Backward Wave Propagation of a Uniaxial Anisotropic μ-Negative Slab Composed of Metallic Spirals

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1. Introduction

It has been theoretically shown that backward waves can be supported not only by double-negative materials with simultaneous negative permittivity and permeability [1] but also by uniaxial anisotropic single-negative slabs with a negative component of permittivity or permeability tensor [2]. The uniaxial anisotropic single-negative materials are potentially advantageous in row loss characteristics as well as a simple configuration because only a single kind of the constituents is required compared with double-negative materials of two kinds of constituents, typically split-ring resonators and wires. Although the backward wave support has already been shown, there is little experimental verification so far, as far as the authors know.

In this paper, a uniaxial anisotropic slab with a negative component of the permeability tensor is designed at microwave frequency band by using a two-dimensional (2D) periodic array of metal spirals on a dielectric substrate and backward wave propagation characteristics supported by the structure are experimentally investigated.

2. A uniaxial anisotropic μ-negative slab

Figure 1 shows the scheme of the single-negative slab under consideration. The slab with an isotropic permeability tensor is sandwiched by double-positive ($\varepsilon > 0$ and $\mu > 0$) isotropic materials. It can be shown theoretically that the TE volume backward waves is supported by the slab [2] under the condition where the slab has the anisotropy with a negative diagonal permeability tensor component of $\mu_{zz} < 0$ and positive ones of $\mu_{xx} > 0$ and $\mu_{yy} > 0$ and with the rest of the permeability tensor components are zero. In addition, the permittivity of the slab is considered to be positive ($\varepsilon > 0$). The dispersion characteristics of the TE volume mode is expressed by

$$-\left(\mu_0^2\delta_1^2 - \mu_{xx}^2\delta_0^2\right)\cos\delta_1 T = 2\mu_0\mu_{xx}\delta_0\delta_1\sin\delta_1 T \;, \quad (1)$$

where, δ_1 is the wavenumber in the slab and δ_0 is the one in the surrounding double-positive ($\varepsilon > 0$ and $\mu > 0$) regions along the x-direction. Also, T is the thickness of the slab. According to (1), it can be directly shown that the TE mode has an anti-parallel phase and group velocities in the x-direction.

3. Implementation using metallic spirals

The anisotropic slab is realized by a 2D periodic array of metallic spirals on a dielectric substrate.

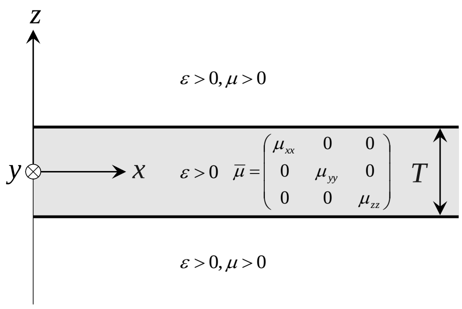

Fig.1: Anisotropic single-negative slab

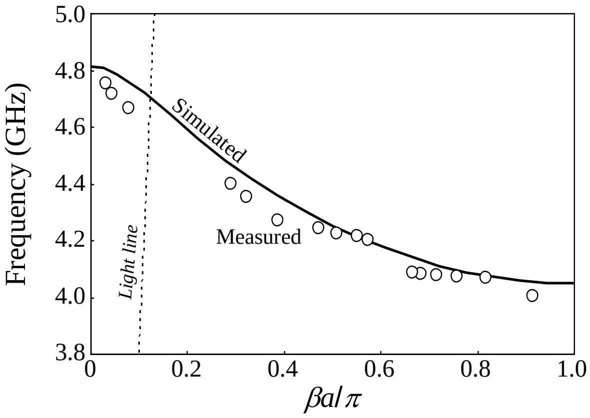

Fig. 2: Measured and simulated dispersion characteristics.

The magnetic moment caused by the induced current is perpendicular to the spiral and the slab has a uniaxial anisotropy with the Lorentz dispersion. The effective permeability tensor component perpendicular to the slab becomes negative ($\mu_{zz} < 0$) in a frequency region above the resonant frequency of the spiral, whereas μ_{xx} and μ_{yy} remain positive ($\mu_{xx} < 0$, $\mu_{yy} < 0$) in this frequency. Therefore, the uniaxial anisotropy of this structure can be realized and the backward TE volume wave can be expected.

In order to confirm the operation, a 2D array of metallic spirals is fabricated on a dielectric substrate with the dielectric constant and thickness of 2.17 and 0.508 mm, respectively. The dimension of the spiral has been designed at the operation frequency of 4.5GHz band. The lattice constant is chosen as 4 mm, both the spiral line width and the spacing between the lines are also chosen as 0.3 mm. The total size of the prototype is 80×80 mm^2.

The dispersion characteristics are obtained experimentally by near-field measurements. In the measurements, the structure is excited by a magnetic probe 3 mm above the surface of the structure and the phase distribution of the magnetic field are measured using a vector network analyzer with another magnetic probe on an automatic *xy*-stage. Figure 2 shows the measured dispersion characteristics with corresponding simulated dispersion characteristics obtained by the finite-element method with the infinite periodic boundary condition. It can be clearly seen from the figure that the measured dispersion characteristics exhibit a negative slope in accordance with the simulated results and the backward wave propagation supported by the structure is confirmed experimentally.

4. Conclusion

A uniaxial anisotropic single-negative slab with a negative component of the permeability tensor has been realized by using a 2D periodic array of metallic spirals on a dielectric substrate. The TE backward wave propagation characteristics supported by the structure have been confirmed experimentally at the 4.5 GHz band.

References

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[2]. M. Hotta, M. Hano, I. Awai, Modal Analysis of finite-thickness slab with single-negative tensor material parameters, IEICE Trans. Electron., Vol.E89-C, no.9, pp1283-1290, Sept., 2006.