Electro-Optic Sampling of Terahertz Pulses Using $BaTiO_3$ in Non-Collinear Cherenkov Phase-Matching Scheme

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***Abstract*— In this paper we report electro-optic (EO) sampling of THz pulses using ferroelectric crystal in the non-collinear Cherenkov phase-matching scheme, where an effective velocity matching is achieved in an EO crystal with a large refractive index in the THz frequency region. We demonstrate efficient THz EO sampling using $LiNbO_3$ and $BaTiO_3$ crystals in the Cherenkov- phase-matching scheme. It is shown that the efficiency of EO sampling with BaTiO3 is smaller than that with $LiNbO_3$, even though the EO coefficient (r_{33}) of $BaTiO_3$ is three times higher than that of $LiNbO_3$. The reason of the poor performance of $BaTiO_3$ is attributed to the strong absorption in the THz frequency region.**

I. INTRODUCTION

SOME ferroelectric crystals exhibit large electro-optic coefficients. For example, $r_{33} = 31$ [pm/V] for $LiNbO_3$, and r_{33} =97 and r_{42} =1640 [pm/V] for $BaTiO_3$, while r_{41} =4.3 [pm/V] for ZnTe, which is the most popularly used non-ferroelectric crystal for THz EO sampling. However, such large EO coefficients have not been exploited for EO sampling of THz radiation so far because of the large velocity mismatch between the optical probe pulse and THz radiation, which seriously degrades the EO sampling efficiency for THz radiation. Recently, we succeeded efficient detections of THz radiation by using non-collinear Cherenkov phase-matching technique and Si-prism-coupled $LiNbO_3$ crystal [1, 2]. The non-collinear Cherenkov phase-matching makes it possible to use nonlinear optical media with a large velocity mismatch, such as $LiNbO_3$ in THz EO sampling. In this paper we report a non-collinear electro-optic (EO) sampling of THz pulsed radiation using $LiNbO_3$ and $BaTiO_3$ and compare the efficiency and detection bandwidth with these ferroelectric crystals.

II. EXPERIMENTAL

The optical configuration of Cherenkov phase matching for EO sampling detection of THz radiation is illustrated in Fig. 1. In this case, the phase matching is achieved between an optical and THz pulse propagating non-collinearly at a Cherenkov phase-matching angle θ_C, satisfying the following equation:

$$\cos\theta_C = \frac{n_g^{EO}}{n_{THz}^{EO}} \qquad (1)$$

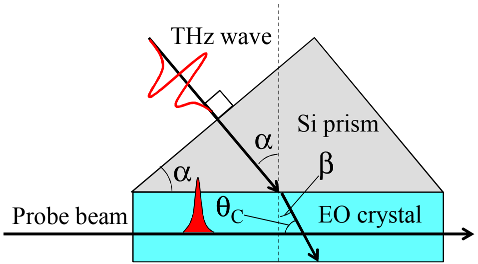

Fig. 1. Optical configuration for Cherenkov phase-matched EOS of THz waves.

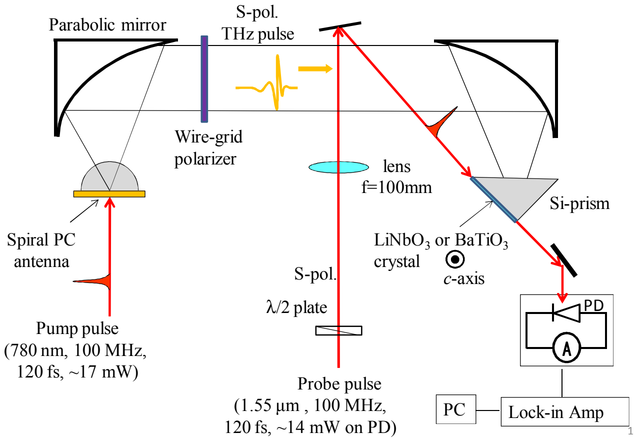

Fig. 2. The experimental setup for the Cherenkov-phase-matched EO sampling using $LiNbO_3$ and $BaTiO_3$.

Here, n_g^{EO} is the group index of the EO crystal at the sampling optical wavelength and n_{THz}^{EO} is the refractive index of the EO crystal in the THz frequency region. An advantage of the non-collinear Cherenkov phase matching is that we can find a appropriate Cherenkov phase matching angle, θ_C, for any electro-optic crystal at a given optical sampling wavelength. When the EO crystal has a much larger refractive index in THz frequency region compared to that in optical region, a coupling prism is used as illustrated in Fig. 1. Moreover, using a low-loss coupling prism (usually made with Si) can also reduce the influence of absorption in the EO crystal. From Snell's law, the incident angle α of THz wave with respect to the prism- EO crystal interface is given as follows:

$$n_{THz}^{Si}\sin\alpha = n_{THz}^{EO}\sin\beta = n_{THz}^{EO}\cos\theta_C\ . \qquad (2)$$

By using Eq. (2), Eq. (1) reduces to the following equation for the apex angle of the coupling prism (α) at the Cherenkov phase-matching condition given by the ratio of the group index of the EO crystal at the sampling optical wavelength n_g^{EO}, and the refractive index of Si, n_{THz}^{Si}, in the THz frequency region:

$$\sin\alpha = \frac{n_g^{EO}}{n_{THz}^{Si}} \quad . \tag{3}$$

Based on Eq.(3), we have prepared a Si prism with an apex angle of $\alpha^{LN} = 41^\circ$ as the coupling optics for $LiNbO_3$ crystal.

