High Index Metamaterial for Terahertz Frequencies

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Abstract

We demonstrate extremely high indices of refraction from large-area, freestanding, flexible terahertz metamaterials. The highest index of refraction of 33.22 is obtained from a multilayer metamaterial at a frequency of 0.851 THz. In addition, we fabricated polarization-independent high index metamaterials composed of hexagonal/square metallic ring and demonstrated polarization-insensitive effective refractive indices.

Keywords : Metamaterial, Terahertz

1. Introduction

Controlling the electromagnetic properties of materials, beyond the limit that is attainable with naturally existing substances, has become a reality with the advent of metamaterials [1,2]. However, from the perspective of engineering indices of refraction, most research efforts were focused on the negative side of whole index spectra and an investigation into the opposite side (positive high indices) was made only recently for a theoretical feasibility test [3]. Here we propose a broadband, extremely high refractive index terahertz metamaterial which can be realized from freestanding and flexible substrates. In addition to this, it will be much better if the metamaterials possess isotropic refractive indices regardless of the incident polarization (i.e. at least two-dimensionally).

2. High Refractive Index Terahertz Metamaterial

The basic building block (single-layer unit cell) of the proposed high refractive index terahertz metamaterial is shown in Fig. 1(a). The substrate is made from a dielectric material (polyimide, $\mathrm{Re}[n] = 1.8$) and the thin I-shaped metallic patch (Au/Cr) is imbedded symmetrically in the substrate. The optical micrographs of the fabricated large-area (2×2 cm^2), freestanding, flexible metamaterials are shown in Fig. 1(b). The gap width (defined by $g = L - a$) plays a crucial role in raising the effective permittivity. For the thin I-shaped metallic patch structure, the scaling of the charge accumulation and effective permittivity shows different asymptotic behaviours depending on the gap width, leading to weakly coupled ($g/L \lesssim 1$) and strongly coupled ($g/L \ll 1$) regimes. In the strongly coupled regime, an accumulated charge on each arm of the capacitor is inversely proportional to the gap width ($Q \propto L^3 g^{-1}$). The behaviour of the charge accumulation differs significantly in the weakly coupled regime, in which the amount of charge increases quadratically with decreasing gap width ($Q \propto (L - g)^2$) in the quasi-static limit. Although decreasing the gap width can enhance the effective permittivity, it is still necessary to suppress the diamagnetic effect for the realization of a high refractive index. A *thin* I-shaped metallic structure can provide a pathway to effectively reduce the diamagnetic effect since a thin I-shaped patch has a small area subtended by the current loops. To confirm the physical origin of the high refractive index with the aforementioned approach, the electric and magnetic field around the metal inclusion of the unit cells of a single-layer metamaterial were calculated for a frequency of 0.33 THz (Fig. 1(c), (d)).

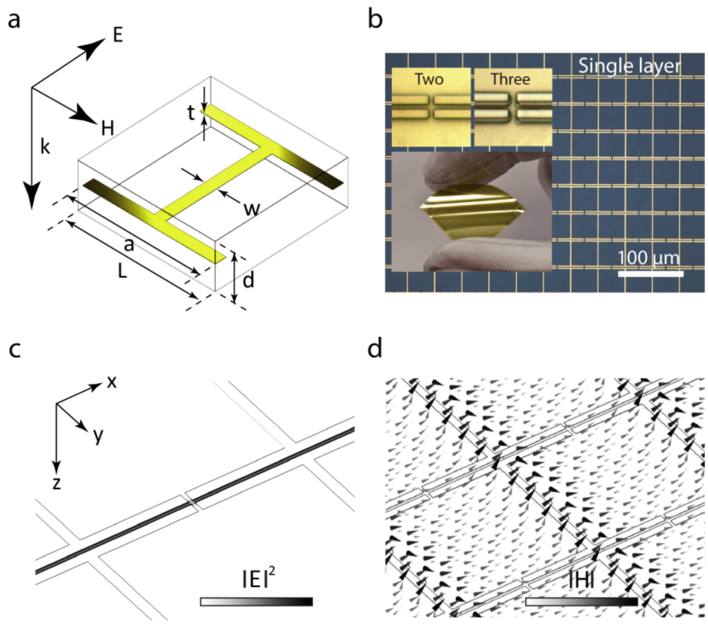

Figure 1: (a) Unit cell structure of the high-index metamaterial (b) Optical micrographs of the fabricated single layer metamaterials (c) Saturated squared electric field (at 0.33 THz) for a single layer metamaterial (d) Vector plot of the magnetic field (at 0.33 THz) in the unit cells

