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The analysis of the electromagnetic characteristics of composite materials with negative effective permittivity

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Abstract A new method based on the finite difference time domain (FDTD) method is presented to numerically analyze the transmission and reflection characteristic of composite materials with negative effective permittivity. The numerical results are compared with the results of the existing theoretical model and the experimental data. The feasibility of analyzing the composite materials using the FDTD method is validated. It is useful for the design and application of the composite materials.

Keywords composite materials, negative permittivity, FDTD, transmission and reflection characteristic

1 Introduction

Composite materials have inspired more and more interest due to their unique physical properties and novel applications. As reported, a negative effective permittivity material can be obtained by arranging discontinuous thin metallic wires [1], while on the other hand, a negative effective magnetic permeability material can be obtained by arranging split-ring-resonators (SRRs) [2]. It is the combination of the SRRs and thin wire composite materials that creates the double negative meta-materials (DNG) [3]. Composite materials have been widely used in the realms of science and engineering, such as restraining the spontaneous emission of semiconductor laser, high-impedance surface, improvement of antenna radiation pattern [4,5] and so on.

Although the physical properties of composite materials could be obtained through the experiments, the theoretical analysis and the value modeling work are also essential. At present, several proposed methods are the integral methods in the theoretical analysis aspect, such as the plane wave

method, N factorial method, transfer matrix method, combined plane wave method, and moment method. These methods are similar to the methods that are used to analyze the energy bands of solids in solid physics. A periodic unit of the composite materials is chosen as the research object in these methods. Energy band structure is presented as the simulation result but it cannot show the transmission and reflection characteristic of the composite materials intuitively.

In this paper, the difference method as well as the FDTD method is employed to analyze the transmission and reflection properties of composite materials to the electromagnetic wave. The simulation results are compared with the existing theoretical models and other experimental data. The feasibility of analyzing the composite materials using the FDTD method is validated, which provides a new method to analyze composite materials.

2 The FDTD method for composite materials

In this paper, composite materials with negative permittivity are selected as the research object. As shown in Fig. 1 [6], the composite materials that are obtained by arranging discontinuous thin wires are constructed on a printed circuit board. The transmission and reflection properties of the materials are analyzed concretely when the incident plane electromagnetic wave transmits along the x direction.

Because the structure of the composite materials is complex, the analysis of the transmission and reflection characteristic of the composite materials using the simplex FDTD methods is not perfect. In this paper, the method is further used to study the composite material expanding infinitely in the y - z plane. In the y - z plane, the unit structure of the composite material is regarded as the research object. The metal wire is supposed to be an ideal conductor with no thickness. The periodic boundary condition (PBC) is adopted around the unit. In the x direction, unit cells selected are decided by the study. The units are arranged periodically with 1, 2 and 3 unit cells in the x directions. berenger perfectly matched layer (BPML) is adopted in this paper too. In this paper, BPML and

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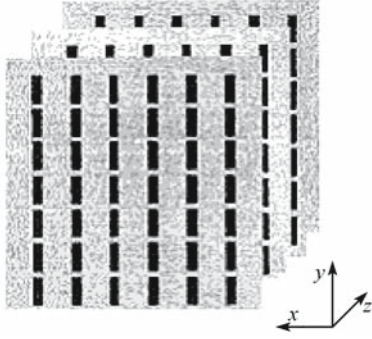


Fig. 1 The negative permittivity medium

gedney perfectly matched layer (GPML) are both appropriate because there is no assistant field in the main calculation zone. In order to introduce the incident electromagnetic wave and select the parameter easily, the entire calculation zone is divided into two parts, namely the entire field zone and the dispersion field zone. As shown in Fig. 2, the units are arranged periodically with one unit cell in the x direction, and the broken line is the connective boundary.

