



Enhancing Output Power of LN-Based THz Sources Using a Vertically Elongated Elliptical Beam

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Abstract

To achieve higher output power from a terahertz source based on a MgO:LiNbO₃ crystal, it is essential to increase the incident pump energy while avoiding optical damage, which generally requires expanding the diameter of pump beam. However, it has been known that expanding the beam diameter leads to a reduction in conversion efficiency. In this study, we systematically measured the dependence of terahertz output on the pump beam diameter at multiple terahertz frequencies and experimentally demonstrated that the efficiency degradation is primarily attributable to terahertz absorption losses within the MgO:LiNbO₃ crystal. To overcome this issue, we introduced a vertically elongated elliptical beam. By maintaining a constant beam diameter along the *Y*-axis, which governs the THz absorption path length within the crystal, while expanding the beam only in the vertical direction, higher pump energy can be injected into the crystal. Experiments using a terahertz parametric source showed that the vertically elongated elliptical beam achieved a 1.5-times higher terahertz output compared with a circular beam. Furthermore, we experimentally demonstrated that the terahertz output energy can be scaled by increasing only the *Z*-axis beam diameter of the pump beam. This effect is expected to become more pronounced at higher pump energies, indicating that vertically elongated elliptical beam is an effective approach for enhancing output power of terahertz sources based on MgO:LiNbO₃ crystals.

Keywords Wavelength conversion · Nonlinear optics · Terahertz parametric generator

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1 Introduction

High-power terahertz (THz) sources play a crucial role in a wide range of applications, including spectroscopic measurements, imaging, and material characterization [1, 2]. In this context, various high-power THz sources have been investigated. Among these approaches, THz generation based on wavelength conversion using well-established high-power near-infrared and visible lasers is regarded as particularly promising. In wavelength-conversion-based THz generation, pump beam is injected into a nonlinear optical crystal, and THz waves are generated through second- or third-order nonlinear optical processes [3–7].

To achieve higher output power, it is necessary to increase the incident pump energy while keeping the power density below the damage threshold of the crystal; therefore, expanding the pump beam diameter is commonly employed. However, in lithium niobate (LiNbO_3 , LN) crystals, the introduction of large-area beams faces two major challenges: the large refractive index mismatch between the pump and the THz wave and the strong absorption of THz wave. The large refractive index mismatch makes it difficult to satisfy phase matching conditions when using large-area beams [8], but this issue has been addressed through the introduction of techniques such as noncollinear phase matching [9] and tilted pulse-front method [10]. In contrast, strong THz absorption remains a limiting factor for power scaling. In noncollinear phase matching schemes, increasing the pump beam diameter leads to a longer transverse propagation path of the THz wave within the crystal before it is extracted into free space, resulting in significant absorption losses [11]. Since LN crystals exhibit a large absorption coefficient on the order of several tens of cm^{-1} in the THz frequency range [12], a trade-off exists between beam expansion and increased THz absorption loss.

To mitigate this trade-off, the use of vertically elongated pump beams has been explored. In Cherenkov-type optical-to-THz converters, such elongated beams are employed to scale up THz energy [13]. For tilted pulse-front THz generation in LN crystals, the benefit of elongated pump beams for suppressing absorption losses has been discussed by Bakunov et al. [14], building on the experimental observations of Wang et al. [15]. However, the quantitative relationship between the pump beam diameter and THz absorption loss has not been systematically investigated across different THz frequencies, and the effectiveness of such beam shaping has not been demonstrated in injection-seeded terahertz parametric generator (is-TPG) based on noncollinear phase matching.

In this study, we first systematically measured the dependence of THz output on the pump beam diameter at multiple frequencies to quantify the impact of absorption loss in LN crystals. Based on these results, we introduced a vertically elongated elliptical beam in which the Y -axis beam diameter, which governs the distance the THz wave must traverse within the crystal before being extracted from the surface, is kept at an optimal value, while the beam is expanded only in the Z -axis direction to increase the pump beam area. We experimentally demonstrate that this beam configuration enables scalable THz energy enhancement without degrading conversion efficiency, using an is-TPG based on noncollinear phase matching [16].

