research.

Data Availability Data sharing was not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Appendix A: Allpass-Based IIR Lowpass Differentiators Design Function

```
def designMethod(L, m, wp, ws, gamma):
    import sympy as sp
    import numpy as np
    import scipy.signal as scs

    def phil(w): return int(w<=wp)*(-(L-2)*w - 2*sp.asin(w/gamma)) + \
        int(w>=ws)*(-(L-2)*w - 2*sp.pi)

    _a = sp.Matrix([1] + [sp.Symbol('a%d' % i, real=True)
                          for i in range(1, L+1)])
    _w = sp.Symbol('w', real=True)

    c = sp.Matrix([sp.cos(n*_w) for n in range(L+1)]).T
    s = sp.Matrix([sp.sin(n*_w) for n in range(L+1)]).T
    sc = sp.Matrix([(n-1)*sp.sinc(_w*(n-1)) for n in range(L+1)]).T

    _lmbd = (sc*_a)[0] / sp.sqrt((c*_a)[0]**2 + (s*_a)[0]**2)
    _grad_lmbd = [_lmbd.diff(_a[i]) for i in range(1, L+1)]

    # Step 1
```



```

w = [(k+2)*wp/(m+2) for k in range(1, m)] + \
     [ws + (k-m+1)*(np.pi-ws)/(L-m+2) for k in range(m, L+1)]

B = sp.Matrix([[sp.sin((phi1(w[k]) + (L - 2*i)*w[k]) / 2)
                for i in range(1, L+1)] for k in range(L)])

c = sp.Matrix([-sp.sin((phi1(w[k]) + L*w[k]) / 2) for k in range(L)])
ap = np.array(list(B**(-1) * c))

w = np.linspace(0, 1, 10001) * np.pi
wpass, wstop = w[w<=wp], w[w>=ws]
dtol = 1e-10
while True:
    lmbd = _lmbd.subs([(a[i], ap[i-1]) for i in range(1, L+1)])
    lmbd = sp.lambdify(_w, lmbd)
    grad_lmbd = [_grad_lmbd[k].subs(
        [(a[i], ap[i-1]) for i in range(1, L+1)]) for k in range(L)]
    grad_lmbd = sp.lambdify(_w, grad_lmbd)

    # Step 2
    def err_pass(w): return -1 - gamma*lmbd(w)
    def err_stop(w): return -w*gamma*lmbd(w)

    ind, _ = scs.find_peaks(abs(err_pass(wpass)))
    w_hat = np.append(np.append(0, wpass[ind]), wp)
    # extremas of the same sign
    if len(w_hat)>m and \
        np.sign(err_pass(w_hat[0]))==np.sign(err_pass(w_hat[1])):
        w_hat = w_hat[1:]
    if len(w_hat)>m and \
        np.sign(err_pass(w_hat[-1]))==np.sign(err_pass(w_hat[-2])):
        w_hat = w_hat[:-1]
    # m+1 sign-alternating extrema
    if len(w_hat) > m:
        if wp >= np.pi/2:
            w_hat = w_hat[:-1]
        elif abs(err_pass(w_hat[0])) > abs(err_pass(w_hat[-1])):
            w_hat = w_hat[:-1]
        else:
            w_hat = w_hat[1:]
    p = int(np.sign(err_pass(w_hat[0])) == 1)

    ind, _ = scs.find_peaks(abs(err_stop(wstop)))
    w_ol = np.append(ws, wstop[ind])
    if len(w_ol) > (L-m+2):
        if abs(err_stop(ws)) > abs(err_stop(wstop[-1])):
            w_ol = w_ol[:-1]
        else:
            w_ol = w_ol[1:]

    # Step 3
    Lhs = [[sp.Matrix([grad_lmbd(w_hat[k]) for k in range(m)]),
            sp.Matrix([(-1)**(p+k) for k in range(1, m+1)]),
            sp.zeros(m, 1)],
            [sp.Matrix([grad_lmbd(w_ol[k]) for k in range(L-m+2)]),
            sp.zeros(L-m+2, 1),
            sp.Matrix([(-1)**(k+1) / w_ol[k] for k in range(L-m+2)])]]
    Lhs = sp.Matrix(Lhs)
    rhs = sp.Matrix(-np.append(1/gamma + lmbd(w_hat), lmbd(w_ol)))
    x = Lhs**(-1) * rhs

```

```

a = ap + np.array(x[:L])

if abs(np.array(x[:L])).max() <= dtol:
    break
else:
    ap = a
return a

```

References

1. J. Ababneh, M. Khodier, Design of approximately linear phase low pass IIR digital differentiator using differential evolution optimization algorithm. *Circuits Syst. Signal Process.* **40**, 1–23 (2021)
2. M.A. Al-Alaoui, Novel approach to designing digital differentiators. *Electron. Lett.* **28**(15), 1376–1378 (1992)
3. M.A. Al-Alaoui, Novel IIR differentiator from the Simpson integration rule. *IEEE Trans. Circuits Syst. I Fundam. Theory Appl.* **41**(2), 186–187 (1994)
4. M.A. Al-Alaoui, A class of second-order integrators and low-pass differentiators. *IEEE Trans. Circuits Syst. I Fundam. Theory Appl.* **42**(4), 220–223 (1995)
5. M.A. Al-Alaoui, Linear phase low-pass IIR digital differentiators. *IEEE Trans. Signal Process.* **55**(2), 697–706 (2007)
6. M.A. Al-Alaoui, Direct approach to image edge detection using differentiators, in *2010 17th IEEE International Conference on Electronics, Circuits and Systems* (2010), pp. 154–157
7. Y. Ferdi, Improved lowpass differentiator for physiological signal processing, in *2010 7th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP 2010)* (2010), pp. 747–750
8. A.L. Goldberger, L.A. Amaral, L. Glass, J.M. Hausdorff, PCh. Ivanov, R.G. Mark, J.E. Mietus, G.B. Moody, C.-K. Peng, H.E. Stanley, PhysioBank, PhysioToolkit, and PhysioNet: components of a new research resource for complex physiological signals. *Circulation* **101**(23), e215–e220 (2000)
9. I. Krstić, Design of IIR lowpass differentiators based on second-order allpass filter application. *Circuits Syst. Signal Process.* **41**(3), 1803–1818 (2022)
10. J. Le Bihan, Novel class of digital integrators and differentiators. *Electron. Lett.* **29**(11), 971–973 (1993)
11. M. Merino, O. Rivera, I. Gómez, A. Molina, E. Dorronzoro, A method of EOG signal processing to detect the directions of eye movements, in *2010 First International Conference on Sensor Device Technologies and Applications* (2010), pp. 100–105
12. R.C. Nongpiur, D.J. Shpak, A. Antoniou, Design of IIR digital differentiators using constrained optimization. *IEEE Trans. Signal Process.* **62**(7), 1729–1739 (2014)
13. J. Pan, W.J. Tompkins, A real-time QRS detection algorithm. *IEEE Trans. Biomed. Eng.* **3**, 230–236 (1985)
14. M.A. Platas-Garza, J. Platas-Garza, J.A. de la Oserna, Dynamic phasor and frequency estimates through maximally flat differentiators. *IEEE Trans. Instrum. Meas.* **59**(7), 1803–1811 (2009)
15. P.A. Regalia, S.K. Mitra, P. Vaidyanathan, The digital all-pass filter: a versatile signal processing building block. *Proc. IEEE* **76**(1), 19–37 (1988)
16. S.A. Skogstad, S. Holm, M. Hivin, Designing digital IIR low-pass differentiators with multi-objective optimization, in *2012 IEEE 11th International Conference on Signal Processing* vol. 1 (2012), pp. 10–15
17. G. Stančić, I. Krstić, Design of IIR fullband differentiators using parallel all-pass structure. *Digit. Signal Process.* **87**, 132–144 (2019)
18. G. Stančić, I. Krstić, S. Cvetković, All-pass-based design of nearly-linear phase IIR low-pass differentiators. *Int. J. Electron.* **107**(9), 1451–1470 (2020)
19. M. Wulf, G. Staude, A. Knopp, T. Felderhoff, Efficient design of FIR filter based low-pass differentiators for biomedical signal processing. *Curr. Dir. Biomed. Eng.* **2**(1), 215–219 (2016)
20. H. Yi, X. Lai, Design of low-pass and band-pass infinite impulse response maximally flat stable digital differentiators. *IET Signal Proc.* **16**(2), 201–219 (2022)
21. T. Yoshida, M. Nakamoto, N. Aikawa, Low-delay and high-functioning digital differentiators in the big data era. *Electron. Commun. Jpn.* **101**(10), 31–37 (2018)

22. T. Yoshida, Low-pass maximally flat IIR digital differentiator design with arbitrary flatness degree, in *2021 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC)* (2021), pp. 226–231

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.



electronics



Article

Going beyond API Calls in Dynamic Malware Analysis: A Novel Dataset

Slaviša Ilić, Milan Gnjatović, Ivan Tot, Boriša Jovanović, Nemanja Maček and Marijana Gavrilović Božović

Special Issue

Intelligent Solutions for Network and Cyber Security

Edited by

Prof. Dr. Lixin Wang, Prof. Dr. Jianhua Yang and Prof. Dr. Qiang Ye



<https://doi.org/10.3390/electronics13173553>

Article

Going beyond API Calls in Dynamic Malware Analysis: A Novel Dataset

Slaviša Ilić ^{1,2,*} , Milan Gnjatović ² , Ivan Tot ¹, Boriša Jovanović ¹ , Nemanja Maček ³ 
and Marijana Gavrilović Božović ⁴ 

¹ Department of Military Electronic Engineering, University of Defence, Veljka Lukića Kurjaka 1, 11000 Belgrade, Serbia; ivan.tot@va.mod.gov.rs (I.T.); borisa.jovanovic@vs.rs (B.J.)

² Department of Information Technology, University of Criminal Investigation and Police Studies, Cara Dušana 196, 11080 Beograd, Serbia; milan.gnjatovic@kpu.edu.rs

³ School of Electrical and Computer Engineering, Academy of Technical and Art Applied Studies, Vojvode Stepe 283, 11000 Beograd, Serbia

⁴ Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia; marijana.gavrilovic@kg.ac.rs

* Correspondence: ilic.slavisa@gmail.com

Abstract: Automated sandbox-based analysis systems are dominantly focused on sequences of API calls, which are widely acknowledged as discriminative and easily extracted features. In this paper, we argue that an extension of the feature set beyond API calls may improve the malware detection performance. For this purpose, we apply the Cuckoo open-source sandbox system, carefully configured for the production of a novel dataset for dynamic malware analysis containing 22,200 annotated samples (11,735 benign and 10,465 malware). Each sample represents a full-featured report generated by the Cuckoo sandbox when a corresponding binary file is submitted for analysis. To support our position that the discriminative power of the full-featured sandbox reports is greater than the discriminative power of just API call sequences, we consider samples obtained from binary files whose execution induced API calls. In addition, we derive an additional dataset from samples in the full-featured dataset, whose samples contain only information on API calls. In a three-way factorial design experiment (considering the feature set, the feature representation technique, and the random forest model hyperparameter settings), we trained and tested a set of random forest models in a two-class classification task. The obtained results demonstrate that resorting to full-featured sandbox reports improves malware detection performance. The accuracy of 95.56 percent obtained for API call sequences was increased to 99.74 percent when full-featured sandbox reports were considered.

Keywords: dynamic malware analysis; classification; cuckoo; sandbox; API; random forest; dataset



Citation: Ilić, S.; Gnjatović, M.; Tot, I.; Jovanović, B.; Maček, N.; Gavrilović Božović, M. Going beyond API Calls in Dynamic Malware Analysis: A Novel Dataset. *Electronics* **2024**, *13*, 3553. <https://doi.org/10.3390/electronics13173553>

Academic Editors: Lixin Wang, Qiang Ye and Jianhua Yang

Received: 6 August 2024

Revised: 4 September 2024

Accepted: 5 September 2024

Published: 6 September 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Due to the rise in the number and complexity of cyber threats, dynamic malware analysis has become an important part of cyber defense. This type of malware analysis is often performed in a sandbox environment, i.e., a virtual machine (VM) environment in which suspected binaries are seeded and their dynamic behavior is monitored. The monitoring result is represented by a report containing evidence of actions performed by a given seeded binary.

However, the interpretation of those reports may be a challenging task, e.g., a benign installation package that generates a significant number of files (which are written to the disk), registry changes, and other modifications to the target system (starting multiple processes, establishing network communication, etc.), might not be easily distinguished from a malware which applies evasion techniques (i.e., a malware that changes its behavior when it detects that it is being run in a sandbox environment) [1]. Thus, the interpretation of sandbox reports often requires a human expert, which makes it time consuming.

To address this problem, relevant machine learning approaches to dynamic malware analysis are dominantly focused on application programming interface (API) calls extracted by a sandbox system. However, in our study, we show that a significant part of both malware and benign software samples do not generate API calls when run in a sandbox environment (cf. Section 3). Thus, we argue that the extension of a feature set beyond API calls may improve malware detection performance. In line with this, the paper makes the following contributions:

(i) We produce a novel dataset for dynamic malware analysis, which contains 22,200 labeled samples (benign and malware). Each sample represents a report generated by the open-source sandbox system Cuckoo when a corresponding binary file is submitted for analysis. These reports contain information on API calls but also on other dynamic behavior features related to file and registry modification, network traffic, etc. It is important to note that there are no other publicly available datasets containing both malware and benign samples represented by a more comprehensive set of features extracted by a sandbox system (cf. Section 2). In addition, we describe the configuration of the sandbox system used in the production of the dataset, aimed at addressing the problem of evasion techniques applied by some malware samples.

(ii) We practically demonstrate that the extension of the feature set beyond API calls improves the malware detection performance. We report on two groups of random forest (RF) models (cf. Ho [2]). The models from the first group were trained and tested on the reported dataset containing full-featured Cuckoo sandbox reports (including, but not limited to, API call sequences). The models from the second group were trained and tested on a dataset derived from the reported dataset, in which each sample is represented by the extracted sequence of API calls. The obtained results show that the models from the first group display better performance in terms of accuracy and macro average F1 measure.

The paper is structured as follows. Section 2 covers related and background work. Section 3 describes the production of the dataset and methods used. Section 4 reports on the experimental settings, results, and optimization. In Section 5, we discuss the results. Finally, Section 6 concludes the paper.

2. Background and Related Work

With respect to the feature extraction task, the field of machine learning for dynamic malware analysis tasks includes two main research directions. The first direction is dominant and supported by datasets containing only API call sequences (cf. Section 2.1). The other direction is significantly less practiced but promising and is based on the assumption that there are additional significant features beyond the API call sequence (cf. Section 2.2).

2.1. API Call Feature Sets

In the given context, API refers to a part of an operational system which, inter alia, enables programs to access resources such as system files, processes, services, etc. (Mira et al. [3]). In the cyber-security community, API call sequences have been acknowledged as indicative of malware detection (Deore et al. [4]). The main idea underlying these approaches is that API call sequences reflect the malware behavior and that malware variants display similar API call-based behavior. For an overview of malware detection using API call sequences, the reader may consult [3].

Düzgün et al. [5] and Alshmarni et al. [6] report on datasets produced by the Cuckoo sandbox. The dataset presented by Düzgün et al. [5] contains a significant number (i.e., 24,411) of categorized malware samples but does not include benign samples. The dataset presented by Alshmarni et al. [6] contains both benign and malware samples, but their number is somewhat reduced (i.e., 1080 benign and 2576 malware). In addition, both of these datasets contain a restricted feature set since each sample is represented as only a sequence of API calls.

Syeda and Asghar [7] report on a dataset containing samples from Windows Portable Executable files. This dataset is relatively small (582 malware and 438 benign samples) and contains API calls only. Six machine learning models were evaluated on this dataset, including inter alia

ensemble methods RF and XGBoost. The RF model displayed the best classification accuracy. Zhang et al. [8] propose an approach to malware detection based on recurrent neural networks (including TextRNN and bidirectional long short-term memory network) and self-attention mechanisms applied to API call sequences. Huang et al. [9] apply a clustering algorithm to API call sequences to capture a common behavior of malware families and then train a neural network on the recorded sequences. Other papers also deal with different approaches to API calls: Huang et al. [10] propose a model based on a sequence-to-sequence neural network and an attention mechanism and evaluate it on sequences of API calls. Chen et al. [11] propose an image-based interpretation of API existence, API sequence, and API frequency features and apply deep transfer learning to generated images.

To further improve malware detection performance, a significant number of researchers have considered additional API call-based features. Alhashmi et al. [12] apply the TF-IDF transformation to extract features from API calls retrieved by means of the static analysis of PE files and dynamic analysis of API hooks. Lee et al. [13] report on a sandbox-like implementation called ARBDroid, designed to analyze obfuscated malware on the Android platform and extract instructions, string values, and API calls. Chen et al. [14] extend the set of API calls with indicators of compromise. Yau et al. [15] consider additional API-based statistical features such as return values and the number of times the API is called. Xu and Chen [16] model a malware instance as a behavioral tree generated from an API call sequence, which describes the control structure between the API calls. Li et al. [17] propose a hybrid feature encoder aimed at extracting semantic features from API names and arguments and generating an API call graph that captures the relations between the API calls. Li et al. [18] apply dynamic analysis and embedding techniques to encode an API sequence, introducing a soft threshold mechanism in a residual network to achieve active filtering of noise components in API sequences. They resort to a BiLSTM model to enhance the temporal correlation among API sequence calls and improve the classification performance. Nunes et al. [19] emphasize the difference between capturing API calls at the user and kernel levels with respect to the classifier's ability to detect malware. Li et al. [20] introduced the PrefixSpan algorithm designed to mine frequent API call sequences from various threads within an execution trace and capture malware behavior sequences.

2.2. More Comprehensive Feature Sets

In contrast to these API call-focused approaches to dynamic malware analysis, some recent efforts are based on more comprehensive feature sets. Jindal et al. [21] produced four datasets containing reports generated by the Cuckoo sandbox and another commercial sandbox. Two sources have served as input to the sandboxes: a vendor dataset (13,760 benign and 13,760 malware) and a dataset derived by random sample selection from the publicly available EMBER dataset for static file analysis (cf. Anderson and Rothl [22]). However, none of these four datasets are publicly available. In the data preprocessing phase, Jindal et al. [21] tokenize the sandbox reports and keep the top 10,000 most common words. In addition, they introduce a classification model that integrates a convolutional neural network, a bidirectional long short-term memory network, and an attention network.

Another commendable approach is introduced by Bosansky et al. [23]. They report on a malware dataset with a significant number of samples (i.e., 48,976 samples) generated by the CAPE sandbox. Another advantage of this dataset is that each sample is labeled with respect to the malware family it belongs to. On the other hand, this dataset does not contain benign samples and considers only six malware families. For example, ransomware samples are not included, which explains the fact that the maximum report size of the considered samples does not exceed 1 GB (the size of the entire unpacked dataset is 563 GB). Bosansky et al. [23] apply the hierarchical multi-instance learning (HMIL) paradigm to process the collected sandbox reports.

Herrera-Silva and Hernández-Álvarez [24], Irshad and Dutta [25], and Sraw and Kumar [26] extend the API call feature set with limited sets of hand-selected features derived from the Cuckoo sandbox reports. These sets contain 50, 5, and 8 additional features, respectively,

relating to, e.g., registry entries, network traffic, etc. They demonstrate that additional features improve malware detection performance. Finally, Sethi et al. [27] extend the API call feature set with a set of features automatically extracted from the Cuckoo sandbox reports. The additional features were extracted by means of the chi-square test and RF algorithms. However, none of these approaches to feature engineering utilize complete sandbox reports.

2.3. Position of Our Approach

Our approach is in line with the second research direction. In line with Refs. [21,23], we produce a dataset containing reports generated by the Cuckoo sandbox. However, in contrast to Ref. [21], we do not consider only a subset of the most common words in the generated reports. Starting from the expectation that less frequent words may have significant information gain, we consider entire and unaltered reports generated by the sandbox system. This means that we do not apply any preprocessing or cleaning technique prior to the feature extraction stage.

In contrast to Ref. [23], we include benign samples and additional malware families, which increases the size of the generated reports, e.g., over 1 GB for 228 malware samples. In addition, it should be noted that there are no other publicly available datasets containing full-featured sandbox reports with such a large number of samples.

Another distinction of our approach is related to the methodology. Recent methodological approaches are focused on recurrent neural networks and attention mechanisms [8,10,11,21] or ensemble detectors, taking into account the observation window [1], which reflects the conceptualization of the underlying features as sequence-like structures. In contrast to them, in our approach, we step away from this conceptualization and apply the random forest model (as in Ref. [7]), which is based on the information gain of the underlying features rather than on their sequentiality.

3. Materials and Methods

One of the aims of this work is to produce a new dataset that meets the desiderata of representativeness, i.e., a dataset for dynamic malware analysis that contains a sufficient number of both benign and malware samples, represented by a more comprehensive set of features generated by the Cuckoo sandbox. The production of this dataset can be summarized in the following points:

(i) *Selection and safe management of malware files.* The collection of 450,000 malware file samples was acquired from the Virus Total database [28], which is considered referential in the professional community. From this file set, we programmatically selected 10,465 samples without subjective bias for inclusion in the dataset. Each malware sample taken from this database is provided in the form of a binary file without extension but with the accompanying JSON file that describes the given sample. In addition, we took measures to ensure that the management of the malware files does not compromise the lab environment set for the purpose of dataset production. The file samples were stored on the disk without extensions. Immediately before the submission of a sample to the sandbox, its extension was automatically extracted from a corresponding JSON file and added to the sample, making it suitable for execution. After collecting sandbox results, the extension was again removed.

(ii) *Selection of benign files.* We collected 74,000 real-life benign files representing correspondence documents and Windows 10 installation executables and libraries (e.g., .exe, .dll, .com, etc.), taken with permission from the archive of a technical company located in Serbia. The company was equipped with cyber-security protection and monitoring tools, and no malware activities have been detected over several years. From this file set, we programmatically selected 11,739 samples without subjective bias for inclusion in the dataset.

(iii) *Dataset comprehensiveness.* The dataset comprehensiveness was considered with respect to two separate but related aspects: diversity of the collected file types and representation of a file sample. The reported dataset contains samples (i.e., reports generated by the sandbox) related to 54 file types. The distribution of the samples with respect to file type is provided in Table 1 (cf. the “Full rep.” columns). In addition, for each file type, this table provides the number of samples that include API calls (cf. the “API calls” columns).

Table 1. File type distribution in the dataset.

File Type	# Benign Instances		# Malware Instances		File Type	# Benign Instances		# Malware Instances	
	Full rep.	API Calls	Full rep.	API Calls		Full rep.	API Calls	Full rep.	API Calls
exe	1395	344	7097	6597	Xlsm	0	0	5	5
dll	6574	3354	238	237	accdb	5	5	0	0
doc	1659	1659	947	947	Cat	5	5	0	0
xls	631	631	477	475	Gdl	5	5	0	0
txt	4	0	803	803	xml	5	5	0	0
fxp	558	558	0	0	Db	4	0	0	0
docx	0	0	269	269	Pptx	0	0	4	4
pdf	118	0	120	0	Sch	3	3	0	0
cdx	223	0	0	0	Ppt	0	0	3	3
dbf	222	222	0	0	Avi	2	2	0	0
xlsx	0	0	190	190	Bin	2	2	0	0
prg	138	138	0	0	bmp	2	0	0	0
html	0	0	128	128	Och	2	2	0	0
none	0	0	60	59	Tbk	2	2	0	0
ppd	52	52	0	0	Msg	0	0	2	2
docm	0	0	45	45	agcoc	1	1	0	0
fpt	35	35	0	0	Bak	1	1	0	0
fpx	0	0	33	33	Fmt	1	1	0	0
zip	7	0	17	0	Ico	1	0	0	0
rar	0	0	24	23	Mem	1	1	0	0
htm	19	19	0	0	Ms	1	1	0	0
crt	12	12	0	0	New	1	1	0	0
inf	10	10	0	0	pr1	1	1	0	0
bat	9	9	0	0	Ses	1	1	0	0
dat	8	0	0	0	Json	0	0	1	1
ini	8	8	0	0	mp3	0	0	1	1
lnk	7	7	0	0	Rtf	0	0	1	1
Total:						11,735	7097	10,465	9823

The rows marked with grey highlight the file type classes containing samples that did not generate API calls, which is elaborated in more detail in Table 2.

For each file type, Table 1 provides information on:

- Number of benign files belonging to the given file type (cf. column “# Benign instances”—“Full rep.”).
- Number of benign files belonging to the given file type whose execution generates API calls (cf. column “# Benign instances”—“API calls”).
- Number of malware files belonging to the given file type (cf. column “# Malware instances”—“Full rep.”).
- Number of malware files belonging to the given file type whose execution generates API calls (cf. column “# Malware instances”—“API calls”).

From Table 1, it can be derived that 23.78 percent of the produced sandbox reports do not include API calls, i.e., there are 5280 such samples: 4638 benign and 642 malware. The distribution of samples that do not include API calls with respect to file type is shown in Table 2. It is common that benign files do not induce operating system API calls, e.g., in cases when they do not create files or access the registry, etc. On the other hand, it is

common that malware samples induce API calls, as they are designed to be lightweight (easily downloadable) and access the registry and files, etc. However, it can be observed from Table 2 that approximately 6 percent of malware samples do not induce API calls. We assume that these malware samples are intentionally developed not to apply operating system APIs in order to avoid antivirus behavioral analysis and possible sandbox detection based on API calls.

