Effective Electromagnetic Parameters of Metamaterial Transmission Line Loaded With Asymmetric Unit Cells

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***Abstract*—In this paper, we propose the generalized extraction procedure for retrieval of the effective constitutive parameters for a metamaterial transmission line loaded with asymmetric unit cells. The asymmetric unit cell is replaced with a transmission line immersed in equivalent bianisotropic medium described by effective parameters ε, μ, and Z_c, and bianisotropic parameters u and η. The proposed retrieval procedure is applied to novel dual-band unit cells and compared with the standard Nicolson–Ross–Weir (NRW) method that is originally developed for the symmetric unit cell and then extended to the asymmetric one using the averaged value of reflection coefficients. It has been shown that, in case of pronounced asymmetry, the NRW method gives only the exact value of refraction, but effective permittivity and permeability are considerably different from the exact values since they are calculated by means of the approximate value of characteristic impedance.**

***Index Terms*—Asymmetric unit cell, split-ring resonator (SRR), effective material parameters, bianisotropic medium, metamaterial transmission line.**

I. Introduction

METAMATERIALS are artificial electromagnetic (EM) composites that can host a number of unusual properties. Among them, the *negative index* or *left-handed* (LH) metamaterials have been a research focus over the past decade. Their distinctive characteristics include the opposite direction of power flow and phase velocity and the inversion of Snell Law, Doppler shift, and Cherenkov radiation [1]. These properties make them suitable candidates for some ground-breaking applications, such as invisibility cloak and sub-wavelength imaging [2].

Alongside with 2-D or 3-D volumetric metamaterials, which interact with free-space radiation, an analogous concept for guided waves has emerged. These structures represent transmission lines or waveguides loaded with sub-wavelength inclusions, and they are termed metamaterial transmission lines or composite right/left-handed (CRLH) transmission lines. They can be used for numerous improvements of practical microwave devices, such as leaky-wave antennas, couplers, shifters, etc. [3].

The key assumption for understanding the EM behavior of metamaterials is that homogenization theory can be applied to them, in the same fashion as it is applied to natural materials. In other words, we assume that we can average Maxwell's equations over small volumes (with respect to wavelength), to obtain equivalent homogeneous medium described by a set of effective constitutive parameters [4]. In the case of metamaterial transmission lines, we assume that the line's conductors are immersed in equivalent homogeneous medium that substitutes the effect of the inclusions, like in planar transmission lines where homogenious medium with the effective permittivity is introduced to emulate the presence of two dielectrics (substrate and air). Apart from providing a simple physical picture, the importance of effective parameters lies in the fact that they can greatly facilitate the design of optimal metamaterial structures.

To determine the values of these effective parameters, several approaches can be used: for example, analytical solutions exist in some simpler cases [5], [6], and there is also a possibility of numerical averaging of fields. However, by far the most frequently used procedure is based on the inversion of scattering data (S-parameters) of a finite slab, called the NRW procedure. It was developed for the measurements of complex permittivity and permeability of natural materials [7], [8], and more recently applied to metamaterials [9], [10]. Effective parameters of metamaterial transmission lines can be deduced from the equivalent-circuit model, but the latter is sometimes not readily available. In such cases, we can resort to the same procedure of parameter retrieval. Formally, the only difference in the procedure is that the impedances have to be normalized with a factor that depends on transmission-line geometry [11].

One of the problems with the standard Nicolson–Ross–Weir (NRW) procedure arises in the case when the metamaterial sample under study has asymmetric reflection. It is obvious that the isotropic medium model cannot reproduce this property, as it is intrinsically symmetric. Smith *et al.* proposed a modification of the procedure to solve this problem by using averaged value of the reflection coefficients, which we will call $\mathrm{NRW}_{\mathrm{avg}}$. It provides the correct value of the index of refraction, but the value of the characteristic impedance remains approximate [12]. Another problem is that the isotropic medium model assumes that the induced electric and magnetic dipoles are mutually independent, but Marques *et al.* reported that the split ring, which is commonly used in metamaterials, has a simultaneous electric and magnetic response, i.e., corresponding

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dipoles are coupled [13]. It is not always possible to neglect that coupling, depending on the orientation of the split rings and their excitation.

To account for both asymmetric reflection and magneto-electrical coupling, bianisotropic medium model can be used, which has already been considered by various authors [13]–[16]. We can distinguish several sources of bianisotropy—cross polarizability of constitutive elements (e.g., split ring), asymmetric position of elements within the unit cell (e.g., due to the substrate) [16], and even in the case of symmetric unit cells with center-symmetric inclusions (i.e., without cross-polarizability), spatial dispersion effects [17]. In any case, a significant improvement over the standard retrieval technique is achieved.

In this paper, we consider the bianisotropic homogenization and retrieval of corresponding parameters for metamaterial transmission lines loaded with asymmetric inclusions, which, to our best knowledge, have not been published in the literature thus far. This paper is organized as follows. In Section II, we discuss properties of transmission lines filled with bianisotropic medium. We then develop the circuit matrix of such transmission lines (we use $ABCD$ matrices as they allow most convenient formulation). From this matrix, we show how material parameters, including bianisotropy parameters u and η, can be retrieved, and discuss potential problems that may occur. We will refer to this procedure as the generalized approach (GA).

In Section III, the proposed GA procedure is applied to novel dual-band unit cells, which consist of a microstrip line loaded with broadside coupled (BSC) split-ring resonators (SRRs), with gaps either on parallel or on perpendicular arms of the SRRs. We compared this approach and the NRW retrieval procedure, originally developed for symmetric unit cells, and found that NRW was not able to extract constitutive parameters such as permittivity, permeability, and characteristic impedance for asymmetric unit cells correctly, even if the average value of reflections was used.

Section IV presents validation of the proposed extraction procedure for the asymmetric unit cells. We provide the simulation results of a homogeneous slab with the effective parameters that we extracted using both the GA and $\mathrm{NRW_{avg}}$ methods and compare them with the simulated response of the real unit cell. To simulate the bianisotropic medium, we replaced it with two isotropic slabs and recomposed the obtained S-parameters to get the final S-parameters.

Any retrieval technique based on analyzing the scattering data of a finite slab can suffer from some problems, e.g., unphysical antiresonances with a negative imaginary part for some of the parameters. Koschny *et al.* reported that these anomalies could be traced back to the periodicity of the structure [18], and Alù reported that they could be associated with a weak form of spatial dispersion [19]. In our current work, however, we found these anomalies to be negligible, so we did not include them in the scope of our study.

II. Generalized Retrieval Procedure

A. Transmission Line Filled With Bianisotropic Medium

Consider a transmission line (i.e., structure that supports a guided TEM wave), with its axis placed along the z coordinate. Assume that the line is immersed in homogeneous bianisotropic medium described by the following constitutive relations (ε_0, μ_0 and c are permittivity, permeability and velocity of light in vacuum, respectively):

$$\begin{aligned}\vec{D} &= \varepsilon_0\varepsilon\vec{E} + \bar{\xi}\vec{H}\\ \vec{B} &= \bar{\zeta}\vec{E} + \mu_0\mu\vec{H}\end{aligned} \tag{1}$$

where

$$\bar{\xi} = \bar{\zeta} = \frac{1}{c}\begin{bmatrix} 0 & -ju & 0\\ ju & 0 & 0\\ 0 & 0 & 0\end{bmatrix}. \tag{2}$$

The reciprocity condition is satisfied because $\bar{\xi} = -\bar{\zeta}^T$ [20]. We note here that the tensors used in the previous reports [13]–[16] are different with respect to (2) since they have only one off-diagonal element. The reason for this difference lies in the fact that the transmission line has an inhomogeneous field structure in the transverse plane, unlike the plane wave. The form of (2) ensures that magneto-electric coupling does not depend on polarization of the transverse field, which leads to a much simpler solution than in the opposite case, as will become clear later on.

