A Wideband ADI-FDTD Algorithm for the Design of Double Negative Metamaterial-Based Waveguides and Antenna Substrates

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Abstract—The accurate modeling of composite double negative metamaterials tailored for enhanced waveguide and antenna structures, is presented in this paper via a novel 3-D ADI-FDTD method. Developing a set of multi-directional operators for the discretization of such complex media, the unconditionally stable technique leads to broadband solutions and minimizes dispersion errors as time-step exceeds the Courant criterion. Hence, efficient microwave devices, loaded by periodic substrates of thin wires and split-ring resonators, can be optimally designed without the need of lengthy simulations.

I. INTRODUCTION

Modern double negative (DNG) metamaterials [1] are synthesized by artificial inhomogeneities which allow the simultaneous tuning of both effective constitutive parameters to negative values. Their significant features have been effectively engineered in the microwave regime [2-4] via split-ring resonators (SRRs) and thin metallic wires, whose fine details require a systematic treatment. Towards this aim, the alternating-direction implicit finite-difference time-domain (ADI-FDTD) method can be proven very instructive [5-7]. However, intensive research has shown a serious increase of its dispersion errors as time-steps become larger.

In this paper, an advanced frequency-dependent ADI-FDTD algorithm is introduced for the precise design of DNG metamaterial-based waveguides and antennas. To model their demanding geometric details and rapidly compute large fields in areas much smaller than the incident wavelength, the new scheme provides a class of 3-D curvilinear operators. Also its wideband profile resolves all propagation or evanescent modes, while a volumetric stencil process treats arbitrary interfaces. So dispersion errors are drastically suppressed for time-steps far above the Courant limit unlike other approaches. These merits are numerically validated by diverse coupled SRR-loaded junctions and “smart” antennas.

II. ENHANCED ADI-FDTD MODELING OF DNG MEDIA

The primary aspect of our technique is the consistent analysis of the metamaterial regions realized either by wires and SRRs or via the equivalent lossy Lorentz models. For instance, the negative effective permeability $\mu_{\text{eff}}$ of an SRR array is described by

$$\mu_{\text{eff}} = \mu_0 \left(1 - \frac{\omega^2}{\omega_c^2 + j \omega \Gamma}\right)$$

where $F$ is the fill factor, $c$ the light velocity and $r, d, l, g, \Gamma$ the SRR dimensions ($\omega_c$ of the wires is equally treated). For the new ADI-FDTD forms in $(u,v,w)$ coordinates, we express magnetic $B = [B_u, B_v, B_w]^T$ and electric $D = [D_u, D_v, D_w]^T$ flux densities, as

$$\mathbf{B} = \mu_{\text{eff}}(\omega) \mathbf{H} = \mu_0 \mathbf{H} - \mathbf{M}$$

$$\mathbf{D} = \varepsilon_{\text{eff}}(\omega) \mathbf{E} = \varepsilon_0 \mathbf{E} - \mathbf{P}$$

with $\mathbf{H} = [H_u, H_v, H_w]^T$, $\mathbf{E} = [E_u, E_v, E_w]^T$ the field intensities and $\mathbf{M}, \mathbf{P}$ the relevant frequency-dependent polarizations. The latter satisfy constitutive relations with the prior Effective Material (EM) expressions (2),(3) in Maxwell’s laws, spatial derivatives are evaluated by the dispersionless $M$th-order operators, that outperform usual schemes,

$$L^{M}_{\xi} \left[ f \right]_{\xi,v,w} = \sum_{\mu=1}^{M} \sum_{\nu=\pm 1}^{\pm 1} \frac{(\Delta \xi)^{\mu+1}}{(3 \nu + 2)!} \frac{\partial^{\nu+1}}{\partial \xi^{\nu+1}} \left[ f \right]_{\xi,v,w} \sum_{\nu=1}^{\nu} s_{\nu} m^{\mu+1},$$

where $s_{\nu}$ the spatial increment, $s_{\nu}$ adjustable coefficients and $R_{\nu}$ a multi-directional approximation. Defining an analogous operator $T^{M}_{\nu}$ for temporal derivatives, each time-step is divided into two sub-iterations. The first spans from $n$ to $n + 1/2$ and the second from $n + 1/2$ to $n + 1$. Indicatively, from Amper’s law, $E_n$ component during the first sub-iteration, becomes

$$4T^{1/2}_{\nu} \left[ E_{n+1/2} \right]_{\nu} = 2J_{n+1/2}^{x}$$

and (c) broadband evaluation of the light velocity and $\omega_{\text{eff}}$.

III. NUMERICAL RESULTS

The $H_1$ snapshots of a patch antenna (Fig. 1a) with rectangular/curvilinear SRRs and the $S$-parameters of a 9.2$\times$4.6$\times$19.3 mm $T$-junction are shown in Figs 1b, 1c. As observed, the wideband technique, by reducing dispersion errors up to 10 orders, attains smooth distributions and very accurate outcomes while the common ADI-FDTD ones are 15-30 dB away from the reference.

IV. REFERENCES