In contrast to the existing datasets, which represent file samples as sequences of API calls, we consider a more comprehensive set of features provided by the Cuckoo sandbox. Besides the API calls, we collect additional features relevant to dynamic malware analysis related to the following:

- Static and dynamic analysis based on YARA rules for code packing, obfuscation, etc.;
- Registry editing;
- File creation and modification;
- Network access;
- Checking user activities and other evasion techniques and behaviors of file samples, etc.

Table 2. The distribution of samples that do not include API calls with respect to file type.

File Type Extension	Instances	Benign Instances	Malware Instances
dll	3221	3220	1
exe	1551	1051	500
pdf	238	118	120
cdx	223	223	0
zip	24	7	17
dat	8	8	0
txt	4	4	0
db	4	4	0
xls	2	0	2
bmp	2	2	0
rar	1	0	1
ico	1	1	0
none	1	0	1
	5280	4638	642

Without omitting the basic static analysis, which is included in the Cuckoo sandbox, we do not perform additional analysis of static features (like in Taheri et al. [29,30]) or compare static and dynamic analyses. We focus our attention on dynamic malware analysis based on raw full-featured sandbox reports (without giving preferences to a particular feature subset), which serve as input for automatic feature extraction techniques and machine learning models.

The produced dataset, which we refer to as the full-featured dataset, is organized in two folders containing benign and malware samples. The size of the malware sample folder is 935 GB, and the size of the benign sample folder is 34 GB. Both folders are organized in subfolders whose names correspond to file type extensions (e.g., “dll”, “exe”, “doc”, etc.). The malware samples folder is of greater size because the malware files induced more activities in the sandbox environment than the benign files. Two short segments from JSON reports are given in Figure 1.

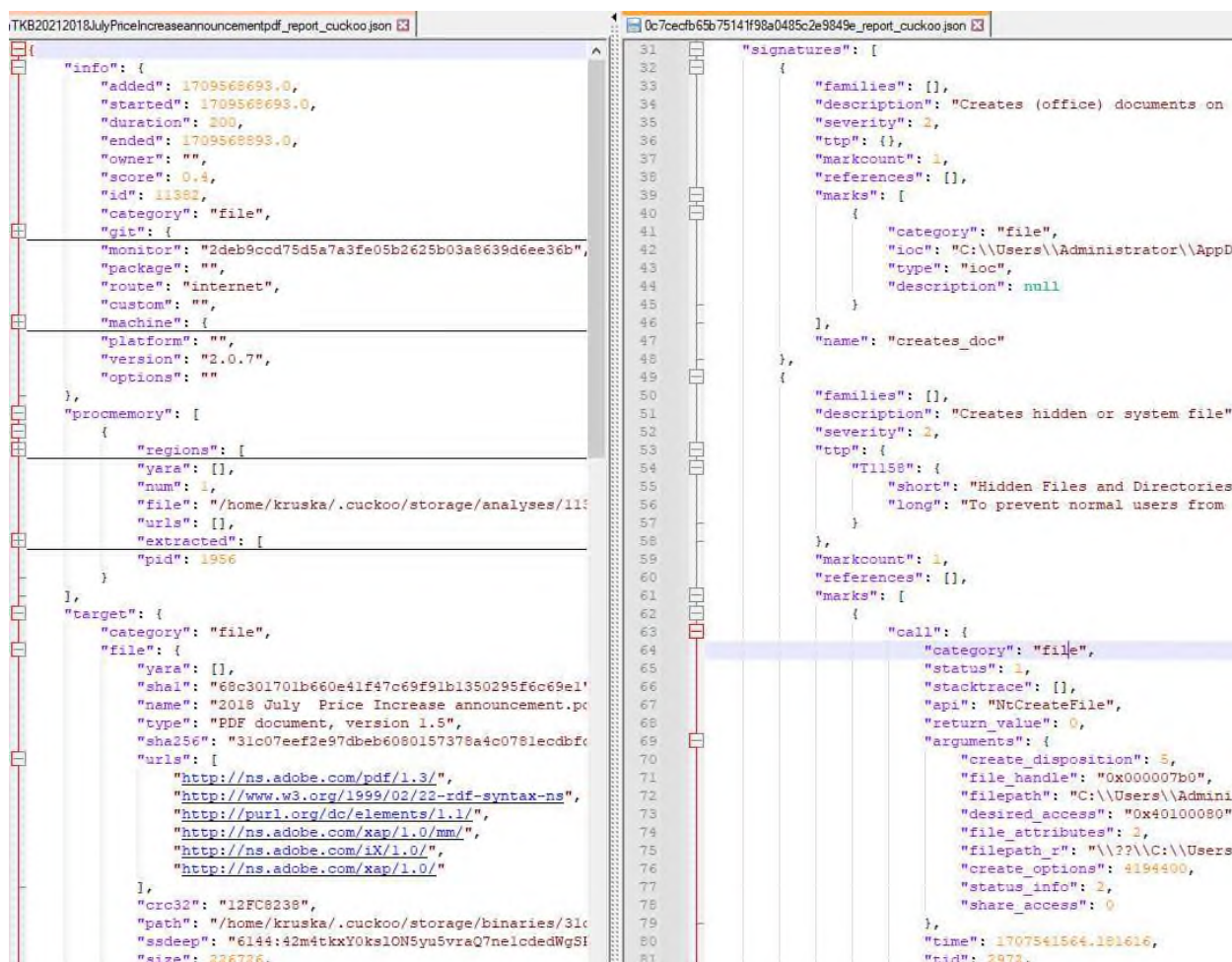


Figure 1. Example segments of benign (left) and malware (right) JSON reports generated by the Cuckoo sandbox.

The malware samples are randomly selected from the Virus Total database, which contains real-world malware examples. The manual inspection of the sandbox reports showed the following:

- Some reports are very big in size (over 2 GB).
- Some samples apply obfuscation techniques (discovered in the basic static file analysis conducted by the sandbox system).
- Some samples implement evasion techniques: checking the browser history, checking whether the running environment is virtual, checking whether a debugger is present, etc.

The benign samples are also real-world files produced over a several-year period by users who were oblivious to the goals of this research.

Thus, we believe that the reported dataset represents a comprehensive real-world representation of both malware and benign samples.

(iv) *Configuration of the sandbox system.* The Cuckoo sandbox version 2.0.7 was used (i.e., the latest release at the moment of this study) based on Python version 2. These particular settings required additional efforts to select correct program dependencies, i.e., adjusting dependency information among program variables, which is discussed in Ilić et al. [31]. Except for the Cuckoo sandbox system, all other codes used in the conduction of this research (i.e., codes for sample submission, reports collection, manipulation, training and validation of machine models, visualization of the results, etc.) were implemented in the latest Python 3 version.

(v) *Selection of the analysis virtual machine operating system.* We set a basic configuration of a Windows 7 virtual machine, which is more vulnerable with respect to malware attacks than more recent operating systems. Microsoft Office 2013 is installed, which supports a wide set of document formats present in the dataset.

(vi) *Configuration of anti-evasion techniques.* We introduced or enabled a set of anti-evasion techniques in the Cuckoo sandbox:

- We configured a Python agent, which monitors events while file samples are being executed and runs silently in the background.
- The analysis virtual machine is configured with usage history and data, a custom username, and software. Special attention was devoted to the browsers' history since we previously noticed frequent checks of Internet browser activities conducted by some malware samples.
- The VMware tools were intentionally omitted, and processing resources of the analysis virtual machine were unusually abundant for a sandbox in order to prevent sophisticated malware samples from recognizing and evading the sandbox techniques.
- The user action imitation technique (e.g., mouse move, click, etc.) integrated into the Cuckoo sandbox was enabled, and the execution time was increased to two minutes per file sample.
- The analysis virtual machine had limited Internet access with the firewall configured in front of the laboratory environment.

(vii) *Configuration of the Python runtime environment.* Some malware file samples, e.g., ransomware samples, perform a significant number of activities when executed in the sandbox system. Thus, the generated sandbox analysis reports were of significant size (i.e., multiple gigabytes). To process such large inputs during the generation of machine learning models, it was necessary to adjust the Python runtime environment by increasing the maximum recursion depth in order to allow for the loading of entire reports from JSON files. Without this change it would not be possible to deal with reports of significant size.

(viii) *Generation of the API call dataset for the feature ablation study.* One of the aims of this study is to demonstrate that the discriminative power of the full-featured sandbox reports discussed in (iii) is greater than the discriminative power of just API call sequences. Thus, for the purpose of the ablation study, we derive a subset that we refer to as the API call dataset. Samples in this dataset contain only information on API calls derived from samples in the full-featured dataset (cf. the "API calls" columns in Table 1). The generation of the API call dataset was performed automatically by applying a regular expression-based Python script. The size of the benign and malware portions of the API call dataset are 848 MB and 18 GB, respectively.

4. Results

4.1. Model and Metrics Selection

In Section 2.3, we briefly discussed the application of random forest models in our malware analysis system. For this purpose, we resort to the scikit-learn library (cf. Pedregosa et al. [32]). However, the training and validation of the underlying models have been performed in experimental settings. We apply a three-way factorial design, i.e., we consider three independent variables: the feature set, the feature representation technique, and the random forest model hyperparameter settings.

The first independent variable is related to the feature set and has two levels: we apply a dataset containing full-featured reports generated by the Cuckoo sandbox and a dataset whose samples contain only API call sequences. Both datasets described in the previous section (i.e., the full-featured and API call datasets) are transformed into pandas data structures (cf. McKinney et al. [33]) and stored as Python pickle files (i.e., byte streams). In addition, each sample is annotated: the label "0" is assigned to benign samples and "1" to malware samples. However, the full feature dataset was further processed. Since the malware part of this dataset was too big to fit into RAM memory, we divided it into three consecutive Python pickle files and then performed the subsampling process in the following steps:

- Loading the panda's data frames and shuffling them.
- Subsampling, i.e., we randomly selected 70 percent of each panda's data frame, keeping the original textual reports representing the selected samples.
- Storing, i.e., all subsample instances were stored in one data frame, which is additionally shuffled. This data frame was transformed into a pickle file.

After this subsampling phase, the selected part of the full features dataset contained 15,542 randomly selected samples (i.e., 8217 benign and 7325 malware).

The second independent variable is related to the feature representation technique and has two levels: we apply the count vectorizer (CV) and the term frequency-inverse document frequency vectorizer (TF-IDF), cf. Pedregosa et al. [32]. Using these techniques, we wanted to examine whether taking into account the importance of a feature to a sample (TF-IDF) will improve performance when compared to taking only term frequencies (CV) into account. For both feature representation techniques, we randomly divided each of the given datasets into a training set (80 percent) and a validation set (20 percent). After combining the first two independent variables (i.e., 2 feature sets $\times$ 2 feature representation techniques), we generated four pickle-based datasets:

- Full-featured samples represented by CV;
- Full-featured samples represented by TF-IDF;
- API calls samples represented by CV;
- API calls samples represented by TF-IDF;

which serve as points of departure for model training and validation.

The third independent variable relates to the random forest model hyperparameters. The first considered hyperparameter is the number of trees in a random forest. This parameter takes values ranging [1, 100]. Other hyperparameters of an RF model include the following: *max_depth*, *min_samples_split*, *min_samples_leaf*, and *max_features*, each of which takes three distinct values ([None, 100, 1000], [2, 100, 1000], [1, 100, 1000], and [sqrt, 0.1, 0.2], respectively). The hyperparameter values are discussed in more detail in Section 4.3.

We apply information gain to estimate the discriminative power of an explanatory feature with respect to the class feature (i.e., the "criterion" hyperparameter was set to the value "entropy"). Finally, we applied the accuracy measure as the dependent variable.

When the independent variables were combined, we obtained a $2 \times 2 \times (100 \times 9)$ factorial design, i.e., we trained and tested 3600 random forest models.

4.2. Experiment

With respect to the underlying dataset (i.e., feature set), these models can be divided into four groups, each of which contains 900 models. Table 3 provides additional information for the optimal model among each of the considered groups. For each of these models, a set of evaluation measure values have been provided (i.e., validation accuracy, precision, and recall for each class, and macro average precision, recall, and F1-score), and information of the underlying dataset (i.e., the number and distribution of samples and the number of features).

The first group of models is related to the experimental condition concerning the full-featured reports represented with CV. Figure 2(left) provides a graphical representation of the validation accuracy with respect to the number of decision trees in a random forest model. The maximum validation accuracy of 99.74 percent was obtained for the random forest model with seven trees. The confusion matrix obtained for this model is given in Figure 2(right), and the derived evaluation measures are provided in Table 3 (cf. the second column).

Table 3. Results, control mechanisms, and metrics in RF.

	CV Full	TF-IDF Full	CV API Calls	TF-IDF API Calls
Num. of trees in the optimal model	7	26	32	66
Validation accuracy (%)	99.74	99.68	95.56	95.4
Precision (benign)	0.997	0.997	0.935	0.933

Table 3. Cont.

	CV Full	TF-IDF Full	CV API Calls	TF-IDF API Calls
Precision (malware)	0.998	0.996	0.982	0.982
Macro average precision	0.997	0.998	0.959	0.957
Recall (benign)	0.998	0.997	0.985	0.985
Recall (malware)	0.996	0.998	0.921	0.918
Macro-average recall	0.997	0.995	0.953	0.952
Macro-average F1	0.997	0.997	0.954	0.954
Num. of samples	15,542	0.997	15,542	15,542
Num. of features	25,066,934	25,066,934	294	294
Benign samples	8217	8217	4968	4968
Malware samples	7325	7325	6891	6891

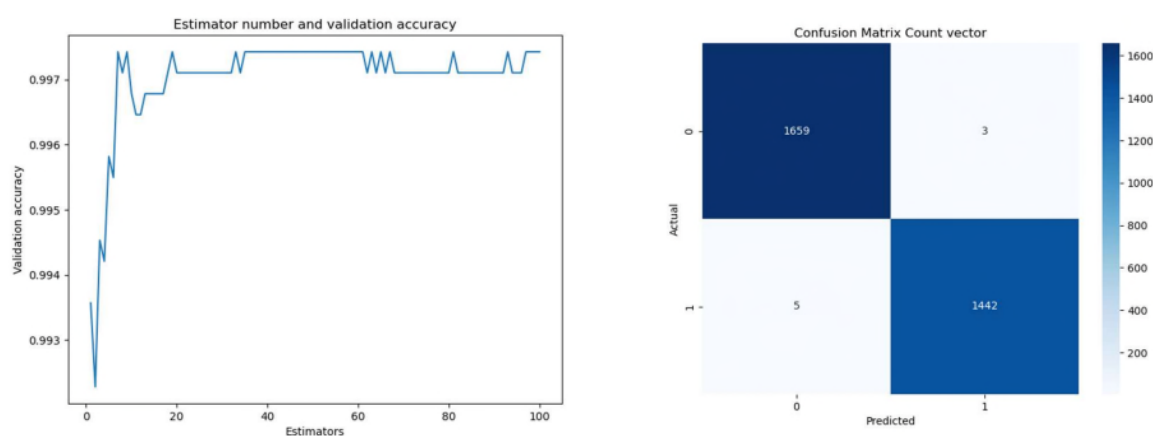


Figure 2. Full-featured reports represented with CV: **(left)** a graphical representation of the validation accuracy with respect to the number of decision trees in a random forest model; **(right)** the confusion matrix obtained for the optimal random forest model (0—benign, 1—malware).

The second group of models is related to the experimental condition concerning the full-featured reports represented with TF-IDF. A graphical representation of the evaluation results is provided in Figure 3(left). The maximum validation accuracy of 99.68 percent was obtained for the random forest model with 26 trees. The confusion matrix obtained for this model is given in Figure 3(right), and the derived evaluation measures are provided in Table 3 (cf. the third column).

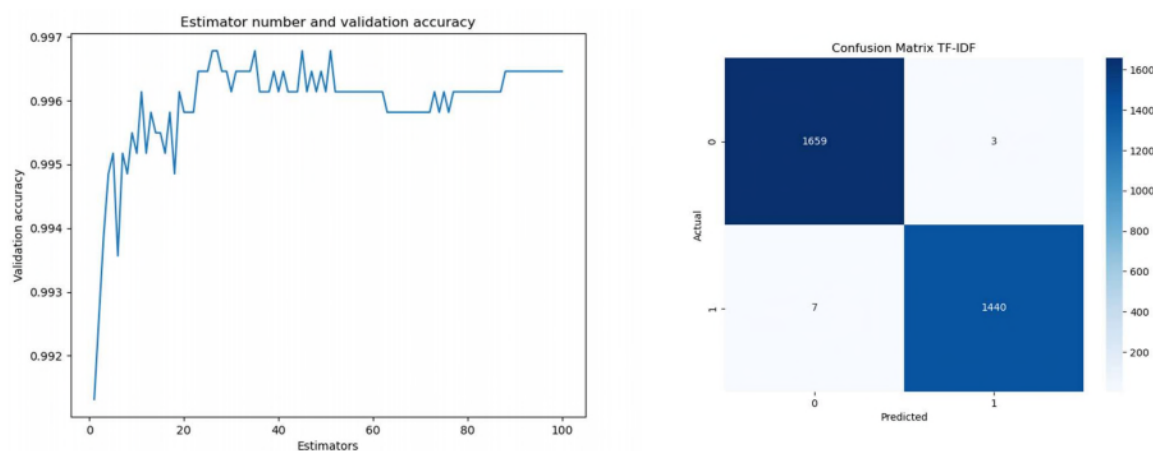


Figure 3. Full-featured reports represented with TF-IDF: **(left)** a graphical representation of the validation accuracy with respect to the number of decision trees in a random forest model; **(right)** the confusion matrix obtained for the optimal random forest model (0—benign, 1—malware).

The third group is related to the experimental condition concerning the API calls sequences dataset represented with CV. The evaluation results are provided in Figure 4. The maximum validation accuracy of 95.56 percent was obtained for the random forest model with 32 trees (cf. also fourth column of Table 3).

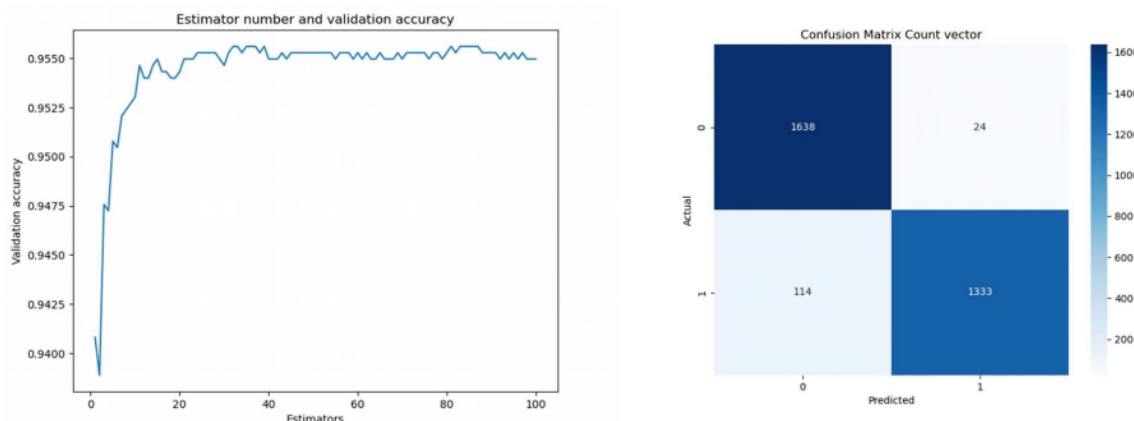


Figure 4. API call sequences represented with CV: (left) a graphical representation of the validation accuracy with respect to the number of decision trees in a random forest model, (right) the confusion matrix obtained for the optimal random forest model (0—benign, 1—malware).

Finally, the fourth group is related to the experimental condition concerning the API calls sequence dataset represented with TF-IDF. The evaluation results are provided in Figure 5. The maximum validation accuracy of 95.4 percent was obtained for the random forest model with 66 trees (cf. also the fifth column of Table 3).

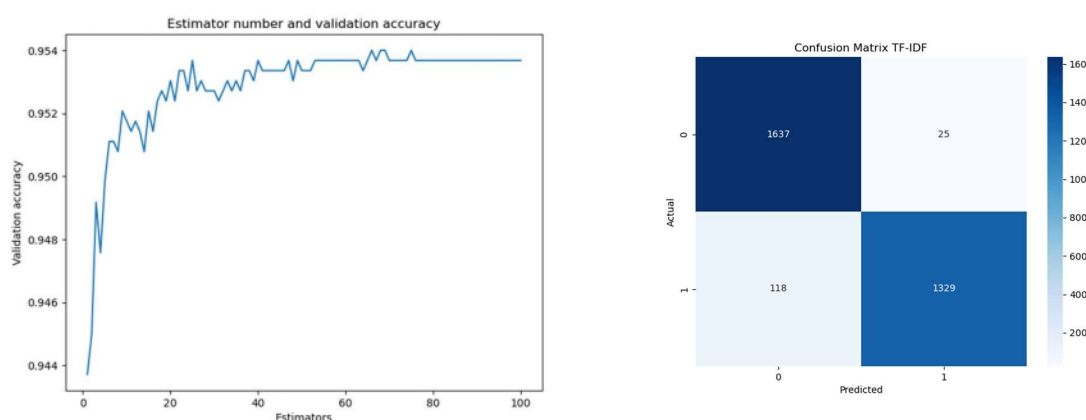


Figure 5. API call sequences represented with TF-IDF: (left) a graphical representation of the validation accuracy with respect to the number of decision trees in a random forest model; (right) the confusion matrix obtained for the optimal random forest model (0—benign, 1—malware).

4.3. Computing Resources and Trade-Offs

The training and testing of the underlying models were performed on a Debian server VM, with resources of 16 virtual CPUs, approximately 900 GB of DDR5 memory, and a 2.5 TB virtual hard disk. During the feature extraction process (by applying the CV and TF-IDF techniques), the entire memory was used, which occasionally caused unexpected termination of the Python scripts until we performed the random subsampling of the malware part of the dataset to 70 percent of its initial size. The value of 70 percent was determined in a process of iterative subsampling in steps of 5 percent, aimed at determining the maximum dataset size, which will engage the entire memory but not cause an unexpected termination of the Python scripts.

The results of the further optimization process are shown in Table 4, where each row represents the group of 100 RF models, in which the hyperparameter representing the

number of trees (i.e., *n_estimators* parameter) takes values in the range [1, 100]. The columns are organized as follows:

- Random forest hyperparameters (*max_depth*, *min_samples_split*, *min_samples_leaf*, and *max_features*) represent parameter values applied to each RF group of models in the optimization process.
- Computing resources (Exec. time, Max. RAM cons., Max. CPU cons.) describe the resources required to load the extracted features from the files stored on the disk (previously saved to the pickle file for both CV and TF-IDF) and to train and test the RF models.
- Results provide the maximum validation accuracy in the group and the number of trees in an RF model at which it was obtained.

Table 4. RF optimization and computing resources.

	Datasets	Random Forest Hyperparameters				Computing Resources			Results	
		Max_depth	Min_samples_split	Min_samples_leaf	Max_features	Exec. Time (h)	Max. RAM Cons. (GB)	Max. CPU Cons. (%)	# Trees at Max. Acc.	Max. Validation Accuracy (%)
1	Full reports CV	None	2	1	sqrt	7.00	19.3	6	89	99.067
2		100	2	1	sqrt	7.80	19.3	6.7	93	99.099
3		None	100	1	sqrt	6.25	17.8	6.78	25	98.874
4		None	2	100	sqrt	5.90	18	6.47	72	89.836
5		None	2	1	0.1	50.21	18.31	6.47	45	99.742
6		1000	2	1	sqrt	7.01	18.34	6.81	87	99.067
7		None	1000	1	sqrt	5.50	18	6.5	33	98.617
8		None	2	1000	sqrt	7.75	18	6.5	69	76.841
9		100	2	1	0.2	70.84	45	22	7	99.743
10	Full reports TF-IDF	None	2	1	sqrt	6.11	20	7	86	99.035
11		100	2	1	sqrt	7.50	20	7	86	99.035
12		None	100	1	sqrt	5.34	18.8	7	79	98.617
13		None	2	100	sqrt	5.00	18	6.44	95	92.879
14		None	2	1	0.1	43.33	19	6.38	94	99.614
15		1000	2	1	sqrt	6.00	19.03	6.47	16	98.874
16		None	1000	1	sqrt	5.00	19.99	6.62	51	97.813
17		None	2	1000	sqrt	5.00	18.44	6.7	55	79.607
18		100	2	1	0.2	61.09	20.4	7	26	99.678
19	API calls CV	None	2	1	sqrt	0.06	18	6	33	95.529
20		100	2	1	sqrt	0.06	18	6	79	95.529
21		None	100	1	sqrt	0.06	18	6	9	94.854
22		None	2	100	sqrt	0.06	18	6	8	92.536
23		None	2	1	0.1	0.06	18	6	21	95.433
24		1000	2	1	sqrt	0.06	18	6	13	95.497
25		None	1000	1	sqrt	0.06	18	6	38	93.921
26		None	2	1000	sqrt	0.06	18	6	16	78.868
27		100	2	1	0.2	0.09	18	6	32	95.561
28	API calls TF-IDF	None	2	1	sqrt	0.07	18	6.5	43	95.24
29		100	2	1	sqrt	0.07	18	6.5	43	95.24
30		None	100	1	sqrt	0.05	18	6.5	22	94.757
31		None	2	100	sqrt	0.03	18	6.5	42	93.149
32		None	2	1	0.1	0.08	18	6.5	92	95.368
33		1000	2	1	sqrt	0.06	18	6.5	43	95.24
34		None	1000	1	sqrt	0.03	18	6.5	93	93.599
35		None	2	1000	sqrt	0.02	18	6.5	14	89.643
36		100	2	1	0.2	0.13	18	6.5	66	95.4

The values highlighted in red represent very long computation time, in blue the highest validation accuracy values, and in green the acceptable validation accuracy values with significantly less computational time.

