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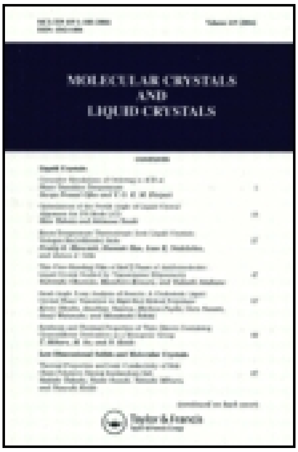

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Polarization Properties of a Liquid Crystal Phase Grating

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POLARIZATION PROPERTIES OF A LIQUID CRYSTAL PHASE GRATING

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Abstract By measuring Stokes parameters of diffracted light versus applied voltages, polarization and diffraction properties of a liquid crystal phase grating (LCPG) are investigated at the first time. With this kind of LC phase gratings, high diffraction efficiencies and contrast ratios can be realized readily. And its polarization properties can be electrically varied as well as diffraction light intensities. A unique property of symmetrical diffraction light intensities but antisymmetrical polarization states in corresponding positive and negative diffraction orders is shown.

INTRODUCTION

The investigations of liquid crystal (LC) gratings have been concentrated mainly on their diffraction characteristics, and demonstrated that they have potential in applications of optical processing and computing, diffractive optics, and image display devices.[1-3] However, since liquid crystal materials are optical anisotropic, investigations of polarization properties of LC gratings are needed. Recently we have investigated polarization characteristics of an amplitude LC grating (ALCG), in which an aluminum (Al) grating electrode structure is used to yield a periodic electric field, and then induce a periodic LC molecular orientation. The LC molecules in this ALCG have an initial homogeneous alignment parallel to the grating direction. We have demonstrated that polarization modulations can be performed readily in this LC grating, as well as its diffraction light intensities. And an interesting property of symmetrical diffraction light intensities but antisymmetrical polarization property between corresponding positive and negative diffraction orders is shown.[4,5] However, due to the amplitude-type electrode grating structure, diffraction efficiencies of the LC grating are not high. In this study, we fabricate a liquid crystal phase grating (LCPG) using the same cell structure but with a transparent indium-tin-oxide (ITO) grating electrode substrate. The polarization properties and diffraction efficiencies of this LCPG are discussed by measuring Stokes parameters of its diffracted light versus the applied voltage.

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EXPERIMENTAL AND RESULTS

STRUCTURE OF THE LCPG

The structure of the LCPG used in this study is shown in Fig. 1. An ITO grating electrode structure is prepared as the upper electrode substrate. Here a grating structure with $a=p/2$(=10μm) is adopted, where a is the width of non-electrode regions and p is the period of grating electrode, as shown in Fig. 1. The lower substrate is composed of uniform ITO electrode. All electrode substrates are spin-coated with polyvinylalcohol (PVA), and then rubbed to obtain homogeneous alignment parallel to the y-axis direction, e.g. the grating direction. Here we fill a nematic liquid crystal (E7) with a positive dielectric anisotropy into this cell. The cell thickness d is controlled by 5μm glass fibers. An ac (1kHz) voltage of sinusoidal wave is applied between the upper and lower electrode substrates.

Because the ITO grating electrode is transparent, if no electric fields is applied, the incident light can pass through the cell straight, but no diffraction. However, when an electric field is applied, the LC molecules are re-oriented. We have investigated LC molecular orientation profiles under an electric field. Based on our experimental results, the LC molecules under electrode regions are tilted with the increase of applied voltage, just like those in uniform, homogeneous alignment cells. However, due to the lateral electric fields induced by grating patterned electrode edges, the LC molecules near every grating electrode edge of the upper substrate are twisted toward the vertical direction from the grating direction. The ones near the lower electrode substrate are tilted out of the substrate surface in the rubbing plane. We refer to the reorientation of LC molecules in the non-electrode regions of upper electrode as the electrically induced hybrid twisted nematic (EHTN) liquid

