Spectral Properties of THz-Periodic Metallic Structures

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We have investigated spectral properties of the periodic arrays of aluminum rods and holes on papers using the terahertz time-domain spectroscopy. The size of a rod (hole) is 600 μm × 100 μm and the spacing is 300 μm. The samples were fabricated by a femtosecond laser micromachining system. The periodic arrays of aluminum rods exhibit high reflection around 0.25 THz when the polarization of the THz pulse is parallel to the long axis of the rod, whereas the periodic arrays of holes exhibit high transmission around 0.25 THz when the polarization of the THz pulse is perpendicular to the long axis of the hole.

Keywords : terahertz, high reflection, Babinet's principle

OCIS codes : (220.4830) Optical systems design; (050.1220) Apertures; (300.6270) Spectroscopy, far infrared

I. INTRODUCTION

Spectral properties of periodic metallic arrays have attracted much attention [1]. For example, the enhanced optical transmission through a metallic screen with a periodic array of holes has been observed [2-5]. The enhanced transmission has been understood by resonant coupling of surface plasmons and incident electromagnetic waves. It has also been demonstrated that periodic arrays of metallic structures could exhibit the high reflection at certain frequencies that are determined by the geometries of metallic structures [6]. The high reflection has been understood by negative effective permittivity or permeability [6-9].

Recently, properties of various materials in the terahertz (THz) frequency range have been intensively investigated by THz time-domain spectroscopy (THz-TDS) [10-14]. The materials include quantum dots, carbon nanotubes, tissue, biomaterials, cancers, explosive materials, pharmacy materials, and so on. The periodic metallic structures can be good effective materials to give interesting properties in the THz range because the THz region is much less demanding than the optical region for the fabrication of sub-wavelength devices. THz transmission properties of hole-type split ring structures and random arrays of slits in a metallic screen have been reported already [15-18]. However, periodic arrays of metallic rods in the THz range have rarely been investigated.

In this paper, we study the transmission properties of a periodic aluminum rod-array and a periodic hole-array in aluminum film using THz-TDS. The samples were fabricated by a femtosecond laser micromachining system. The periodic arrays of aluminum rods exhibit very low transmission around 0.25 THz when the polarization of the THz pulse is parallel to the long axis of the rod, whereas the periodic arrays of holes exhibit high transmission around 0.25 THz when the polarization of THz pulse is perpendicular to the long axis of the hole. The polarization-dependent transmission properties were simply explained by Babinet's principle [19].

II. EXPERIMENT

Figure 1 shows the periodic arrays of aluminum rods and holes which were fabricated by a commercial aluminum tape on the paper and a femtosecond laser micromachining system. The central wavelength and the width of input pulse are 785 nm and 184 fs, respectively, and the average power and the repetition rate are 1 watt and 1 KHz, respectively. The size of the rod (hole) is

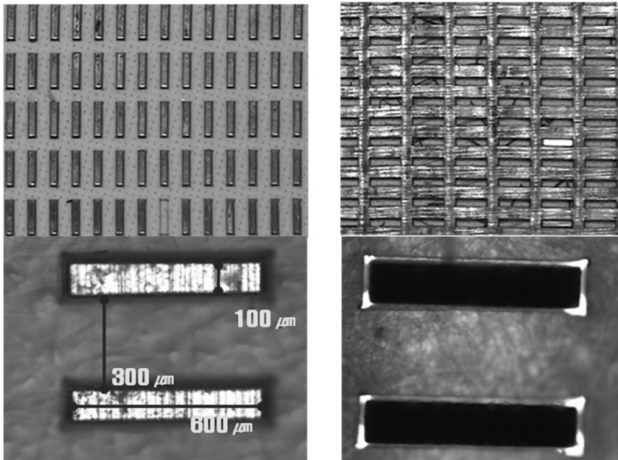*Corresponding author: iron74@gist.ac.kr

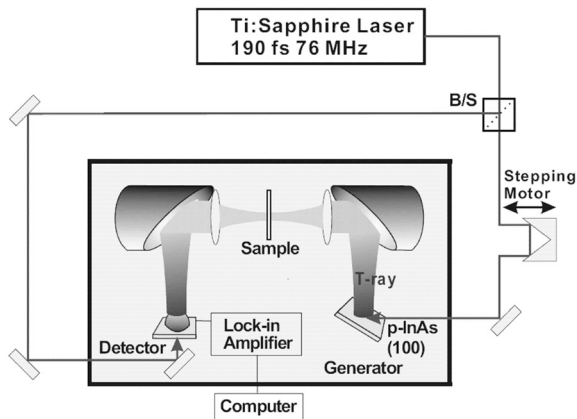FIG. 1. Periodic aluminum rod-array and periodic hole-array in aluminum film.