The maximum accuracy values (cf. cells marked in blue in the last column) were obtained with the combination of a *max_depth* value of 100 and *max_features* of 0.2 but at a significant cost in terms of execution time (over 70 and 60 h for full reports dataset with CV and TF-IDF, respectively; cf. cells marked in light red). Additional experimental settings,

which obtained slightly lower but still satisfying validation accuracies at significantly lower execution times, are marked in green.

It can be observed that increasing the values of the *min_samples_split* and *min_samples_leaf* hyperparameters did not positively affect the validation accuracy. However, setting the hyperparameters *max_depth* to 100 and *max_features* (i.e., the number of the features considered at node split) to 0.1 and 0.2 (i.e., 10 and 20 percent of all features, respectively) increased the validation accuracy and computational time.

With the increase in the value of the *max_features* hyperparameter, the number of trees at which the maximum validation accuracy was achieved decreased to only 7 for CV and 26 for TF-IDF. This indicates that, in practice, the number of trees in an RF model may be decreased to 30, which would significantly reduce the execution time required for the development of a model (i.e., from approximately 70 h to 20 h for CV and from approximately 61 h to 18 h for TF-IDF).

The RF models obtained from the API call dataset were less time demanding but also achieved lower validation accuracy. Such results are due to the significantly lower number of features considered in the API call dataset, i.e., 294 API-related features compared to over 25 million features present in the full report dataset.

5. Discussion

The main result given in Table 3 is that the RF models trained and evaluated on the full-featured datasets display higher validation accuracy than the RF models trained and evaluated on the API call dataset. This is in line with the starting assumption that the discriminative power of the full-featured sandbox reports discussed is greater than the discriminative power of just API call sequences.

Finally, the validation accuracy achieved on datasets containing CV features is slightly higher than the validation accuracy achieved on datasets containing TF-IDF features. This difference is not necessarily significant, but a possible underlying reason may be that the raw count of occurrences of tokens in CV is more indicative than the normalized values in TF-IDF.

The full-featured dataset contains samples that induce API calls, as well as samples that do not induce API calls. The validation accuracy obtained on this dataset is 99.74 percent. On the other hand, the API call dataset contains only samples that induce API calls, and the validation accuracy obtained on this dataset is 95.56 percent. Thus, we demonstrated that considering a more comprehensive feature set (i.e., going beyond API calls) improves the classification accuracy of malware and benign samples (i.e., the samples that do not induce API calls were classified with high accuracy).

The question that may arise here is why the second dataset contains only samples that induce API calls. First, if we also considered samples that do not induce API calls in the second dataset (i.e., if we added 6.13 percent of malware samples and 39.52 percent of benign samples), the accuracy result in the second case would be lower. However, this would not affect our conclusion: the validation accuracy obtained in the first case would still be higher than in the second case. Second, our samples were selected randomly to avoid subjective bias. Still, we do not claim that the share of samples that do not induce API calls is representative of a real-life distribution. Thus, if we included all samples in the second dataset, another question could arise: has the validation accuracy of models based only on API calls been artificially decreased by increasing the share of samples that do not induce API calls? To prevent this, we decided to evaluate these models on a dataset containing only samples that induce API calls, which maximizes the obtained accuracy. It is important to note that even in this “maximized” condition, the accuracy obtained when considering API calls is only lower than the accuracy obtained by the more comprehensive feature set—in line with our starting hypothesis.

6. Conclusions

In the research community, API call sequences are widely acknowledged as discriminative features in the context of dynamic malware analysis. However, a significant number

of benign samples do not use operating system API calls (e.g., reading of documents, etc.), and some malware instances are implemented in a way that does not leave any trace with respect to API calls. Only this observation would be enough to justify the extension of a feature set beyond API calls.

Still, even if we consider only binary files whose execution induces API calls, in this study, we demonstrated that extending the feature set beyond API calls may improve the malware detection performance. The accuracy of approximately 95.56 percent obtained for API call sequences was increased to 99.74 percent when full-featured sandbox reports were considered. This improvement comes with a cost: the number of features and the computational time for random forest models are significantly increased (cf. Table 4).

However, we believe that the significance of improvement justifies these costs. As part of future work, we intend to train and evaluate recurrent neural network-based models on the reported dataset and perform additional analyses of the features not related to API calls.

Author Contributions: Conceptualization, S.I. and M.G.; methodology, S.I. and M.G.; software, S.I.; validation, N.M., I.T., B.J. and M.G.B.; formal analysis, S.I. and M.G.; investigation, S.I.; resources, S.I.; data curation, S.I.; writing—original draft preparation, S.I. and M.G.; writing—review and editing, M.G., N.M., I.T., B.J. and M.G.B.; visualization, S.I.; supervision, M.G.; project administration, S.I. All authors have read and agreed to the published version of the manuscript.

Funding: The authors received no specific funding for this study.

Data Availability Statement: The reported dataset is available from authors upon request.

Acknowledgments: The company Tehnika KB doo (Belgrade, Serbia) contributed to this work with an archive of real-life benign files as a source for sandbox reports. Their support is gratefully acknowledged and highly appreciated.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the presented work.

References

1. Ficco, M. Malware Analysis by Combining Multiple Detectors and Observation Windows. *IEEE Trans. Comput.* **2022**, *71*, 1276–1290. [\[CrossRef\]](#)
2. Ho, T.K. Random decision forests. In Proceedings of the 3rd International Conference on Document Analysis and Recognition, Montreal, QC, Canada, 14–16 August 1995; Volume 1, pp. 278–282. [\[CrossRef\]](#)
3. Mira, F. A Review Paper of Malware Detection Using API Call Sequences. In Proceedings of the 2019 2nd International Conference on Computer Applications & Information Security (ICCAIS), Riyadh, Saudi Arabia, 1–3 May 2019; pp. 1–6. [\[CrossRef\]](#)
4. Deore, M.; Tarambale, M.; Ratna Raja Kumar, J.; Sakhare, S. GRASE: Granulometry Analysis with Semi Eager Classifier to Detect Malware. *Int. J. Interact. Multimed. Artif. Intell.* **2024**, *8*, 120–134. [\[CrossRef\]](#)
5. Düzgün, B.; Çayır, A.; Demirkıran, F.; Kahya, C.N.; Gençaydın, B.; Dağ, H. Benchmark Static API Call Datasets for Malware Family Classification. *arXiv* **2022**. [\[CrossRef\]](#)
6. Alsharni, A.; Alliheedi, M.A. Enhancing Malware Detection by Integrating Machine Learning with Cuckoo Sandbox. *arXiv* **2023**, arXiv:2311.04372. [\[CrossRef\]](#)
7. Syeda, D.; Asghar, M. Dynamic Malware Classification and API Categorization of Windows Portable Executable Files Using Machine Learning. *Appl. Sci.* **2024**, *14*, 1015. [\[CrossRef\]](#)
8. Zhang, S.; Wu, J.; Zhang, M.; Yang, W. Dynamic Malware Analysis Based on API Sequence Semantic Fusion. *Applied Sciences* **2023**, *13*, 6526. [\[CrossRef\]](#)
9. Huang, Y.; Chen, T.; Hsiao, S. Learning Dynamic Malware Representation from Common Behavior. *J. Inf. Sci. Eng.* **2022**, *38*, 1317–1334. [\[CrossRef\]](#)
10. Huang, Y.; Sun, Y.; Chen, M. TagSeq: Malicious behavior discovery using dynamic analysis. *PLoS ONE* **2022**, *17*, e0263644. [\[CrossRef\]](#)
11. Chen, L.; Yagemann, C.; Downing, E. To believe or not to believe: Validating explanation fidelity for dynamic malware analysis. *arXiv* **2019**, arXiv:1905.00122. [\[CrossRef\]](#)
12. Alhashmi, A.; Darem, A.; Alanazi, M.; Alashjaee, M.; Aldughayfiq, B.; Ghaleb, A.; Ebad, A.; Alanazi, A. Hybrid Malware Variant Detection Model with Extreme Gradient Boosting and Artificial Neural Network Classifiers. *Comput. Mater. Contin.* **2023**, *76*, 3483–3498. [\[CrossRef\]](#)
13. Lee, D.; Jeon, G.; Lee, S.; Cho, H. Deobfuscating Mobile Malware for Identifying Concealed Behaviors. *Comput. Mater. Contin.* **2022**, *72*, 5909–5923. [\[CrossRef\]](#)

14. Chen, T.; Zeng, H.; Lv, M.; Zhu, T. CTIMD: Cyber threat intelligence enhanced malware detection using API call sequences with parameters. *Comput. Secur.* **2024**, *136*, 103518. [\[CrossRef\]](#)
15. Yau, L.; Lam, Y.; Lokesh, A.; Gupta, P.; Lim, J.; Singh, I.; Loo, J.; Ngo, M.; Teo, S.; Truong-Huu, T. A Novel Feature Vector for AI-Assisted Windows Malware Detection. In Proceedings of the 2023 IEEE International Conference on Dependable, Autonomic and Secure Computing, International Conference on Pervasive Intelligence and Computing, International Conference on Cloud and Big Data Computing, International Conference on Cyber Science and Technology Congress (DASC/PiCom/CBDCom/CyberSciTech), Abu Dhabi, United Arab Emirates, 14–17 November 2023; pp. 0355–0361. [\[CrossRef\]](#)
16. Xu, Y.; Chen, Z. Family Classification based on Tree Representations for Malware. In Proceedings of the 14th ACM SIGOPS Asia-Pacific Workshop on Systems, Seoul, Republic of Korea, 24–25 August 2023; pp. 65–71. [\[CrossRef\]](#)
17. Li, C.; Cheng, C.; Zhu, H.; Wang, L.; Lv, Q.; Wang, Y.; Li, N.; Sun, D. DMalNet: Dynamic malware analysis based on API feature engineering and graph learning. *Comput. Secur.* **2022**, *122*, 102872. [\[CrossRef\]](#)
18. Li, S.; Wen, H.; Deng, L.; Zhou, Y.; Zhang, W.; Li, Z.; Sun, L. Denoising Network of Dynamic Features for Enhanced Malware Classification. In Proceedings of the 2023 IEEE International Performance, Computing, and Communications Conference (IPCCC), Anaheim, CA, USA, 17–19 November 2023; pp. 32–39. [\[CrossRef\]](#)
19. Nunes, M.; Burnap, P.; Rana, O.; Reinecke, P.; Lloyd, K. Getting to the root of the problem: A detailed comparison of kernel and user level data for dynamic malware analysis. *J. Inf. Secur. Appl.* **2019**, *48*, 102365. [\[CrossRef\]](#)
20. Li, N.; Lu, Z.; Ma, Y.; Chen, Y.; Dong, J. A Malicious Program Behavior Detection Model Based on API Call Sequences. *Electronics* **2024**, *13*, 1092. [\[CrossRef\]](#)
21. Jindal, C.; Salls, C.; Aghakhani, H.; Long, K.; Kruegel, C.; Vigna, G. Neurlux: Dynamic Malware Analysis Without Feature Engineering. *arXiv* **2019**, arXiv:1910.11376. [\[CrossRef\]](#)
22. Anderson, H.; Rothl, P. EMBER: An Open Dataset for Training Static PE Malware Machine Learning Models. *arXiv* **2018**, arXiv:1804.04637. [\[CrossRef\]](#)
23. Bosansky, B.; Kouba, D.; Manhal, O.; Sick, T.; Lisy, V.; Kroustek, J.; Somol, P. Avast-CTU Public CAPE Dataset. *arXiv* **2022**, arXiv:2209.03188. [\[CrossRef\]](#)
24. Herrera-Silva, J.; Hernández-Álvarez, M. Dynamic Feature Dataset for Ransomware Detection Using Machine Learning Algorithms. *Sensors* **2023**, *23*, 1053. [\[CrossRef\]](#)
25. Irshad, A.; Dutta, M. Identification of Windows-Based Malware by Dynamic Analysis Using Machine Learning Algorithm. In *Advances in Computational Intelligence and Communication Technology*; Gao, X.-Z., Tiwari, S., Trivedi, M.C., Mishra, K.K., Eds.; Springer: Singapore, 2021; Volume 1086, pp. 207–218. [\[CrossRef\]](#)
26. Sraw, J.; Kumar, K. Using Static and Dynamic Malware features to perform Malware Ascription. *ECS Trans.* **2022**, *107*, 3187–3198. [\[CrossRef\]](#)
27. Sethi, K.; Kumar, R.; Sethi, L.; Bera, P.; Patra, P. A Novel Machine Learning Based Malware Detection and Classification Framework. In Proceedings of the 2019 International Conference on Cyber Security and Protection of Digital Services (Cyber Security), Oxford, UK, 3–4 June 2019; pp. 1–4. [\[CrossRef\]](#)
28. Virus Total. Virustotal-Free Online Virus, Malware and Url Scanner. Available online: <https://www.virustotal.com/en> (accessed on 9 April 2024).
29. Taheri, R.; Javidan, R.; Shojafar MP, V.; Conti, M. Can Machine Learning Model with Static Features be Fooled: An Adversarial Machine Learning Approach. *arXiv* **2020**, arXiv:1904.09433. [\[CrossRef\]](#)
30. Taheri, R.; Ghahramani, M.; Javidan, R.; Shojafar, M.; Pooranian, Z.; Conti, M. Similarity-based Android malware detection using Hamming distance of static binary features. *Future Gener. Comput. Syst.* **2020**, *105*, 230–247. [\[CrossRef\]](#)
31. Ilić, S.; Gnjatović, M.; Popović, B.; Maček, N. A pilot comparative analysis of the Cuckoo and Drakvuf sandboxes: An end-user perspective. *Military Tech. Cour.* **2022**, *70*, 372–392. [\[CrossRef\]](#)
32. Pedregosa, F.; Varoquaux, G.; Gramfort, A.; Michel, V.; Thirion, B.; Grisel, O.; Blondel, M.; Prettenhofer, P.; Weiss, R.; Dubourg, V.; et al. Scikit-learn: Machine Learning in Python. *J. Mach. Learn. Res.* **2011**, *12*, 2825–2830. Available online: <http://jmlr.org/papers/v12/pedregosa11a.html> (accessed on 3 September 2024).
33. McKinney, W. Data structures for statistical computing in python. In Proceedings of the 9th Python in Science Conference, Austin, TX, USA, 28 June–3 July 2010; PANDAS Conference Paper. Volume 445, pp. 51–56.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.



**31st Summer School and
International Symposium on
the Physics of Ionized Gases**

Belgrade, Serbia,
September 5 - 9, 2022

CONTRIBUTED PAPERS
&
**ABSTRACTS of INVITED LECTURES,
TOPICAL INVITED LECTURES and PROGRESS REPORTS**

Editors:
Dragana Ilić, Vladimir Srećković,
Bratislav Obradović and Jovan Cvetić



**БЕОГРАД
2022**

**31st Summer School and
International Symposium on
the Physics of Ionized Gases**



September 5 – 9, 2022, Belgrade, Serbia

S P I G 2022

CONTRIBUTED PAPERS

&

**ABSTRACTS OF INVITED LECTURES,
TOPICAL INVITED LECTURES AND
PROGRESS REPORTS**

Editors

**Dragana Ilić, Vladimir Srećković,
Bratislav Obradović and Jovan Cvetić**

**University of Belgrade –
School of Electrical
Engineering**

**University of Belgrade –
Faculty of Physics
Serbian Academy of
Sciences and Arts**

Belgrade, 2022

PUBLICATIONS OF THE ASTRONOMICAL OBSERVATORY OF BELGRADE
FOUNDED IN 1947

EDITORIAL BOARD:

Dr. Srdjan SAMUROVIĆ, Editor-in-Chief (Astronomical Observatory, Belgrade)

Dr. Rade PAVLOVIĆ (Astronomical Observatory, Belgrade)

Dr. Miroslav MIĆIĆ (Astronomical Observatory, Belgrade)

Dr. Branislav VUKOTIĆ (Astronomical Observatory, Belgrade)

All papers in this Publication are peer reviewed.

Published and copyright © by Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia

Director of the Astronomical Observatory: Dr. Gojko Djurašević

Typesetting: Tatjana Milovanov

Internet address <http://www.aob.rs>

ISSN 0373-3742

ISBN 978-86-82296-02-7

Number of copies / tiraž : 200

Production: Skripta Internacional, Mike Alasa 54, Beograd

CIP - Каталогизација у публикацији - Народна библиотека Србије, Београд

537.56(082)

539.186.2(082)

539.121.7(082)

533.9(082)

**SUMMER School and International Symposium on the Physics of Ionized Gases
(31 ; 2022 ; Belgrade)**

Contributed papers & abstracts of invited lectures, topical invited lectures and progress reports / 31st Summer School and International Symposium on the Physics of Ionized Gases - SPIG 2022, September 5-9, 2022, Belgrade, Serbia ; editors Dragana Ilić ... [et al.]. - Belgrade : Astronomical Observatory, 2022 (Beograd : Skripta Internacional). - 302 str. : ilustr. ; 24 cm. - (Publications of the Astronomical Observatory of Belgrade, ISSN 0373-3742)

Na nasl. str.: University of Belgrade, School of Electrical Engineering; University of Belgrade, Faculty of Physics; Serbian Academy of Sciences and Arts. - Tiraž 200. - Str. 17-18: Preface / editors Dragana Ilić ... [et al.]. - Bibliografija uz svaki rad. - Registar.

ISBN 978-86-82296-02-7

1. Ilić, Dragana, 1978- [уредник] [аутор додатног текста]

а) Јонизовани гасови – Зборници б) Атоми – Интеракција – Зборници в) Плазма – Зборници

COBISS.SR-ID 72751881

SPECTROSCOPIC CHARACTERIZATION OF LASER-INDUCED PLASMA ON DOPED TUNGSTEN

BILJANA STANKOV¹, MARIJANA R. GAVRILOVIĆ BOŽOVIĆ²,
JELENA SAVOVIĆ³ and MILIVOJE IVKOVIĆ¹

¹*Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade,
Serbia*

²*Faculty of Engineering Sciences, University of Kragujevac, Sestre Janjić 6, 34000
Kragujevac, Serbia*

³*Vinca Institute of Nuclear Sciences, University of Belgrade, Mike Petrovića Alasa
12-16, 11000 Belgrade, Serbia.*

E-mail ivke@ipb.ac.rs

Abstract. In this paper, the dependence of plasma characteristics, excitation temperature, and electron number density on the presence of fusion relevant doping elements (La and Th) in tungsten is evaluated and compared with a pure tungsten sample. It was found that different doping elements have little to no influence on plasma temperature, while electron number density seems to be more sensitive to the doping element type.

1. INTRODUCTION

The properties of tungsten, i.e., high melting point, high thermal conductivity, and low tritium retention, make it a promising material for fusion-related applications. On the other hand, its high Z number limits allowed concentration in plasma, which, with poor machinability, explosion dust potential, and irradiation-induced transmutations, pose a significant challenge for stable and safe operation. Although a large variety of tungsten grades and alloys already exist, numerous attempts to further optimize these materials are ongoing, Waseem et al., 2016. Investigations are needed to address many different issues related to the plasma-facing material (PFM) performance when exposed to thermal loads, neutron irradiation, and the plasma, Pintsuk et al. 2019. Erosion of tungsten under high localized thermal loads occurring during plasma disruption, vertical displacement events (VDEs), and the edge-localized mode (ELM) have an analogy with W erosion during laser ablation, Oderji et al. 2016. Following this analogy, the present research was undertaken to study plasma properties produced by laser ablation of pure and doped tungsten

(with La and Th) using optical emission spectroscopy methods. Both doping elements are relevant for fusion technology, Gietl et al., 2022, and Raj et al., 2022. The idea is to get insight into the dependence of plasma characteristics on different doping elements present in tungsten targets, which is essential for clarifying the impact of these elements in fusion-related applications.

2. EXPERIMENTAL SETUP

Different tungsten targets (pure W; 98,5%W+1.5%La₂O₃, 98%W+2%ThO₂) were placed on the PC controllable x-y table. A Q-switched Nd:YAG pulsed laser (Quantel, $\lambda = 532$ nm, energy 40 mJ, pulse duration 0.6 ns) was used to induce plasma on the target. The laser beam was focused on a target using a lens of 10 cm focal length. Light emitted from a plasma was collected with a fiber optic cable ($\varnothing = 400$ μ m) and detected using an imaging spectrometer Shamrock 303 Andor equipped with the Andor iStar DH734 camera. The iCCD camera was operated in the full-vertical binning mode and controlled using a pulse generator (DDG 535, Stanford Research Systems). Delay was set to 0.5 μ s, and the gate used was 2.5 μ s. All measurements were performed in an argon atmosphere at 10 mbar pressure.

3. RESULTS

Typical spectra obtained with the employed setup are shown in Fig 1.

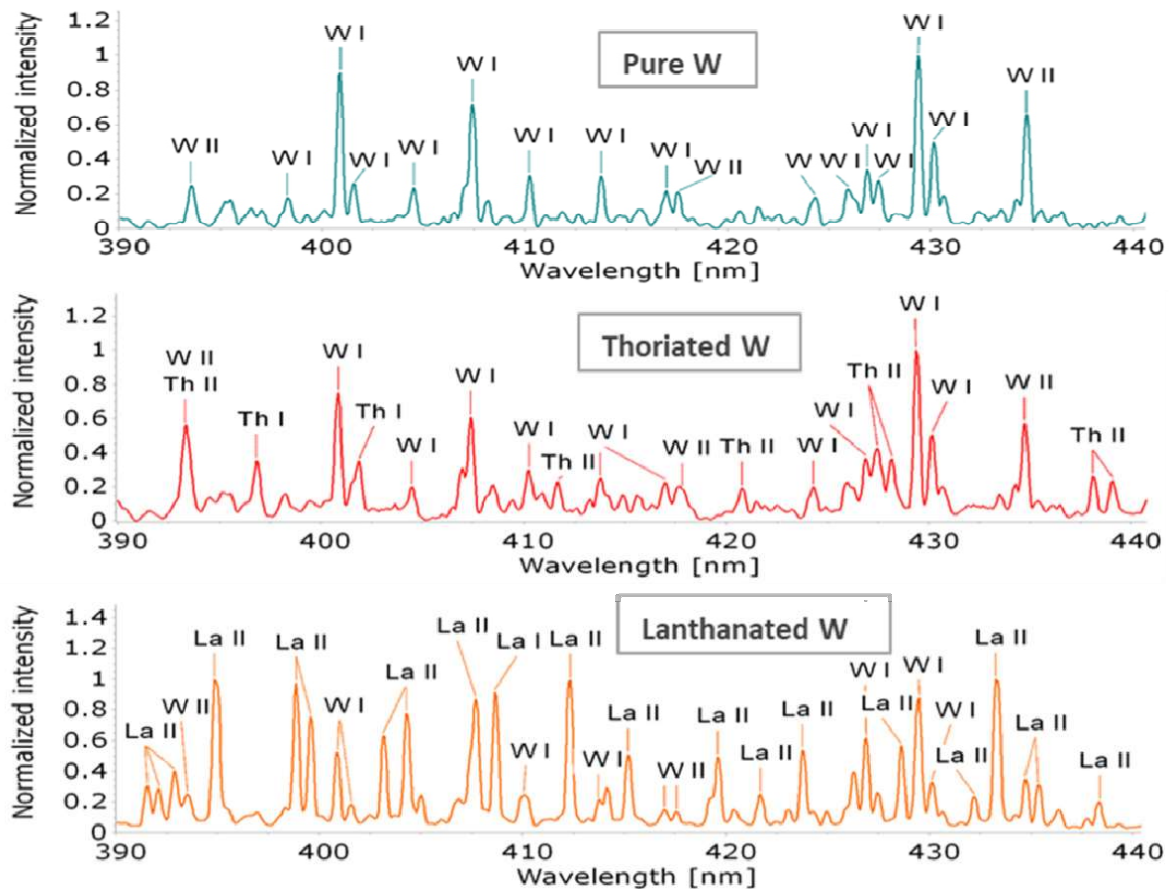


Figure 1: Characteristic LIBS spectra of pure and doped tungsten samples.

The most dominant lines belong to neutral and singly ionized tungsten for all target materials. These rich spectra of tungsten were suitable for excitation temperature determination by a Boltzmann plot method. An example of a Boltzmann plot for a pure tungsten target is given in Fig 2. The excitation temperature, T_{exc} calculated from the lines of singly ionized W was $13500\text{K} \pm 1000\text{K}$, slightly higher than the calculated temperature using neutral W lines ($12300\text{K} \pm 900\text{K}$). The observed difference in temperature values obtained from a neutral atom and ion emissions is expected for spatially integrated measurements. As explained by J.A. Aguilera et al., 2004, in that case, the Boltzmann plots of neutral atoms and ions provide two different apparent excitation temperatures that correspond to the respective population averages of the local electronic temperature in the plasma. For all target materials, the obtained temperature values were similar (within the measurement uncertainty), implying an insignificant influence of doping elements on the plasma temperature.

