The figure of merit of MS lines has been included for comparison purposes. Conductors: $\sigma = 3.8 \times 10^7$ (Aluminum), $t = 2 \mu m$; Substrate: sapphire, $\varepsilon_r = 10$, $\tan \delta = 10^{-4}$, $h = 500 \mu m$; Ferroelectric film: $\varepsilon_{eff} = 700$, $\tan \delta = 5 \times 10^{-2}$, $h_i = 0.5 \mu m$. $3 \mu m < g < 30 \mu m$.

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cases, some improvements based on the determination of effective boundaries, forced continuity of the dispersive effective refractive index, and the elimination of the measurement/simulation noise influence on effective impedance of the DNG cell were proposed in Ref. 10.

The approach presented in this Letter is related to the extraction from scattering parameters. The main difference relies on the fact, that the shape of parameterized characteristics for effective permittivity and permeability is assumed a priori, and their parameters are optimized in order to obtain the best fitting to the reference responses.

2. PARAMETER FITTING OF DISPERSION MODELS

Within the presented method, effective material parameters are found by fitting scattering parameters of the equivalent representation to the scattering parameters of the reference structure. The reference structure is a detailed DNG geometry simulated in the electromagnetic solver, while the effective representation is a slab of an isotropic, homogeneous material described by dispersive Drude (electric permittivity) and Lorentz (magnetic permeability) models. The coefficients of the dispersive models are the parameters in the optimization process. The optimization goal is to minimize the difference between the scattering parameters obtained for the reference structure and the homogeneous structure. The homogeneous cell should provide the same transmission/reflection behaviour as the SRR/wire based DNG cell.

The simulation procedure for the DNG reference cell (structure from [2], dimensions given in Fig. 1), is similar to the one used in Ref. 11. An automeshing algorithm is used in CST Microwave studio [12] to create the computational grid for the SRR/wire geometry. Hundred mesh points per medium wavelength are chosen, resulting in ~38,400 mesh cells. The excitation pulse has a Gaussian distribution in time domain that is transformed into 1000 intermediate frequencies from 7 to 12 GHz in the frequency domain. The ports are at the \( \pm x \) limits of the mesh volume where open boundary conditions are used. The structure is excited by the first mode of a waveguide port, with the electric field polarized in the \( y \) direction and propagating along the \( x \) direction. Magnetic boundary conditions are applied at the faces along the axis of the rings (\( \pm z \) limits) and electric boundary conditions are used at the \( \pm y \) faces of the mesh volume. The ring and the wire are made of copper and placed on a 0.25 mm thick dielectric slab characterized by \( \varepsilon_r = 3.84 \) and \( \tan \delta_r = 0.018 \). The numerical problem is solved by a time domain solver until the residual accuracy is \(-50 \) dB. Obtained scattering parameters \( S_{11\text{ref}} \) and \( S_{21\text{ref}} \) are presented in Figure 2.

The effective representation of the DNG MTM cell is a homogeneous slab with its thickness the same as for the MTM unit cell (5 mm for the structure from Fig. 1) and modelled as an isotropic medium with dielectric dispersion described by Drude model and magnetic dispersion characterized with Lorentz model. The Drude/Lorentz description of a DNG MTM is a common approach [13], where the Drude model of \( \varepsilon_{\text{eff}} \) represents an artificial medium composed of a lattice of wires [14], and the Lorentz model of \( \mu_{\text{eff}} \) accounts for the effects in SRRs [1].

The scattering parameters for the homogenized DNG cell are obtained analytically. The effective permittivity and permeability models are assumed to be of the Drude and Lorentz form, respectively (the assumed time-dependence notation is \( \exp(+j\omega t) \)), the values of \( \varepsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) are relative to those in free space):

\[
\varepsilon_{\text{eff}}(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega - i\nu_c)}
\]

where \( \varepsilon_\infty \) electric permittivity at the high frequency limit, \( \omega_p \) radial plasma frequency, \( \nu_c \) collision frequency,
where \( \mu_0 / \mu_\infty \) magnetic permeability at the low/high frequency limit, \( \omega_0 \) radial resonant frequency, \( \delta \) damping frequency.

From the assumed material parameters effective impedance and refractive index are obtained (\( Z_0 \) is the impedance of free space):

\[
Z_{\text{eff}} = Z_0 \sqrt{\mu_{\text{eff}} / \epsilon_{\text{eff}}} \tag{3}
\]

\[
n_{\text{eff}} = \sqrt{\mu_{\text{eff}} \epsilon_{\text{eff}}} \tag{4}
\]

As the MTM structure is a passive medium, the signs in Eqs. (3) and (4) are determined by the requirement \( \text{Re}(Z_{\text{eff}}) \geq 0 \) and \( \text{Re}(\epsilon_{\text{eff}}) \geq 0 \).

