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EXPERIMENTAL CONFIRMATION OF GUIDANCE PROPERTIES USING PLANAR ANISOTROPIC LEFT-HANDED METAMATERIAL SLABS BASED ON S-RING RESONATORS

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Abstract—We experimentally studied the guidance properties of the S-shaped metamaterial slabs. A peek of transmitted power due to the bulk guidance modes is observed in the negative band of the metamaterial, which is larger than a conventional dielectric waveguide made of FR4. The peek transmission frequency is shown related with the change of the negative band of the S-shaped metamaterial slab. Our results show good agreement with the theoretical predictions.

1. INTRODUCTION

In 1968, the physical properties of the negative index material with simultaneously negative permittivity and permeability or left handed materials (LHMs), such as the reversed Doppler effect, Cerenkov radiation, and Snell's law, were predicted by Veselago [1]. Pendry et al. then proposed the metallic rods to realize negative permittivity [2] and split ring resonators (SRRs) to realized negative permeability [3].

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Later, composite medium with simultaneously negative permeability and permittivity was fabricated by combining the metallic rods and SRRs, and then verified by the prism experiments [4]. Besides the prism experiments, the T-junction waveguide [5] was proposed to overcome the affections of losses and the beam shift [6] experiments have been carried out to verify the theoretical prediction in Ref. [7]. A "superlens" formed by a slab of negative refractive index material has the power to focus all Fourier components of a 2D image [8], thus is useful for sub-wavelength imaging [9]. Photonic crystals have also been shown to have such imaging properties [10]. Many different types of structures have been designed and verified to be LHMs [11, 12]. Based on the magnitude and phase information of the transmitted and reflected power, retrieval methods have been proposed [13] to obtain the constitutive parameters of the designed metamaterials. Numerical simulations such as the finite difference time domain method (FDTD) have also been utilized to verify the refraction and imaging properties of LHMs [14]. Besides negative refraction, various other properties of LHMs have now been extensively investigated [15, 16]. For example, the abnormal behaviors of evanescent waves were studied in Ref. [17]. Negative Goos-Hänchen shift has also been theoretically predicted [18, 19]. Metamaterials can be used to achieve high directive antennas [20–22]. The guidance properties [23, 24] and coupling properties [25, 26] of LHM slab have been shown quite different from traditional dielectric waveguide. The guidance modes of anisotropic LHM slab have also been investigated, and infinite bulk modes are found under some specific conditions [27]. However, the guidance properties have not been experimentally verified.

In this paper, the guidance properties of an anisotropic LHM slab are experimentally studied utilizing the S-shaped LHMs [12]. A waveguide port is put several wavelength away from an S-shaped LHM slab, then the propagating power is mainly illuminated onto the slab with a small incident angle, and the evanescent part can be coupled into the slab and stimulate guidance mode in the slab [27]. By measuring the transmitted power near the end of the slab, the guidance properties can be verified. The experimental results show that in the negative pass band of the S-shaped LHM slab, guidance power can reach the end of the slab, which shows some agreements with the theoretical predictions in [27].

2. EXPERIMENTAL SETUP

Figure 1 shows the setup for the experiment. In a parallel plate wave guide, the source is placed at point S in the figure. And the slab is several wavelength away from the source. A probe is used to measure the transmitted power at point A. The absorbers are placed in order to prevent the power go directly to the measurement region, while a gap is left in the upper absorber of the slabs. The width of the gap in the upper absorbers is about 1 cm.

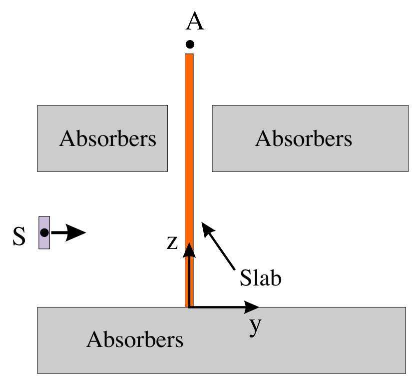

Figure 1. The experimental setup. The source is placed at point S in the figure 6 cm away from the slab, and the transmission is measured near the end of the slab denoted as A. The absorbers are placed in order to prevent the power go directly to the measurement region. The whole setup is placed between a parallel waveguide.

