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Full Length Research Paper

A magnetotunable negative refractive index material

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A magnetically tunable negative refractive index material is made by incorporating periodic metallic wire array (PMWA) into yttrium iron garnet (YIG) slices. Applied by external magnetic field, the effective permeability of YIG is negative in certain frequency band. PMWA also exhibit negative effective permittivity in certain frequency band. In the overlapping area of two bands, the effective permeability and effective permittivity are negative simultaneously. Consequently, negative refraction occurs in the composite. The negative refractive phenomenon is observed by prism experiment from 7.5 to 8.5 GHz under 2200Oe external magnetic field. The experimental results show that the composite medium consisting of PMWA with negative effective permittivity and YIG slices with negative effective permeability is negative refractive index material.

Key words: Periodic metallic wire array, yttrium iron garnet, magnetotunable, negative refractive index material.

INTRODUCTION

Negative refractive index material (NRIM) is a kind of metamaterial which exhibit negative refractive phenomenon. As electromagnetic wave oblique incidences at interface of NRIM and air, the propagating directions of transmitted field and incidence field locate on the same side of the normal. This phenomenon does not violate the well-known Snell's law of refraction, because the refractive index of NRIM is negative (Veselago, 1968).

The theory foundations of NRIM root from thesis, the permittivity ε and the magnetic permeability μ determine the propagation of electromagnetic waves in matter. While ε and μ of matter are both less than zero, the index of refraction is negative relative to vacuum (Veselago, 1968). There are non of these metamaterials in nature, but it can be fabricated. The composite medium based on a periodic array of interspaced conducting nonmagnetic split ring resonators and continuous wires exhibits a frequency permeability and permittivity (Smith et al., 2000).

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region with simultaneously negative values of effective A lot of similar structures are proposed subsequently (Gokkavas et al., 2006; Zhang et al., 2005; Chen et al., 2004). Using material consisting of a two-dimensional array of repeated unit cells of copper strips and split ring resonators on interlocking strips of standard circuit board material (Vipul et al., 2011), the effective index of refraction is experimentally verified to be negative (Shelby et al., 2001).

In this paper, we perform a series of experiments to test the negative refractive characteristics of NRIM made by incorporating periodic metallic wire array (PMWA) into yttrium iron garnet (YIG) slices (He et al., 2007). PMWA is used to provide negative permittivity, similar with previous experiments. Applied external magnetic field, YIG is used to provide negative permeability in certain microwave frequency band, unlike previous experiment (Dewar, 2005; Ran et al., 2005). The composite of YIG and PMWA have negative refractive index when permittivity and permeability are both negative in the overlap frequency band (Zhao et al., 2007). If no using of external magnetic field, YIG is normal positive permeability material in all frequency bands. So the composite is normal medium without external magnetic field. Due to the magnetotunable property of YIG, this NRIM is a

