Frequency conversion of terahertz waves by ultrafast optical pumping of metamaterials

N. Sato[1], **F. Miyamaru**[1], **M. Hangyo**[2], **M. I. Bakunov**[3] **and M. W. Takeda**[1]

[1]Department of Physics, Faculty of Science, Shinshu University
3-1-1, Asahi, Matsumoto, Nagano, Japan
Email: s082013@shinshu-u.ac.jp
[2]Laser Terahertz Division, Institute of Laser Engineering, Osaka University, Osaka, Japan
[3]University of Nizhny Novgorod, Nizhny Novgorod, 603950, Russia

Abstract

We demonstrate the frequency conversion of THz waves by suddenly changing the refractive index of the semiconductor substrate that is attached on the metamaterial surface. By illuminating the femtosecond laser beam on the semiconductor surface at the time when the THz wave at the resonant frequency stays in the vicinity of metamaterial surface, the center frequency of the THz wave shows blue shift at most 2 % with respect to the original center frequency.

1. Introduction

Terahertz (THz) technologies have shown remarkable development during the past decade in various applications, e.g., medical diagnostics, security applications, and information technology. However, the frequency conversion of the THz wave through a nonlinear optical effect has not been achieved so far because of a relatively low radiation power of the THz wave and essentially lower photon energy than thermal energy at room temperature. Consequently, the frequency conversion of the THz wave is very challenging.

The frequency conversions of electromagnetic waves were demonstrated by a sudden change of refractive index of the materials that the electromagnetic wave travels through [1]. For example, Geltner et al. reported the frequency conversion of light at 800 nm, which is traveling through ZnSe crystal, by pumping the ZnSe crystal with 10-ps laser pulse [2].

In this paper, we demonstrate the THz frequency conversion with metamaterials by optically pumping the semiconductor substrate, which is attached on the metamaterial surface. In the previous studies of the frequency conversion, the electromagnetic wave that was traveling inside the pumped material was used. In our study, however, we convert the frequency of the electromagnetic wave that is resonantly localized in the vicinity of metamaterial surface.

2. Experiment

The metamaterial, which consists of an array of double-ring SRRs, is fabricated on 100-μm-thick polyethylene terephthalate (PET) film; the refractive index of the PET film is $n_{\mathrm{PET}} = 1.56$ at 0.5 THz. The geometrical parameters of our metamaterial are shown in Fig. 1(a). We put a 10-mm-thick high resistivity silicon plate on a metal surface of the metamaterial. A schematic of the experimental configuration is shown in Fig. 1(b).

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We measured the transmission spectrum of our sample by using THz time domain spectroscopic system (THz-TDS). We used a regenerative amplified Ti:Sapphir femtosecond laser system delivering 100 fs pulses at 800 nm central wavelength and 1 kHz repetition frequency. THz wave was emitted through an optical rectification process in ZnTe crystal by pumping with the femtosecond laser. After transmitting through our metamaterial, the THz wave was detected by using electro-optic sampling technique. The THz wave was focused onto the metamaterial surface with 8-mm-diameter spot. To make an ultrafast change of the refractive index at Si surface, the control beam, which is divided from the pump and sampling beam for emission and detection of the THz wave, is illuminated on the same area of Si surface to that of aforementioned THz wave. We can vary the arrival timing between the THz wave and control beam by changing the length of the optical path of the control beam with respect to the THz wave.

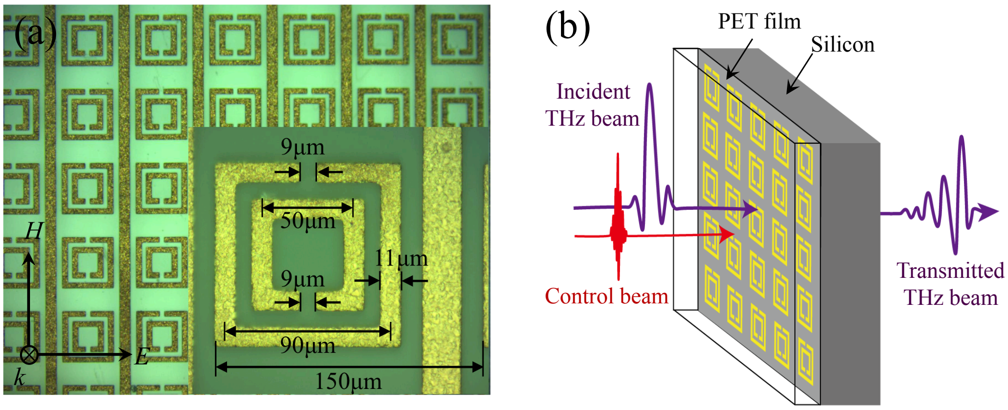

Fig.1 (a) Microscopy photograph of the metamaterial used in our experiment. The geometrical parameters are shown in the inset. (b) Schematic of optical configuration of our frequency conversion experiment.

3. Results and Discussion

Fig. 2 shows the waveform of the measured THz wave in time domain for different optical power of the control beam. As a reference, we also plot the THz waveform without the control beam. For the transmitted THz wave without the control beam (black solid line), the oscillation of almost single period is observed in the time range after t = 12 ps. This oscillation is attributed to the resonant characteristics of the SRR used in our metamaterial. The lifetime of this oscillation can be estimated to be 3 ps from the measured waveform. This indicates that the THz wave at this frequency stays in the vicinity of the metamaterial for several picoseconds.

