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Measuring effective electro-optic coefficient at 1040 nm by spectral intensity modulation with THz time-domain spectroscopy

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ABSTRACT

We report a single method for measuring the effective electro-optics (EO) coefficient only by spectral intensity modulation with a terahertz time-domain spectroscopy (THz-TDS) device. Compared with conventional methods, the measuring device based on THz-TDS by probing the spectral intensity modulation is simple, rapid, and highly sensitive. It does not require special preparation process, electrode contact or applying high voltage on the sensor samples. The EO coefficients of four kinds of materials, namely, ZnTe and GaP crystals, DAST wafer and GaSe film, are measured at 1040 nm. The results showed good agreement with literature data by the conventional methods.

1. Introduction

A knowledge of the electro-optic (EO) coefficient of nonlinear EO materials is key to the design and modelling of optical components in device applications such as high speed optical switches and EO deflectors. A variety of measuring methods have been reported for the EO coefficient either in the form of a bulk crystal [1] or as a film [2] or layers on a substrate [3], such as the ellipsometric method [4], the interferometric method [5], the waveguide method [6], and the reflection method [7].

In all the above methods, an external electric field has to be applied onto the samples so that the process for preparing the sample and making the electrode connection must be optimized carefully. However, this will not only increase the test complexity, but also inevitably introduce some additional effects onto the samples such as air gaps [8], strain [9] and thermo-optic effect [10]. Therefore, the determination of the EO coefficient is generally achieved with a poor accuracy. In addition, different setups of the light-to-field configuration have to be implemented in general for bulk materials and thin film samples [1]. Therefore, an appropriate technique with simple, rapid, and highly sensitivity for measuring the EO coefficients of the multiple forms of a sample is very essential.

Terahertz time-domain spectroscopy (THz-TDS) [11], which allows the reliable generation and detection of broadband THz radiation, has become a mature device to be applied to THz spatial resolution and THz imaging [12]. Free-space EO sampling [13] (EOS) is one of the most common methods to detect the amplitude and spectrum of the THz electric field used in THz-TDS. The EOS is based on the modulation of the birefringence of the sensor crystal by the incident THz wave due to the Pockels effect. The polarization ellipticity of the probe laser pluses will be modulated when it scans the EO pulse and this is induced by the incident THz wave within the sensor crystal. The EOS will exhibit an exact cross-correlation of the incident terahertz and optical pulses if the time duration of the probe pulse is significantly shorter than the temporal features of the EO pulse, which can yield information of both the amplitude and phase of the incident THz wave. Based on the principle of electro-optic detection of THz radiation, we can also measure the effective EO coefficient of the sensor crystal with the determined field amplitude from the THz emitter. For different materials, the EO coefficients are varied with wavelength [20]. Therefore, the EO coefficients should be measured with different wavelength laser.

In this paper, we report a single method for measuring the effective EO coefficient only by spectral intensity modulation with a THz-TDS device where the field amplitude from the THz emitter has been determined. Compared with the conventional methods, the measuring device based on a THz-EOS system by probing the spectral intensity modulation is simple, rapid, and highly sensitive. It does not require special preparation process, electrode contact or applying high voltage on the sensor samples. Samples of four kinds of materials are selected, including ZnTe and GaP crystals, DAST wafer and GaSe film. The EO

