Analysis of the Probing Process in Electro-Optic Sampling System Based on EO Effect

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Abstract

The probing process and basic theory of detection in EO sampling system are discussed. Two different types of EO crystal are analyzed and experiment setups are designed for them, respectively. This analysis provides preconditions to the measurement of ultrafast electromagnetic signal such as microwave, high-speed electric pulse, and THz pulse.

Keywords: Electro-optic effect, $LiTaO_3$, GaAs, phase retardance, Electro-optic sampling

1. Introduction

The development of techniques on probing high-speed electrical pulse has been driven by the rapid advances in high-speed electronic components from fast transistors in both silicon[1] and GaAs/AlGaAs[2] to fast photodiode and photoconductive switches with picosencond rise time. Optical techniques are appropriate for ultrafast measurement of these devices, because they overcome many of the limitations imposed by conventional electronic test systems. The primary conventional test instruments for high-speed pulse are the sampling oscilloscope and network and spectrum analyzers.

Since the electrical signals to be measured have to be conveyed to the test instrument, an electrical probe capable of high-speed operation must be used. Such electrical probes suffer from several problems[3]. A variety of optical techniques have been developed to address the limitations associated with conventional electrical testing. These methods take advantage of recent and continuing advances in high repetition rate femtosecond laser sources and their application in optical sampling experiments.

The ability to use optical pulses to measure the properties of electrical devices and circuits relies on some physical property that allows the electrical signal to modulate test beam. The most widely exploited physical phenomenon for this purpose is the electro-optic effect and photoconductive sampling. The latter has narrower bandwidth and the measurement resolution of it is limited by the life time of minority carriers. Therefore EO effect is more and more popular in recent decade, which is based on the polarizability of a material to an applied electric field. It has an extremely broad response band width into the THz frequency regime limited only by the resonant coupling to infrared lattice vabrations[3]. THz bandwidth is more than enough for the measurement of electronic signal. This paper emphasis on analysis of the probing process in EO sampling system relied on EO effect. The basic theory is introduced and two most commonly examples are presented and compared. Furthermore, the approximation condition is discussed.

2. Analysis of probing process based on Electro-Optic (EO) effect

2.1 Introduction of EO effect and the derivation in LiTaO3 and GaAs

The EO effect refers to the process by which an electric field can alter the refractive index of a material. The EO effect offers a means of transferring information from the electrical to the optical domains by modulating the polarization and/or phase of optical radiation transmitted through an electro-optically active medium. In most EO sampling system including probes of high-speed electric pulse, the EO effect emphasis on the anisotropic materials requirements for EO effects and the quantitative description of these effects by the EO tensor. The action of an external applied E-field is to deform the zero field index ellipsoid, in formula (1).

$$(\frac{x_1^2}{n_1^2})+(\frac{x_2^2}{n_2^2})+(\frac{x_3^2}{n_3^2})=1 \quad (1)$$

The expression for new index ellipsoid referred to the principal axes x1x2x3 is given by

$$a_{11}x_1^2+a_{22}x_2^2+a_{33}x_3^2+2a_{23}x_2x_3+2a_{31}x_1x_3+2a_{12}x_1x_2=1 \qquad (2)$$

Where the values of the coefficients a_{ij} are calculated from the applied field and the electro-optic tensor of the material by

$$\begin{bmatrix} a_{11}-\frac{1}{n_1^2} \\ a_{22}-\frac{1}{n_2^2} \\ a_{33}-\frac{1}{n_3^2} \\ a_{23} \\ a_{31} \\ a_{12} \end{bmatrix} = \begin{bmatrix} \gamma_{11} & \gamma_{12} & \gamma_{13} \\ \gamma_{21} & \gamma_{22} & \gamma_{23} \\ \gamma_{31} & \gamma_{32} & \gamma_{33} \\ \gamma_{41} & \gamma_{42} & \gamma_{43} \\ \gamma_{51} & \gamma_{52} & \gamma_{53} \\ \gamma_{61} & \gamma_{62} & \gamma_{63} \end{bmatrix} \begin{bmatrix} E_{x1} \\ E_{x2} \\ E_{x3} \end{bmatrix} \qquad (3)$$