Now, let us assume that a guided wave propagates along the z-axis, with all quantities depending on the z coordinate as $e^{-\gamma z}$; and on time as $e^{j\omega t}$.[1] We also assume that the wave is of a TEM type, i.e., z components of $\vec{E}$ and $\vec{H}$ vectors are zero. Now we can derive the following relations from the curl Maxwell's equations:

$$\begin{aligned}\vec{i_z} \times (-\gamma\vec{H}) &= j\omega\vec{D}\\ \vec{i_z} \times (-\gamma\vec{E}) &= -j\omega\vec{B}\end{aligned} \tag{3}$$

where $\vec{i_z}$ is the unit vector in the z-direction. The constitutive relations can be rewritten as

$$\begin{aligned}\vec{D} &= \varepsilon_0\varepsilon\vec{E} + \vec{i_z} \times \left(j\frac{u}{c}\vec{H}\right)\\ \vec{B} &= \mu_0\mu\vec{H} + \vec{i_z} \times \left(j\frac{u}{c}\vec{E}\right).\end{aligned} \tag{4}$$

Combining (3) and (4) yields

$$\left(\gamma - \frac{\omega}{c}u\right)(\vec{i_z} \times \vec{H}) = -j\omega\varepsilon_0\varepsilon\vec{E} \tag{5}$$

$$\left(\gamma + \frac{\omega}{c}u\right)(\vec{i_z} \times \vec{E}) = j\omega\mu_0\mu\vec{H}. \tag{6}$$

Combining (5) and (6) yields the wave equation

$$\left(\gamma^2 + \frac{\omega^2}{c^2}(\varepsilon\mu - u^2)\right)\vec{E} = 0 \tag{7}$$

which gives the following dispersion relation:

$$\gamma = \pm j\frac{\omega}{c}\sqrt{\varepsilon\mu - u^2} \tag{8}$$

or, since $\gamma = j(\omega)/(c)n$,

$$n = \pm\sqrt{\varepsilon\mu - u^2}. \tag{9}$$

Different signs in (8) and (9) indicate two possible directions of propagation along the z-axis. The correct solution for a given direction should be chosen based on the passivity criterion.

[1] The complex quantities are defined as, e.g., $n = n' - jn''$.

The characteristic impedance of the medium (i.e., the ratio between the electric and magnetic field strengths) can be obtained by substituting (8) in (5), yielding (normalized by $z_0 = \sqrt{\mu_0/\varepsilon_0}$)

$$z_{1,2} = \frac{n \pm ju}{\varepsilon} \tag{10}$$

where $z_{1,2}$ correspond to propagation along the positive and negative z-direction, respectively. From (10), it is clear that the impedance value is different for propagation in different directions, thus giving different reflections.

From (5) and (6), we deduce that the electric and magnetic field vectors are proportional and normal to each other in every point of transverse plane. Furthermore, polarization vectors $\vec{D}$ and $\vec{B}$ are proportional to $\vec{E}$ and $\vec{H}$, respectively. Therefore, Maxwell's equations governing the field distribution in the transverse plane will not change, except for the factor of proportionality, compared with transmission line filled with air. Consequently, the line characteristic impedance (i.e., the voltage to current ratio) will change proportionally,

$$Z_{c1,2} = z_{1,2} Z_{\text{air}} \tag{11}$$

where Z_{air} is the of transmission line characteristic impedance in the air. Alternatively, the characteristic impedances can be written as

$$Z_{c1,2} = Z_c \pm \eta \quad Z_c = \frac{Z_{c1} + Z_{c2}}{2} \tag{12}$$

where $Z_c = (n)/(\varepsilon) Z_{\text{air}}$ represents their mean value, and $\eta = (ju)/(\varepsilon) Z_{\text{air}}$, based on (10), represents the offset from the mean value. We will use this form later, as it allows us a more convenient formulation.

B. Conditions for Negative Index of Refraction

In his seminal paper, Veselago proved that a material without losses will exhibit negative refractive index when ε and μ are simultaneously negative [1]. However, this condition is too strict, when we take into account losses, which exist in all natural materials. The necessary condition in the lossy case is found to be [21], [22]

$$\varepsilon' \mu'' + \mu' \varepsilon'' < 0. \tag{13}$$

This condition was derived using the standard dispersion relation, $n = \sqrt{\varepsilon\mu}$. For bianisotropic media, however, the proper relation is given by (9), and the condition for negative index has to be derived starting from that.

To obtain a negative refractive index, we have to have a solution of (9) with $n'' > 0$ and $n' < 0$ (to ensure a positive power flow and negative phase velocity, respectively) [21]. In other words, n has to lie in the second quadrant of the complex plane. This implies that n^2 will necessarily lie in the lower half-plane, i.e., $\text{Im}\{n^2\} < 0$. By substituting (9), we obtain

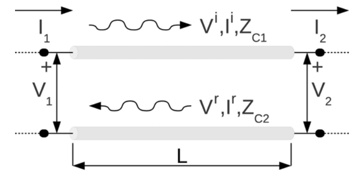


Fig. 1. Section of an asymmetric transmission line of length L.

$$\varepsilon' \mu'' + \mu' \varepsilon'' < 2u'u''. \tag{14}$$

An important consequence of (14) is that it shows it is possible to have both ε' and μ' negative and still not obtain a negative refractive index if the product $u'u''$ is negative.

C. Network Parameters of a Transmission-Line Section

Let us assume that we have a transmission-line section of length l, filled with bianisotropic medium having $\varepsilon hbox-$, μ-, and u-parameters. We can regard this section as a two-port network, which can be described by its scattering parameters (S-parameters), or any other type of network parameters (impedance, admittance, etc.). We will use the $ABCD$-parameter description as we found it most convenient for our discussion. The $ABCD$-parameter matrix is defined by [23]

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{15}$$

with referent directions for voltages and currents indicated in Fig. 1.

Our aim is to obtain $ABCD$-parameters as a function of transmission-line properties derived in Section II-B, namely, propagation constant γ (the same for both directions), defined by (8), and characteristic impedances Z_{c1} and Z_{c2} (for incident and reflected wave, respectively), defined by (12). To this end, we represent the state at arbitrary point of transmission line with voltages of incident and reflected waves, V^i and V^r, respectively. The relation between these voltages at ports 1 and 2, written in matrix form, will be

$$\begin{bmatrix} V_1^i \\ V_1^r \end{bmatrix} = \begin{bmatrix} e^{\gamma l} & 0 \\ 0 & e^{-\gamma l} \end{bmatrix} \begin{bmatrix} V_2^i \\ V_2^r \end{bmatrix}. \tag{16}$$

Total voltage and total current anywhere along the line can be expressed as

$$\begin{bmatrix} V \\ I \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{1}{Z_{c1}} & -\frac{1}{Z_{c2}} \end{bmatrix} \begin{bmatrix} V^i \\ V^r \end{bmatrix} = Q \begin{bmatrix} V^i \\ V^r \end{bmatrix}. \tag{17}$$

The inverse relation is

$$\begin{bmatrix} V^i \\ V^r \end{bmatrix} = Q^{-1} \begin{bmatrix} V \\ I \end{bmatrix}. \tag{18}$$

By substituting (18) into (16) and multiplying by Q from the left side, we obtain the $ABCD$ matrix

$$ABCD = Q \begin{bmatrix} e^{\gamma l} & 0 \\ 0 & e^{-\gamma l} \end{bmatrix} Q^{-1} \tag{19}$$

which, after substituting value of Q and some manipulation, comes down to

$$\begin{bmatrix} \cosh\gamma l + \frac{\eta}{Z_c}\sinh\gamma l & \left(Z_c - \frac{\eta^2}{Z_c}\right)\sinh\gamma l \\ \frac{\sinh\gamma l}{Z_c} & \cosh\gamma l - \frac{\eta}{Z_c}\sinh\gamma l \end{bmatrix}. \tag{20}$$

It can be seen from (20) that when $\eta = 0$, i.e., in the symmetric case, $ABCD$-parameters are reduced to those of the standard transmission line.

