# Electromagnetic response of two-dimensional metamaterials constructed of a metal-mesh and dielectric spheres in the terahertz region

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**Abstract**

Mie resonances of dielectric spheres exhibit artificial dispersion in effective permeability and permittivity. We propose a simple and possible way to construct a two-dimensional metamaterial with negative refractive index in the terahertz region. The dielectric spheres made of $TiO_2$ are periodically arranged on a metal-mesh. The transmission peaks caused by the interaction between the $TiO_2$ spheres and the metal-mesh are obtained. The transmission and the phase shift spectra suggest that the negative refractive index is realized by the combination of the negative permittivity of the metal-mesh and the negative permeability of $TiO_2$ of the Mie resonance.

## 1. Introduction

Displacement currents in resonant modes of a dielectric resonator exhibit effective magnetic dipoles resulting in artificial magnetism. The first TE and TM modes of the Mie resonance of the dielectric spheres produce artificial dispersion in the effective permeability and permittivity, respectively [1]. To disperse dielectric spheres in transparent host materials is the simplest way to make isotropic metamaterials because the Mie resonant modes of spheres are isotropic. It is also a merit that mass production method for various sizes of dielectric spheres can be provided.

High-refractive index dielectrics are required to obtain the negative permeability [2]. In the terahertz range, $TiO_2$ has the high refractive index with low loss. The refractive index $n$ of $TiO_2$ is approximately $n = 10 + i0.5$ at 0.5 THz [3]. There are several reports on $TiO_2$ dielectric metamaterials with negative permeability [4]. The negative permittivity is also obtained in metamaterials by using the lowest TM mode of the Mie resonance, which makes it possible to design all-dielectric negative refractive index metamaterials. However, the background permittivity, which results from the permittivity of the materials of the spheres, is rather high to obtain the negative permittivity. The composite structures composed of dielectric resonators and a metal-mesh have been proposed to obtain negative refractive index [5]. Electromagnetic waves with the frequency below its cutoff frequency of the metal-mesh are blocked, in which the effective permittivity of the metal-mesh is negative and the effective refractive index is pure imaginary. When artificial magnetism of the Mie resonance exhibits the negative permeability, a pass band should be obtained in the corresponding frequency range.

ISBN 978-952-67611-2-1  

In this paper, we propose the easy method to fabricate a two-dimensional metamaterial in the terahertz range, which are composed of the $TiO_2$ spheres and the metal-mesh. By selecting the proper sizes, the sprinkled spheres are just filled in the openings of the metal-mesh and arranged roughly periodically. We measured the transmission spectra of the composite structures for various filling factors of openings of the metal-mesh, and discussed the results.

## 2. Experiment and discussion

Figures 1(a) and (b) show micrographs of a metal-mesh and $TiO_2$ spheres. The metal-mesh was knitted with stainless wires of the diameter $l$ = 20 μm with the period of $p$ = 88 μm. The opening width of the metal-mesh was $w$ = 68 μm. The average diameter of the spheres was $d$ = 75 μm with the standard deviation of 2.4 μm. Because the sphere diameter was slightly larger than the opening width of the metal-mesh, the spheres sprinkled on the metal-mesh were fitted in the openings of the metal-mesh as shown in Fig. 1(c). The transmission spectra of the samples were measured using a terahertz time-domain spectroscopic system.

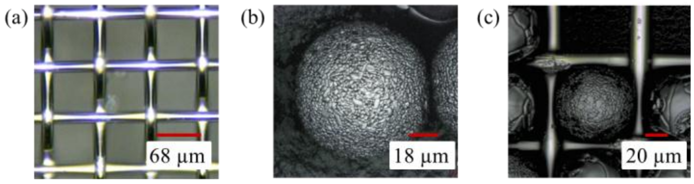


Fig. 1: Micrographs of (a) the metal-mesh, (b) $TiO_2$ sphere, and (c) composite structure.