FIG. 2. Scheme of terahertz time-domain spectroscopy experimental setup.

FIG. 3. Measured time-domain waveforms and their spectra in frequency domain.

about 600 μm $\times$ 100 μm and the spacing between rods (holes) is about 300 μm. The total size of the sample is 8 mm $\times$ 8 mm.

The terahertz time-domain spectroscopy setup is shown Fig. 2. For the generation of THz pulses, the p-type (100) InAs wafer with about 10^{16}/cm^3 carrier concentration [20] and the femtosecond laser with the 76 MHz repetition rate and the 190 fs pulse width were used. The average power of the input laser is 1.3 watts and its beam diameter on the InAs wafer is 4 mm. The 5-μm gap dipole antenna on the low temperature grown GaAs wafer was used to detect the generated THz pulses.

III. EXPERIMENTAL RESULTS

Figure 3 shows the characteristics of THz pulses after passing through air and the paper. All measured data were acquired in the air tight box under 10-% humidity. The signal to noise ratio is over 1000:1. In the time-
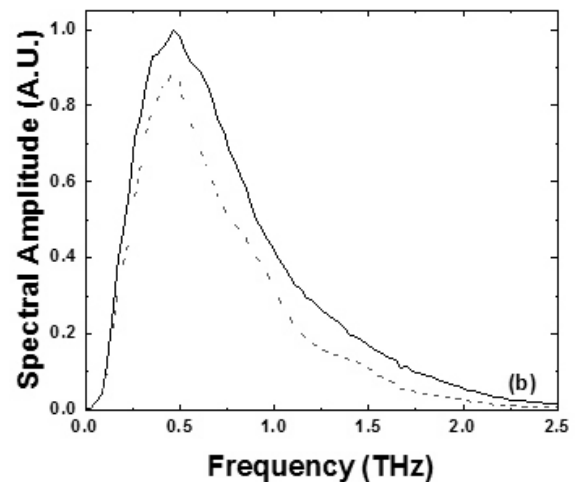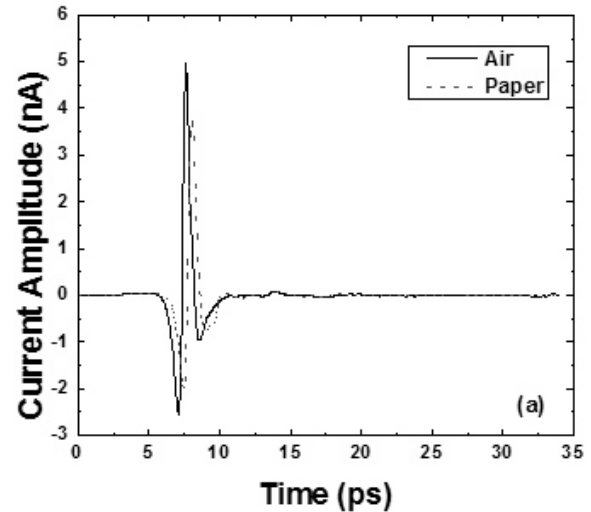
domain waveforms, the peak amplitude of the THz pulse passed through the paper is reduced about 25 % for the case of air. The phase delay between the THz pulses is about 0.5 ps. However, the spectral characteristics of THz pulses passed through air and the paper are almost the same.

