Frequency up-shifter for THz light via relativistic Doppler reflection

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***Abstract*—We realize the relativistic Doppler reflection of THz light from a counter-propagating plasma mirror in silicon (Si) with a practically simple geometry, which allows us to easily apply the frequency up-shift to the THz optics. The average frequency of the reflected THz light is 1.4 times higher than that of the input THz light. In view of application, the important facts are that the frequency up-shift can be achieved by a low pump energy density (1.3 μJ mm^{-2}), and that shifted frequency is almost constant in the pump energy range above this threshold.**

I. INTRODUCTION

INTENSE single cycle terahertz (THz) pulses have been easily obtained and paid much attention to various fields in this decade. The optical rectification in nonlinear crystals is commonly used for the laboratory-based intense THz light generation. In this method, the spectral shape of the THz output is mainly determined by the phase-matching condition in the crystal interacted with the pump pulse. To realize the desirable spectra for each application, great efforts have been made with designing and developing new crystals and pump laser systems. For the practical use, a tailoring method of the output THz spectra without changing the crystal and pump laser is, however, preferably required.

Roskos and coworkers have proposed a frequency up-shift method for THz light using the relativistic Doppler reflection from a counter-propagating plasma mirror in a silicon (Si) plate[1] and demonstrated their method[2]. The principle of the up-shift method is explained in Fig. 1(a). The optical pump light irradiates the Si plate, and induces carriers near the surface. When the carrier has sufficiently high density to reflect the THz light, the front plane of carrier acts as the plasma mirror for the THz light. The plasma mirror propagates with the speed of the pump light in Si, and reflects the counter-propagating THz light with the significant frequency up-shift. In this study, we realized the relativistic Doppler reflection with the practically simple method described latter, and observed the frequency up-shift at various pump energies. We also investigated the pump wavelength dependence of the Doppler reflection.

II. EXPERIMENT

Figure 1(b) shows the schematic of the up-shifter adopted in this study. This scheme which has been proposed in our previous study[3] can easily realize the counter-propagating geometry between THz and plasma mirror. (I) The surface of a 1-mm thick Si plate is irradiated with the THz pulse that propagates through Si. (II) The THz pulse arriving at the back surface is partially reflected back to the input surface due to the Fresnel reflection. Prior to the arrival of the reflected THz pulse at the input surface, the pump pulse shines into the Si surface to generate the photo induced plasma. (III) The returned THz pulse is reflected again by the plasma mirror near the input surface, and detected after propagation through the Si plate.

We employed two laser systems in this study: a Ti:sapphire (the center wavelength of 800 nm, the pulse duration of 50 fs, and the pulse energy of 1.5 mJ) and a Yb:YAG thin-disk (1030 nm, 1.3 ps, and 6 mJ)[4] regenerative amplifiers operated at 1 kHz repetition rate. The output pulse was split into three pulses: the pulse for the THz light generation, the pump pulse to generate the plasma mirror, and the probe pulse used for the electro-optic (EO) sampling. The THz light with a center frequency of 0.52 THz was generated by the tilted pulse front method in a LiNbO$_3$ crystal, and detected by the EO sampling in a ZnTe crystal.

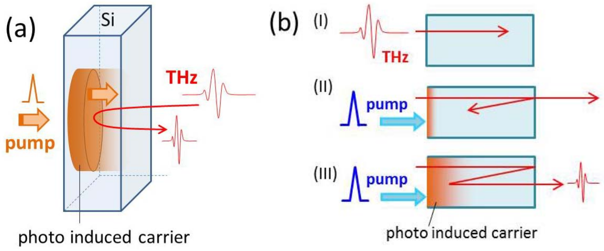

Fig. 1. (a) Principle of the relativistic Doppler reflection. (b) Schematic diagram to realize the Doppler reflection.

III. RESULTS AND DISCUSSION

(i) *Frequency up-shift.*

Figures 2(a) and (b) show the temporal waveforms and Fourier transformed spectra, respectively, of the reflected THz pulse at different six delay times (Δt) with respect to the pump pulse. We defined $\Delta t = 0$ when the reflected THz light collides with the pump light at the input surface. The horizontal axis corresponds to a round trip time of the reflected THz pulse in the Si plate. When the delay time was much smaller than zero ($\Delta t << 0$), the THz light was just reflected by the Fresnel reflection at the input surface. As increasing Δt, the pump light starts to penetrate into Si, and generates the low density carrier which does not reflect the THz light, but absorbs it. The intensity of reflected THz light, therefore, decreased as increasing Δt. At $\Delta t = 0$, the phase of the THz light jumped by π due to the plasma mirror reflection. As further increasing Δt, the round trip time decreased (red arrow in Fig. 2(a)), because the THz pulse was reflected by the counter-propagating plasma mirror.

Figure 2(c) shows the THz spectra measured with the detailed scan of the THz delay. Around $\Delta t = 1.3$ ps, we found the frequency up-shift due to the Doppler reflection. The Doppler reflection continued until $\Delta t = 2$ ps, which was in good agreement with the previous theoretical prediction[1]. At much larger delay time ($\Delta t >> 0$), the frequency up-shift disappeared in the spectra. This indicates that the plasma mirror behaves as the static mirror, because the pump light was completely absorbed in Si before colliding with the THz light.

