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Electro-optical measurement of highly intense electric field with high frequency

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ABSTRACT

The transient electric field of highly intense electromagnetic pulse (EMP) will seriously damage the military and civil installations, so it is significantly important to measure such electric field of EMP with high frequency. This paper describes a fiber-optic sensor for measuring highly intense electric field with high frequency. The sensor consists of a probe of electrooptic(EO) crystal, optic fiber, polarizer, photodetector, processing circuits and single-chip microprocessor. According to Pockels effect, the polarized light will be modulated by the electric field to be measured when it penetrates the EO crystal. Then, its polarized direction will vary following the variation of electric field. The change of polarized direction is converted to the variation of light intensity by polarizer. In order to gain good performance, it is important to choose suitable crystal carefully. The interrelated optical axises of the components are adjusted on the basis of the theoretical analysis and calculations. A special temperature compensating method is used to decrease the temperature effect. At the meantime, the low noise circuit is used. The testing results show that the linearity is 0.2%, the error of the measurement is approximately 0.5% and the risetime is less than 4ns.

Keyword: EMC, fiber-optic sensor, highly intense electric field, temperature compensation

1. INTRODUCTION

Mankind throws emphasis more and more on electromagnetic pollution, now. Electromagnetic compatibility(EMC) is requested for various electronic devices[1]. The transient electric field of highly intense electromagnetic pulse will seriously damage the military and civil installations, even do harm to the health of living things. So it is significantly important to measure such electric field of EMP with high frequency. In traditional, the devices (such as static voltage meter, specialized probe, etc) applied to measure electric field are all made of electrical active substance, which will cause induced electric field easily. The perturbation of induced electric field will interfere with the testing electric field, which limits the validity and resolution of measurement. Especially, when there are lots of space charges, induction and inflow of space charges will result in serious errors and dangerousness. Furthermore, traditional instrument with big volume is very inconvenient in practical application. Fiber-optic electric field sensor has superior performances that have not in the traditional instruments, such as small volume, good insulativity, high corrosion resistance, not disturbing electric field to be measured, large range of measurement, etc[2,3]. The electric field sensor using an optical modulator makes possible accurate measurement without disturbing the electromagnetic field to be measured and is expected to have application in EMC measurement. With the advancement of new principle of measurement, various fiber-optic electric field and voltage sensors are developed.

2.THEORY

1893, Pockels, German physical scientist, discovered that refractive rates of some transparent optic medium vary with the electric field load-on its two ends. It is Pockels effect or linear electrooptic effect. According to Pockels effect, the polarized light coming from polarizer P_1 will be modulated by the electric field to be measured when it penetrates the Pockels crystal, and its polarized direction will vary following the change of the electric field. In other words, a phasic difference is generated between ordinary light and extraordinary light. When the beam go through polarizer P_2, the variation of phase is converted to the change of the light intensity by the polarizer P_2, so the electric signal coming from photodetector contains the characteristic of the electric field to be measured. Fig. 1 shows the method of Pockels effect.

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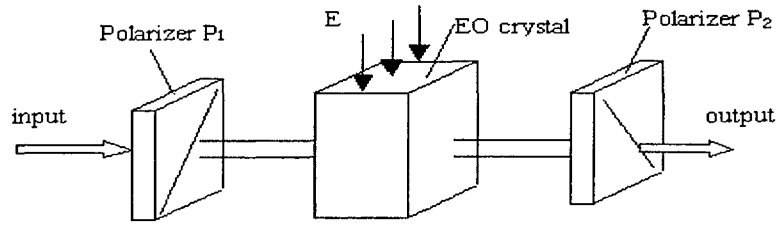

Fig. 1 the method of Pockels effect

The phasic difference $\Delta\varphi$ due to the electric field to be measured can be given as

$$\Delta\varphi = 2\pi n^3 \gamma_e lE / \lambda \qquad (1)$$

Where

n -------- the refractive rates of crystal

λ ---------wave length of the light

γ_e -------- effective EO coefficient

l--------- the length of EO crystal

E ------- the intensity of electric field to be measured

2.1 Selection of EO crystal

Only piezoelectricity crystals without symcenter maybe have electrooptic effect, because the EO coefficient γ_e is a three-order tensor. The crystals with good electrooptic and steadily physical properties are very little. Diagram (I) displays some typical EO crystals that are applied usually in electric field sensor.

