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Electro-Optical Effect Measurement of Thin-Film Material Using PM Fiber Mach-Zehnder Interferometer*

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Abstract: A polarization-maintaining (PM) fiber Mach-Zehnder (MZ) interferometer has been established to measure the EO effect of very thin film materials with optical anisotropy. Unlike a common MZ interferometer, all the components are connected via polarization-maintaining fibers. At the same time, a polarized DFB laser with a maximum power output of 10mW is adopted as the light source to induce a large extinction ratio. Here, we take it to determine the electro-optical coefficients of a very thin superlattice structure with GaAs, KTP, and GaN as comparative samples. The measured EO coefficients show good comparability with the others.

Key words: electro-optic effect; polarization-maintaining fiber; Mach-Zehnder interferometer
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1 Introduction

The development of optical switches and modulators demands high-performance electro-optical (EO) materials, especially micrometer scale thickness thin-film materials with superior characteristics. The EO coefficient is an important factor for evaluating the quality of these thin-film materials.

Unlike bulk materials[1,2], it is difficult to determine the EO coefficients of thin-film materials because they are so thin that they usually induce a very small signal that is hard to detect. The Mach-Zehnder inteferometer (MZI) method appears to be the most suitable way to measure the EO coefficients of film materials because of its high precision and dependability[3,4]. Nevertheless, since it is subject to poor stability and relatively low sensitivity, the free space MZ interferometer cannot satisfy the demand. A fiber-optic MZ interferometer system was proposed to solve these problems[5], but the selected polarity axes of the system are easily changed during the light transmission in single mode fibers, and thus the accuracy of measurement cannot be as high as desired.

In this work, we improved the MZI by connecting all the components by polarization-maintaining fibers and selecting the polarization angle of light by rotating the sample in the plane vertical to the axes of incident light. At the same time, a polarized DFB laser with high power output was adopted as the light source to excite a large extinction ratio. With this method, we measured the EO coefficient of a $Si_{0.75}Ge_{0.25}$/10.3nm-Si/2.5nm-$Si_{0.5}Ge_{0.5}$ superlattice[6], the optical anisotropy of which was demonstrated by reflectance difference spectroscopy[7]. Different kinds of super-lattice materials were also adopted as samples to verify the applicability of this MZ interferometer.

2 Working principles

As can be seen in Fig. 1, the intensity of light from the Mach-Zehnder interferometer can be expressed as

$$I = \frac{1}{2}[E_1^2 + E_2^2 + 2E_1E_2\cos(\phi_2 - \phi_1)] \quad (1)$$

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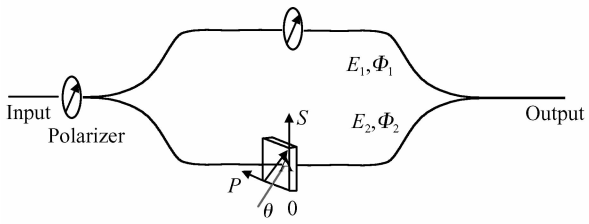

Fig. 1 Polarization axes direction of light in the MZI

where E_1 and E_2 are the field amplitudes of the light in each arm of the interferometer, and $\phi_2 - \phi_1$ is the phase difference between them. When the optical phase of the sample arm is modulated at a frequency ω with modulation amplitude A, the phase difference can be expressed as

$$\phi_2 - \phi_1 = \phi + A\cos\omega t \tag{2}$$

where ϕ is the phase difference without applied voltage. For a small signal modulation, the interferometer output intensity can be expressed as

$$I = I_0 + I_\omega \tag{3}$$

in which

$$I_0 = \frac{1}{2}[E_1^2 + E_2^2 + 2E_1E_2\cos\phi] \tag{4}$$

and

$$I_\omega = -E_1E_2A\sin\phi\cos\omega t = I_{sig}\cos\omega t \tag{5}$$

I_ω can be detected by a lock-in amplifier. The product of the field amplitudes and phase modulation amplitude A can be determined respectively by

