Polarization-independent Metamaterial with Unnaturally High Refractive Index in the Terahertz Region

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Abstract— Refractive index is the most important property of material in optics and most naturally existing transparent materials possess small positive indices of refraction. With the progress of metamaterials, we can manipulate the electromagnetic properties of materials. Metamaterials promise unexpected physical phenomena through creating artificial "atoms" with an array of period metallic structure. However most researches are focusing on the negative refractive index materials at present, on the contrary the opposite side of high refractive index materials attracts far less attention. Previous approaches using metamaterials were not successful in realizing broadband isotropy high refractive indices. Here we design a broadband, isotropy three-dimensional metamaterial with extremely high index of refraction in terahertz region which composed of strongly coupled unit cells. We increase the effective permittivity through strong capacitive coupling and decrease the diamagnetic response with a thin metallic structure in the unit cell. A peak refractive index of 67.9 at 2.14 THz is observed under TE mode and a peak refractive index of 66.9 at 2.16 THz under TM mode. Both of polarizations maintain low loss with figure of merit go to as high as 2.12 and 2.48 separately. Moreover, the refractive index does not fall sharply at higher frequencies, and shows an extremely broadband behavior with a full-width at half-maximum (FWHM) of more than 2 THz.

1. INTRODUCTION

Metamaterial is a kind of artificial material composed of dense arrays of sub-wavelength strongly coupled unit cells. Plenty of unexpected electromagnetic phenomena have been realized by specially designed metamaterials [1], including controlling refractive-index [2–4], which is the most important property of material in optics. However, most of the previous researches on metamaterials in the terahertz region was focused on the negative refractive index materials [5]. High refractive index metamaterial was experimentally investigated only recently [6–11]. Expanding the refractive index into a high positive regime will complete the spectrum of achievable refractive index and provide more design flexibility for transformation optics [12–14].

The universality and scalability of the metamaterial design enables their deployment across the electromagnetic spectrum. Especially attractive are the metamaterials designed to operate in the terahertz (THz) region of the optical spectrum. Because of its special properties, the terahertz can be widely applied to medical imaging, communication, sensing and national defense [15]. However, previous approaches using metamaterials were not successful in realizing polarization-independent broadband high refractive index. The proposed metamaterials exhibit polarization dependency because of the structural anisotropy of the unit cell. In this letter, we design a broadband, isotropy three-dimensional metamaterial with extremely high index of refraction in terahertz region.

According to the Maxwellian macroscopic description, the effective permittivity of a metamaterial can be expressed as $\varepsilon = 1 + (P/\varepsilon_0 E)$ and the effective permeability can be defined by $\mu = 1 + (M/H)$, where E, H, P, and M represent the electric field, magnetizing field, polarization, and magnetization, respectively, and the refractive index of materials is determined by effective permeability and effective permittivity. In order to achieve high effective refractive index, it is required to implement a large capacitance unit cell structure to maximize the effective permittivity. Here we design a two-layer high refractive index metamaterial. The upper layer is made of a strongly coupled, thin 'I'-shaped metallic patch. Then an alike structure which is rotate by 90 degrees around the propagation axis of the incident terahertz wave act as the under layer. The upper and under layer form a symmetrical structure together.

As a demonstration of the properties of the high refractive index metamaterial, the electromagnetic response of the structure is simulated using the finite-elements method COMSOL Multiphysics simulation package. The thin 'I'-shaped metallic patch is considered to be embedded symmetrically in the dielectric substrate and illuminated with a plane wave at normal incidence.

The basic building block (two-layer unit cell) of the proposed high-refractive-index terahertz metamaterial is shown in Figure 2(a), together with the polarization of an incident TE terahertz

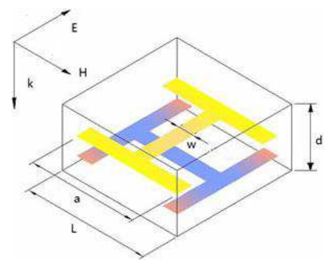


Figure 1: Schematic view of unit cell structure of the high-index metamaterial.