For the measurement based on the method of polarized light, anything disturbing the polarized status of the polarized beam should be avoided to guarantee the precision of the sensor, such as natural birefringence, natural rotary polarization, strain and stress, etc. Because natural rotary polarization and birefringence (which are usually temperature dependent) all will cause additional phase retardation, the crystals without natural birefringence and rotary polarization is best EO crystal. According to these rules, $Bi_4Ge_3O_{12}$ (BGO) is suitable , which belongs to cubic crystal class $\bar{4}3m$. When there is not electic field , BGO , the isotropic crystal, is a ideal sensitive crystal to voltage or electric field.

crystal	class	EO coefficient $\lambda = 0.63\mu m$ ($10^{-10} cm/v$)	n	ε	pyroelectricity	Optical rotation
L_iNbO_3	T_d	$\gamma_{13}^T = 10$, $\gamma_{33}^T = 32.2$ $\gamma_{51}^T = 32$, $\gamma_{22}^T = 6.7$	$n_o = 2.286$ $n_e = 2.220$	$\varepsilon_1^T = 84.6$ $\varepsilon_2^s = 28.6$	Y	N
$Bi_4Ge_3O_{12}$	Cube $\bar{4}3$	$\gamma_{41}^T = 0.95$	$n_o = 2.11$	16	N	N
$Bi_{12}SiO_{12}$	Cube $\bar{4}3$	$\gamma_{41}^T = 4.35$	$n_o = 2.45$		N	Y

Diagram (I) , Optical parameters of three typical EO crystals

If the electric field E is along the direction <110>,the angle between the direction of the electic field E and new axis x' or y' of refractive rates is 45°, and z' is orthometric with x' and y' (see fig. 2). New refractive rates are given by [3,4]

$$n_x' = n + \frac{1}{2} n^3 \gamma_{41} E$$

$$n_y' = n - \frac{1}{2} n^3 \gamma_{41} E \quad (2)$$

$$n_z' = n$$

Then, the phasic difference is

$$\Delta\varphi = \frac{2\pi}{\lambda}(n_x' - n_y')l = \frac{2\pi}{\lambda} n^3 \gamma_{41} E \quad (3)$$

2.2 Method of interference measurement

The method of interference measurement is usually applied to measure phasic variation, because it is very difficult to measure the phasic variation accurately. In order to obtain optimally output of the beam , it is necessary to calculate the angle between the polarized direction of beam and the optical axis of polarizer and the angle between the optical axis of polarizer P_1 and the optical axis of polarizer P_2. Fig.3 shows the relation of P_1, P_2, x_1 and x_2. P_1 and P_2 are the optical axis of polarizer, x_1 and x_2 are the polarized direction of two beams in crystal, and ø is the angle between P_1 and x_1. After the light go through polarizer P_1, the beam reaching crystal is linear polarized light and its amplitude is E_0. The light whose polarized direction parallel to the optical axis of polarizer can go throught the polarizer, so the amplitude A_1 and A_2 of input beam in the direction of x_1 and x_2 can be expressed as

$$A_1 = E_0 \cos\phi \quad (4)$$

$$A_2 = E_0 \sin\phi$$

A phase difference is generated between A_1 and A_2 by the birefringence caused by the electric field to be measured, when the beams penetrate the EO crystal. At the end of output, the constituents of A_1 and A_2 along the optical axis of polarizer P_2 can be written as

$$A_1' = E_0 \cos\phi \cos(\phi - \alpha) \quad (5)$$

$$A_2' = E_0 \sin\phi \sin(\phi - \alpha)$$

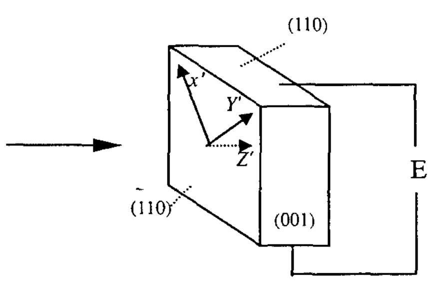

Fig. 2 new optic axises of the BGO

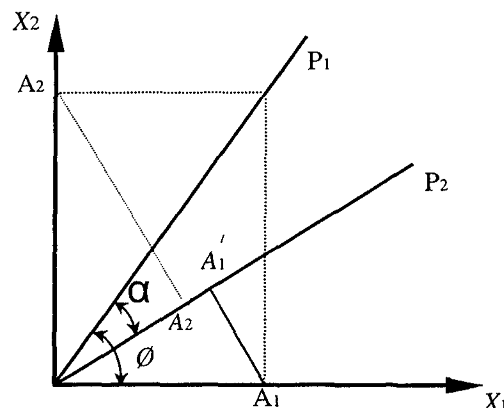

Fig. 3 Method of interference measurement

According to the theory of light interference, beam A_1' and beam A_2' will interfere with each other. The intensity of output light can be given by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\Delta\varphi \quad (6)$$

with

$$I_1 = E_0^2 \cos^2\phi \cos^2(\phi - \alpha) \qquad I_2 = E_0^2 \sin^2\phi \sin^2(\phi - \alpha)$$

