Dark Hanle resonance narrowing by blocking the central part of the Gaussian laser beam

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ABSTRACT

We present Hanle electromagnetically induced transparency (EIT) resonances obtained from the outer parts of the Gaussian laser beam. The signal from the outer parts only was obtained by placing circular opaque masks of different diameters in the center of the laser beam just in front of the detector. The Hanle EIT resonances obtained in that way are narrower and for high laser intensities even more contrasted. Suggested explanation for the line narrowing is based on lower power broadening in the wings of the Gaussian laser beam as well as on the traversing of the coherently prepared atoms through the beam. The resonance contrast to linewidth ratio, when the central part of the beam is blocked, is higher or equal to the ratio obtained when the whole laser beam is detected, for all laser intensities used in the experiment. Due to high ratio of contrast and linewidth, resonances obtained in proposed way could be useful in frequency metrology and magnetometry.

Keywords: Hanle EIT resonances, Gaussian laser beam, metrology

1. INTRODUCTION

Coherent effects in Doppler broadened alkali atom vapor have been intensively investigated over the past decade. Coherent population trapping (CPT) [1, 2], electromagnetically induced transparency (EIT) [3], and electromagnetically induced absorption (EIA) [4] have been observed and examined in pump-probe and in Hanle configuration [5, 6]. All these phenomena strongly depend on the intensity of the applied laser field. The dependence of CPT and EIT lineshapes on the laser intensity has been extensively studied [7-9].

Typical radial laser beam profile in experiments studying CPT and EIT is Gaussian. The influence of Gaussian laser beam profile on EIT lineshapes is studied in only few papers [10-12]. However, the focus was on the overall effect of the laser beam having Gaussian profile, not on the influence of particular laser beam segments. The intensities in the center and in the wings of such beam are very different. Nevertheless, the order of magnitude lower intensity in the wings can still contribute to the coherent effects [13]. The Hanle EIT line narrowing in the wings of the Gaussian laser beam was shown in [13] and explained by transit of coherently prepared atoms through the Gaussian laser beam and by the power broadening/narrowing.

There are several papers showing the narrowing of EIT lines such as: separated, in space and/or time, laser beams tuned to Raman resonance of the atomic transitions [14], narrowing of EIT in buffer gas cells [15, 16] and cells with antireflection coatings [17]. The goal of this work is to show the proof of the principal for narrowing the Hanle EIT resonances in vacuum Rb cell and to present a simple change in relatively standard experimental setup for obtaining such narrow resonances.

In this work we study EIT resonances originating from outer parts of the Gaussian laser beam, after the whole beam passes through the Rb vapor cell. Our investigation was performed on ^{87}Rb atoms at D1 line in the Hanle configuration. In the experiment, the detection of the signal from the outer parts of the Gaussian beam was accomplished by placing circular opaque masks of different diameters in front of the large area photodetector. Apart from the line narrowing in the outer parts of the Gaussian laser beam the contrast of the Hanle EIT resonances could be enhanced depending on the laser intensity. The contrast to linewidth ratio of the resonances obtained in proposed way is equal or higher than in the case of the whole beam detection. Narrower and more contrasted resonances are important for applications of the CPT and EIT effects in atomic frequency standards [18] and magnetometry [19].

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2. EXPERIMENT

The experimental setup is shown in Fig. 1. External cavity diode laser is frequency locked to F_g=2 → F_e=1 transition in ^{87}Rb, where F_g and F_e correspond to angular momentum of the ground and excited state hyperfine levels, respectively. The energy level diagram, given in the insert in Fig. 1, shows magnetic sublevels either coupled by the laser light, or populated due to spontaneous emission. Linearly polarized laser light allows for multiple Λ schemes and formation of dark states among ground Zeeman sublevels of F_g=2 level. The locking is performed by Doppler-free dichroic atomic vapor laser lock (DDAVLL) method using auxiliary vacuum Rb cell. The variable neutral density filter is used for the laser power adjustments. The laser beam, introduced into the single mode fiber with the collimator, provides the Gaussian beam at the exit of the fiber. After passing through the Glen-Thomson polarizer the laser beam becomes linearly polarized. The laser beam is then expanded to 3 mm in diameter. The dependence of the laser intensity on the radial distance r from the beam center is Gaussian

$$I(r) = I_0 \exp(-2r^2 / r_0{}^2) \tag{1}$$

where I_0 is the maximal intensity and r_0 is $1/e^2$ beam radius.

