Effect of defect on the energy distribution inside the left-handed metamaterials*

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Abstract The electromagnetic field energy distribution inside the left-handed metamaterials (LHMs) with or without blank and line defects is firstly investigated. The LHMs consist of an array of periodic unit cells of copper hexagon split ring resonators (SRRs) and wires. The internal energy distribution of the LHMs is measured in a microwave measuring line device at X-band frequencies. It is found that the LHMs only respond to the electromagnetic field around the resonance frequency. The electromagnetic field amplitude inside the LHMs generally decreases with the introduction of defects. It is suggested that the electromagnetic field energy reduction may arise from the symmetry breaking in the LHMs.

Keywords: **left-handed metamaterials, electromagnetic field energy distribution, defect.**

In 1968, Veselago theoretically studied metamaterials with simultaneously negative values of permittivity and permeability over a certain frequency band. In such materials, the electric, magnetic and wave vector components form a left-handed coordinate system, hence the name left-handed metamaterials (LHMs) is used for description[1]. In 1996, Pendry et al. successively proposed a theoretical model that could realize negative permittivity by periodic arrangement of metallic wires[2] and negative permeability by periodic array of SRRs[3]. Later, Shelby and Smith et al. researched and firstly designed artificial LHMs at microwave frequencies, and the negative refraction was also experimentally verified in the wedge prism of this LHMs[4—6]. Recently, other metallic inclusions such as the Ω-like structures and S-shaped resonators have also presented left-handed properties over microwave frequencies[7,8].

All the above experiments demonstrate the response behaviors of electromagnetic waves outside the LHMs, but those behaviors inside the LHMs are rarely studied. Recently, Cummer and Popa investigate some behaviors of electromagnetic waves inside the LHMs(wires/SRRs), and find that the phase velocity and energy flow vector are reversed in such metamaterials[9]. In addition, the inside field measurements enable the probing of important parameters not easily accessible through outside field measurements. We have reported the defect effects in 1D and 2D negative permeability metamaterials, and found that the defect can remarkably affect the transmitted behaviors[10—12]. However, the study of electromagnetic behaviors inside the LHMs with defects has never been reported. By removing the SRRs cells in LHMs, that is, introducing the blank and line-defects to the LHMs, the energy distribution inside the LHMs with defects is compared with that of perfect LHMs by the measuring line device.

1 Samples and experiments

Using the etching technique, the copper hexagonal SRRs and wire patterns are fabricated on the opposite sides of a circuit board, the thickness of which is 0.6 mm. And the deposited copper layer is 0.02 mm in thickness. The wires are 9.9 mm long and 0.5 mm wide. The dimensions of the SRRs structures are $d_1=1.0$ mm, $d_2=2.2$ mm, $c=0.3$ mm, and $g=0.3$ mm. The unit cell consists of three SRRs and one wire in the y-z planes [Fig.1(a)]. The perfect LHMs samples are based on eight unit cells along the y direction with the lattice spacing $a=5.0$ mm and $b=3.5$ mm. And there are two strips in the x direction with the distance of 5.0 mm between them. The defects are created by removing the SRRs in the

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perfect LHMs. As show in Fig. 1(b), the blank-defect is introduced by taking away the SRR in the near center of each strip. Likewise, we get the line-blank defect LHMs sample by removing the middle three SRRs of each strip along the z direction.

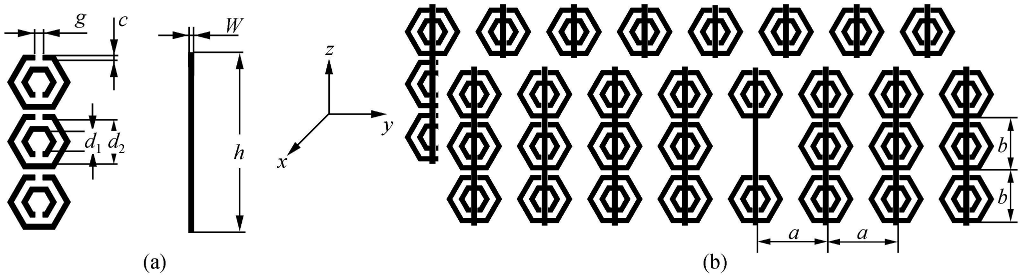

Fig. 1. Schematics of LHMs structure. (a) Unit cell(three SRRs/one wire); (b) LHMs sample with blank defect.

Our experimental configuration is as follows. An AV3618 Network Analyzer is used to measure all the S_{12} parameters between 8 and 12 GHz. With the S_{12} parameters, the inside energy distribution of all the LHMs is measured in the measuring line (Fig. 2). The cross section of the rectangular waveguide in both devices is $a \times b = 22.86\ \text{mm} \times 10.16\ \text{mm}$. The incident microwave propagates along the y direction, while the electric field is along the z direction, and the magnetic field is along the x direction.

