Negative refractive index characteristics of a uniaxial anisotropic μ-negative slab

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Abstract

Negative refractive index characteristics of a uniaxial anisotropic slab with a negative component of the permeability tensor are first confirmed. A two-dimensional array of metallic spirals is fabricated on a dielectric substrate and the wave propagation guided by the structure is measured by near-field measurements at 4.5 GHz band. The ω-β relation is obtained by the measured phase distributions and the refractive index characteristics are calculated. The measured refractive indices take negative values in accordance with numerical prediction.

1. Introduction

Loss reduction is a major concern for scientists/engineers of metamaterials with negative refractive indices [1], [2]. It has been theoretically shown that negative refractive index characteristics can be realized not only by using isotropic double negative materials with simultaneous negative permittivity and permeability but also by uniaxial anisotropic single-negative slabs with a negative component of permittivity or permeability tensor [3]. The uniaxial anisotropic single-negative materials are potentially advantageous in low loss characteristics as well as easy fabrication due to their simple structures compared with double-negative materials using two kinds of constituents of split-ring resonators and wires [4], [5]. However, their negative refractive index characteristics have not been confirmed experimentally yet.

In this paper, a uniaxial anisotropic single-negative slab with a negative component of the permeability tensor is realized by using a planar periodic array of metallic spirals on a dielectric substrate. TE wave propagation characteristics supported by the structure are experimentally investigated by near-field measurements and negative refractive index characteristics of the structure are discussed.

2. A uniaxial anisotropic μ-negative slab

Let us consider a homogeneous anisotropic slab with a permeability tensor of

$$\bar{\mu} = \begin{pmatrix} \mu_{xx} & 0 & 0 \\ 0 & \mu_{yy} & 0 \\ 0 & 0 & \mu_{zz} \end{pmatrix} \tag{1}$$

and with an isotropic positive permittivity of ε (> 0) as shown in Fig. 1. It can be shown theoretically that when the slab is sandwiched by double positive ($\varepsilon > 0$ and $\mu > 0$) isotropic materials, the slab can support TE volume backward waves depending on the signs of the tensor components as shown in Table 1 [2]. For instance, for a uniaxial anisotropic slab with the negative parameter of $\mu_{zz} < 0$ with the positive other parameters of $\mu_{xx} > 0$, $\mu_{yy} > 0$ and $\varepsilon > 0$, the y-polarized TE volume backward waves with anti-parallel phase and group velocities can propagate in the x-direction with the dispersion characteristics given by

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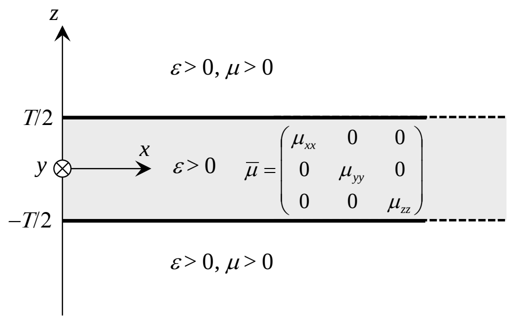


Fig. 1: Anisotropic slab

Table 1: TE modes supported by the anisotropic slab

μ_{xx}	μ_{yy}	μ_{zz}	TE mode
−	±	+	Surface mode (Evanescent)
−	±	−	Surface mode (Evanescent)
+	±	−	Volume mode (Backward)
+	±	+	Volume mode (Forward)

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

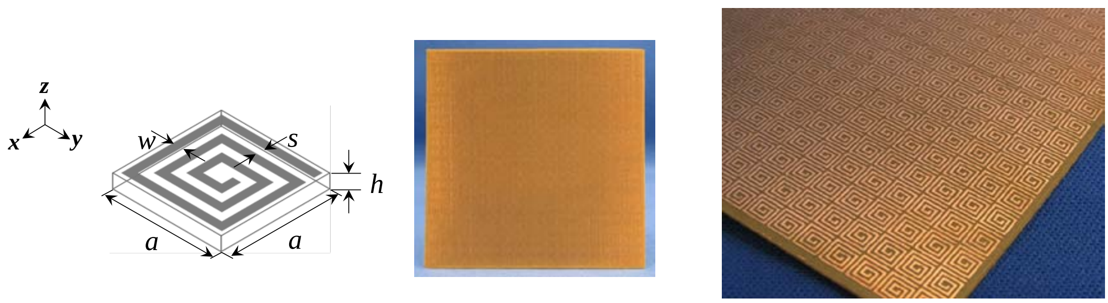
Here, δ_1 is the wavenumber in the slab and δ_0 is the one in the surrounding double positive ($\varepsilon > 0$ and $\mu > 0$) regions along the x-direction. Also, T is the thickness of the slab.

