Metafilm: Metamaterial Array Embedded in Organic Thin Film

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Abstract: A flexible metamaterial device consisting of metal split rings embedded in a transparent polymer film is demonstrated. The device is useful to construct three-dimensional metamaterial systems to develop novel terahertz- and photonic applications.
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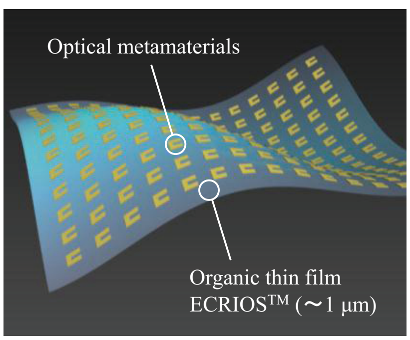
1. Creating three-dimensional, flexible metamaterials

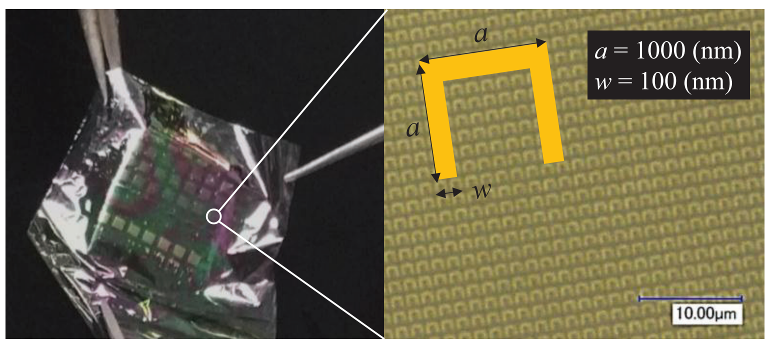
Metamaterials are artificial materials consisting of multiple nanostructures such as minute resonators, arranged periodically with a pitch smaller than the wavelength of electromagnetic waves. They can exhibit extraordinary permittivity and permeability values that are not found in nature. Using this property, we can create novel devices to manipulate electromagnetic waves more sophisticatedly [1, 2]. Metamaterials will provide promising functional devices in particular for photonic applications such as optical imaging, sensing, and communication.

Optical metamaterials are at present normally fabricated by forming a metal nanostructure array on a flat substrate, using electron-beam lithography and lift-off processing [3]. To develop innovative applications, it is needed to develop 3D metamaterial technology, namely a technology to make curved metamaterials on nonplanar substrates and make multilayer metamaterials consisting of a stack of many layers of nanostructure arrays. For this purpose, we propose a flexible metamaterial film device, hereinafter called the "Metafilm."

The Metafilm is a metamaterial consisting of a metal nanostructure array embedded in a flexible, transparent polymer film (Fig. 1(a)). It can easily be attached on a substrate with a curved and uneven surface to make a metamaterial layer along the nonplanar surface. The multi-layer metamaterial can be made simply by stacking many Metafilm layers. The Metafilm can be designed for use in a wide wavelength range of from millimeter- and terahertz waves to visible light.



(a)



(b)

Fig. 1. (a) Schematic image of metafilm.(b) Optical microscope image of metamaterial array embedded in organic thin film.

2. Device structure and fabrication

To make the Metafilm, we used ECRIOS™ polymer as a base material. The ECRIOS™ is a polyimide with excellent transparency and heat tolerance developed by Mitsui Chemicals Inc., using the technology of macromolecular design. Figure 2 depicts the measured optical transmittance of a 20-µm thick ECRIOS™ film, showing high transparency for visible and infrared light.

The fabrication process was as follows. First, ECRIOS™ dissolved in N-methyl-2-pyrrolidone was coated on a substrate and thermally cured at 260° C for 2 hours. The resultant thickness of the ECRIOS™ layer was 500 nm. Then, a metamaterial consisting of an array of square split rings made of metal (5-nm Ti/30-nm Au) was formed on the

ECRIOS™ layer, using electron-beam lithography and lift-off processing. After that, ECRIOS™ was again coated thereon and thermally cured. The total thickness of the film was 1 μm. Finally, the film was peeled from the substrate. Figure 1(b) shows the peeled film, the Metafilm.