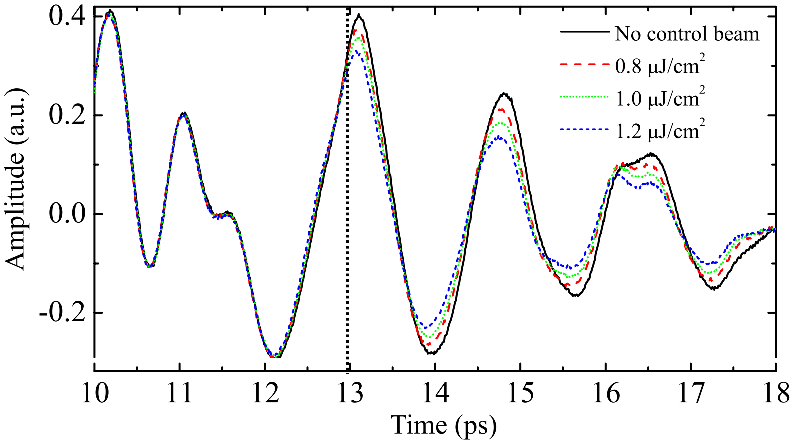

Fig. 2. Measured THz waveforms transmitted through the metamaterial with different powers of the control beam. A vertical dotted line indicates the time when the control beam is illuminated. We also plot the THz waveform transmitted through the metamaterial without the control beam.

We set the timing of the control pulse with respect to the THz wave at around $t = 13$ ps as indicated by a vertical dotted line in Fig. 2. After excitation of Si surface by the control beam, we can observe that the THz waveform changes apparently. For 0.8 $\mu J/cm^2$ of the control beam (red dashed line), the period of the oscillation is slightly shortened compared with that of black solid line. As the power of the control beam increases, the period of the oscillation is more shortened. These results indicate clearly that the frequency of the THz wave, which stays in the vicinity of the metamaterial, can be converted with changing the refractive index of Si by illuminating the control beam temporally.

In order to observe the characteristics of the frequency conversion more clearly, we analyze the spectral intensity of the THz wave by performing Fourier transform of the time-domain waveform in the time range from 13 ps to 18 ps. Fig. 3(a) shows the Fourier intensity spectra of the THz wave after illuminating the control beam. We also plot the Fourier intensity spectrum without the control beam (black solid line). Again, we can confirm that the frequency of the THz wave shifts to higher frequency by illuminating the control beam and the frequency shift increases with increasing the power of the control beam. Fig. 3 (b) shows the center frequency of the Fourier spectrum (filled triangle) as a function of the power of the control beam. The center frequency shows almost linearly with increasing the power of the control beam. It is noted that the value of the frequency shift reaches at most 2 % with respect to the original center frequency. The calculated resonant frequency of our sample is also plotted in Fig. 3(b) as open squares. In this calculation, we assume the Drude model as an electrical characteristic of Si. An excellent agreement is observed between the experiment and calculation.

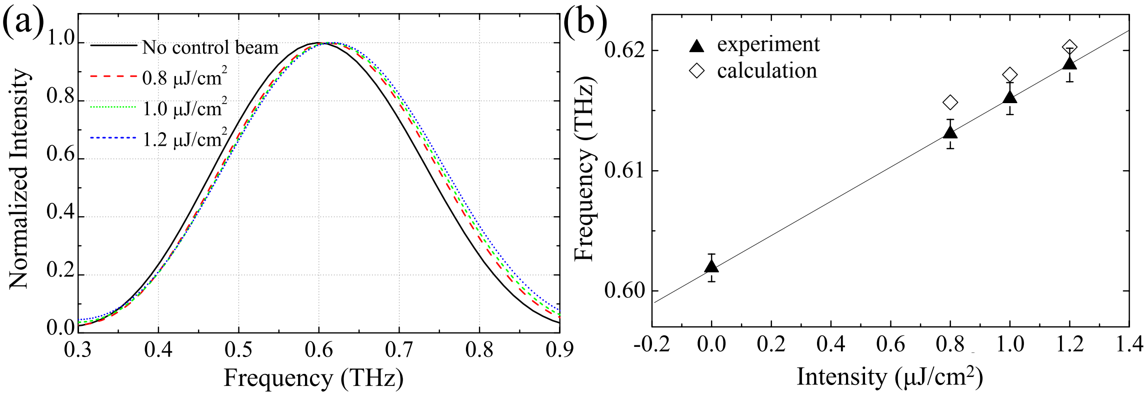

Fig. 3 (a) Measured Fourier intensity spectra, which is derived from the time-domain waveform in the range from 13 ps to 18 ps, for different powers of the control beam. We also plot the same spectrum without the control beam. (b) Measured (filled triangle) and calculated (open square) centre frequency of the THz wave as a function of the control beam power.

4. Conclusion

In conclusion, we demonstrated the frequency conversion of the THz wave by suddenly changing the refractive index of Si substrate that is attached on the metamaterial. By illuminating the femtosecond laser beam on Si surface at the time when the THz wave at the resonant frequency stays in the vicinity of metamaterial surface, the center frequency of the THz wave shows blue shift at most 2 % with respect to the original center frequency. Our results shows possibility of the frequency conversion of the THz wave without any nonlinear optical effect and promise a useful application in THz region.

References

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