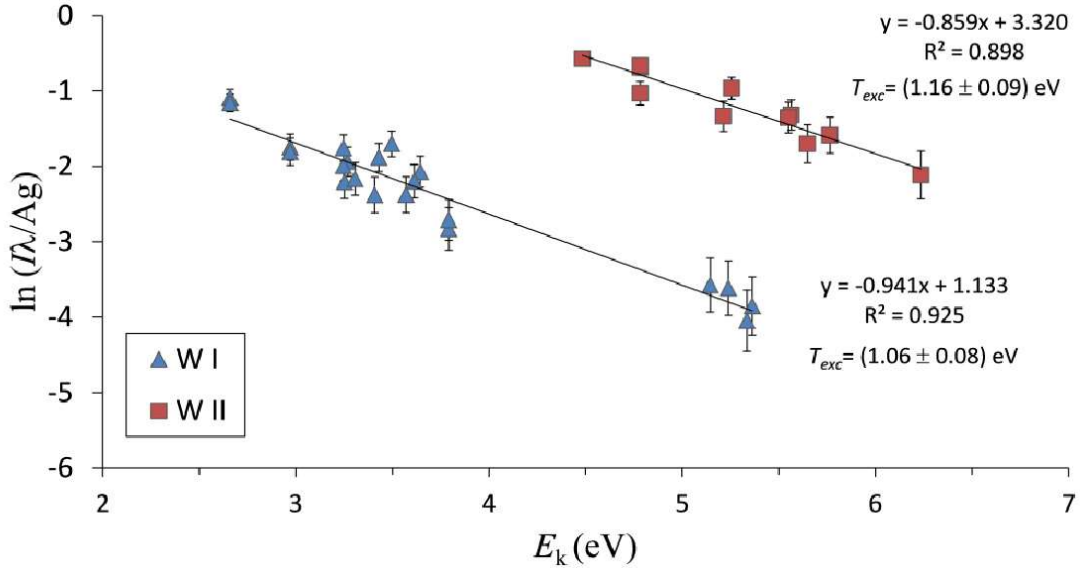


Figure 2: Boltzmann plot used to determine excitation temperature in LIBS plasma induced on a pure tungsten target.

For electron number density, N_e , estimation, a Stark broadening of the H_α line was used, Fig. 3. Based on the FWHM of the H_α spectral line and using the approximative formula (1), N_e was calculated. The results are shown in Table 1.

$$N_e [m^{-3}] = 10^{23} * (w_{SA} [nm] / 1.098)^{1.47135} \quad (1)$$

Table 1: Electron number density determined using Stark broadening of H_α line.

Target	H_α	$N_e (10^{22} \text{ m}^{-3})$
Pure W	0.503	2.84
Thoriated W	0.557	3.37
Lanthanated W	0.510	2.91

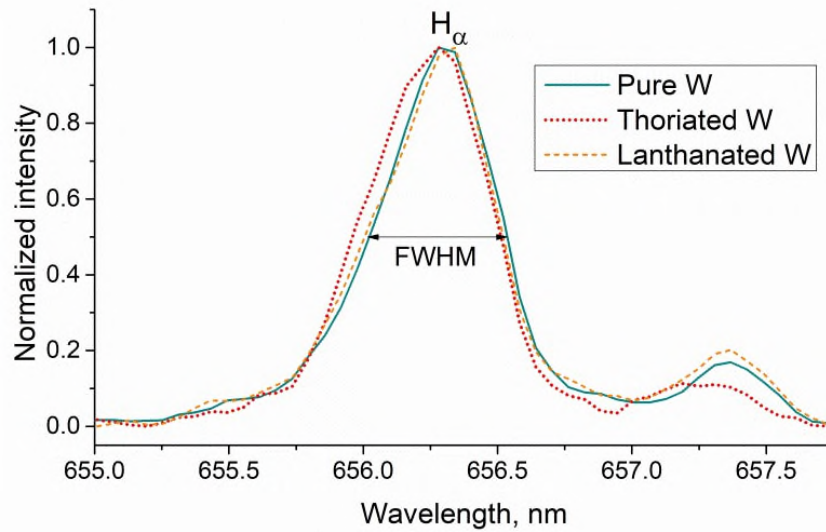


Figure 3: Stark broadened H_{α} line profiles used to evaluate N_e .

4. CONCLUSION

Different doping elements seem to have a negligible impact on laser-induced plasma excitation temperature. Electron number density shows slightly higher values in the case of thoriated W compared both to pure and lanthanated tungsten. A possible reason for this is the lower energy needed for significant erosion of thorium doped tungsten, already observed in experiments with tungsten-based cathodes, Casado et al., 2002. For a deeper understanding of the influence of doping elements on plasma properties, temporally and spatially resolved measurements are needed and are currently underway.

Acknowledgements

The research was funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia, Contract numbers: 451-03-68/2022-14/200024 and 451-03-68/2022-14/200017, and supported by the Science Fund of the Republic of Serbia, Grant no. 3108/2021.

References

- Oderji H.Y., Farid N., et al.: 2016, *Spectrochimica Acta Part B*, **122**, 1.
 Pintsuk G., Hasegawa A.: 2019, *Comprehensive Nuclear Materials 2nd edition*, Elsevier.
 Waseem O., Ryu H.J.: 2016, *Nuclear Material Performance*, Chapter 7, InTech.
 Aguilera J.A., Aragón C.: 2004, *Spectrochimica Acta Part B*, **59**, 1861.
 Gietl H., et al. 2022 *Journal of Alloys and Compounds*, **901**, 163419.
 Raj D., Kannan U.: 2022, *Annals of Nuclear Energy*, **174**, 109162.
 Casado E., Colomer V., et al.: 2002, *J. Phys. D: Appl. Phys.*, **35**, 992.

A Synthesizable Digital Frequency-Locked Loop Widely Tunable up to 640 MHz in 130 nm CMOS

Dejan D. Petković, Đorđe S. Gačić, Marijana R. Gavrilović Božović, Vladimir M. Milovanović

Department of Electrical Engineering and Computer Sciences

Faculty of Engineering, University of Kragujevac,

Sestre Janjić 6, 34000 Kragujevac, Serbia

{dejo, djole, marijana, vlada}@uni.kg.ac.rs

Abstract—Frequency-locked loops (FLLs) represent a viable way of generating a range of frequencies from a single reference frequency by using a negative feedback electronic control system that compares the frequency of a controlled oscillator to the reference one. A digital synthesizable FLL is designed in 130 nm CMOS technology for a target frequency of up to 640 MHz. It employs a wide-tuning range digitally controlled oscillator (DCO) assembled from tri-state inverters in the form of a matrix. The FLL can optionally use a bang-bang or a soft-programmable standard proportional-integral-derivative (PID) controller to regulate the feedback loop. Its design practically minimizes metastability occurrence. The proposed digital FLL occupies $100\mu\text{m} \times 330\mu\text{m}$ and consumes 3.5 mW in typical operating conditions. The reference clock is 16 MHz, and the output oscillation frequency is set to 640 MHz, while the achieved frequency resolution is 2.8 MHz.

Keywords—Frequency-locked loop, digitally controlled oscillator, clock generator, synthesizable, CMOS technology, PID controller, metastability.

I. INTRODUCTION

Nowadays, phase-locked loops (PLLs) and delay-locked loops (DLLs) represent ubiquitous chip design blocks. Countless chip applications require either a clock generator or a frequency synthesizer, which implies implementing one of these blocks within the system. The main function of this design block is to generate a stable and accurate output signal whose phase is adjustable relative to the phase of the input signal while consequently maintaining the relationship between input and output frequency. However, even complex systems very frequently require a clock generator, which only multiplies the input frequency without taking special care of the clock phase and the absolute jitter. In such instances, only an FLL is necessary for such requirements.

By definition, an FLL is a negative feedback control system that locks the output frequency signal to the target frequency. Principally, it continuously controls the oscillator frequency in an automated way until its output frequency matches the target value, after which that value is maintained at the output. There are various ways to implement an FLL [1]. Moreover, FLLs as integrated circuits can also be classified into two groups: digital and analog FLLs. Although an obvious drawback of the former is the maximum frequency and its resolution, they possess numerous other advantages over their analog counterparts. They occupy less space, exhibit greater resistance to PVT variations, are easily portable to various technologies,

and hence enable reusability, scalability, a simpler design flow methodology, and faster design cycles. Taking all this into account, it generally seems better to go into the development of the digital FLLs whenever the system architecture specification allows it. Therefore, the focus of this work and of the authors in general is to design and improve simple but powerful synthesizable digital chip building blocks.

This paper concretely proposes a synthesizable digital FLL similar to the one in [2], with improved FLL locking speed [3] and reduced metastability risk. The oscillator is a tri-state inverter ring-based DCO from [4] modified by adding an independent DCO supply voltage with level shifters and by choosing a five-stage [5] instead of a three-stage oscillating ring topology.

The rest of the paper includes three additional sections. Section II describes the proposed digital FLL on a system, block, and circuit level. Section III presents the implementation and achieved simulation results. Finally, Section IV concludes the paper and mentions future work.

II. PROPOSED DIGITAL FREQUENCY-LOCKED LOOP

This paper proposes a relatively simple but efficient digital FLL, whose block-level system architecture is depicted in Fig. 1. Practically, the proposed FLL is comprised of two blocks: the digitally controlled oscillator and the control logic block, which generates the DCO input signals based on the current DCO frequency. The configuration inputs of the FLL, such as the frequency multiplier (or the frequency control word, FCW), PID controller coefficients, and mode selection, are not displayed in the figure for the sake of simplicity.

A. Frequency-Locked Loop Control Logic

The FLL control logic consists of two independent processing branches, which represent two mutually exclusive FLL control modes. Both modes receive as an input a binary value that corresponds to the number of DCO clock periods within the reference clock period. Also, both control modes generate a binary value, which represents the oscillator control word directly proportional to the output frequency. The main difference between the modes is the FLL locking speed and setup simplicity. The aim of the FLL control logic is to equalize the frequency multiplier input and the DCO clock period count value as fast and precisely as possible, which

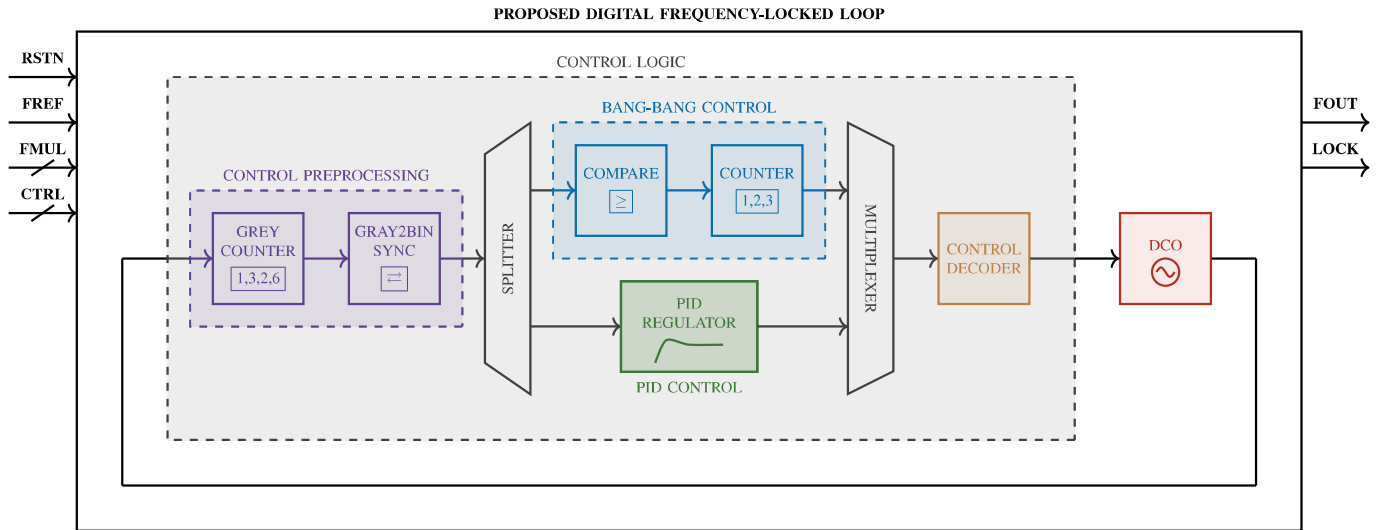


Fig. 1: Proposed digital frequency-locked loop block diagram composed of: the control logic block (left) and the digitally controlled oscillator (right).

leads to the DCO achieving the desired frequency. It is divided into several stages, as described in the following sections.

1) *Control Preprocessing*: The control preprocessing stage includes several blocks whose function is to convert the information about the DCO clock frequency into a control logic binary value input. Firstly, to determine the oscillation speed of the DCO, a counter is required. Grey counter was chosen over its binary counterpart because it significantly reduces the counter sampling metastability since in Grey code each successive value differs by a single bit. The drawback of this approach is that the Grey counter has a lower maximum operating frequency than the binary counter. In order to reduce the metastability risk even to a greater extent, each bit of the Grey counter output passes through a double flip-flop synchronizer to safely cross into the reference clock domain. Afterwards, the synchronized Grey counter value is converted to binary format and sampled for further processing.

2) *Bang-Bang Control*: The first FLL control block is very similar to a bang-bang (or on-off) controller, a feedback controller that switches between two states. It compares the input frequency multiplier with the sampled DCO counter value and decides whether to increment, decrement, or disable the succeeding block, an up-down counter. This ensures gradual control and locking upon reaching the desired frequency.

3) *PID Control*: In the second control mode, the DCO control word is generated by a configurable PID controller. A PID controller is a feedback-loop-based control mechanism that works by continuously correcting and scaling the input error signal, that is the difference between the measured process variable (the sampled DCO counter value) and the desired setpoint reference (the frequency multiplier input). The correction and scaling are distributed into three components: proportional (P), integral (I), and derivative (D), implemented as configurable fixed-point inputs fed from a register bank.

The purpose of the P component is to control the speed of the control system's response by directly multiplying the

error signal by a constant factor. The I component is used for reducing the steady-state error, by scaling the error by a constant factor and summing the result over time. The D component is proportional to the error change rate, and its aim is to limit the output in order to decrease potential overshoots or oscillations caused by the P and I components, without decreasing the controller speed. Since in this system the setpoint is constant and there are no fast input changes that may cause these issues, the P and I components are sufficient for a smooth and stable system response.

4) *Control Decoder*: The role of the control decoder is to convert the control data from one binary value to a set of DCO control inputs. There are three such inputs: *Row On*, a unary (thermometer) coded vector, which turns on several entire DCO tri-state inverter rows; *Row Select*, a one-hot coded vector, which enables one additional DCO tri-state inverter row; and *Column Select*, a unary coded vector, which enables several DCO tri-state inverter columns. In order for an inverter to be turned on, either *Row On* or both *Row Select* and *Column Select* for the corresponding bit should be set to 1. The width of each vector is equal to the input width. This is all described in much more detail in the following section.

B. Digitally Controlled Oscillator Structure

“At the heart of every phase-locked loop lies an oscillator, playing a critical role in the performance that can be achieved.” [7]

The digitally controlled oscillator proposed in this paper is a ring-based oscillator, suitable for a clock generator system. The ring oscillator is a cascaded combination of delay stages connected in a closed-loop chain [8]. Ring architectures are more compact than LC-based oscillators and benefit from their regular, periodic spatial structure. The generalized structure of the DCO used within the described FLL is based on a matrix of CMOS tri-state inverters [9]. This matrix is composed of N -stage tri-state inverter rings connected in parallel. N represents

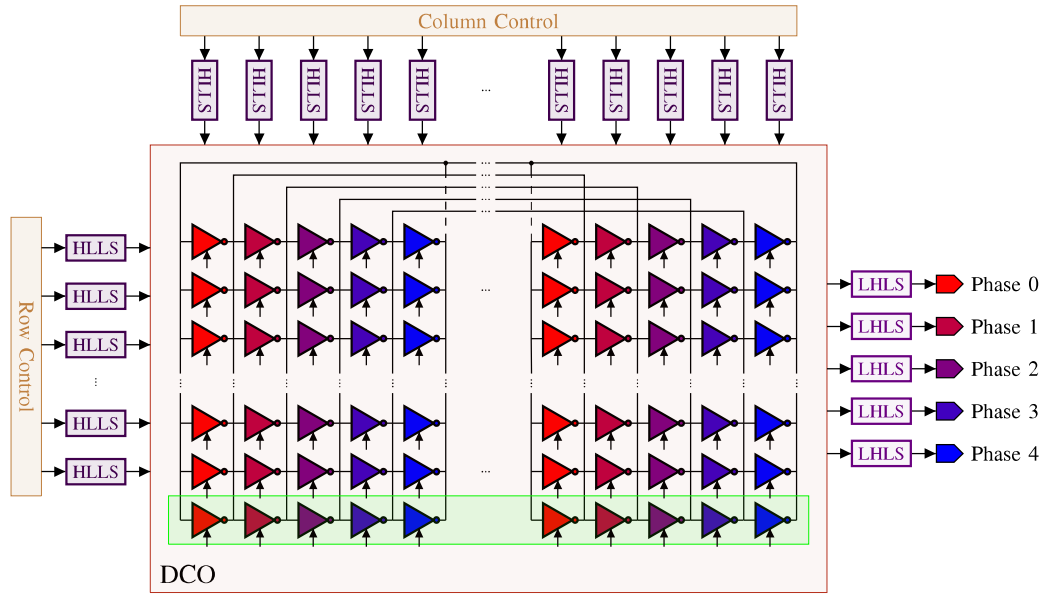


Fig. 2: Five-stage tri-state inverter ring-based digitally controlled oscillator (DCO) with level shifters and highlighted always-on row.

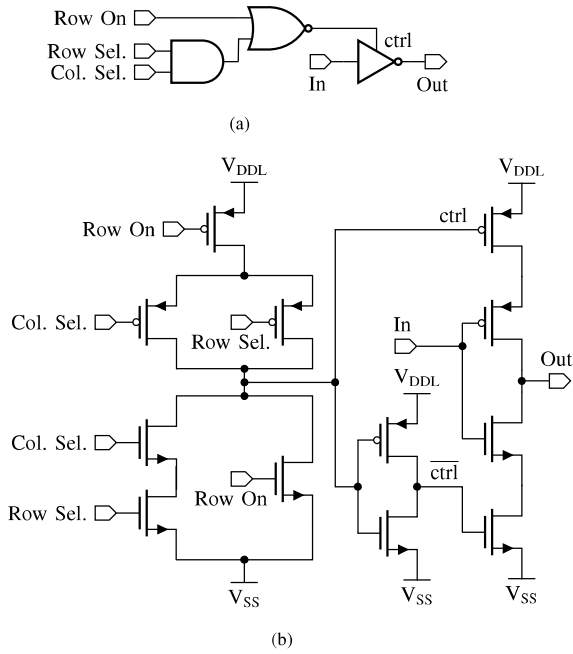


Fig. 3: DCO cell at the (a) logic circuit level and (b) CMOS transistor level.

the number of DCO stages (phases) and must be an odd number greater than or equal to 3 (for single-ended DCOs). Physically, the matrix can be reshaped into a square, which leads to simpler control logic. One or more rings are always enabled and define the base DCO frequency. Other tri-state inverters turn on and off depending on their control logic.

The formula for the oscillation frequency of this particular DCO implementation is as follows:

$$f_{\text{osc}} = \frac{1}{2Nt_d} \approx \frac{I_d}{2NC_{\text{load}}V_{\text{DDL}}} \quad (1)$$

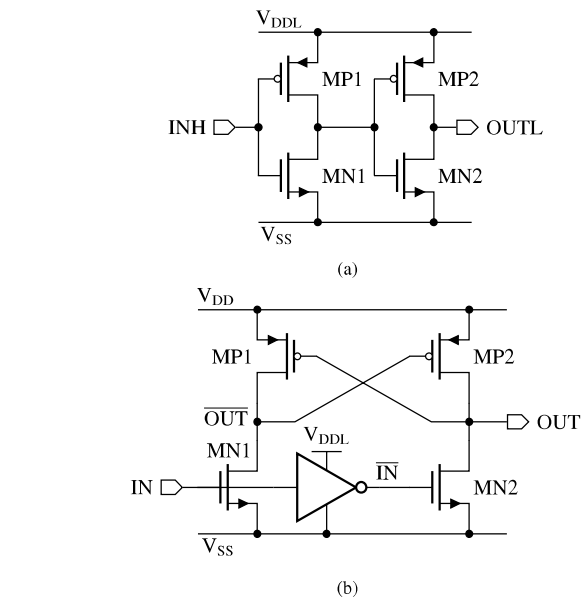


Fig. 4: Schematic of (a) high-low and (b) low-high level shifters [6].

where N is the number of tri-state inverters within the ring, t_d denotes the cell delay of a single inverter, I_d is the current flowing through one inverter, C_{load} is the load capacitance of that inverter, and V_{DDL} is the DCO power supply. The product Nt_d is doubled to get clock periods instead of half periods.

1) *Proposed DCO Architecture*: When it comes to topology, with the increase in the number of DCO stages, the frequency step, K_{DCO} , decreases, thereby increasing the precision of the DCO. The maximum oscillator frequency also decreases, and in order to improve it, the supply voltage can be increased, but this leads to higher power consumption. If the supply voltage and capacitive load per phase remain

the same, increasing the number of stages does not affect power consumption. However, if the total number of tri-state inverters remains the same and gets divided into a larger number of stages, this reduces the capacitive load per phase, leading to lower power consumption. In mathematical terms, this can be explained as follows: An N -stage ring operating at a frequency of f_{osc} consumes a dynamic power equal to $P = Nf_{osc}C_{tot}V_{DDL}^2$, where C_{tot} denotes the total load capacitance seen by one stage. Also, $f_{osc} = 1/(2Nt_d)$. Thus, $P = C_{tot}V_{DDL}^2/(2t_d)$, a quantity independent of N [7].

In this paper, a DCO topology with five stages is proposed because of the satisfying trade-off between performance and power consumption. Fig. 2 shows the structure of the DCO used in the proposed FLL implementation. Each stage of the DCO consists of 54 tri-state inverters, giving a total of 270 inverters. Tri-state inverters are arranged in 18 rows and 15 columns. The FLL control logic controls 17 rows and all 15 columns, which means there are 255 frequency steps. The remaining row with 3×5 tri-state inverters is always on. As more inverters in each stage are turned on by the FLL control logic, the current driving strength of the stage increases while its capacitive load remains essentially constant, resulting in an increase in the output oscillation frequency [4].

2) *DCO Cell Block Diagram*: In order to efficiently adjust the output frequency of the DCO, a set of DCO control inputs that specifically target the DCO column/row matrix structure is introduced: signals *Row On*, *Row Select*, and *Column Select*, described in the *Column Decoder* section. Accordingly, each individual tri-state inverter has its own control unit in the form of an AND-OR standard cell, and together they form a larger block called a DCO cell. Fig. 3 shows the DCO cell schematic at logic circuit level and CMOS transistor level.

3) *DCO Level Shifters*: The DCO operates at its own supply voltage (named V_{DDL}), which is different from the supply voltage of the rest of the FLL logic. The advantage of such a design is the ability to adjust the DCO supply voltage independently after chip fabrication in order to set up the desired frequency resolution and range, depending on the process corner in which the fabrication was carried out. Furthermore, by being able to reduce the DCO supply voltage, one can significantly reduce the DCO power dissipation because of its quadratic dependence on the supply voltage.

An independent DCO power domain was achieved by inserting level shifters at the inputs and outputs of the DCO, as shown in Fig. 2. Since the DCO power domain is lower than the rest of the system, high-low level shifters (HLLS) are placed at the DCO control inputs and low-high level shifters (LHLS) at the output phases. Conventional level shifter circuits used in this system are shown in Fig. 4. The HLLS is practically a buffer composed of two inverters used as pull-up or pull-down logic. The LHLS is a positive-feedback-based regenerative logic circuit [6] that consists of two cross-coupled PMOS, two NMOS transistors, and an inverter.

The level shifters could introduce a potential disturbance of the duty cycle at the output of the LHLS, which can be mitigated with additional buffering of the DCO outputs.

III. IMPLEMENTATION AND RESULTS

The proposed digital FLL is implemented using SystemVerilog in 130 nm CMOS technology. The DCO is implemented as an independent macro using only standard cell libraries. The entire design occupies $33000 \mu m^2$, 13 % of which is the DCO. The reference clock is 16 MHz, the DCO clock is set to 640 MHz, and the frequency resolution is 2.8 MHz. The power supplies for the FLL logic and the DCO are 1.2 V and 1.1 V, with RMS current consumption of 0.9 mA and 2.185 mA, respectively. The FLL layout is displayed in Fig. 5.

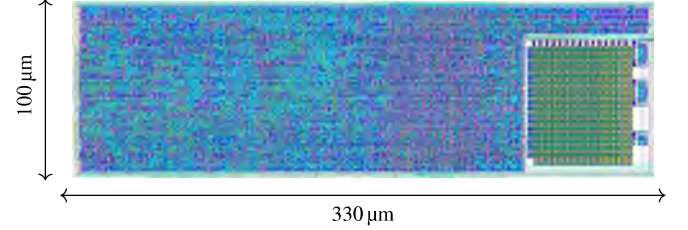


Fig. 5: Digital FLL layout, with the DCO in the bottom right corner.