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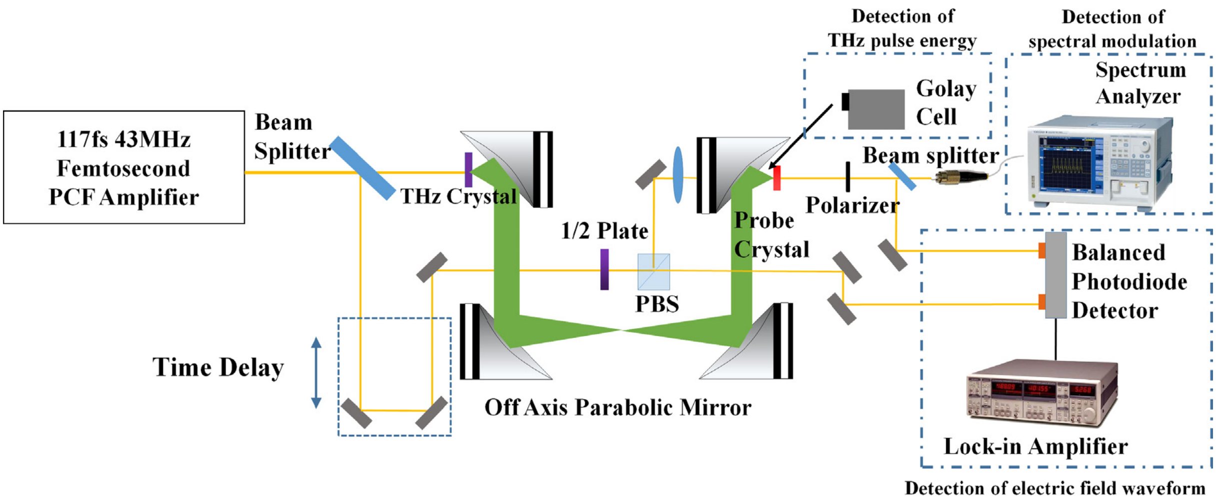

Fig.1. Schematic of the experimental setup.

coefficients of these samples at 1040 nm are measured and the results showed good agreement with the literature data.

2. Experimental setup

In our experiment, a THz-TDS system, shown in Fig. 1, uses a femtosecond Yb- doped photonic crystal fiber amplifier as the pump source [21], delivering 28 W, 115 fs at a central wavelength of 1040 nm and a repetition rate of 43 MHz. A conventional configuration for free-space THz generation and detection is employed. The THz wave emitter is a 3 mm ⟨1 1 0⟩ -cut GaP crystal [22]. The output power and the waveform of the emitted THz wave are characterized by a Golay cell (GC-1P, TYDEX) and the standard THz-TDS, respectively. The generated THz radiation is collected and focused onto the samples, instead of the detector, with four 90° off-axis parabolic mirrors for EOS to characterize the modulated amplitude and phase of the THz wave. In addition to the conventional configuration, we use an alternative approach to measure the spectral intensity modulation of the probe pulse by the THz electric field. To measure the spectral intensity change caused by THz wave, part of the probe beam is imported into a spectrometer. A polarizer is also inserted between the sample (detection crystal) and the spectrometer (YOKOGAWA AQ6370B) as a spectral intensity analyzer. In our experiment, both the incident THz wave and the probe beam is kept constant for all test samples.

3. Basic theory

In a THz-TDS system, the EOS is a well-known technique to measure the amplitude profile of the THz wave by an EO crystal detector whose crystal axis orientation and the relevant EO coefficient have been determined. When the THz signal enters the detection crystal, the index ellipsoid of the detector is modulated due to the EO effect, resulting in phase retardation and polarization rotation of the probe light. Such small changes in transmission can be measured by the balanced detection technique [14]. On the other hand, we can also estimate the effective EO coefficient of the detection crystal (sample) if the electric field intensity of the incident THz wave has been determined. According to the above backgrounds, the value of the peak electric field of incident THz wave (E_{THz}) is obtained by [15]:

$$\mathrm{E}_{THz} = \sqrt{\frac{P_{THz}}{2c\varepsilon_0 A_{THz}}} \tag{1}$$

where P_{THz} is the THz pulse peak power, A_{THz} is the THz pulse spot area at the surface of the Golay cell, c is the speed of light and ε_0 is the electric permittivity of free space. The THz peak field used in our experiments is ~0.03 MV/cm. After the E_{THz} is determined, the detector will be replaced with the test samples. On the other hand, the phase retardation due to the THz field E_{THz} is proportional to $n_{eff}^3\gamma_{ij}$, where n_{eff} and γ_{ij} denote the effective refractive index and the corresponding EO coefficient related to the crystal axis orientation (components of the EO tensor) at the probe laser wavelength, respectively [16]. According to Eq. (2), the EO coefficient of the test samples can be calculated [15]:

