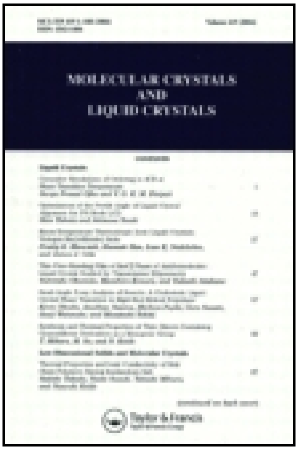

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ELECTRIC-FIELD DISTRIBUTIONS IN COPLANAR ELECTRODE POLED POLYMERS MEASURED BY ELECTRO-OPTIC EFFECTS

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Abstract Electric-field distributions in coplanar-electrode configurations are measured by the linear electro-optic (EO) effects in poled EO polymers. Thermoplastic poling of an isotropic guest-host polyimide system was employed to investigate the electrostatic factors determining the field distribution inside the EO polymer. Electrostatic analysis of the field distribution shows that the introduction of a new boundary condition formed by the polymer surface is necessary to account for field distributions measured by the linear EO effect.

1. Introduction

Polymeric materials have been widely studied as electro-optic (EO) materials for their high processability and compatibility with current microelectronic techniques as well as for the intrinsic high-bandwidth response of organic molecules.[1] [2] In EO polymers, the centrosymmetry of polymer thin films is removed by a dc electric field poling to achieve a macroscopic polar alignment of nonlinear optical chromophores. In thin film samples, two configurations of electrodes are commonly adopted for the electric field poling, parallel and coplanar. In the parallel-plate configuration, EO polymer is sandwiched between two thin electrode plates on top of a substrate. In the coplanar electrode structure, two thin separate electrodes with a narrow gap inbetween them are deposited on top of substrate, and then EO polymer film is spin-coated. (See Figure(1)) In coplanar electrode configurations, the film covers both electrodes and the dc poling and EO effect measuring fields pass through and above the film making the electric field distribution complicated. When a practical EO device is designed for light modulations, coplanar electrode design has a merit as far as processability is concerned, compared to parallel plate electrode design. It removes at least one or two steps of metalization process for poling and modulation operation. In addition to the practical reason, the coplanar electrode configuration is found to be useful for the electro-optic sampling of high-speed signal transmissions in integrated circuits [3] and also for high frequency light modulator [4]. In this paper, the electric field distribution in the coplanar electrode configuration is examined experimentally by preparing (electric field poling) thin film samples and measuring EO effect.

Theoretical analysis of electrostatics with appropriate boundary conditions is compared with the experimental measurement and we find that there is a good agreement.

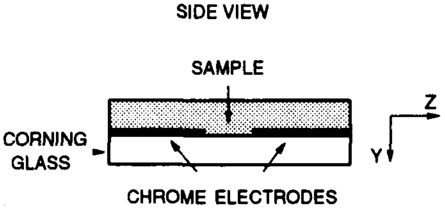

Figure 1. Sample geometry is shown. Chrome electrodes are patterned on top of optical substrate. NLO polymer is spin-coated onto the patterned electrode.

2. Experimental

To study the electric field distribution experimentally from EO measurement, we employed a guest-host polyimide system. Since we are interested in the field distribution, we should be careful in selecting model system to get rid of effects other than the electrostatics. Structural anisotropy inherent to polymer films and charge concentration near electrodes, for example, may distort the electric field distribution. To minimize the structural anisotropy we chose LQ2200 compound (*Hitachi Chemical Co.*) as the host polyimide system, which is known to possess an isotropic structure (optically and dielectrically).[7] Furthermore, the guest-host polyimide system should have a sufficient thermal stability of EO response at room temperatures after poling to study the field distribution.[8] In this regard, a stilbene dye, 4-(dicyanomethylene) -2-methyl -6-(p-dimetylaminostyryl -4H-pyran) (DCM) molecule, was chosen as guest nonlinear optical molecules, and we adopted the post-imidization (thermoplastic) poling for the electric field poling.[9] It's known that charge injection occurs in the coplanar electrode configuration when the dc poling field is applied at temperatures above the glass transition temperature T_g of polymer[11]. Sometimes the charge injection seems to lead to an apparent enhancement of EO response.[12] In order to take care of this charge injection problem, we kept the poling temperature at least 50°C below T_g.