Now, a particular material illustrated which is the simplest case is one of the most commonly used materials for the ultrafast electric pulse probing applications is lithium tantalite, $LiTaO_3$. $LiTaO_3$ is a birefringent material with point group symmetry 3m. The form of the contracted γ_{ijk} matrix for a material of this symmetry is [10]

$$\gamma_{ijk} = \begin{bmatrix} 0 & -\gamma_{22} & \gamma_{13} \\ 0 & \gamma_{22} & \gamma_{13} \\ 0 & 0 & \gamma_{33} \\ 0 & \gamma_{51} & 0 \\ \gamma_{51} & 0 & 0 \\ -\gamma_{22} & 0 & 0 \end{bmatrix} \qquad (4)$$

If the case in which the applied E-filed in the crystal is along the c-axis is considered, that is, by convention, taken to be the x_3 direction, the equation (3) gives

$$\begin{bmatrix} a_{11}-\frac{1}{n_1^2} \\ a_{22}-\frac{1}{n_2^2} \\ a_{33}-\frac{1}{n_3^2} \\ a_{23} \\ a_{31} \\ a_{12} \end{bmatrix} = \begin{bmatrix} 0 & -\gamma_{22} & \gamma_{13} \\ 0 & \gamma_{22} & \gamma_{13} \\ 0 & 0 & \gamma_{33} \\ 0 & \gamma_{51} & 0 \\ \gamma_{51} & 0 & 0 \\ -\gamma_{22} & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ E_{x3} \end{bmatrix} \quad (5)$$

Which, after multiplied out, leads to relations:

$$\begin{aligned} a_{11} &= \frac{1}{n_o^2}+\gamma_{13}E_{x3} \\ a_{22} &= \frac{1}{n_o^2}+\gamma_{13}E_{x3} \\ a_{33} &= \frac{1}{n_e^2}+\gamma_{13}E_{x3} \end{aligned} \quad (6)$$

Then, the new index ellipsoid with electric field applied is

$$\left(\frac{1}{n_0^2}+\gamma_{13}E_{x3}\right)x_1^2+\left(\frac{1}{n_0^2}+\gamma_{13}E_{x3}\right)x_2^2+\left(\frac{1}{n_e^2}+\gamma_{33}E_{x3}\right)x_3^2=1 \quad (7)$$

And at last, we could calculate the new n_1, n_2, n_3

$$\begin{aligned} n_1 &= n_0-\frac{1}{2}\gamma_{13}n_0^3E_{x3}^{(1)} \\ n_2 &= n_0-\frac{1}{2}\gamma_{13}n_0^3E_{x3}^{(2)} \\ n_3 &= n_e-\frac{1}{2}\gamma_{33}n_e^3E_{x3}^{(3)} \end{aligned} \quad (8)$$

Where $E_{x3}^{(2)} = 0$.

Usually, only two indexes and polarizations are taken into consideration since the electric field applied on $LiTaO_3$ is along x_3 direction. Thus, the propagation of the probe laser pulse beam is expressed:

$$\begin{aligned} e_1 &= A\exp j[\omega t-(\omega c)n_1x_2] \\ e_2 &= A\exp j[\omega t-(\omega c)n_3x_2] \end{aligned} \quad (9)$$

When thickness of the crystal is L, the phase retardance that is the difference in phase experienced by rays polarized along the two optical axes would be

$$\Gamma = (\omega / c)(n_1 - n_3) = \frac{2\pi}{\lambda}(n_o - n_e)L + \frac{\pi}{\lambda}\left(n_0^3\gamma_{13} - n_e^3\gamma_{33}\right)L * E \qquad (10)$$

Where λ is the wave length of the probe laser. From (10) we can see that the phase retardance has two related parts, one is static phase shift Γ_s that is independent on the external electric field, the other is electric induced phase shift Γ_e.