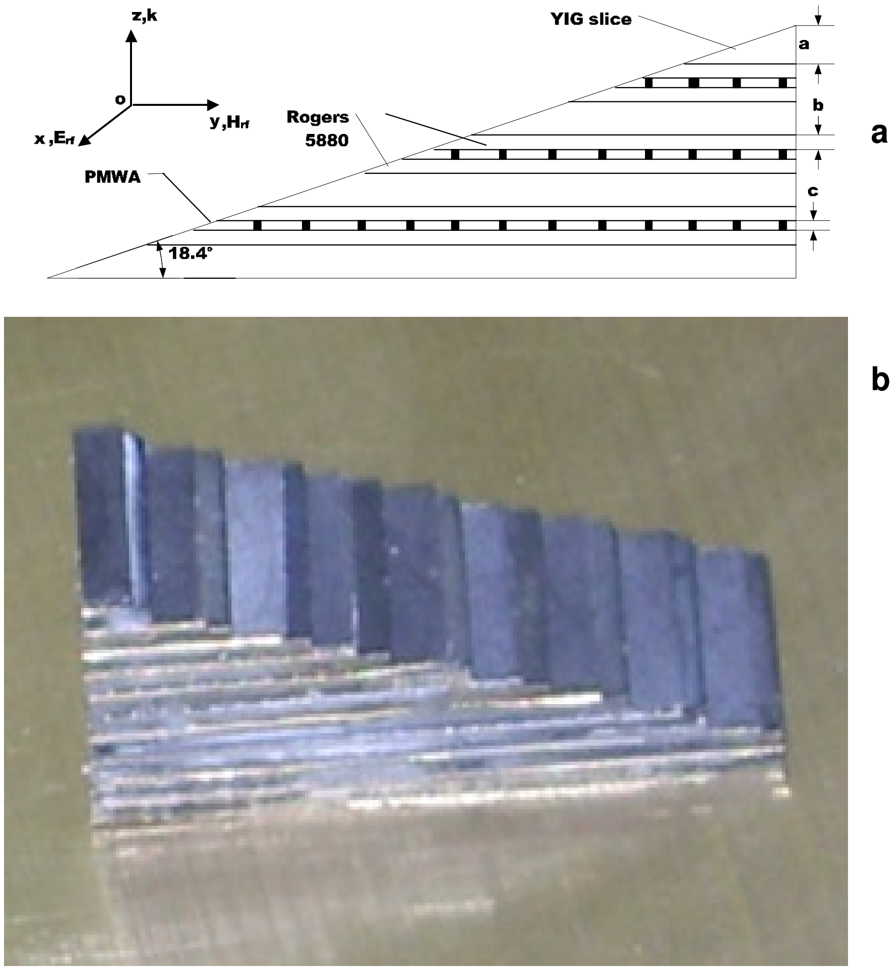

Figure 1. The tunable NRIM sample. (a) Structure of the tunable NRIM sample and (b) photo of the tunable NRIM sample.

magnetotunable NRIM.

The structure

A cuneiform NRIM have the acute angle of 18.4°, as shown in Figure 1a. The NRIM is constituted by 1 mm-thick YIG slices and 0.018 mm-thick copper PMWA layers cascaded alternately. The structure and photo of the NRIM sample are shown in Figure 1. The parameters are: a = 1 mm, b = 0.254 mm and c = 0.018 mm. The PMWA is made by metallic wires (0.2 mm-wide and 0.018 mm-thick) etched on one side of a 0.254 mm-thick Rogers 5880 circuit board material substrate by printed circuit board (PCB) technology. Rogers 5880 circuit board material substrate have dielectric constant of 2.2, so dispersion and losses for high frequency applications are minimized. There is 1.308 mm space between neighbor metallic wires. The YIG slices are tailored to variable calculated size rectangle by pottery incising technology to form cuneiform with PCBs and 5880 substrates. PCBs and 5880 substrates and structures are tailored by scissors. The tailored YIG slice, Rogers 5880 substrate, Rogers 5880 PCB with PMWA are conglutinated to a cuneiform block by electric glue in turn, as shown in Figure 1b. The width of the block is 1.016 cm to fit the X-band waveguide dimension, so that it can be settled into the waveguide of experiment device. The physical parameters of the YIG used in current experiment are as follows: saturation magnetization 4_{π} M_s = 1830Gs, Line width ΔH = 22Oe and Permittivity ε_1 = 13.8.

THE PRISM EXPERIMENT STEPS

To determine the refractive index, we measured the deflection of a beam of microwave radiation as the beam passed through the prism-shaped sample. Figure 2 shows the experimental setup for observing negative index phenomenon of the NRIM. The experiment devices are composed of a magnetic field generator, a PPW and a pair of rectangular waveguide adaptors. The PPW is made of two copper plates spaced 10.16 mm apart.

