DOI 10.1007/s10946-024-10218-1
Journal of Russian Laser Research, Volume 45, Number 3, May, 2024

ENHANCED TERAHERTZ EMITTER BY MULTIPLEXING PUMP TITLED PULSE FRONT IN $LiNbO_3$ CRYSTAL

Feilong Gao,[1] Shaodong Hou,[2*] Bingyuan Zhang,[1] and Qi Song[1]

[1]*Shandong Key Laboratory of Optical Communication Science and Technology*
School of Physics Science and Information Technology
Liaocheng University
Liaocheng 252059, China

[2]*Changzhou Inno Machining Co., Ltd.*
No. 18-69, Changzhou 213164, China

*Corresponding author e-mail: hsd@hust.edu.cn

Abstract

It is crucial to enhance the efficiency of terahertz radiation in a single crystal for the application of intense field terahertz waves. We devise a trapezoidal lithium niobate prism that, upon side incidence of the terahertz wave, retroreflects the femtosecond laser onto the crystal's symmetric plane. The conversion efficiency of pump power to THz pulse power for circular cavity increases by 36% compared to that of the conventional cavity. The findings demonstrate that the utilization of sample multiplexing pump can significantly enhance the efficiency of terahertz generation.

Keywords: coherent terahertz emitter, optical rectification, multiplexing pump.

1. Introduction

The advancements in THz radiation have resulted in a wide range of applications, including time-domain spectroscopy utilizing pump-probe techniques, nonlinear terahertz physics, and the control of low-energy elementary excitations [1, 2]. The primary challenge in THz technology lies in enhancing THz energy and optimizing phase and polarization modulation. The utilization of coherence techniques presents a potential solution to address these issues [3, 4].

In order to achieve coherent THz radiation, various principles and structures have been reported, including optical rectification in a collinear nonlinear crystal, photoconductive antennas, ferrimagnetic domain walls, laser-plasma filaments, air plasmas, and superconductors. The generation of coherent cycle-engineered THz waveforms in a GaP crystal through optical rectification was achieved by utilizing two collinear femtosecond laser pulses [5]. Continuous-wave coherent terahertz radiation with frequency up to 3.5 THz through photomixing in LT-GaAs photoconductors has been demonstrated [6]. The field-driven coherent THz spin wave emission for ferrimagnetic domain walls was realized [7]. A nearly single-cycle coherent terahertz pulse emitted from a linear-dipole array formed by a two-color laser filament in air was reported [8]. The generation of THz waves in the ionized plasma induced by pulsed laser was demonstrated with phase and polarization individually controlled [9]. The coherent continuous-wave terahertz radiation generated by intrinsic Josephson junctions in the layered high-temperature superconductor $Bi_2Sr_2CaCu_2O_8$ was also demonstrated [10].

Manuscript submitted by the authors in English on April 24, 2024.

The reuse of the pump radiation is not taken into account in previous works on coherence THz generation, due to its rather complex structures. To achieve efficient THz generation through optical rectification, it is necessary to ensure that the group velocity of the optical pump pulse matches the phase velocity of the THz radiation [11]. The velocity matching can be express as follows:

$$v_g \cos\gamma = \nu, \tag{1}$$

where v_g is the group velocity of pump wave, v is the phase velocity of THz wave, and γ is the required pulse front tilt (PFT) angle.

The base angle of the $LiNbO_3$ (LN) crystal should be designed as 63.5° due to the phase matching [12]. The critical angle of the wedge prism for most glass, which has a refractive index of 1.52, is 41.2. In PTF crystal prism with a base angle of 63.5°, the total reflection of the pump laser occurs at the output surface of the THz wave. The pump laser and the THz wave are separated.

We design an isosceles trapezoidal crystal specifically for the THz generation, whereby the remaining pump light is emitted perpendicularly from the other surface. By placing a reflector at the output surface in an appropriate position, a pump multiplexing system can be established. The remaining pump light is reflected back to the crystal for generating the THz wave. The pump multiplexing system offers evident advantages, including the amplification of THz output power and the utilization of residual pump light.

2. Experimental Setup

The experimental setup is shown in Fig. 1.