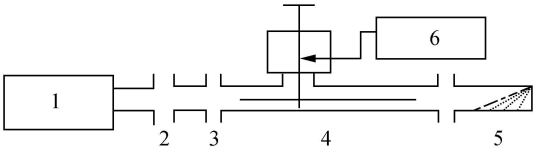

Fig. 2. Schematic diagram of experimental setup used for energy distribution experiment. 1 microwave generator; 2 isolator; 3 attenuator; 4 measuring line; 5 load; 6 photoelectric galvanometer.

2 Principle, results and discussion

In this work, only the relative value of the electromagnetic field energy is of interest, so it can be measured by a crystal diode detector of the measuring line device. The volt-ampere characteristic of the crystal diode detector is nonlinear, and the output current can be described in the form of

$$I = qE^n,$$

where E is the electric field intensity. When there exists a little signal, we obtain that $n = 2$, and it follows the square demodulation. So the output current is directly proportional to the power of the electromagnetic field.

The transmission spectra of LHMs with or without defects are shown in Fig. 3. We define the resonance frequency as the frequency of a resonant peak value. It can be seen that for all the LHMs, a left-handed pass band occurs between 9.2 and 10.2 GHz, where a resonance frequency is 9.6 GHz. Then all the LHMs samples are put into the measuring line, and the electromagnetic field energy distribution inside all the LHMs is measured.

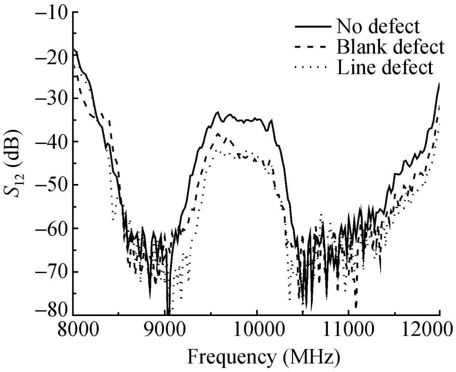

Fig. 3. The transmission spectra of LHMs with or without defects.

2.1 The energy state inside the LHMs

First, the electromagnetic field energy versus position is obtained in the measuring line where there are no LHMs samples but air only. It is found that the electromagnetic field energy amplitude changes little with the position, so the effect of air on the field distribution inside the samples can be neglected.

All the LHMs samples are placed into the measuring line in turn, and located between 28 and 63 mm along the vertical axis with the defect introduced at 48 mm. The frequency of the signal generator is selected at 9.6 GHz, namely the resonance frequency of the LHMs. The coaxial probe is set at the center of the measuring line, and the photoelectric galvanometer will display the maximal value by regulating attenuator and tuning stopcock, when the measuring line is at its best state. Then the probe is located at the central axis of each unit cell, and the electromagnetic field energy is measured at different frequencies and sample positions. The three-dimensional results for all the LHMs samples are shown in Fig. 4. From Fig. 4, we can find that all the LHMs only respond to the electromagnetic field around the resonance frequency just where the energy peak exits. In FIG. 3 of Ref. [8], the energy peak related to negative refraction is obtained at the resonance frequency of their LHMs samples, so the resonance frequency is important to study the LHMs.

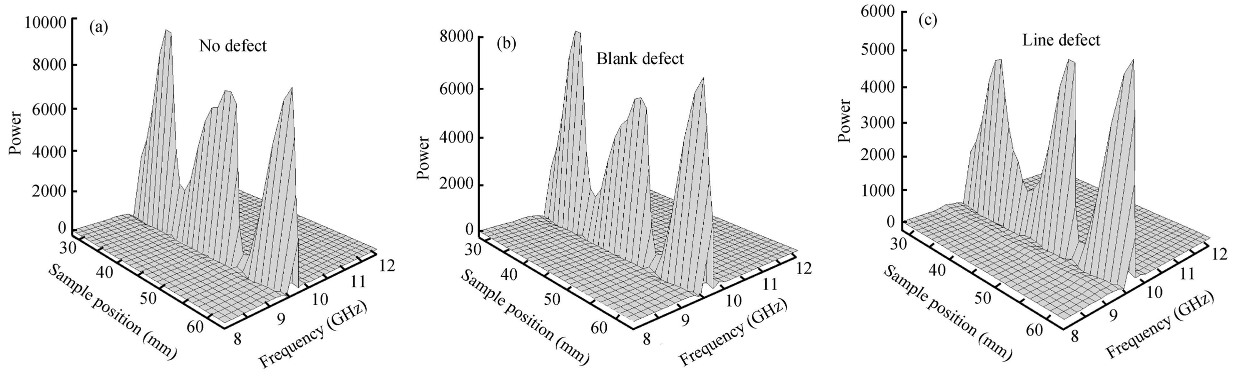

Fig. 4. Three-dimensional results of the electromagnetic field energy distribution inside the LHMs. (a) LHMs without defect; (b) LHMs with blank defect; (c) LHMs with line defect.

