

Efficient electro-optic sampling detection of terahertz radiation via Cherenkov phase matching

メタデータ	言語: eng 出版者: 公開日: 2012-04-26 キーワード (Ja): キーワード (En): 作成者: TANI, Masahiko, HORITA, Kazuki, KINOSHITA, Tetsuya, QUE, Christopher T., ESTACIO, Elmer, YAMAMOTO, Kohji, BAKUNOV, Michael I. メールアドレス: 所属:
URL	http://hdl.handle.net/10098/5251

Efficient electro-optic sampling detection of terahertz radiation via Cherenkov phase matching

Masahiko Tani,¹ Kazuki Horita,¹ Tetsuya Kinoshita,¹ Christopher T. Que,¹
Elmer Estacio,^{1,*} Kohji Yamamoto,¹ and Michael I. Bakunov²

¹Research Center for Development of Far-Infrared Region, University of Fukui, Fukui 910-8507, Japan

²University of Nizhny Novgorod, Nizhny Novgorod, 603950, Russia

*estacio@fir.u-fukui.ac.jp

Abstract: We experimentally demonstrate an efficient electro-optic sampling scheme based on Cherenkov phase matching of broadband terahertz radiation with 800-nm femtosecond probe beam in a 0.5 mm-thick LiNbO₃ crystal coupled to a Si prism. The electro-optic signal from a Cherenkov-phase-matched LiNbO₃ crystal is found to be comparable to that with a 4 mm-thick ZnTe crystal using a collinear phase matching. The Cherenkov phase matching technique can be achieved with any probe wavelength and hence has an advantage over the collinear phase matching method.

©2011 Optical Society of America

OCIS codes: (190.4360) Nonlinear optics, devices; (040.2235) Far infrared or terahertz.

References and links

1. D. H. Auston, "Subpicosecond electro-optic shock waves," *Appl. Phys. Lett.* **43**(8), 713–715 (1983).
 2. D. H. Auston, K. P. Cheung, J. A. Valdmanis, and D. A. Kleinman, "Cherenkov radiation from femtosecond optical pulses in electro-optic media," *Phys. Rev. Lett.* **53**(16), 1555–1558 (1984).
 3. M. Theuer, G. Torosyan, C. Rau, R. Beigang, K. Maki, C. Otani, and K. Kawase, "Efficient generation of Cherenkov-type terahertz radiation from a lithium niobate crystal with a silicon prism output coupler," *Appl. Phys. Lett.* **88**(7), 071122 (2006).
 4. S. B. Bodrov, M. I. Bakunov, and M. Hangyo, "Efficient Cherenkov emission of broadband terahertz radiation from an ultrashort laser pulse in a sandwich structure with nonlinear core," *J. Appl. Phys.* **104**(9), 093105 (2008).
 5. M. I. Bakunov and S. B. Bodrov, "Si–LiNbO₃–air–metal structure for concentrated terahertz emission from ultrashort laser pulses," *Appl. Phys. B* **98**(1), 1–4 (2010).
 6. S. B. Bodrov, A. N. Stepanov, M. I. Bakunov, B. V. Shishkin, I. E. Ilyakov, and R. A. Akhmedzhanov, "Highly efficient optical-to-terahertz conversion in a sandwich structure with LiNbO₃ core," *Opt. Express* **17**(3), 1871–1879 (2009), <http://www.opticsinfobase.org/abstract.cfm?uri=oe-17-3-1871>.
 7. K. Suizu, K. Koketsu, T. Shibuya, T. Tsutsui, T. Akiba, and K. Kawase, "Extremely frequency-widened terahertz wave generation using Cherenkov-type radiation," *Opt. Express* **17**(8), 6676–6681 (2009), <http://www.opticsinfobase.org/abstract.cfm?uri=oe-17-8-6676>.
 8. J. Hebling, K.-L. Yeh, M. C. Hoffmann, B. Bartal, and K. A. Nelson, "Generation of high-power terahertz pulses by tilted-pulse-front excitation and their application possibilities," *J. Opt. Soc. Am. B* **25**(7), B6–B19 (2008).
 9. P. Y. Han, M. Tani, F. Pan, and X.-C. Zhang, "Use of the organic crystal DAST for terahertz beam applications," *Opt. Lett.* **25**(9), 675–677 (2000).
 10. C. Winnewisser, P. U. Jepsen, M. Schall, V. Schyja, and H. Helm, "Electro-optic detection of THz radiation in LiTaO₃, LiNbO₃ and ZnTe," *Appl. Phys. Lett.* **70**(23), 3069–3071 (1997).
 11. L. Pálfalvi, J. Hebling, J. Kuhl, A. Peter, and K. Polgar, "Temperature dependence of the absorption and refraction of Mg-doped congruent and stoichiometric LiNbO₃ in the THz range," *J. Appl. Phys.* **97**(12), 123505 (2005).
 12. A. Nahata, A. S. Welington, and T. F. Heinz, "A wideband coherent terahertz spectroscopy system using optical rectification and electro-optic sampling," *Appl. Phys. Lett.* **69**(16), 2321–2323 (1996).
 13. D. F. Edwards, "Silicon (Si)," in *Handbook of Optical Constant of Solids*, E. D. Palik, ed. (Academic, 1985).
 14. R. W. Boyd, *Nonlinear Optics*, 3rd ed. (Academic, 2008), Chap. 11.
 15. J. Hebling, A. G. Stepanov, G. Almasi, B. Bartal, and J. Kuhl, "Tunable THz pulse generation by optical rectification of ultrashort laser pulses with tilted pulse fronts," *Appl. Phys. B* **78**(5), 593–599 (2004).
 16. G. Gallot, J. Zhang, R. W. McGowan, T.-I. Jeon, and D. Grischkowsky, "Measurements of the THz absorption and dispersion of ZnTe and their relevance to the electro-optic detection of THz radiation," *Appl. Phys. Lett.* **74**(23), 3450–3452 (1999).
-