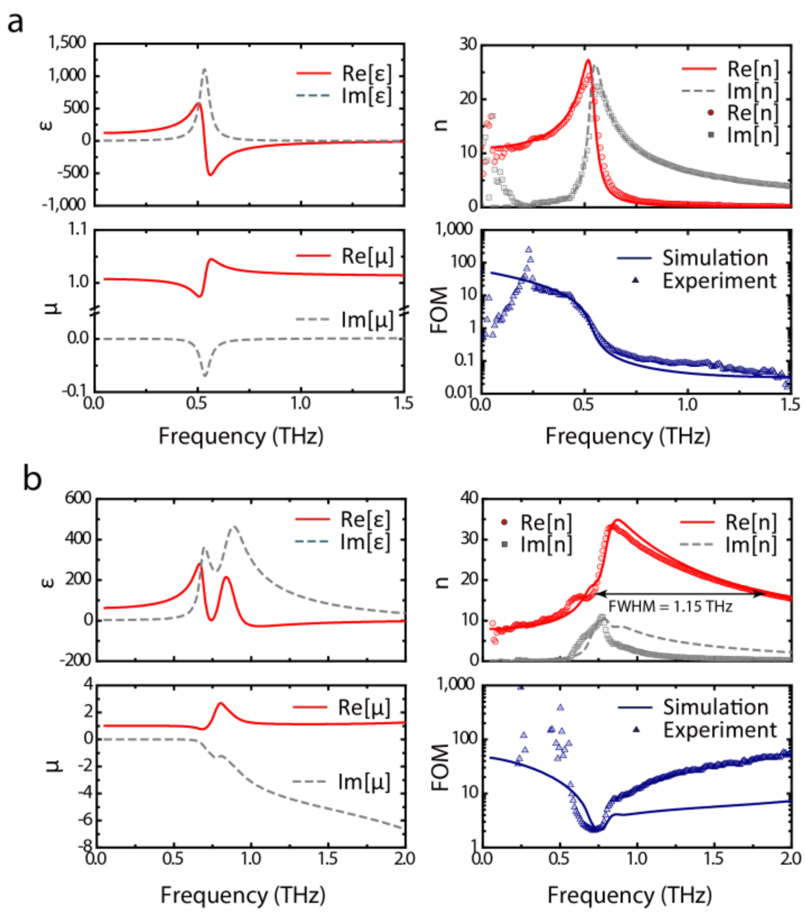

Figure 2: (a) Effective permittivity (top left), permeability (bottom left), refractive index (top right), and figure of merit (bottom right) for a single-layer metamaterial (b) Effective parameters for a five layer metamaterial

To experimentally probe the enhancement of the effective refractive index, terahertz time-domain spectroscopy [3] (THz-TDS) was performed for a frequency range of 0.1–2 THz. The complex refractive indices extracted from the THz-TDS measurements were compared with the numerically obtained refractive indices from the *S*-parameter extraction methods. Considering the uncertainties in the material parameters used for the simulation and the errors in the gap-width measurements, the experimentally acquired complex refractive index was in excellent agreement with the simulated refractive index. From the single layer metamaterial characterization, the peak refractive index of $n = 24.34$ at 0.522 THz was observed with a value of $n = 11.18$ at the quasi-static limit. The loss associated with the single layer metamaterial is quantified by the figure-of-merit ($\mathrm{FOM} = \mathrm{Re}(n)/\mathrm{Im}(n)$) and experimental and numerical values of the FOM are plotted in the lowest panel of Fig. 2(a). For most frequency ranges, especially in the lower portion below the electric resonance, the FOM stays above 10 with a peak FOM exceeding 100. In order to investigate the *bulk* properties, quasi-three-dimensional high-index metamaterials containing up to five layers were fabricated and tested. The measured complex refractive index and the FOM are plotted in Fig. 2(b) along with the corresponding numerically extracted parameters for this five-layer high-index metamaterial with small interlayer spacing ($d = 1.62$ μm). From the THz-TDS measurements and subsequent parameter extraction, the highest index of refraction of 33.22 is obtained at a frequency of 0.851 THz.

3. Polarization-Independent High Index Terahertz Metamaterial

For the realization of polarization-insensitive refractive indices, two different types of high index metamaterials are designed and tested. One of the simplest polarization-insensitive structures is square-metallic-rings arranged periodically in square lattices (schematically shown in Fig. 3a). In addition, we have implemented a hexagonal-metallic-ring structure (in hexagonal lattices) as shown in Fig. 3a. Figure 4 shows the refractive indices of the square ring and hexagonal ring metamaterials with a variation in a polarization angle (See insets of Fig. 4). While the angle of polarization changed from 0 to 45 degree, the refractive indices remain unchanged within the experimental error for both types of metamaterials. As can be seen in Fig. 4b, the maximum refractive index approaches to ~35 near the electrical resonance frequency.