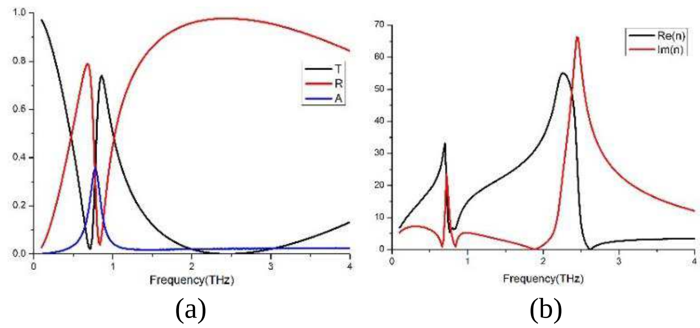


Figure 2: (a) Simulated transmission (T) and reflection (R) and absorption (A) spectra of the structure. (b) Numerically extracted values of complex refractive index (n) obtained from the S-parameter retrieval method.

wave. The substrate was implemented with polyimide ($n_{poly} = 1.8 + 0.04i$), and the metals used to construct the metamaterials were gold. The complex dielectric constant of gold for the frequency range of interest can be fitted using the Drude model with a plasma frequency of $\omega_p = 1.37\times10^{16}\,\text{s}^{-1}$ and collision frequency of $\gamma = 4.07 \times 10^{13}\,\text{s}^{-1}$. The geometric parameters used for simulation of the metamaterial are: $L = 40\,\mu\text{m}$, $a = 39\,\mu\text{m}$, $w = 3\,\mu\text{m}$, $d = 1\,\mu\text{m}$. The thickness of both metallic patch is 100 nm. The gap width between the metallic patches is defined as $g = L - a$. It's worth noting that both metallic structure are the same size.

As can be seen from Figure 2(a), there are two reflectivity peaks in the interval of 0.1–4 THz, corresponds to two peaks index of refraction of $n = 33.1$ at 0.7 THz and $n = 55.1$ at 2.26 THz are observed in Figure 2(b). Each layer of matellic structure provide a refraction peak, respective. But each peak are caused by different mechanism. The electric field was strongly concentrated in the gap along the long side between each 'I'-shaped metallic structure in the upper layer at a incident frequency of 0.65 THz and a different electric field distribution along the short side produced by the under layer at a higher incident frequency of 2.26 THz. Meanwhile both of the magnetic field penetrated deeply into the unit cell because of the negligible metallic volume fraction. The saturated of electric field and magnetic field of both layer are shown in Figures 3(a), (b), (c), (d), respective. So it is apparent that the upper layer and under layer produce a lower peak of refractive at a lower frequency and he under layer produce a higher peak of refractive at a higher frequency. Actually we can find that when the incident wave is polarized along the central beam (defined as a TE wave) at 0.65 THz, there is a larger capacitance of the upper layer comparing with the case of the under layer illuminated with a wave at 2.25 THz. However the capacitance of the under layer illuminated with a wave at 0.65 THz is far less than the case of the upper layer with a wave at 2.25 THz. In a broad sense, the peak of refraction is influenced by both of the two layers.

After the possibility of realizing a dualband high refractive index for double-layer metamaterial, further insights can be acquired with an investigation into three-dimensional high refractive index metamaterials. In order to investigate the bulk properties, a high refractive index metamaterials containing up to four layers were tested. Figure 4(a) shows the simulated transmission/reflection plotted as a function of frequency; and the simulation complex refractive index are plotted in Figure 4(b). As can be seen in the picture, there are still two high refractive index peaks for the three-dimensional metamaterial. The index of refraction of 24.9 and 67.9 are obtained at a frequency of 0.48 THz and 2.14 THz, respectively. Meanwhile, the refractive index does not fall sharply at higher frequencies, and shows an extremely broadband high refractive index with a