1. Introduction

Cherenkov radiation mechanism is an established way to achieve phase matching between an ultrashort optical pulse and terahertz waves in an electro-optic (EO) material with large collinear velocity mismatch, such as LiNbO_3 (LN) [1,2]. To produce a Cherenkov cone of terahertz waves, the optical pulse should be focused to a size of the order of or smaller than the terahertz wavelength. Phase matching is achieved between the moving optical pulse and a plane terahertz wave propagating under a certain angle to the laser path.

In recent years, several improvements of this technique have been developed. In particular, to minimize strong terahertz absorption in LN, it was proposed to align the laser beam parallel with and near the lateral surface of the LN crystal and put, additionally, a Si-prism coupler on the surface to output the Cherenkov radiation from the crystal [3]. The most up-to-date generation scheme is based on using a thin LN layer attached to a Si-prism (or sandwiched between the prism and a substrate) [4,5]. The structure provides guiding of the pump laser pulse in the LN layer over a long distance, thus, preventing the diffraction distortion of the pulse and increasing the interaction length between the laser pulse and terahertz radiation. This results in a corresponding increase in terahertz emission. Using such a scheme with 8 mm long Si/LN/BK7 structure (with 30-50 μm thick LN layer), Ti:sapphire laser pulses of relatively low energy ($\sim 40 \mu\text{J}$) were converted into terahertz pulses of ~ 3 THz bandwidth with efficiency over 0.1% [6]. In the similar structure with a thinner (of 3.8 μm thickness) layer of MgO-doped LN sandwiched between a Si prism and undoped LN [7], a quasi-continuous terahertz radiation tunable in a wide frequency range 0.1-7.2 THz was generated with $10^{-5}\%$ efficiency via difference frequency generation process. Another promising way to achieve noncollinear phase matching between the laser pulse and terahertz waves in the materials with large velocity mismatch, similar to Cherenkov mechanism, is using tilted-pulse-front pumping (for recent review of this method, see, for example, Ref [8]).

In the present paper, we demonstrate experimentally that Cherenkov phase matching mechanism can also be used for efficient EO sampling of broadband terahertz pulses. Using a 0.5 mm-thick LN crystal attached to a Si prism we obtained an EO signal comparable to that obtained with a standard collinear sampling technique with ZnTe crystal.