D. Parameter Retrieval

Scattering parameters (S-parameters) are usually obtained as a result of measurements or EM simulation and can be unambiguously transformed to the $ABCD$ matrix [23]. Once we have it, we can easily see from (20) that we can obtain the effective parameters as

$$\gamma = \pm\cosh^{-1}\frac{A+D}{2} \tag{21}$$

$$Z_c = \frac{\sinh\gamma l}{C} = \pm\frac{1}{C}\sqrt{1-\left(\frac{A+D}{2}\right)^2} \tag{22}$$

$$\eta = \frac{A-D}{2C}. \tag{23}$$

If the unit cell is symmetric,[2] we can substitute S-parameters and simplify the expressions to obtain

$$\gamma = \pm\frac{1}{L}\cosh^{-1}\frac{1-S_{11}^2+S_{21}^2}{2S_{21}} \tag{24}$$

$$Z_c = \pm\sqrt{\frac{(1+S_{11})^2-S_{21}^2}{(1-S_{11})^2-S_{21}^2}} \tag{25}$$

and $\eta = 0$, which, as expected, agrees with the previous reports on the NRW procedure [9], [11], [24].

The $\mathrm{NRW}_{\mathrm{avg}}$ procedure proposed in [12] was intended to circumvent the problem of dealing with asymmetric unit cells by using a standard retrieval technique (for symmetric structures, i.e., (24) and (25) or similar ones), but with the averaged value of reflections S_{11} and S_{22}, i.e., $S_{11\mathrm{avg}} = \sqrt{S_{11}S_{22}}$. However, it can be shown that the $\mathrm{NRW}_{\mathrm{avg}}$ approach gives the correct value of index of refraction, but the characteristic impedance is different from the true mean value, as defined in (12) and (22). The disagreement between the impedances calculated both ways is expected to be proportional to the degree of asymmetry. As the characteristic impedance is crucial for the retrieval of effective EM parameters, this disagreement will translate to them as well, as will be shown later.

A few additional comments are needed about the given relations. First, the sign in (21) should be chosen based on the passivity criterion

$$\mathrm{Re}\{\gamma\} > 0. \tag{26}$$

[2]Symmetry implies $A = D$ for $ABCD$-parameters, and $S_{11} = S_{22}$ for S-parameters.

However, the problem of branching for $\cosh^{-1} z$, which leads to ambiguity in the imaginary part of γ (or, equivalently, in the real part of n) remains. This is the consequence of the fact that it is not possible to differentiate the phase change of ϕ from $\phi + 2k\pi, k \in Z$. One approach to solving this problem is to use Kramers–Kronig relations to estimate the correct branch [25].

In most previous reports [7]–[11], the sign of the characteristic impedance in (22) or (25) is chosen based on the criterion $\mathrm{Re}\{Z_c\} > 0$ or a similar one, which can be very sensitive to small numerical errors [24]. However, it is clearly visible from (22) that the characteristic impedance sign is related to the sign chosen for the propagation constant in (21), and, therefore, only one criterion is sufficient, as is found in [24].

E. Effective Parameters of the Equivalent Medium

Once we have found the propagation constant γ and characteristic impedance of an equivalent transmission line $Z_{c1,2}$, we can readily obtain the index of refraction n and characteristic impedance of the equivalent medium $z_{1,2}$ as

$$n = -j\frac{c}{\omega}\gamma \quad z_{1,2} = \frac{Z_{c1,2}}{Z_{\mathrm{air}}}. \tag{27}$$

The bianisotropic medium effective parameters ε, μ, and u can be expressed in terms of n and $z_{1,2}$ by rearranging (9) and (10),

$$\varepsilon = \frac{2n}{z_1+z_2} \quad \mu = 2n\frac{z_1 z_2}{z_1+z_2} \quad u = -jn\frac{z_1-z_2}{z_1+z_2}. \tag{28}$$

Combining (27) and (28) with the expressions linking them with S-parameters derived in previous sections enables us to retrieve effective parameters from simulated or experimental data. We will refer to this relation as the GA.

Another option for describing asymmetric unit cells would be to use ε and μ that depend on the direction of propagation. They could be obtained as

$$\varepsilon_{1,2} = \frac{n}{z_{1,2}} \quad \mu_{1,2} = nz_{1,2}. \tag{29}$$

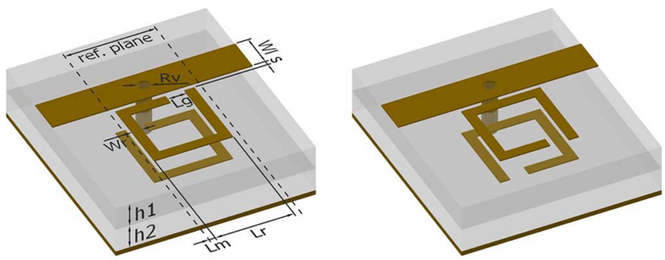
While mathematically equivalent, we feel that this approach is less physically justified. For the sake of comparison, we will include these values in our practical examples of extraction, and we will refer to them as the GA with a wave incoming from port 1 and port 2 (GA_1 and GA_2, respectively).

III. Asymmetric Unit Cells

Here we investigate the EM properties of the metamaterial transmission line consisting of a microstrip line loaded with broadside-coupled asymmetric split-ring resonators (ASRRs) placed on one side of the transmission line.

It is shown that rotating the individual split rings significantly affects EM properties of the metamaterial transmission line due to different electrical and magnetic interactions that are caused by different mutual orientations of the SRRs in space and by their different orientation relative to the transmission line [26], [27].

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.



(a) (b)

Fig. 2. Asymmetric unit cells with gaps oppositely displaced from the middle of the ring side. (a) Gaps near the microstrip line. (b) Gaps far from the microstrip line. Relevant dimensions: $h_1 = 0.635$ mm, $h_2 = 1.575$ mm, $\varepsilon_{r1} = 10.2$, $\varepsilon_{r2} = 2.2$, $L_r = 3.15$ mm, $L_g = 0.75$ mm, $L_a = 2$ mm, $L_m = 0.25$ mm, $L = L_r + 2L_m$, $W_l = 1.4$ mm, $W_r = 0.4$ mm, $R_v = 0.5$ mm, $s = 0.2$ mm.

Using the proposed generalized retrieval procedure, we explore novel asymmetric unit cells realized on a two-layer substrate. Gap-bearing sides of the SRRs are placed one above the other, not opposite to each other, as is the case with standard BSC SRRs. Unlike the standard design, novel SRRs exhibit the resonant frequencies much closer to each other (about 500 MHz), which is suitable for modern wireless systems.

We examine two types of SRRs with gap-bearing sides parallel to the microstrip line and perpendicular to it. The gaps can be moved symmetrically with respect to the center of SRR branches, to the left and to the right sides, as shown in Fig. 2 for SRRs with gaps parallel to the microstrip line.

To investigate the effectiveness of the proposed extraction procedure with respect to the NRW method, we study the metamaterial unit cells that are not distinctly asymmetric as those consisting of SRRs with gaps parallel to the microstrip line, and also the highly asymmetric unit cells with gaps perpendicular to the microstrip line.

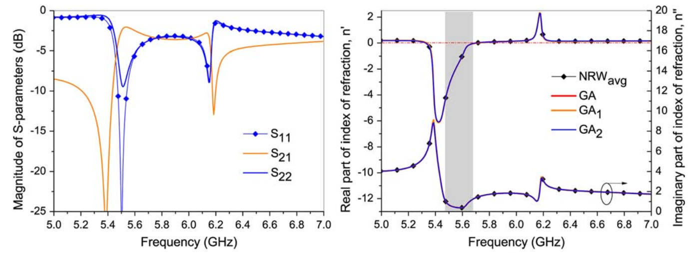
A. Unit Cell With Gaps Parallel to the Microstrip Line

This type of unit cells can be designed with gap bearing sides near the microstrip line and far from it, as shown in Fig. 2. Unit cells comprise BSC SRRs with gaps symmetrically displaced from the center. Their asymmetry is caused only by the fact that gaps are placed at different substrate layers (top and bottom). Microstrip line is connected to the ground plane with cylindrical via, R_v, placed in the center between reference planes (denoted by dash lines).

Unit cells are simulated using the WIPL-D Pro 10.0 3-D EM solver,[3] which is based on the method of moments, and S-parameters are de-embedded at the reference planes.