As for $BaTiO_3$, the apex angle of Si prism is calculated to be $\alpha^{BTO} = 42^\circ$, which is almost the same with that for $LiNbO_3$. Therefore, we used the same Si prism also for EO sampling with $BaTiO_3$ crystal.

The experimental setup for the Cherenkov-phase-matched EO sampling using $LiNbO_3$ and $BaTiO_3$ is shown in Fig. 2. A spiral photoconductive antenna (PCA) was pumped with 780-nm fs-laser pulses (the SHG output from a dual-wavelengths fs-fiber-laser, C-FIBER-780-SP-3, Menlo Systems) to generated THz radiation, which was prepared in a vertically polarized state by a wire-grid polarizer. The probe laser pulses at 1.55 μm (the fundamental output from the same fs-fiber-laser) was also vertically polarized along with the *c*-axis of the EO crystals. The probe laser was detected by an InGaAs photo-diode (PD), and the signal modulation in the PD synchronized with the bias modulation for the PCA was amplified by a lock-in amplifier. The THz waveforms were measured by scanning the time-delay between the pump and probe optical pulses.

III. RESULTS AND DISCUSSION

Fig. 3(a) shows the THz waveforms detected with $LiNbO_3$ and $BaTiO_3$ in the Cherenkov phase-matching scheme for the same THz radiation source in the same experimental condition. Fig. 3(b) shows corresponding amplitude spectra. We can see that the EO sampling signal with $BaTiO_3$ is about a half of that with $LiNbO_3$ at the peak of the waveform even though the EO coefficient (r_{33}) of $BaTiO_3$ (r_{33} = 97 pm/V) is three times higher than that of $LiNbO_3$ (r_{33} = 31 pm/V). The spectral bandwidth with $BaTiO_3$ is also much reduced compared with that of $LiNbO_3$. The poor performance of $BaTiO_3$ as the THz EO sampling detector is explained by its strong absorption in THz frequency region compared to $LiNbO_3$: the absorption coefficient for extra-ordinary ray (polarization parallel to the *c*-axis) of $BaTiO_3$ at 0.9 THz is 47 cm^{-1}, while that of $LiNbO_3$ is 11 cm^{-1}, respectively [3].

In the past, EO sampling of THz radiation by using $BaTiO_3$ in the collinear scheme was reported by Pradarutti *et al* [4]. They used InAs as the THz surface emitter and 530-nm laser pulses as the probe. An EO signal $\Delta I/I \sim 0.15 \times 10^{-5}$ at the peak of the THz waveform and a SNR (or a peak dynamic range) of $2.5\text{x}10^2$ was obtained. Although the direct comparison of our result with theirs is not possible due to different experimental conditions (emitter, probe wavelength, etc) it is noteworthy that relatively high EO signal and SNR can be achieved with $BaTiO_3$ by using the Cherenkov-phase-matching even at a probe wavelength of 1.55 μm, where phase-matching condition is poor in the collinear geometry: the coherence length with 1.55 μm is 0.09 mm while 0.105 mm for 530 nm probe wavelength at 1 THz.

IV. SUMMARY

THz EO sampling with $BaTiO_3$ in non-collinear Cherenkov phase-matching scheme seems to be promising because of its large EO coefficient if the influence of its strong absorption of THz waves could be reduced, such as by using an optical waveguide structure in $BaTiO_3$ crystal.

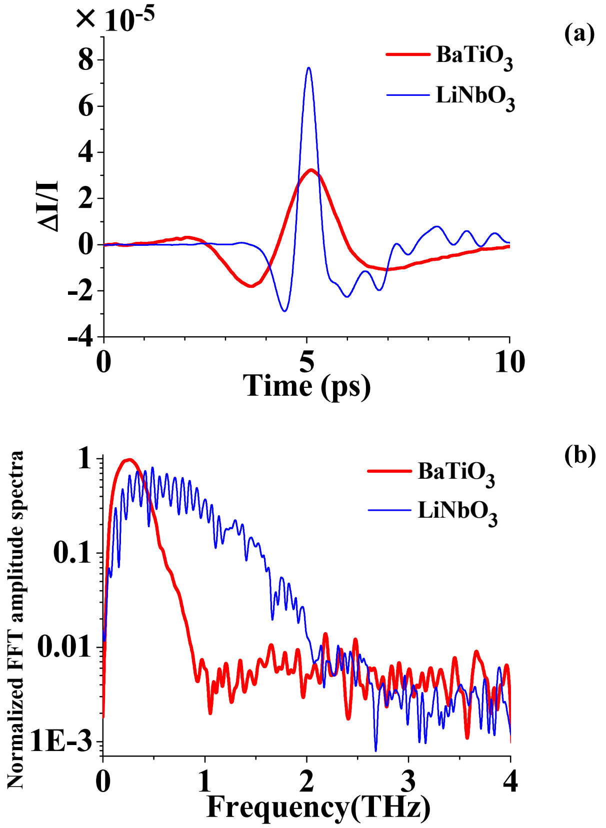

Fig. 3. (a) THz waveforms detected with Cherenkov-phase-matched EO sampling using $LiNbO_3$ and $BaTiO_3$. (b) Corresponding FFT amplitude spectra of the waveforms shown in (a).

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