Arrayed silicon prism coupler for a terahertz-wave parametric oscillator

Kodo Kawase, Jun-ichi Shikata, Hiroaki Minamide, Kazuhiro Imai, and Hiromasa Ito

Using room-temperature parametric oscillation of a $LiNbO_3$ crystal pumped by a Q-switched Nd:YAG laser with a simple configuration, we have realized a widely tunable coherent terahertz- (THz-) wave source in the range between 1 and 3 THz. Inasmuch as the THz wave is affected by total internal reflection at the crystal edge, we used a Si prism coupler to couple out the THz wave. We introduce an arrayed Si-prism coupler that increases the efficiency and decreases the diffraction angle. By use of the arrayed-prism coupler, there is a sixfold increase in coupling efficiency and a 40% decrease in the far-field beam diameter, compared with the use of a single-prism coupler. We discuss the negative effect of the free carriers at the Si-prism surface that is excited by the scattered pump beam, and the positive effect of cavity rotation on the unidirectional radiation of the THz wave from a Si prism. © 2001 Optical Society of America

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1. Introduction

The terahertz- (THz-)wave region is a technically as well as a scientifically undeveloped region in which both generation and detection are difficult. Widely tunable sources that cover the region between 1 and 3 THz (with wavelengths from 100 to 300 μm) are limited to free electron lasers or photomixers. The University of California at Santa Barbara now plays a central role in exploring the THz region with free electron lasers. However, the number of researchers who can access such an apparatus is limited because of its large size. In photomixers, two optical lasers are mixed to generate tunable THz waves. This would become a reliable source if we could do away with the limitation on the output that is due to the nondestructive limit of a photomixer. A p-type germanium laser is another widely tunable source in this region, but it is used primarily for pure science, inasmuch as a large current, a strong magnetic field, and ultralow temperatures are required. Although the aforementioned widely tunable sources can be used at the laboratory level, they do not satisfy all the needs of researchers interested in practical applications. Thus, there is significant potential for the expansion of applied research on the THz band if simple, convenient, tunable sources are made available.

The generation of THz electromagnetic waves from the megahertz region to the THz region has been extensively studied for approximately ten years by use of femtosecond laser pulses. Applied research, such as time-domain spectroscopy, makes use of its high time resolution. In contrast, our research focuses on the development and application of tunable THz-wave sources with high temporal and spatial coherence, which is a fundamentally different approach to the THz region from that of the femtosecond pulse method. Specifically, the parametric oscillation of a widely tunable THz-wave by use of nonlinear optical characteristics of phonon polaritons of $LiNbO_3$ has been achieved with a Q--switched Nd: YAG laser as the pump source.[1,2] Induced Raman scattering by polaritons[3,4] that consist of hybrids of the THz wave and optically active transverse lattice vibration (transverse optical phonon, A_1 softest mode, 248 cm^{-1}) in a $LiNbO_3$ crystal results in a strong parametric interaction of the three waves: the pump, the idler (the near-infrared wave close to the pump wavelength), and THz waves. When the pump wave exceeds some threshold, an idler wave and a THz wave are generated with coherence similar to that of

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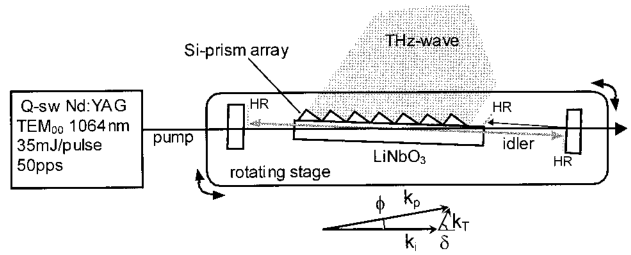

Fig. 1. TPO with a Si-prism array. The Si-prism array was introduced to increase the output and to reduce the diffraction angle of the THz wave by increasing the coupling area. An array of seven right-angle Si-prism couplers was placed on the y surface of the $LiNbO_3$. The total base length was 8 mm $\times$ 7 = 56 mm.