2. Experimental

Figure 1 shows the schematic of the experimental setup. The experiment was performed with a Ti:sapphire laser (800 nm wavelength, 80 fs pulse duration, and 82 MHz repetition rate) as a light source. The laser pulses were split into pump and probe beams. The pump beam of 20 mW average power triggered a photoconductive bowtie antenna on a low-temperature-grown GaAs substrate, which was biased with a 10 V AC voltage. A hyper-hemispherical Si lens having a 13 mm diameter was used as an output coupler for generated terahertz radiation from the substrate to free space. The terahertz beam was collimated and focused onto a LN crystal through a right triangular high-resistivity-Si prism by a pair of parabolic mirrors (50 mm diameter and 76 mm focal length). The prism was cut at an angle of 41° (complementary to the Cherenkov angle 49°) [4], and the incident terahertz beam was aligned to the normal of the prism face. The 1% MgO-doped stoichiometric LN crystal, bonded to the prism bottom surface, was 0.5 mm-thick and had $10 \times 5 \text{ mm}^2$ lateral dimensions (exactly the same as that of the prism bottom surface). The *c*-axis of the LN crystal was oriented perpendicularly to the triangular face of the prism, and the polarization of the terahertz radiation was aligned parallel to the *c*-axis. The probe beam (~ 1 mW power on the photodetector) was focused onto the $10 \times$

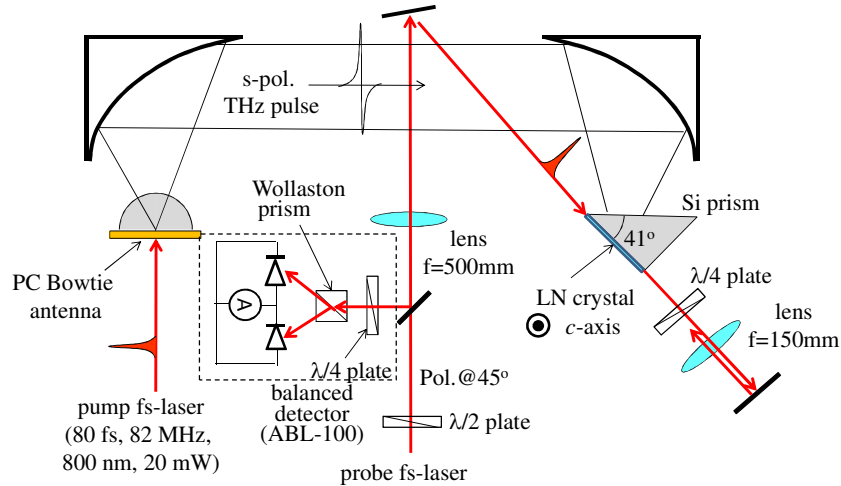


Fig. 1. Schematic of the experimental setup.

0.5 mm² facet of the LN crystal by a 500 mm-focus lens. The polarization of the beam was at 45° to the *c*-axis of the LN crystal. This polarization was electro-optically modulated by the terahertz field incident on the LN crystal. To compensate the parasitic transformation of the polarization due to birefringence of the LN crystal, the probe beam was sent through a quarter wave plate, reflected back by a mirror, and made to pass through the same quarter wave plate and the LN crystal again (a 150 mm focus lens was used for collimation) [9]. Changes in polarization were measured by a balanced photodetector (ABL-100, Zomega Corp.) with its output signal fed to a lock-in amplifier; having the AC bias voltage of the terahertz emitter as the reference signal. In the balanced photodetector, the probe beam was $\pi/2$ -phase biased with a quarter wave-plate and divided into the vertical and horizontal polarization components (I_A and I_B) with a Wollaston prism. Each component was detected by a pair of photodiodes (A and B). The difference signal from the two photodiodes ($\Delta V = V_A - V_B$) was fed to the lock-in amplifier. The EO signal is given as $\Delta I/I = (I_A - I_B)/(I_A + I_B) = \Delta V/(V_A + V_B)$.

