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# Measurement of negative refraction index from simulative results and experimental data by a new metamaterial sample

Peng Gao, Chunmin Zhang *, Jingjing Ai, Gang Li, Yongqiang Kang

*School of science, Xi'an Jiaotong University, Xi'an 710049, China*
*Non-equilibrium Condensed Matter and Quantum Engineering Laboratory, the Key Laboratory of the Ministry of Education, Xi'an 710049, China*

## HIGHLIGHTS

- This paper confirms the negative refraction from both simulation and experiment.
- The experiment shows good agreement with the simulation result, and proposed the cell size will affect the location of the resonant frequency.
- The small FTSRRs–MWs sample is chosen to recover the effective negative index by utilizing the negative permittivity and permeability, as well as the angle detection from the experimental data, which shows the negative refraction directly.

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## ABSTRACT

This work presents simulations and experimental measurements of two negative refraction metamaterial samples at microwave frequencies. The two samples are composed of Four-Triangle Split Resonant Rings and Metal Wires (FTSRRs–MWs) with different cell sizes which are found to play an important role in the location of resonant frequency. The small cell sample is chosen to recover the effective index by utilizing the simulative permittivity and permeability, as well as the angle detection from the experimental data. The experimental data shows good agreement with the simulation result.

## 1. Introduction

Almost all electromagnetic phenomena and devices result from interactions between waves and materials. Usually, the material properties are characterized by an electric permittivity $\varepsilon$ and a magnetic permeability $\mu$. The thinnest material in nature is free space or air, whose permittivity is $\varepsilon_0$ and permeability is $\mu_0$. The relative permittivity and permeability of a material are defined as $\varepsilon_r = \varepsilon/\varepsilon_0$ and $\mu_r = \mu/\mu_0$, respectively, which define another important material parameter, the refractive index, as $n = \sqrt{\varepsilon_r \cdot \mu_r}$. In nature, most materials have the permittivity larger than $\varepsilon_0$ and the permeability larger than $\mu_0$. The metamaterial opens a door to realize all possible material properties by designing different cellular architectures and using different substrate materials. All possible properties of isotropic and lossless materials in the $\varepsilon - \mu$ domain are divided into four parts. The first part ($\varepsilon > 0$ and $\mu > 0$) represents right-handed materials (RHMs), which support the forward propagating waves. From the Maxwell's equations, the electric field **E**, the magnetic field **H**, and the wave vector **K** form a right-handed system. The second part ($\varepsilon < 0$ and $\mu > 0$) and the fourth part ($\varepsilon > 0$ and $\mu > 0$) denote electric plasma and magnetic plasma, which support evanescent waves. The third part ($\varepsilon < 0$ and $\mu < 0$) is the well-known

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* Corresponding author at: School of science, Xi'an Jiaotong University, Xi'an 710049, China. Tel.: +86 0 29 8266 8016; fax: +86 0 29 8266 8016.
*E-mail address:* zcm@mail.xjtu.edu.cn (C. Zhang).

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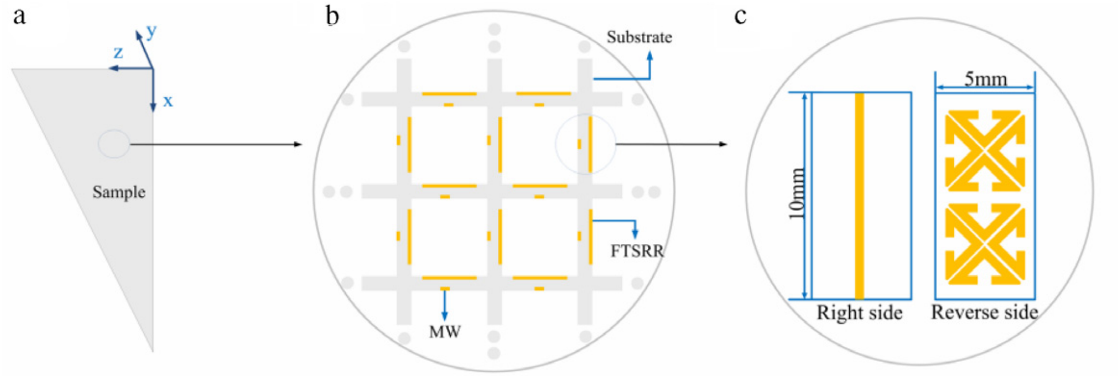

**Fig. 1.** (Color online) (a) A prism metamaterial sample (b) an infinite array of FTSRR–MW-loaded square waveguide (c) a unit of two-tier FTSRRs and MW.