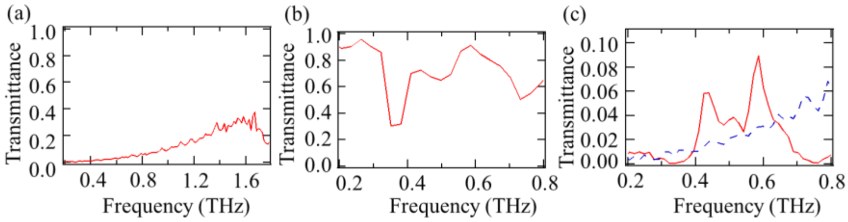


Fig. 2: Transmission spectra of (a) the metal-mesh, (b) $TiO_2$ spheres, and (c) composite structure. The dashed line in (c) is the transmission of a metal-mesh

The transmission spectrum of the metal-mesh is shown in Fig. 2(a). Its cut-off frequency is estimated to be 2.2 THz from $w$. The electromagnetic waves below the cut-off frequency are blocked, i.e., the effective permittivity of the metal-mesh is negative. Figure 2(b) shows the transmission spectrum of the $TiO_2$ spheres randomly dispersed on a polypropylene tape. The resonances of the first TE and TM modes are observed at 0.38 and 0.52 THz, respectively. Figure 2(c) shows the transmission spectra of the composite structure of the spheres and the metal-mesh. The ratio of the numbers of the spheres to openings of the metal-mesh $f$ was approximately 0.75. Two transmission peaks larger than the transmittance of the metal-mesh are observed at 0.42 and 0.57 THz. The peak frequencies are higher than the transmission dips of the TE and TM modes of the spheres in Fig. 2(b). It is conceivable that the transmission peak at 0.42 THz is attributed to the propagation mode with the negative refractive index caused by the negative permeability of the TE mode of the spheres and the negative permittivity of the metal-mesh. The origin of the peak at 0.57 THz, which is observed at the frequency higher than that of TM mode of the spheres, is unknown at present.

Figure 3 shows the transmission and phase shift spectra for different values of $f$. The peak values at 0.42 and 0.57 THz increase with $f$. For $f$ near 1, the spheres pile on the spheres in the first layer and the peaks begin to vanish. This supports that the transmission peaks are caused by the cooperative effect between the spheres and the metal-mesh. In the phase shift spectrum for $f$ = 0.75, the phase shift is negative at the transmission peak frequency of 0.42 THz. The negative value of the phase shift with the transmission peak implies the negative refractive index. The phase shift is 0 at the transmission peak frequency of 0.57 THz. The phase shift of 0 indicates the impedance matching condition. The origin of the peak at 0.57 THz, therefore, is presumed to be the canceling of the phase shift of the metal-mesh with that of the resonance of the TM mode. Similar cases have been reported in the composite system of the metal apertures and the split-ring resonators [6,7]. The interference between the aperture and the resonant mode of the split-ring resonators causes the transmission peaks (reflection dips). The analogy is suggested in the system of the dielectric resonators and the metal-mesh.

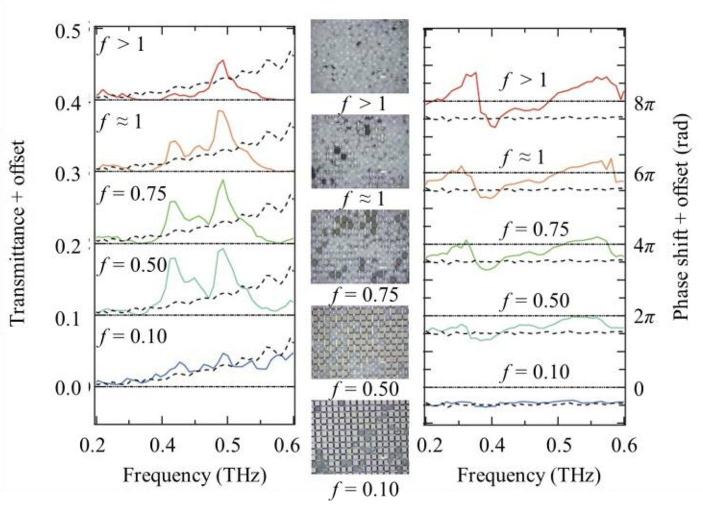


Fig. 3: Transmission and phase shift spectra of the composite of the $TiO_2$ spheres and the metal-mesh for various ratios of the numbers of the $TiO_2$ spheres to the opening of the metal-mesh *f*. The dashed lines indicate the metal-mesh for comparison. The dotted straight lines indicate the offset.

## 4. Conclusion

The proposed method allows arranging the dielectric spheres periodically in the open-area of the metal-mesh very easily. The transmission and the phase shift spectra suggest that the negative refractive index is obtained by the Mie resonance of the dielectric spheres. For the exact evaluation of the effective refractive index, however, the transmission and reflection coefficient must be measured and the numerical simulation is required. They are undergoing.

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