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Generation of THz pulses with a uniform wavefront in a PPLN crystal

Yu. Sahakyan

Yerevan State University, Alex Manoogian str. 1, 0025 Yerevan, Armenia

yuri.sahakyan@ysu.am

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Abstract

In present paper, we propose a scheme for generating terahertz (THz) radiation with uniform power distribution by optical rectification of femtosecond laser pulses in periodically polarized lithium niobate (PPLN) crystals. Using a triangular prism-shaped crystal and polarizing the laser along the optical axis, maximum nonlinear coefficient is utilized for efficient THz emission. The periodic domain structure of specific area of the crystal offers quasi-phase matching, which enables cumulative THz radiation with improved uniformity in beam. Moreover, the crystal cutting along the Cherenkov angle allows emitted THz waves to exit with small absorption and reflection losses. The suggested model has a promising method of achieving efficient and uniform THz sources.

Keywords: TERAHERTZ RADIATION, PERIODICALLY POLED LITHIUM NIOBATE, CHERENKOV RADIATION, OPTICAL RECTIFICATION

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1. Introduction

Terahertz (THz) electromagnetic radiation, spanning the frequency range of 1–10 THz, has attracted significant attention due to its importance in both fundamental research and diverse practical applications.

Many materials have molecular absorption lines in the terahertz range, which makes the THz domain interesting and attractive for various applications. In particular, THz waves can be used to study the composition and electrical properties of solid, gaseous, and liquid substances [1, 2]. THz technologies are already being applied in security systems, biomedicine, and elsewhere [3].

However, it should be noted that despite the attractiveness of THz waves for numerous applied and fundamental problems, this domain is still technologically underdeveloped and therefore has not yet found widespread large-scale application [4].

Despite notable progress, the development of efficient and versatile methods for THz generation remains a central challenge in modern physics [5–10].

Among the existing approaches, optical rectification of femtosecond laser pulses in periodically poled lithium niobate (PPLN) crystals stands out as one of the most widely employed techniques for producing narrowband THz radiation. To mitigate the effect of absorption in nonlinear crystals, it has been proposed to arrange the laser beams and the nonlinear crystal in such a way that, by appropriately selecting the PPLN crystal period, the generated terahertz radiation propagates at a Cherenkov angle relative to the direction of propagation of the optical waves [11–12].

Since terahertz wave absorption in lithium niobate crystals is significant, the region of the nonlinear crystal where terahertz waves are generated should be selected as close as possible to the crystal's output surface. In this case, the generated terahertz waves travel only a short distance within the crystal, and therefore absorption within the crystal is significantly reduced.

The spatially periodic modulation of the nonlinear response in PPLN enables quasi-phase-matching conditions, thereby facilitating efficient THz generation and allowing for the realization of relatively high output powers.

To obtain broadband terahertz radiation, it is necessary that the THz pulses emitted from each layer of the crystal reach the output surface simultaneously [12]. In other words, the pulses radiated from each layer should arrive at the next layer exactly at the moment when the optical pulse reaches the corresponding point of that layer. To generate terahertz radiation, it is proposed to use a nonlinear lithium niobate crystal, part of which is periodically poled, while the rest remains unpoled. Such a model is suggested with the aim of obtaining terahertz radiation with a uniform wavefront.

2. Methodology

To obtain uniformly distributed terahertz radiation, the number of PPLN layers in the direction of terahertz radiation propagation must be the same throughout the generated region.

The PPLN crystal has the shape of a triangular prism. The front surface of the PPLN sample is in the form of a right triangle, with its sides oriented along the crystal’s X and Y axes. The femtosecond laser beam propagates parallel to the domain walls of the PPLN crystal and is polarized along the optical axis of the crystal. This configuration makes it possible to utilize the maximum nonlinear coefficient, the d_{33} component.

Figure 1 shows the schematic diagram of the proposed model. The incident optical beam with a plane amplitude front is indicated by red arrows, with its electric field component oscillating in a direction perpendicular to the plane of the figure. The ABCD section of the crystal is periodically poled perpendicular to the plane of the figure, with one layer poled toward the observer and the next layer in the opposite direction.

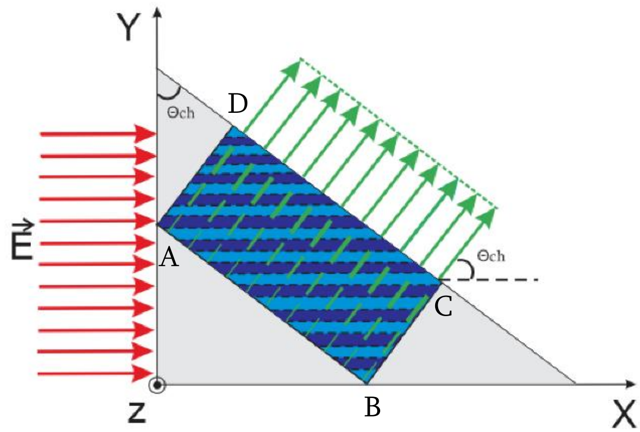

Figure 1. Schematic representation of the model.