2 Experimental Setup

In an is-TPG, a high-power pulsed pump beam and a continuous-wave seed beam are incident on a LN crystal under noncollinear phase matching conditions, generating a monochromatic THz wave corresponding to the frequency difference between the two beams. By varying the frequency and incident angle of the seed beam, the noncollinear phase matching condition can be tuned, enabling broadband frequency tunability from 0.4 to 5 THz [16]. The linewidth of the generated THz wave depends on the pump pulse duration; when a 500-ps pump pulse is used, a THz pulse with a duration of approximately 200 ps and a linewidth of about 1.6 GHz is obtained [17]. As shown in Fig. 1a, the generated THz wave is emitted at an angle of approximately 64° relative to the pump beam inside the LN crystal and is extracted from the Y-surface of the crystal. In this study, this is-TPG configuration was employed to evaluate the effect of the pump beam diameter on THz absorption loss in LN-based THz sources.

First, the conversion efficiencies from the pump beam to the THz wave and the Stokes beam were measured using a circular beam. The experimental setup is shown in Fig. 1b. The pump source was a pulsed beam (pulse duration: 500 ps) obtained by amplifying the output of a microchip Nd:YAG laser [18] to an energy of 30 mJ. The beam was shaped into a collimated beam with a diameter of 2.0 mm and, in each experiment, was reduced to the desired beam diameter using a long-focal-length lens with $f=1000$ mm. Consequently, the pump beam used in this experiment was not a perfectly collimated beam but rather a soft-focused beam defined at the LN crystal

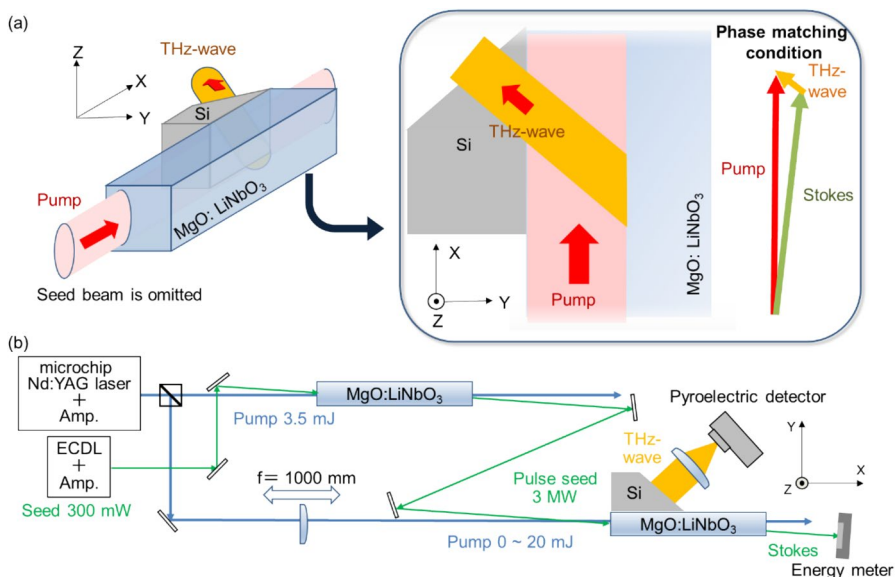


Fig. 1 **a** Propagation direction of the generated THz wave under noncollinear phase matching conditions. The seed beam is omitted for clarity. **b** Schematic of the is-TPG configuration employing a vertically elongated elliptical beam

entrance position. The seed beam diameter must be larger than that of the pump beam (2.0 mm); however, in conventional continuous-wave seed beam, the power density is insufficient, resulting in reduced THz generation efficiency. Therefore, a pulsed seed was employed. The pulsed seed was generated by injecting the output of an external cavity diode laser (ECDL) into the LN crystal simultaneously with the pump beam, where it was converted into a pulsed beam with a peak power of up to 3 MW through optical parametric amplification. The THz wave was generated by the interaction between this pulsed seed and the pump beam [19, 20]. The generated THz wave was focused by a lens and detected using a pyroelectric detector. Since the pyroelectric detector saturates at approximately 0.15 μJ , a calibrated THz attenuator was used to adjust the intensity to an appropriate level. The Stokes beam, including higher-order Stokes components generated through cascading processes [21], was evaluated using an energy meter.

3 Results and Discussion

First, to examine the influence of crystal absorption on the conversion efficiency when the pump beam diameter is expanded, the conversion efficiency was measured as a function of the diameter of a circular pump beam under a constant power density of 2.5 GW/cm^2 (Fig. 2). Measurements were performed at three different frequencies because the THz absorption coefficient of LN crystals strongly depends on frequency, allowing the effect of absorption on the conversion efficiency to be clearly evaluated. Figures 2a–c shows the results at 1.0, 1.5, and 2.0 THz, respectively, obtained by adjusting the wavelength of the seed beam and optimizing the phase matching condition for each frequency.

