Electromagnetic Resonance in Standing U-shapes Fabricated with the Super-fine Ink-jet Printer

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Metamaterials promise to improve flexibility of electromagnetic systems from microwave to visible regions. In the terahertz region, the metamaterials are composed of few-micron-wide metallic lines. In ref. 1, we have demonstrated the planar terahertz metamaterials fabricated with the super-fine ink-jet (SIJ) printer which has been developed by Murata *et al.* (SIJTechnology, Inc.) [2]. The spatial resolution of the SIJ printing is comparable to that of the photolithography. Nevertheless, the process of the SIJ printing is far simpler than that of the photolithography. Another advantage of the SIJ printing is capability of three-dimensional (3D) fabrication [2, 3]. To design the magnetic metamaterials, the 3D structures along the light propagation direction are required. In this paper, a 3D structure, i. e. standing U-shaped split-ring resonator (USRR) array is fabricated and a LC resonance is observed in the terahertz frequency range.

Figure 1 (a) shows a microphotograph, schematic, and 3D topographic image of the standing USRR array fabricated on a high-resistivity silicon substrate with silver nanopaste (Harima Chemicals, Inc.). A typical size of the USRRs is shown in Fig. 1(a) and the whole size of the USRR array was 4 × 4 mm^2 including 2500 elements. The few-tens of micron-height pillers can be fabricated by stopping the ink-jet nozzle. After printing, the USRR array was annealed at 240 Celsius degree for an hour.

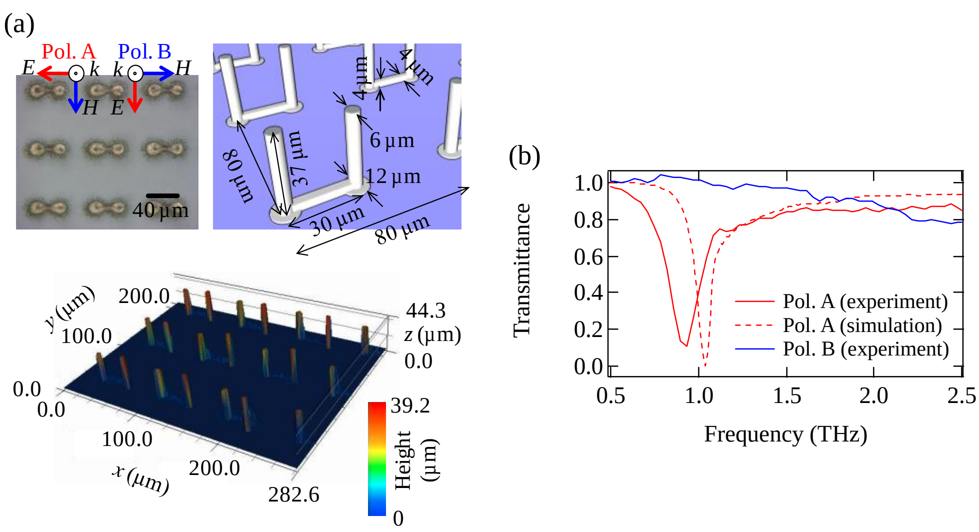

Fig. 1: (a) Microphotograph, schematic, and 3D topographic image of the USRR array. (b) Transmission spectra normalized by that of the substrate.

The transmission spectra for the incident polarization of Pol. A and Pol. B in Fig. 1(a) were measured with the terahertz time-domain spectroscopy (Fig. 1 (b)). For Pol. A, the resonance is observed at 0.92 THz. It is confirmed that this resonance is the LC one from the finite-difference time-domain (FDTD) simulations (the details are not shown here).

Figure 2 shows the incident angle dependence of the transmission spectra. The transmission dip is almost independent of the incident angle for polarizations active for the LC resonance (Fig. 2(a) and (b)). This LC resonance is, however, induced by both of incident electric and magnetic fields so that the USRR array is a bi-anisotropic metamaterial [4]. Similarly, the transmittance spectra for the inactive polarizations (Fig. 2(c), 2(d)) are independent of incident angle. These results are consistent with Tao's results [5]. They fabricated planar arrays of split ring resonators on bimaterial cantilevers designed to bend out of plane in response to a thermal stimulus. They pointed out that the total polarization induced by the electric and magnetic fields is almost conserved for change of incident angle in their bi-anisotropic structure, which is also theoretically explained by the bi-anisotropic nature [4]. Then, it is concluded that the total polarization in the resonance at 0.92 THz in the USRR array is almost conserved for the change of the incident angle, resulting the independence for the incident angle.

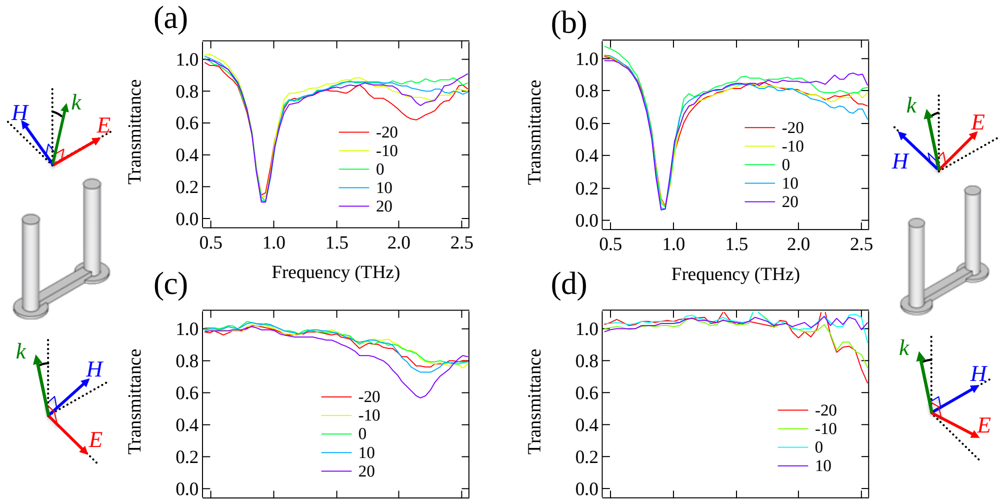

Fig. 2: Incident angle dependence of the USRR array for the active polarizations ((a) and (b)) and inactive polarizations ((c) and (d)).

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