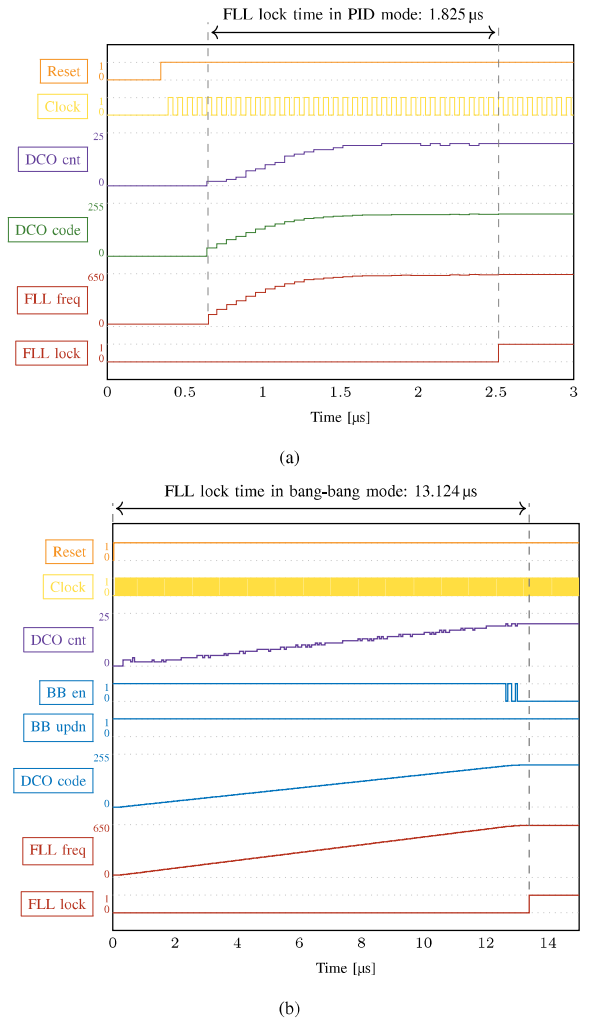


Fig. 6: FLL simulation in (a) PID mode and (b) bang-bang mode.

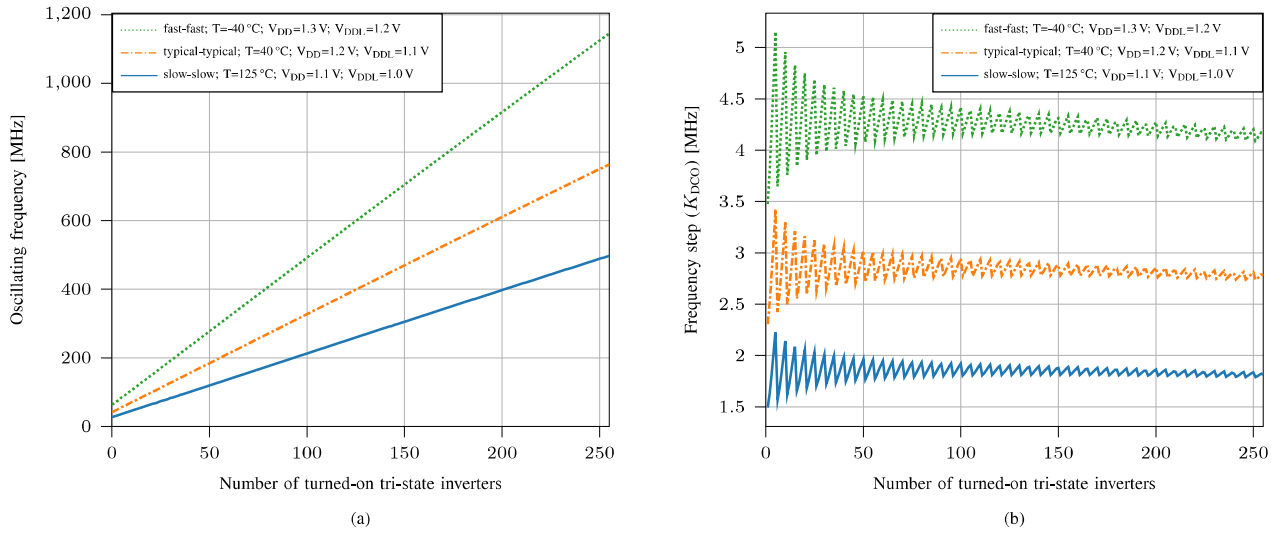


Fig. 7: (a) Oscillation frequency and (b) frequency step dependence on the number of turned-on tri-state inverters for the slowest, typical and fastest corners.

A. Frequency-Locked Loop Functional Simulation

FLL simulation in both control modes is displayed in Fig. 6. From the waveforms, it can be noticed that both modes achieve a stable FLL lock with an output frequency extremely close to the desired frequency, with the error being in the range of the DCO resolution (below 3 MHz). However, in PID mode ($P=15$, $I=15$, $D=0$), locking is performed much faster, within $1.83\mu\text{s}$ in comparison with $13.13\mu\text{s}$ in bang-bang mode.

B. PVT Dependence of the Digitally Controlled Oscillator

To determine the behavior of the DCO in realistic conditions, it is necessary to check various PVT (process, voltage, temperature) corners. Three important PVT corners were analyzed: the worst (slow) case corner (slow-slow, $V_{DD}=1.1\text{V}$, $V_{DDL}=1\text{V}$, 125°C), the typical case corner (typical-typical, $V_{DD}=1.2\text{V}$, $V_{DDL}=1.1\text{V}$, 40°C), and the best (fast) case corner (fast-fast, $V_{DD}=1.3\text{V}$, $V_{DDL}=1.2\text{V}$, -40°C).

In order to significantly reduce post-extraction simulation time without losing accuracy, the DCO simulations were performed on the extracted DCO cell and level shifters, with an additional parasitic capacitor at each DCO phase whose value was derived from the extraction results of the entire FLL. Fig. 7 shows the DCO frequency and the frequency step, K_{DCO} , dependence on the number of turned-on tri-state inverters (i.e., on the DCO control word) for the worst, typical, and best PVT corner cases. TABLE I shows the frequency range and average K_{DCO} in the three analyzed corners.

Although in the worst corner the frequency does not reach 640 MHz, this can easily be achieved by increasing the DCO supply voltage, V_{DDL} . Frequency dependence on each of the

PVT parameters can also be analyzed independently. Respectively, the frequency will increase with a faster process corner, a higher supply voltage, or a lower temperature.

C. Digitally Controlled Oscillator Timing

A simple post-extraction simulation of the DCO in the typical case corner is depicted in Fig. 8, displaying generated clock signals at each of the five phases of the DCO. The signals shown are obtained at the input of the LHLS (V_{DDL} voltage domain) and at the LHLS output (V_{DD} voltage domain).

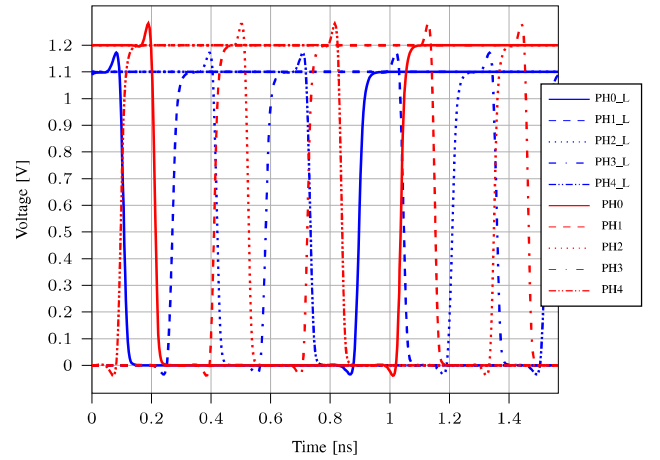


Fig. 8: Generated clock of 5 DCO phases in V_{DD} and V_{DDL} power domain.

As shown by equation (1), f_{osc} depends on t_d , the cell delay of a single tri-state inverter, which is practically an arithmetic mean of the rising and falling clock edge delay (t_{lh} and t_{hl}). Another important parameter to consider is the duty cycle, or the ratio between clock pulse width and period.

The obtained values for clock edge delays at the buffered level shifter outputs are $t_{lh} = 26\text{ps}$ and $t_{hl} = 20\text{ps}$. The duty cycle ratio is approximately 48% – 52%. The shift between two adjacent phases is approximately 940 ps.

TABLE I: DCO frequency range and average frequency step, K_{DCO} .

Corner	f_{min}	f_{max}	Avg. K_{DCO}
Slow	27.2 MHz	502 MHz	1.8 MHz
Typical	42 MHz	764 MHz	2.8 MHz
Fast	63.3 MHz	1.146 GHz	4.2 MHz

D. Frequency-Locked Loop Power Spectrum

Normalized power spectrum of the proposed FLL in PID mode during the process of maintaining the 640 MHz frequency at its output is shown in Fig. 9. The data was obtained from a 15 μm gate-level digital simulation, which includes an ideal noiseless SystemVerilog model of a DCO. The simulation output is a fully deterministic square wave made of ones and zeros, sampled at 10 GHz, and saved for further processing.

The highest power peak in the graph represents the FLL's oscillating frequency, or the carrier frequency. The level of the strongest spurious tone is -23.6 dBc , which is more than two orders of magnitude below the carrier frequency level. In the zoomed-in region, the reference frequency spurs can also be seen left and right from the carrier at 16 MHz offset. The level of the stronger reference spur is -43.8 dBc .

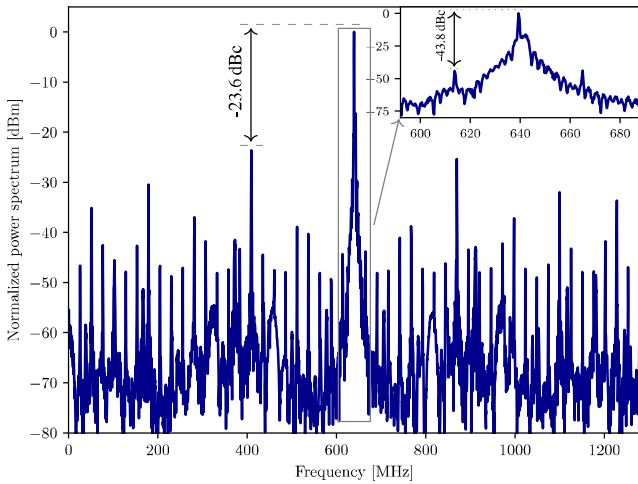


Fig. 9: FLL power spectrum, with the carrier frequency at 640 MHz, the strongest spur (center-left) level of -23.6 dBc , and reference frequency spurs at $640 \pm 16\text{ MHz}$ (top-right, zoomed in) with the level of -43.8 dBc .

E. Digitally Controlled Oscillator Phase Noise

Due to random phase deviations, the power spectrum of a real oscillator is also smeared at frequencies around f_{osc} . Random phase disturbance sources [10] in terms of flicker and thermal noise are manifested as $1/f^3$ and $1/f^2$ regions, respectively, in the simulated open-loop DCO phase noise profile given in Fig. 10 and obtained for the typical PVT corner, with V_{DDL} of 1.1 V, and f_{osc} of 640 MHz.

IV. CONCLUSION

This paper presents a synthesizable digital FLL with a simple but efficient design architecture. The tri-state inverter ring-based DCO allows decent frequency resolution and fast performance, along with simple control, portability, and scalability. Two FLL control modes were presented: the bang-bang control and the PID control. Data conversion between clock domains and metastability protection were explained in detail.

The FLL is fully synthesizable, implemented using SystemVerilog, and, depending on the technology library, can be made using only standard library cells with no modifications while

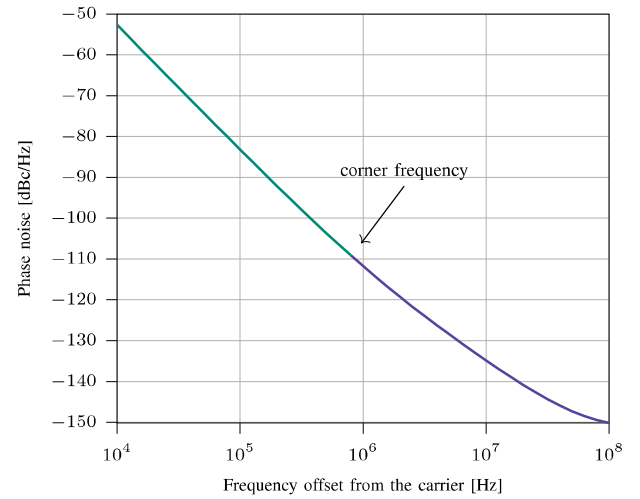


Fig. 10: Phase noise spectrum of the DCO: the flicker noise region (left), the thermal noise region (right), and the corner frequency at $\approx 800\text{ kHz}$.

exploiting the digital design flow methodology. It was sent for fabrication in a 130 nm CMOS technology node.

Future work will include chip testing upon fabrication and packaging, as well as the implementation of additional synthesizable digital blocks, such as the PLL, time-to-digital converter (TDC), low-dropout regulator (LDO), and so on.

REFERENCES

- [1] I. Ali, H. Abbasizadeh, M. R. U. Rehman, M. Asif, S. J. Oh, Y. G. Pu, M. Lee, K. C. Hwang, Y. Yang, and K.-Y. Lee, "An ultra-low power, adaptive all-digital frequency-locked loop with gain estimation and constant current DCO," *IEEE Access*, vol. 8, pp. 97 215–97 230, 2020.
- [2] A. Musa, W. Deng, T. Siriburanon, M. Miyahara, K. Okada, and A. Matsuzawa, "A compact, low-power and low-jitter dual-loop injection locked PLL using all-digital PVT calibration," *IEEE Journal of Solid-State Circuits*, vol. 49, no. 1, pp. 50–60, 2014.
- [3] W. Deng, D. Yang, T. Ueno, T. Siriburanon, S. Kondo, K. Okada, and A. Matsuzawa, "A fully synthesizable all-digital PLL with interpolative phase coupled oscillator, current-output DAC, and fine-resolution digital varactor using gated edge injection technique," *IEEE Journal of Solid-State Circuits*, vol. 50, no. 1, pp. 68–80, 2015.
- [4] J. A. Tierno, A. V. Rylyakov, and D. J. Friedman, "A wide power supply range, wide tuning range, all static CMOS all digital PLL in 65 nm SOI," *IEEE Journal of Solid-State Circuits*, vol. 43, no. 1, pp. 42–51, 2008.
- [5] A. V. Rylyakov, J. A. Tierno, D. Z. Turker, J.-O. Plouchart, H. A. Ainspan, and D. Friedman, "A modular all-digital PLL architecture enabling both 1-to-2GHz and 24-to-32GHz operation in 65nm CMOS," in *2008 IEEE International Solid-State Circuits Conference - Digest of Technical Papers*, 2008, pp. 516–632.
- [6] Y. Osaki, T. Hirose, N. Kuroki, and M. Numa, "A low-power level-shifter with logic error correction for extremely low-voltage digital CMOS LSIs," *IEEE Journal of Solid-State Circuits*, vol. 47, no. 7, pp. 1776–1783, 2012.
- [7] B. Razavi, *Design of CMOS Phase-Locked Loops: From Circuit Level to Architecture Level*. Cambridge University Press, 2020.
- [8] R. B. Madhusudhana, P. Jose, P. Babu, and V. Logeshwaran, "CMOS based digital controlled oscillators (DCO) – a review," *International Journal of Applied Engineering Research*, vol. 10, no. 20, pp. 18 626–18 630, 2015.
- [9] M. Terosiet, E. Zianbetov, F. Vallette, M. M. Louerat, P. Garda, D. Galayko, and S. Feruglio, "A comprehensive in-depth study of tri-state inverter based DCO," *Microelectronics Journal*, 2020.
- [10] V. Milovanović and B. Nikolić, "An HDL model of a digitally controlled oscillator for rapid digital PLL prototyping," in *2017 IEEE 30th International Conference on Microelectronics (MIEL)*, 2017, pp. 205–208.

European Winter Conference on Plasma Spectrochemistry

Ljubljana, Slovenia,
January 29th – February 3rd, 2023

Book of Abstracts



NATIONAL INSTITUTE
OF CHEMISTRY



Book of abstracts of the 19th European Winter Conference on Plasma Spectrochemistry

Publisher:
National Institute of Chemistry
Hajdrihova 19
1000 Ljubljana
Slovenia

Editors:
Vid Simon Šelih and Martin Šala, National Institute of Chemistry, Slovenia

Graphical design:
Repster

Ljubljana, January 2023
Publication is not for sale

Kataložni zapis o publikaciji (CIP) pripravili v Narodni in univerzitetni knjižnici v Ljubljani
COBISS.SI-ID 139103747
ISBN 978-961-6104-85-2 (PDF)

Study of the beryllium spectral line shape using Laser Induced Breakdown Spectroscopy

Marijana Gavrilović Božović¹, Biljana Stankov², Miroslav Kuzmanović³, Milivoje Ivković²

¹Faculty Of Engineering Sciences University of Kragujevac, Kragujevac, Serbia, ²Institute of Physics University of Belgrade, Belgrade, Serbia, ³Faculty of Physical Chemistry, University of Belgrade, Belgrade, Serbia

Beryllium is a naturally occurring element in metal-poor stars and has been chosen as the element to cover the first wall of ITER (International Thermonuclear Experimental Reactor). Erosion of beryllium under transient plasma loads will determine the lifetime of the ITER first wall, so the presence of Be dust particles in plasma should be monitored. In addition, the Be deposits on other fusion reactor components should be studied by, for example, a calibration-free LIBS method. This method requires determination of the plasma parameters, which can be derived from the parameters and shape of the Be spectral lines. The study of the Be lines shapes was performed using spectra recording of the plasma emission due to interaction of the fourth harmonic Nd:YAG laser radiation at 266 nm, pulse energy 70 mJ at 10 Hz repetition rate with the BeO target. The target made from BeO ceramics was rotated by the motor in the low-pressure chamber. The 1:1 image of the plasma plume was projected by optical mirrors on the entrance slit (20 μm wide) of a 0.5 m Ebert-type spectrometer with an iCCD camera operated in the image mode and controlled using a pulse generator (DDG 535, Stanford Research Systems) triggered optically by the plasma. The plasma emission was accumulated over 160 ablation events to exclude the influence of shot-to-shot fluctuations in the signal. The acquisition gate width was 100 ns. Since previous studies have shown some discrepancies between obtained line shape parameters and theory², the main task was to enable spatially and temporally resolved measurements of Be lines of interest, which was readily achievable with the used experimental setup. Careful inspection of the ablation and plasma creation process provided insurance that the dust-free environment is indeed obtained in the experimental setup. This is a quite important aspect since dust can have a significant influence on the line shape parameters. Knowledge about its impact on the line shapes will be highly beneficial in the future, where large amount of ITER-related dust is expected to be formed and interfere with the plasma and its emission. Further improvement of this study is the possibility of testing the less obvious influence of self-absorption on the line shapes and intensities. This was achieved using the setup with the lens and flat mirror³.

beryllium, LIB S, spectral line shapes, plasma diagnostics, plasma fusion reactor

Stankov et.al., Rev. Sci., 2018, 89,053108.

Stankov et.al., EPL, 2018, 123, 63001.

Konjević, Physics reports, 1999, 316 (6), 339-401.



**32nd Summer School and
International Symposium on
the Physics of Ionized Gases**

Belgrade, Serbia,
August 26 - 30, 2024

CONTRIBUTED PAPERS
&
**ABSTRACTS of INVITED LECTURES,
TOPICAL INVITED LECTURES and PROGRESS REPORTS**

Editors:
**Bratislav Obradović, Jovan Cvetić,
Miroslav Kuzmanović and Nikola Cvetanović**



**БЕОГРАД
2024**

PUBLICATIONS OF THE ASTRONOMICAL OBSERVATORY OF BELGRADE
FOUNDED IN 1947

EDITORIAL BOARD:

Dr. Srdjan SAMUROVIĆ, Editor-in-Chief (Astronomical Observatory, Belgrade)

Dr. Rade PAVLOVIĆ (Institute of Physics, Belgrade)

Dr. Miroslav MIĆIĆ (Astronomical Observatory, Belgrade)

Dr. Branislav VUKOTIĆ (Astronomical Observatory, Belgrade)

All papers in this Publication are peer reviewed.

Published and copyright © by Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia

Director of the Astronomical Observatory: Dr. Luka Č. Popović

Typesetting: Tatjana Milovanov

Internet address <https://publications.aob.rs>

ISSN 0373-3742

ISBN 978-86-82296-08-9

Financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia

CIP - Каталогизacija y publikaciji - Narodna biblioteka Srbije, Beograd

537.56(082)

539.186.2(082)

539.121.7(082)

533.9(082)

SUMMER School and International Symposium on the Physics of Ionized Gases (32 ; 2024 ; Beograd)

Contributed papers & abstracts of invited lectures, topical invited lectures and progress reports / 32nd Summer School and International Symposium on the Physics of Ionized Gases - SPIG 2024, August 26 – 30, 2024, Belgrade, Serbia ; editors Bratislav Obradović ... [et al.]. - Belgrade : Astronomical Observatory, 2024 (Beograd : Skripta Internacional). - 215 str. : ilustr. ; 24 cm. - (Publications of the Astronomical Observatory of Belgrade, ISSN 0373-3742)

Na nasl. str.: University of Belgrade, Faculty of Physical Chemistry; Serbian Academy of Sciences and Arts. - Tiraž 200. - Str. 17-18: Preface / editors Bratislav Obradović ... [et al.]. - Bibliografija uz svaki rad. - Registar.

ISBN 978-86-82296-08-9

1. Kuzmanović, Miroslav, 1967- [urednik] [autor dodatnog teksta]

a) Јонизовани гасови - Зборници b) Атоми - Интеракција - Зборници

v) Плазма - Зборници

COBISS.SR-ID 150439689

FAST PHOTOGRAPHY IN THE SERVICE OF SPATIALLY AND TEMPORALLY RESOLVED LIBS DIAGNOSTICS OF DOPED TUNGSTEN

BILJANA STANKOV¹ , MARIJANA R. GAVRILOVIĆ BOŽOVIĆ² ,
DRAGAN RANKOVIĆ³ , JELENA SAVOVIĆ⁴  and MILIVOJE IVKOVIĆ¹ 

¹*Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia*

²*Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia*

³*Faculty of Physical Chemistry, University of Belgrade, 11158 Belgrade, Serbia*

⁴*Vinca Institute of Nuclear Sciences, University of Belgrade, Mike Petrovića Alasa 12-16, 11000 Belgrade, Serbia.*

E-mail biljanas@ipb.ac.rs

Abstract. The spectroscopic diagnostic of laser induced plasma is challenged by its spatial inhomogeneity and dynamic evolution, which simultaneously alters plasma parameters and emission of ablated material in plasma plume (Lazic at al. 2006, A. Singh at al. 2010). Those difficulties become more pronounced when conducting spatially and temporally resolved measurements. Choosing appropriate conditions for LIBS, such as delay time, gate width, and observed plasma section is paramount. At atmospheric pressure, plasma tends to stay more localized in the vicinity of the target, with specific flattened shape. In contrast, plasma expanding into low pressure exhibits rapid and pronounced dispersion, potentially causing plasma to move out of the field of view, and/or not being captured completely. This can make determining the time of the maximum plasma emission intensity challenging. In this study influence of different additives in tungsten samples on plasma plume dynamics and expansion is investigated and possible impact on the spectroscopic diagnostics is assessed.

Acknowledgements. The research was funded by the Ministry of Science, Technological Development and Innovations of the Republic of Serbia, Contract numbers: 451-03-68/2022-14/200024 and 451-03-65/2024-03/200146, and supported by the Science Fund of the Republic Serbia, Grant no. 7753287 "NOVA2LIBS4fusion".

References

- V. Lazic and S. Jovicevic: 2006, *Spectrochimica Acta Part B: Atomic Spectroscopy*, vol. **61**, no. 7, 856
- A. Singh and P. K. Rai, "Challenges in Diagnostics of Laser-Induced Plasma," *Journal of Physics D: Applied Physics*, vol. **43**, no. 43, p. 434013, 2010.

**The Third Serbian International Conference on Applied Artificial Intelligence, Kragujevac –
Book of Abstracts**

Editor

Professor Nenad Filipović

Technical assistants

Đorđe Ilić

Jelena Živković

Proofreaders

Neda Vidanović Miletić

Milena Đorđević

Publisher

University of Kragujevac, Serbia

Press

DONAT GRAF doo Beograd

Impression

130 copies

Year of publication

2024

ISBN 978-86-81037-79-9

CIP - Каталогизација у публикацији Народна библиотека Србије, Београд

004.8(048)

**SERBIAN International Conference on Applied Artificial Intelligence (3 ;
2024 ; Kragujevac)**

Book of Abstracts / The Third Serbian International Conference on Applied
Artificial Intelligence, (SICAAI), May 23-24, 2024, Kragujevac, Serbia ; [editor
Nenad Filipović]. - Kragujevac : University, 2024 (Beograd : Donat graf). - 150
str. : ilustr. ; 30 cm

Kor. nasl. - Tiraž 130. - Str. 8-10: Welcome message / Nenad Filipović.

ISBN 978-86-81037-79-9

a) Вештачка интелигенција -- Апстракти

COBISS.SR-ID 144834825



UNMANNED VEHICLES - TECHNICAL PERSPECTIVE OF AI APPLICATIONS AND SOCIAL IMPACT

Vladimir Djapic¹, Isidora Grujic^{2*}, Marijana Gavrilović Božović², Mina Vasković Jovanović², Jasna Radulović² and Milan Čabarkapa²

¹ Belgrade Office of the Institute for Artificial Intelligence Research and Development of Serbia, Fruškogorska 1, 21000 Novi Sad, Serbia

e-mail: vladimir.djapic@ivi.ac.rs

² Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia

e-mail: isidora@kg.ac.rs, marijana.gavrilovic@kg.ac.rs, mina.vaskovic.jovanovic@kg.ac.rs, jasna@kg.ac.rs, mcabarkapa@kg.ac.rs

**corresponding author*

Abstract

Unmanned autonomous vehicles, driven by advancements in artificial intelligence (AI), are transforming numerous sectors including transportation, exploration, and public service. This paper reviews the technical and social dimensions of autonomous cars, boats, and drones, emphasizing their AI applications in perception, decision-making, and control. An autonomous vehicle requires a comprehensive sensor suite to perceive its environment, navigate safely, and make informed decisions. The sensor suite typically includes a combination of sensors such as LIDAR, RADAR, GPS, IMU, cameras, and depth sensors. These sensors provide vehicles with essential information about their surroundings, enabling them to operate autonomously and avoid obstacles. The essential modules and systems that enable autonomous navigation are Guidance, Navigation, and Control (GNC), Perception, and Prediction. The basis for transport automation is the GNC system that utilizes GPS and IMU sensors. Perception is the term used in robotics since a robot needs to perceive, be aware, sense the world / objects around it so it can avoid them if they are on its way. Prediction is a module that anticipates the future motion trajectories of the perceived obstacles. The output of this module gives information to a robot path planner which generates an appropriate trajectory to go around or avoid an obstacle (other traffic participant) that is on the way.