3. Results and discussion

Figure 2(a) shows the terahertz waveforms measured with the Cherenkov-phase-matched LN crystal (LN/Si-prism structure) compared with a 4 mm-thick ZnTe crystal. The corresponding amplitude spectra are shown in Fig. 2(b). The integrated amplitude spectrum of the LN/Si-prism in Fig. 2(b) is larger than that of the 4 mm-thick ZnTe by a factor of 1.25. The terahertz waveform was also measured with a 1-mm thick ZnTe crystal (not shown). The two waveforms from the 1 mm- and 4 mm-thick ZnTe crystals were of identical shape and scaled in amplitude according to the crystal thickness, thus indicating that the coherence length in a ZnTe crystal exceeds 4 mm in the observed terahertz frequency range.

In the signal from the LN/Si-prism structure, the main cycle is followed by additional oscillatory features that can be attributed to multiple reflections of the terahertz waves from the boundaries of the LN crystal. Correspondingly, the spectrum for the LN/Si-prism structure exhibits some undulations [Fig. 2(b)]. This undesirable effect can be eliminated by using a thicker LN slab and adjusting the laser beam close to the LN-Si boundary. This will result in a longer time delay between the main terahertz pulse and the first echo pulse coming from the LN-air boundary, thereby making it more convenient to filter out the echo signals.

In the standard collinear EO detection scheme, the signal from a LN crystal is much weaker than that of a ZnTe crystal due to a large velocity mismatch between the probe optical pulse and terahertz waves [10]. The terahertz phase refractive index n_{THz} of LN is more than

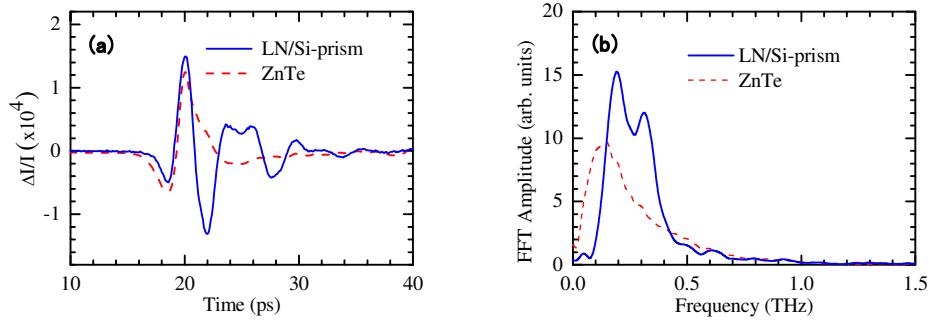


Fig. 2. (a) Terahertz waveforms measured with the LN/Si-prism structure (solid) and a 4 mm-thick ZnTe crystal (dashed). (b) Corresponding Fourier transform amplitude spectra.

two times larger than its optical group refractive index n_g ($n_{\text{THz}} = 4.75$ at 0.5 THz and $n_g = 2.25$ at 800 nm-wavelength) [8,11]. Therefore, the coherence length $L_c(v) = c(2v|n_{\text{THz}}(v) - n_g|)^{-1}$ [12] is as small as $\sim 120 \mu\text{m}$ for $v = 0.5$ THz and 800-nm probe. Using the LN/Si-prism structure allows for the compensation of the large velocity mismatch between the optical probe and terahertz pulses. Since the conventional coherence length is inadequate for characterization of the noncollinear terahertz-optical interaction in the LN/Si-prism structure, a new expression for the coherence length is introduced,

$$L_c(v) = \frac{c}{2v|n_{\text{Si}} \cos \beta - n_g|}, \quad (1)$$

where n_{Si} is the terahertz phase refractive index of the Si prism and β the crossing angle of the terahertz and optical probe beams. According to Eq. (1), the perfect phase matching ($L_c \rightarrow \infty$) is achieved at $\cos \beta = n_g/n_{\text{Si}}$. In the physically reversed situation of Cherenkov emission from the laser pulse to the Si prism [3], the angle $\beta_{\text{Ch}} = \arcsin(n_g/n_{\text{Si}})$ is the Cherenkov angle. Using $n_{\text{Si}} = 3.418$ [13], we obtain the Cherenkov angle $\beta_{\text{Ch}} = 48.8^\circ$, and, therefore, the optimal apex angle of the prism is $90^\circ - 48.8^\circ = 41.2^\circ$. Figure 3 shows the dependence $L_c(v)$, calculated using Eq. (1), for different β . According to Fig. 3, even for an essential detuning of β from the optimal angle 48.8° the LN/Si-prism structure provides orders of magnitude larger coherence