3. Implementation and experiments

The uniaxial anisotropic material can be realized simply by a periodic array of metallic spirals as shown in Fig. 2(a). Since the magnetic moment caused by the induced current is perpendicular to the spiral, the structure operates as a uniaxial anisotropic slab. The effective permeability tensor component perpendicular to the slab (the z-direction in this configuration) exhibits the Lorentz dispersion characteristics and becomes negative ($\mu_{zz} < 0$) in a frequency region above the resonant frequency of the spiral. It is noted that even in this frequency range, μ_{xx} and μ_{yy} remain positive and the uniaxial anisotropy can be realized.

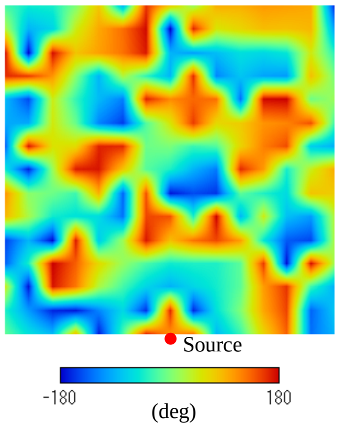
In order to confirm the operation of the uniaxial anisotropic μ-negative slab, a two-dimensional array of metallic spirals is fabricated on a dielectric substrate as shown in Figs. 2(b) and 2(c). The dimensions of the unit cell are designed to operate at a 4.5 GHz band by using the commercial electromagnetic simulator HFSS. The thickness and dielectric constant of the substrate are chosen to be h = 0.508 mm and ε_r = 2.17, respectively. The lattice constant is chosen as a = 4 mm, the spiral line width and the spacing between the lines are also chosen as w = 0.3 mm and s = 0.3 mm, respectively. The total size of the substrate is 80 × 80 mm^2.

The near-field measurements are carried out by using the vector network analyzer Agilent E5071C in the frequency band of the operation. The slab is excited by a magnetic probe 3 mm above the surface of the slab and the magnetic field distributions are measured with another magnetic probe using an automatic xy-stage. Fig. 3 shows the measured phase distributions at 4.26 GHz within the frequency



(a) Unit cell (b) Prototype (general view) (c) Prototype (close view)

Fig. 2: Uniaxial anisotropic μ-negative material composed of metallic spirals



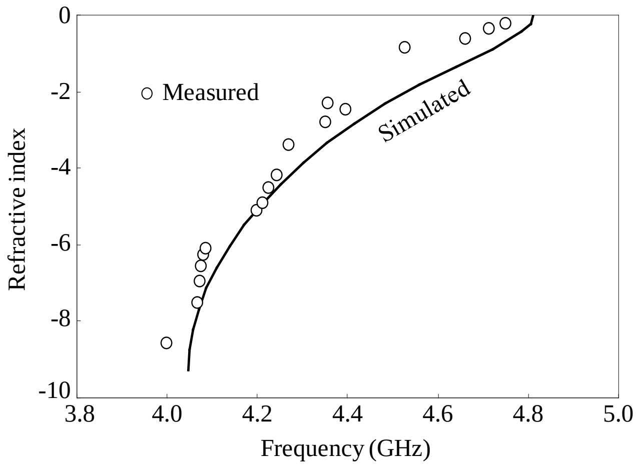


Fig. 3: Measured phase distribution (4.26 GHz)

Fig. 4: Refractive indices

range of the operation obtained in advance by numerical simulations. The source probe is located at the center in the second row of the spirals from the edge. The source location is shown in a red dot in Fig. 3. It can be seen from the figure that the phase advances with the propagation in the slab and the backward wave propagation is confirmed. Fig. 4 shows the frequency characteristics of the refractive index calculated by the measured ω-β relation at some frequencies in the backward propagation band. Simulated refractive indices are also shown in the figure. The measured results agree well with the simulated ones and the negative refractive index characteristics of the slab are experimentally confirmed.

4. Conclusion

A uniaxial anisotropic single-negative slab with a negative component of the permeability tensor has been realized by using a planar periodic array of metallic spirals on a dielectric substrate. TE wave propagation characteristics supported by the structure have been observed by near-field measurements and negative refractive index characteristics of the structure have first been confirmed.

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