For the extraction of the effective parameters, we use the GA procedure that gives two different values for the effective permittivity, permeability, and characteristic impedance. The effective EM parameters of an asymmetric unit cell can also be presented by bianisotropic parameters u and η and average values of effective permittivity, permeability, and characteristic impedance (GA) that is more suitable for the direct comparison with the $\mathrm{NRW}_{\mathrm{avg}}$ approach. It should be pointed out that the

[3][Online]. Available: http://www.wipl-d.com/



(a) (b)

Fig. 3. Unit cell with ASRRs with gaps near the microstrip line. (a) Magnitude of S-parameters. (b) Extracted index of refraction. The rectangular bar denotes the frequency range with double negative effective parameters.

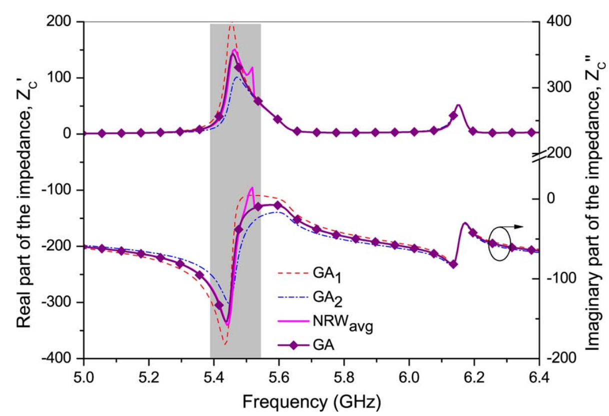
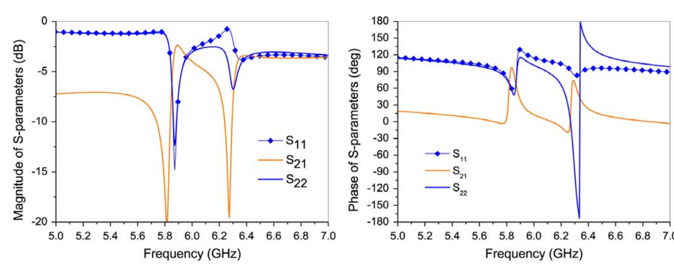


Fig. 4. Characteristic impedance extracted using different retrieval procedures for the unit cell with ASRRs with gaps near the microstrip line.



(a) (b)

Fig. 5. (a) Magnitude and (b) phase of S-parameters for ASRRs with gaps far from the microstrip line.

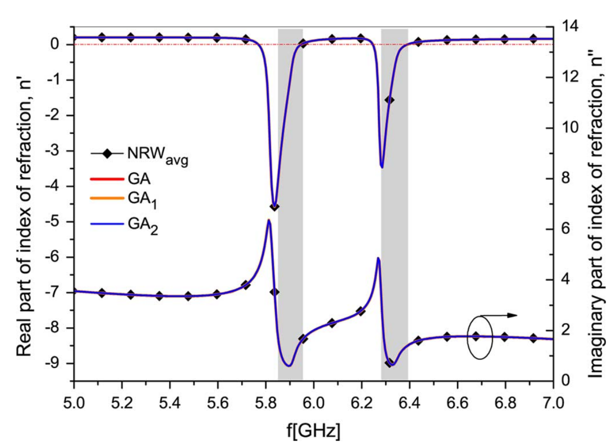
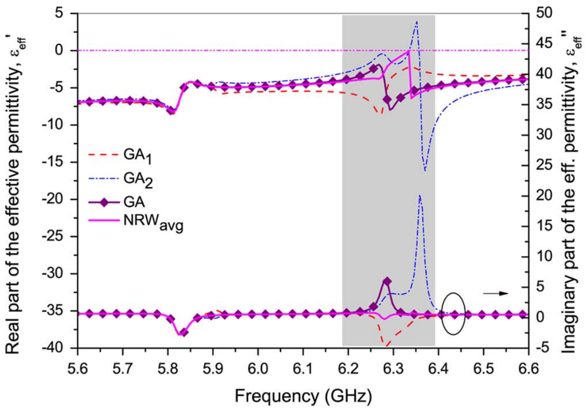
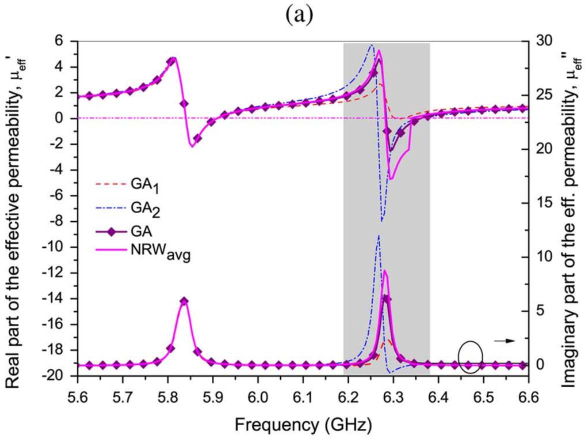


Fig. 6. Effective index of refraction extracted using different retrieval procedures for unit cell with ASRRs with gaps far from the microstrip line. Rectangular bars denote the frequency ranges with double-negative effective parameters.



(a)



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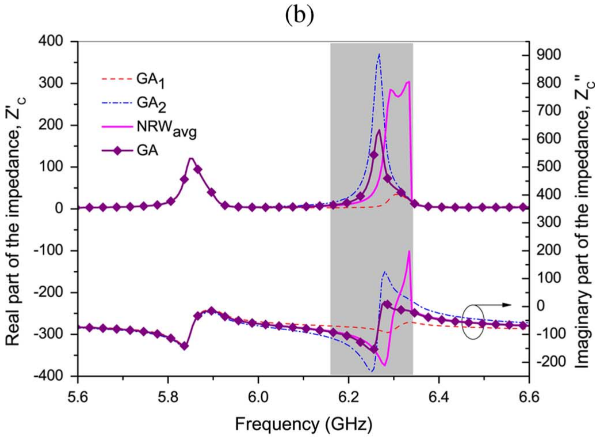
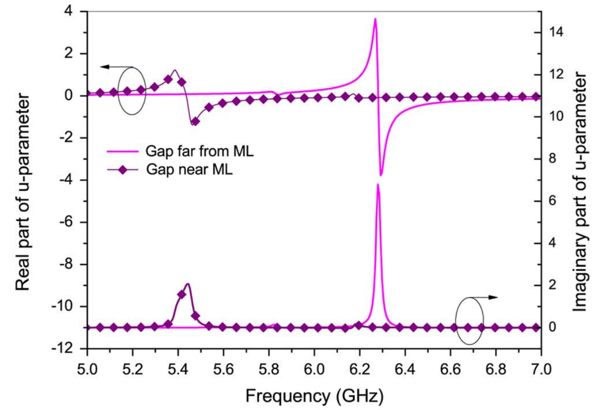


(c)

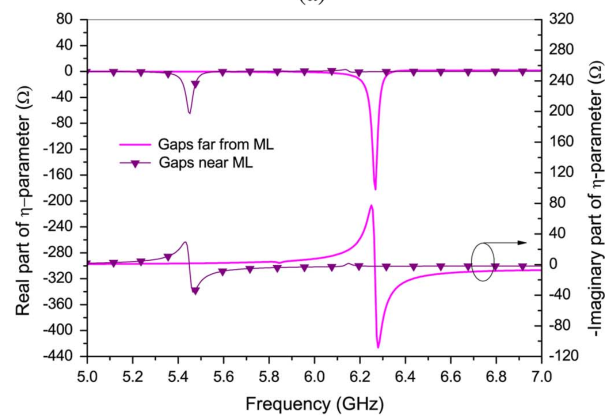
Fig. 7. (a) Effective permittivity, (b) permeability, and (c) characteristic impedance extracted for ASRRs with gaps far from the microstrip line. Rectangular bars denote the frequency range in which the $\mathrm{NRW_{avg}}$ and GA give different results.

$\mathrm{NRW_{avg}}$ method describes the asymmetric unit cell with the single value of the effective permittivity, permeability, and characteristic impedance as if it were symmetric. We compare $\mathrm{GA_1}, \mathrm{GA_2}$, and the GA with the $\mathrm{NRW_{avg}}$ approach.