The pump laser has a central wavelength of $\lambda = 1040$ nm and a full-width-at-half-maximum intensity duration of $\tau_{\mathrm{FWHM}} \approx 115$ fs, delivering up to an energy of 0.05 μJ at a repetition rate of 43 MHz. The pump beam is split into two arms, namely, the pump arm and the probe arm, by utilizing a beam sampler. A 90% of laser pulse is incident on a blazing grating with a groove density of 1200 lines/mm at an incident angle of $\sim 22°$ to create the pulse-front tilt. The PFT pulses are focused into a 0.5% MgO-doped stoichiometric LN isosceles trapezoid prism with a base angle of 63.5° using a lens ($f = 60$ mm) positioned behind the grating. A half-wave plate is positioned in front of the LN crystal to adjust the polarization of the incident laser beam parallel to the optical axis of the LN crystal. The THz radiation is collected and focused onto the photoconductive antenna (PCA) or Golay cell, using two 90° off-axis parabolic mirrors (OAP) with a focal length of 45 mm to record the THz pulse and measure the THz power. The laser beam is modulated using an optical chopper, with a frequency of 1000 Hz for recording the THz pulses and a frequency of 10 Hz for measuring the THz output power. The mirrors reflecting the pump beam are silver coated, and the OAP mirrors are coated with gold film.

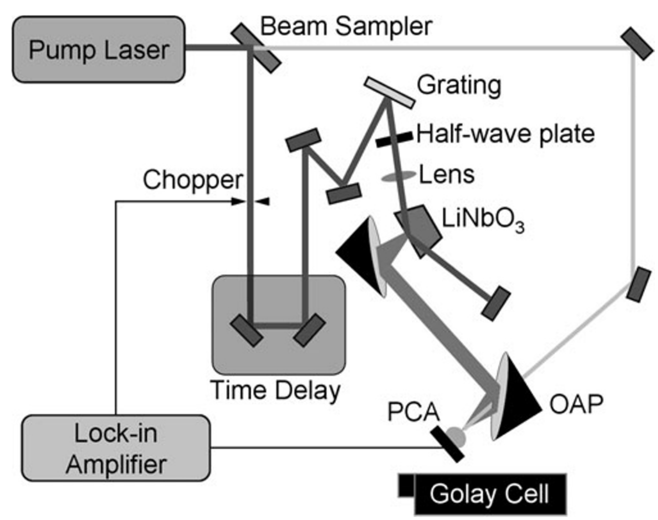

Fig. 1. Experimental setup for THz generation using multiplexing pump.

In order to reuse the laser beam, a reflector is placed on the other side of the LN isosceles trapezoid prism at distances of 35, 37, and 39 mm, which are equal to integer multiples of the THz pulse optical path. The laser beam is adjusted to be perpendicular to the reflector, ensuring that the phase matching condition is satisfied.

3. Experimental Details and Discussion

In Fig. 2, we show the temporal waveform and corresponding THz spectrum. The multiplexing pump in Fig. 2 exhibits about 30% enhancement in the THz intensity, while enabling observation of the THz modulation with a frequency spacing of 0.05 THz. The THz spectrum range for multiplexing pump is relatively narrow.

The pump light with different frequencies initially induce a time delay and pulse front tilt through utilizing the grating. The time delay still persists, when the pump light propagates in the crystal; therefore, phase matching can be achieved by vertically incident pump light into the LN crystal, using a reflector. The THz wave can be detected, when the optical path of the multiplexing pump is adjusted to be equal to the reference optical path during an integer number of times by adjusting the distance between the reflector and the LN crystal.

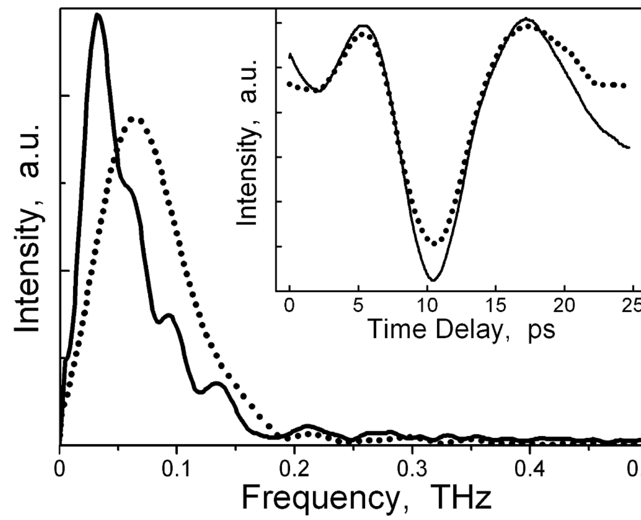

Fig. 2. THz temporal waveform (inset) and corresponding spectrum of the THz pulses measured by photoconductive antenna for the signal cavity (dotted curves) and the multiplexing pump cavity (solid curves).