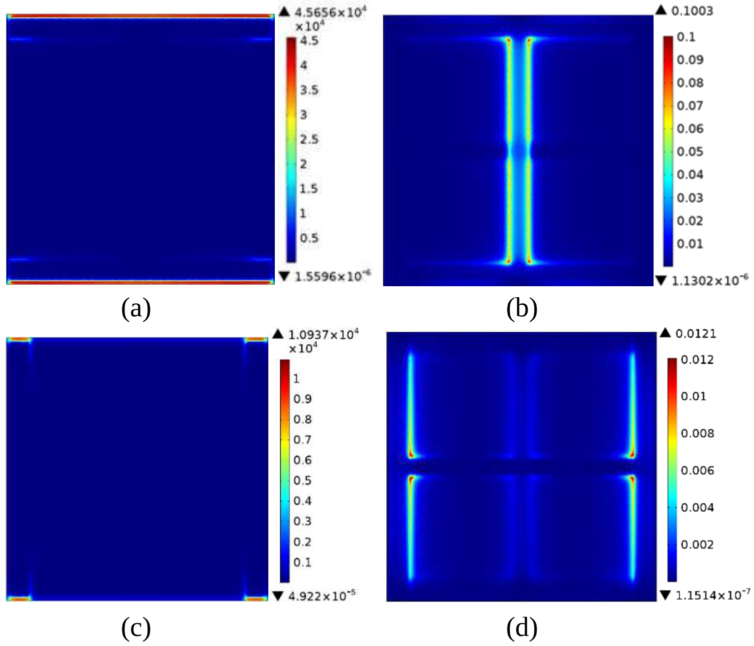


Figure 3: Saturated (a) electric and (b) magnetic field of upper layer at 0.65 THz, (c) electric and (d) magnetic field of under layer at 2.25 THz for a double-layer metamaterial, respectively.

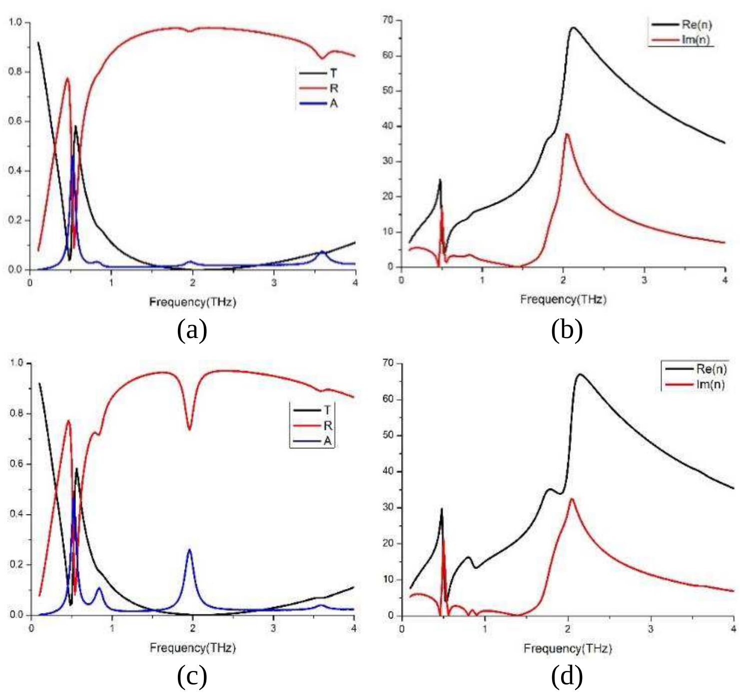
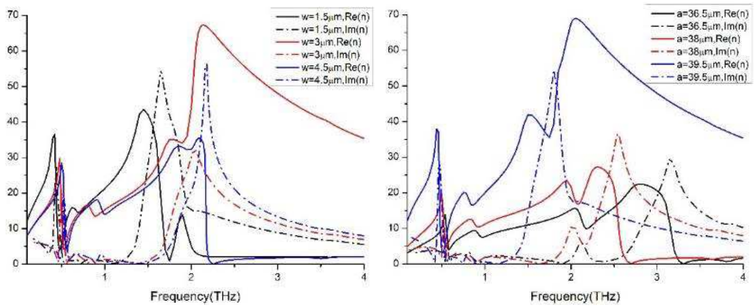