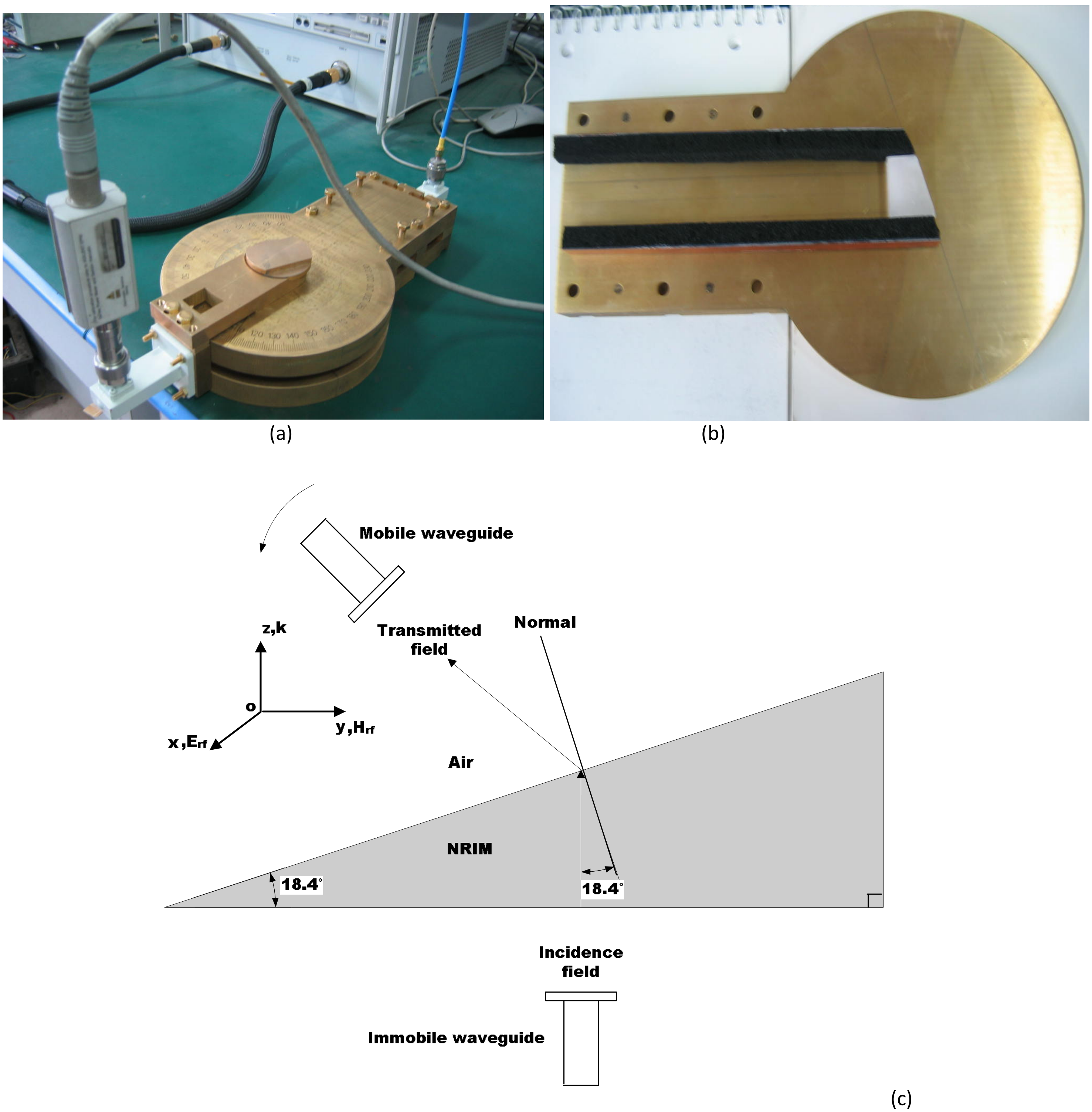

Figure 2. Method to observe negative index phenomenon of NRIM sample. (a) Prism experiment device, (b) prism experiment of an olefin sample and (c) prism experiment of the NRIM sample.

The copper plates have table tennis racket shape and high conductivity. The radius of the circular plates was 100 mm. The top could be rotated to measure transmitted power at arbitrary plate has a pivot in the center, about which an attached waveguide refraction angles. The detector was rotated around the circumference of the circle in 1° step. The waves were laterally confined by sheets of nonmagnetic absorber placed 40 mm apart. The device is similar to that used in reference. A prism-shaped section was cut from the

