A frequency-agile terahertz-wave parametric oscillator

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Abstract: We demonstrated a pulse-to-pulse frequency-tunable LiNbO$_3$ terahertz-wave parametric oscillator, pumped with a Q-switched Nd:YAG laser. Rapid tuning from 1 to 2 THz, with random frequency accessibility, was achieved by rotating the pump beam angle using an optical beam scanner and a telescope.

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References and links
1 Introduction

The terahertz wave (THz-wave) region is spectroscopically significant, because it contains a large number of molecular rotation absorption lines. For example, terahertz time domain spectroscopy of propane-air flames has shown that panoramic terahertz absorption measurements provide complete flame characterization for determining species concentration and flame temperature [1]. In such analyses, frequency-agile THz-wave sources with continuous tunability over a broad spectral range are expected to improve the sensitivity, resolution, and speed of measurement. Although several tunable sources have been reported, such as free electron lasers [2], p-Ge lasers [3], and parametric oscillators, no source has yet achieved rapid frequency tuning over a wide tuning range.

We studied a THz-wave parametric oscillator (TPO) using noncollinear phase matching in a LiNbO$_3$ crystal pumped with a Q-switched Nd:YAG laser [4]. Despite its simplicity, the TPO was able to operate at room temperature, yet still provide a widely tunable (1~3 THz) THz-wave [5]. However, rapid frequency tuning was difficult to obtain using the conventional tuning method, because of the need to rotate the TPO cavity to vary the phase matching angle. In this paper, we describe a novel method of tuning a TPO using an optical beam scanner and a 1:1 telescope. This produced a TPO that was a frequency-agile THz-wave source over a broad spectral range.

2 Experimental setup

![Fig. 1. Schematic of the 1.064 μm-pumped LiNbO$_3$ frequency-agile TPO; FPI: Metal-mesh scanning Fabry-Perot interferometer, L1: f = 1000 mm lens for pump beam focusing, L2, L3: f = 200 mm lenses for the 1-to-1 telescope, PC: The computer used for scanner control, $k_p$, $k_T$, and $k_i$: wave vectors for the pump, THz, and idler waves.](image)

A schematic of the frequency-agile TPO is shown in Fig. 1. The pump laser was a Q-switched Nd:YAG laser that operated at a 50-Hz repetition rate; it had a maximum pulse energy of 36 mJ, and a 25-ns pulse duration. The pump beam was focused into the LiNbO$_3$ crystal using a f = 1000 mm lens (L1) to increase the power density. The pump diameter at L1 was 1 mm (FWHM), reduced to 0.5 mm at the input surface of the LiNbO$_3$ crystal. In order to rotate the pump beam angle, the pump beam was reflected by a mirror on the optical beam scanner, which was a commercial device (HARMONIC...
DRIVE SYSTEMS Inc., LSA-20A-30) that provided a maximum angular deflection angle of ± 1.5 degrees. The scanner mirror rotated in proportion to the computer-controlled DC voltage, with a beam angular coefficient per voltage of 0.31 degrees/volt. The scanner had excellent linearity, and the angular deviation was less than 0.06 % per rotation angle. The response time of the beam scanner was 1 millisecond for a 1-degree step rotation at the optimum inertia. The image at the center of the scanner mirror was relayed onto the end of the LiNbO₃ crystal of the TPO using a 1:1 telescope that consisted of two f = 200 mm lenses, (L2, L3) with a lens interval of 400 mm. After passing through the telescope, the pump beam was injected into the TPO at the incidence angle, θ₁, provided by the optical beam scanner. Although the idler cavity axis was fixed in our experimental setup, we were able to vary the phase matching angle inside the crystal by rotating the pump beam. Compared with the conventional tuning method using idler cavity rotation, this method has advantages of speed and random wavelength accessibility. A similar tuning method was used in a mid-infrared periodically-poled LiNbO₃ optical parametric oscillator that was developed as a lidar transmitter source [6], where kilohertz-repetition-rate pulse-to-pulse wavelength tuning was achieved using an acousto-optic beam deflector.