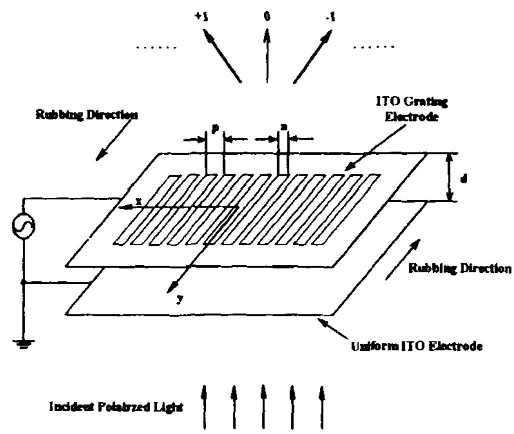

FIGURE 1 Structure of the LC phase grating used in this study

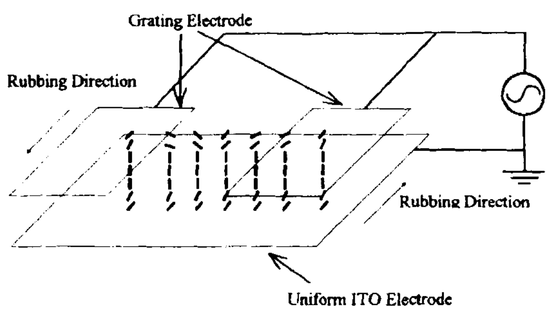

FIGURE 2 LC molecular orientation profiles in a period of grating under an electric field

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crystal orientation effect.[6] Furthermore, we have determined that the molecules in left and right areas of every non-electrode region are inversely twisted. Figure 2 shows liquid crystal molecular orientation profiles in one period of the grating. Obviously a periodic LC molecular orientation is induced, and the azimuthal angles and polar angles of LC molecules depend on their positions and the electric field strength. Therefore, as the light transmitted through different positions experiences various optical retardations and twist effects, which depend on the strength of electric fields, optical properties of the complicated LC phase grating can be electrically controlled.

In order to study polarization and diffraction properties of the LC grating, an optical system is set up for measuring Stokes parameters of its diffracted light versus the applied voltage, as shown in Fig. 3. The light beam from a He-Ne laser source (632.8nm) passes through a polarizer to obtain necessary polarized light, and then is normally incident on the uniform ITO substrate of the grating. To measure the Stokes parameters,

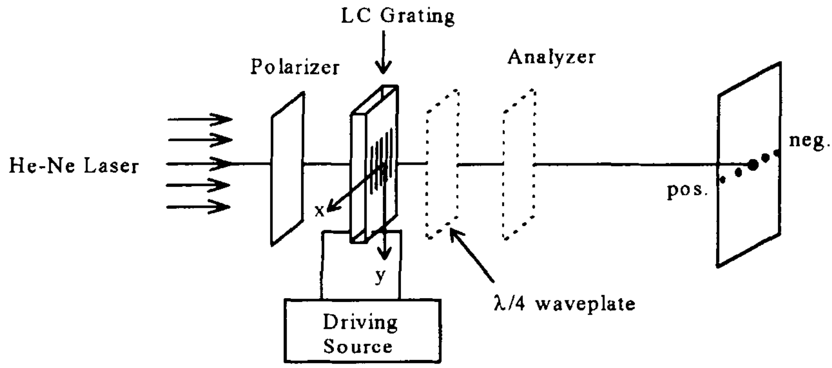

FIGURE 3 Optical measurement setup for Stokes parameters

we insert an analyzer behind the LC grating cell, and detect diffraction light intensities of I_x, I_y and $I_{45°}$ in interest diffraction orders as a function of applied voltage. And then a λ/4 waveplate is located before the analyzer of 45° with respective to x axis, while the slow axis of λ/4 waveplate is parallel to the y axis. The measured diffraction light intensity is defined as $I_{q,45°}$. With these light intensities, we can calculate Stokes parameters of diffracted light in the following equation.[7]

$$\begin{cases} S_0 = (I_x + I_y)/(I_x + I_y) = 1 \\ S_1 = (I_x - I_y)/(I_x + I_y) \\ S_2 = [2I_{45^\circ} - (I_x + I_y)]/(I_x + I_y) \\ S_3 = -[2I_{q,45^\circ} - (I_x + I_y)]/(I_x + I_y) \end{cases} \tag{1}$$

Clearly the diffraction light intensity is given by (I_x+I_y). To analyze polarization properties, we adopt normalized Stokes parameters, where all Stokes parameters are normalized by the diffraction light intensity of interest diffraction orders, so that S_0 is always 1, but the Stokes parameters of S_1, S_2, and S_3 are a function of applied voltages.

