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Numerical modeling of pulse propagation through a double-negative metamaterial with adjacent absorptive and gain Lorentz dispersions: A comparison

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ABSTRACT

The state-of-the-art time-domain numerical techniques, the finite-deference time-domain (FDTD) method and the pseudospectral time-domain (PSTD) method, are applied to simulate the physical propagation process of a pulse through a double-negative metamaterial with adjacent absorptive and gain Lorentz dispersions. The algorithmic feasibility and modeling accuracy of the two numerical methods combined with the common techniques for Lorentz dispersion implementation are demonstrated from the obtained simulation results and compared with the analytical solution. It is shown that the FDTD method with material parameters averaged at the slab's two interfaces works better than that without averaging and also better than the case of PSTD method with the same time and space discretization parameters. The proposed techniques are useful for the ultra-accurate modeling of pulse interaction with metamaterials.

1. Introduction

A sufficient requirement for a negative refractive index is that both the permittivity and permeability are simultaneously negative [1]. A medium having such a property is often called a double-negative material or, more traditionally but less rigorously, a left-handed material. Although a negative-index material is not naturally available, electric and magnetic dipoles in the artificial materials operating in the effective medium limit have been shown to exhibit an effective negative refractive index [2]. Of great interest, a negative index media with zero loss at a specific operating frequency would potentially allow a perfect imaging [3], which foreshows its wide applications in microscopy, semiconductor device processing, and optical memories [4]. There has been reported to use gain to offset loss and therefore it is possible to achieve a zero loss operating condition through a mixture of two semiconductor quantum dots and with the permittivity and permeability both being real and negative [5].

In this work, both the finite-deference time-domain (FDTD) method [6] and the pseudospectral time-domain (PSTD) method [7] are applied to accurately modeling a type of Lorentz metamaterials with adjacent loss and gain resonances. The PSTD method seems superior to the FDTD method in view of the fact that in the former algorithm, both electric and magnetic field components locate at the same location within a cell. This advantage circumvents the ensuing problems, such as the

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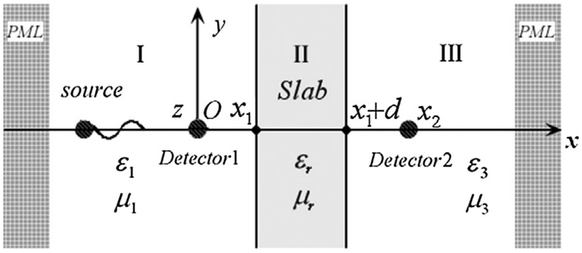

Fig. 1. Schematic configuration for the numerical simulations.

artificial transition layers at the object's boundaries [8] due to the staggering field components applied in the algorithms like the FDTD method. Unfortunately, the PSTD method is weak in representing the abrupt change of electromagnetic field at an interface, say, between the free space and a double-negative metamaterial. It would introduce spurious aliasing errors on the electromagnetic field on all cells within the computational space, which is also the reason why a spatially smoothed source is required in order to excite electromagnetic waves in the PSTD method [9]. The FDTD algorithm doesn't have such a phenomenon due to the fact that the spatial derivatives are calculated from the field values on two adjacent cells.

Furthermore, the artificial transition layer occurring in the FDTD algorithm can be efficiently alleviated by using smaller size of spatial cells or applying spatial averaging at the boundaries [10]. Therefore it is of interest to investigate whether the FDTD method with or without material parameter averaging at the two interfaces outperforms the PSTD method in modeling this special type of metamaterials. For the negative vales of permittivity and permeability cannot be directly assigned into the FDTD or PSTD updating equations, the dispersion-implementation approach must be incorporated into them to model such a highly-dispersive metamaterial and herewith we utilize the piecewise linear recursive convolution (PLRC) algorithm as it is accurate in simulating various metamaterials with multiple Debye or Lorentz dispersions [11].

2. System configuration

The configuration of the system studied is shown in Fig. 1, where Regions I and III are the free space with $\varepsilon_1 = \varepsilon_3 = 1$, and $\mu_1 = \mu_3 = 1$. A flat slab of thickness d occupies Region II between the interfaces $x = x_1$ and $x = x_1 + d$, and infinitely extends in both y and z directions. The source is placed in the left part of Region I to generate the incident pulse. Detector 1 is placed in the right-hand side of the source to record the temporal waveform of incident pulse when the slab is removed, which avoids the influence of the reflected pulse from the slab's interfaces. As an accurate reference, this detector is set at the origin of x axis for the sake of mathematical convenience. Detector 2 is utilized to record the waveform of pulse transmitting through the plane $x = x_2$. The whole computational space is truncated by the uniaxial perfectly-matched layers (UPML) at both ends to absorb the outgoing waves [12]. The flat slab is made from the type of special metamaterial with the material parameters proposed in Ref. [5], whose relative permittivity and permeability has an identical dispersion model with impedance matched to free space and given by

$$\varepsilon_r(\omega) = \mu_r(\omega) = 1 + \sum_{m=1}^{2} (-1)^{m+1} \frac{\omega_{pm}^2}{\omega_{0m}^2 - j2\omega\delta_m - \omega^2}, \quad (1)$$

where ω_{p1} and ω_{p2} are the two plasma angular frequencies, ω_{01} and ω_{02} are the resonance angular frequencies; δ_1 and δ_2 are the damping or gain coefficients, respectively. The other material parameters in the numerical simulations are $f_{01} = \omega_{01}/2\pi = 3$ GHz, $f_{02} = \omega_{02}/2\pi = 1.5 f_{01}$, $\delta_1 = \delta_2 = \sqrt{(\omega_{02} - \omega_{01})^2/8}$, $\omega_{p1} = \omega_{p2} = \sqrt{(\omega_{02}^3 - \omega_{01}^3)/(\omega_{01} + \omega_{02})}$. Under this set of material parameters, the 'perfect' frequency for this metamaterial is

$$f_p = \omega_p/2\pi = \sqrt{(\omega_{01}^2 + \omega_{02}^2)/(8\pi^2)} = 3.8243\text{GHz}, \quad (2)$$

at which frequency the condition $\varepsilon_r(\omega_p) = \mu_r(\omega_p) = -1$ for a perfect lens is satisfied [3]. The relative permittivity and the permeability, as well as the complex refractive index, share the same expression given by (1) and are illustrated in Fig. 2 as functions of frequency, where the 'perfect' frequency f_p is exclusively marked.

Apparently, such a metamaterial is absorptive in the frequency range below f_p, while active at the frequencies above f_p. In the frequency region near f_p, the imaginary part is nearly linear but quite steep, implying a dramatic transition of the property of medium from loss to gain. The analytical solution to the complex transmission coefficient in frequency domain is given by

$$T(\omega) = \exp\{j\omega[n(\omega)d + (x_2 - d)]/c_0\}, \quad (3)$$

where c_0 is the speed of light in free space, $n(\omega) = Re[n(\omega)] + jIm[n(\omega)]$ is the complex refractive index of metamaterial. On the other hand, based on the simulation results about the waveforms recorded by Detector 1 and Detector 2, the numerical