The magnitude of S-parameters for the unit cells with gaps near the microstrip line [see Fig. 2(a)] is shown in Fig. 3(a). It can be seen that the difference between reflection coefficients S_{11} and S_{22} exists only around the first resonance. The extracted index of refraction in Fig. 3(b) is the same for the GA and $\mathrm{NRW_{avg}}$ approaches thanks to the conveniently defined average reflection coefficient used for the $\mathrm{NRW_{avg}}$ extraction. The unit



(a)



(b)

Fig. 8. Comparison of the extracted parameters. (a) Bianisotropy parameter u and (b) difference between effective characteristic impedances η for unit cells with gaps parallel to microstrip line.

cell exhibits the LH band around 5.5 GHz denoted with a rectangular bar and also the right-handed (RH) band around 6.15 GHz that corresponds to the second resonance.

The characteristic impedances extracted using three different methods are compared in Fig. 4. It can be seen that the values extracted by the GA fit exactly between the two corresponding values extracted by $\mathrm{GA_1}$ and $\mathrm{GA_2}$, as was expected according to (12). It is important to point out that, only at the first resonance, the characteristic impedance extracted by the $\mathrm{NRW_{avg}}$ method is different, but not considerably, from those extracted using the GA approach, which means that asymmetry is not much pronounced.

B. Unit Cell With Gaps Far From the Microstrip Line

The unit cell with gaps far from the microstrip line [see Fig. 2(b)] has very different S-parameters and extracted index of refraction than the unit cell with gaps near the microstrip line [see Figs. 5 and 6]. The difference between the reflection coefficients at port 1 and port 2 appears near the second resonance, which is evident from their phase in Fig. 5(b). The extracted index of refraction in Fig. 6 has two LH bands around 5.9 and 6.35 GHz that are marked by rectangular bars.

The effective permittivity, permeability, and characteristic impedance extracted using $\mathrm{GA_1}, \mathrm{GA_2}$, GA, and $\mathrm{NRW_{avg}}$ are shown in Fig. 7. It can be seen that all four retrieval procedures give the same results in the frequency range where symmetrical

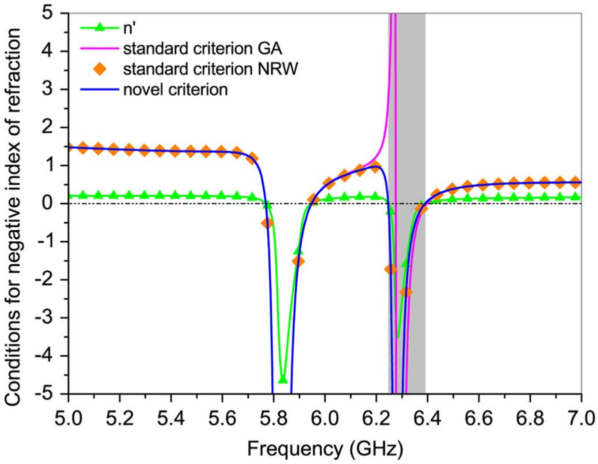
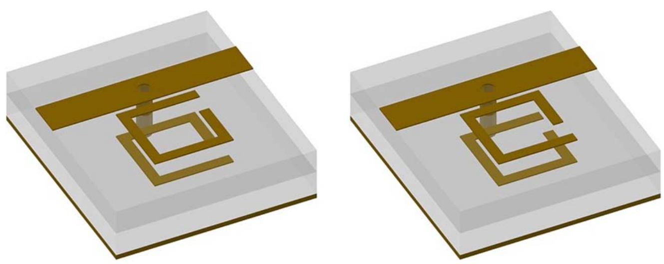


Fig. 9. Comparison of standard and novel criteria for negative index of refraction for the unit cell with parallel gaps far from the microstrip line. Effective parameters are extracted using the GA approach. The rectangular bar denotes the range in which the cell has asymmetric response and two criteria also predict different ranges of negative index of refraction.



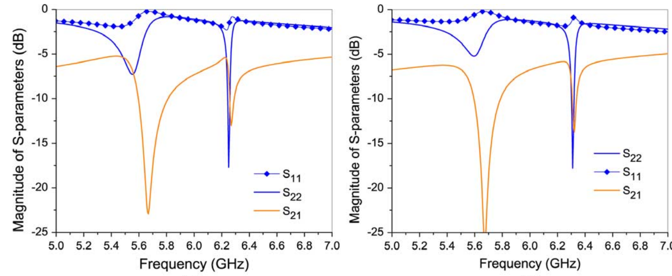
(a) (b)

Fig. 10. Layout of unit cells consisting of ASRRs with gap-bearing side perpendicular to the microstrip line. (a) Upper gap close to the microstrip line. (b) Upper gap far from the microstrip line.

response exists $(S_{11} = S_{22})$. Effective parameters extracted by the GA and $\mathrm{NRW}_{\mathrm{avg}}$ are different only around the second resonance, where the asymmetry is most significant, as it is marked by rectangular bars at Fig. 7. In the whole frequency range of interest, the effective permittivity extracted applying the $\mathrm{NRW}_{\mathrm{avg}}$ and GA is negative, while the effective permeability changes the sign at two resonances that correspond to the LH bands.

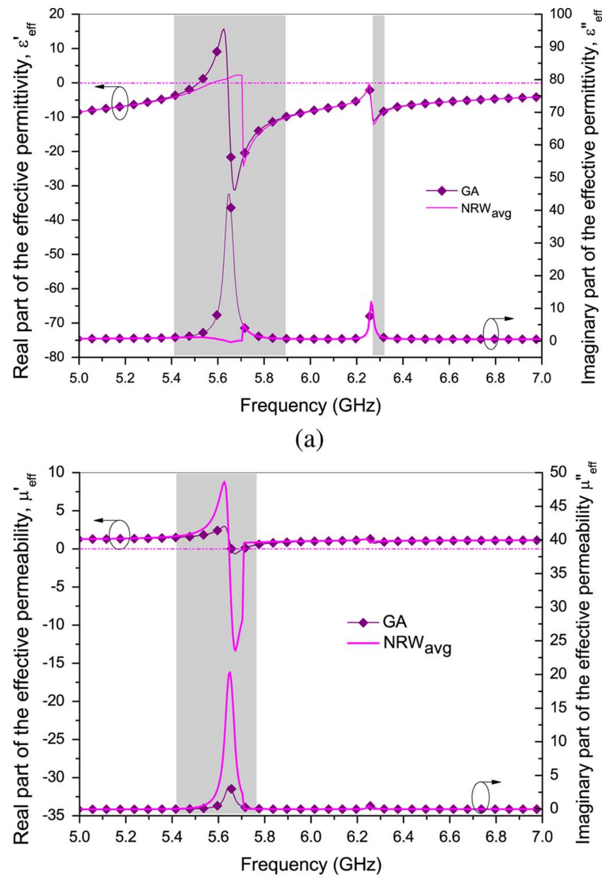
The generalized extraction procedure introduces two novel parameters as a measure of unit cells asymmetry: u- and η-parameters. Fig. 8 clearly shows that the unit cell with gaps far from the microstrip line exhibits the maximum value of u- and η-parameters about three times greater than the unit cell with gaps near the microstrip line. It is also seen that bianisotropy occurs in the vicinity of either the first or the second resonance of the corresponding unit cells. It is interesting to mention that bianisotropy is considerably smaller if gaps are placed at the opposite sides of SRRs like standard BSC SRRs, even if they are oppositely displaced from the center. In that case, bianisotropy occurs at both resonances.