Another example is a little more complicated, concerns the EO effect in GaAs which is a cubic material and has a point group symmetry $\bar{4}3m$. So it is not birefringent in the zero field case. The contracted EO tensor for GaAs is given by

$$\gamma_{ijk} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \gamma_{41} & 0 & 0 \\ 0 & \gamma_{41} & 0 \\ 0 & 0 & \gamma_{41} \end{bmatrix} \qquad (11)$$

In an applied E-field with components along all the principal axes, the index ellipsoid can be derived from equations (2) and (3) and is described by

$$\frac{x_1^2}{n_1^2} + \frac{x_2^2}{n_2^2} + \frac{x_3^2}{n_3^2} + 2r_{41}x_2x_3E_{x1} + 2r_{41}x_1x_3E_{x2} + 2r_{41}x_2x_1E_{x3} = 1 \qquad (12)$$

If we consider a specific example in which a field is applied only along the x_3 direction, E_3, then this relation reduces to

$$\frac{x_1^2}{n_1^2} + \frac{x_2^2}{n_2^2} + \frac{x_3^2}{n_3^2} + 2r_{41}x_2x_1E_{x3} = 1 \qquad (13)$$

In equation (13), the final cross term on the left side means that the relation cannot be directly cast in the form of an index ellipsoid. Such case is different from LiTaO3 in which a transformation is required to find a new coordinate axes for which the relationship can be put in the form of an ellipsoid. The cross term in this instance only involves the x1x2 axis, thus, the x3 axis is unchanged by the transformation. If the coordinate axes are rotated 45 degree, the transformed coordinate axes are

$$\begin{aligned} x_1 &= \frac{x_1^{'}}{\sqrt{2}} + \frac{x_2^{'}}{\sqrt{2}} \\ x_2 &= \frac{x_2^{'}}{\sqrt{2}} - \frac{x_1^{'}}{\sqrt{2}} \end{aligned} \qquad (14)$$

Then Equation (13) can be written,

$$x_1^{'2}\left(\frac{1}{n_o^2} + \frac{1}{2}\gamma_{14}E_{x3}\right) + x_2^{'2}\left(\frac{1}{n_o^2} - \frac{1}{2}\gamma_{14}E_{x3}\right) + \frac{x_3^{'2}}{n_o^2} = 1 \qquad (15)$$

which is again in the form of an index ellipsoid in the transformed coordinate frame. In such coordinate frame, optical waves propagating in the x3 direction and polarized along the $x_1^{'}x_2^{'}$ directions will see refractive indexes that vary with applied field E_{x3} as

$$n_{x1'} = n_o + \frac{1}{2}\gamma_{41} n_o^3 E_{x3}$$
$$n_{x2'} = n_o - \frac{1}{2}\gamma_{41} n_o^3 E_{x3} \qquad (16)$$
$$n_{x3'} = n_o$$

The same principle and method for calculate the phase retardance in GaAs as in LiTaO3:

$$\Gamma = (\omega / c)(n_{x1'} - n_{x2'}) = \frac{2\pi}{\lambda}\gamma_{41} n_o^3 L * E_{x3} \qquad (17)$$

2.2 Electro-optic sampling system for measurement of ultrafast electromagnetic waves

The basic theory of EO sampling technology is linear EO effect of EO crystals which has been employed to measure ultrafast electric pulse by Kolner early in 1983[4]. Today, EO effect has been widely applied to measure free space THz radiation[5,6]and the electric field of the planar microwave devices[7-9]. The EO sampling measurement is a typical pump-probe detection system in which the laser beam is split into two paths. One is to generate ultrafast signal, the other is to detect the signal by EO effect. When the probe pulse and the ultrafast electromagnetic waves pass through the EO crystal simultaneously, the ultrafast EM waves will cause the change of the index of EO crystal which results in the change of polarization of probe laser pulse. The time domain waveform of the measured signal can be obtained by detecting the change of the polarization and adjusting the delay between the probe pulse and the signal. The schematic diagram of general EO sampling system is shown in Fig. 1. The details of linear EO effect based on which the probing of the electric field is realized will be discussed in the following.