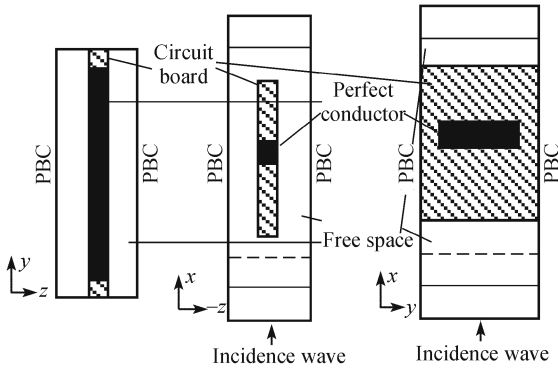


Fig. 2 Partition of the calculation zone and setting of the boundary condition

The entire calculation zone comprises three parts. The first part is free space with $\epsilon_r = \mu_r = 1$. The second part is the circuit board on which the ideal conductor is constructed. μ_r and ϵ_r are relative permittivity and permeability of the insulating material of the printed circuit board, respectively. The last part is the ideal conductor. The tangential component of the electrical field on its surface equals to zero and each component of the electrical field and magnetic field in it all equals to zero too. Through numerical simulation, it was found that the PBC adopted could be the electric field boundary condition and magnetic field boundary condition or that one part is the electric field boundary condition and the other is magnetic field boundary condition. In the y - z plane, the calculation zone is limited in one unit cell when one of these boundary conditions is adopted. In this paper, the magnetic field boundary condition is adopted. The periodic length at the direction of y is assumed as a_y and as a_z at the

direction of z . Based on the Floquet theorem, at the periodic boundary condition there is

$$\begin{aligned} H_x(x, y + a_y, z) &= H_x(x, y, z)e^{-jk_y a_y} \\ H_x(x, y, z + a_z) &= H_x(x, y, z)e^{-jk_z a_z} \\ H_y(x, y, z + a_z) &= H_y(x, y, z)e^{-jk_z a_z} \\ H_z(x, y + a_y, z) &= H_z(x, y, z)e^{-jk_y a_y} \end{aligned} \quad (1)$$

To the incident electromagnetic wave from the x direction, $k_y = k_z = 0$, and the equation can be:

$$\begin{aligned} H_x(x, y + a_y, z) &= H_x(x, y, z) \\ H_x(x, y, z + a_z) &= H_x(x, y, z) \\ H_y(x, y, z + a_z) &= H_y(x, y, z) \\ H_z(x, y + a_y, z) &= H_z(x, y, z) \end{aligned} \quad (2)$$

The absorbing boundary of BPML of the calculation zone comprises non-physics absorbing media. H_x and E_x are in standard FDTD difference format. H_x , H_z , E_y , and E_z are divided into $H_{yx} + H_{yz}$, $H_{zx} + H_{zy}$, $E_{yx} + E_{yz}$ and $E_{zx} + E_{zy}$ respectively. The detailed difference format is shown in Refs. [7,8].

3 Numerical simulation results

The dimension of the composite material adopted in this paper equals to the data in Ref. [6], that is $a_x = 9.3$ mm, $a_y = 9$ mm, and $a_z = 6.5$ mm. The board with parameters $\mu_r = 1$ and $\epsilon_r = 4.41$ has a refractive index of 2.1 and a thickness of 1.5 mm. The depositing discontinuous wire strips have a height of 8.65 mm (along y axis) and a thickness of 0.35 mm (along x axis). The gap of the two strips is 0.35 mm. The dimension of the difference mesh in the FDTD method is adopted as $\Delta x = 3.0 \times 10^{-4}$ m, $\Delta z = 1.5 \times 10^{-4}$ m. In order to simulate modeling accurately, the mesh is adopted as a gradual changed non-uniform mesh with $\Delta t = \Delta y_{\min}/2c$ because of the complex structure at the direction of y . The incident electromagnetic plane wave perpendicular to the metal wire is set as $E_y = 1000\sin(2\pi ft)$ and the frequency adopted is from 1–24 GHz. The measured transmission and reflection characteristics of the composite material are displayed in Fig. 3 when the unit-cells are 1, 2 and 3 along the x -axis. From the graph, it is found that when there is only one unit cell, the composite materials cannot exhibit a stop-band. On the contrary, the electromagnetic wave about 10 GHz is restrained strongly, which bear analogy to the case of resonance. But when there are 2 unit cells along the x axis, the composite material exhibits a stop-band from 5–20 GHz. Although the stop-band extends from 5–20 GHz when there are 3 unit cells, the composite material has stronger restraint to the electromagnetic wave and lower transmission rate. So, it is concluded that when the periodicity along the x -axis increases, the width of the stop-band remains unaltered, and