The dimensions of the LiNbO₃ crystal used in the TPO were 5 × 50 × 8 mm³ (z, x, y). Both facets of the crystal were polished and anti-reflection coated for operation at 1.064 µm. The y-surface of the crystal, where the Si-prisms are arrayed [7], was also polished, to reduce scattering of the pump and idler waves. Since the absorption coefficient of a LiNbO₃ crystal in the THz-wave region is quite large, the pump beam was passed near the y-surface of the LiNbO₃ crystal in order to minimize the THz-wave path inside the crystal, thereby reducing absorption loss. The crystal was placed inside a Fabry-Perot cavity that consisted of mirrors M₁ and M₂. M₁ was highly reflective at 1.07 µm, while the reflectivity of M₂ was 40 %. Only one-half of each mirror was coated, allowing the pump wave to pass through the other, uncoated half. The THz-wave exiting the LiNbO₃ through the arrayed Si-prism coupler was detected with a 4K Si-bolometer.

3 Tuning properties

![Tuning Properties](image)

Fig. 2. Measured output characteristics of the THz-wave (circles) and idler wave (triangles) from a LiNbO₃ TPO at a fixed pump energy (20 mJ/pulse).
Figure 2 shows the measured tuning range of the THz-wave and idler wave from the frequency-agile TPO at a fixed pump energy of 20 mJ/pulse. The closed circles and open triangles are the THz-wave output and the idler-wave output, respectively. The scale for the THz-wave frequency is marked on the lower horizontal axis, and the corresponding scale for the idler wavelength is marked on the upper horizontal axis. We obtained tunability from 1 to 2 THz by varying the pump incidence angle from 0.9 to 1.85 degrees, respectively. The maximum THz-wave output was 150 pJ/pulse at 1.4 THz. Compared with the idler output, the THz-wave output decreased rapidly in the higher frequency region. The rapid decrease was due to the larger absorption loss inside the LiNbO$_3$ crystal, which limited the upper frequency to $\sim$ 2 THz. The incidence angle $\theta_{IN}$ in the low frequency region was too small to completely separate the pump and idler beams at the input mirror, M$_1$, and the small angle limited the lower frequency to $\sim$ 1 THz. The decreased parametric gain and the small angle resulted in the oscillation threshold increase in the lower frequency region. The oscillation threshold at 1.5 THz was 14.5 mJ/pulse, and this increased to 16 mJ/pulse at 1.1 THz. We used an undoped LiNbO$_3$ crystal in this experimental setup, since it was of better quality than our MgO-doped crystals. The tuning range can be extended to 2.6 THz using a MgO:LiNbO$_3$ crystal, because a doped LiNbO$_3$ crystal has a larger parametric gain than an undoped LiNbO$_3$ crystal [8, 9].

The measured tuning characteristics were in good agreement with the theoretical curve, and showed that the pump incidence angle changed as expected. We also confirmed that measuring the THz wavelength or the idler wavelength at one incidence angle was sufficient to calibrate the THz wavelength of the frequency-agile TPO.

![Fig. 3. Fabry-Perot scans of the THz-wave. The solid line shows the Fabry-Perot scan obtained with a pump incidence angle $\theta_{IN}$ of 1.73 degrees. The wavelength was 167 $\mu$m. The dashed line shows the scan obtained with an angle of 1.49 degrees. The wavelength was 193 $\mu$m.](image)