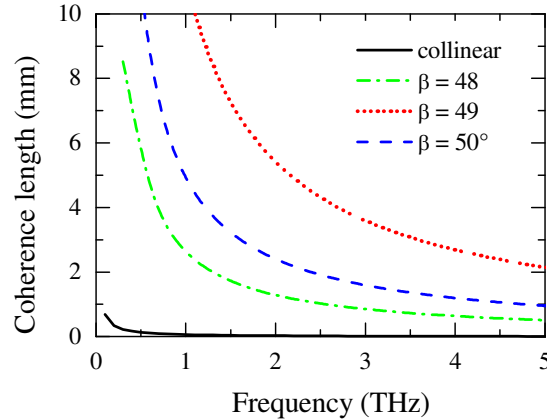


Fig. 3. Coherence length L_c defined by Eq. (1) as a function of the terahertz frequency v for $\beta = 48^\circ, 49^\circ$, and 50° at 800 nm wavelength.

length L_c as compared to the standard collinear scheme in a LN crystal.

When a perfect phase matching is achieved, the differential phase retardation $\delta\varphi(\tau)$ experienced by the probe beam in the LN crystal of the LN/Si-prism structure due to the terahertz field $E_{\text{THz}}(\tau)$ over a distance L can be presented as [10]

$$\delta\varphi(\tau) = \frac{\omega_{\text{opt}}}{2c} (n_e^3 r_{33} - n_o^3 r_{13}) E_{\text{THz}}(\tau) L, \quad (2)$$

where τ is the time delay between the probe and terahertz pulses; n_o and n_e are the refractive indices of the probe's ordinary and extraordinary rays, respectively; r_{13} and r_{33} are the EO coefficients, and ω_{opt} is the optical probe angular frequency. According to Eq. (2), we define the figure of merit of the Si-prism coupled LN crystal for EO sampling as

$$\text{FOM}_{\text{LN}} = \frac{1}{2} (n_e^3 r_{33} - n_o^3 r_{13}). \quad (3)$$

Substituting into Eq. (3) $n_o = 2.255$ and $n_e = 2.176$ at 800 nm, $r_{13} = 9.6$ pm/V and $r_{33} = 30.9$ pm/V [14], we obtain $\text{FOM}_{\text{LN}} \approx 104$ pm/V.

For the collinear EO sampling in a <110>-cut ZnTe crystal of thickness L , the differential phase retardation is given by [10]

$$\delta\varphi(\tau) = \frac{\omega_{\text{opt}}}{c} n_{\text{opt}}^3 r_{41} E_{\text{THz}}(\tau) L, \quad (4)$$

where n_{opt} is the optical refractive index and r_{41} is the EO coefficient of ZnTe. The corresponding figure of merit

$$\text{FOM}_{\text{ZnTe}} = n_{\text{opt}}^3 r_{41} \quad (5)$$

is estimated as $\text{FOM}_{\text{ZnTe}} \approx 96$ pm/V by using $r_{41} = 4.04$ pm/V and $n_{\text{opt}} = 2.87$ at 800 nm [15]. Comparing FOM_{LN} and FOM_{ZnTe} ($\text{FOM}_{\text{LN}}/\text{FOM}_{\text{ZnTe}} \sim 1$), one can conclude that EO sampling efficiency is expected to be similar with the LN/Si-prism structure and a ZnTe crystal for the same interaction length L .