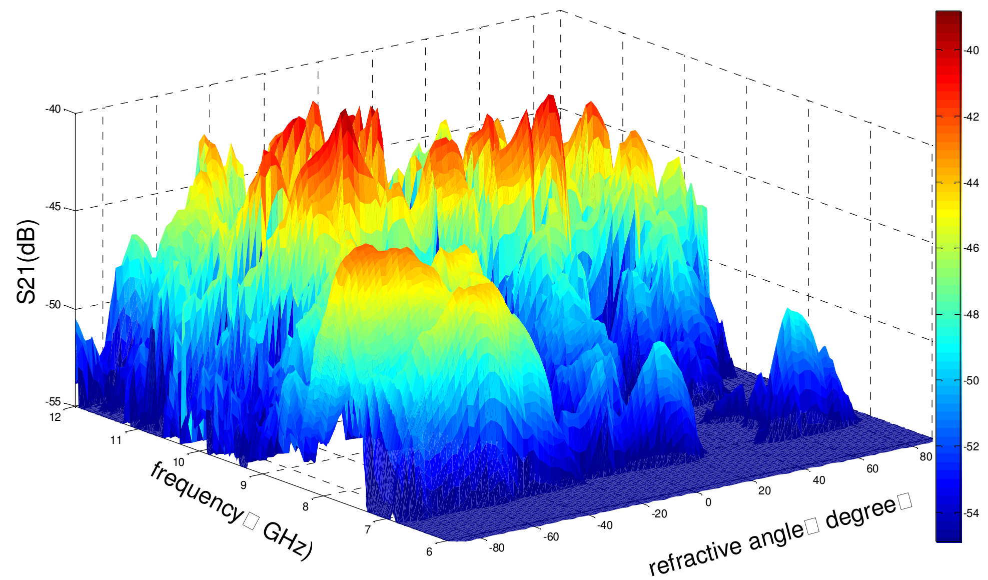

Figure 3. Prism experimental results of the NRIM sample.

NRIM shown in Figure 1. The normal to the NRIM refraction surface was at an angle of 19° with respect to the normal of the incident surface. The sample was placed between top and bottom parallel, circle copper plates. Whole device is put into the magnetic field generator used in foregoing transmission experiments.

The beam-deflection experiment was carried out in two steps. Firstly, we used an olefin sample with the same shape of NRIM prism shape to test validity of the designed experiment device, as shown in Figure 2b. A power meter was used to measure transmitted power at arbitrary refraction angles. We got that the measured refractive angle of the olefin sample is 19°, namely refractive index n ≈ 1.5358. The result is close to olefin's theoretical refractive index $n = 1.4967$ calculated by permittivity and permeability. So the designed prism experiment device is proofed to be valid.

Secondly, we used the prism experiment device to test our NRIM prism sample. By academic analysis and numerical simulation, negative refraction phenomenon occurs when both permittivity and permeability are negative. Forgoing transmission experiment shows that the permittivity and permeability of the sample is negative in certain microwave frequency band, under the applied external magnetic field. The 2200Oe external magnetic field is applied to the NRIM prism sample. By rotating an attached waveguide, S21 transmission parameters at arbitrary refraction angles could be measured by Agilent N5230A scalar microwave network analyzers.

RESULTS

The refractive direction is turned from 90° to 90°, by 1° step, 3-Dimension relations of frequency-S21-angle are obtained, as shown in Figure 3. From frequency band 7.5 GHz to 8.5 GHz, the peak values of S21 appear corresponding negative angle, namely, the refraction microwave energy concentrate in negative direction. By Snell's law, when wave beam pass through the interface between air and medium, $n_1 \sin\theta_1 = n_2 \sin\theta_2$, where n_1, n_2 are refractive index of air and medium, respectively, θ_1 is the angle of incidence and θ_2 is the angle of refraction. The experiment's results demonstrate $\theta_2 < 0$, which means that the refractive wave and incidence wave are in the same side of interface normal. Consider the refractive index of air ($n_1 > 0$) and the angle of incidence ($\theta_1 > 0$), we have that the refractive index of the designed composite medium $n_2 < 0$. So, negative refractive phenomenon is observed. Then the designed medium is sure to be NRIM.

Conclusion

A simple novel method to fabricate magnetotunable NRIM is realized. We use YIG slice under external magnetic field to obtain negative permeability. The PMWA shows plasma-like behavior in certain frequency band. Compounding YIG slice and PMWA alternately, a magnetotunable NRIM is made. By cutting the composite into cuniform, prism experiment is done to verified existence of negative refraction phenomenon and NRIM. But fabricating method of the NRIM is still inappropriate for extensive practical application. Future direction of the research is to find a new material having similar electromagnetic character with YIG, which can be tailored easily, so that PMWA could more closely embed in it. The characters of the NRIM should also be researched, such as reverse Doppler effect, reverse Cerenkov radiation and fiber applications (Belal et al., 2011).

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