$$2E_1E_2 = I_{max} - I_{min} \tag{6}$$

$$A = \pi\gamma_\theta n_\theta^3 V_{rms}/\lambda \tag{7}$$

I_{max} and I_{min} are the maximum and minimum of the interferometer output intensity, and θ denotes the shift of the polarization direction relative to the polarization axes created by the applied electrical field. γ_θ and n_θ are the electro-optical coefficient and refractive index under the polarization angle θ. V_{rms} is the root mean square modulating voltage loaded on the sample. When the phase shift ϕ equals $\frac{(2m+1)\pi}{2}$ ($m = 0, 1, 2, \cdots$), where I_{sig} reaches its maximum value, through Eqs. (5～7), we can get the electro-optical coefficient γ_θ as

$$\gamma_\theta = \frac{2\lambda I_{sig}}{\pi n_\theta^3 V_{rms}(I_{max} - I_{min})} \tag{8}$$

It should be noted that some effects that do not result in phase modulation, such as RF pickup and change of absorption coefficient of the film coming from the change of refractive index, will result in an offset δ for I_{sig}. As a result, real I_{sig} can be expressed as

$$I_{sig} = E_1E_2A\,|\,\delta + \sin\phi\,| \tag{9}$$

If the offset is large, the amplitude is half the peak-to-peak value. If the offset is small, the resulting signal will be two different alternating peak heights. The amplitude can then be calculated from the average of the two heights[8].

3 Experiment layout and results analysis

The experiment result validates the theory as mentioned above. Figure 2 shows the layout for electro-optic measurements. The phase shift between the two arms can be changed by a polarization-maintaining fiber phase shifter (FPS) in one arm of the interferometer through the voltage applied on it. The DC part of the interference signal I_0 and the AC part I_ω can be read out on the oscillator and lock-in amplifier. The sample is sandwiched between two pieces of ITO-coated glass through which the electrode can be educed and

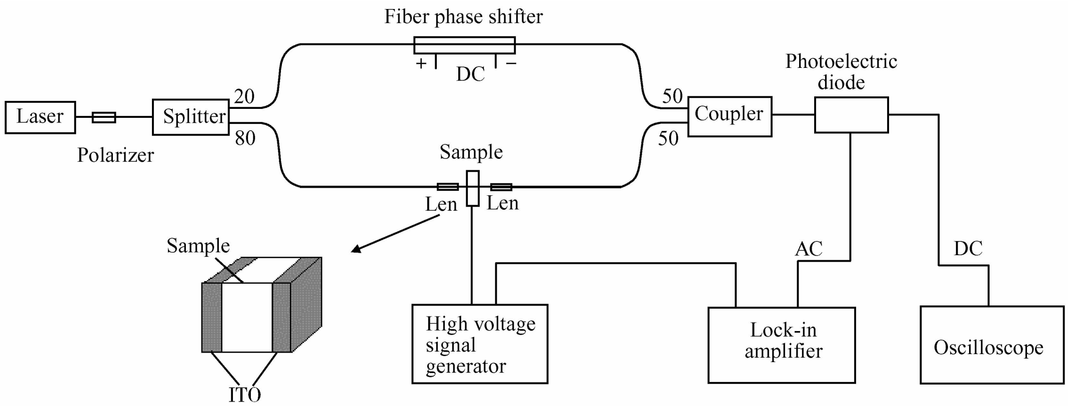

Fig. 2 Experimental layout for the measurement of electro-optical coefficient and diagram of ITO electrodes on the sample

connected to a high voltage source. The sample is added by a clamp which can be rotated and placed on the sample branch of the interferometer. The growth direction is parallel to the direction of incident light, which is collected by two collimators. By changing the applied voltage on the FPS, changes in I_0 can be seen on the oscilloscope through a photodiode.

To get a larger response and clearer image, we give the DC and AC response of KTP as a function of the voltage applied on FPS, as can be seen in Fig. 3. The incident light power is 1.2mW and the applied voltage on the sample is 10.1V (25kHz). One can note that there is a phase shift between I_{sig} and I_0 which is compatible with Eqs. (4) and (9). The AC part (I_{sig}) also shows two different alternating peak heights, indicating that there is a small offset δ as described above.