For comparison, the slab shown in Fig. 1 is set for different cases as shown in Fig. 2, where, the blank rectangular shown by (a) means free space, (b) means a slab of FR4 substrate, and (c) means an S-shaped LHM slab. Fig. 2(h) is the side view of a unit cell of the S-ring. The period of the unit cell is 4 mm and totally 50 cells is used to form a 20 cm slab shown by Fig. 2(c). The S-ring is made of copper and printed on both side of an FR4 substrate [12]. The dielectric constant of FR4 is about 4. Fig. 2(d) means the slab is composed of two FR4 slab with a free space gap while Fig. 2(e) means the slab is composed of S-shaped LHM slab with a free space gap, and similarly for cases (f) and (g).

3. EXPERIMENTAL RESULTS

We firstly test the isolation of the setup. As shown by Fig. 3(a), by filling the upper gap in Fig. 1 with absorbers and removing the slab, the transmitted power is measured at point A. The results are shown by the dash dotted line in Fig. 4, where the measured power is below −52 dB, comparing with the source. Thus very little power can

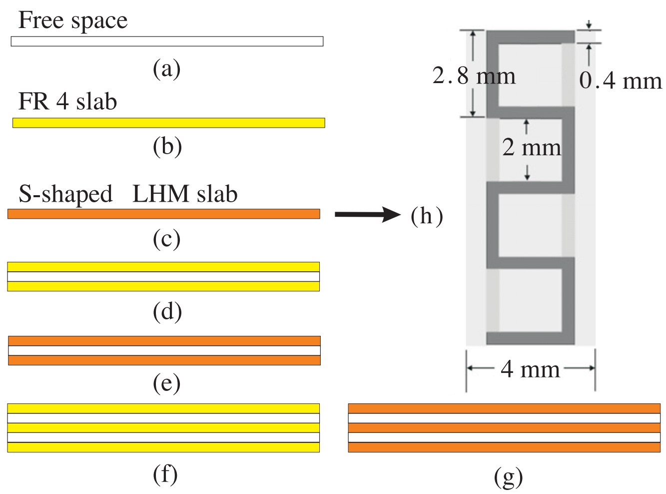

Figure 2. The scheme for the slabs: (a) represents the free space; (b) represents a blank FR4 slab; (c) represents an S-shaped LHM slab; (d) means a slab composed of two FR4 slabs; (e) means a slab composed of two S-shaped LHM slabs; (f) means a slab composed of three FR4 slabs; (g) means a slab composed of three S-shaped LHM slabs; (h) the dimensions of the S-ring.

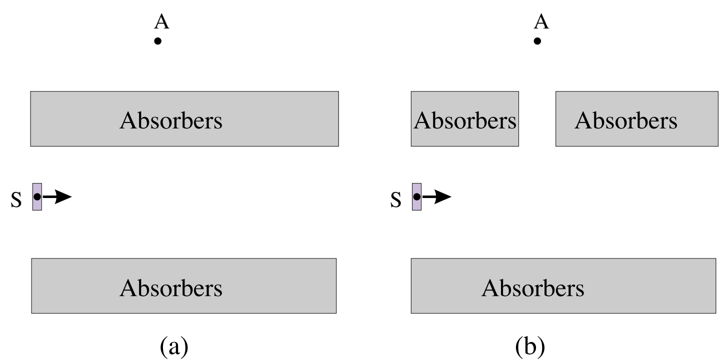

Figure 3. Setup for testing the isolation of the source and the measurement point: (a) The upper gap is filled with absorber; (b) The upper gap is unchanged and no slab is used.

penetrate the absorbers and reach point A, and the source and the test point A are well separated. Then we measured the power transmitted without any slab as shown by Fig. 3(b), but the gap is left, and 8 dB of power increase is observed as shown by the dotted line in Fig. 4. This

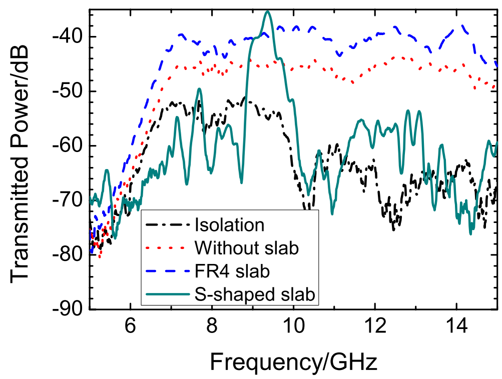

Figure 4. The power measured at point A for different cases: (dash doted line) total isolation by absorbers as shown by Fig. 3(a); (dotted line) the gap of the absorbers stays unchanged, and no slab is used as shown by Fig. 3(b); (dashed line) an FR4 slab is placed instead of an S-shaped LHM slab for the case Fig. 2(b); (solid line) an S-shaped slab is placed for the case Fig. 2(c).

increase is due to the reflections and diffractions caused by the gap.