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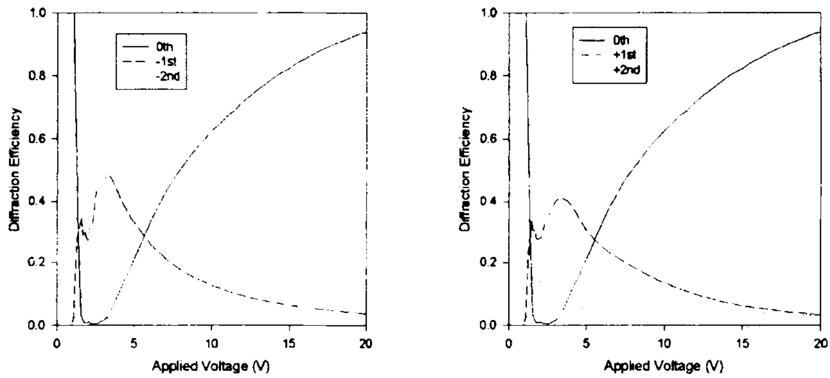
DIFFRACTION PROPERTIES

Here we give the experimental results when a linearly polarized light parallel to the y axis is incident on the phase grating. Figure 4 shows diffraction efficiencies of light in the 0th, ±1st and ±2nd orders with voltage up to 20V, where diffraction efficiency is defined as the



(a) (b)

FIGURE 4 Diffraction efficiencies of the LC phase grating versus applied voltages. (a) 0th and negative orders, (b) 0th and positive orders

ratio of diffraction light intensity to the transmission light intensity of the 0th order in the absence of electric field. It is obvious that diffraction efficiencies of various orders can be varied greatly by changing the voltage applied to the cell. Particularly at ±1st orders the maximum diffraction efficiencies are up to about 45%. And as the diffracted light of ±1st orders is almost zero when no electric field is applied, much high contrast ratios (>800) can be realized readily in these diffraction orders. Additionally, the contrast ratio in the 0th order is much than 200. Furthermore, comparing the diffraction properties of positive and negative orders, we are confirmed that there is a symmetry of diffraction light intensity modulations in corresponding positive and negative diffraction orders.

POLARIZATION PROPERTIES

The Stokes parameters of the 0th and the ±1st orders are shown in Figs. 5(a)-(c) as a function of the applied voltages. Obviously, when no electric field is applied to the LC grating cell, diffracted light of the 0th order is linearly polarized light parallel to the polarization direction of incident light. However, when a voltage is applied, the polarization properties of light in various diffraction orders are different with each other. The light of the 0th order is almost linearly polarized in the whole range of voltages with the same polarization direction as that of incident light, e.g., y axis direction. In other words, the polarization state of diffraction light in the 0th order is not a function of applied voltages. However, the diffraction light of the ±1st orders is found to be elliptically polarized, and their polarization states can be changed significantly by the applied voltage. We also measure the Stokes parameters of diffraction light in other orders and verify that these diffraction light is elliptically polarized. Therefore, polarization modulations of

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diffracted light can be easily implemented in this kind of LC grating, as well as that in the amplitude type LC grating.