However, it is found there is a shift ΔI between the two minimum values in Fig. 3(a). The reason is that the polarity direction of incident light is not parallel to either of the two polarization axes of the sample. As can be seen in Fig. 1, the polarization vector of the incident light can be decomposed into two mutual vertical vectors along the two polarization axes of the sample. Under this condition, Equation (9) can be changed into:

$$I_{sig}(\phi) = AE_1E_2\cos^2\theta\,|\,\delta+\sin\phi\,| + BE_1E_2\sin^2\theta\,|\,\delta+\sin(\phi+\xi)\,| \qquad (10)$$

in which $\xi=\frac{2\pi}{\lambda}(n_s-n_p)L$ is the phase shift between the two polarity axes, $m=0,1,2\cdots$, and A and B are the phase modulation amplitudes in the S and P directions, respectively. From Eq. (10), we can deduce that

$$\Delta I = I_{sig}(2m\pi) - I_{sig}[(2m+1)\pi] = BE_1E_2\sin^2\theta(\,|\,\delta+\sin\xi\,|-|\,\delta-\sin\xi\,|\,) \qquad (11)$$

For general conditions, $\delta\neq0$ and $\xi\in(0,\pi)$, and as a result, we can get $\Delta I\neq0$ in Fig. 3 (a). ΔI is zero only when $\theta,\xi=m\pi$. The result under this condition can be seen in Fig. 3(b). Comparably, θ is easier to change than ξ. Thus, the measured results of γ_{13} and γ_{63} will be accurate when the polarity of incident light is parallel to one of the polarity axes of the sample materials. As a result, in the condition that $\xi\neq m\pi$, we can determine the polarization axes of EO materials through the value of ΔI before the real measurement is performed.

The intensity ratio as a function of the modulation voltage for different materials is shown in Fig. 4. Through Eq. (8), we can see that the slope of the curves is proportional to the EO coefficient of different materials. The EO coefficients can then be calculated. For GaAs, the measured and calculated results are $r_{41}=0.43$pm/V. For KTP, $r_{23}=8.9$pm/V, and for SiGe superlattice (10-period 0.5nm-$Si_{0.75}Ge_{0.25}$/10.3nm-Si/2.5nm-$Si_{0.5}Ge_{0.5}$), $r_{13}=0.24$pm/V and $r_{63}=0.13$pm/V. From the result, we can see that there is a good linear relationship between the applied voltage and the intensity ratio. The measured EO effect of KTP and GaAs are 2～3 times less than the reported results, which might be due to the bad characteristics of the sample itself. We also measured the EO effect of GaN thin film materials, and the measured result is similar to what was reported in Ref. [9].

It should be noted that it is difficult to measure the EO coefficient of thin-film material because of its small value. As far as we know, no experimental result has been reported on the EO co-

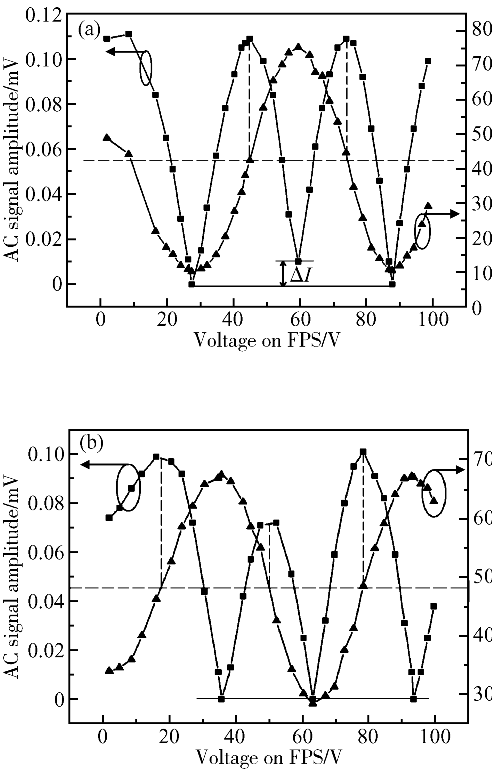

Fig. 3 DC and AC signal amplitude of KTP under 1.55μm incident light (a) The polarization direction of incident light is not parallel to the polarization axes of material; (b) The incident light is parallel to the polarization axes of material

