Electrooptical Properties of a Polymer/LC Grating Fabricated by UV Irradiation

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Electrooptical properties of a polymer/LC grating, which is fabricated by UV irradiation using a mixture of liquid crystal and prepolymer, have been investigated. The diffraction light can be easily controlled by an applied voltage. The response times depend strongly on the applied voltage. On the other hand, recovery times depend slightly on the applied voltage. The response and recovery times around tens of millisecond have been achieved for a lower driving voltage (10 V). Experimental results also show that the high diffraction efficiency of 30 % for the 1st-order and good extinction ratio over 60 : 1 are obtained. The groove depth which influences the diffraction efficiency, has also been measured and discussed in various fabrication conditions.

Keywords: polymer/LC grating, UV irradiation, diffraction efficiency, electrooptical properties

1. Introduction
Electro-optic gratings [1-3] are very useful in many areas in which the diffraction efficiency of a grating needs to be controlled by a voltage signal, such as optical interconnection, optical communication and optical computing. These gratings are usually fabricated by using crystal materials, therefore a high driving voltage is required. Recent years, liquid crystal (LC) electro-optic gratings have attracted attention, because they can be operated at a low voltage with a low power consumption.

There are various types of liquid crystal grating, such as surface-relief type [4,5], patterned electrodes type [4,6,7], patterned alignment layers type [8], polymer-dispersed liquid crystal (PDLC) type [9] and etc. We have proposed a simple method to fabricate a polymer/LC grating by a single-step process using a mixture of liquid crystal and prepolymer [10]. The polymer/LC grating has independent layers of liquid crystal and polymer, and has a periodic groove structure of cured polymer filled with the liquid crystal. Such the structure can be fabricated spontaneously after polymerization by UV irradiation through a photo mask. In this paper, electrooptical properties of this polymer/LC grating have been investigated, and the groove depth which influences diffraction efficiency has been measured in various fabrication conditions.

2. Experimental
We adopt the same fabrication method of the polymer/LC grating as reported in previous paper [10]. Monomer HX-620 with photo-initiator Irg-184 and nematic liquid crystal E7 are used in these experiments. Three percent of Irg-184 is doped into HX-620 by weight. The refractive indices of cured HX-620 are 1.479, and those of E7 for extraordinary and ordinary rays are 1.724 and 1.515, respectively (25 °C, 670 nm).

The mixture is sandwiched between ITO (indium-tin-oxide)-coated glass substrates which are coated with polyvinylalcohol (PVA) and treated by rubbing. The thickness of liquid crystal cells is controlled by using a polymer spacer with the thickness of 11 µm.

These cells are irradiated by collimated UV light through a chrome photo mask with a grating.
pattern. A high pressure Hg lamp is used as a UV light source (peak intensity at 365 nm). The UV intensity is 20 mW/cm². The temperature during the polymerization and phase separation for forming the grating structure is maintained by a hot plate. The grating lines of the photo mask are set along the rubbing direction.

In our fabrication method, the cured polymer layer with a periodic groove structure can be obtained. In order to measure the groove depth of the grating, the fabricated grating cells are treated to remove one of the glass substrates, and the liquid crystal is washed away. The groove depth of the polymer/LC grating fabricated under various conditions is measured by using interference microscope.

Electrooptical properties of the polymer/LC grating are measured using a diode laser (670 nm) as a light source, where a polarizer is placed between the light source and a liquid crystal grating cell. The liquid crystal cell is driven by the 1 kHz sinusoidal AC voltages. The diffraction light through the liquid crystal grating is measured using a photodiode detector. Response property is measured using a storage oscilloscope connected to the photodiode. All measurements are carried out at room temperature.

3. Results and Discussion
3.1 Groove Depth of the Polymer/LC Grating

Figure 1 (a) and (b) show the structure of the polymer/LC grating. Figure 1 (a) shows a photomicrograph of the polymer/LC grating investigated with a polarizing microscope. The periodic stripes corresponding to the photo-mask can be investigated. The observation under crossed polarizers also shows that a good homogenous alignment along the rubbing direction of the substrate is obtained. Figure 1 (b) shows a SEM photograph of the cured polymer surface, where the sample is treated as described above, and the cured polymer surface is coated with thin Au-Pd film. The surface-relief structure with periodic grooves is observed.