ABCD represents the periodically poled section of the nonlinear crystal. The incident optical beam on the crystal is indicated with red arrows. The generated THz radiation is shown in green — inside the crystal (with dashed lines) and outside the crystal (with an arrow).

The light-blue section of the crystal shown in Figure 1 does not participate in THz generation, since that part is not periodically poled and therefore no cumulative radiation is produced there.

In the PPLN crystal, THz radiation from each domain is emitted at the Cherenkov angle (θ_{Ch}) relative to the direction of laser beam propagation:

$$\cos\theta_{Ch} = \frac{n(\omega_{Laser})}{n(\omega_{THz})}$$

where $n(\omega_{Laser})$ is the refractive index corresponding to the group velocity of the laser radiation and $n(\omega_{THz})$ is the refractive index at the generated THz frequency.

The crystal in Figure 1 is cut at the Cherenkov angle, which allows the generated THz radiation to exit the crystal with minimal reflection losses.

The periodically inverted domain structure of the PPLN crystal enables efficient superposition of the THz fields emitted from individual domains. As a result, the generated THz radiation is a quasi-monochromatic wave with a central frequency f_{THz}, determined by the spatial periodicity Λ of the PPLN crystal.

If the thickness of the layers (Λ/2) is chosen such that the THz radiation generated in each layer reaches the next layer with a complete phase shift, then the radiation emitted from all the layers will add up, resulting in cumulative radiation from the crystal surface.

The wave vector diagram associated with THz generation in the crystal is presented in Fig. 2.

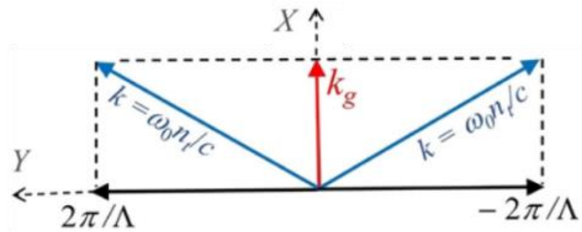

Figure 2. The wave vectors diagram.

As shown in Fig.2, the generated terahertz radiation propagates in both directions at the Cherenkov angle. As proposed in [13], in this model as well the crystal is cut at an oblique angle, and consequently, the generated radiation is emitted out of the crystal.

3. Conclusions

The generation of THz radiation with uniform power distribution in a PPLN crystal through the optical rectification (OR) of a laser beam has been investigated. The results of the study confirm that periodically poled lithium niobate crystals can effectively generate evenly distributed terahertz radiation by optical rectification of ultrashort laser pulses. Extraction of the THz waves with low loss is possible by quasi-phase matching and cutting the crystal at the Cherenkov angle, paving the way towards compact and THz sources.

References

1. J. Federici, L. Moeller. J. Appl. Phys., **107**, 111101 (2010).
2. R. Horodecki et al. Rev. Mod. Phys., **81**, 865 (2009).
3. Federici J., Schulkin B., Huang F., Gary D., Barat R., Oliveira F., Zimdars D., "THz imaging and sensing for security applications - explosives, weapons and drugs," Semicond. Sci. Technol. **20**, S266–S280 (2005).
4. Fischer B, Hoffmann M, Helm H.,. Modjesch G, Jepsen P., "Chemical recognition in terahertz time-domain spectroscopy and imaging," Semicond. Sci. Technol. **20**, S246–S253 (2005).
5. A. Leitenstorfer, A. Moskalenko, T. Kampfrath, et al., "The 2023 terahertz science and technology roadmap," J. Phys. D **56**, 223001 (2023).
6. Y. Zhang, K. Li, and H. Zhao, "Intense terahertz radiation: generation and application," Front. Optoelectron. **14**, 4–36 (2021).
7. X. Zhang, A. Shkurinov, and Y. Zhang, "Extreme terahertz science," Nat. Photonics **11**, 16–18 (2017).
8. M. Hoffmann and J. Fulop, "Intense ultrashort terahertz pulses: generation and applications," J. Phys. D **44**, 083001 (2011).

9. N. H. Matlis, F. Ahr, A. Calendron, et al., "Acceleration of electrons in THz driven structures for AXSIS," Nucl. Instrum. Methods Phys. Res. A **909**, 27–32 (2018).
10. M. Hibberd, A. Healy, D. Lake, et al., "Acceleration of relativistic beams using laser-generated terahertz pulses," Nat. Photonics **14**, 755–759 (2020).
11. Avetisyan Yu. H., Kocharyan K. N., "A new method of terahertz difference frequency generation using periodically poled waveguide," Tech. Dig. CLEO-1999 (Baltimore, USA, May 1999). pp. 380-381.
12. Avetisyan Y. H., Sasaki Y., Ito H. "Analysis of THz-wave surface-emitted difference-frequency generation in periodically poled lithium niobate waveguide," Appl. Phys. B. **73**, 511-514 (2001).
13. Yu. Avetisyan, A. Makaryan, "Narrowband terahertz generation in a plane-parallel Rb:KTP crystal using a phase mask" Journal of the Optical Society of America B **41**, 4, 873-878(2024)