Generation of frequency-tunable THz waves by using birefringent crystal and grating pair

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Abstract: By using a birefringent crystal and a grating pair, we succeeded in generating frequency-tunable THz waves. The carrier-envelope phase of the THz waves were free from the instability of the optics.

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1. Introduction

Femtosecond or picosecond frequency-tunable THz electromagnetic sources are useful for the studies of spectroscopy, pulse propagation phenomena and coherent phenomena, including the coherent control of materials [1].

Frequency-tunable THz electromagnetic waves are normally generated by exciting THz wave emitters with intensity-modulated light pulses created by a femtosecond laser pulse and (1) pulse interference optics and a grating pair [2] or (2) a liquid-crystal spatial modulator [3].

The first method produces THz waves with a stable frequency. However, if the optics is unstable or the optical table vibrates, the carrier-envelope phase of the THz waves becomes unstable. With the second method, vibration of the optical table is not a concern. However, as the THz frequency increases, we need a larger number of pixels. Otherwise, we will obtain an unnecessary THz frequency component due to the residual higher order components of the pulse modulation. Increasing the number of the pixels, however, is not realistic.

Here, we propose a method of generating frequency-tunable THz waves that uses a birefringent crystal instead of interference optics. This method is basically the same as the method (1). However, it is free from the instability caused by the vibration of the optical tables, as a pulse pair is produced within the crystal. Therefore, the carrier-envelope phase of the THz waves is stable.

2. Frequency-tunable THz wave generation using birefringent crystal

Frequency-tunable THz waves can be obtained by exciting a photoconductive (PC-) antenna with a sinusoidally intensity-modulated laser pulse [2].

To obtain a sinusoidally intensity-modulated laser pulse, a linearly polarized laser pulse is first guided to a grating pair to produce a chirped pulse. The chirped pulse is then guided to a birefringent crystal that has two principal axes with wavelength-independent refractive indices n_o and n_e ($n_e > n_o$). The polarization angle of the linearly polarized laser pulse is set to 45 degrees with respect to both principal axes of the refractive indices of the crystal.

When the chirped laser pulse transmits through the birefringent crystal, it splits into two pulses with the time separation t_d given by $t_d = (n_e\text{-}n_o)L/c$, where L is the length of the crystal and c is the speed of light. As the pulse pair is produced in the crystal, their time separation t_d is fixed. The chirped pulse pair produces a laser pulse with a sinusoidal intensity modulation. The stability of the carrier-envelope phase of the THz wave depends on the stability of the time separation t_d. Therefore, the THz waves generated by this method have a fixed carrier-envelope phase.

The crystal used in the experiment is YVO_4, which has a tetragonal structure. It is birefringent and transparent in the near-infrared wavelength region. The refractive indices are roughly wavelength independent and n_e-n_o ~ 0.21.

3. Experimental setup

The output of a mode-locked $Ti:Al_2O_3$ laser (a pulse width of ~150 fs, a repetition rate of 100 MHz, laser wavelength set to 810 nm) was divided by a beam splitter into pump and gate pulses.

The pump pulse was first guided to a grating pair (1800 lines/mm gold-coated holographic grating) to produce a chirped pulse. The incident angle of the laser pulse to the grating was 63 degree. The chirped pulse was then guided to the YVO_4 crystal to produce a pair of chirped pulses with a fixed delay time between them. This pulse pair produced a sinusoidally intensity-modulated pulse. This intensity-modulated pulse was focused onto a PC-antenna (emitter) fabricated on low-temperature grown (LT-) GaAs by an objective lens.

The gate pulses were guided and focused onto another PC-antenna (receiver) by another objective lens. An optical chopper modulated the pump beam with a frequency of 1.3 kHz. The current in the receiver was amplified and fed to a lock-in amplifier. To obtain the temporal profiles of the THz waves, the output of the lock-in amplifier was measured as a function of the delay time between the pump and probe pulses.

4. Experimental results and discussions

Figure 1 shows the laser spectrum modulated by a 1.0-mm thick YVO_4 crystal. The periodic modulation was stable, and the modulation was almost 100 %. The measured time separation between the pulses created by the crystal was ~0.8 ps. We were able to obtain similar data even when the data acquisition time was set to ~5 min, which shows that the interference spectrum of the pulse pair created by the crystal was very stable. In fact, because there is virtually no change of the refractive indices or the crystal thickness, the time separation between the pulses is fixed.