The Gaussian beam passes through 5 cm long vacuum Rb cell containing natural abundance of rubidium isotopes. The cell is placed in the solenoid used for scanning the axial magnetic field between ±300 μT. The cell and the solenoid are placed inside the triple layered μ-metal cylinder to eliminate Earth's and stray magnetic fields.

The opaque circular masks of different diameters are placed in front of the photodiode with large detection surface (area 80 mm^2). The sensitivity of the photodiode is 0.57 A/W at 780 nm and has variable transimpedance gain with nominal value of 1 MΩ (selectable between 1 kΩ and 10 MΩ). The aim of the mask is to allow only the outer part of the beam to reach the detector while the central part is blocked. The signal obtained from the photodiode while scanning the external magnetic field is recorded by the digital oscilloscope and transferred to the computer.

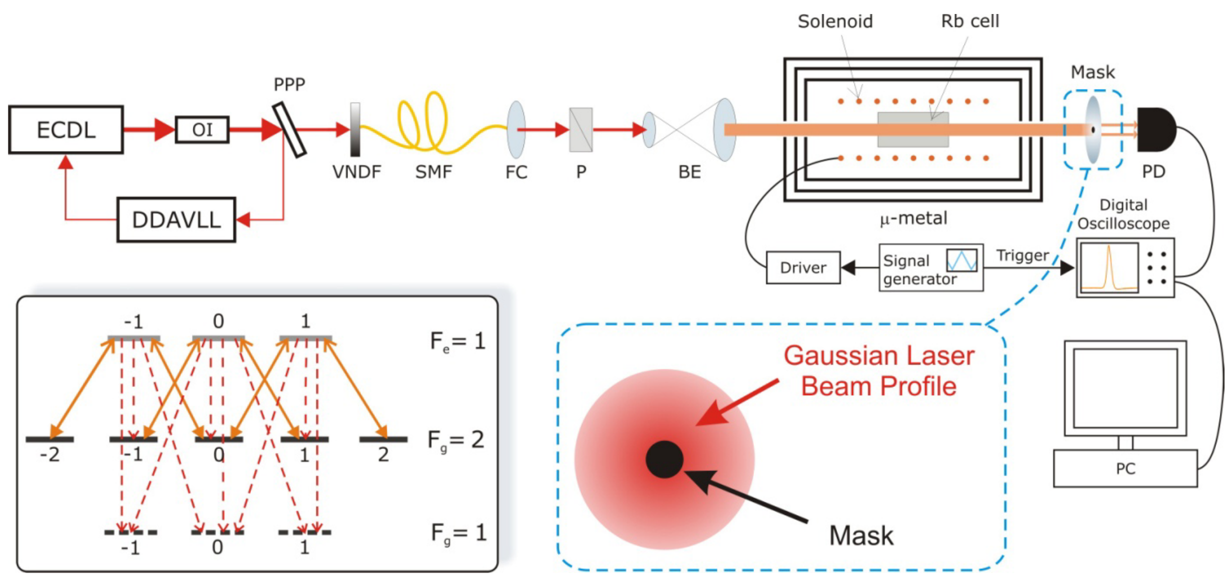

Figure 1. Experimental setup. The circular mask placed in front of the detector blocks the central part of the beam allowing only the outer part of the beam to reach the photodiode. ECDL – External cavity diode laser, OI – Optical insulator, DDAVLL – Doppler-free dichroic atomic vapor laser lock, PPP – Planparallel plate, VNDF – Variable neutral density filter, SMF – Single mode fiber, FC – Fiber collimator, P – Polarizer, BE – Beam expander, PD – Photodiode. Insert: Energy-level diagram for magnetic sublevels of the F_g=2 → F_e=1 transition where solid lines represent linearly polarized laser light coupling Zeeman sublevels and dotted lines correspond to the de-excitation from excited levels.

3. RESULTS AND DISCUSSIONS

We studied Hanle EIT resonances after blocking the central part of the Gaussian beam in front of the detector. Figure 2 presents the Hanle EIT curves obtained when the mask of 2.25 mm in diameter blocks the central part of the Gaussian beam (red curve). The resonance obtained without the mask is shown by the green curve. The laser intensity in both cases was 3 mW/cm^2. It is obvious that the line obtained using the mask is narrower and has greater amplitude i.e. contrast.