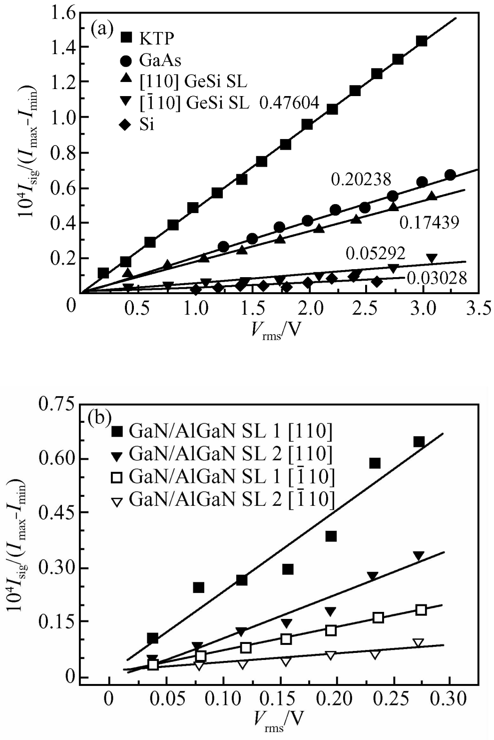

Fig. 4 Intensity ratios as function of applied modulation voltage for different materials

efficient of SiGe/Si/SiGe and GaN/AlGaN superlattices before, although Zhang *et al*.[10] reported that the second nonlinear coefficient of SiGe/Si/SiGe is 0.6×10^{-6} esu ($1\text{esu}=4.189\times10^{-4}$ m/V), which is about 240pm/V. If we use $\chi^{(2)}=\frac{1}{2}n_0^4\gamma$, which may be not suitable for SiGe/Si/SiGe material, to estimate the EO coefficient, the calculated EO coefficient is 3.2pm/V with the refractive index of silicon $n_0=3.5$. But this is just an estimation. Rong *et al*.[11] gave a pure calculated result for the EO coefficient. That is $r_{13}=8$pm/V and $r_{63}=1$pm/V, which is about ten times larger than our result. There are two main reasons: first, the larger and more precise result can only be obtained under a high electrical field. But for thin-film samples, only a small voltage can be applied to the sample. A large part of that voltage is applied to the substrate material, following which, the measured EO coefficient is actually smaller then the real value. The second reason is that the fabrication process of thin-film superlattice using UHV/CVD has not been optimized. A higher EO effect can be expected under a better working condition of the equipment.

4 Conclusions

In summary, a polarization-maintaining fiber MZ interferometer was established to measure the EO effect of different kinds of thin-film materials. Unlike a common MZ interferometer, all the components are connected together with polarization-maintaining fibers to guarantee that the light polarization remains constant during the measurement. The incident polarization direction can be chosen by rotating the sample in the plane vertical to the incident light direction. At the same time, a polarized DFB laser with high power output is adopted as the light source to excite a large extinction ratio. Experimental results of SiGe/Si/SiGe and GaN/AlGaN superlattices and GaAs, KTP, and GaN materials show that this polarization-maintaining fiber MZ interferometer is efficient in measuring the EO coefficients of thin-film materials with optical anisotropy, not just bulk materials. Furthermore, with these EO materials, a high speed EO modulator can be fabricated and utilized in future systems on chip.

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利用保偏光纤马赫-曾德(MZ)干涉仪测量薄膜材料电光系数*

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摘要： 利用保偏光纤 MZ 干涉仪测量了光学各向异性薄膜材料的电光效应. 与传统 MZ 干涉仪相比，该干涉仪中所有的部件都采用保偏光纤进行连接. 光源采用一个偏振输出最大功率为 10mW 的 DFB 激光器，用以得到高的信噪比. 用该激光器测量超晶格材料的电光系数，同时用 GaAs，KTP 和 GaN 材料作为对比材料. 测量的电光系数和已有结果有较好的可比性.

关键词： 电光效应；保偏光纤；MZ 干涉仪
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