$$\gamma_{ij} = \mathrm{C}_{(\gamma_{ij})}\frac{\lambda_0 \sin(\Delta I/I)}{n_{eff}^3 E_{THz}\mathrm{L}} \tag{2}$$

where $C_{(\gamma_{ij})}$ is a coefficient appropriate for the crystal axis orientation, λ_0 is the probe laser wavelength, and L is the sample thickness. The maximum modulation signal is $\frac{\Delta I}{I} = \frac{I_1 - I_2}{I_1 + I_2}$ [17], with signals I_1 and I_2 measured by the photodiode pair of the balanced detection at the peak THz field E_{THz}. In our experiment, $\Delta I/I$ is treated as the maximum spectral intensity modulation by a spectrometer instead of the EOS method. It is evident that probing the spectral intensity modulation is simple, rapid, and highly sensitive. We choose to average over multiple peak points of the spectral intensity modulation to reduce the measurement error.

4. Experimental results and discussion

In our experiment, four kinds of EO materials were prepared, including ZnTe and GaP crystals, DAST wafer and GaSe film. Among these samples, ZnTe and GaP are ⟨1 1 0⟩ cut with a thickness of 0.5 mm and 0.05 mm respectively, so that $n_{eff} = n_o$, $\gamma_{ij} = \gamma_{41}$ and $C_{(\gamma_{ij})} = \frac{1}{2\pi}$ for ZnTe and GaP samples in Eq. (2). Because the crystal axis orientations of the DAST wafer and the GaSe film are unknown, we selected the maximum modulation signal corresponding to the incidence angle as the initial (effective) crystal axis orientation by rotating the samples in the wafer plane. The sample thicknesses of the DAST wafer and the GaSe film are 0.25 mm and 0.1 mm, respectively. The maximum modulation spectral signals ΔI/I with and without the incident THz wave for the four samples are shown in Fig. 2.

The spectral intensities are increased after the THz wave is incident onto the samples. Multiple peak points of the spectral intensity modulation are chosen for averaging to decrease the measurement error. By measuring the modulation and using Eq. (2), the EO coefficients at 1040 nm could be obtained and then compared with the literature data. The results are summarized and listed in Table 1.

Since the EO coefficients at 1040 nm are seldom reported in the literature, we have to compare our experimental results with the corresponding literature data at the nearest wavelength of 1040 nm or by