This abstract discusses the dual nature of AI in autonomous vehicles highlighting significant benefits such as improved safety, reduced congestion, and enhanced energy efficiency while addressing critical challenges including data integrity, safety reliability, ethical conflicts, and potential job displacement. Particular attention is given to unmanned aerial systems, detailing their diverse applications from aerial surveillance to disaster response, and discussing the accompanying technical hurdles in localization and navigation. The paper also examines ethical considerations concerning AI in autonomous vehicles, with a focus on decision-making algorithms, accountability, and societal impacts such as privacy and cybersecurity. In conclusion, while unmanned vehicles present remarkable opportunities for innovation and efficiency, they require careful regulation, rigorous interdisciplinary research, and robust ethical frameworks to fully realize their potential and safeguard societal interests.

Keywords: AI-driven systems, autonomous systems, ethical considerations, societal impact, unmanned vehicles.

The electromagnetic field of a current conductor in the presence of lossy half-space

Marijana Gavrilović Božović¹, Mina Vasković Jovanović¹, Milan Čabarkapa¹, Nikola Mijailović², Milan Vesković³, Jasna Radulović^{1*}

¹ University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia

² HTEC group, Belgrade, Serbia

³ University of Kragujevac, Faculty of Technical Sciences, Čačak, Serbia

ARTICLE INFO

* **Correspondence:** jasna@kg.ac.rs

DOI: 10.5937/engtoday2400010G

UDC: 621(497.11)

ISSN: 2812-9474

Article history: Received 19 May 2024; Revised 1 July 2024; Accepted 8 July 2024

ABSTRACT

In this paper, the electromagnetic field problem of a line current conductor in the presence of homogenous and isotropic lossy half-space is analyzed. The main difficulty in this analysis is to take correctly into account the influence of ground finite conduct since the use of integral transformations in Maxwell's equations leads to Sommerfeld integral, hard to evaluate even numerically. Charge Simulation Method, based on the equivalence theorem of different electromagnetic systems, is proposed here for the numerical approach. Two independent, equivalent systems created of appropriately chosen, shaped, and arranged fictitious sources are suggested for the determination of EM field components, in the air and in the lossy half-space. Point-matching method based on the boundary conditions between media is applied for the determination of the fictitious source intensities. The proposed procedure has the advantage that it takes into account the influence of the finite ground conductivity, without calculation of Sommerfeld integral and it ensures excellent accuracy with a small number of fictitious sources. Also, the features of the proposed method are simple implementation on a standard PC, fast and accurate simulation procedure, and easy generalization for some other cases of arbitrarily oriented wires of finite lengths above a lossy half space.

KEYWORDS

Lossy half-space, Line current conductor, Charge Simulation Method.

1. INTRODUCTION

Determination of the electromagnetic (EM) field of line current conductor located in the air, in the presence of homogeneous and isotropic lossy half-space, still attracts interest of many researchers [1-4], even though it has been more than a century since Sommerfeld published his solution of the Hertzian-dipole radiation above real ground [5]. His approach was to decompose the original field by an infinite number of plane waves and then apply the law of diffraction, reflection, and boundary conditions on a planar interface between the two media. This is far from a trivial task since it requires solving a semi-infinite integral with a very complex integrand, called Sommerfeld integral (SI), which describes the influence of a lossy half-space. Because SI is hard to evaluate both analytically and numerically, most of the methods for calculations have some limitations regarding under-integral parameters or calculation time.

One of the earliest attempts to solve the problem was based on transmission line analogies that led to useful results, particularly at low frequencies, see e.g. [6]. Although this method, known as Carson's method, does not provide a closed-form solution, it is still the standard method for determining the frequency-dependent impedance of overhead transmission lines. Over the past several decades, a number of studies for the calculation of magnetic field in the surrounding of an electric power transmission lines have been published [7–13], because of concerns about possible detrimental health effects from these kinds of fields [14–16]. Novel approach based on the use of artificial intelligence techniques was applied in [16–19] to estimate electric and magnetic fields around an overhead power transmission lines. Recently simple approximation that can be used for modeling of one type of Sommerfeld integrals typically occurring in the expressions that describe sources buried in the lossy ground, is proposed [20].

This problem has also been theoretically studied in the case of geophysical applications, where there is an assumption of a uniform ground and no propagation, which leads to a quasi-static approximation. Electromagnetic field at the surface of the ground in Fourier integral form is derived in [21]. The classical study in this area considered the EM fields of a phased line current over a conducting half-space [22]. A very interesting theoretical approach is exposed in [23], where the EM field components created at the ground surface by an overhead line current are expressed in terms of the Neumann and Struve functions, and derived in a new series expansions and computations.

There are many papers on the subject that deal with various facets of SI problem in analysis of dipole antennas in the presence of lossy half-space [24–34]. In some of them, different simpler models were proposed, and the results obtained by rigorous Sommerfeld's integral formulation were quoted [24–26], in the other the SI is approximately evaluated using different known functional solutions [27–29]. One interesting approach is proposed in [30] where the boundary element method, combined with the exponential approximation technique, is used for treating the integral equation for loaded wire above a lossy medium. In a number of papers [31, 32] a discrete complex image method, based on the replacement of the lossy half-space by a few complex images is used. Complex and exact modelling of the SI using images is given in [33]. In [34] the key to obtain the solution was to split the incident field into evanescent and traveling contributions. In most of these papers, the integral equations are approximately solved by the moment method, the so-called point-matching method [35,36].

The current paper describes the details of the numerical solution for EM field of current conductor above lossy half-space that relies on theoretical investigations of the Sommerfeld solution. An analytical solution developed in [37,38] for the problem of the current conductor above lossy half-space is based on transformations that substitute Sommerfeld integral (obtained by the integral transformation method) with Hankel's function and their asymptotic expansion. In these references, the obtained analytical solutions are compared with the known results from the literature for the special case when ground is well conductive [39], and the obtained results show an excellent accordance expansion. This practically justifies the proposed presentation of the complex integrals by Hankel's functions and their asymptotic developments. Charge Simulation Method [40–42] based on the theorem of equivalence of different electromagnetic systems, is used for numerical calculations, due to the nature of the problem, system geometry and the influence of finite earth conductivity. Compared to other boundary methods, CSM is significantly faster and conceptually much simpler since numerical integration and singularisation of the integrand are not required.

Two independent, equivalent systems are suggested in this study. The first system is applied for EM field component determination in the air, and it consists of a primary line current conductor and several fictitious line current conductors. The second system is applied for field component determination in lossy half-space and it consists of fictitious line current conductors only. The positions of fictitious sources are not strictly defined in advance, which enables experienced researchers to choose the optimal configurations, which is the privilege of the method. EM field components contain Hankel's functions which represent linear combinations of Bessel's functions. Hankel's functions with different arguments, real in the air and complex in the ground, are obtained using recurrent relations [43]. The complex intensities of unknown currents are determined by the point-matching method, where boundary conditions in a finite number of points located on the boundary between two media have to be satisfied. Using this procedure, electromagnetic field components can be calculated, in any point above and below the ground surface. The problem solved here for certain cases is transformed into the application of various forms of image theorem, a special case of the equivalence theorem. The accuracy check of the applied method can be performed through some special regimes analysis [38]. The main contribution of the proposed procedure is that it takes into account the influence of the finite ground conductivity, without calculating Sommerfeld integral and ensures excellent accuracy with a small number of fictitious sources. Finally, the advantage of the proposed procedure is that it can also be extended to the more demanding thin wire geometries which are commonly met in practice.

2. FORMULATION OF THE PROBLEM

2.1. Lonely Current Conductor

Thin, long conductor, with constant current amplitude, I , and frequency ω , located in homogeneous, isotropic, linear lossy space, with dielectric constant $\varepsilon = \varepsilon_0 \varepsilon_r$, magnetic permeability $\mu = \mu_0 \mu_r$ and specific conductivity σ is shown in Fig. 1. It is placed in cylindrical coordinate system (r, θ, z) , along z -axis by direction $r = 0$, $\theta = 0$.

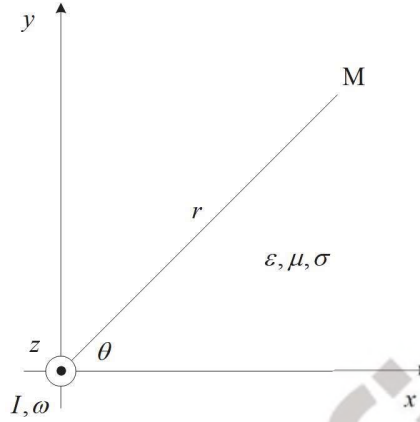


Figure 1: Lonely current conductor.

Electromagnetic field in surrounding of the conductor satisfies Maxwell's equations

$$\text{rot} \mathbf{H} = \mathbf{J} + \underline{\sigma} \mathbf{E} \quad (1)$$

$$\text{rot} \mathbf{E} = -j\omega\mu\mathbf{H} \quad (2)$$

where

$$\underline{\sigma} = \sigma + j\omega\varepsilon \quad (3)$$

is complex specific conductivity of space,

$$\mathbf{J} = J\hat{z}, J = I\delta(x)\delta(y) = \frac{I}{2r\pi}\delta(r) \quad (4)$$

where $\mathbf{J}$ is the current density, and δ denotes Dirac's functions.

The axial electric field component satisfies the wave equation

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dE_z}{dr} \right) + k^2 E_z = j \frac{\omega\mu I}{2\pi r} \delta(r) \quad (5)$$

where $k^2 = -j\omega\mu\underline{\sigma}$, and k is a complex propagation constant of lossy space.

This equation can be written in the form

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dE_z}{dr} \right) + k^2 E_z = 0 \quad (6)$$

because only a lonely current conductor is considered here.

Solutions of this wave equation are Bessel's functions of the first kind, $J_0(kr)$, and of the second kind, $N_0(kr)$. Since only one solution that propagates from source to periphery is of importance, the linear combination of Bessel's functions, known as Hankel's function of the second kind is used:

$$H_0^{(2)}(kr) = J_0(kr) - jN_0(kr) \quad (7)$$

The solution of the wave equation, which at large distances satisfies radiation conditions,

$$\frac{\partial E}{\partial r} + E \left(j + \frac{1}{2kr} \right) = 0, \quad r \rightarrow \infty \quad (8)$$

has the following form

$$E_z = CH_0^{(2)}(kr) \quad (9)$$

where C is an unknown integration constant, obtained from the condition that low frequency magnetic field intensity

$$H_\theta = j \frac{kC}{\omega\mu} H_1^{(2)}(kr) \quad (10)$$

tends towards a constant value

$$\lim_{\omega \rightarrow 0} H = \frac{I}{2r\pi} \quad (11)$$

Since it is known that

$$J_1(kr) \rightarrow \frac{kr}{2} \text{ and } N_1(kr) \rightarrow -\frac{2}{\pi kr} \text{ for } kr \rightarrow 0 \quad (12)$$

integration constant is obtained in the form

$$C = -\frac{\omega\mu I}{4} \quad (13)$$

Finally, electromagnetic field components are

$$E_z = -\frac{\omega\mu I}{4} H_0^{(2)}(kr) \quad (14)$$

$$H_\theta = -j \frac{kI}{4} H_1^{(2)}(kr) \quad (15)$$

In the radiation zone, far field approximation of Hankel's functions can be expressed as

$$H_0^{(2)}(kr \rightarrow \infty) = \sqrt{\frac{2}{\pi kr}} e^{-j\left(kr - \frac{\pi}{4}\right)} \quad (16)$$

In the immediate vicinity of the conductor, near field approximation for Hankel's functions can be taken,

$$H_0^{(2)}(kr \rightarrow 0) = 1 - j \frac{2}{\pi} \ln(kr) \quad (17)$$

2.2. Line above lossy half-space

Thin, long conductor, with constant current amplitude, I , and frequency ω , located in air parallel above homogeneous, isotropic and linear lossy half-space, with dielectric constant $\epsilon = \epsilon_0 \epsilon_r$, magnetic permeability $\mu = \mu_0 \mu_r$ and specific conductivity σ , is shown in Fig. 2. It is placed in a cylindrical coordinate system (r, θ, z) , along z -axes, with $r=h$, $\theta=\pi/2$.

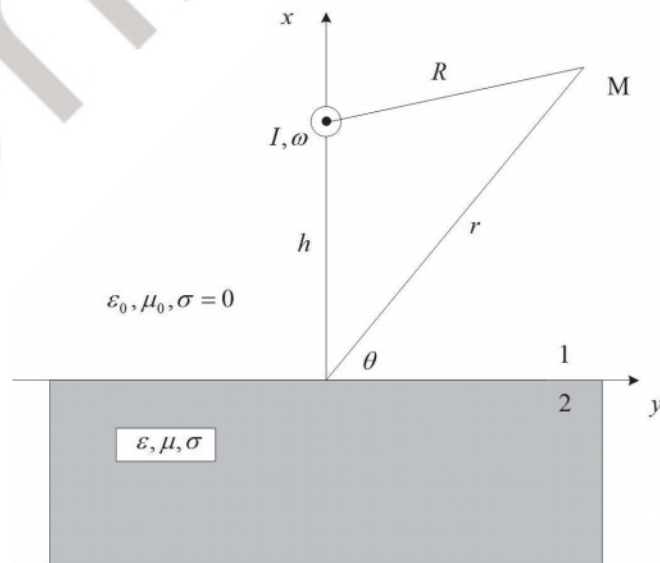


Figure 2: Linear conductor above lossy half –space.

The electric field has only axial component,

$$\mathbf{E} = E_z \hat{z}, \quad E_r = 0, \quad E_\theta = 0, \quad E_z = E_z(r, \theta) \quad (18)$$

while magnetic field has both radial and circumferential component, which can be expressed from Maxwell's equations

$$\mathbf{H} = H_r \hat{r} + H_\theta \hat{\theta}, \quad H_r = -\frac{1}{j\omega\mu r} \frac{\partial E_z}{\partial \theta}, \quad H_\theta = \frac{1}{j\omega\mu} \frac{\partial E_z}{\partial r}, \quad H_z = 0 \quad (19)$$

Axial component of electric field satisfies differential equation in the air

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial E_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 E_z}{\partial \theta^2} + k_0^2 E_z = j \frac{\omega\mu_0 I}{2\pi r} \delta(r-h) \delta\left(\theta - \frac{\pi}{2}\right), \quad (20)$$

and wave equation in lossy half-space

$$\frac{1}{r} \frac{\partial E_z}{\partial r} \left(r \frac{\partial E_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 E_z}{\partial \theta^2} + k^2 E_z = 0 \quad (21)$$

where k_0 and k are the phase constant of air and lossy half-space, respectively,

$$k_0 = \omega \sqrt{\epsilon_0 \mu_0} \quad (22)$$

$$k = \omega \sqrt{\epsilon \mu} \sqrt{\frac{1 + \left(\frac{\sigma}{\omega \epsilon}\right)^2 + 1}{2}} - j \omega \sqrt{\epsilon \mu} \sqrt{\frac{1 + \left(\frac{\sigma}{\omega \epsilon}\right)^2 - 1}{2}} \quad (23)$$

and

$$R = \sqrt{r^2 + h^2 - 2rh \sin \theta} \quad (24)$$

2.3. . Method of solution

Charge Simulation Method (CSM) is proposed as a suitable numerical approach to this problem, because of its nature, system geometry and the influence of finite earth conductivity. As already stated in the Introduction part, CSM is based on the theorem of equivalence of different electromagnetic systems, [36,37,38].

Two independent, equivalent systems are suggested, with the geometries shown in Fig. 3. The first one is applied for field component determination in the air, and the second for field component determination in the lossy half-space. The first equivalent system consists of a primary, linear, very long current conductor, with uniform amplitude current I , and N fictitious, also linear, very long parallel conductors, with uniform amplitude currents I_{1n} , $n = 1, 2, \dots, N$. The second equivalent system consists of M fictitious, linear, very long current conductors, with uniform amplitude currents I_{2n} , $n = 1, 2, \dots, M$. The intensities of unknown currents are determined with the points adjustment method, satisfying boundary conditions in a finite number of points located on the boundary between two spaces.

The position of fictitious sources is not strictly defined, and it is up to the researcher to choose the optimal one. The variant, which is chosen as optimal, is shown in Fig. 3.

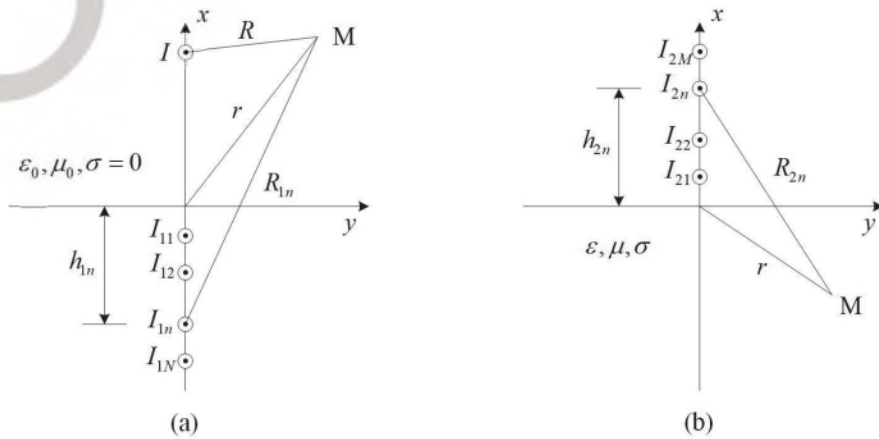


Figure 3: Equivalent systems for EM field calculation. (a) In the air. (b) In the lossy half-space..

Using the procedure given in section 2.1, EM components in lossy half-space are determined with

$$E_{2z} = -\frac{\omega\mu}{4} \sum_{n=1}^M I_{2n} H_0^{(2)}(kR_{2n}) \quad (25)$$

$$H_{2r} = -j \frac{k}{4} \sum_{n=1}^M \frac{h_{2n} \cos \theta}{R_{2n}} I_{2n} H_1^{(2)}(kR_{2n}) \quad (26)$$

$$H_{2\theta} = -j \frac{k}{4} \sum_{n=1}^M \frac{r - h_{2n} \sin \theta}{R_{2n}} I_{2n} H_1^{(2)}(kR_{2n}) \quad (27)$$

and, in the air

$$E_{1z} = -\frac{\omega\mu_0 I}{4} H_0^{(2)}(k_0 R) - \frac{\omega\mu_0}{4} \sum_{n=1}^N I_{1n} H_0^{(2)}(k_0 R_{1n}) \quad (28)$$

$$H_{1r} = -j \frac{k_0 I}{4} \frac{h \cos \theta}{R} H_1^{(2)}(k_0 R) - j \frac{k_0}{4} \sum_{n=1}^N \frac{h_{1n} \cos \theta}{R_{1n}} I_{1n} H_1^{(2)}(k_0 R_{1n}) \quad (29)$$

$$H_{1\theta} = -j \frac{k_0 I}{4} \frac{r - h \sin \theta}{R} H_1^{(2)}(k_0 R) - j \frac{k_0}{4} \sum_{n=1}^N \frac{r - h_{1n} \sin \theta}{R_{1n}} I_{1n} H_1^{(2)}(k_0 R_{1n}) \quad (30)$$

where

$$R_{1n} = \sqrt{r^2 + h_{1n}^2 - 2rh_{1n} \sin \theta} \quad \text{and} \quad R_{2n} = \sqrt{r^2 + h_{2n}^2 - 2rh_{2n} \sin \theta} \quad (31)$$

The intensities of unknown currents are determined using the point-matching method, satisfying boundary conditions in finite number of points located on the boundary between two spaces. Here, the boundary conditions for tangential components of the magnetic field and normal component of the magnetic flux densities are satisfied, so $H_{1r} = H_{2r}$ and $\mu_0 H_{1\theta} = \mu H_{2\theta}$. The total number of unknown currents is $L = N + M$. Boundary conditions are satisfied in L points on the boundary surface, in N points for the first boundary condition, and in M points for the second boundary condition.

3. NUMERICAL RESULTS

Using the procedure described in the previous section, electromagnetic field components can be calculated in any point that belongs to one, or another half-space, for different parameters of the lower one.

The assumption is that the conductor is infinite and thin, with a current amplitude 1 A, $\Psi = 0$, located on the distance of 1m from the lossy half-space. Investigations have shown that most types of lossy ground have $\epsilon_r \geq 3$ and $\mu_r = 1$. For frequencies of a few MHz, the conductivity σ is in the range $0.001 \text{ S/m} \leq \sigma \leq 0.1 \text{ S/m}$. In this paper, three types of lossy ground are considered. The electrical characteristics of these types are shown in the Table 1.

Table 1: Electrical characteristics of three types of ground

Types of lossy ground	ϵ_r	σ [S/m]
dry earth (sand)	4	10^{-3}
wet earth	20	10^{-2}
fresh water	80	10^{-3}

Complex current intensities of the fictitious sources for each of these types of grounds are obtained. Also, the estimation of an optimal number of fictitious sources for each type of ground has been performed, based on the error analysis in satisfying the boundary conditions, with L ranging from 2 to 50.

For example, in the case of dry earth, with $f = 10 \text{ MHz}$, the error analysis shows that quite satisfactory accuracy is obtained even with $N = 5$, $M = 5$, that is to say only $L = 10$ fictitious sources being used. The obtained values for current intensities of fictitious sources for this case are presented in Table 2, in the air and the lossy ground. The rest of the results are also illustrated for this particular example.

Table 2: Calculated intensities of currents of fictitious sources in the air and in the lossy ground.

	In the air [A]		In the lossy ground [A]
I_{11}	$-0.02136 + j0.03279$	I_{21}	$-0.02591 + j0.05116$
I_{12}	$0.15192 - j0.18325$	I_{22}	$0.22662 - j0.47136$
I_{13}	$-0.50836 + j0.40626$	I_{23}	$-0.96061 + j2.02271$
I_{14}	$0.73974 - j0.20655$	I_{24}	$1.87039 - j3.83576$
I_{15}	$-0.35549 - j0.16771$	I_{25}	$-0.35179 + j2.56912$

Table 3 gives calculated tangential and normal components of the magnetic field in various points which belong to air, or to dry earth, again for the case of $L = 10$ fictitious sources.

Table 3: Calculated tangential and normal components of the magnetic field in various points which belong to air, or to dry earth.

r [m]	θ [°]	H_r [A/m]	H_θ [A/m]
0.5	45	$0.20641 + j0.00609$	$-0.05946 - j0.007941$
0.8	80	$0.42965 + j0.00101$	$-0.445626 - j0.00824$
1.2	85	$0.28229 + j0.00036$	$0.66106 - j0.00714$
0.7	-75	$0.01507 - j0.00029$	$0.09715 - j0.00051$
0.4	-20	$0.10362 + j0.00887$	$0.08276 + j0.00111$
1.5	-60	$0.01468 - j0.00214$	$0.06755 - j0.01915$

The distribution of the intensity of the tangential component of the magnetic field in the air versus r , when θ takes values 20° , 40° and 60° , for the chosen case is presented in Fig. 4. The distribution of the intensity of the normal component of the magnetic field in the air versus r , when θ takes values 20° , 40° and 60° is presented in Fig. 5.

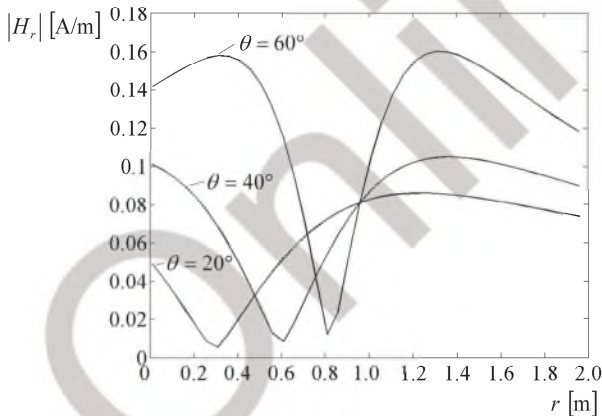


Figure 4: Tangential component of the magnetic field in the air versus r .

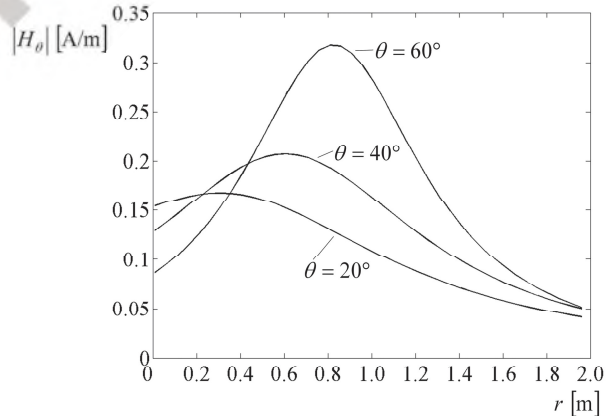


Figure 5: Normal component of the magnetic field in the air versus r .