In Fig. 3, we present the polarization characteristics of the input laser beam. For both single and multiplexing pumps, the highest THz wave power is achieved, when the polarization of the pump radiation

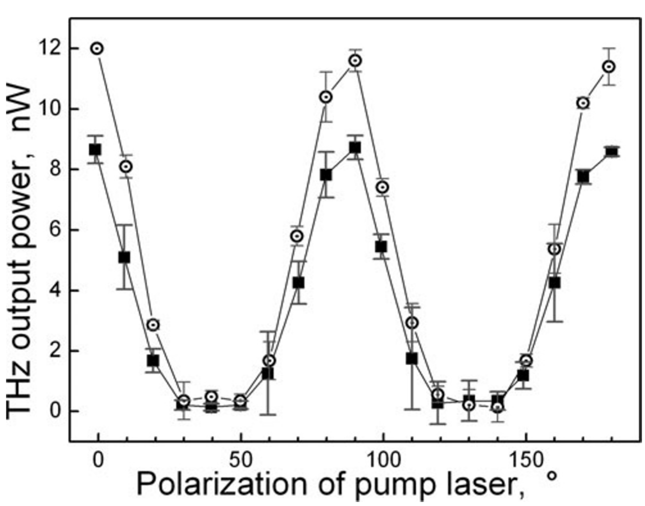

Fig. 3. THz output power as a function of polarization of the pump radiation for single pump (■) and multiplexing pump (⊙).

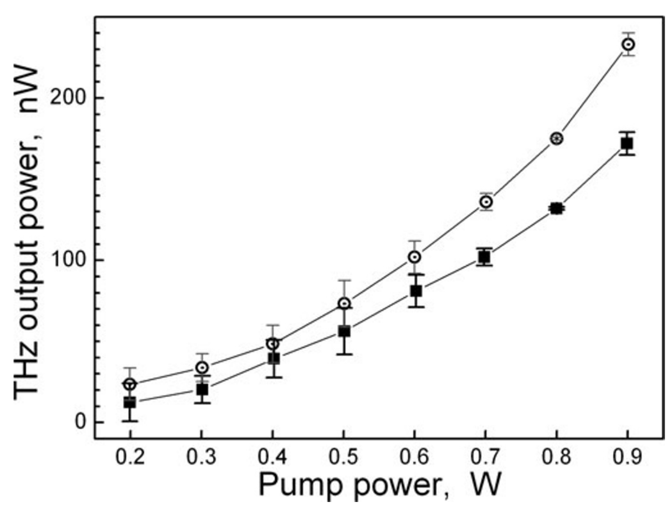

Fig. 4. Dependence of the THz power on the pump power for single pump (■) and multiplexing pump (⊙); here, error bars are ×10.

is parallel to the crystal axis. Moreover, the THz wave cannot be detected, when the laser polarization is perpendicular to the crystal axis.

In Fig. 4, we compare the output powers of the THz radiations for single and multiplexing pump configurations; we show them as dependences of the pump power density. The maximum THz output power achieved in the single pump configuration is 170 nW for a pump power of 0.9 W, with a corresponding conversion efficiency of $1.9 \cdot 10^{-7}$. The maximum THz output power for the multiplexing pump configuration achieved at the same pump power is 230 nW, and the corresponding conversion efficiency is $2.6 \cdot 10^{-7}$.

The terahertz wave generated by the multiplexing method exhibits enhanced output power, due to three contributing factors: (i) the PTF angle decreases as the pump light propagates through the crystal, resulting in incomplete phase matching within the LN crystal; (ii) there is a significant divergence of the laser beam when passing through the LN crystal, resulting in the fact that only 20% of the pump laser reentering the crystal; (iii) the laser beam possesses a broad wavelength range, and only the remaining portion of THz generated can be utilized for optical rectification.