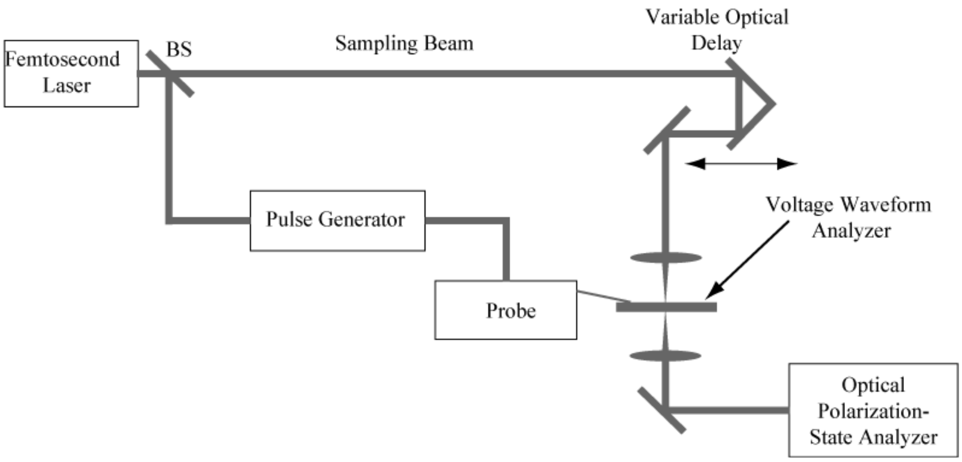

Fig.1 schematic diagram of general EO sampling system

2．3 Design and analysis of balanced-detection of electric fields by photoreceiver

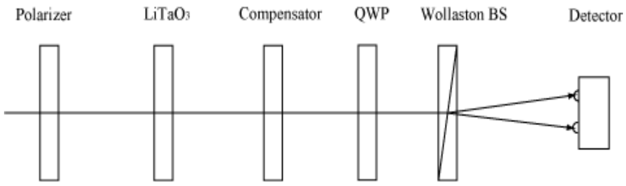

Fig. 2 scheme for birefringent crystal such as LiTaO3

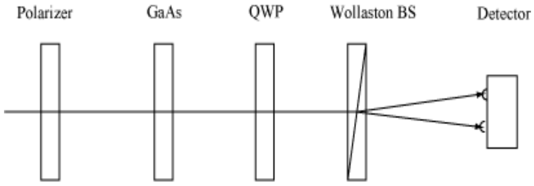

Fig. 3 scheme for non-birefringent crystal such as GaAs

Fig. 2 and 3 show the two experiment designs for the EO detection of LiTaO3 and GaAs, respectively, which are details of optical polarization state analyzer in Fig. 1. Before the continuance of mathematical deduction, the role of these optical components will be explained. A polarizer makes sure the probe beam is linear polarization which is rotated by a half wave plate (HWP) to a certain angle so that the probe beam has two equal polarization components along the two principal axis of EO crystal. These axis are named o- and e- axis in the following description:

$$\vec{E} = \begin{pmatrix} E_o \\ E_e \end{pmatrix}$$

While the probe beam is propagating through the EO crystal, the polarization components of the o- and e- axis experience a different phase shift. From equation (10), we could see that there are two phase shift components which are static phase shift and e-field induced phase shift. In order to make the measured Γ proportional to the external e-field, a Babinet compensator should be utilized when a birefringent EO crystal is used such as LiTaO3 without an external e-field. When a non-birefringent EO crystal is employed, equation (17) is applicable, so the compensator is not necessary. Then, only e-field induced phase shift remains that can be converted into an amplitude variation and separated by the application of a QWP and a Wollaston prism. At last, orthogonal probe beam components are subtracts by the photoreceiver.

In Fig. 2, the linear polarization of the probe beam is rotated by the HWP by an angle of $\frac{\pi}{4}$ to the axes of the crystal, then:

$$\vec{E}_1 = E_0 \begin{pmatrix} \cos\frac{\pi}{4} \\ \sin\frac{\pi}{4} \end{pmatrix} = \frac{1}{\sqrt{2}} E_0 \begin{pmatrix} 1 \\ 1 \end{pmatrix} \qquad (18)$$

