An Analytical study of Terahertz-waves Measurements by ZnTe Electro-Optic Crystal

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Abstract: - An analysis for intensity measurement of terahertz-waves generated by TPO and detection of the THz pulses occurs via free-space electro optic detection in ZnTe crystal has been carried out. The pump-probe technique has been used to observe the dynamics of an optically excited ZnTe electro-optic crystal. The THz pulses generated by TPO are 10-25 ns pulses at a repetition rate of 1 Hz. ZnTe crystal is being use for intensity measurement of THz-waves. In this theoretical proposed experiment, a short pump pulse (THz-wave) and probe pulse (near IR laser) with duration of typically 10 to 25 ns interacts in the ZnTe. In electro-optic sampling the two effects namely Pockels effect and Kerr effect have been discussed and interaction of two beams from or transmission through the ZnTe, the probe pulse Intensity contains information about the THz-waves' intensity and so on.

Key words: Terahertz parametric oscillator, Terahertz electro optic sampling, Pockels effect, Kerr effect THz spectroscopy

1. **Introduction**

In the last decade, time-domain THz spectroscopy and imaging have become widely used techniques in various fields of physics, chemistry and biology. The access to the interesting THz spectral region, which has remained almost unexplored for a long time, has been enabled by rapid progress in two fields: (1) the development of powerful THz sources such as photoconductive switches irradiated by ultra short laser pulses or optical rectification of femtoseconds laser pulses in nonlinear crystals and (2) the development of sensitive THz detection schemes utilizing e.g. electro-optic sampling of THz fields with femtosecond optical pulses or photoconductive autocorrelation techniques.

THz detection systems can be separated into three categories: The first uses bolometers, which are essentially heat detectors [1]. The second uses electro-optic detection in a crystal such as (110) oriented ZnTe in which the THz electric field induces a polarization change on a synchronized probe pulse [3-5]. The third uses micro-fabricated antennas on semiconductors such as low-temperature grown GaAs [LT-GaAs] or radiation-damaged Si on Sapphire which are time gated by a synchronized probe pulse [2, 6]. Of these three detection methods, bolometers have the disadvantage that, for proper operation, they need to be cooled by liquid helium. Electro-optic detection has the great advantage that it measures the amplitude and phase of the THz electric field, and is inherently simple, but multiple reflections in the detection crystal, and reshaping of the THz pulse due to phase matching issues and absorption, distort the THz pulse [7, 8].

2. Principle of Free-Space Electro-Optic Sampling

As we know that ZnTe is isotropic semiconductor have a <110> crystal orientation. When an electric field is applied across an isotropic transparent substance the refractive index of medium changes anisotropically. The result of this electro-optic effect may be to introduce new optic axes into naturally doubly refracting crystals. The change in refractive index as a function of the applied field can be written as

$$\Delta\left(\frac{1}{n^2}\right) = \gamma\varepsilon + P\varepsilon^2 \qquad (1)$$

Where 'γ'is the linear electro-optic coefficient and 'P' is the quadratic electro-optic coefficient. In equation (1) linear variation in the refractive index associated with $r\varepsilon$ is known as the Pockels effect while the variation arising from the quadratic term is called the Kerr effect.

In the case of the Pockels effect, the precise effect of the applied electric field depends on the crystal structure and symmetry of the material under consideration. With ZnTe, if the THz electric field is applied along the z-direction then the x and y principle axes are rotated through 45^0 into new principle axes x' and y' and the refractive indices in these new directions become

$$n_{x'} = n_o + \frac{n_o^3}{2}\gamma_{41}E_z^2 \qquad (2)$$

$$n_{y'} = n_o - \frac{n_o^3}{2}\gamma_{41}E_z^2 \qquad (3)$$

In agreement with equation (1) assuming that the Pockels constant γ is very small, i.e.

$$\Delta\left(\frac{1}{n^2}\right) = -\frac{2\Delta n}{n^3} = \gamma_{41}E_z^2 \qquad (4)$$