In our experiment, the interaction length for the Cherenkov-phase-matched LN crystal was determined by the focal spot size of the terahertz beam in the LN crystal rather than the crystal length. The lateral focal spot size of the terahertz beam in the LN crystal can be estimated as

$$L = 1.22 \frac{\lambda_{\text{THz}}}{n_{\text{Si}}} \frac{f}{b \cos \beta} \sim 4 \text{ mm}, \quad (6)$$

where we used the focal length of the parabolic mirror $f = 76$ mm, the effective terahertz beam radius $b = 15$ mm, $\beta = 49^\circ$, and the terahertz wavelength $\lambda_{\text{THz}} \sim 1.5$ mm corresponding to the central frequency $\nu \sim 0.2$ THz of the spectrum in Fig. 2(b). For a ZnTe crystal, the interaction length can be limited, in principle, either by the crystal thickness or by the coherence length L_c . For the 800 nm-wavelength light and terahertz frequencies less than 0.5 THz [Fig. 2(b)], the coherence length L_c exceeds 4 mm [12], as it was confirmed by our measurements using ZnTe crystals of different thicknesses. Therefore, the interaction length for the ZnTe crystal, used in the experiment, was limited by the crystal thickness $L = 4$ mm. Thus, the interaction lengths for the Si-prism-coupled LN crystal and ZnTe crystal were practically the same.

It should be noted, however, that the finite probe beam diameter limits the detection bandwidth in the Cherenkov-phase matched EO sampling because the phase of the terahertz wave is not constant over the probe beam diameter. This prevents the high-frequency components with half-wavelengths shorter than the probe beam diameter from being detected. In the generation counterpart of our detection scheme [3], this effect corresponds to destructive interference of the terahertz waves emitted from the closest and farthest points of

the laser beam from the LN-Si boundary. This can be circumvented by enclosing the laser beam in a thin slab waveguide similar, for example, to the Si-prism/PET/MgO-doped LN/undoped LN structure used in Ref [7]. for terahertz generation, see Sec. I. Since terahertz waves with frequencies in the range as wide as 0.1-7.2 THz were successfully generated in such a structure [7], the detection counterpart of the structure should, evidently, reliably operate in the same range. Essentially, due to a small difference in the terahertz refractive indices of the MgO-doped LN layer and undoped LN substrate, multiple reflection effect should be negligible for a sufficiently thick substrate.

The influence of the absorption and reflection losses is finally considered. The terahertz absorption on the half-thickness of the LN crystal (0.25 mm) is less than 3% for $\nu < 0.5$ terahertz [11], while the absorption on the half-thickness of the ZnTe crystal (2 mm) is ~5% [15]. The reduction of the terahertz pulse amplitude due to reflection loss in the LN/Si-prism structure is 28% larger than that for the ZnTe crystal (refractive indices of 4.75 for LN [11], 3.15 for ZnTe [16], and 3.41 for Si [13] at $\nu = 0.2$ THz were used for the estimate). As a result, the overall efficiency of the Cherenkov-phased-matched LN should be 26% lower than that of ZnTe in the perfect phase-matching condition. Thus, there is a discrepancy between the theoretical prediction above and nearly equal efficiencies observed in the experiment (the amplitude of the detected signal appeared even slightly larger for the LN/Si-prism than for ZnTe EO sampling, Fig. 2). The possible reasons for the discrepancy are crystal imperfections in ZnTe and misalignment in the optical or terahertz beams, the latter is inevitable to some extent even with very careful experimentation. Although the discrepancy is not well explained at present, our result attests the validity of the Cherenkov phase matching scheme in EO sampling detection of terahertz pulse waves.

4. Conclusion

To conclude, we have demonstrated efficient EO sampling of broadband terahertz radiation in the Cherenkov phase matching scheme with a Si-prism-coupled LN crystal. The EO sampling efficiency is comparable to that of a 4 mm-thick ZnTe crystal in a standard collinear phase matching scheme. The experimental results are in good agreement with estimates derived from theory. Our results put forward the Cherenkov phase matching mechanism as a useful tool not only for generation but also for detection of broadband terahertz radiation. An essential advantage of the Cherenkov phase matched EO sampling technique is its feasibility even at different laser wavelengths. In particular, this technique has the advantage to be conveniently implemented using a compact 1.55- μm femtosecond fiber laser.

Acknowledgments

M. I. Bakunov acknowledges support from RFBR and the Federal Targeted Program "Scientific and scientific-pedagogical personnel of the innovative Russia."