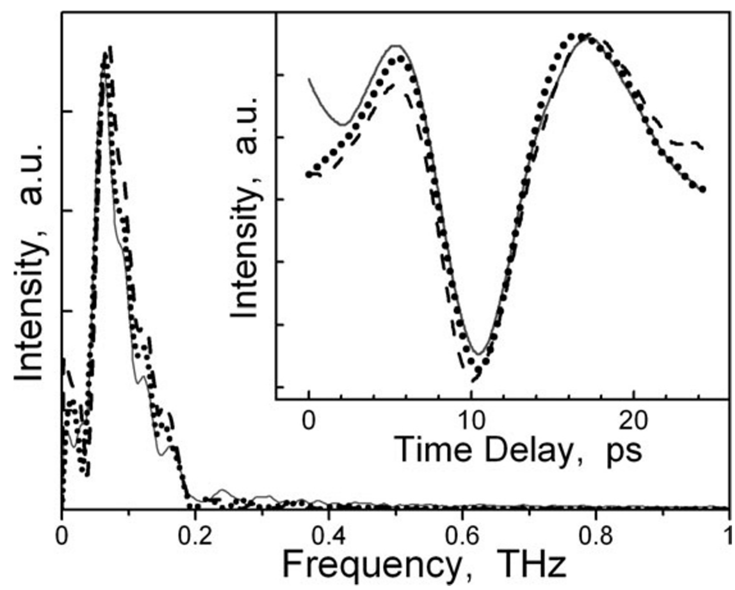

Fig. 5. Coherent spectrum of the THz pulses by multiplexing pump for scanning distances 35 mm (dashed curves), 37 mm (dotted curves), and 39 mm (solid curves).

We designed three optical paths for multiplexing pump, with lengths of 35, 37, and 39 mm, respectively, corresponding to the THz wave optical paths of 38, 40, and 42 times; see Fig. 5. The terahertz wave coherence spectrum is obtained by varying the optical path length, with only slight variations in the intensity observed. The modulation of THz wave in Fig. 5 confirming the coherent superposition.

4. Conclusions

By utilizing a simple reflector, the remaining portion of the laser beam could be effectively reused to enhance the THz output power and achieve the coherent terahertz radiation. The circular cavity method exhibited a 36% increase in the conversion efficiency of the pump power to the THz pulse power compared to the single pump method in LN crystal by optical rectification, while also enabling observation of THz modulation with a frequency spacing of 0.05 THz. The terahertz coherence spectrum was obtained by changing the distance of the reflector integer multiple to the THz generation light path. The method of pump multiplexing with enhancement of the THz output power made it suitable for potential applications as coherent terahertz emitter.

Acknowledgments

This work was supported by the Natural Science Foundation of Shandong Province under Grant No. ZR2021QF025, the National Natural Science Foundation of China under Grants Nos. 62205136 and 62205219, and the Research Foundation of Liaocheng University under Grants Nos. 318052316 and 318052037.

References

1. R. G. Ungureanu, O. V. Grigore, M. P. Dinca, et al., *Laser Phys. Lett.*, **12**, 045301 (2015).
2. Q. Song, H. Chen, M. Zhang, et al., *APL Photonics*, **6**, 056103 (2021).
3. Q. Song, Y. Zhou, E. S. Jia, et al., *Sci. China Technol. Sci.*, **66**, 3267 (2023).
4. Z. Z. Peng, Z. Y. Ruan, F. L. Gao, et al., *J. Liaocheng Univ. (Nat. Sci. Ed.)*, **37**, 14 (2024); DOI: 10.19728/j.issn1672-6634.2023110007
5. L. Shu, Y. Li, L. Chen, et al., *Laser Phys. Lett.*, **11**, 085404 (2014).
6. S. Matsuura, M. Tani, and K. Sakai, *Appl. Phys. Lett.*, **70**, 559 (1997).
7. S. H. Oh, S. K. Kim, D. K. Lee, et al., *Phys. Rev. B*, **96**, 100407 (2017).
8. Z. Zhang, Y. Chen, M. Chen, et al., *Phys. Rev. Lett.*, **117**, 243901 (2016).
9. X. Xie, J. Dai, and X. C. Zhang, *Phys. Rev. Lett.*, **96**, 075005 (2006).
10. L. Ozyuzer, A. Koshelev, C. Kurter, et al., *Science*, **318**, 1291 (2007).
11. J. A. Fülöp, L. Pálfalvi, S. Klingebiel, et al., *Opt. Rxpress*, **18**, 12311 (2010).
12. L. Wang, G. Tóth, J. Hebling, et al., *Laser Photonics Rev.*, **14**, 2000021 (2020).