the pump wave. To generate a THz wave by parametric oscillation in a $LiNbO_3$ crystal, it is necessary to have some means of extracting the THz wave from the crystal inasmuch as the refractive index of the $LiNbO_3$ crystal for the THz wave is large enough ($n \approx 5.2$) to cause total internal reflection ($n = 1$). We introduced a Si-prism coupler ($n \approx 3.4$) to extract the THz wave that is generated inside a nonlinear crystal, thereby substantially improving the exit characteristics.[2] We describe the characteristics of the oscillation and a novel coupling method for THz waves that incorporate an arrayed Si prism. We also report that the scattered pump beam strongly affects the output, because it excites a free carrier in the Si prism, which absorbs the THz wave. In addition, we explain the importance of cavity rotation to reduce variation in the radiation angle.

2. Experimental Setup

The basic configuration of the source consisted of a Q--switched Nd:YAG laser (1.064 μm) and a parametric oscillator, as shown in Fig. 1. The $LiNbO_3$ crystal used in the experiment was cut from a wafer 5 mm (thick) $\times$ 65 mm (along the x axis) $\times$ 6 mm (along the y axis). The x surfaces at both ends were cut parallel, mirror polished, and antireflection coated for operation at 1.064 μm. The y surface was also mirror polished to minimize the coupling gap between the prism base and the crystal surface and to prevent scattering of the pump beam, which excites a free carrier at the Si-prism base. The pump wave entered the x surface of the crystal and passed through the $LiNbO_3$ close to the y surface to minimize the absorption loss of the THz wave ($\alpha > 10\ \mathrm{cm}^{-1}$). An idler wave (1.067–1.075 μm) and a THz wave (100–330 μm) were generated by parametric oscillation. The idler wave was amplified in a 15-cm-long resonator that consists of flat mirrors with a high-reflectivity (HR) coating. Only one-half of each mirror was HR coated, so that the pump wave could pass through the uncoated part. In the experiment, the beam diameter, pulse width, and repetition rate of the pump wave were 1.5 mmφ, 25 ns, and 50 Hz, respectively, and the typical excitation intensity was 30 mJ/pulse.

Oscillation was easily confirmed by observation of the idler wave. As shown in the inset of Fig. 1, the THz wave was generated in the direction that satisfies the noncollinear phase-matching condition. Here, $\mathbf{k}_j$ is the wave vector with $j = p$, i, and T representing the pump, idler, and THz waves, respectively. As the relationship $\mathbf{k}_p > \mathbf{k}_i \gg \mathbf{k}_T$ holds, the angle ϕ between the pump and the idler waves is small ($\phi \approx 1$ deg), whereas the angle δ between the idler and the THz waves is large ($\delta \approx 65$ deg). The mirrors and crystal were installed on a precise, computer-controlled rotating stage (nanoradian stage from Harmonic Drive Systems, Inc), and we obtained tunability by rotating the stage slightly to vary the angle of the resonator with respect to the pump wave. When we varied the incident angle of the pump wave into the $LiNbO_3$ to between 3.13 and 0.84 deg, angle ϕ between the pump wave and the idler wave in the crystal varied between 1.45 and 0.39 deg, whereas the angle δ between the THz wave and the idler wave varied between 67.3 and 64.4 deg. With this slight variation in the phase-matching condition, the wavelength of the THz wave could be varied between 100 and 330 μm; the corresponding idler wave varied between 1.075 and 1.067 μm.

We introduced a Si-prism array to obtain higher THz-wave output by increasing the coupling area. An array of seven Si-prism couplers was placed on the y surface of the $LiNbO_3$, as shown in Fig. 1. The right-angle prisms were fabricated from high resistivity Si ($\rho > 1\ \mathrm{k\Omega\ cm}$, $\alpha \cong 0.6\ \mathrm{cm}^{-1}$). We cut each sample from a bulk Si crystal by using a precise diamond cutter to dimensions of 8.0 mm (base) $\times$ 6.1 mm (face) $\times$ 5.1 mm (side) $\times$ 5.0 mm (thickness), and the angles were 50, 40, and 90 deg. The total base length was 8 mm $\times$ 7 = 56 mm. A prism angle of 40 deg was chosen so that the THz wave would emerge almost normal to the prism face (6.1 mm $\times$ 5.0 mm). The base of the prisms was pressed against the y surface of the $LiNbO_3$ crystal by a specially designed holder to maximize coupling efficiency.