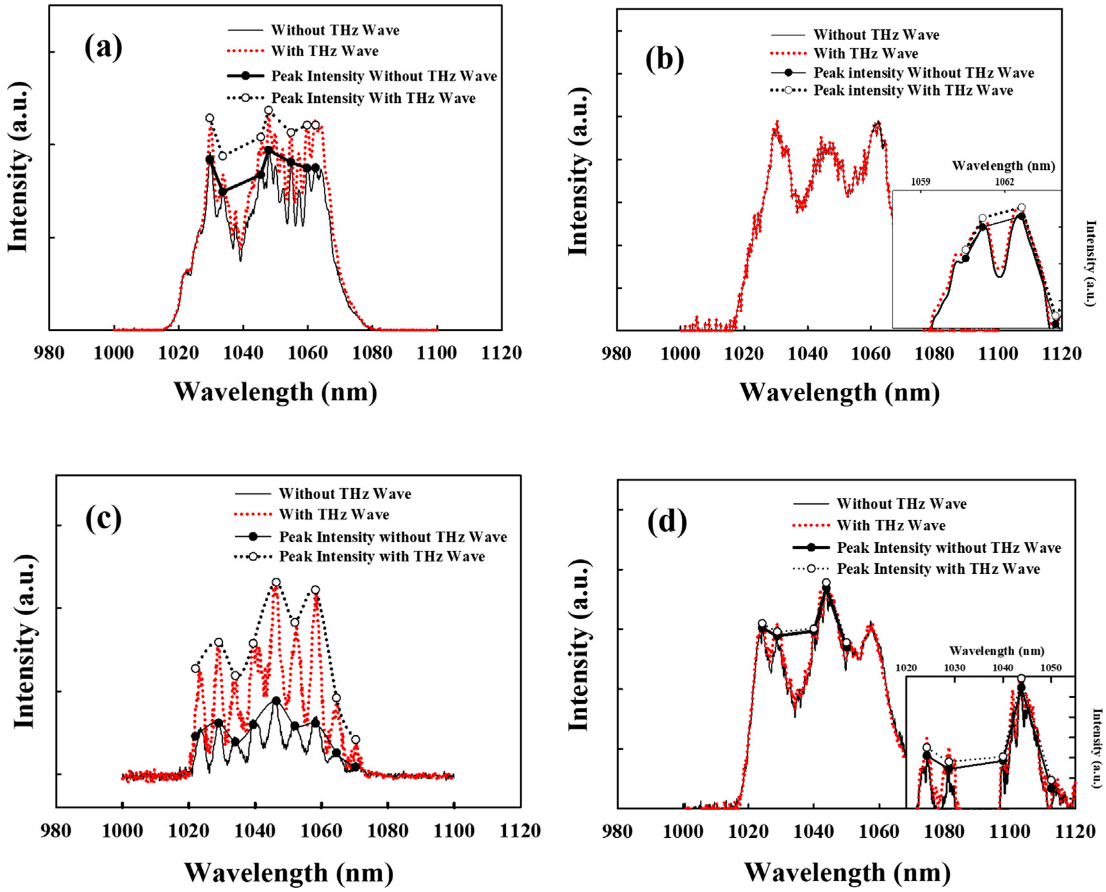

Fig. 2. The maximum modulation spectral signals with and without THz for the four samples, (a) ZnTe with a thickness of 0.5 mm, (b) GaP with 0.05 mm thickness, (c) DAST with 0.25 mm thickness, and (d) GaSe with 0.1 mm thickness. Insets, the corresponding scale up.

fitting the dispersion of the EO coefficients [20,24]. It has shown that our results using the maximum spectral modulation for ZnTe, GaP, DAST and GaSe at 1040 nm are in good agreement with the results determined by other measurement methods within the limits of experimental errors and determined center wavelength. Moreover, thanks to the comparison with the literature data, the unknown the corresponding EO coefficient related to the components of the EO tensor of the DAST wafer and the GaSe film can be determined to be γ_{11} and γ_{22}, respectively.

In order to verify that $\Delta I/I$ could be treated as the maximum spectral intensity modulation instead of the maximum phase retardation by the EOS method, we also performed a control experiment for the same samples of ZnTe and GaP crystals in the conventional way. In the EOS experiment, the THz wave induces a phase difference $\Delta\Phi$, being proportional to the THz field E_{THz}, which is measured as a differential voltage relative to the unperturbed signal in a standard balanced detection scheme. The measured phase retardations modulated by the THz field E_{THz} are shown in Fig. 3 for the samples of ZnTe and GaP crystals with a thickness of 0.5 mm and 0.05 mm respectively. The maximum phase retardation ($\Delta\Phi$) is 247.2 mV/rad for ZnTe crystal and 70.02 mV/rad for GaP crystal. The EO coefficients can be calculated according to [25]:

$$\gamma_{41} = \frac{c\Delta\Phi}{\omega n_o^3 E_{THz} L} \tag{3}$$

where ω is the center frequency of the pump laser, c refers to the speed of light in vacuum, and n_o is the refractive index of the ordinary beam of the sample crystal. The EO coefficient values of γ_{41} are calculated from Eq. (3) as 3.88 pm/V for the 0.5 mm ZnTe crystal and 1.009 pm/V for the 0.05 mm GaP crystal, respectively. By comparison with the results of the previous experiments, the data are consistent.