Where γ_{41} is the electro-optic coefficient for ZnTe,

Now as we know that ZnTe is an isotropic material , the refractive index tensor reduces to a scalar, i.e. to a multiple of the unit tensor, $\left(\frac{1}{n^2}\right)_{ij} = n\delta_{ij}$, so that the index ellipsoid is a sphere. When the THz filed applied along z, the symmetry becomes axial, with two principle values for n, n_e along z and n_o for the direction in the XY plane. From the definition of s_{ijkl} one obtains the relations

$$\frac{1}{n_e^2} - \frac{1}{n^2} = s_{zzzz}E^2 = s_{33}E_{THz}^2 \qquad (5)$$

$$\frac{1}{n_o^2} - \frac{1}{n^2} = s_{xxzz}E^2 = s_{13}E_{THz}^2 \qquad (6)$$

As we know that here we assumed that Pockels effect is very small i.e.; main contribution to birefringence to electro-optical crystal is due to Kerr's effect, it means

$$\Delta n_p << \Delta n_K \qquad (7)$$

This can be approximately written as

$$n_e - n \approx -\frac{1}{2}s_{33}n^3E_{THz}^2 \quad (8)$$

$$n_o - n \approx -\frac{1}{2}s_{13}n^3E_{THz}^2 \quad (9)$$

Where it has been assumed that $n_e \approx n_o \approx n$. The THz field induced birefringence $n_e - n_o$ is then obtained by subtracting equation and taking into account that $s_{33} - s_{13} = s_{66}$. Also $\Delta n_e \neq \Delta n_o$ but $\Delta n_e \approx \Delta n_o = \Delta n$. Therefore

$$\Delta n = n_e - n_o = -\frac{1}{2} s_{66} n^3 E_{THz}^2 \qquad (10)$$

Introducing the parameter B,

$$B = \frac{1}{2} s_{66} \frac{n^3}{\lambda_{THz}} \qquad (11)$$

Where B is called the Kerr constant.

Finally we arrive at

$$\Delta n = -\lambda_{THz} B E_{THz}^2 \qquad (12)$$

From Equation (11) and (12), it is clear that the parameters $n^3 s_{66}$ or B are an adequate figure of merit to measure the index change induced in an isotropic crystal like ZnTe.

3 Proposed Experimental Setup

An experimental setup for detection of the THz pulse occurs via free-space electro-optic detection in another <110> oriented ZnTe crystal is shown in figure (1). The THz pulse and the visible pulse are propagated collinearly through the ZnTe crystal. The THz pulse induces a birefringence in ZnTe crystal which is read out by a linearly polarized visible pulse. When both the visible pulse and the THz pulse are in the crystal at the same time, the visible polarization will be rotated by the THz pulse. We "map" the THz pulse intensity by monitoring the Nd:YAG or visible pulse polarization rotation after the ZnTe crystal at a variety of delay times with respect to the THz pulse.

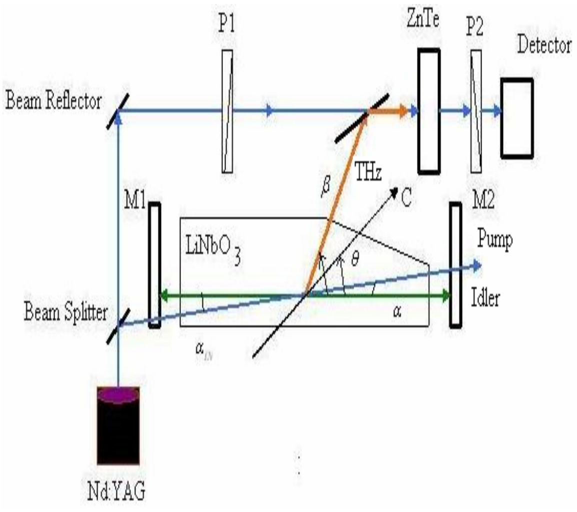

Fig. 1 Schematic diagram of THz generation by TPO and detection via free-space electro optical sampling (ZnTe)

The ability to read out the full electric field, both amplitude and delay, is one of the attractive features of time-domain THz spectroscopy. Note, the visible and THz pulses are collinearly propagated through the ZnTe crystal even though in the figure they appear to be propagating at an angle.

4 Results and Discussion

In our suggested experiment we want to detect 10-25 ns THz pulses (generated THz by TPO) [10] and THz wave will be used as modulation source for electro-optical phenomena in ZnTe crystal. In this phenomenon basically modulation is because of two phenomena, Pockels effect and Kerr optical effect. Pockels effect is linear electro-optic effect and here we consider only nonlinear electro-optic effect, Kerr effect. THz wave will change the refractive index of according to the equation (12)