The explanation for this narrowing could be given by observing the development of the atomic ground state Zeeman coherence during passage of atoms through Gaussian laser beam. The lifetime of atomic coherence is longer than the atom transit time through the laser beam. Thus, the light in the wings of the Gaussian laser beam can also "probe" the induced atomic coherence and polarization of the atom coming from central parts of the laser beam. Such "probing" leads to the line narrowing in the wings of the beam due to atomic interference with the beam i.e. a kind of Ramsey-like effect [13]. Also, due to lower intensity in the wings of the Gaussian laser beam the power broadening is significantly reduced [13, 20]. It is therefore a reasonable assumption that outer parts of the Gaussian laser beam, after passing through the alkali vapor cell, should yield narrower EIT resonances.

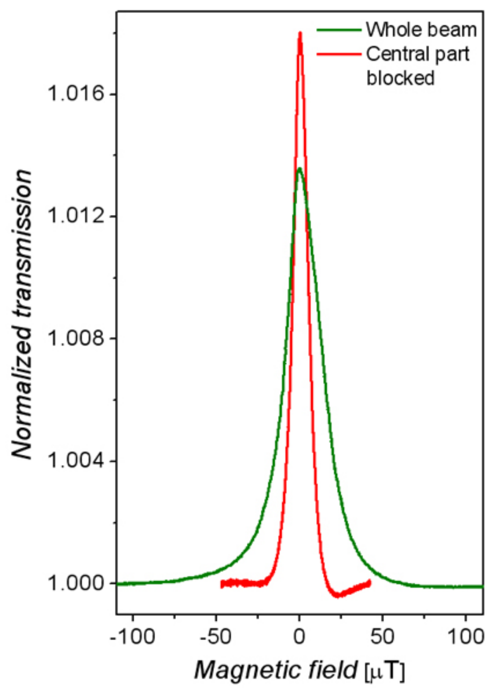

Figure 2. The experimental Hanle EIT resonances obtained when the whole beam is detected (green curve) and when the central part of the beam is blocked by using opaque circular mask of 2.25 mm in diameter placed in front of the detector. The laser intensity is 3 mW/cm^2.

In Fig. 3 (a) and (b) the dependence of the Hanle EIT linewidth and contrast on the beam intensity, with and without the mask, is shown. It is obvious that if one blocks the central part of the Gaussian laser beam, the Hanle EIT resonances will be significantly narrower for the whole laser intensities range in the experiment. Apparently, this masking effect is more prominent at higher laser intensities. At higher laser intensities masking also provides the resonances with higher contrast. One can notice that in the range of extremely low laser intensities the resonances obtained with mask are narrower but they have lower contrast in comparison with those obtained with whole beam. For many applications it is important to have narrow lines but they also should have high enough contrast in order to be useful. To resolve situation what is get what is lost, the contrast to linewidth ratio vs. laser intensity is shown in figure 3 (c). It is obvious that only at extremely low laser intensities the ratio contrast/linewidth is comparable for the two cases, detection of whole beam and when the central part is blocked. For all other intensities detection of outer part of the beam will give resonances with much higher contrast to linewidth ratio. It is clear that using this very simple method of detection, in the worst case one can get the same contrast to linewidth ratio in comparison to whole beam detection. Otherwise this method will provide us narrower and more pronounced lines.