5. Conclusion

We have reported the measurements of effective EO coefficients at 1040 nm by spectral intensity modulation with a THz-TDS device. The effective EO coefficients of four kinds of materials, namely, ZnTe and GaP crystals, DAST wafer and GaSe film, are measured. The results, $\gamma_{41} = 3.93 \times 10^{-12}$ m/V (ZnTe), $\gamma_{41} = 0.94 \times 10^{-12}$ m/V (GaP), $\gamma_{11} = 65.71 \times 10^{-12}$ m/V (DAST) and $\gamma_{22} = 1.3 \times 10^{-12}$ m/V (GaSe), are in good agreement with values determined by conventional methods. Compared with the conventional methods, the measuring

Table 1
Measured results of EO coefficients for four samples prepared at 1040 nm.

Sample	Thickness L (mm)	$\Delta I/I$	γ_{ij} (this work)	γ_{ij} (literature data)
ZnTe crystal ⟨1 1 0⟩	0.5	0.26	$\gamma_{41} = 3.93 \times 10^{-12}$ m/V	$\gamma_{41} = 4.19 \times 10^{-12}$ m/V(@1064 nm) [18]
GaP crystal ⟨1 1 0⟩	0.05	0.0104	$\gamma_{41} = 0.94 \times 10^{-12}$ m/V	$\gamma_{41} = 1.1 \times 10^{-12}$ m/V (@1153 nm) [19]
DAST wafer	0.25	2.1737	$\gamma_{eff} = 65.71 \times 10^{-12}$ m/V	$\gamma_{11} \approx 66 \times 10^{-12}$ m/V (@1042 nm) [20]
GaSe film	0.1	0.0172	$\gamma_{eff} = 1.3 \times 10^{-12}$ m/V	$\gamma_{22} \approx 1.1 \times 10^{-12}$ m/V (@1064 nm) [23]

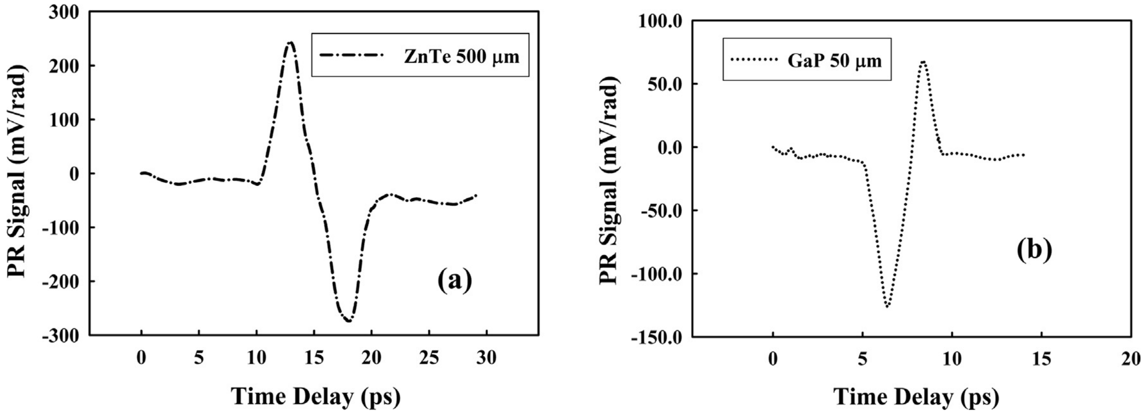

Fig. 3. Phase retardation signals with samples (a) ZnTe with 0.5 mm thickness and (b) GaP with 0.05 mm thickness.

device by a THz-EOS system by probing the spectral intensity modulation is simple, rapid, and highly sensitive. It does not require special preparation process, electrode contact or applying high voltage on the sensor samples. In general, the THz-based EOS system could serve as a promising method for effective EO coefficient measurement of any kind of samples.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

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