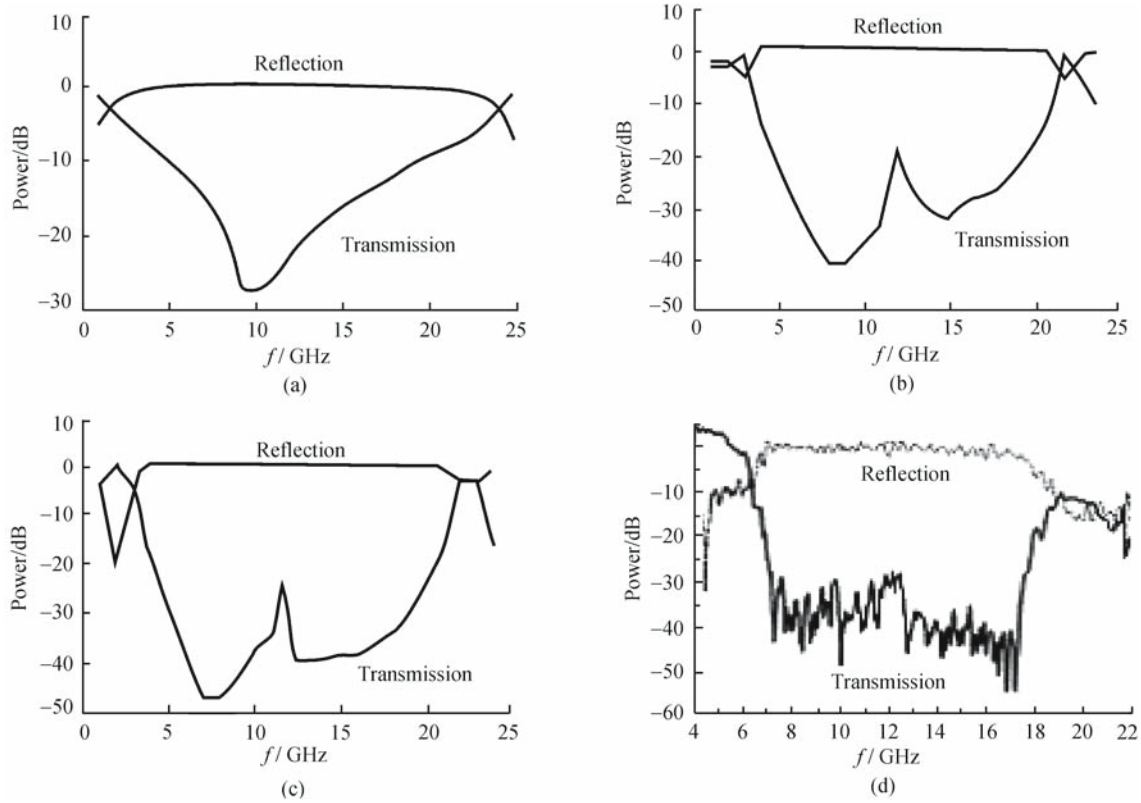


Fig. 3 The transmission and reflection characteristics of the composite material. (a) 1 unit cell at the x direction; (b) 2 unit cell at the x direction; (c) 3 unit cell at the x direction; (d) Ekme's Result of experimentation

the composite material has stronger and stronger restraint with lower and lower transmission rate.