Figure 4 (a) show the time-domain waveforms of THz pulses passed through the array of aluminum rods when the polarization of the THz pulse is parallel to the long axis of aluminum rod (red line) and perpendicular to the axis (blue line). Their spectral characteristics are shown in Fig. 4 (c). One can see that the spectrum shows very low transmission around 0.25 THz when the polarization of the THz wave is parallel to the long axis of the aluminum rod. The wavelength of 0.25 THz exactly is two times the length of a long side of rod, ($\lambda \sim 1200$ μm). For the case of hole arrays, resonant transmissions are observed around 0.26($\lambda \sim 1200$ μm), 0.37($\lambda \sim 1800$ μm), and 0.65 THz ($\lambda \sim 1800$ μm) when the polarization of THz wave is perpendicular to the long axis of the
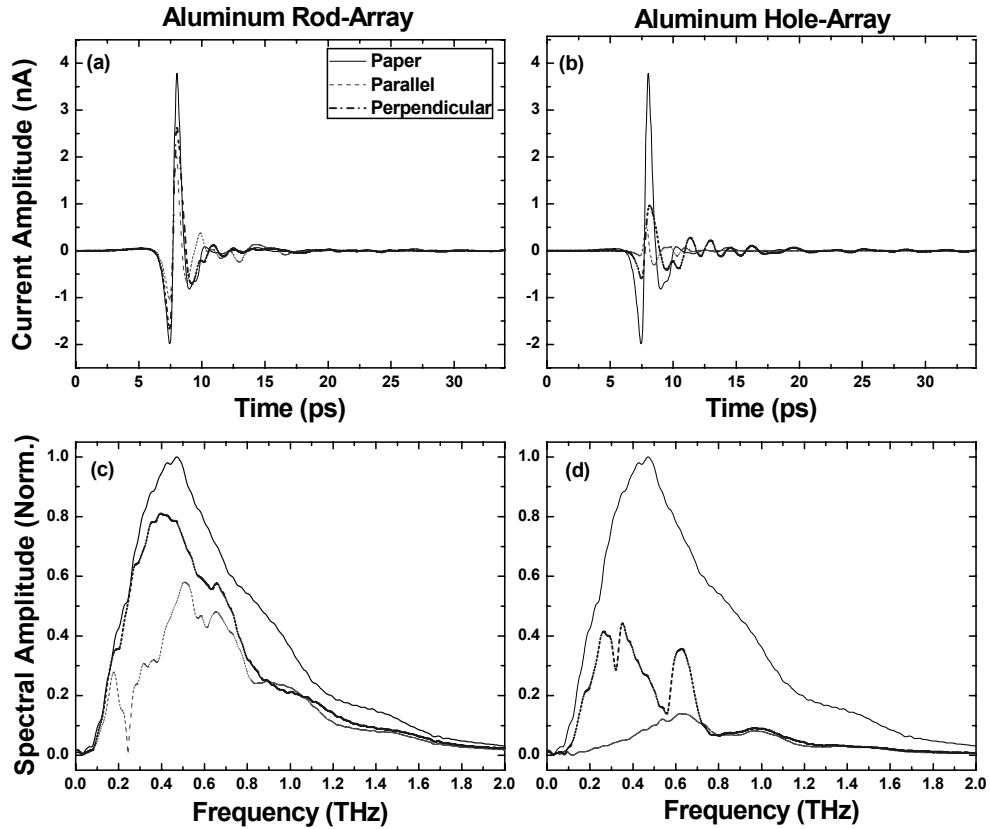
FIG. 4. Measured time-domain waveforms after passing through the aluminum rod-array and the hole-array in aluminum film (a), (b) and their spectra in frequency-domain (c), (d)
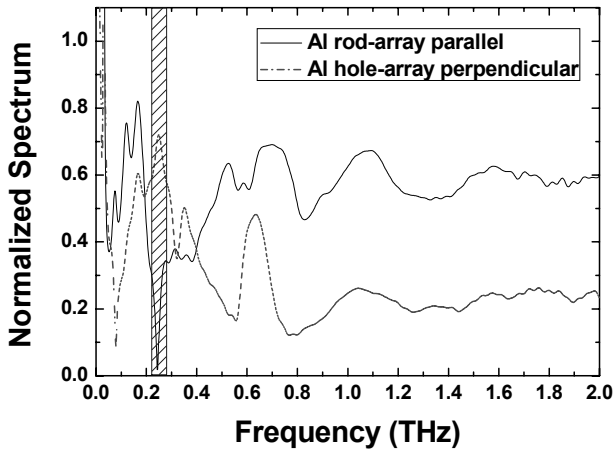

FIG. 5. Normalized transmission spectra of the rod-array for the parallel polarized THz pulse and of the hole-array for the perpendicularly polarized THz pulse.

holes.

Figure 5 shows the transmission spectra of the rod-array for the parallel polarized THz pulse and of the hole-array for the perpendicularly polarized THz pulse. The transmission intensity was normalized to that of the paper. The rod-array shows very low transmittance

of 3% and the hole-array shows high transmittance of 70% at 0.25 THz. This result can be explained by Babinet's principle that has been used in understanding diffraction phenomena from an aperture in a perfect conductor screen and its complementary structure. Babinet's principle gives the relations between the transmission and reflection coefficients of the original and its complementary structures, i.e., $t_c = -r$ and, $r_c = -t$ where $t(t_c)$ and $r(r_c)$ are the reflection and the transmission coefficients of the original (complementary) structure. From the relations, one can understand qualitatively why the rod-array shows very low transmittance at 0.25 THz, while the hole-array shows high transmittance at 0.25 THz. However, we can not demonstrate quantitatively the relations because the reflection was not measured directly and there is also absorption.

IV. CONCLUSION

Spectral properties of the periodic arrays of aluminum rods and holes have been studied by using the terahertz time-domain spectroscopy. The periodic arrays of aluminum rods exhibit very low transmission around 0.25 THz when the polarization of the THz pulse is parallel

to the long axis of the rod, whereas the periodic arrays of holes exhibit high transmission around 0.25 THz when the polarization of the THz pulse is perpendicular to the long axis of the hole.

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