As another example, we fabricated and tested a window-type high index metamaterial (see the inset of Fig. 4c for the structural details). In addition to the two-dimensional isotropy of refractive indices, this window-type metamaterial has advantages for exhibiting higher electrical resonant frequency. Higher resonant frequency makes it possible to utilize broader high refractive index with low loss and large transmission. The polarization-angle-resolved refractive indices for the window-type high index metamaterials are shown in Fig. 4c, which shows similar polarization independency along with higher electrical resonance frequency as predicted.

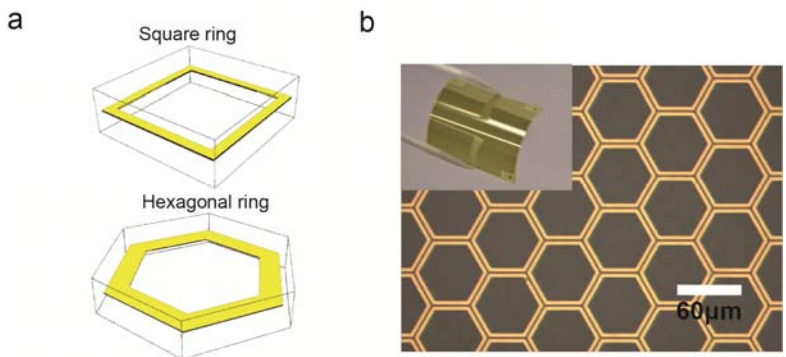

Figure 3: (a) Schematics of polarization-insensitive high refractive index metamaterials. Square metallic ring structure (top) and hexagonal metallic ring structure (bottom) are shown schematically. (b) Optical micrograph of the fabricated hexagonal ring type metamaterial.

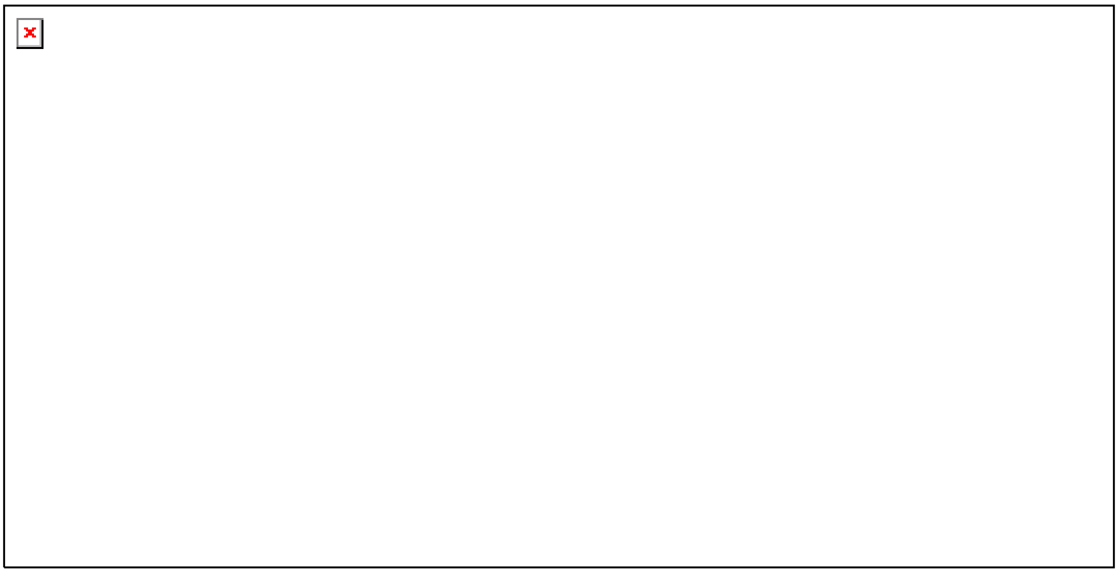

Figure 3: (a) Polarization-angle-resolved effective refractive index of a square ring metamaterial. Real (top panel) and imaginary (bottom) part of the complex effective refractive index were plotted. Inset shows the definition of a polarization angle used in this work. (b) Polarization-angle-resolved effective refractive index of a hexagonal ring metamaterial. (c) Polarization-angle-resolved effective refractive index of a window-type high index metamaterial.

References

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