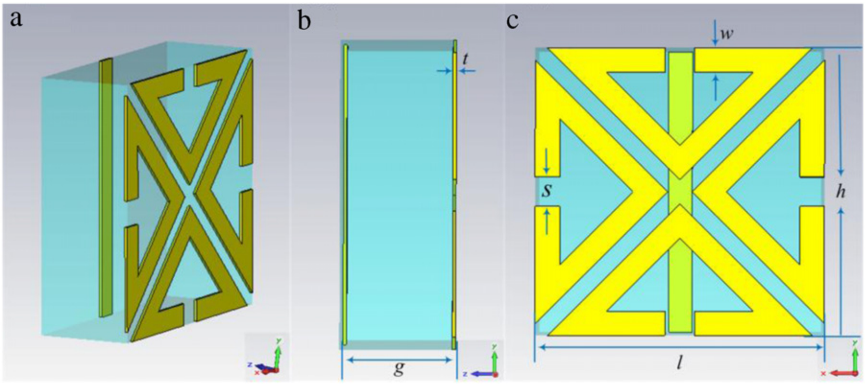

**Fig. 2.** (Color online) A single FTSRR–MW used in the work (a) constructional drawing (b) side view and (c) top view.

left-handed materials (LHMs), which was proposed by Pendry et al. [1–3] in 1968 and experimented by Smith et al. [4,5] in 2001. In LHMs, the electric field **E**, the magnetic field **H**, and the wave vector **K** form a left-handed system. Since the negative refraction was realized, a variety of studies aimed at verifying the existence of NIM has been reported and exhibited [6–12].

## 2. Design and optimization of new samples

In this paper, we start by considering a new FTSRRs–MWs metamaterial sample as described in Fig. 1(a). It is a multiple-tier FTSRRs–MWs combined structure attached to the substrate with the length of 10 mm, the width of 5 mm and the thickness of 0.6 mm, as shown in Fig. 1(c). The sample is a prism with periodic structure, and the parameters of the FTSRR are depicted in Fig. 2. As functions of the permittivity and permeability, sample can be excited within SRRs and MWs, as shown in Fig. 1(b) and (c). Fig. 1(b) is a part of the aerial view of FTSRR–MW periodic sample, the gray gridding represents the substrate and the golden yellow lines stand for the FTSRRs–MWs. In Fig. 1(c), a unit cell is demonstrated with the right side of the substrate inserted a metal wire and the reverse side loaded split resonant rings.

Fig. 2 shows the configuration and dimensions of the model unit. A single layer of the whole structure is composed of copper strips with thickness $t$ printed on both sides of the thin sheet of FR4 substrate (as seen in Fig. 2(b)) with relative permittivity 4.4 and relative permeability 1. The unit is repeated in the $x$ direction and the $z$ direction with a periodicity of 5 mm (in Fig. 2(c)). The dimensions of the conducting wires and the split-ring structures are $w$. The copper wires provide negative permittivity in the $x$–$z$ plane. The FTSRRs with the slits in each triangle form a magnetic resonator, providing negative permeability ability for the $y$-polarized magnetic fields.

The model is made up of four uniform triangles, which have more resonators and more complicated configuration to produce perfect resonant effect. In the experiments and applications of the metamaterial, however, enhancing the resonant frequency is an important problem that is urgent to be solved. Recall the earlier discussions [13–17], the metamaterial device functions produce the required resonant frequency via altering the material parameters. Hence one should determine the material parameters once the metamaterial structures are designed. The Triangle SRRs–MWs periodic structure metamaterial was analyzed by us previously, which has a good wide negative refraction. The design of the metamaterial is an essential path between theory and practice. So, based on large amount of full wave electromagnetic simulations and $S$-parameter retrievals, in which the numerical simulations are repeated to optimize the constitutive parameters for a single metamaterial particle.