In preparing samples, 10μm gap coplanar chromium electrodes were patterned on top of fused quartz. In order to study the electric field distribution vertical to the electrode plane, six samples were prepared. Sample 1 has the EO polymer (DCM-LQ2200) of 2μm thickness right on top of the coplanar electrodes. After curing at 250°C for half an hour, it was poled at the poling field strength of 50V/μm at 200°C (about 50°C below T_g) for 1 minute to minimize the charge injection. In the sample 2, the base polymer with thickness of 2μm was spin-coated on top of coplanar electrodes and fully cured at 300°C. After that, the same EO polymer was spin-coated on top of the fully cured bare polymer, and cured again at 250°C for half an hour. The poling was performed at the identical condition as sample 1. The same step was repeated for the samples 3, 4, 5, and 6, only the bare polymer thickness increased through successive spin-coating and curing. In this way, EO polymer of the same thickness is positioned on top of the electrodes with different vertical distance from the electrode, bare polymer films providing different spacings.

Since the EO signal has a good thermal stability at room temperature, it is easy to do the EO measurement and compare the signals. The cross-polarizer lock-in technique was employed to measure the EO response.[8][15] Figure(2) shows the measured EO signal as a function of the film thickness. Nonlinear optical molecules residing inside the EO polymer give rise to the measured EO signal, the magnitude providing informations on the field distributions in the top layer. That is, the electric field distribution determines both the orientational distribution function of guest molecules and the amount of detected EO response. Different thickness samples will sample the field distribution at different vertical positions above the coplanar electrodes. As expected, the EO signal decreases rapidly as the film gets thicker.

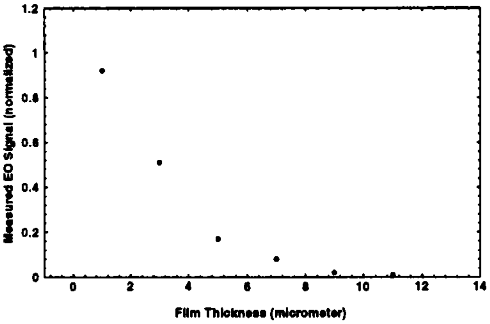

Figure 2. Measured EO signal using a corss-polarizers lock-in technique for different thickness polymer films.

3. Theoretical Analysis

In the electrostatics, electric field distribution is obtained from the electrostatic potential. Electrostatic potential satisfies Laplace equation in the absence of free charges. In this case, the field distribution is determined solely from the boundary conditions. For two electrodes with a finite potential difference, the electric field distribution is given in an elementary way. However, the dielectric constants of polymer films being different from that of the air, the presence of a film on top of conductor (electrodes) provides another boundary condition for the Laplace equation. One way to solve the boundary-value problem like this is to introduce image charges. The image-charge method is very useful for the geometrically symmetric shaped electrodes, which is the case for coplanar electrodes. The position and size of the image charges depend on the thickness and the dielectric constant of the polymer film.[5]