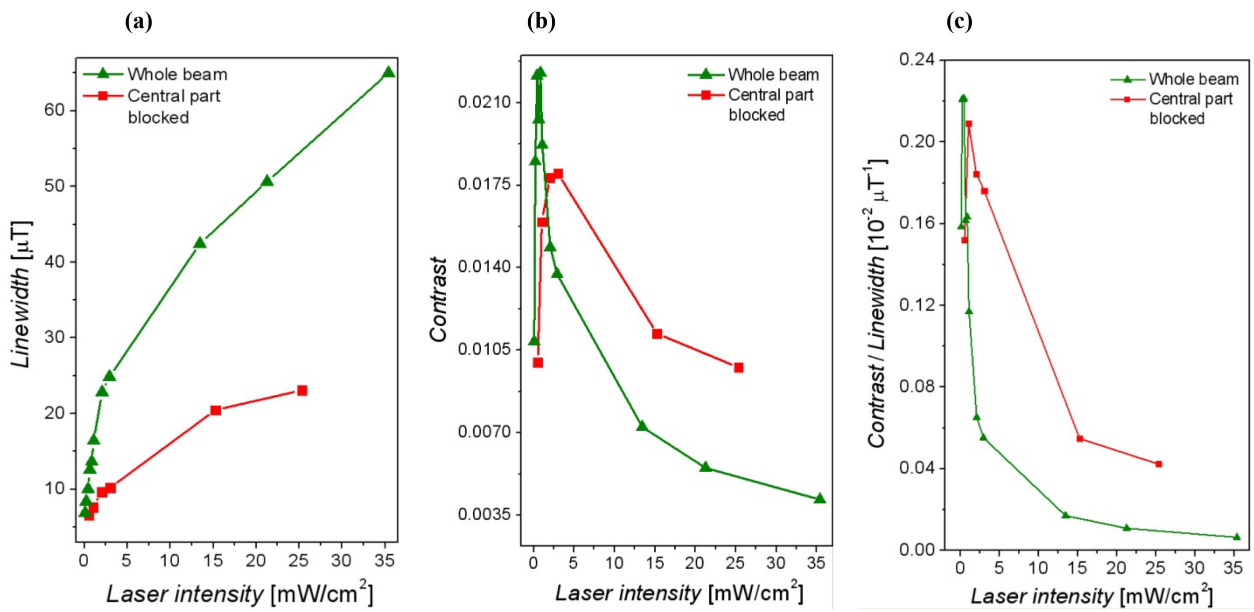

Figure 3. (a) Linewidth, (b) contrast, and (c) contrast to linewidth ratio of experimental Hanle EIT resonances versus laser intensity when the whole beam is detected (green curve) and when the central part of the beam is blocked (red curve). Circular mask diameter is 2.25 mm and the laser intensity is 3 mW/cm^2.

In the figure 4 the shapes of the Hanle EIT resonances for three different mask diameters are shown. Laser intensity was 3 mW/cm^2. It could be noticed that larger mask diameter gives narrower resonances. Quantitative confirmation for previous statement is given in figure 5 (a) where linewidths of Hanle EIT resonances vs. mask diameter are shown for three different laser intensities (0.5 mW/cm^2 , 2 mW/cm^2, and 15 mW/cm^2). Regardless of laser intensity the linewidths drops with mask diameter increment. This result is expected because it is already shown that outer parts of the Gaussian laser beam provide narrower resonances [13]. However, the effect of linewitdh decreasing while increasing the mask diameter is not so pronounced compared to the measurements when only small parts of the Gaussian laser beam are detected as in [13]. Namely, blocking the central part of the Gaussian laser beam, that gives the widest resonances, yields integral detection of the rest of the beam. Increasing the mask diameter for a certain value, one will additionally block only a small ring that will not significantly decrease the linewidth as in case when only small part of the Gaussian laser beam is detected. As a consequence of nonlinear linewidth dependence on position along the beam diameter [13] the linewidth drop in figure 5 (a) is more pronounced at higher laser intensities.

In figure 5 (b) the contrast to linewidth ratio vs. mask diameter for three different laser intensities is shown. For the low intensities (0.5 mW/cm^2 and 2 mW/cm^2) these ratios overlaps thus it is hard to say what mask diameter is optimal. At higher laser intensities (15 mW/cm^2) the situation is clear: using the mask with larger diameter for blocking the central part of the Gaussian beam will give better contrast to linewidth ratio.