When a dielectric slab is placed in the gap, part of the power which is originally evanescent in free space will turn to be guided wave in the slab, as determined by the guidance conditions. For the case shown by Fig. 2(b) where only a dielectric FR4 slab is used, about 4 dB more power can be detected at point A, because of the above reason. When an anisotropic metamaterial slab is used instead of a normal dielectric slab, bulk mode can be exited when for the slab, the permittivity in x direction and permeability in y direction are negative, with positive permeability in z direction [19]. When the S-shaped LHM slab is used, the results are shown by the solid line in Fig. 4. Here we can see a peek transmission, about 4 dB larger than the FR4 slab, between 9 GHz and 10 GHz, which coincides with the negative band of the S-shaped rings. The result means power is guided to the end of the slab. This is an evidence of the bulk guided modes in anisotropic metamaterial slabs. Since part of waves are guided for both the dielectric and LHM slabs, the power decays little as it propagates in the slab, but when the slab is absent, the power will decay exponentially, thus power detected at point A is relatively large for both dielectric and LHM slabs, comparing with the case without any slab.

Then the thickness of the slab is increased by combining several FR4 slabs or LHM slabs. Fig. 5 shows the power measured at point A when the slab is shown as cases (d) and (e) in Fig. 2 are considered. We can also observe a peek transmission for the LHM slab between about 8 GHz and 9 GHz. Fig. 6 shows the power measured at point A for the cases (f) and (g) in Fig. 2. Also a peek transmission for the LHM slab between about 7 GHz and 8 GHz is observed. It is interesting to see that the transmitted power shifts to a lower frequency when more layers of LHM slab are used. This is because the capacitances between the S rings are increased when more layers are used, which leads to a decease of the resonance frequency for the S rings. Hence the negative band shifts to the lower frequency region, which agrees with the shift of the transmitted frequency band.

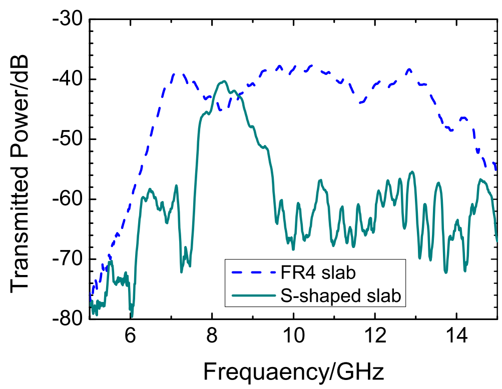

Figure 5. The power measured at point A for different cases: Two FR4 slab is placed instead of an S-shaped LHM slab (dashed line); an S-shaped slab is placed as shown by Fig. 1 (solid line).

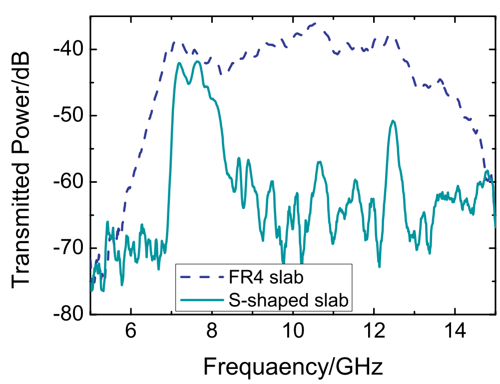

Figure 6. The power measured at point A for different cases: Three FR4 slab is placed instead of an S-shaped LHM slab (dashed line); an S-shaped slab is placed as shown by Fig. 1 (solid line).

4. CONCLUSION

In conclusion, the guidance properties of the S-shaped metamaterial slab are experimentally studied in the parallel plate waveguide. By measuring the transmitted power at the end of the slab, the guidance phenomena are experimentally confirmed. The transmitted frequency band is in the negative band of the S-shaped metamaterial, and will change as the negative band of the metamaterial changes. Our experimental results are in good agreement with the theoretical predictions.

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