We measured the THz-wave linewidth and wavelength with a scanning Fabry-Perot interferometer consisting of a pair of Ni metal-mesh mirrors with a 65-$\mu$m grid. The measured finesse of the interferometer was approximately 10 for a mirror separation of several millimeters. Figure 3 shows examples of THz-wavelength measurements using the frequency-agile TPO. The solid and dashed lines show the Fabry-Perot scans for pump incidence angles $\theta_{IN}$ of 1.73 and 1.49 degrees, respectively. The separation of the
mirrors was increased from 36 to 436 µm. The horizontal axis shows the displacement of one of the metal-mesh mirrors, while the vertical axis is the intensity of the THz-wave transmitted. The separation between the neighboring peaks directly corresponds to half the THz wavelength. The measured wavelengths for 1.73 and 1.49 degrees were 167 and 193 µm, respectively. The spectral linewidths estimated from the Fabry-Perot traces were about 100 GHz, which is the typical THz-wave linewidth of a TPO without injection seeding. The linewidth can be dramatically reduced to its Fourier transform limit < 200 MHz by narrow linewidth laser injection [10].

Fig. 4. Pulse trains passed through a Fabry-Perot interferometer with a displacement of 49 µm. (a) The pump incidence angle, θ_{IN}, was fixed at 1.73 degrees. (b) θ_{IN} was fixed at 1.49 degrees. (c) θ_{IN} was varied between 1.73 and 1.49 degrees with a 25-Hz square-wave signal to the optical scanner. The displacement of the Fabry-Perot mirror was fixed at 49 µm in order to confirm fast frequency tuning and its repeatability. At the displacement in Fig. 3, the 167 µm-wave easily passed through the interferometer, while most of the 193-µm wave was blocked. The power ratio of the transmitted THz-waves at 167 and 193 µm was close to 4:1. Figures 4(a)∼(c) show the transmitted THz-wave pulse train outputs detected by the 4K Si-bolometer. Figs.4 (a) and (b) show the pulse trains for fixed wavelengths of 167 and 193 µm, respectively. The amplitude of the transmitted THz-wave signal in Fig.4 (b) decreased to 0.1 according to the Fabry-Perot transmission. The THz-wave pulses in Figs.4 (a) and (b) arrived at the bolometer every 20 milliseconds, due to the 50-Hz repetition rate of the Nd:YAG laser operation. Fig.4(c) shows the pulse train when the THz wavelength was switched between 167 and 193 µm. The beam scanner was supplied with a 25-Hz square-wave signal in order to modulate the angle θ_{IN} between 1.73 and 1.49 degrees. The pulse train consisted of both large and small amplitude pulses that alternately passed the Fabry-Perot interferometer. The amplitude ratio was nearly 3.6:1.
The interval of 40 milliseconds was due to the 25-Hz modulation of the THz wavelength. The repetition rate of the pump pulse limited the frequency agility in the present setup. However, since the response time for the optical beam scanner is 1 millisecond, it is possible to obtain kilohertz-repetition-rate pulse-to-pulse frequency tuning.

The conventional tuning method has the advantage of a fixed THz-wave beam direction, because the cavity rotation cancels the variation in the direction of the THz-wave beam[11]. The variation in the angle of the beam direction of the THz-wave exiting the Si prism remains large with the novel tuning method, because of the fixed idler cavity. When the THz-wave was extracted from the LiNbO$_3$ crystal through an arrayed Si prism with a base angle of 53 degrees, the variation in the beam direction of the THz-wave of the frequency-agile TPO was about 2.8 degrees for the tuning range from 1 to 2 THz. The change in THz-wave beam direction should be canceled out as the level is normalized in spectroscopic measurement. The frequency-agile tunability of the novel tuning method is still useful for practical spectroscopic applications.

4 Summary

In summary, we experimentally demonstrated a pulse-to-pulse frequency-tunable THz-wave parametric oscillator based on a LiNbO$_3$ crystal pumped with a Q-switch Nd:YAG laser. Rapid tuning from 1 to 2 THz with random frequency accessibility was achieved by rotating the pump beam angle using an optical beam scanner and a 1:1 telescope. Pulse-to-pulse tuning between 167 and 193 µm was shown with a fixed-length Fabry-Perot interferometer used as a frequency-selective filter. The frequency agility of this THz-wave source makes it suitable for spectroscopic applications, such as the determination of species’ concentrations.

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