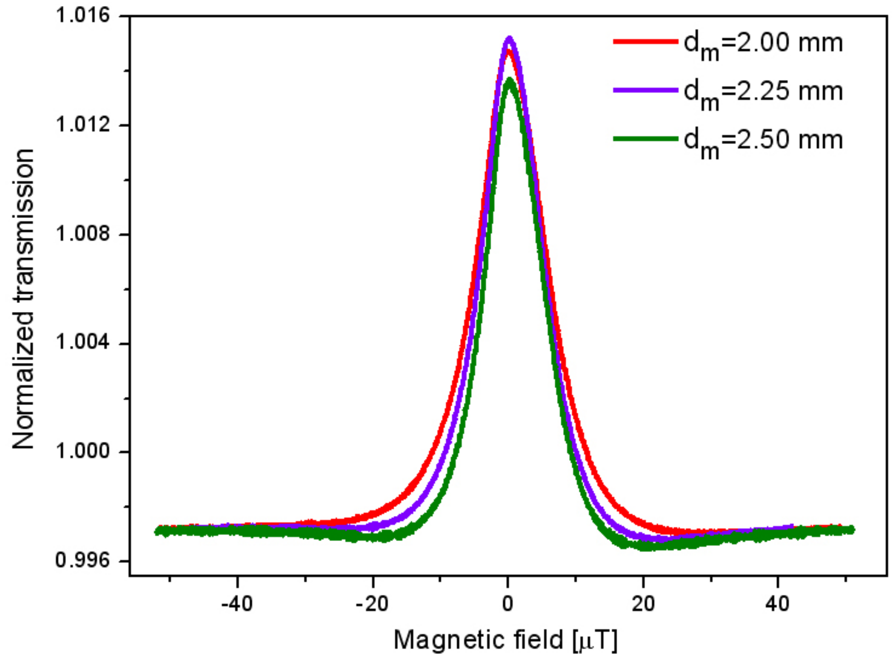

Figure 4. The experimental Hanle EIT resonances obtained by blocking the central part of the Gaussian laser beam with opaque circular masks of different diameters. The red, the violet, and the green curves correspond to masks diameters d_m of 2.00 mm, 2.25 mm and 2.50 mm, respectively. The laser intensity is 3 mW/cm^2.

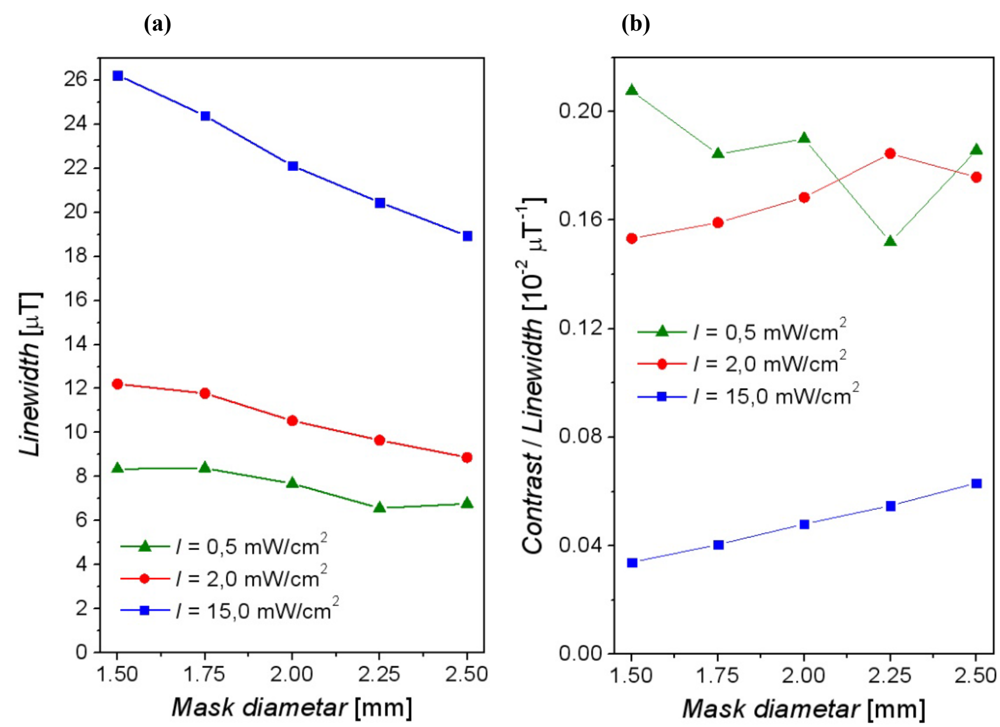

Figure 5. (a) Linewidth and (b) contrast to linewidth ratio of experimental Hanle EIT resonances versus the diameter of the mask used for blocking the central part of the Gaussian laser beam. The blue, the red, and the green curves are for the laser intensities I = 15 mW/cm^2, 2 mW/cm^2, and 0.5 mW/cm^2, respectively.

4. CONCLUSION

In this work we have presented results of the Hanle EIT resonances obtained from the outer parts of the Gaussian laser beam, after the entire laser beam passes through the Rb vacuum cell. The outer parts of the laser beam were detected by placing circular opaque masks of different diameters into the center of the beam. The linewidths and contrasts of the Hanle EIT lines obtained in proposed way depend on the mask diameter used for blocking the central part of the laser beam. The contrast to linewidth ratio is the same or even better for resonances obtained in the proposed way then for those obtained in common way i.e detecting the whole laser beam. The explanation for Hanle EIT lines narrowing is based on the interference between the atomic coherence carried by the coherently prepared atoms and the light in the wings of the Gaussian laser beam. This result could be of interest in applications of EIT where narrow resonances with higher contrast are of main interest e.g. atomic frequency standard and magnetometers.

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