For beam diameters below 0.8 mm, different dependencies were observed at the three frequencies. These behaviors can be mainly explained by THz diffraction and absorption losses. At 1.0 THz (Fig. 2a), the conversion efficiency increased as the beam diameter was expanded from 0.5 to 0.9 mm. Due to the relatively long wavelength at 1.0 THz, a smaller beam diameter results in a larger diffraction angle, causing a significant portion of the generated THz wave to miss the effective aperture of the pyroelectric detector (or the collection optics).

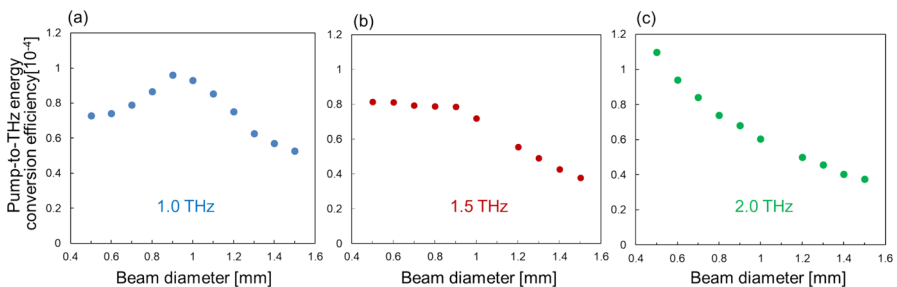
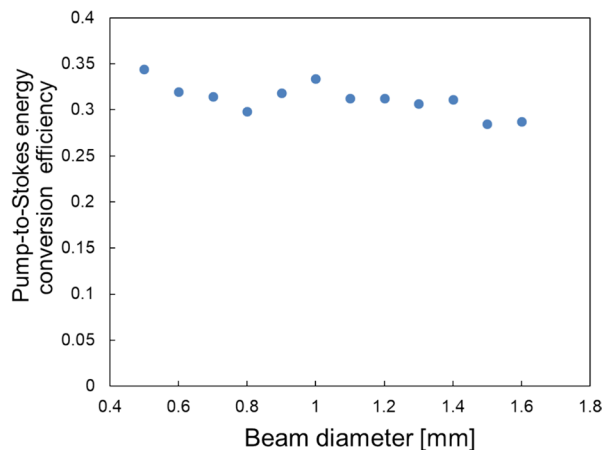


Fig. 2 Pump-to-THz energy conversion efficiency as a function of the pump beam diameter (FWHM) at **a** 1.0 THz, **b** 1.5 THz, and **c** 2.0 THz

Expanding the beam diameter suppresses this diffraction loss and improves the collection efficiency, leading to the observed increase in conversion efficiency. In contrast, at 2.0 THz (Fig. 2c), the conversion efficiency decreased with increasing beam diameter in the range of 0.5–1.4 mm. The absorption coefficient at 2.0 THz is relatively large, and absorption loss is already significant at a beam diameter of 0.5 mm. As the beam diameter increases, the transverse propagation distance of the THz wave within the crystal becomes longer, resulting in further absorption loss. At 1.5 THz (Fig. 2b), however, the conversion efficiency remained nearly constant even when the beam diameter was reduced. At this frequency, diffraction is less significant than at 1.0 THz, maintaining sufficient THz wave reaching the detector, and the absorption coefficient is smaller than that at 2.0 THz. Consequently, for beam diameters below approximately 0.9 mm, the effect of absorption loss is negligible, leading to little change in conversion efficiency. Furthermore, for all frequencies, the conversion efficiency decreased as the beam diameter exceeded 0.9 mm. This decrease was most pronounced at 2.0 THz. Since LN crystals exhibit larger absorption coefficients at higher THz frequencies [12], these results are consistent with the assumption that the reduction in conversion efficiency with increasing beam diameter is dominated by absorption loss.

From the results shown in Fig. 2 alone, it is difficult to conclusively determine that the reduction in conversion efficiency is caused by crystal absorption, since other factors, such as changes in parametric gain associated with beam diameter variation, may also contribute. Therefore, we measured the conversion efficiency of the Stokes beam, which is generated simultaneously with the THz wave. Since the Stokes beam experiences negligible absorption within the crystal, its conversion efficiency provides a direct measure of the nonlinear parametric gain, effectively decoupled from the frequency-dependent THz absorption losses that would otherwise obscure the intrinsic gain behavior. Figure 3 shows the conversion efficiency of Stokes as a function of the pump beam diameter. In this measurement, the THz frequency was fixed at 1.0 THz, because the Stokes beam experiences almost no absorption in LN crystals and exhibits weak frequency dependence.

