Non-collinear electro-optic sampling techniques for efficient detection of THz radiation

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Terahertz time-domain spectroscopy (THz-TDS) has been proved to be a useful tool for material evaluation and analysis in scientific research. It is also expected to be widely used in industrial applications, such as security and quality inspection due to non-invasive and see-through characteristics of THz waves. One of the key technologies for THz-TDS is the electro-optic (EO) sampling detection of pulsed THz radiation. Efficiency of EO sampling has a crucial importance in applications of THz-TDS. In this paper EO sampling techniques based on non-collinear Cherenkov phase-matching for efficient detection of THz pulsed radiation are reviewed. The non-ellipsometric "heterodyne EO sampling," which requires no polarization optics, is proposed and demonstrated. It is also shown that metallic parallel plate waveguide structures can enhance EO sampling sensitivity significantly.

Figure 1 shows THz waveforms detected by Cherenkov phase-matched EO sampling [1] using $LiNbO_3$ (LN) crystal coupled to a Si prism (Si-prism/LN) for optical sampling wavelengths with 780-nm and 1.55-µm. As demonstrated in Fig. 1 the Cherenkov phase-matched EO sampling can be used with any optical sampling wavelengths. For comparison, the THz waveform detected with a standard collinear EO sampling scheme using a 4-mm thick ZnTe crystal is also shown. The results indicate that by using a Si-prism/LN, we can obtain an EO signal comparable in magnitude to that obtained by standard, ZnTe-based collinear EO sampling.

Figure 2 shows a comparison of the THz waveforms detected using the "heterodyne EO sampling" [2] and ordinary EO sampling by using the same Si-prism/LN device. In the heterodyne EO sampling, the modulation of the sampling optical beam intensity is achieved through the interference of the sampling optical wave and the sum frequency generation (SFG) or difference frequency generation (DFG) arising from its interaction with the incident THz radiation. Thus, the detection optics needed to implement heterodyne EO sampling is significantly simpler compared with ordinary EO sampling.

Recently, we found that frequency resolved detection of THz radiation by heterodyne EO sampling, using the phase-matching angle dependent property in the DFG or SFG process, is possible. We also found that EO sampling efficiency is much enhanced by using metallic waveguide structures as the focusing optics for THz radiation. Figure 3 shows THz waveforms detected by heterodyne EO sampling, in which a tapered metallic parallel plate (V-groove) waveguide was used to focus THz waves to the EO crystal. The EO signal was enhanced by about 20 times by using a metallic waveguide structure and a thin (40 µm-thick) LN crystal.

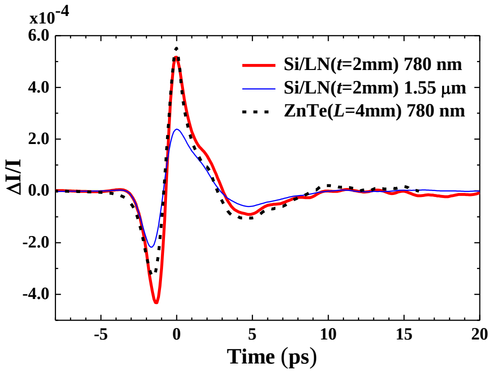

Fig. 1. THz waveform detected with Si-prism/LN in Cherenkov phase-matching scheme at 780 nm and 1.55 µm. For comparison, THz waveform detected with a 4-mm ZnTe is also shown.

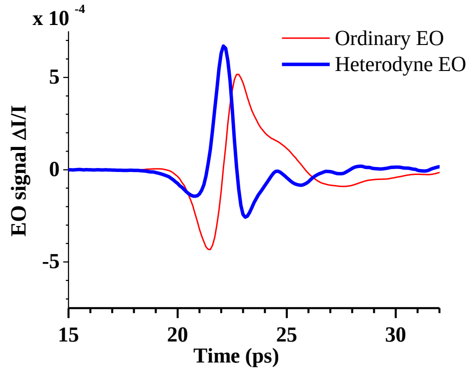

Fig. 2. THz waveforms detected with heterodyne and ordinary EO sampling.

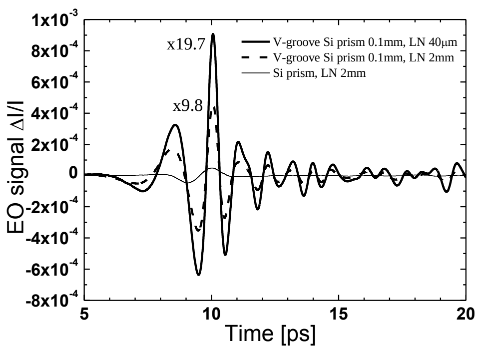

Fig. 3. THz waveforms with and without the parallel plate waveguide.

[1] M. Tani, *et al*, Opt. Express, **19**, (2011) 19901

[2] M. Tani, *et al*, Opt. Express, **21** (2013) 9277