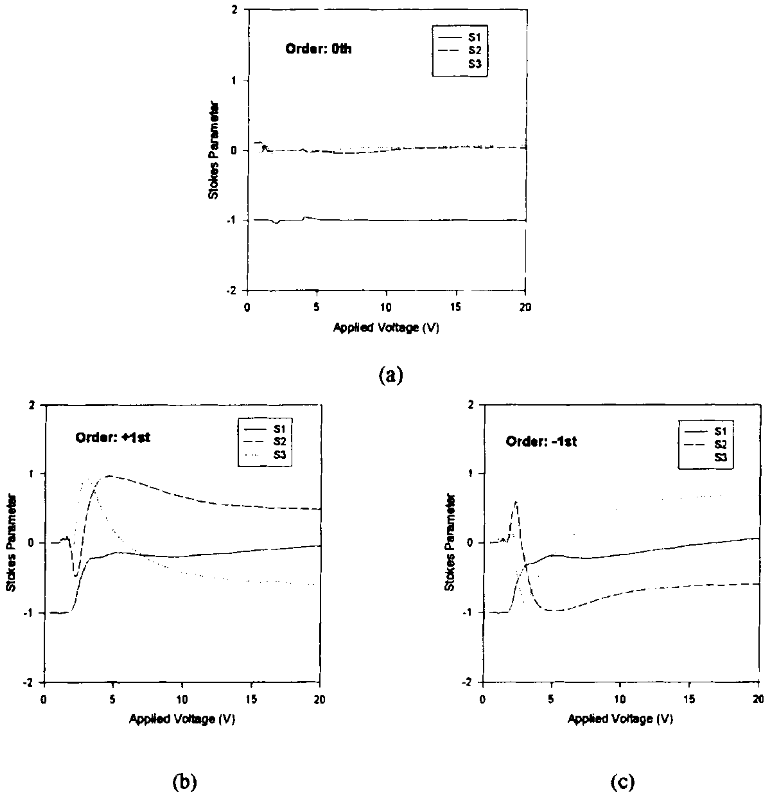

FIGURE 5 Polarization Properties of (a) the 0th order, (b) the +1st order, and (c) the -1st order

Comparing the polarization behavior of light in the -1st order with that in the +1st order, we find that the Stokes parameter S_1 is similar, but the Stokes parameter S_2 and S_3 are almost antisymmetric each other. The relationship means that the major axes of diffraction light ellipses in the -1st order and the +1st order are antisymmetric with respect to y axis, and their rotation directions are also antisymmetric, e.g. if the elliptically polarized light in the +1st order is left-handed rotation, the elliptically polarized light in the -1st order is right-handed rotation. We also demonstrate a similar relationship in other diffraction orders. Noting the diffraction efficiencies in negative and positive orders, we suggest that polarization properties of diffracted light in corresponding

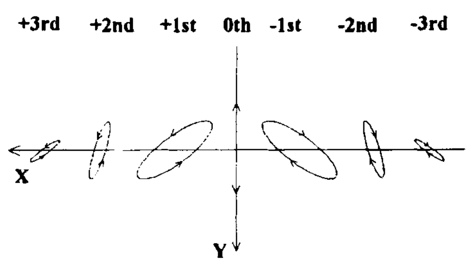

FIGURE 6 A model of polarization states of diffracted light

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negative and positive orders are antisymmetric with each other, although the diffraction light intensities are symmetric. A model of polarization states of diffracted light in the 0th, ±1st, ±2nd and ±3rd orders is depicted schematically in Fig. 6.

We also investigate polarization and diffraction modulation properties of this grating when a linearly polarized light parallel to the x-axis direction is used, and demonstrate the similar antisymmetrical polarization property.

We are trying to find the reason of antisymmetric polarization pro-perties in this kind of LC grating.[5] According to our present results, we suggest that the cause of antisymmetrical polarization property is perhaps related to two inverse twisted domains induced by inhomogeneous electric fields.

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CONCLUSION

Polarization and diffraction properties of the LC phase grating with a grating electrode structure are investigated at the first time by measuring Stokes parameters of its diffracted light. The diffraction efficiencies can be significantly controlled by the voltage applied to the grating cell. And high diffraction efficiencies (more than 45% in the ±1st orders) and contrast ratios (>800 in the same orders) are observed, compared with those in the amplitude type LC grating. The diffraction light intensities in corresponding negative and positive orders are identical, however, their polarization states are antisymmetric, as well as that in amplitude type LC grating. This kind of LC grating can be used as not only a field-controllable light intensity modulator, but also a field-controllable polarization modulator. Due to its high diffraction efficiencies and contrast ratios, this kind of LC gratings are expected to be applicable to optical information processing, optical interconnections and diffractive optics.

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