Where E_0 is the original electric field of the probe laser beam. Now, the probe beam has two equal components along the e-axis and o-axis. After propagating through the LiTaO3, the two field components experience different phase retardation and induced a static phase shift. The compensator is made of quartz which is positive crystal, note that the LiTaO3 is negative crystal, so if the axes of compensator is placed as the same direction as LiTaO3, this phase shift could be compensated to make the probe beam back to linear polarization state as is expressed in Equ.(18). After o-component and e-component separated by Wollaston prism, intensity of the two components are $I_o = |E_o|^2$ and $I_e = |E_e|^2$, thus the output signal of the photoreceiver is zero. The deduction process is

$$\begin{aligned} \vec{E}_{crystal} &= \frac{1}{\sqrt{2}} E_0 \begin{pmatrix} 1 & 0 \\ 0 & e^{i\Gamma} \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}} E_0 \begin{pmatrix} 1 \\ e^{i\Gamma} \end{pmatrix} \\ \vec{E}_{compensator} &= \frac{1}{\sqrt{2}} E_0 \begin{pmatrix} 1 & 0 \\ 0 & e^{-i\Gamma} \end{pmatrix} \begin{pmatrix} 1 \\ e^{i\Gamma} \end{pmatrix} = \frac{1}{\sqrt{2}} E_0 \begin{pmatrix} 1 \\ 1 \end{pmatrix} \end{aligned} \qquad (19)$$

Then, when the E-field applied to the crystal, there is:

$$\vec{E}_2 = \vec{E}_1 \begin{pmatrix} 1 \\ e^{-i\Gamma} \end{pmatrix} \qquad (20)$$

The Jones matrix of QWP, with its fast axis having an angle of $\frac{\pi}{4}$ with the o- and e-axis of the coordinate system is

$$W = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -i \\ -i & 1 \end{pmatrix} \qquad (21)$$

The E-field after the QWP then is

$$\vec{E}_3 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -i \\ -i & 1 \end{pmatrix} \cdot \vec{E}_1 \begin{pmatrix} 1 \\ e^{-i\Gamma} \end{pmatrix} = \frac{1}{2} E_0 \begin{pmatrix} 1 - ie^{-i\Gamma} \\ -i + e^{-i\Gamma} \end{pmatrix} \qquad (22)$$

The WP separates the o- and e- component from each other. Finally, the photoreceiver subtracts the intensities $I_1 = |E_o|^2$ and $I_2 = |E_e|^2$. Thus, the output signal is

$$I_\Delta = |I_o - I_e| = \frac{E_0^2}{4} \left| \left(-i + e^{-i\Gamma}\right)\left(i + e^{i\Gamma}\right) - \left(1 - ie^{-i\Gamma}\right)\left(1 + ie^{i\Gamma}\right) \right| = E_0^2 \sin(\Gamma) \qquad (23)$$

When the case is as Fig. 3, electrical field of input linear polarized laser beam in arbitrary angle is:

$$E_0 \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}$$

Jones Matrix of QWP can be expressed as:

$$\begin{pmatrix} \cos^2\phi + i\sin^2\phi & (1-i)\cos\phi\sin\phi \\ (1-i)\cos\phi\sin\phi & \sin^2\phi + i\cos^2\phi \end{pmatrix}$$

Where ϕ is the angle of optical axis of QWP with the X coordinate. GaAs is not birefringence crystal. When there is no electrical field, polarization state of incident laser beam doesn't change after propagating through GaAs. Polarization state of laser after passing through QWP:

$$\begin{pmatrix} \cos^2\phi + i\sin^2\phi & (1-i)\cos\phi\sin\phi \\ (1-i)\cos\phi\sin\phi & \sin^2\phi + i\cos^2\phi \end{pmatrix} E_0 \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}$$
$$= E_0 \begin{pmatrix} \cos^2\phi\cos\theta + \cos\phi\sin\phi\sin\theta + i(\sin^2\phi\cos\theta - \cos\phi\sin\phi\sin\theta) \\ \sin^2\phi\sin\theta + \cos\phi\sin\phi\cos\theta + i(\cos^2\phi\sin\theta - \cos\phi\sin\phi\cos\theta) \end{pmatrix}$$

To get balance, o- and e- component should have same intensity which is expressed as following:

$$(\cos^2\phi\cos\theta + \cos\phi\sin\phi\sin\theta)^2 + (\sin^2\phi\cos\theta - \cos\phi\sin\phi\sin\theta)^2$$
$$= (\sin^2\phi\sin\theta + \cos\phi\sin\phi\cos\theta)^2 + (\cos^2\phi\sin\theta - \cos\phi\sin\phi\cos\theta)^2$$

$$\cos^4\phi\cos 2\theta + \sin^4\phi\cos 2\theta - 2\cos^2\phi\sin^2\phi\cos 2\theta + 4\cos\phi\sin\phi\cos\theta\sin\theta\cos 2\phi = 0$$
$$\cos 2\phi\cos(2\phi - 2\theta) = 0$$