In Fig. 9, we compare the standard condition for negative index of refraction (13), which is valid for symmetrical unit cells, and consequently for the effective parameters extracted by the $\mathrm{NRW}_{\mathrm{avg}}$ method, and the novel condition (14), which is derived for asymmetric unit cells. Both conditions are calculated using the effective parameters extracted by the GA method. In case of the unit cell with parallel gaps far from the microstrip line, it can be seen that around the first resonance both curves, for standard and novel criteria, are overlapped as was expected since the cell is symmetrical in that range. Around the second resonance, the curve corresponding to the novel criterion crosses the axis exactly at the points where the real part of the index of refraction is equal to zero, which was not the case with the curve corresponding to the standard criterion. In this case, the standard criterion predicts a somewhat narrower range of the negative index. Finally, we applied the standard condition using the parameters extracted by the $\mathrm{NRW}_{\mathrm{avg}}$ method and showed that it completely overlapped with the



(a) (b)

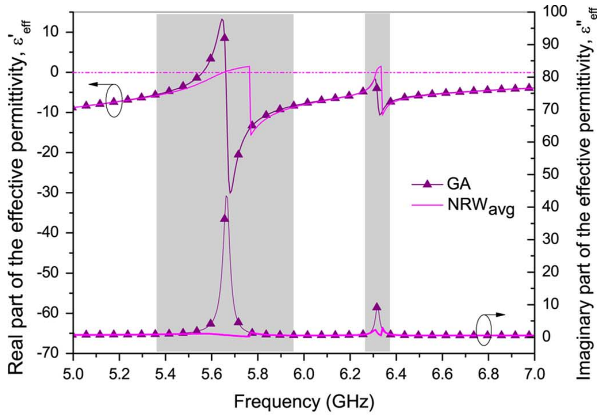
Fig. 11. Magnitude of S-parameters for unit cells with the gap perpendicular to the microstrip line. (a) Upper gap close to the microstrip line. (b) Upper gap far from the microstrip line.



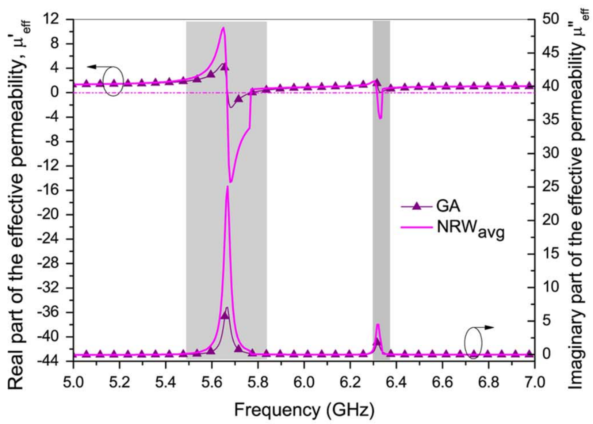
(a)

(b)

Fig. 12. Effective parameters extracted using the GA and $\mathrm{NRW}_{\mathrm{avg}}$ methods for unit cell with upper gap close to the microstrip line. (a) Permittivity. (b) Permeability. Rectangular bars denote the frequency range in which the $\mathrm{NRW}_{\mathrm{avg}}$ and GA give different results.



(a)



(b)

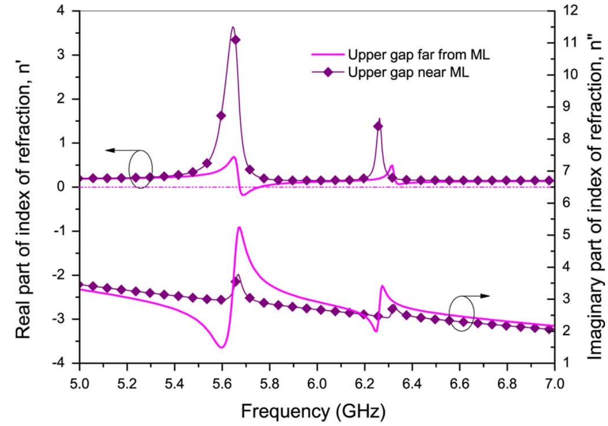
Fig. 13. Effective parameters extracted using the GA and $\mathrm{NRW_{avg}}$ methods for unit cell with upper gap far from the microstrip line. (a) Permittivity. (b) Permeability. Rectangular bars denote the frequency range in which the $\mathrm{NRW_{avg}}$ and GA give different results.

novel criterion. This proves validity of the novel criterion since both methods give the same index of refraction not only for the symmetric response, but also for the asymmetric one.

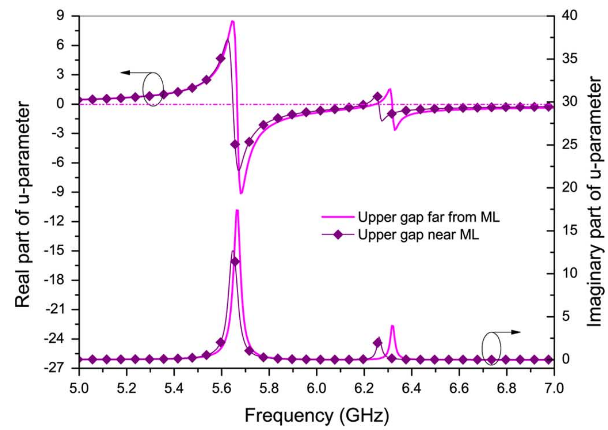
C. Unit Cells With Gaps Perpendicular to the Microstrip Line

Unit cells with gaps perpendicular to the microstrip line are shown in Fig. 10, and we can distinguish two cases in respect to the position of the upper gap: (a) when it is near the microstrip line and (b) when it is far from the microstrip line. In both cases, gaps are placed near port 1 of the unit cell. If we interchange the ports by putting port 1 instead of port 2, only the sign of u- and η-parameters will be changed.

Magnitude of S-parameters for the unit cells with perpendicular gaps are shown in Fig. 11. The extracted effective permittivity and permeability for unit cells with the upper gap near and far from the microstrip line are presented in Figs. 12 and 13, respectively. It can be seen that the position of perpendicular gaps does not influence resonant frequencies too much. S_{11} is also different from S_{22} around both resonances, but more pronounced at the first resonance. Extracted effective permittivity and permeability using the GA and $\mathrm{NRW_{avg}}$ are significantly different around 5.7 GHz, not only that the values are different, but also they have the opposite signs.



(a)



(b)

Fig. 14. (a) Extracted index of refraction and (b) u-parameter for unit cells with gaps perpendicular to the microstrip line.

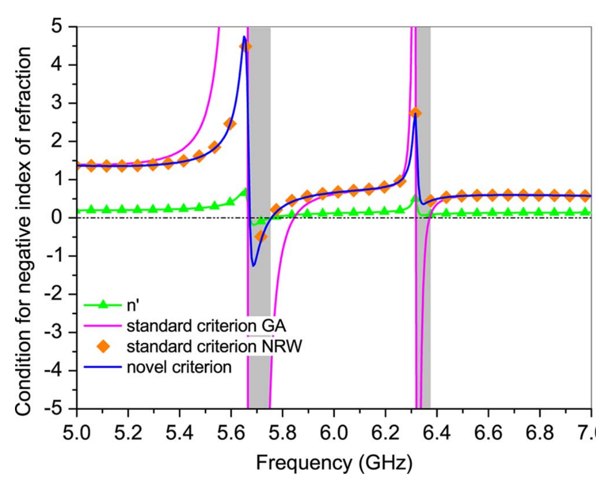


Fig. 15. Comparison of standard and novel criteria for negative index of refraction for unit cell with perpendicular gaps far from the microstrip line. Rectangular bars denote the range in which the cell has asymmetric response and two criteria predict different ranges of negative index of refraction.

Characteristics of unit cells with perpendicular gaps are compared in Fig. 14. It can be seen that the real part of the index of refraction is positive in the whole range of interest for the unit cell with the gap near the microstrip line, while the unit cell with the gap far from the microstrip line exhibits a narrow band with the negative index of refraction. Asymmetry is also much more pronounced if the gaps are far from the microstrip line,

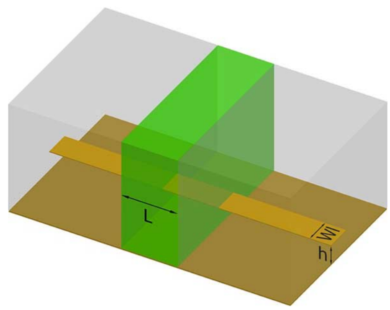


Fig. 16. Effective medium slab of the asymmetric unit cell (green box in online version) and input microstrip lines immersed in the effective dielectric (light gray boxes). Relevant dimensions: $L = L_r + 2L_m, h = h_1 + h_2$, where L_r, L_m, h_1, h_2 and W_l are given in Fig. 2.