Contrasting the experimental data and the result of the numerical simulation, it is found that the measured transmission and reflection characteristics agree with the result obtained by means of FDTD, that is, the flanks of pass-bands are stop-band. There are some differences in the detail between the two results because of the following three aspects. Firstly, the composite material for numerical simulation is adopted as expanding infinitely in the y - z plane and the unit-cells are 2 and 3 at the x direction. But for the experimental composite material, the number of unit-cells is 15 located at the x direction, 15 at the y direction, and 20 at the z direction. Secondly, in the analysis, the discontinuous metallic wire used is an ideal conductor, but is not actually an ideal conductor in reality. Thirdly, the refractive index of the actual circuit board, on which the discontinuous metallic wire is constructed, is assumed to be Sect. 2.1, and its relative permittivity and permeability are not presented in Ref. [6]. In this paper, the relative permittivity and permeability of the circuit board are assumed as $\mu_r = 1$ and $\varepsilon_r = 4.41$. From the analysis, it is found that the feasibility to analyze the composite materials using the FDTD method is validated and the simulation results are trusted. Furthermore, the transmission and reflection characteristic in the stop-band of the composite materials are compared with the Drude model wherein relative permittivity is negative. It is supposed that

the incident plane electromagnetic wave is a sine wave, the frequency is 10 GHz, and $E_y = 1000\sin(2\pi ft)$. When the incident plane electromagnetic wave is vertical to the media board, the value of the electric field behind the media board is shown in Fig. 4.

From the graph, it is found that the results obtained by two different methods almost have the same values. After the incident electromagnetic wave transmits steadily, it cannot penetrate the media board in the stop-band.

4 Conclusions

In this paper, the negative permittivity composite materials obtained by arranging discontinuous thin metallic wires on a circuit board is selected as the research object. The method involves expanding the composite material infinitely in the plane perpendicular to the incident plane electromagnetic wave. Numerical analysis of the transmission and reflection characteristic of the composite materials is given by using the proposed method. The simulation results are compared with the existing theoretical model and experimental data. The feasibility for analyzing the composite materials using the FDTD method is validated. Based on this, the theoretical foundation for designing and applying the composite materials is provided.

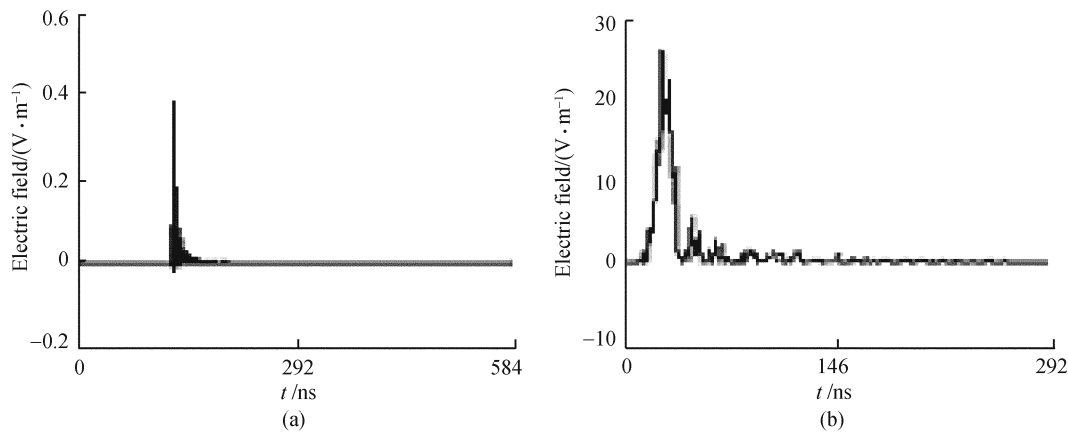


Fig. 4 The value of the electric field behind the media board
(a) Drude model; (b) Composite material

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