So the balance condition is $\phi = \theta + \frac{\pi}{4}$. Put the optical axis of GaAs parallel to that of QWP, when electrical field is applied on GaAs, phase difference Γ is generated. The Jones Matrix of GaAs is expressed as:

$$\begin{pmatrix} \cos^2\phi + e^{i\Gamma}\sin^2\phi & (1-e^{i\Gamma})\cos\phi\sin\phi \\ (1-e^{i\Gamma})\cos\phi\sin\phi & \sin^2\phi + e^{i\Gamma}\cos^2\phi \end{pmatrix}$$

After passing through GaAs, polarization state of light is expressed as:

$$E_0 \begin{pmatrix} \cos^2\phi + e^{i\Gamma}\sin^2\phi & (1-e^{i\Gamma})\cos\phi\sin\phi \\ (1-e^{i\Gamma})\cos\phi\sin\phi & \sin^2\phi + e^{i\Gamma}\cos^2\phi \end{pmatrix} \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} = \frac{\sqrt{2}}{2} E_0 \begin{pmatrix} \cos\phi + e^{i\Gamma}\sin\phi \\ \sin\phi + e^{i\Gamma}\cos\phi \end{pmatrix}$$

After passing through QWP:

$$E_0 \begin{pmatrix} \cos^2\phi + i\sin^2\phi & (1-i)\cos\phi\sin\phi \\ (1-i)\cos\phi\sin\phi & \sin^2\phi + i\cos^2\phi \end{pmatrix} \frac{\sqrt{2}}{2} \begin{pmatrix} \cos\phi + e^{i\Gamma}\sin\phi \\ \sin\phi + e^{i\Gamma}\cos\phi \end{pmatrix} = \frac{\sqrt{2}}{2} E_0 \begin{pmatrix} \cos\phi + ie^{i\Gamma}\sin\phi \\ \sin\phi - ie^{i\Gamma}\cos\phi \end{pmatrix}$$

$$I_\Delta = \frac{1}{2} E_0 \left| (\cos\phi + ie^{i\Gamma}\sin\varphi)(\cos\phi - ie^{-i\Gamma}\sin\varphi) - (\sin\phi - ie^{i\Gamma}\cos\phi)(\sin\phi + ie^{-i\Gamma}\cos\phi) \right|$$
$$I_\Delta = E_0 \left| i\sin 2\phi\sin\Gamma \right| = E_0 \sin 2\phi\sin\Gamma \qquad (24)$$

The relation expressed in equation (23) and (24) obviously rests upon the assumption that the value of Γ is very small. The half wave voltage of LiTaO3 and GaAs is 2.8kV/cm and 13.3kV/cm[11], respectively, which is the voltage needed to get π phase shift in vertical modulation. Our detection mechanism is horizontal modulation, so the HWV can be calculated by the following equaltion:

$$V_{horizontal} = V_{vertical} * \left(\frac{d}{L}\right)$$

In which the dictation of parameters are the same as Euq. (10) and (17). In the most typical experiment of ultrafast pulse measurement[12],[13], the value of L/d is about 1/4 and 3/10. So, the HWV is around 700V/cm, and 3.9kV/cm for the two crystals. In practice, the voltage applied is usually less than 10V, thus phase retardance is pretty small that means $\sin\Gamma \approx \Gamma$. Therefore, the sine relation can be regarded as linear relation, and the output current is directly proportional to the phase retardance which is proportional to the external applied E-field in both cases.

3. Conclusion

We analyzed the probing process in EO sampling system based on EO effect. The EO effect mechanism by LiTaO3 and GaAs crystals are illustrated. The relation between the external E-field and the phase retardance is subtracted respectively. Then, the detection principle of the measured signal using photoreceiver is calculated and discussed for two experimental cases. This work offers the fundamental theory of detection mechanism through EO effect which is important for the future design and analysis in such EO sampling system of ultrafast measurement setups.

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