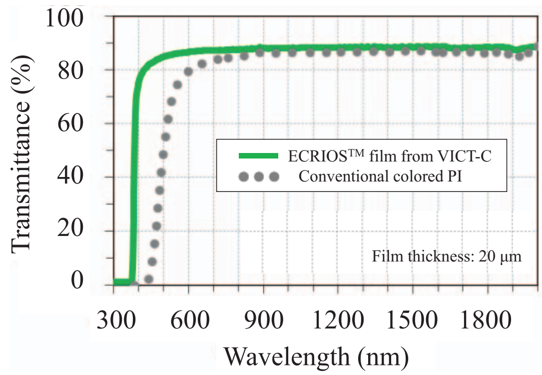


Fig. 2. Measured transmission spectra of ECRIOS™ film.

3. Device operation and simulation

We prepared five samples of Metafilm with different dimensions of the split ring. The dimensions were a = 150, 300, 500, 700, and 900 nm for the five samples, and w = 50 nm for all samples (see Fig. 1(b) for a and w). An ECRIOS™ film without the split-ring array was also prepared as a control to measure the absorption of light in a simple ECRIOS™ film.

Figure 3(a) shows the transmission spectra of the samples measured for incident electromagnetic waves whose electric field is parallel to the gap of the split ring. In Fig. 3(a), the light absorption of ECRIOS™ is subtracted to show the intrinsic transmission of the split ring array. The transmission spectrum shows two absorption peaks caused by LC resonance and Mie scattering. The LC resonance is due to basic-mode oscillation of current induced in the split rings by incident electromagnetic wave (see Fig. 3(c) for a 300-nm ring). Its frequency depended on the dimension of the split ring and changed from 30 THz (for 900-nm rings) to 170 THz (for 150-nm rings). Figure 3(b) depicts simulated transmission spectra that were calculated using the finite element method. The results are consistent with measured data. Using these results, we evaluated the effective relative permeability of the Metafilm as a function of frequency. Figure 3(d) shows the result for a Metafilm with 500-nm split rings. The effective relative permeability changed significantly at about 60 THz (5.0-μm wavelength) and decreased to -0.5, a value smaller than that of vacuum.

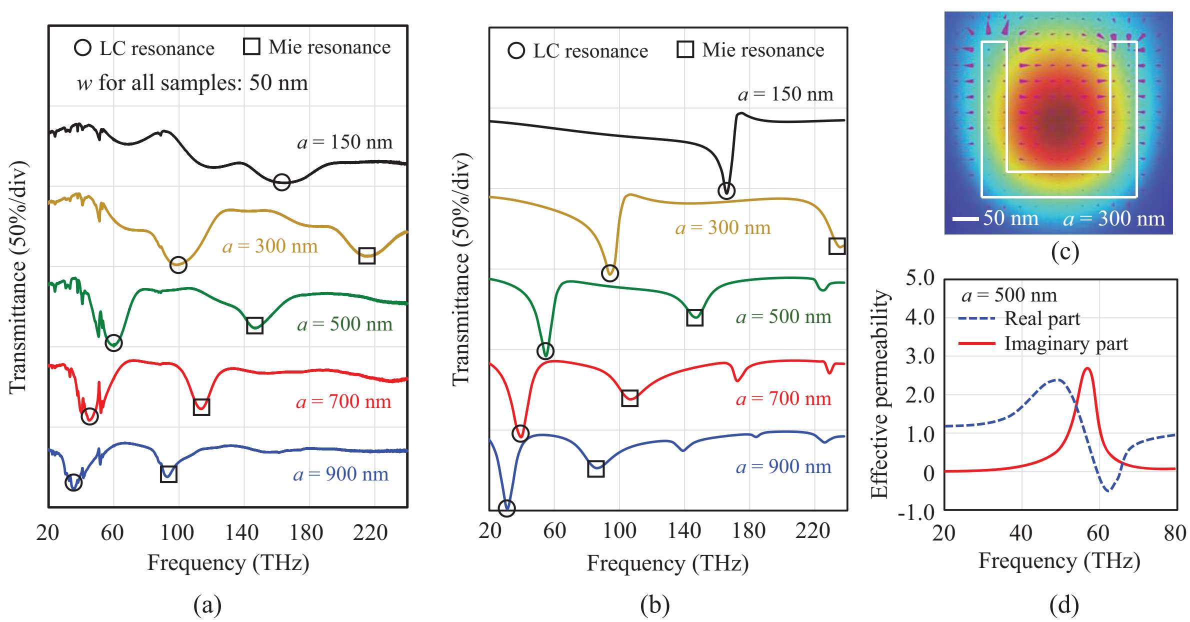


Fig. 3. Measured (a) and calculated (b) transmission characteristics of metafilm with different ring size. (c) Magnetic field distribution around ring (arrow: electric field). (d) Retrieved effective relative permeability of metafilm with 500-nm ring.

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