Figure 4: Simulated transmission (T) and reflection (R) and absorption (A) spectra of the structure for (a) TE polarization and (c) TM polarization, respectively; numerically extracted values of complex refractive index (n) obtained from the S-parameter retrieval method for (b) TE polarization and (d) TM polarization.

full-width at half-maximum (FWHM) of more than 2.24 THz. The four-layer metamaterials leads to different mechanism in the refractive spectra compared to double-layer metamaterials [16, 17] because of the coupling between layers. Considering the effective wavelength of a terahertz wave inside the metamaterial, the thickness ($d = 2\,\mu$m) in the direction of propagation is much smaller than the effective wavelength, which justifies the application of homogenization theory, so the four-layer metamaterial can be considered as a Fabry-Pérot etalon. So the four-layer metamaterials maintain low loss with figure of merit go to as high as 2.12.



(a) (b)

Figure 5: Geometrical parameter-dependent effective refractive index. (a) Effective refractive index plotted as a function of central beam width w. (b) Effective refractive index plotted as a function of gap width g.

As the proposed high-index metamaterial is a symmetrical structure, we can easily predict that the metamaterial has an isotropous refractive index. Figures 4(a), (c) show the simulated transmission (T) and reflection (R) and absorption (A) spectra of the structure for TE polarization and TM polarization, respectively. Figures 4(b), (d) show numerically extracted values of complex refractive index (n) obtained from the S-parameter retrieval method for TE polarization and TM polarization, respectively. It is noted that there are still two refractive in peaks in the interval of 0.1–4 THz. They are $n = 39.6$ at 0.48 THz and $n = 66.9$ at 2.16 THz respectively. And it also keeps the feature of broadband, and the figure of merit maintains 2.48. There are still some differences when the incident wave changes from TE wave into TM wave. This is mainly caused by the different spatial locations between them.

The value of the refractive index is a sensitive function of the gap width (g) and the central beam width (w) for the proposed high-index metamaterials. In order to verify this two geometrical size dependency, the effective refractive index are numerically estimated for samples having different geometrical parameters. The dependency of refractive on the central beam width (w) is plotted in Figure 5(a). For this simulation, the parameter of the structure is $L = 40\,\mu\text{m}$, $d = 2\,\mu\text{m}$, $a = 39\,\mu\text{m}$. In the plot, we can find that when the central beam width is too narrow, the current loops decrease, leading to a decrease of the refractive index. However, when the central beam width (w) is too board, there is a great of diamagnetic effect in the structure which also resulting the refractive index decreases. It is also worthwhile to note that, the central beam width control can also be used to tune the electric resonance frequency of the metamaterial, which is caused by the change in the inductance of the metallic patch. Figure 5(b) shows the numerically estimated index of refraction as a function of the gap width. As the gap width decreases, there is a great increase of the capacitive due to coupling between unit cells. As a result, the index of refraction is drastically increased. Therefore, an even higher index of refraction can be achieve by further reducing the gap width (g). As the gap closes, this increase is expected to continue until the gap width approaches the Thomas–Fermi length scale [18] or the quantum tunneling scale of electrons. Moreover, the effective refractive index is proportional to the substrate index; thus, the introduction of a higher-index substrate will lead to greater amplification of the refractive index and an unprecedentedly large effective refractive index.

In summary, we have designed a dualband polarization-independent broadband metamaterial with high refractive index in the terahertz region. The obtained dependence of the effective refractive index on the geometric parameters provides us with a general recipe for designing such metamaterials. Moreover, we can predict that a high-performance high-index metamaterials can also be realized to even higher frequency ranges, such as mid-infrared frequencies via rational design.

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