The THz-wave output and temporary waveform were measured with a 4 K Si bolometer (Infrared Laboratories, Inc.) and a Schottky diode detector.[5] At the same time, the intensity of the idler wave was measured by a powermeter and recorded together with the bolometer output in a computer by use of a digital oscilloscope. We measured the THz wavelength by constructing a scanning Fabry–Perot etalon with two Ni metal meshes (65-μm grid). For the 25-ns pulse width of the pump wave, the pulse widths of the idler and THz waves were approximately 10 ns. Hence, the THz wave consists of several tens of thousands of cycles during the oscillation time, which provided sufficient coherency. We measured the polarization of the THz wave to be parallel to the z axis of the crystal using a wire grid polarizer, and polarizations of the THz wave, the pump, and the idler coincide.

3. Experimental Results

Typical input–output characteristics of a THz-wave parametric oscillator (TPO) with a Si-prism array, for

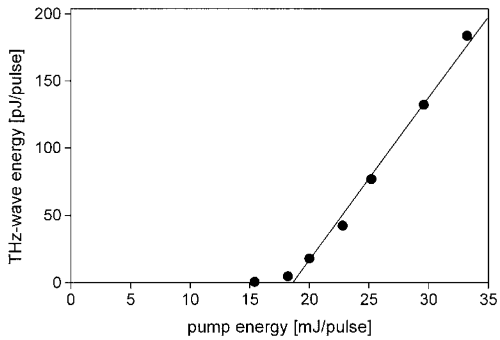

Fig. 2. Typical input–output characteristics of a TPO with a Si-prism array. The THz-wave output increased to greater than six times that of a single-prism coupler because of its wide base.

which the oscillation threshold was 18 mJ/pulse, are shown in Fig. 2. With a pump power of 34 mJ/pulse, the THz-wave output from the prism array was 192 pJ/pulse (19.2 mW at the peak, 9.6 nW on average), as calibrated based on the sensitivity of the bolometer. Inasmuch as the Si-bolometer output becomes saturated at approximately 5 pJ/pulse, we used several sheets of thick paper as an attenuator after calibration. The minimum sensitivity of the Si bolometer is approximately 1 fJ/pulse, therefore, the dynamic range of measurement with the TPO as the source is 192 pJ/1 fJ, which exceeds 50 dB. For the single-prism coupling, the typical output was approximately 30 pJ/pulse (3.0 mW at the peak) at best under similar conditions: 180-μm THz wavelength and 1-mJ/pulse idler output. In comparison, the prism array was capable of emitting more than six times as much THz-wave energy as the single-prism coupling because it is seven times wider at its base.

A small portion of the pump beam was reflected from the end mirror or scattered at the crystal edge and shone on the emitting face of the Si prism, generating a free carrier that strongly absorbed the THz wave. A HR mirror was therefore installed in front of the last Si prism (rightmost in Fig. 1) to intercept the reflected pump beam, as illustrated in Fig. 1. The HR mirror needed to be close to the y surface of the $LiNbO_3$ crystal to intercept the pump beam inasmuch as only 10 $\mu J/cm^2$ of pump is enough to generate the free carrier in Si.[6] Without the HR mirror, the THz-wave output from the last Si prism decreased to between 10^{-2} and 10^{-3} of the output with the HR mirror in place. Because of the difficulty to create a perfect shield for the scattered pump, it is difficult to obtain maximum THz-wave output (~ 3 mW) by use of single-prism coupling, even with a HR mirror. On the other hand, it is much easier to extract maximum THz-wave output (~ 20 mW) from the arrayed prism because the last prism acts as a perfect auxiliary shield for the scattered pump.