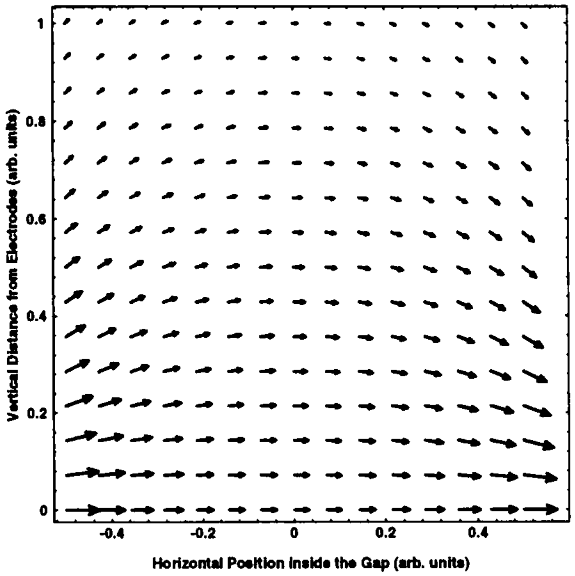

Figure 3. Computer simulated plot of electric field lines in coplanar electrode configuration. x-axis (abscisca) and y-axis (ordinate) are equally scaled. Coplanar electrodes (not shown here) are placed on the left (x=-1.0) and right (x=+1.0) bottom. The dielectric constant ϵ of polymer thin film is taken as 3.4 [Ref.6]. The position of image charge is on the mirror-reflected point of the electrodes with respect to the polymer thin film top surface, plane of $y = +1.0$. That is, in this particular example the film thickness is half of the electrode gap size. The magnitude of the image charge is $\frac{\epsilon-1}{\epsilon+1}$.

Figure (3) shows the computer plotting of the simulated electric field distribution for a thick polymer film when the proper image charge and the dielectric constant of the polymer film are taken into account. Field strength gradually decreases as the vertical distance from the substrate increases. Field components along the substrate, responsible for the EO effect in the coplanar electrode configuration, also are not uniform across the gap. These variations will lead to a change of EO effects for films with different thicknesses.

From the simple variation of the field distribution, two effects accumulate to result in a large difference in the EO effect for films with different thicknesses. First, most importantly, the orientational distribution of nonlinear optical molecules is different. Ratio of the dipolar interaction energy to the thermal energy, $x = \frac{\mu E_p}{kT}$, varies inside the polymer film since the electric field distribution is not uniform. This means that one single distribution function cannot describe the thermodynamic molecular alignment properly. The second effect, equally important, comes in when the linear EO effect is measured. These two effects combine to give an overall variation on the EO effect for coplanar electrode poled polymer thin films with different thicknesses. The phase-shift difference $\Delta\phi = \phi_{\parallel} - \phi_{\perp}$ between the parallel and perpendicular components of a linearly polarized light along 45° relative to the poling field direction can be expressed in terms of the EO molecular hyperpolarizability $\beta_{ijk}(-\omega;\omega,0)$. For a linearly shaped molecule like DCM, $\beta_{333}(-\omega;\omega,0)$, the principal axis component along the molecular axis, is dominant. In the lowest order, $\Delta\phi$ is [16] [17]

$$\Delta\phi \propto \beta_{333}(-\omega;\omega,0)\frac{\mu E_p}{kT}E^0$$

Here both the poling field E_p and the measuring field E^0 have distorted field distribution as shown in Figure (2), while the optical field E^{ω} passing through the film is not affected by field distortions.

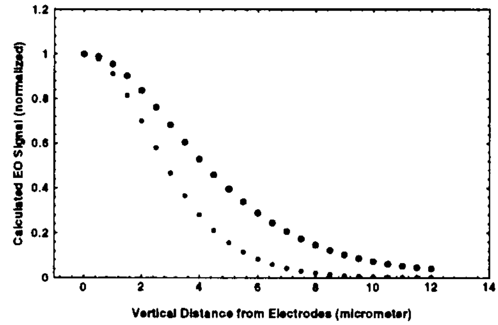

Figure 4. Calculated EO signal (closed circles) for different thickness polymer films. The magnitude decrease rapidly as the film thickness increases. Calculated electrostatic fields along the susbstrate plane (open circles) are shown for comparison.

In Figure(4), these calculated magnitudes of EO signal (closed circles) are drawn for EO polymer thin films with different thickness base polymer. Also drawn are the algebraic sum of electric field horizontal components (open circles), not the squared values, for comparison. It is obvious that the measured EO signals are in good agreement with the calculated EO signals. This suggests that distortions of the electrics fields in coplanar electrodes affects both the orientational distributions of chromophores and the EO measurements, resulting in quite reduced overall signals for thick films.

4. Conclusion

The electric field distributions in coplanar electrode configurations are investigated by measuring electro-optic response in poled DCM-LQ2200 guest-host polyimide system. Electro-optic effects for films with different thicknesses provide informations on the field distributions. Rapid decrease of the measured electro-optic response as the film thickness increases agrees well with the calculated electric field distributions when proper boundary conditions are taken into account.

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