The reflection coefficient \( R \) at the boundary between free space and MTM slab of effective impedance \( Z_{\text{eff}} \):

\[
R = \frac{Z_{\text{eff}} - Z_0}{Z_{\text{eff}} + Z_0} \tag{5}
\]

Transmission \( T \) through the homogenized slab of effective impedance \( Z_{\text{eff}} \), refractive index \( n_{\text{eff}} \), and thickness \( d \) gives:

\[
T = \exp \left( -j \frac{\omega}{c} n_{\text{eff}} d \right) \tag{6}
\]

where \( \omega \) radial frequency and \( c \) velocity of light in free space.

The dependence between reflection/transmission and scattering parameters [6]:

\[
S_{11} = \frac{(1 - T^2) R}{1 - R T^2} \tag{7}
\]

\[
S_{21} = \frac{(1 - R^2) T}{1 - R T^2} \tag{8}
\]

The Eqs. (1)-(8) relating scattering parameters with effective MTM permittivity and permeability are implemented in Matlab [15]. An optimization algorithm [16] searches for the values of \( \epsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) subparameters (namely: \( \epsilon_\infty, \omega_\infty, \omega_\infty, \mu_\infty, \mu_\infty, \omega_0, \delta \)) providing the best fit between the scattering parameters of the homogenized (S11, S21) and the reference structure (S11, S21, ref). The optimizer goal function takes the form:

\[
G = \sum_i (|S_{11} - S_{11,\text{ref}}|^2 + |S_{21} - S_{21,\text{ref}}|^2) \tag{9}
\]

where scattering parameters are fitted at \( f \) frequencies in the frequency range of interest.

The optimized parameters of Drude and Lorentz models for the structure in Figure 1 are given in Table 1. A comparison of magnitude and angle of scattering parameters obtained by optimization with the reference results in Figure 2 shows a very good fitting. Corresponding \( \epsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) characteristics given in Figure 3 show a DNG behaviour in the frequency range 9.69–10.24 GHz. On the same figure effective permittivity and permeability extracted according to the method from [9] are presented. The obtained \( \epsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) values agree very well in the given frequency range. A small discrepancy for electric permittivity characteristic occurs at the frequency close to the resonant frequency of the magnetic permeability \( \omega_0 \) (note the small negative value of \( \epsilon'' \) which is a common problem of this method [9]).

3. DISCUSSION

The DNG MTM are generally anisotropic structures and their electromagnetic properties depend on the polarization of the applied field. The simple isotropic model presented in this article allows for the extraction of the diagonal components of permittivity and permeability tensors corresponding to the orientation of the

Figure 3. Effective magnetic permeability \( \mu'' \) and electric permittivity \( \epsilon'' \) (top) and \( \epsilon' \) (bottom) obtained by parameter fitting of dispersive models (\( \mu' \), \( \epsilon' \) solid thick line; \( \mu'' \), \( \epsilon'' \) solid thin line) and by direct extraction from scattering parameters according to the method from [9] (dotted line); the dashed vertical lines limit the DNG frequency band.
excitation field. For many MTM structures, however, it is sufficient description.

The presented approach is limited to non and weak bianisotropic structures (for Ey and Hz field excitation, the SRR/wire configuration from Figure 1 is an example of such a structure [17]). The simple Drude/Lorentz model description does not take into account magnetoelectric couplings and for bianisotropic MTM more complicated methods of extraction should be used (e.g. [18]).

The a priori assumed Drude/Lorentz type shape of the effective parameters can be regarded as a limitation of the presented method. However, due to the strong resonant behaviour of DNG lattices, the extracted parameters of MTM structures are very often of such a shape [10, 11, 19]. On the other hand, there is no problem with the continuity of the fitted $\varepsilon_{eff}$ and $\mu_{eff}$ characteristics. The imaginary parts of permittivity and permeability are positive ($\varepsilon'' > 0$ and $\mu'' > 0$), which is not always the case with traditional extraction from scattering parameters [9, 19, 20]. Some numerical ambiguities known for the extraction from scattering parameters (e.g. multiple branches of the logarithm function for the extraction of the real part of effective refraction index [8, 10]) are also avoided.

The method can be straightforwardly adopted to the fitting of effective description for single negative structures (e.g. MTM with negative magnetic permeability), as well as to arbitrary types of dispersive models. The delivered dispersive models can be directly implemented in commercial solvers [12] for higher order simulations of large structures composed of many MTM unit cells.

4. CONCLUSIONS

By optimization of parameterized Drude and Lorentz models the effective electric permittivity and magnetic permeability for SRR/wire structure have been found. The scattering parameters obtained for the equivalent representation agree very well with the reference results. The proposed approach helps to avoid some numerical problems occurring in the known extraction methods and can be applied to the extraction of effective material parameters for single and double negative metamaterials.

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