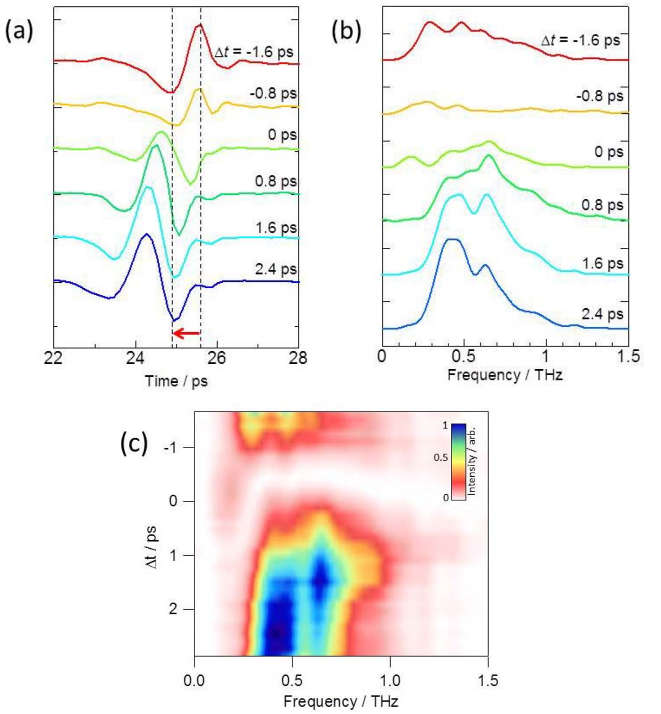

Fig. 2. (a) THz waveforms and (b) Fourier transformed spectra at the different THz delay (Δt). (c) 2D plot of THz spectra taken by the detailed scan of Δt. The pump wavelength and energy density were 800 nm and 3.8 μJ mm^{-2}, respectively.

(ii) *Pump power dependence.*

Figure 3 shows the average frequency <ν> of the reflected THz spectra as a function of Δt, measured at different four pump energy densities. The frequency up-shift was observed at all the energy densities except for 0.2 μJ mm^{-2}. Requirement for the Doppler reflection is that the plasma frequency of carrier, ν_p is much higher than the critical frequency,[1] $\nu_{cr} = \sqrt{(1+\beta)/(1-\beta)}\ \nu_i$, where $\beta = U/c$, U and c are the speed of plasma and the incident THz light in Si, respectively, and ν_i is the frequency of the incident THz light. The averaged critical frequency in our experiment is estimated to be 1.6 THz from the center frequency of incident THz light, $\nu_i = 0.52$ THz. The plasma frequencies at the surface were calculated to be ν_p = 0.7 and 1.9 THz at the pump energy densities of 0.2 and 1.3 μJ mm^{-2}, respectively. This simple picture explains our result that the threshold energy density for the Doppler up-shift was between 0.2 and 1.3 μJ mm^{-2}.

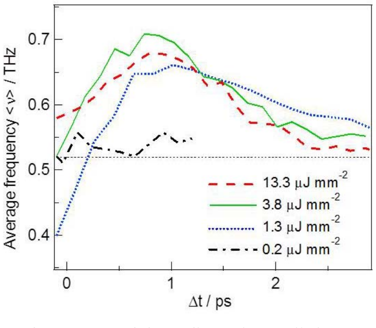

Fig. 3. Average frequency of the reflected THz light as a function of the THz delay. The pump wave length was 800 nm.

Another important feature in Fig. 3 was that up-shifted frequency was not largely changed with increasing the pump energy density above the threshold (1.3 μJ mm^{-2}). The ratio of up-shifted frequency, $<\nu>/<\nu_i>$, was always about 1.4, because the Doppler up-shift depends not on the carrier density corresponding to the pump energy, but on the speed of the plasma mirror corresponding to the speed of the pump light.

Roskos and coworkers simulated the reflected THz spectra by a 1D-FDTD method and reported that the ratio of up-shifted frequency was above 4 at the center frequency of 1 THz[1]. Our result is much smaller than the simulated value. One of the reasons is that the high frequency component was easily absorbed by the low density carriers penetrated into Si.

(iii) *Pump wavelength dependence.*

The Doppler reflection using 1030 nm pump light was also investigated in terms of the pump wavelength dependence. From the analytical calculation by Roskos and coworkers[1], the ratio of up-shifted frequency using 1030 nm pump was expected to be about 2. However, the reflected THz light could not be clearly observed at the positive delay time ($\Delta t \geq 0$) even with the high pump energy density. This result can be explained by Fig.4. The absorption coefficient at 1030 nm is about one-tenth of that at 800 nm for Si. As a result, 1030 nm pump light can penetrate deeper, and generate the plasma with the low carrier density to deeper region. Therefore, the THz light returning to the input surface was almost absorbed in the region with the low density carrier before being reflected by the high density plasma.

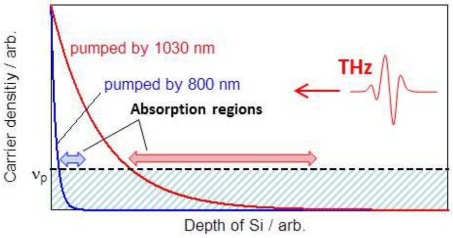

Fig. 4. Schematic carrier density distribution in Si in case that the carrier densities at the surface are identical at 800 and 1030 nm pump.

IV. SUMMARY

We realized the Doppler up-shift of the THz light using a practically simple method. The small threshold (1.3 μJ mm^{-2}) of the pump energy density for the up-shift suggested to be suitable for application of the frequency up-shifter in the THz optics. We also concluded that pump pulse at 800 nm with 50 fs pulse duration is more appropriate for inducing the Doppler reflection of THz light in Si than 1030 nm with 1.3 ps.

REFERENCES

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