The spatial intensity distribution of the THz-wave radiation was measured by a transverse shift of the Si bolometer with a 1.4-mm-wide incident slit. The beam pattern and diffraction of the THz wave in the z plane are shown in Fig. 3 and 4 for the single- and

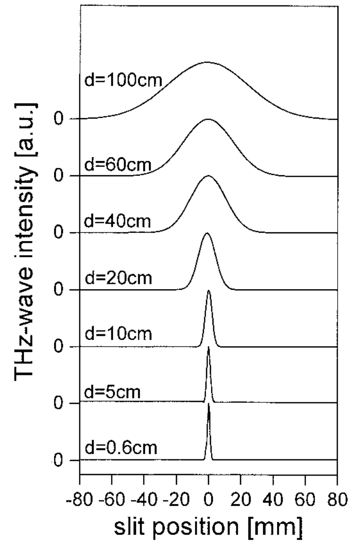

Fig. 3. Intensity cross section of the THz wave in the horizontal direction at distance d from a single Si-prism coupler. The measured diffraction angle of the THz wave in the far field was 1.4 deg.

arrayed-prism couplers, respectively. In Figs. 3 and 4, d indicates the distance between the prism coupler and the slit. For both measurements, the THz wavelength was 170 μm and the angle between the THz beam and the y surface of the crystal was 50 deg.

With single-prism coupling, both the near- and the far-field patterns were Gaussian-like, as shown in Fig. 3. The diffraction angle in the far field was measured to be 1.4 deg. With an arrayed-prism coupling, the far-field pattern was almost Gaussian-like, whereas the near-field pattern was asymmetric, as shown in Fig. 4. In the near field, higher output was observed from the prisms closest to the pump exit surface (right-hand side in Figs. 1 and 4) because, as

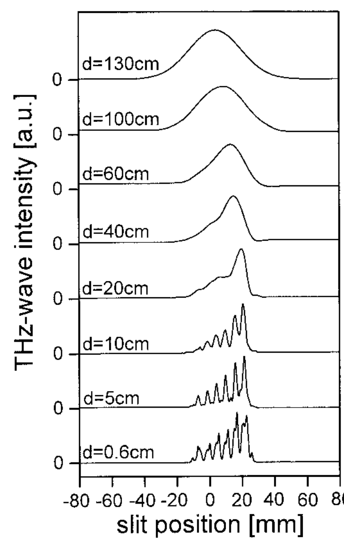

Fig. 4. Intensity cross section of the THz wave in the horizontal direction at distance d from the Si-prism array. A comparison of the FWHM at d = 100 cm proved that the diameter of the THz wave was 40% smaller than that of a single-prism coupler.

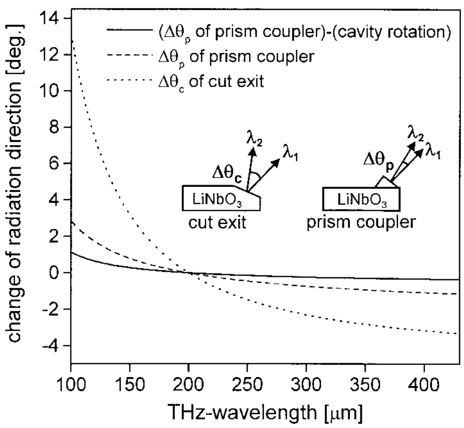

Fig. 5. Calculated radiation angle changes for two different THz coupling methods: cut exit and Si-prism coupler. The dotted and dashed curves indicate the radiation angle changes for the cut exit $\Delta\theta_c$ and the Si-prism coupler $\Delta\theta_p$, respectively. The solid curve represents the actual change in THz-beam direction when observed from outside the TPO. Inasmuch as the TPO cavity can be angle tuned by rotation of the stage in the direction counter to $\Delta\theta_p$, the actual angle change is much smaller than $\Delta\theta_p$. For comparison, the changes in radiation angle are set at zero for $\lambda_{THz} = 200$ μm.

the distance between the pump and the y surface of the crystal decreases, the absorption loss of the THz wave decreases. The output of each prism was distinguishable at $d < 10$ cm, whereas the beam pattern became continuous at $d > 20$ cm. The diffraction angle of the THz wave emitted from the prism array coupler was apparently smaller than that of single-prism coupling, compared with the FWHM of the beam pattern at distance $d = 100$ cm. At $d = 100$ cm, the FWHM is 58 mm for the single-prism coupling and 34 mm for the arrayed-prism coupling. The far-field diffraction angle is decided by the emitting aperture width and the wavelength. The smaller diffraction angle was obtained by the prism array because it has a seven times wider emitting aperture than a single prism.