Then,

$$I = I_0[\cos^2\alpha - \sin 2\phi \sin 2(\phi - \alpha)\sin^2\frac{\Delta\varphi}{2}] \quad (7)$$

The input and output polrizers are either crossed or parallel to each other in the fiber-optic sensor. For convenience, from now on, the polarizers are referred to as crossed polarizers when they are crossed and as parallel polarizers when they are parallel.

For crossed polarizers ($\alpha = \pi/2$), the intensity of output light can be described simply as

$$I = I_0 \sin^2 2\phi \sin^2 \Delta\varphi/2 \quad (8)$$

with $I = E_0^2$

The expression shows us that the intensity of output beam is due to the angle between the optical axis of polarizer and the polarized direction of the polarization along direction x_1 and x_2. In order to make the effect of $\Delta\varphi$ maximal in the intensity of output, φ is evaluated as $\pi/4$. Hence, if turning the crystal and making the angleφ is $\pi/4$, we can obtain the maximum intensity of output light. And the intensity of the output light is

$$I = I_0 \sin^2(\Delta\varphi/2) \quad (9)$$

2.3 Optic bias

By the expression (9), the intensity variation of output beam due to $\Delta\varphi$ is nonlinear , which make it difficult to measure the electic field accurately (see fig.5). Distinctly, the quiesent operating point is $\Delta\varphi = 0 rad$, and its linear rate is very bad in the region of measurement. If we shift the quiesent operating point from $0 rad$ to $\pi/2$ *rad*, the output due to phase difference is linear approximately in a very large range of measurement. A quarterwave plate being placed between the input polarizer and out put polarizer is applied to make a $\pi/2$ phase shift fixedly between ordinary light and extraordinary light. Then, the intensity of output beam is expressed as

$$\begin{aligned} I &= I_0 \sin^2(\Delta\varphi/2 + \pi/4) \\ &= \frac{I_0}{2}(1 + \sin\Delta\varphi) \\ &= \frac{I_0}{2}(1 + \Delta\varphi) = \frac{I_0}{2}(1 + \Gamma_m) \end{aligned} \quad (10)$$

due to $\Delta\varphi \ll 1$, where $\Gamma_m = 2\pi n_0^3 \gamma_e El/\lambda_0$.

If $\Gamma_m < 0.24$, the response of the sensor is linear approximately due to the E and the nonlinear error is less than 1%. In order to decrease the measurement errors, the modulation index Γ_m can be much less than 0.24, but little the modulation index Γ_m will bring about a small range of measurement. When the electric field change from 5k*v/m* to 500K*v/m*, the nonlinear error is less than 0.2% by experimental results. The sensor with a quarterwave can be seen in fig. 4.

3. TEMPERATURE COMPENSATION

The best temperature stability of an optical fiber sensor using bulk crystals reported so far is ~1% over a temperature range of 80°C . Even if a crystal is properly chosen and well prepared for sensor applications, the bulk crystals might have temperature dependent strain birefringences that are generated during its annealing process, temperature sensitive stress birefringence induced by mechanical pressure, or other types of randomly varying birefringence, all of which may exist simultaneously[6]. The $Bi_4Ge_3O_{12}$ of class $\bar{4}3m$ often exhibit unwanted birefringences due to strain, stress or precipitates, whose magnitudes significantly vary with environmental changes such as temperature and pressure, even though it possesses neither natural birefringence (which is usually temperature dependent) nor optical activity (which often quenches the linear electrooptic effect). Therefore, it is necessary to find a method that can eliminate the effects of such birefringences on the stability of the fiber-optic sensor to build a sensor that is stable with respect to environment