The ZnTe being an isotropic material in its transverse geometry must be used to generate phase retardation δ. The expression for 'δ'

as a function of E_{THz} according to Equation (12),

$$\delta\lambda = \frac{2\pi\Delta nl}{\lambda} = 2\pi BlE_{THz}^2 \qquad (13)$$

'l' being the propagation length and B the Kerr constant. The half wave voltage to induce $\delta = \pi$ is

$$V_\pi = \frac{d}{(2Bl)^{1/2}} \qquad (14)$$

The E_{THz} field will generate the half wave voltage according to equation (13). Modulating the birefringence of the ZnTe crystal via an applied electric field (THz), will modulate the polarization ellipticity of the optical beam passing through ZnTe, The ellipticity modulation of the optical beam can then be polarization analyzed to provide information on both the amplitude and phase of the applied field (THZ). The detection system will analyze a polarization change from the electro-optic ZnTe crystal and correlate it with the amplitude and phase of the testing (Nd:YAG) electric field. For weak field detection, the power of f the laser beam modulated by the electric field of the THz pulse E_{THZ} (E_{THZ}=V/d) is[9]

$$P_{out}(V) = P_o\left(1 + \pi V \big/ V_\pi\right) \qquad (15)$$

Where P_o is the output optical probe power with no THZ field applied to the ZnTe crystal, and V_π is the half wave voltage by E_{THz} applied to the crystal, and intensity of THz field and Electric field of THz is related

$$I_{THz} = P/A = {}^{1/2\varepsilon_o.E^2CA}\big/_{A} = \frac{1}{2}C.\varepsilon_o E^2,$$

where $\varepsilon_o = 8.85418*10^{-12}(F/m)$, C is velocity of light. Therefore

$$I_{THz} = 1.33*10^{-3}.E^2$$

or $I_{THz} \infty E_{THz}^2$

or $I_{THz} = \alpha E_{THz}^2$, where α =1.33*10^{-3}

Where 'α' is some constant and $I_{THz} = \alpha\left(\frac{V}{d}\right)^2$,

so $I_{THz} \infty \left(\frac{P_{out}}{P_o}\right)^2$ (16)

Fro equation (14), (15) and (16), we get

$$\frac{P_{out}}{P_o} = (1 + \pi\sqrt{\frac{2BlI_{THz}}{\alpha}})$$

$$\text{Or } I_{THz} = (\frac{P_{out}}{P_o} - 1)^2.\frac{\alpha}{2\pi^2 Bl} \qquad (17)$$

As $\frac{\alpha}{2\pi^2 Bl}$ =Constant

From equation we analyzed that

$$I_{THz} \infty \left(\frac{P_{out}}{P_o}\right)^2$$

This is analytical solution of our proposed experimental setup.

From this equation we see that THz electric field measured will be directly depend on the ratio of the out put power of Nd:YAG to input power of Nd:YAG as shown in figure (2). From equation (17) we also see that the measured THz fields will intensity inversely proportional to the length of electro-optic crystal as shown in figure (3).

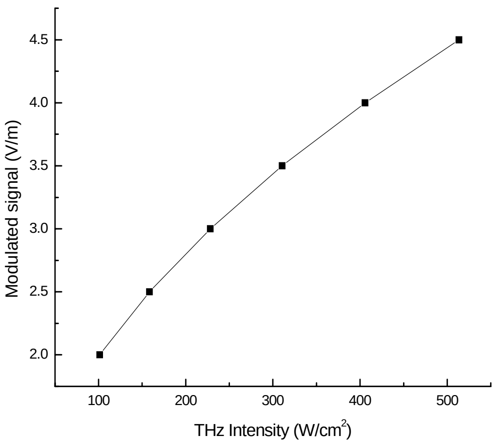

Fig. 2 Relationship between THz field intensity and Modulated laser signal

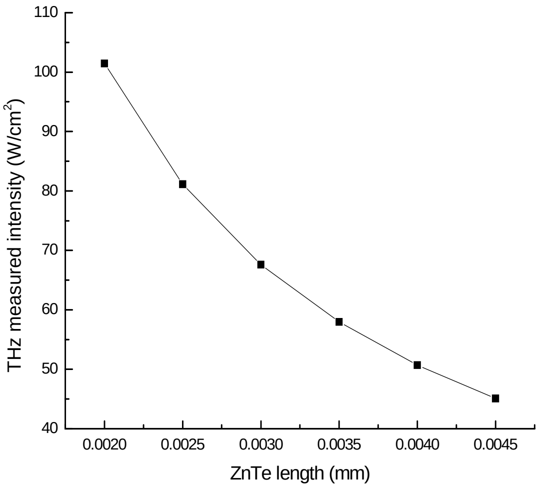

Fig. 3 Relationship between THz field intensity and ZnTe crystal length

5 Conclusions

An analytical method of terahertz-waves intensity measurement generated by TPO [10] and detection of the THz pulses via free-space electro-optic detection in ZnTe crystal has been analyzed. This electro-optic detection setup forms the basis of THz detecting system. In this technique we have considered both electro-optic techniques Pockels effect and Kerr electro-optic effect but Kerr effect is dominant.

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