Fig. 3 Conversion efficiency of Stokes beam as a function of the pump beam diameter at 1.0 THz



As shown in Fig. 3, the conversion efficiency of Stokes beam remained nearly constant over the beam diameter range of 0.5–1.6 mm. This result supports the conclusion that the decrease in conversion efficiency of THz wave observed in Fig. 2 with increasing beam diameter is primarily attributable to THz absorption loss.

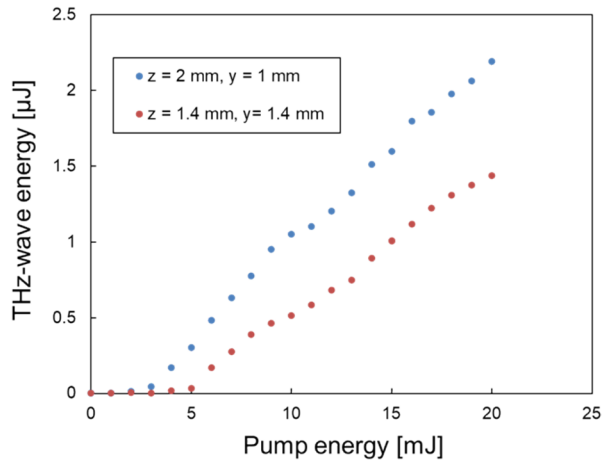
In conventional is-TPG systems employing continuous-wave seed beam, it is well known that reducing the pump beam diameter along the *Y*-axis shortens the interaction length between the pump beam and the THz wave, resulting in a decrease in conversion efficiency [11]. In contrast, when high-intensity pulsed seed is used, as in the present study, the peak intensity of the seed beam is approximately 108 times higher than that of a continuous-wave beam. Consequently, the nonlinear gain becomes relatively insensitive to variations in the interaction length. In other words, even when the *Y*-axis beam diameter is reduced and the interaction length is shortened, sufficiently high gain can be maintained owing to the high peak intensity, and no pronounced degradation in conversion efficiency is observed. Since power scaling using a vertically elongated elliptical beam requires a large beam area, the use of pulsed rather than continuous-wave seeding is appropriate, and under these conditions, the lower limit of the *Y*-axis beam diameter is not a critical issue. Nevertheless, although no efficiency degradation was observed within the beam diameter range investigated in this study, further reduction of the beam diameter is expected to eventually lead to a decrease in conversion efficiency, as the reduction in interaction length associated with noncollinear phase matching becomes dominant.

From the measurements described above, it has been clarified that expanding a circular pump beam to enable the use of higher pump energy increases the transverse propagation distance of the THz wave within the crystal, thereby enhancing absorption loss. To increase the incident pump energy while suppressing absorption loss, we therefore introduced a vertically elongated elliptical beam, in which the beam diameter along the *Y*-axis, which governs the distance the THz wave traverses within the crystal, is kept constant at an efficient value, while only the beam diameter along the *Z*-axis, which does not contribute to absorption, is expanded. To compare the effects of circular and vertically elongated elliptical beams, THz generation was performed using both beams with the same beam area (Fig. 4). For the vertically elongated elliptical beam, the beam diameters were set to 2 mm along the *Z*-axis and 1 mm along the *Y*-axis, whereas a circular beam with a diameter of 1.4 mm was used. Because the beam areas were identical in both cases, the power densities were also the same.

As a result, the THz output obtained with the vertically elongated elliptical beam was 1.5 times higher than that obtained with the circular beam. This result is consistent with the conversion efficiency shown in Fig. 2b. These findings demonstrate that flattening the pump beam effectively suppresses THz absorption loss, enabling highly efficient THz generation. When considering further power scaling, a circular beam would require a diameter larger than 1.4 mm, in which case the influence of crystal absorption would become even more pronounced. Under such conditions, suppression of crystal absorption using a vertically elongated elliptical beam can provide a simple and effective solution.