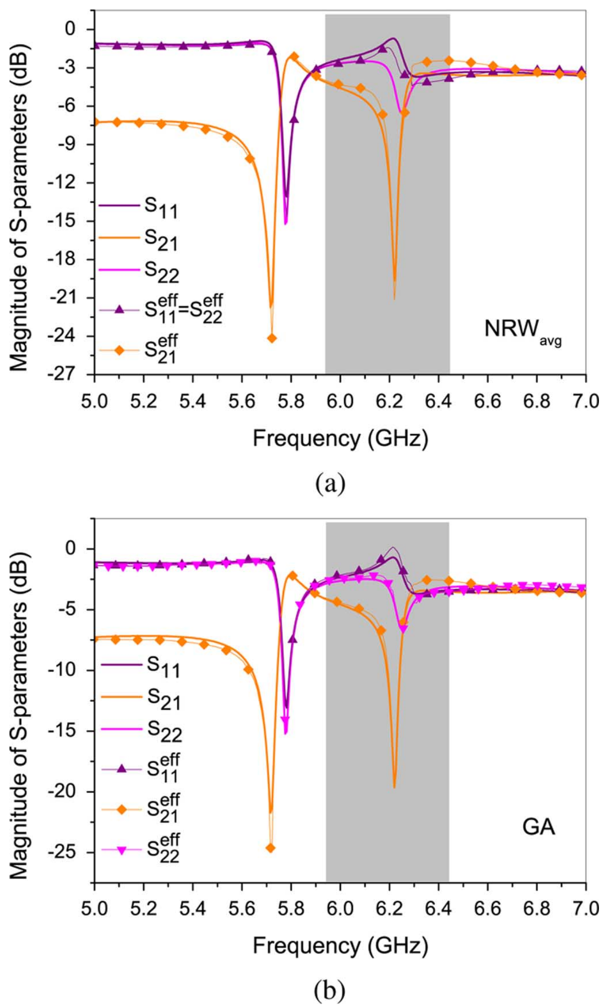


Fig. 17. Magnitudes of S-parameters simulated and recovered using the effective parameters. (a) $\mathrm{NRW_{avg}}$ and (b) GA retrieval methods. Rectangular bars denote the range of different magnitudes of S_{11} and S_{22}.

as was also the case with the unit cells containing the gaps parallel to the microstrip line. For both unit cells with perpendicular gaps, the maximum value of u-parameter ($u_{\mathrm{far}} = 8.6$ and $u_{\mathrm{near}} = 6.6$) is considerably greater than in the case of gaps parallel to the microstrip line ($u_{\mathrm{far}} = 3.69$ and $u_{\mathrm{near}} = 1.21$).

In Fig. 15, we compare the standard condition for the negative index of refraction and the novel condition for the unit cell with the upper gap far from the microstrip line. For calculating both conditions, we used the effective parameters extracted by the GA method. It can be seen that around the first resonance

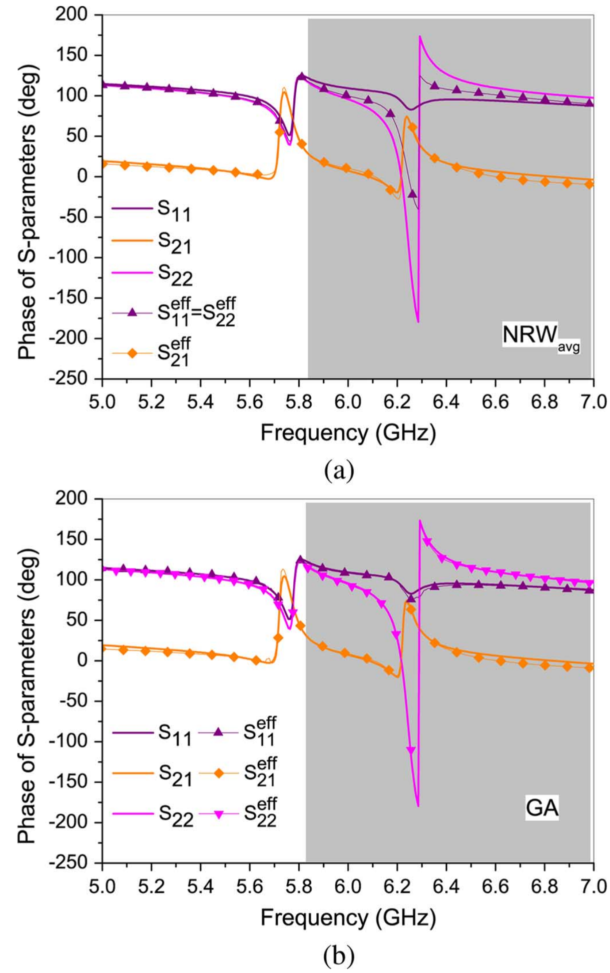


Fig. 18. Phases of S-parameters simulated and recovered using effective parameters. (a) $\mathrm{NRW_{avg}}$ and (b) GA retrieval methods.

the novel criterion exactly coincides with points where the real part of the negative index of refraction becomes zero. That is not the case with the standard criterion, which predicts considerably wider range of negative index. Around the second resonance at 6.3 GHz, the standard criterion predicts negative index of refraction while the real part of the index is positive. As a proof of validity of the novel criterion, we added the curve that corresponds to the standard criterion, but with data extracted by means of the $\mathrm{NRW_{avg}}$ method, which completely overlaps the novel criterion.

IV. Validation of the Extraction Methods

A. Decomposition Method

In order to validate the proposed method, an independent simulation of the microstrip line immersed in a slab of homogeneous material with the extracted effective parameters can be used, as depicted in Fig. 16. Input microstrip lines are immersed in the effective dielectric $\varepsilon_{\mathrm{eff}}^{\mathrm{ML}} = 3.15$. When calculating S-parameters of the effective medium slab, input microstrip lines are de-embeded. We can readily apply this procedure to restore the S-parameters for the NRW extraction, which uses an isotropic medium described by ε and μ, but to the authors' best knowledge, there is no EM solver capable of handling bianisotropic media.

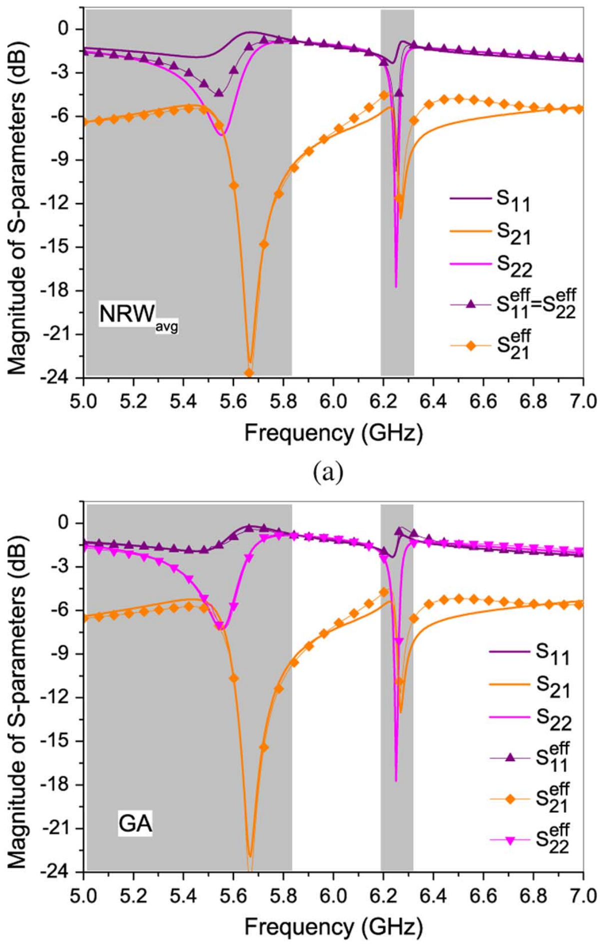


Fig. 19. Magnitudes of S-parameters simulated and recovered using the effective parameters. (a) $\mathrm{NRW}_{\mathrm{avg}}$ and (b) GA retrieval methods. Rectangular bars denote the range of different magnitudes of S_{11} and S_{22}.