In previous experiments,[4] a cut exit was used to avoid total internal reflection, as illustrated in Fig. 5. A cut exit was made at the corner of the $LiNbO_3$ crystal, so that the THz wave emerged approximately normal to the exit surface. In this case, the refractive-index dispersion of $LiNbO_3$ and the change of phase-matching angle δ directly influenced the THz-wave direction change, $\Delta\theta_c$. On the other hand, when a Si-prism coupler is used, radiation is almost all in one direction and variation in the phase-matching angle is substantially reduced. Figure 5 shows the calculated changes in radiation angle for these two coupling methods. For comparison the changes in the radiation angle are set at zero for $\lambda_{THz} = 200$ μm. The dotted and dashed curves indicate the changes in the radiation angle for the cut exit, $\Delta\theta_c$, and for the Si-prism coupler, $\Delta\theta_p$,[7] respectively. The solid curve represents the change in THz-beam direction when observed from outside the TPO. It is important to note that, inasmuch as the TPO cavity can be angle tuned by rotation of the stage in the direction counter to $\Delta\theta_p$, the actual angle change is much less than $\Delta\theta_p$. For the observed tuning range of 100–420 μm, $\Delta\theta_c = 16.5$ deg, $\Delta\theta_p = 4.0$ deg, and the actual change, $\Delta\theta_p -$ (cavity rotation) = 1.5 deg.

4. Conclusions

We have demonstrated efficient THz-wave generation by introducing an arrayed Si-prism coupler into a THz-wave parametric oscillator (TPO). Output was greater than six times that with a single-prism coupler. The dynamic range of the TPO spectroscopic system was greater than 50 dB, which is sufficient for many applications. The diffraction angle that we observed by using the prism array was much smaller than that with the single-prism coupler, because of the phased-array-like effect. Furthermore, we explained the importance of cavity rotation to reduce the variation in the THz-wave radiation angle by 63%.

One can increase the THz-wave output by increasing the pump beam diameter in the z-axis direction, so that the THz wave is coupled out from a wider area of the y surface of the crystal. In this case, the diffraction angle of the THz wave in the vertical direction decreases, a decision made based on the diameter of the pump beam.

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References

1. K. Kawase, M. Sato, T. Taniuchi, and H. Ito, “Coherent tunable THz-wave generation from $LiNbO_3$ with monolithic grating coupler,” Appl. Phys. Lett. **68,** 2483–2485 (1996).
2. K. Kawase, M. Sato, K. Nakamura, T. Taniuchi, and H. Ito, “Unidirectional radiation of widely tunable THz wave using a prism coupler under noncollinear phase matching condition,” Appl. Phys. Lett. **71,** 753–755 (1997).
3. J. Shikata, K. Kawase, M. Sato, T. Taniuchi, and H. Ito, “Enhancement of THz-wave output from $LiNbO_3$ optical parametric oscillators by cryogenic cooling,” Opt. Lett. 24, 202–204 (1999).
4. M. A. Piestrup, R. N. Fleming, and R. H. Pantell, “Continuously tunable submillimeter wave source,” Appl. Phys. Lett. **26,** 418–419 (1975).
5. T. Nozokido, J. J. Chang, C. M. Mann, T. Suzuki, and K. Mizuno: “Optimization of a Schottky barrier diode in the submillimeter wave region,” Int. J. Infrared Millim. Waves **15,** 1851–1866 (1994).
6. T. Nozokido, H. Minamide, and K. Mizuno, “Modulation of submillimeter wave radiation by laser-produced free carriers in semiconductors,” Electron. Commun. Jp. Part 2 Electron **80**(no.6), 1–9 (1997).
7. T. Walther, K. R. Chapin, and J. W. Bevan, “Comment on ‘Unidirectional radiation of widely tunable THz wave using a prism coupler under noncollinear phase matching condition’,” Appl. Phys. Lett. **73,** 3610–3611 (1998).