Finally, we verified whether output power scaling is achievable using the vertically elongated elliptical beam. The *Y*-axis beam diameter was fixed at 0.80 mm,

Fig. 4 THz output obtained using a circular pump beam and a vertically elongated elliptical beam at 1.5 THz



while the Z-axis beam diameter was varied to 0.90, 1.18, and 1.70 mm. In this experiment, a continuous-wave seed beam was employed. Figure 5a shows the THz output as a function of pump power density for the three Z-axis beam diameters, along with linear fits. Figure 5b extracts the THz output at a constant power density of 2.5 GW/cm^2 as a function of the Z-axis beam diameter. The THz output increases approximately linearly with the Z-axis beam diameter, indicating that the conversion efficiency remains constant regardless of the Z-axis beam

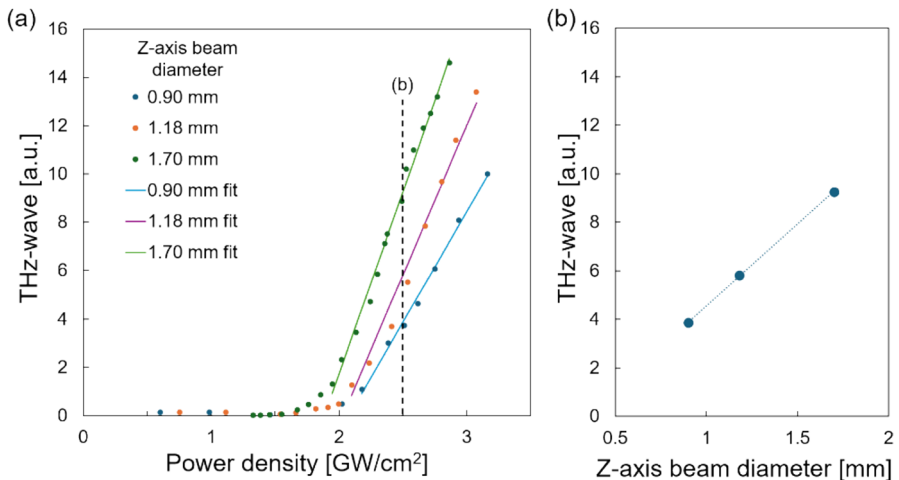


Fig. 5 Scaling of THz output with the Z-axis beam diameter at 1.5 THz with a fixed Y-axis beam diameter of 0.8 mm. **a** THz output as a function of pump power density for Z-axis beam diameters of 0.90, 1.18, and 1.70 mm. Solid lines represent linear fits. **b** THz output extracted from the linear fits at a constant power density of 2.5 GW/cm^2 (dashed line in (a)) as a function of the Z-axis beam diameter. The dotted line represents a linear fit, confirming that the THz output scales proportionally with the beam area

expansion. This directly demonstrates the scalability of THz output energy using the vertically elongated elliptical beam.

Although the present study employed an is-TPG, which is a monochromatic THz source, the same discussion regarding beam diameter and generation efficiency is applicable to broadband THz sources based on the tilted pulse-front method, where the effect of elongated pump beams has been studied both theoretically and experimentally [14, 15]. The frequency-resolved absorption analysis presented in this work is expected to provide additional quantitative guidance for optimizing beam design in such systems as well.

4 Conclusion

In this study, we systematically investigated the relationship between the pump beam diameter and THz conversion efficiency at multiple THz frequencies in a LN-based is-TPG and demonstrated that the efficiency degradation with increasing beam diameter is primarily attributable to THz absorption loss within the crystal. Based on these findings, we introduced a vertically elongated elliptical beam in which the Y-axis beam diameter, which governs the THz propagation distance within the crystal, is kept at an optimal value while only the Z-axis beam diameter is expanded. Experiments showed that the elliptical beam achieved a 1.5-times higher THz output compared with a circular beam of equal cross-sectional area. Furthermore, by fixing the Y-axis beam diameter and increasing only the Z-axis beam diameter, we confirmed that the THz output scales linearly with the beam area, directly demonstrating the scalability of this approach. This beam shaping strategy is applicable not only to is-TPG systems but also to broadband THz sources employing the tilted pulse-front method [22] and is expected to be effective for other nonlinear crystals satisfying noncollinear phase matching conditions, such as LiTaO₃ [23] and KTiOPO₄ [6], which exhibit even stronger THz absorption than LN crystals.

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Author Contributions K.M. and S.M. conceived the study. S.M. performed the experiments and wrote the original draft. J.N., F.B., K.K., and K.M. contributed to validation of the results. K.K. and K.M. acquired funding. K.M. supervised the project. All authors reviewed and revised the manuscript.

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Data Availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Competing interests The authors declare no competing interests.

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