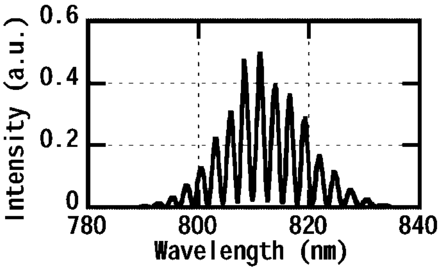

Fig.1. Modulated spectrum of laser with 1.0-mm thick YVO4.

Figure 2(a) shows the intensity-modulated laser pulse after a grating pair and the 1.0-mm thick YVO_4 crystal. The intensity-modulated pulse has a periodically modulated component and a nearly-dc component with the pulse width of ~30 ps. Therefore, as shown in Fig. 2(b), the Fourier spectrum of Fig. 2(a) has a dc component in addition to the ~0.24 THz frequency component.

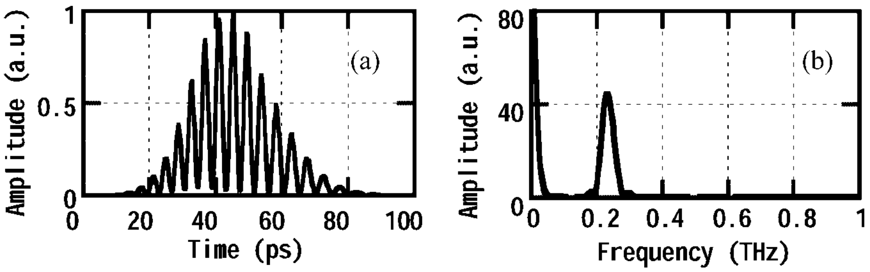

Fig. 2. (a) Intensity-modulated laser pulse and (b) its Fourier transformation.

Figure 3 shows the THz wave emitted from the PC-antenna excited by the laser pulse shown in Fig. 2(a). In this case, since the THz wave was proportional to the temporal change of the carrier density created in the

PC-antenna [4], the THz wave showed amplitudes both plus and minus signs. The Fourier-transform of Fig. 3(a) is shown in Fig. 3(b). One can see only the ~0.24 THz frequency component; the nearly-dc component is eliminated. Since the interference spectrum created by the crystal is stable, the carrier-envelope phase of the THz wave is stable regardless the instability of the optical table.

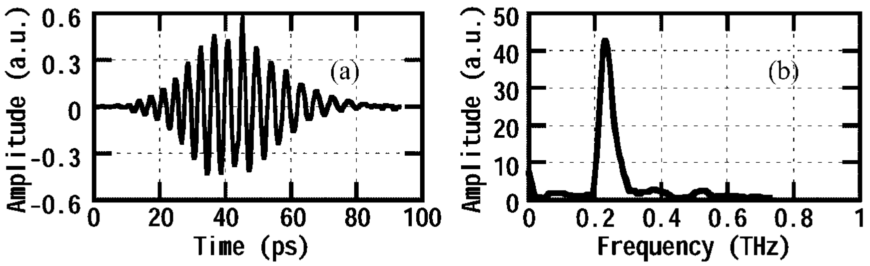

Fig. 3. (a) THz wave and (b) its Fourier transformation.

Figure 4 shows the grating distance dependence of the center frequency ν (circles) and spectral width Δν (squares) of the THz wave obtained by our method. In this case, since the crystal length was fixed and the distance *d* between gratings was changeable, both ν and Δν depended on the distance *d* between the gratings [2]. In the theory, both ν and Δν are inversely proportional to *d*. The solid curves are fitting curves using this relation. The agreement between experiment and theory is satisfactory. Since both Δν and ν are inversely proportional to *d*, Δν/ν remains constant despite any change in the distance between the gratings.

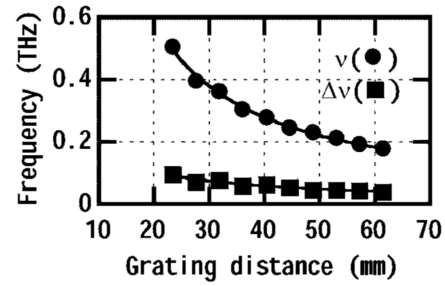

Fig.4. Grating distance dependence of THz wave frequency ν (circles) and spectral width Δν (squares).

For the practical application of the THz waves, especially for the coherent control of materials, the stability of the carrier-envelope phase becomes very important. We consider that our method of generating frequency-tunable THz waves with a stable carrier-envelope phase will be useful for such applications.

5. Summary

By using a birefringent crystal and a grating pair, we generated frequency-tunable THz waves. As the pulse pair is created in the crystal, the carrier-envelope phase of the THz waves is stable regardless the instability of the optical table.

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