The error analysis has been done for the remaining two ground types, and it has been estimated that the optimal number of fictitious sources for wet earth is $L = 12$, and that it is necessary to increase the total number of fictitious sources for fresh water to at least $L = 16$.

After the calculation of the electromagnetic field components, the resultant magnetic field is obtained as:

$$H_e = \sqrt{\mathbf{H}\mathbf{H}^*} = \sqrt{H_r^2 + H_\theta^2} \quad (32)$$

The distribution of the intensity of the resultant magnetic field in the air versus r , for $\theta = 45^\circ$, of the line source with sinusoidal current over the three types of imperfect ground is illustrated in Fig. 6.

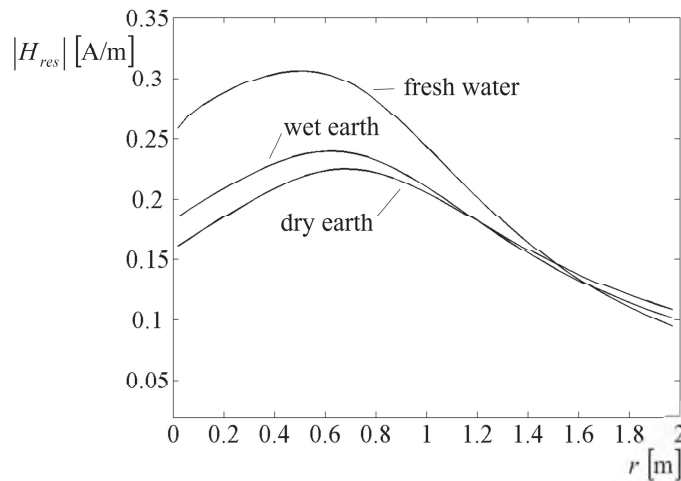


Figure 6: Resultant magnetic field versus r , and $\theta = 45^\circ$, for three types of imperfect ground.

4. CONCLUSION

The simulation model for analyzing a single current conductor placed above a homogenous and isotropic lossy half-space is proposed in this paper. The three cases when lossy half-space is substituted with the three different types of ground are particularly considered. CSM method, based on the theorem of equivalence of different electromagnetic systems and very applicable to systems that include two or more homogenous media, is proposed for numerical solution of the problem. This simulation model has a general character since it is not limited by the values of the parameters of the homogeneous ground. Also, the main contribution of this study is that proposed method provides taking into account the influence of the finite ground conductivity, without the calculation of Sommerfeld integral, and ensures excellent accuracy with the small number of fictitious sources. Compared to other boundary methods, CSM is conceptually significantly faster and much simpler due to the fact that numerical integration and singularisation of the integrand are not required. Finally, the advantage of the proposed procedure is in the fact that this approach can also be generalized for the cases of various thin-wire geometries which are commonly met in practice.

ACKNOWLEDGEMENTS

This work is partially supported by the Ministry of Science, Technological Development and Innovation of Republic of Serbia under contract number 451-03-66/2024-03/200107.

REFERENCES

- [1] K. A. Michalski and J. R. Mosig, "On the complete radiation pattern of a vertical Hertzian dipole above a low-loss ground", *IEEE Journal of Microwaves*, Vol.1(3), pp. 747-762, <https://doi.org/10.1109/JMW.2021.3084947>, (2021)
- [2] K. Ioannidi, Ch. Christakis, S. Sautbekov, P. Frangos, and S. Atanov, "The radiation problem from a vertical short dipole antenna above flat and lossy ground: Novel formulation in the spectral domain with closed – form analytical solution in the high frequency regime", *International Journal of Antennas and Propagation*, Vol. 2014, pp. 1-9, <https://doi.org/10.1155/2014/989348>, (2014)
- [3] A. Chrysostomou, S. Bourgiotis, S. Sautbekov, K. Ioannidi, and P. Frangos, "radiation of a vertical dipole antenna over flat and lossy ground: accurate electromagnetic field calculation using the spectral domain approach along with redefined integral representations and corresponding novel analytical solution", *Elektronika ir elektrotechnika*, Vol. 22(2), pp. 54-61, <https://doi.org/10.5755/j01.eie.22.2.14592>, (2016)
- [4] J. Mosig, K. Michalski, "Sommerfeld integrals and their relation to the development of planar microwave devices", *IEEE Journal of Microwaves*, Vol. 1(1), pp. 470-480, <https://doi.org/10.1109/JMW.2020.3032399>, (2021)
- [5] A. Sommerfeld, "Über die Ausbreitung der Wellen in der Drachtlosen Telegraphie", *Annalen der Physik*, Vol. 333(4), pp. 665-736, <https://doi.org/10.1002/andp.19093330402>, (1909)
- [6] J. R. Carson, "Wave propagation in overhead wires with ground return", *Proceedings of the 32nd Annual North American Power Symposium*, Waterloo (Canada), (reprinted of the 1926 original edition), pp. 539-554, (2000)

- [7] R. G. Olsen, S. L. Backus, and R. D. Steams, "Development and validation of software for predicting ELF magnetic fields near power lines", *IEEE Transactions on Power Delivery*, Vol. 10(3), pp.1525–1534, <https://doi.org/10.1109/61.400937>, (1995)
- [8] A. Geri, A. Locatelli, G. M. Veca, "Magnetic fields generated by power lines", *IEEE Transactions on Magnetics*, Vol. 31(3) pp. 1508–1511, <https://doi.org/10.1109/20.376316>, (1995)
- [9] M. Abdel-Salam, H. Abdallah, M. Th. El-Mohandes, and H. El-Kishky, "Calculation of magnetic fields from electric power transmission lines", *Electric Power Systems Research*, Vol. 49(2), pp. 99–105, [https://doi.org/10.1016/S0378-7796\(98\)00078-9](https://doi.org/10.1016/S0378-7796(98)00078-9), (1999)
- [10] G. Filippopoulos and D. Tsanakis, "Analytical calculation of the magnetic field produced by electric power lines" *IEEE Transactions on Power Delivery*, Vol. 20(2), pp. 1474–1482, <https://doi.org/10.1109/TPWRD.2004.839184>, (2005)
- [11] R. Djekidel, A. Bessedik, A. Hadjadj, "Electric field modeling and analysis of ehv power line using improved calculation method", *Facta universitatis Series: Electronics and Energetics*, Vol. 31(3), pp. 425-445, <https://doi.org/10.2298/FUEE1803425D>, (2018)
- [12] R. Wang , J. Tian, F. Wu, Z. Zhang, and H. Liu , "PSO/GA combined with charge simulation method for the electric field under transmission lines in 3D calculation model", *Electronics*, Vol. 8(10), p. 1140, <https://doi.org/10.3390/electronics8101140>, (2019)
- [13] J. Radulović, V. Ranković, M. Bojić, and J.Škerlić, "Environmental impacts of the electromagnetic field levels near overhead transmission lines", *Environmental Engineering and Management Journal*, Vol.13(3), pp. 627-633, <https://doi.org/10.30638/eemj.2014.066>, (2014)
- [14] D. Dib and M. Mordjaoui, "Study of the influence high-voltage power lines on environment and human health (Case study: The electromagnetic pollution in Tebessa City, Algeria)", *Journal of Electrical and Electronic Engineering*, Vol. 2(1), pp. 1-8, <https://doi.org/10.11648/jjee.20140201.11>, (2014)
- [15] S. Boumous, N.Guettaf, A.Hamel, I. Lariche, and H. Nouri, "Effect on human body of the magnetic field induced by the high voltage transmission line", *European Journal of Electrical Engineering*, Vol. 23(2), pp.149-155, <https://doi.org/10.18280/ejee.230209>, (2022)
- [16] J. G. Gurney, S. Davis, S. M. Schwartz, B. A. Mueller, W. T. Kaune, and R. G. Stevens, "Childhood cancer occurrence in relation to power line configurations: A study of potential selection", *Epidemiology*, Vol. 6 (1), pp. 31-35, <https://doi.org/10.1097/00001648-199501000-00007>, (1995)
- [17] J. Radulović and V. Ranković, "Feedforward neural network and adaptive network-based fuzzy inference system in study of power lines", *Expert Systems with Applications*, Vol. 37(1), pp. 165-170, <https://doi.org/10.1016/j.eswa.2009.05.008>, (2010)
- [18] J. Radulović and V. Ranković, "Application of RBF neural network and ANFIS for electromagnetic field prediction around the power lines", *Proceedings of the ninth International Conference on Telecommunications in Modern Satellite, Cable and broadcasting Services "TELSIKS 2009"*, Niš (Serbia), pp. 457-460, <https://doi.org/10.1109/TELSIKS.2009.5339473>, (2009)
- [19] E. Turajlić, A. Alihodžić, and A. Mujezinović, "Artificial neural network models for estimation of electric field intensity and magnetic flux density in the proximity of overhead transmission line", *Radiation Protection Dosimetry*, Vol. 199(2), pp. 107-115, <https://doi.org/10.1093/rpd/ncac229>, (2022)
- [20] M. Rančić, R. Jankoski, S. Silvestrov, and S. Aleksić, "Analysis of horizontal thin-wire conductor buried in lossy ground: New model for Sommerfeld type integral", *Springer Proceedings in Mathematics & Statistics "Engineering Mathematics I"*, Vol 178, pp. 33-49, https://doi.org/10.1007/978-3-319-42082-0_3, (2016)
- [21] G. A. Skianis, "A class of Fourier integrals based on the electric potential of an elongated dipole", *SpringerPlus*, Vol. 3(1), p. 729, <https://doi.org/10.1186/2193-1801-3-729>, (2014)
- [22] J.R. Wait, "EM fields of a phased line current over a conducting half-space", *IEEE Transactions on Electromagnetic Compatibility*, Vol. 38(4), pp. 608–611, <https://doi.org/10.1109/15.544318>, (1996)
- [23] O. M. Abo-Seida, "Estimation of the electromagnetic field created at the earth's surface by an overhead line current", *Applied Mathematics and Computation*, Vol. 149(2), pp. 559–565, [https://doi.org/10.1016/S0096-3003\(03\)00161-9](https://doi.org/10.1016/S0096-3003(03)00161-9), (2004)
- [24] P. L. Tokarsky, "Dipole field over a lossy half-space: An approximate analysis", *Telecommunications and Radio Engineering*, Vol. 55(5), p. 6, <https://doi.org/10.1615/TelecomRadEng.v55.i5.40>, (2001)
- [25] S. Sautbekov, M. Sautbekova, K. Baisalova, and M. Pshikov, "Calculation of Sommerfeld integrals in dipole radiation problems", *Mathematics*, Vol. 12(2), p. 298, <https://doi.org/10.3390/math12020298>, (2024)

- [26] K. A. Michalski and H.-I. Lin, "On the Sommerfeld half-space problem: appraisal of approximate solutions with extensions to plasmonics", *Journal of Electromagnetic Waves and Applications*, Vol. 32(4), pp. 483–503, <https://doi.org/10.1080/09205071.2017.1395368>, (2018)
- [27] S. Bourgiotis, P. Frangos, S. Sautbekov, and M. Pshikov, "The evaluation of an asymptotic solution to the Sommerfeld radiation problem using an efficient method for the calculation of Sommerfeld integrals in the spectral domain", *Electronics*, Vol. 10(11), p. 1339, <https://doi.org/10.3390/electronics10111339>, (2021)
- [28] M. Rančić and S. Aleksić, "Horizontal dipole antenna very close to lossy half-space surface", *Przegląd Elektrotechniczny (Electrical Review)*, Vol. 88, pp. 82–85, (2012)
- [29] M. P. Rančić and P. D. Rančić, "Vertical linear antennas in the presence of a lossy half-space: An improved approximate model", *AEU - International Journal of Electronics and Communications*, Vol. 60(5), pp. 376–386, <https://doi.org/10.1016/j.aeue.2005.04.003>, (2006)
- [30] D. Poljak, B. Jajac, and R. Šimundić, "Current induced along horizontal wire above an imperfectly conducting half-space", *Engineering Analysis with Boundary Elements*, Vol. 23(10), pp. 835–840, [https://doi.org/10.1016/S0955-7997\(99\)00019-3](https://doi.org/10.1016/S0955-7997(99)00019-3), 1999
- [31] R. M. Shubair and Y. L. Chow, "A simple and accurate complex image interpretation of vertical antennas present in contiguous dielectric half-spaces", *IEEE Transactions on Antennas and Propagation*, Vol. 41(6), pp. 806–812, <https://doi.org/10.1109/8.250457>, (1993)
- [32] B. A. Arand, M. Hakkak, K. Forooghi, and J. R. Mohassel, "Analysis of vertical wire antenna above lossy ground using discrete complex image method", *AEU - International Journal of Electronics and Communications*, Vol. 57(5), pp. 333–337, <https://doi.org/10.1078/1434-8411-54100180>, (2003)
- [33] B. A. Arand and M. Hakkak, "Horizontal wire antenna above lossy half-space", *Proceedings of the 2003 IEEE International Symposium on Antennas and Propagation: URSI North American Radio Science Meeting, Columbus (USA)*, Vol. 4, pp. 970–973, <https://doi.org/10.1109/APS.2003.1220434>, (2003)
- [34] H. F. Arnoldus, "Numerical evaluation of Sommerfeld-type integrals for reflection and transmission of dipole radiation", *Computer Physics Communications*, Vol. 257, p. 107510, <https://doi.org/10.1016/j.cpc.2020.107510>, (2020)
- [35] A. Khalatpour, R. Sarraf Shirazi, and G. Moradi, "Analysis of vertical wire antennas above lossy half-space using matrix pencil method", *AEU - International Journal of Electronics and Communications*, Vol. 64(8), pp. 784–789, <https://doi.org/10.1016/j.aeue.2009.05.006>, (2010)
- [36] M. P. Rančić and P. D. Rančić, "Field pattern of the vertical dipole antenna above a lossy half-space," *Serbian Journal of Electrical Engineering*, Vol. 2(2), pp. 125–136, <https://doi.org/10.2298/SJEE0502125R>, (2005)
- [37] D. Veličković and J. Radulović, "Line conductor over semi-conducting half space", *Proceedings of the Fourth International Conference of Applied Electrostatics "PES '96"*, Niš, 1996, pp. 53–58, (1996)
- [38] J. Radulović, "Jedan novi pristup za proračun elektromagnetnog polja lineičnog provodnika iznad poluprovodnog poluprostora", *PhD Thesis, University of Kragujevac (Serbia)*, (2001)
- [39] M. Štafl, "Electrodynamics of electrical machines", *Academia, Prague (Czechoslovakia)*, (1967)
- [40] D. Rabah, C. Abdelghani, and H. Abdelchafik, "Efficiency of some optimisation approaches with the charge simulation method for calculating the electric field under extra high voltage power lines", *IET Generation, Transmission & Distribution*, Vol. 11(17), pp. 4167–4174, <https://doi.org/10.1049/iet-gtd.2016.1297>, (2017)
- [41] H. Das, "Implementation of basic charge configurations to charge simulation method for electric field calculations", *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, Vol. 3(5), pp. 9607–9611, (2014)
- [42] M. Dhamodaran and R. Dhanasekaran, "A comparative study of computational electromagnetics", *Proceedings of ICMTSET 2013 & IRCEBM 2013, Dubai (UAE)*, pp. 128–132, (2013)
- [43] G. B. Arfken, H. J. Weber, F. E. Harris, "Mathematical methods for physicists - A comprehensive guide", *Academic Press, Cambridge (USA)*, <https://doi.org/10.1016/C2009-0-30629-7>, (2012)

29. IKT konferencija



Z B O R N I K R A D O V A

ISBN 978-86-85525-29-2

jul 2023.

Zbornik radova 29. IKT konferencije

“YU INFO 2023”

Urednici: Prof. dr Miodrag Ivković, Doc. dr Dražen Drašković

Tehnička priprema: Doc. dr Dražen Drašković, dr Nenad Korolija
(Elektrotehnički fakultet Univerziteta u Beogradu)

Izdavač: Informaciono društvo Srbije

Datum izdanja: 7. jul 2023.

Datum konferencije: 12-15. mart 2023. godine

Sajt konferencije: <http://www.yuinfo.org>

CIP – Каталогизација у публикацији
Народна библиотека Србије, Београд

004 Рачунарство. Рачунарска техника.

004.4 Рачунарски софтвер

004.8 Вештачка интелигенција

005 Менаџмент

ISBN 978-86-85525-29-2

KORISNIČKI INTERFEJS NOVE GENERACIJE ZA ZAŠTITU OSETLJIVIH GRUPA KORISNIKA NEXT GENERATION USER INTERFACE FOR THE PROTECTION OF VULNERABLE GROUPS OF USERS

Milan Čabarkapa¹, Mina Vasković Jovanović¹
Marijana Gavrilović Božović¹, Jasna Radulović¹
Fakultet inženjerskih nauka, Univerzitet u Kragujevcu¹

Sadržaj – Najnovija istraživanja pokazuju da veštačka inteligencija ima veliki potencijal u detekciji različitih vrsta onlajn pretnji. U isto vreme, rešenja koja su trenutno implementirana zavise od konkretne aplikacije i ne mogu raditi na nivou operativnog sistema. Drugim rečima, rešenja koja su implementirana na nivou korisničkog interfejsa, tj. interakcije čovek-računar (eng. Human-computer interaction) još uvek nisu ugledala svetlost dana u realnom svetu i pomaci u nauci u ovom pravcu mogu značajno doprineti zaštiti osetljivih grupa korisnika na internetu. Imajući to u vidu, autori predlažu unapređenje trenutnih rešenja primenjujući metodološke principe iz oblasti interakcije čovek-računar i spuštanje velikog dela implementacije na nivo operativnog sistema. Ovakav pristup će dovesti do potpunog agnosticizma u smislu zavisnosti od aplikativnog nivoa trenutnih rešenja na bazi veštačke inteligencije i mašinskog učenja.

Na osnovu rezultata implementiranog projekta H2020 NGI_Trust C.A.S.P.E.R., u ovom radu će biti predložen novi smer istraživanja ka potpunom ispitivanju i implementaciji inicijalnih rezultata ovog EU projekta. Da bi se ovo postiglo, saradnja dve grupe eksperata je neophodna. Prvo su AI (Artificial Intelligence) istraživači koji se bave primenom AI na različitim tipovima podataka: tekst, govor i audio, kao i slika i video. Drugo su istraživači u oblasti naprednih softverskih arhitektura koji bi mogli da sprovedu kodiranje naprednih rešenja od nivoa operativnog sistema, preko dizajniranja sistema, pa sve do nivoa aplikacije. Dalje, određene karakteristike moraju biti ugrađene na nivou operativnog sistema, da bi se odgovorilo na neadekvatne i zlonamerne sadržaje u realnom vremenu. U radu će biti razmotreno i prilagođavanje predloženog rešenja uređajima poput telefona i tableta. Specifičnosti mobilnih uređaja se itekako moraju uzeti u obzir, kako u smislu metodologije zasnovane na veštačkoj inteligenciji, tako i same implementacije rešenja na nivou interakcije čovek-računar, tj. na nivou operativnog sistema uređaja. Ovim aspektima će se dati poseban fokus u ovom istraživanju i biće prezentovane razlike u odnosu na rezultate i arhitekture rešenja koja se predlažu za standardne PC računare i laptopove.

Abstract - The latest research shows that artificial intelligence has great potential in detecting different types of online threats. At the same time, the solutions that are currently implemented depend on the specific application and cannot work at the level of the operating system. In other words, solutions that are implemented at the user interface level (human-computer interaction) has not yet

seen the light of day in the real world. Advances in science in this direction can significantly contribute to the protection of sensitive groups of users on the Internet. Having this in mind, the authors suggest improving current solutions by applying methodological principles from the field of human-computer interaction and putting a large part of the implementation to the level of the operating system.

Based on the results of the implemented H2020 NGI_Trust C.A.S.P.E.R. project, this paper will propose a new direction of research towards a complete examination and implementation of the initial results of this EU project. In order to achieve this, the cooperation of two groups of experts is necessary. First group consists of AI (Artificial Intelligence) researchers who apply AI to different types of data: text, speech and audio, as well as image and video. Second group consists of researchers in the field of advanced software architectures who could implement the coding of advanced solutions from the operating system level, through system design, until the application level. Furthermore, certain features must be built in at the operating system level to respond to inappropriate and malicious content in real time. Adaptation of the proposed solution to devices such as phones and tablets will also be discussed in the paper. The specifics of mobile devices must be taken into account, both in terms of the methodology based on artificial intelligence, and the implementation of the solution at the level of human-computer interaction (operating system level). These aspects will be given special focus in our future research and differences will be presented in relation to the results and solution architectures proposed for standard PCs and laptops.

1. UVOD

Trenutna tehnološka rešenja za zaštitu dece na internetu mogu se opisati kroz sledećih nekoliko grupa rešenja:

- Softver za roditeljsku kontrolu (eng. *Parental Control Software*): Ovaj softver omogućava roditeljima da prate i kontrolišu onlajn aktivnost svoje dece, uključujući pristup određenim veb lokacijama, aplikacijama i onlajn uslugama. Softver za roditeljsku kontrolu takođe može ograničiti vreme korišćenja uređaja i blokirati pristup neodgovarajućem sadržaju [1]-[3].
- Sigurno pretraživanje (eng. *Safe Search*): Sigurno pretraživanje je funkcija dostupna na većini pretraživača koja omogućava korisnicima da

filtriraju eksplicitan ili sadržaj namenjen odraslima iz svojih rezultata pretrage [4]-[6].

- Praćenje društvenih medija (eng. *Social Media Monitoring*): Neki društveni mediji nude funkcije koje omogućavaju roditeljima da prate aktivnosti svoje dece na društvenim medijima, uključujući njihove objave, poruke i prijatelje [7]-[9].
- Filtriranje sadržaja (eng. *Content Filtering*): Alati za filtriranje sadržaja blokiraju pristup veb lokacijama ili aplikacijama sa neodgovarajućim sadržajem, kao što su pornografske ili kockarske veb stranice [10]-[12].
- Obrazovni alati (eng. *Educational Tools*): Obrazovni alati se mogu koristiti za podučavanje dece o bezbednosti, privatnosti i sigurnosti na internetu. Ovi alati mogu biti u obliku igara, video zapisa ili interaktivnih resursa [13]-[15].
- Otkrivanje cyberbullying-a (eng. *Cyberbullying Detection*): Neki programi i usluge mogu otkriti slučajeve cyberbullying-a analizirajući onlajn aktivnost i identifikujući obrasce uznemiravanja ili agresije [16]-[18].
- Roditeljske kontrole na uređajima (eng. *Parental Controls on Devices*): Mnogi uređaji, uključujući pametne telefone, tablete i igraće konzole, nude funkcije za roditeljsku kontrolu koje omogućavaju roditeljima da prate i kontrolišu onlajn aktivnost svoje dece na uređaju [19]-[21].

Internet i računarski sistemi imaju i druge ranjive grupe korisnika poput starih ljudi, kao i što pojedine zemlje i regioni imaju potrebu za specifičnim vidovima zaštite kao odgovor na napade koji su kontekstualno mogući isključivo u tim zemljama i regionima.

Trenutna rešenja imaju velika ograničenja i fokusiraju se na jedan tip napada i aplikacije, a gledano u odnosu na današnje izazove to je potpuno nedovoljno. Iz svih ovih razloga je proizašla i motivacija autora u radu [22]. Naša ideja je nastavak u ovom pravcu kroz implementaciju rešenja i inicijalizacija novog pravca budućeg istraživanja koji će moći da da odgovor na veoma heterogene potrebe različitih grupa korisnika u smislu vrste napada i vrste uređaja gde se rešenje implementira. U ovom radu je predložena jedna *real-time* softverska arhitektura sposobna da radi cenzuru neadekvatnog sadržaja na delu ekrana gde se sadržaj nalazi, kao i uvođenje jedne nove implementacione paradigme sposobne da reaguje i na drugim uređajima.

Nakon uvida, drugo poglavlje se bavi HCI metodologijom na nivou operativnog sistema. Treće poglavlje predlaže softversku arhitekturu koja bi bila adekvatna za implementaciju pomenute paradigme na različitim hardverskim uređajima, uz diskusije sa stanovišta različitih aspekata i problema koji se mogu javiti u implementaciji. Finalno četvrto poglavlje je zaključak.

2. HCI METODOLOGIJA - NIVO OPERATIVNOG SISTEMA

Rad u okviru evropskih projekata NGI Trust C.A.S.P.E.R and NGI Trust C.A.S.P.E.R 2.0 doneo je od inicijalne verifikacije koncepta publikovane u radu [22]. Koncept se sastoji u spuštaju analize na nivo operativnog sistema i praćenje neadekvatnog sadržaja i reakciju na njega na nivou korisničkog interfejsa. Ovakva arhitektura je potpuno aplikativno nezavisna. Rad [22] predstavlja prvi rezultat i uvođenje aplikativnog agnosticizma u smislu rešavanja problema zaštite dece na internetu od različitih vrsta napada kroz tekstualne, audio i video sadržaje. Rešenje koje je testirano na laboratorijskom nivou, predlaže odvojeno tretiranje vizualnog, tekstualnog i audio sadržaja. Ideja ovog rada je i da da uvid u najznačajnije algoritme u smislu tretmana ovih vrsta sadržaja. Njih dajemo kroz zasebna podpoglavlja u okviru ovog poglavlja.

2.1. Analiza slika

Gruba podela metoda za obradu slika sa pornografskim sadržajem je na: metode zasnovane na karakteristikama (*feature-based*), metode zasnovane na regijama (*region-based*) i metode zasnovane na delovima tela (*body part-based*).