Once upon a time, Kyung S. Lee developed a good method of temperature to decrease the effects of such birefringences[5]. The input and output polarizers are either crossed or parallel to each other in the fiber-optic sensor. If the slow axis of the linear birefringence induced by the electrooptic effect and the slow (or fast) axis of a quarterwave plate are in the plane normal to the direction of a propagating beam and are oriented at 45°with respect to the input polarizer, the power transfer funtions of crossed polarizers and parallel polarizers are given by, respectively (see fig. 4)

$$\frac{p_\parallel}{p_i} = \frac{1}{2}[1 - (\delta_{0l} + \sum_{n=1}^{N} \delta_{nl} \sin 2\theta_n)] \quad (11)$$

$$\frac{p_\perp}{p_i} = \frac{1}{2}[1 + (\delta_{0l} + \sum_{n=1}^{N} \delta_{nl} \sin 2\theta_n)] \quad (12)$$

with $\delta_{ol} = 2\pi n_0^3 \gamma_{41} El/\lambda_0$ (for cubic crystal class $\bar{4}3m$) and $\delta_{nl} = k_0 n_0 l \Delta\varepsilon_{nl}/\lambda_0$, respectively, and here δ_{nl} is the phase retardation due to the nth linear birefringence, θ_n is the angle between the x axis and the slow axis of the nth linear birefringence. First, two terms on the right-hand sides of Equations (11) and (12) represent the well-known power transfer function of a typical electrooptic voltage sensor in the absence of unwanted birefringences, and the third term is the perturbation term due to unwanted birefringences present in the electrooptic crystal. Hence, if there are N unwanted linear birefringence with slow axis having azimuth angles $\theta_i \left(\theta_i \neq I \times \pi/2 ; I = 0,1,2,\cdots\right)$ in the plane transverse to the direction of wave propagation, N linear birefringences will individually contaibute to the intensity transmission of the sensor. However, if the unwanted birefringences remain constant over over the environmental changes, the output singal of the sensor remains stable. On the other hand, if the unwanted birefringences vary with the environmental changes, the sensor becomes unstable.
For ac voltage sensor, detecting ac singal is in fact identacal to measuring the modulation index Γ_m. By equations (11) and (12) ,the modulation index $\Gamma_{m\parallel}$ of the beam after the parallel polarizers is given by

$$\Gamma_{m\parallel}(T,P) = \frac{\Gamma_m}{1 - \sum_{n=1}^{N} \delta_{nl}(T,P)\sin 2\theta_n} \qquad (13)$$

and the modulation index $\Gamma_{m\perp}$ of the beam after the crossed polarizers is given by

$$\Gamma_{m\perp}(T,P) = \frac{\Gamma_m}{1 + \sum_{n=1}^{N} \delta_{nl}(T,P)\sin 2\theta_n} \qquad (14)$$

where $$\Gamma_m = 2\pi n_0^3 \gamma_{41} El/\lambda_0 \text{ (for cubic crystal class } \bar{4}3m \text{)} \qquad (15)$$

Here $\delta_{nl}(T,P)$ is the phase retardation due to the unwanted birefringence and is a function of temperature T and pressure P. Γ_m is the modulation index of the sensor without unwanted birefringences and is assumed to be constant over the temperature varition, because Γ_m is usually much less temperature dependent than $\delta_{nl}(T,P)$. Two equations can be expanded in a Taylor series, a series of powers of $\sum \delta_{nl}(T,P)\sin 2\theta_n$. Adding these expressions together, we can obtain

$$\Gamma_{m\parallel}(T,P) + \Gamma_{m\perp}(T,P) = 2\Gamma_m(1 + A^2 + A^4 + \cdots) \cong \Gamma_m \qquad (16)$$

for small A[$=\sum \delta_{nl}(T,P)\sin 2\theta_n$]. Therefore, averaging $\Gamma_{m\parallel}$ and $\Gamma_{m\perp}$ results in eliminating the birefringences term A and gives rise to the modulation index Γ_m. This tells us that $\Gamma_{m\parallel}$ and $\Gamma_{m\perp}$ should be simultaneously measured and added together to remove the effect of the unwanted linear birefringences.
By the method of temperature compensation, we can modify the design of the fiber-optic sensor to eliminate unwanted linear birefringences. If the output polarizer is replaced by a Wollaston prism or one polarizating beam splitter, the crossed polarizers and parallel polarizers are existing simultaneously in the same system. The polarized beam coming from crystal will split into two beams , the beam coming from crossed polarizers and the beam coming from parallel polarizers, when it reach at the Wollaston prism. Using for the beams , we can eliminate the perturbations caused by temperature variation.