2.2 The energy variation from blank and line defects

By taking away the SRRs we get the blank defect and line defect LHMs. The electromagnetic field energy inside all the LHMs is intercepted from Fig. 4 at 9.6 GHz, and the normalized result is shown in Fig. 5. As shown in Fig. 5, the inside energy of LHMs gradually weakens in the case of no defect, blank defect and line defect. The more the SRRs are removed, the more the electromagnetic field energy inside the LHMs decreases. The amplitude reduces by 23% ultimately at 34 mm where the normalized result is maximal. Fig. 5(b) is excavated from Fig. 4 at 48 mm where the defects are introduced, and the result is consist with that of Fig. 5(a). The electromagnetic field amplitude inside the LHMs generally decreases with the introduction of defects.

When the frequencies of the signal generator are selected outside the left-handed pass band, the inside energy of all the LHMs is almost zero. Therefore, all the LHMs do not respond to the electromagnetic field among the non-resonance frequencies, which is in good agreement with the experimental results in Section 2.1.

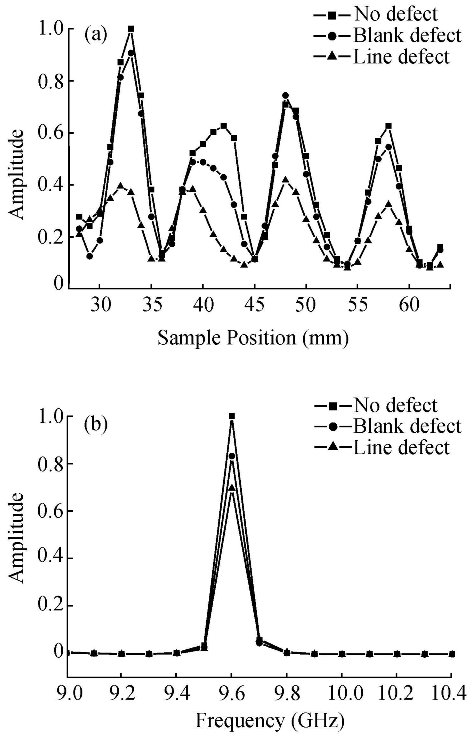

Fig. 5. (a) Normalized electromagnetic field energy versus sample position at 9.6 GHz; (b) normalized electromagnetic field energy versus frequency at 48 mm.

2.3 The energy distribution of different positions inside the LHMs

It is also seen that at 48 mm where the defects are introduced, the normalized field amplitudes inside the LHMs without defect, with blank defect and line defect are 0.70, 0.74 and 0.33, respectively. At 43 mm where there is no defect, the normalized results inside the LHMs reduce to 0.33 and 0.12 from 0.58.

The energy periodically changes with the sample positions, and the spatial periodicity is about 10 mm. The electromagnetic field energy in the adjacent unit cells varies from strong to weak, and from weak to strong.

In free space, the wavelength at 9.6 GHz is 31.25 mm. It is about five times bigger than the spacing lattice of the LHMs along the wave vector. Therefore, the LHMs is nearly a continuous and uniform medium, and the electromagnetic field energy changes continually in each unit cell.

2.4 Discussion

The defects are introduced by removing the SRRs in this work. It is suggested that the electromagnetic field energy reduction may arise from the symmetry breaking in the LHMs. Without defects, the coupling effect of the electromagnetic field between SRRs is relatively strong, and electromagnetic field energy is a little larger in the LHMs related to the reciprocity between the SRRs and wires.

When some SRRs are removed from the LHMs, the periodic distribution of SRRs is destroyed, which makes the average distance between the SRRs become greater. The coupling effect between SRRs becomes weak, and the reciprocity between the SRRs and wires also lowers, consequently the electromagnetic field energy in the LHMs declines. Compared with the blank defect, the breakage to the LHMs by the line defect is greater. It makes good sense to control the electromagnetic field energy distribution inside the LHMs with the introduction of defects.

3 Conclusions

The energy distribution property inside the LHMs with defects is investigated. The effect of defect on the energy distribution inside the LHMs is measured in the measuring line. On this base, the following results are found:

(1) For all the LHMs, a left-handed pass band occurs from 9.2 to 10.2 GHz, where the resonance frequency is about 9.6 GHz.

(2) All the LHMs only respond to the electromagnetic field around the resonance frequency.

(3) The electromagnetic field amplitude inside the LHMs generally decreases with the introduction of defects, and the amplitude reduces by 23% ultimately. The inside energy of LHMs gradually weakens in the case of no defect, blank defect and line defect.

(4) The electromagnetic energy changes with sample positions periodically, and the periodicity is about 10 mm. The electromagnetic field energy in the adjacent unit cells follows the strong-weak-strong variation.

The periodic ordinal structure of the LHMs is destroyed by the defects. The reciprocity between the SRRs and wires weakens, so the electromagnetic field energy in the LHMs declines.

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