Metode zasnovane na karakteristikama izdvajaju obeležja sa slika korišćenjem vizuelnog govora, ili korišćenjem konvolucionih neuralnih mreža (*Convolutional Neural Networks - CNN*). Prvi pristup je jednostavniji i manje kompleksan od CNN, ali je osetljiv na promene poza, promene scene, ili skaliranje slike.

Metode zasnovane na regijama zasnivaju se na detekciji regije od interesa (*Regions of Interest - ROI*) najčešće pomoću detekcije piksela u boji kože. Na taj način se izbegava osetljivost na promenu pozadine, kao što je u prethodnom metodu slučaj, ali je nedostatak to što se ništa osim regiona u boji kože ne uzima u razmatranje.

I poslednji tip su metode zasnovane na delovima tela. Kod ovih metoda prvo se izdvajaju unapred definisana obeležja koja opisuju pornografski sadržaj, kao što su grudi, pupak, zadnjica, a nakon toga se kao skup vektora prosleđuju na dalju klasifikaciju. Problem sa ovim metodama je dvosmislenost i veliki broj lažno pozitivnih rezultata, usled velikih varijacija u prikazima obeležja u trening setovima. Brze CNN za ovu vrstu detekcije postoje, ali su ograničene na upotrebu samo kod ove grupe metoda.

Navedene metode se mogu koristiti i kod detekcije nasilja nad decom, kao osetljivom grupom korisnika, tako što bi se prvo detektovao uopšteno pornografski sadržaj, a nakon toga izvršiti procena starosti korisnika.

Detekcija maltretiranja na slikama moguć je obradom sadržaja komentara vezanih sa neku sliku, a ne samo obradom same slike od interesa [23]. Ispituje se i istorija interakcije korisnika koji su postavljali komentare, kao i broj velikih slova u komentarima. Na taj način se direktno otkriva slika nasilja, ali se ne uklanja slika pre nego što je šteta načinjena oštećenoj strani.

Slike maltretiranja često prikazuju ponižavajuće scene u kojima je lice mete ubačeno u sliku preko lica žrtve sa

originalne slike. Različite metode za detekciju krivotvorenih fotografija mogu se naći u [24], posebno za detekciju zamene lica na slikama, kao i detekciju pornografskog sadržaja na slikama i u snimcima. Najskoriji rad u kome se obrađuje prepoznavanje pornografskog sadržaja na slikama [25] navodi tačnost od 97,5%, korišćenjem modernog *YOLO* pristupa (*You Only Look Once*) [26]. Smanjuje se broj potrebnih podprozora za obradu, kao i broj test primera da bi se dobila robusna ocena sadržaja i izvršila pouzdana klasifikacija.

Iz video snimaka se mogu uzimati ključne slike (*frames*) čijom obradom bi se vršila detekcija pornografskog sadržaja usrednjavanjem, većinskim “izglasavanjem”, ili korišćenjem rekurentnih neuralnih mreža (*Recurrent Neural Networks - RNN*). Iako RNN povećavaju tačnost za 1-2%, povećavaju i kompleksnost. Stoga se obrada svake slike iz video zapisa može u teoriji sprovesti, ali je računarski neprihvatljiva.

Da bi moglo da se radi sa ograničenim računarskim resursima potrebno je da se ispituju kompleksnosti dostupnih metoda za detekciju pornografskih sadržaja. U [25] je prikazan ponderisani model učenja sa više instanci koji je u stanju da obradi 5 slika u sekundi (Frames per Second - FPS) korišćenjem procesora Intel Xeon E5-2630, dok se uz dodatak grafičkog procesora GeForce GTX Titan X može postići detekcija u realnom vremenu od 55 FPS. Kako je potrebno obezbediti da roditeljska kontrola zaštiti decu od slanja, kao i od prijema, neorikladnog sadržaja, neophodno je implementirati rešenje na strani korisnika, na neki od uređaja (tablet, mobilni telefon, računar), ili na korisničku mrežnu opremu.

2.2. Detekcija neprikladnog audio sadržaja

Kada je u pitanju audio sadržaj, potrebno je izvršiti detekciju i blokiranje neprikladnih audio zapisa, kao što su na primer seksualno vrištanje i stenjanje. U istraživanju koje su sprovedli autori rada [27] više stotina poželjnih i nepoželjnih audio isečaka je obrađeno, s ciljem da se izvrši klasifikacija i blokiranje onih sadržaja koji su neprikladni. Korišćenjem i analizom spektograma dobijenih Radonovom transformacijom došlo se do zaključka da se neprikladni pornografski audio sadržaji mogu lako detektovati zato što se značajno razlikuju od prikladnih audio isečaka korišćenih u pornografiji, kao što su glasovi, ili muzika. Tačnost metoda opisanog u [27] je 91,25%.

Neke od najpoznatijih platformi za obradu audio zapisa su razvijene kao komercijalni servisi, kao što je na primer Google Cloud Speech API (eng. *Application Program Interface*), koji prepoznaje 120 različitih jezika i jezičkih varijanti. Neke akademske institucije razvijaju svoja rešenja, ali najčešće ne nude API pristup, iako je moguće razviti okruženje koje bi omogućilo korišćenje biblioteka dostupnih kroz *web API*.

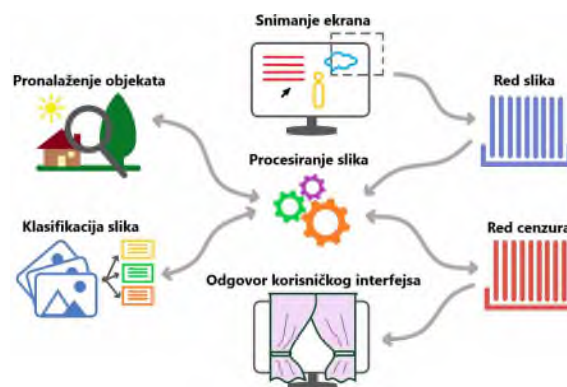
2.3. Tretiranje tekstualnog sadržaja

Da bi se detektovao neadekvatan tekstualni sadržaj, prvo se radi OCR (eng. *optical character recognition*). Sistem za otkrivanje teksta i optičko prepoznavanje karaktera (OCR) zasniva se jako moćnom *Tesseract-OCR Engine*-u koji ima podršku za preko 100 jezika i može se dodatno

obučiti i fino podesiti za dodatne jezike [28]. Sledeći korak je da se primeni detekcija zasnovana na veštačkoj inteligenciji. Predložene su različite metode za otkrivanje sajber napada u tekstualnim podacima (poruke, komentari, članci, blogovi, postovi, tvitovi). Većina postojećih studija koristi konvencionalno mašinsko učenje ili modele dubokog učenja za otkrivanje incidenata sajber pretnji i obučeni su za određene jezike. U okviru rada [22] predložen je metod za detekciju višezjezičnog sajber maltretiranja u tekstu pomoću KSLM-R fino podešenih modela. Smatramo da su rezultati postignuti u ovom referenciranom radu dobra polazna osnova, ali da performanse nisu zadovoljavajuće (najbrži odgovor nakon nekoliko sekundi), da je reakcija spora i da će od vida implementacije u realan proizvod zavistiti da li će rešenje dobiti neku veliku upotrebnost vrednost.

3. SOFTVERSKA ARHITEKTURA REŠENJA

Na slici 1 je prikazana predložena implementaciona arhitektura softvera koja predstavlja glavni doprinos ovog rada.



Slika 1. Predložena softverska arhitektura adaptabilna i za mobilne uređaje

Prvo, jedan modul treba da se pokreće kao nit rešenja za snimanje ekrana. Drugi modul treba implementirati kao nit koja obrađuje sliku ekran i šalje ga relevantnom klasifikatoru za obradu slike i/ili teksta. Treće, predlaže se modul kao nit za reakciju iliti odgovor korisničkog interfejsa koji treba da se koristi za senčenje ili pokrivanje celog ekrana ili dela ekrana.

Dodatno, za implementaciju, potrebno je da postoje dva reda za čekanje (eng. *Queue*) koja se koriste za sinhronizaciju na HCI nivou, tj. na nivou korisničkog interfejsa. Prvi red se koristi za prikupljanje snimaka ekrana, dok je drugi prikupljanje pokrivača za neprikladan sadržaj koji će moći da prekrije deo ekrana na kome se nalazi neadekvatan sadržaj.

Dakle, u našem predloženom rešenju postoje tri glavna modula koji mogu, ali i ne moraju da rade u tri niti. Sve niti su radne instance (eng. *Workers*) koje stalno rade. Svaka instanca se može podeliti na više od jedne instance niti. Ako dođe do kašnjenja jedne radne instance, korišćenjem više niti po instanci rešenje se može izbalansirati i kašnjenje će biti nadoknađeno. Ovo potencijalno može biti

veoma važno dostignuće koje treba eksperimentalno potvrditi.

Takođe, u predloženoj arhitekturi postoje dva reda za čekanje koji se koriste za bezbednu razmenu podataka. Prvi red prikuplja snimke ekrana za dalju obradu dok drugi red se koristi za prikupljanje reakcionih pokrivača. Ako postoji slučaj da hvatač ekrana i reakciona nit rade brže od obrade slike, potrebno je dodati još jednu ili više niti za zadatke obrade slike. Ovo je zavisno od hardvera računara, tableta ili mobilnog telefona, ali autori smatraju da rešenje implementirano na ovaj način može biti inherentno i prilično jednostavno prilagodivo u smislu ove zavisnosti.

Kao što smo videli, snimak ekrana se stavlja u red. Pre stavljanja u red, postoji provera da li postoji značajna razlika između trenutnog i prethodnog snimka ekrana. Ovo se mora uraditi da bi se sprečilo čuvanje u redu nekoliko skoro istih snimaka ekrana i pokretanje nepotrebne obrade slike koja je jako zahtevna sa stanovišta računarskih resursa. Razlika između dva snimka ekrana je podesiva. Implementacija ovakve funkcije bi dala mogućnost da se izostavi suvišno snimanje ekrana, na primer, malog pomeranja kursora miša. Optimizacija ovog dela bi mogla biti veoma intrigantna za R&D zajednicu. Prema našem istraživanju i mišljenju, unapređenje ove funkcije je moguće i moglo bi dodatno optimizovati HCI metodologiju.

Snimak ekrana se mora čuvati u RAM memoriji i ne sme se ići na interakciju sa file sistemom, jer će performanse biti znatno niže. Glavni problem niti snimanja ekrana je hvatanje dela ekrana reakcije Optimizacija ovoga bi bi bila moguća na način na koji bismo mogli da koristimo novu Python VX biblioteku ili naprednim izborom načina na koji senčimo ekran u reakcijskoj niti. Rešavanje ovog problema bi značajno doprinelo našem cilju da imamo potpuno preciznu reakciju korisničkog interfejsa u realnom vremenu na neprikladan sadržaj.

Procesorski najzahtevniji zadatak je obrada slike. Nit za obradu slike analizira snimak ekrana tako što prvo primenjuje detekciju objekata, a zatim klasifikaciju objekata. Za početak, analiza treba da se vrši na celom snimku ekrana iako se uočava razlika. Optimizacija niti za obradu slike je potpuna obrada razlike dok deo ekrana za reakciju korisničkog interfejsa ostaje takav kakav jeste. Ovo bi se moglo uraditi ako postoji snimak ekrana bez crno-belo prekrivenog ekrana iz razloga reakcije interfejsa na neadekvatan sadržaj..

Preprocesiranje slike se takođe mora uraditi (promena veličine i formata) da bi se pripremila za detekciju objekata i klasifikaciju objekata. Treba naglasiti da se dva različita AI modela moraju koristiti: jedan za detekciju objekata, a drugi za klasifikaciju objekata. Na ovaj način moguće je primeniti neki od algoritama klasifikacije potencijalno veoma prilagodiv mobilnim uređajima u kontekstu od interesa poput *Mobile Net V3*.

Reakcioni modul je namenjen pokrivanju neadekvatnih sadržaja. Ova reakcija može da se sprovodi crtanjem crnih ili belih pravougaonika ispred ovakvog sadržaja na delu

ekrana. Implementirajući na ovaj način, rešenje je potpuno u HCI paradigmi i nezavisno je od aplikacija koje su istovremeno aktivne na ekranu. Da bi znao koji deo ekrana treba da bude pokriven, rešenje koristi red za čekanje na slici 1 nazvan red cenzura. Predlaže se metodologija direktnog pamćenja kao metodologija koja treba da se koristi za crtanje pravougaonika cenzure. Ova metodologija potencijalno ima najveću brzinu reakcije.

Pošto Windows kao operativni sistem sam odlučuje koji deo ekrana da osveži (ponovo iscrta), nije uvek moguće ukloniti pravougaonik za osudu pre snimanja novog snimka ekrana. Ono što je moguće je naterati prozore da osveže ceo ekran. Ovo je deo optimizacije koji bi takođe bio veliki pomak u odnosu na postojeće stanje. Problematično je zato što su biblioteke za pravljenje snimaka ekrana i crtanje ekrana najčešće nije direktno povezana sa Windows-om i stoga ne možemo da koristimo svu funkcionalnost koju pruža Windows kao OS. Prema našem istraživanju, to će biti moguće uraditi preko druge Python biblioteke koja komunicira direktno sa Win32 API modulom [29].

4. ZAKLJUČAK

Kao što se moglo videti na osnovu dosadašnjih istraživanja, veštačka inteligencija ima veliki potencijal u detekciji neadekvatnog sadržaja na internetu. Poseban problem je zaštita osetljivih grupa korisnika. Trenutna rešenja su na nivou aplikacije ili tretiraju samo jednu vrstu napada/pretnji. Na nivou istraživanja, napravljen je pomak kroz NGI Trust Horizon 2020 C.A.S.P.E.R projekat, koji predlaže HCI metodologiju koja bi dala detekciju/reakciju na nivou korisničkog interfejsa. Istraživanje je dalo obećavajuće rezultate, ali implementirano samo u delovima. U ovom radu je predložena softverska arhitektura koja bi mogla da se koristi za implemetaciju realnog proizvoda. Ona koristi HCI metodologiju, ali i razmatra razne aspekte koji mogu da budu i prednosti i izazovi u dolasku do finalnog cilja. Zbog svoje robusnosti, modularnosti i hardverskoj prilagodivosti, predloženo rešenje se može koristiti ne samo na desktop računarima, nego i na tabletima i mobilnim telefonima. i implementaciji inicijalnih rezultata ovog EU projekta. Da bi se postigao cilj dolaska do finalnog rešenja koje će ugledati svetlost dana u praksi, saradnja dve grupe eksperata mora da bude veoma intenzivna i jaka. Prvo su AI istraživači koji se bave primenom AI na različitim tipovima podataka, a drugo su istraživači u oblasti naprednih softverskih arhitektura koji bi mogli da sprovedu kodiranje u ovom radu predloženog softverskog arhitektonskog rešenja od nivoa operativnog sistema, preko dizajniranja sistema, pa sve do nivoa aplikacije.

LITERATURA

- [1] X. Bao, M. Chen, J. Yu and X. Pan, Online child protection: A survey, *IEEE Communications Magazine*, 54(6), pp 46-53, 2016, doi: 10.1109/MCOM.2016.7470924
- [2] Kaspersky Safe Kids:
<https://www.kaspersky.com/safe-kids>

- [3] Norton Family Premier:
<https://us.norton.com/norton-family-premier>
- [4] P. P. Shah and A. Joshi, SafeSearch in online search engines: An overview, *Digital Investigation*, 23, pp 83-92, 2017, doi: 10.1016/j.diin.2017.07.008
- [5] Google SafeSearch:
<https://www.google.com/preferences>
- [6] Bing SafeSearch:
<https://www.bing.com/account/general>
- [7] K. E. Mansfield, M. Cikara and R. K. Thomas, Social media and parental control: A comparison of parental Facebook monitoring strategies and their effects on children's Facebook disclosure, *Journal of Family Issues*, 42(2), pp 198-219, 2021, doi: 10.1177/0192513X20921705
- [8] Facebook Parent Dashboard:
<https://www.facebook.com/help/315699785688681>
- [9] Instagram Parent's Guide:
https://about.instagram.com/en_US/blog/announcements/parents-guide-to-instagram
- [10] A. Ustinova and T. Strufe, An analysis of web content filtering systems, *Proceedings of the 10th ACM Symposium on Information, Computer and Communications Security*, pp 703-715, 2015, doi: 10.1145/2714576.2714599
- [11] OpenDNS FamilyShield:
<https://www.opendns.com/setupguide/#familyshield>
- [12] Net Nanny: <https://www.netnanny.com/>
- [13] S. Park, J. Kim and J. Hong, Evaluating the effectiveness of internet safety education: A meta-analysis of school-based programs, *Computers & Education*, 2020, doi: 10.1016/j.compedu.2019.103752
- [14] Common Sense Education:
<https://www.commonsense.org/education/>
- [15] Be Internet Awesome:
https://beinternetawesome.withgoogle.com/en_us
- [16] J. A. Pater, T. Hooley and R. Bond, Empowering bystanders of cyberbullying: An exploratory study into the efficacy of a cyberbullying bystander intervention program, *Journal of School Violence*, 18(1), pp 115-126, 2019, doi: 10.1080/15388220.2018.1468337
- [17] Bark: <https://www.bark.us/>
- [18] NetSanity: <https://netsanity.net/>
- [19] H. T. Tsai, Y. C. Cheng and Y. H. Yang, Empowering or limiting parental control? A longitudinal study of parental control and smartphone addiction among Chinese primary school students, *Journal of Educational Computing Research*, 57(5), pp 1315-1336, 2019, doi: 10.1177/0735633118805627
- [20] Apple Screen Time:
<https://support.apple.com/en-us/HT208982>
- [21] Google Family Link:
<https://families.google.com/familylink/>
- [22] A. Jevremovic, M. Veinovic, M. Cabarkapa, M. Krstic, et al., Keeping Children Safe Online With Limited Resources: Analyzing What is Seen and Heard, *IEEE Access*, vol. 9, pp 132723-132732, 2021, doi: 10.1109/ACCESS.2021.3114389.
- [23] M. Dadvar, D. Trieschnigg, R. Ordelman and F. D. Jong, Improving cyberbullying detection with user context, *Advances in Information Retrieval*, Springer, pp 693-696, 2013.
- [24] A. Subin, Awesome-Deepfake/Porn Detection Using Deep Learning, 2019, [online] Available: <https://github.com/subinium/awesome-deepfake-porn-detection>
- [25] J. Xin, W. Yuhui and T. Xiaoyang, Pornographic image recognition via weighted multiple instance learning, *arXiv:1902.03771*, 2019, [online] Available: <http://arxiv.org/abs/1902.03771>
- [26] J. Redmon, S. Divvala, R. Girshick and A. Farhadi, You only look once: Unified real-time object detection, *Proc. IEEE Conf. Comput. Vis. Pattern Recognit. (CVPR)*, pp 779-788, Jun. 2016.
- [27] M. Jong Kim and H. Kim, Audio-based objectionable content detection using discriminative transforms of time-frequency dynamics, *IEEE Trans. Multimedia*, vol. 14, no. 5, pp 1390-1400, Oct. 2012.
- [28] Tesseract-OCR GitHub repository:
<https://github.com/tesseract-ocr/tesseract>
- [29] <https://pipi.org/project/pivin32/>



DEEP TECH 2M

BOOK OF ABSTRACTS

DEEP TECH OPEN SCIENCE DAY 2024

1ST DEEP TECH OPEN SCIENCE DAY CONFERENCE
APRIL 5, 2024, KRAGUJEVAC, SERBIA



European Institute of
Innovation & Technology



Funded by the
European Union



1st Deep Tech Open Science Day Conference 2024

ISBN 978-86-6335-113-4

- Editors:** Fatima Živić, Faculty of Engineering, University of Kragujevac
Ana Kaplarević- Mališić, Faculty of Science, University of Kragujevac
Nenad Grujović, Faculty of Engineering, University of Kragujevac
Boban Stojanović, Faculty of Science, University of Kragujevac
- Publisher:** Faculty of Engineering, University of Kragujevac
Sestre Janjić 6, 34000 Kragujevac, Serbia
- For the Publisher:** Slobodan Savić
Faculty of Engineering, University of Kragujevac
- Technical editors:** Strahinja Milenković, Faculty of Engineering, University of Kragujevac
Milica Kostić, Faculty of Engineering, University of Kragujevac
- Printed by:** Faculty of Engineering, University of Kragujevac
Sestre Janjić 6, 34000 Kragujevac, Serbia
- Circulation:** 100 copies (electronic publication on CDs) and online

Copyright © 2024 by Faculty of Engineering, University of Kragujevac

The publication of this Book of Abstracts was funded through the EIT's HEI Initiative DEEPTech- 2M project, <http://deeptech2m.eu/> "Deep Tech Materials and Manufacturing Talent Development for an Improved EU Economy and Climate", supported by EIT Digital and coordinated by EIT RawMaterials, funded by the European Union.

Real-time video analytics for detecting illegally parked vehicles

Marijana Gavrilović Božović, Ivan Krstić, Mina Vasković Jovanović*

Faculty of Engineering, University of Kragujevac, Serbia

email: mina.vaskovic.jovanovic@kg.ac.rs

Abstract

In this research, a system that helps improve traffic flow, enhance safety, and ensure fair enforcement of parking regulations by detecting illegally parked vehicles is proposed. The system is composed of fixed standardized cameras with AI video analytics. Cameras need to be strategically installed at fixed locations throughout the monitored area, such as street corners, parking lots, or key intersections, providing optimal coverage. The AI system performs real-time analysis of the video streams with the capability to identify a range of infractions, including vehicles parked in prohibited areas, obstructing traffic flow, or contravening parking rules and regulations. Once a violation is confirmed by the decision-making process, the system generates a report detailing the offense, including relevant information such as timestamp, location, and photographic evidence.

The fixed camera model provides a cost-effective and scalable solution for parking enforcement, enabling continuous monitoring of parking compliance in urban areas without the need for a mobile platform. Reports generated by the system can trigger various enforcement actions, from issuing automated citations to sending alerts to parking enforcement officers or notifying relevant authorities for further action. The authors believe that with the current AI-based video analytics & hardware technology level, a reaction time of three minutes can be achieved in urban conditions characteristic of a city as large as the City of Kragujevac.



DEEP TECH 2M

BOOK OF ABSTRACTS

DEEP TECH OPEN SCIENCE DAY 2024

1ST DEEP TECH OPEN SCIENCE DAY CONFERENCE
APRIL 5, 2024, KRAGUJEVAC, SERBIA



European Institute of
Innovation & Technology



Funded by the
European Union



1st Deep Tech Open Science Day Conference 2024

ISBN 978-86-6335-113-4

Editors:	Fatima Živić, Faculty of Engineering, University of Kragujevac
	Ana Kaplarević- Mališić, Faculty of Science, University of Kragujevac
	Nenad Grujović, Faculty of Engineering, University of Kragujevac
	Boban Stojanović, Faculty of Science, University of Kragujevac
Publisher:	Faculty of Engineering, University of Kragujevac
	Sestre Janjić 6, 34000 Kragujevac, Serbia
For the Publisher:	Slobodan Savić
	Faculty of Engineering, University of Kragujevac
Technical editors:	Strahinja Milenković, Faculty of Engineering, University of Kragujevac
	Milica Kostić, Faculty of Engineering, University of Kragujevac
Printed by:	Faculty of Engineering, University of Kragujevac
	Sestre Janjić 6, 34000 Kragujevac, Serbia
Circulation:	100 copies (electronic publication on CDs) and online

Copyright © 2024 by Faculty of Engineering, University of Kragujevac

The publication of this Book of Abstracts was funded through the EIT's HEI Initiative DEEPTech- 2M project, <http://deeptech2m.eu/> "Deep Tech Materials and Manufacturing Talent Development for an Improved EU Economy and Climate", supported by EIT Digital and coordinated by EIT RawMaterials, funded by the European Union.

Virtual Laboratory Exercises Which Utilize Audio Signals to Enhance Understanding of Electronics Fundamentals

Isidora Grujić, Marijana Gavrilović Božović*, Vladimir M. Milovanović

Faculty of Engineering, University of Kragujevac, Serbia

email: marijana.gavrilovic@kg.ac.rs

Abstract

Introductory analog electronics courses are traditionally considered among the most challenging in higher education curricula. Students usually encounter several key new concepts and paradigms, including incremental analysis of nonlinear electrical circuits and devices, as well as frequency domain analysis, time- and frequency-domain duality, filters, and signal filtering in general. Laboratory exercises serve as an indispensable tool to practically reinforce these concepts and diminish abstract barriers faced by first-time learners. However, they are often limited due to resource constraints. To address this challenge, a virtual laboratory exercise has been developed. This exercise demonstrates field-effect transistor amplifier quiescent point biasing, superimposed with a small audio signal and accompanying distortion. This implementation aims to bridge the gap between theory and practice, thereby enhancing students' insight into analog electronics.

Implemented virtual laboratory exercises showcase (i) a common-source field-effect transistor (FET) amplifier with purely resistive load, and (ii) an RC-based first-order low-pass filter. These exercises enable the injection of not only generic audio signals like sine or square waves, but also samples from different music genres at the circuit input. Sound reproduction is supported for both the input and output signals. Amplitude and frequency of an input, as well as the resistor, capacitor, supply voltage, and simple switch unified MOSFET model values, are manually adjusted with the idea of observing the influence of gain, distortion and filtering. This facilitates a smoother transition between theoretical concepts, which often remain vague, and the actual, usually time-restrictive, laboratory demonstrations, thus boosting students' understanding.