4. DESIGN OF THE SYSTEM

Considering the linear rate and temperature compensation, we design a practical sensor. Fig. 4 shows the structure of the sensor system.

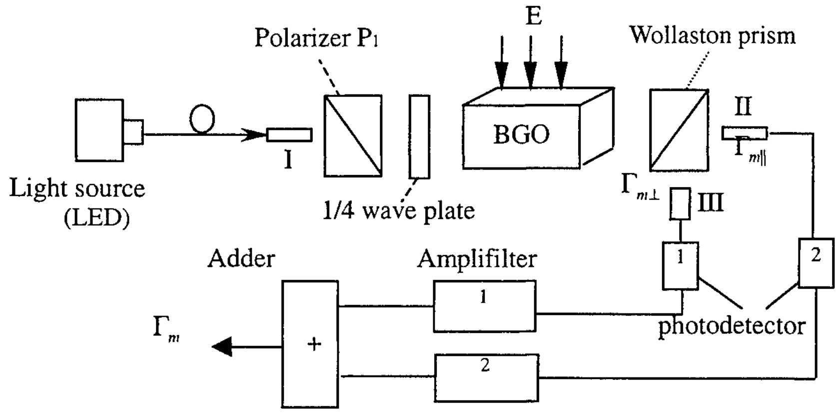

Fig. 4 the practical system with temperature compensation

I, II, III ----- coupled fiber

The sensing head consists of an input polarier, a quarterwave plate, electrooptical crystal, Wollaston prism (WP) and two detectors. Light from LED is initially linearly polarized by the input polarizer. Then the quarterwave plate changes the linear polarization to circular polarization. Because of the electrooptical crystal effect induced by the modulating electric field applied to the crystal , the circularly polarized light is changed to elliptically polarized light. The elliptically polarized light splits into two orthogonal linearly polarized beams. The reflected and transmitted signals from WP are equivalent to the signals transmitted from the crossed polarizers and from the parallel polarizers, respectively. Signals reflected and signals transmitted from the WP are detected by photodetector 1 and 2, respectively, and are processed by electronics and a computer until the output yields $(\Gamma_{m\parallel} + \Gamma_{m\perp})/2$.

In order to decrease interference of noise, we use some low noise devices. Photodetector 1 and 2 all are PIN photodiode that is low noise. Electric signals from photodetectors are amplified by OPA-128 (which is made by B-B Corporation and has very low null shift). The use of these low noise devices will ensure that the precision of the sensor is very fine.

5. EXPERIMENTAL RESULTS

By experimental results, the relative error of the sensor is less than 0.2% , when the measurement range changes from 5k*v/m* to 50k*v/m*. Fig. 6 shows the variation of the measurement due to the variation of electric field.

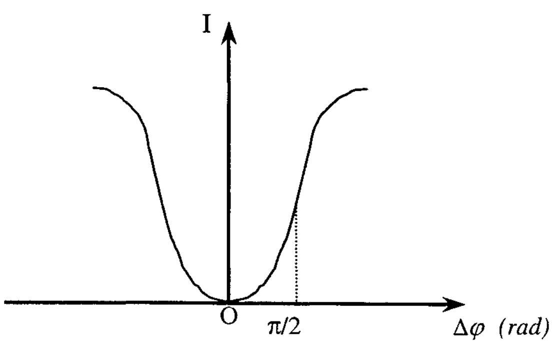

Fig. 5 the diagram of bias point

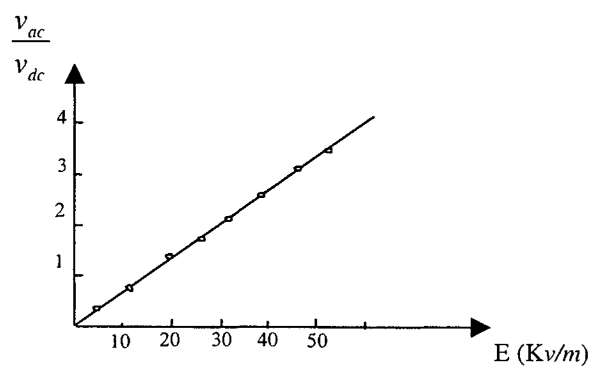

Fig.6 Variation of V_{ac}/V_{dc} due to E

The stability is very good in the laboratory in a long time. The measurement range is from 500v/m to 500kv/m with 0.5% error. And the frequency response covers a wide range from 50Hz to 300MHz, which means that the risetime is less than 4ns.

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