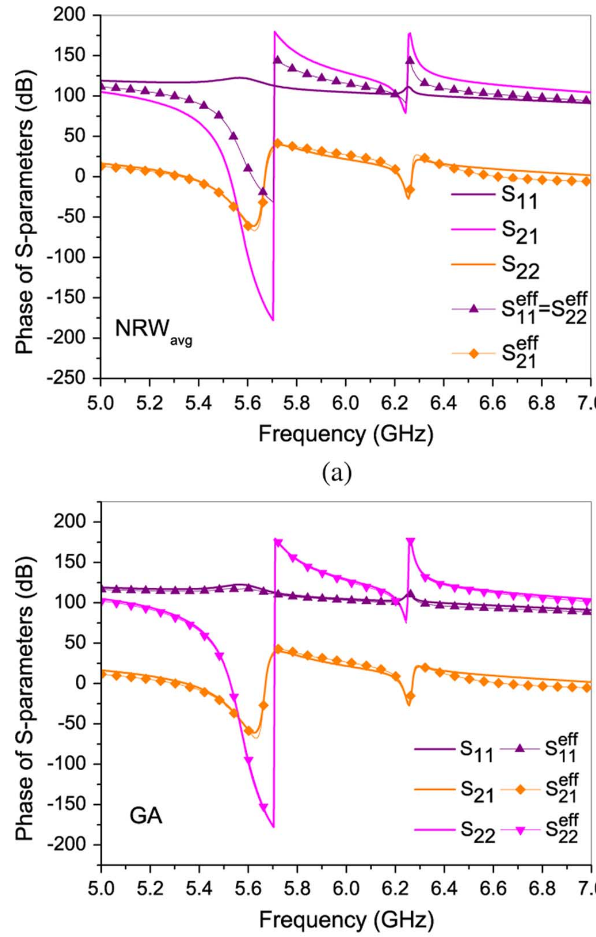


Fig. 20. Phases of S-parameters simulated and recovered using the effective parameters. (a) $\mathrm{NRW}_{\mathrm{avg}}$ and (b) GA retrieval methods.

Therefore, we propose the following work-around: we simulate two isotropic slabs corresponding to the GA_1- and GA_2-parameters described above, to obtain two sets of $ABCD$-parameters, denoted $ABCD_{\mathrm{GA1}}$ and $ABCD_{\mathrm{GA2}}$, respectively. Now, if we observe (19) more closely, we note that it represents what is known as *eigendecomposition* of a matrix in linear algebra, where $e^{\pm\gamma l}$ represents eigenvalues, and columns of matrix Q represent eigenvectors. From (17) and (19), it follows that the matrices $ABCD_{\mathrm{GA1,2}}$, since they imply a single value of impedance $Z_{c1,2}$, respectively, will decompose in the following form:

$$ABCD_{\mathrm{GA1,2}} = Q_{1,2}\,\mathrm{diag}(e^{\gamma l}, e^{-\gamma l})Q_{1,2}^{-1} \tag{30}$$

where

$$Q_{1,2} = \begin{bmatrix} 1 & 1 \\ \frac{1}{Z_{c1,2}} & -\frac{1}{Z_{c1,2}} \end{bmatrix} \tag{31}$$

respectively. Note that the eigenvalues $e^{\pm\gamma l}$ are the same for all three matrices.

From the simulation of the slabs GA_1 and GA_2, we obtain two sets of S-parameters, which can be converted to $ABCD_{\mathrm{GA1,2}}$. We then perform the eigendecomposition of these matrices to obtain the form of (30). This decomposition is readily available in software packages like MATLAB, and we only need to arrange eigenvalues and eigenvectors in the same order as in (30), which can be done according to the passivity criterion (26). Now we can obtain the matrix Q as

$$Q = \begin{bmatrix} Q_1(1,1) & Q_2(1,2) \\ Q_1(2,1) & Q_2(2,2) \end{bmatrix} \tag{32}$$

and finally, the resulting $ABCD$ matrix according to (19).

B. Unit Cell With Gaps Parallel to the Microstrip Line

The S-parameters resulting from the described approach for the unit cell with gaps parallel and far from the microstrip line [see Fig. 2(b)], compared with the original simulations, are shown on Figs. 17 and 18, for both the $\mathrm{NRW}_{\mathrm{avg}}$ and GA method. The $\mathrm{NRW}_{\mathrm{avg}}$ method [see Figs. 17(a) and 18(a)] results in symmetric response (therefore only one reflection coefficient $S_{11}^{\mathrm{eff}} = S_{22}^{\mathrm{eff}}$ is reconstructed), which clearly fails to reproduce reflection in the range of pronounced asymmetry correctly (marked with a rectangular bar). This is most visible in phase, where the obtained value behaves as mean of the original phases of S_{11} and S_{22} (this is expected because of the used averaging procedure).

The GA method, however, clearly distinguishes two different values of reflection coefficients, which are very close to the original values [see Figs. 17(b) and 18(a)]. It is clearly visible that the effective parameters extracted by the GA method allow the recovery of all S-parameters, which is not the case with the parameters retrieved by the $\mathrm{NRW}_{\mathrm{avg}}$ method, that can restore only S_{21}, but not S_{11} and S_{22} in the range where asymmetry is present. The unit cell has symmetric response out of that range and both methods work correctly. We believe that the presented results clearly show that the GA method is advantageous over the $\mathrm{NRW}_{\mathrm{avg}}$ when asymmetry is present, while it gives exactly the same results as the well-established NRW method for symmetric response.

C. Unit Cell With Gaps Perpendicular to the Microstrip Line

Results for the unit cell with gaps perpendicular to, and upper gap near the microstrip line [see Fig. 10(b)], compared with the original simulations, are shown in Figs. 19 and 20, for the $\mathrm{NRW}_{\mathrm{avg}}$ and GA methods. Again, the $\mathrm{NRW}_{\mathrm{avg}}$ method [see Figs. 19(b) and 20(b) reproduces only the mean value of reflection, the disparity here being even more striking, due to the greater asymmetry of the unit cell. The GA method closely reproduces both reflection coefficients once again [see Figs. 19(b) and 20(b)]. To conclude, the GA method is able to restore all S-parameters in the whole frequency range of interest, while the $\mathrm{NRW}_{\mathrm{avg}}$ method recovers them only in the range of symmetric response. Especially good agreement is obtained in the phases of S-parameters. There are small discrepancies in the recovered magnitude of S_{21} around the second resonance, which appear equally in both methods.

V. CONCLUSION

In this paper, we have presented the GA for the extraction of effective parameters for the metamaterial transmission line loaded with asymmetric unit cells. To describe the asymmetry, we have introduced an equivalent bianisotropic medium, which emulates the effect of asymmetric unit cells. Besides standard constitutive parameters such as permittivity, permeability, and characteristic impedance, the equivalent medium is described by two additional parameters, u and η, which are very useful as a measure of asymmetry.

We derived a novel condition necessary for achieving a negative index of refraction in the bianisotropic medium. According to it, the criterion valid for isotropic medium is relaxed in the range in which the real and imaginary part of the u-parameter are both negative or positive, while the criterion becomes more strict if they have different signs.

The proposed generalized extraction procedure and the $\mathrm{NRW}_{\mathrm{avg}}$ method, adopted for asymmetric unit cells, are applied to novel dual-band unit cells. They consist of BSC SRRs with gaps displaced from the center (to the left and to the right or up and down), along two gap-bearing sides, which are placed one above the other. It was shown that unit cells with gaps parallel with the microstrip line exhibit asymmetry only around one resonance. Unit cells with gaps perpendicular to the microstrip line have a very asymmetric response around both resonances. Therefore, the effective permittivity and permeability extracted using the GA and $\mathrm{NRW}_{\mathrm{avg}}$ methods are significantly different.

To conclude, we have shown that the $\mathrm{NRW}_{\mathrm{avg}}$ procedure gives the correct index of refraction in the whole frequency range, but wrong effective permittivity, permeability, and characteristic impedance in the range of asymmetric response.

This was proven through the validation procedure where the asymmetric unit cell was replaced by effective medium slabs with the parameters extracted by the proposed GA method. The all original S-parameters were successfully restored, which was not the case when the parameters extracted by the approximate $\mathrm{NRW}_{\mathrm{avg}}$ method are used.

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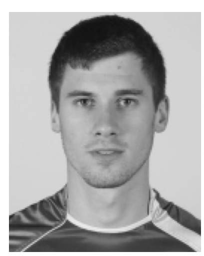

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