# Generation of coherent tunable THz waves by using birefringent crystal and grating pair


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**Abstract.** Laser pulses with temporally sinusoidal intensity modulation excited a photoconductive antenna to produce coherent tunable THz waves. The laser pulses with sinusoidal intensity modulation were generated by modulating a femtosecond laser pulses with a birefringent crystal and a grating pair. The carrier-envelope phase (CEP) of the THz waves created by this method was unaffected by the instability of the optics.


## 1. Introduction

Coherent tunable THz electromagnetic sources are useful for the studies of spectroscopy, pulse propagation phenomena, and coherent phenomena, including the coherent control of materials [1]. Coherent tunable THz electromagnetic waves can be generated by exciting THz wave emitters with intensity-modulated laser pulses. The intensity-modulated laser pulses are created by modulating a femtosecond laser pulse with a Michelson interferometer and a grating pair [2]. The THz waves thus generated have a stable frequency. However, if the optics is unstable or the optical table vibrates, the carrier-envelope phase (CEP) of the THz waves becomes unstable.

Here, we propose a method of generating coherent tunable THz waves that uses a birefringent crystal instead of a Michelson interferometer. This method is basically the same as the method mentioned above. However, it is unaffected by the instability caused by the vibration of the optical tables, because a pulse pair is produced within the crystal. Therefore, the CEP of the THz waves is stable.

## 2. Coherent tunable THz wave generation

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 $t_d = (n_e - n_o)L/c$, 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 CEP 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 CEP.

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

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.

A laser pulse with sinusoidal intensity modulation was generated by modulating the pump pulse with the $YVO_4$ crystal and a grating pair (1800 lines/mm gold-coated holographic grating). This laser pulse was focused by an objective lens onto a PC-antenna (emitter) fabricated on low-temperature grown (LT-) GaAs to produce a frequency-tunable THz wave.

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.

## 3. Experimental results and discussions

Figure 1(a) shows the temporal profile of the laser pulse modulated by a 1.0-mm thick $YVO_4$ crystal and a grating pair. The distance between the gratings was set at ~49 mm. The laser pulse had a periodic intensity modulation, which lasted for ~80 ps. There was virtually no change of the refractive indices or the crystal thickness, the time separation between the pulses was fixed. Therefore, the periodic modulation was stable.

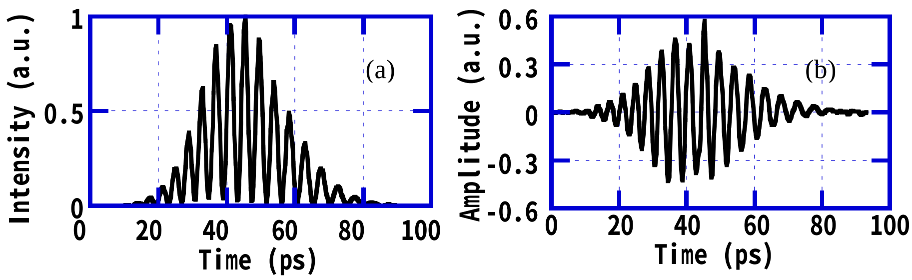


**Fig.1.** (a) Intensity-modulated laser pulse and (b) THz wave.

Figure 1(b) shows the THz wave emitted from the PC-antenna excited by the laser pulse shown in Fig. 1(a). Since the THz wave was proportional to the temporal change of the carrier density created in the PC-antenna, the THz wave showed amplitudes with both plus and minus signs. The Fourier-transform of Fig. 1(b) showed that the THz wave has only the ~0.24 THz frequency component; the spectral component corresponding to the overall pulse width of ~30 ps observed in Fig. 1(a) is eliminated. Since the interference spectrum created by the crystal is stable, the CEP of the THz wave is stable regardless the instability of the optical table.

Figure 2 shows the grating distance dependence of the center frequency (ν) and spectral width (Δν) of the THz wave. Since the crystal length is fixed and the distance *b* between the gratings is changeable, both ν and Δν are inversely proportional to *b*. The solid curves are fitting ones using this relation. The agreement between experiment and theory is satisfactory.

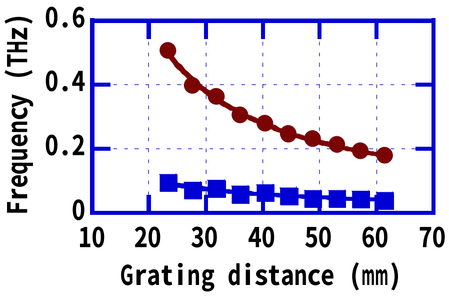


**Fig. 2.** Grating distance dependence of THz wave center frequency (circle) and spectral width (square).

## 4. Conclusions

By using a birefringent crystal and a grating pair, we generated coherent tunable THz waves. As the pulse pair is created in the crystal, the CEP of the THz waves is stable regardless of the instability of the optical table. The insertion of a Babinet-Soleil compensator will control the CEP of the THz waves. We consider that our method of generating THz waves with a stable CEP will be useful for nonlinear processes and coherent control of materials in the THz region.

## References

1 R. Ascazubi et al, Appl. Phys. Lett. **81**, 4344, 2003.
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