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Low loss broadband polarization independent fishnet negative index metamaterial at 40 GHz

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Abstract

We present a polarization independent fishnet negative index metamaterial at 40 GHz. The structure is investigated theoretically using finite element method simulations and experimentally by measuring the amplitude and phase of the S-parameters. The experimental setup for free space measurements of both transmission and reflection is hereby introduced. The internal properties are thereafter retrieved and show the double-negative behavior of the structure. This negative index metamaterial exhibits very high transmission (−0.13 dB), low reflection (−33.1 dB) and a high figure of merit ($\text{FOM} = |\text{Re}(n)/\text{Im}(n)| = 42$), where the real part of the refractive index is nearly −1 ($\text{Re}(n) = -0.93$) at 40 GHz.

Keywords: Metamaterial; Negative refractive index; Double negative; Fishnet; Free space measurement; Microwave

1. Introduction

Metamaterials are artificially engineered materials, which exhibit properties that do not exist in nature. These composite structures give access to control the internal electromagnetic properties, i.e. the electric permittivity ε and the magnetic permeability μ, in such a manner that a variety of attractive phenomena like negative refraction and cloaking can take place. In recent years, negative index metamaterials (NIM), which have negative refractive index n rising from $\varepsilon < 0$ and $\mu < 0$ simultaneously, have aroused interest of many researchers due to the promising planar perfect lens application that may overwhelm the diffraction limited conventional lens [1]. The basic idea to achieve negative μ is to excite circular currents that generate a magnetic resonance, whereas negative ε can be produced using continuous metallic wires for frequencies below the plasma frequency. This concept was first concretized by Smith et al. who utilized a combination of split ring resonators and metallic wires [2] and later by Dolling et al. using cut-wire pairs [3]. Another NIM structure called fishnet was reported in the same year by Zhang et al. and showed better performance due to the combined electromagnetic response of the wires and slabs [4].

However, the presented fishnet structures until now suffer from low FOM due to high losses and small negative index bandwidth due to the resonant behavior of the structure [5–9]. To enhance the efficiency of these NIMs, the well-known cross structure is modified, so that a better impedance matching to free space overlaps with the negative index region, giving rise to higher transmission and larger bandwidth. In this study, we present a polarization independent fishnet structure that is designed to have a refractive index $n = -1$ at 40 GHz

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with high transmission, low loss and large bandwidth characteristics.

2. Theory and simulation results

The proposed unit cell is a combination of a cross and a cylinder, which introduces an additional parameter R to the well-known cross design (see Fig. 1). This parameter is important to control the normalized impedance z for a better matching to free space. The substrate used is Duroid 5880 with a thickness $t = 790$ μm separating two thin copper layers with a thickness $s = 17.5$ μm each. The choice of the dielectric substrate material has also a major impact on the efficiency of the NIM since the substrate losses influence dramatically the transmission of the whole structure [10]. The used material has a dielectric constant $\varepsilon_r = 2.2$ and a very low loss factor $\tan\delta = 0.0009$ at around 40 GHz. The unit cell has a period $a = 5$ mm, the metal slabs have a width $w = 1.5$ mm and the cylinder a radius $R = 2$ mm. Due to the symmetric configuration, the structure works for arbitrary linear polarizations. The propagation direction of the incident electromagnetic wave is perpendicular to the metallic layer surface.

The numerical simulations were performed using the commercial finite element solver High Frequency Structure Simulator (HFSS) [11]. To reduce the computing time and expense, we simulated only a quarter of the unit cell illustrated in Fig. 1 since the structure has two planes of symmetry. To ensure the excitation and detection of linear polarized electromagnetic plane waves, two hollow waveguides with excitation ports were used in front and behind the unit cell. Perfect electric and magnetic conductors and symmetric boundaries were then set accordingly on the surrounding four walls of the whole structure. The amplitude and phase of the simulated S-parameters are depicted in Fig. 2.

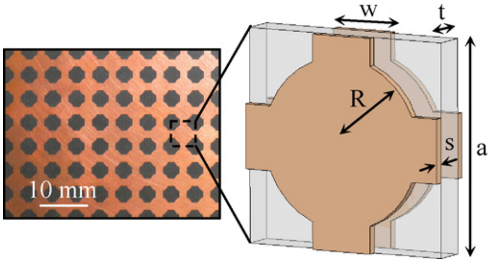

Fig. 1. Proposed fishnet NIM, the "cross-circle" structure.

The transmission spectrum in Fig. 2a exhibits a bandpass behavior with a high transmission band between 39.2 GHz and 49.2 GHz. The transmission reaches −0.13 dB at 40 GHz with a peak value of −0.05 dB at 41.8 GHz, whereas the reflection is −33.1 dB at 40 GHz and −44.9 dB at 41.8 GHz. Fig. 2b shows the phase spectrum of the simulated unit cell. The jump in the phase of S_{21} can allude to a sign change of the refractive index to negative values [12].

The working principal of the NIM is based on the achievement of negative permittivity generated by the metallic wires parallel to the incident electric field **E** at frequencies below the plasma frequency and negative permeability by exciting circular currents and producing a magnetic resonance. The effective plasma frequency of the designed structure should be thus larger than the magnetic resonance frequency to ensure a common frequency range with $\varepsilon < 0$ and $\mu < 0$, which arouses a negative refractive index. The evidence of the predicted magnetic resonance can be effected through the investigation of the surface current distribution, as shown in Fig. 3.

At a frequency of 39.2 GHz the current density on the substrate surfaces reach very high values, proving the existence of a magnetic resonance. Hereby, the

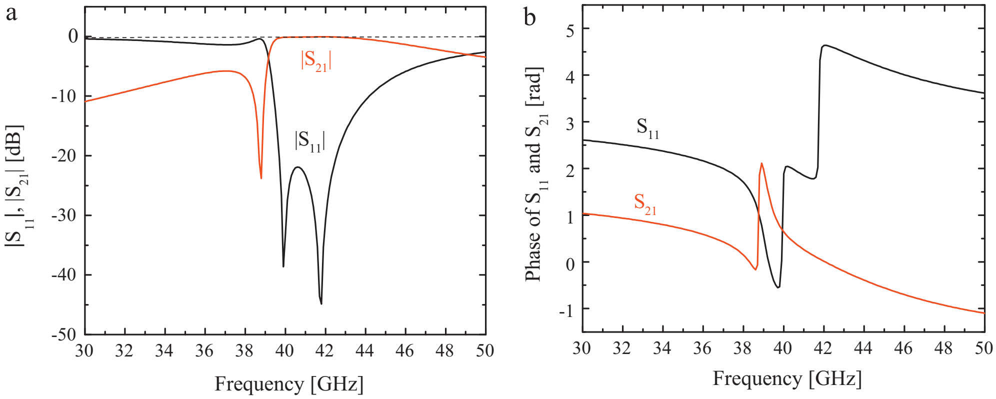

Fig. 2. (a) Amplitude and (b) phase spectra of the simulated S-parameters.