In order to obtain diffraction gratings with a high efficiency, we have investigated the groove depth of the grating in various fabrication conditions, such as the concentration of liquid crystal, the curing temperature, the energy of UV irradiation and the period of the grating pattern.

Figure 2 shows the groove depth dependence of the polymer/LC grating in various liquid crystal concentrations. We have fabricated the polymer/LC gratings with varying the LC concentration.

![A photomicrograph of the polymer/LC grating, where the grating period is 4 µm.](image1)

![A SEM photograph of the cured polymer surface, where the grating period is 200 µm.](image2)

![Fig. 1 The structure of the polymer/LC grating](image3)

![Fig. 2 LC concentrations dependence of the groove depth.](image4)
concentration from 20 wt% to 83 wt%. The polymer/LC grating cells with 100 µm period have been obtained by 10 minutes of UV irradiation at 25 °C. Around 50 % of the LC concentration, the depth of the polymer/LC grating is maximum. When the LC concentration is above 80 %, large light scattering effects are observed and the groove depth of the grating can not be measured. The similar results are obtained at 50 °C as reported previously [11]. The concentration of liquid crystal affects the grating structure, and it is selected to become PDLC type grating or polymer/LC type grating.

Figure 3 shows the curing temperature dependence of the groove depth. The polymer/LC grating cells have been fabricated by irradiating 10 minutes of UV light in the curing temperature range from 24 °C to 100 °C. The period of the grating is 100 µm , and the concentration of the liquid crystal is 50 %. The groove depth increases as the curing temperature increases. When the temperature is above 40 °C, the groove depth becomes almost constant. It was also observed that the transmittance reduces by a light scattering effect in lower curing temperature.

We have also changed the intensity of UV irradiation and the duration of UV irradiation to fabricate the polymer/LC grating. Figure 4 shows the dependence of the groove depth on the energy of UV light, where the irradiation times are changed from 0.1 min to 10 min. The temperature is maintained at 50 °C during the curing process. The period of the grating is 100 µm , and the concentration of the liquid crystal is 50 %. As a result, the groove depth changes with varying the energy of UV irradiation. We think that it is a good method to control the depth of the polymer/LC grating. Although the groove depth can be controlled by varying the LC concentration or curing temperature, the gratings fabricated in some condition may have a light scattering effect which reduces the diffraction efficiency as described above.

Fig. 3 Curing temperature dependence of the groove depth.

Fig. 4 Energy of UV irradiation dependence of the groove depth.

Fig. 5 The grating period dependence of the groove depth.

In the following experiments, the polymer/LC grating cells have been fabricated using the 50 % mixture of liquid crystal and prepolymer by 10 minutes of UV irradiation at 50 °C. We chose this
irradiation condition for obtaining a thicker groove depth and making sure of photocuring process completely.

Figure 5 shows the groove depth of the polymer/LC gratings whose periods are from 4 µm to 200 µm. When the grating periods are above 30 µm, the thicker groove depth is obtained. The groove depth decreases rapidly as the grating period decreases in a short period region, because it is strongly affected by the UV light diffraction in photocuring process.

3.2 Diffraction Efficiency

Figure 6 shows the diffraction efficiency of the 1st-order versus the grating period curve. The measurement is done at no applied voltage. When a grating period is sufficiently larger than the incident light wavelength, diffraction efficiency can be applicable to a function of θ, where $\theta = \pi d (n_{LC} - n_p) / \lambda$, d is the groove depth, $n_{LC}$ is the refractive index of liquid crystal, $n_p$ is the refractive index of polymer, and $\lambda$ is the incident light wavelength [5]. Thus, diffraction efficiency is strongly influenced by the groove depth. It is clear that the diffraction efficiency changes with the groove depth as shown in Fig. 4. The diffracted angle is decided by grating period ($\Lambda$) as $\Lambda \cdot \sin \alpha_m = m \cdot \lambda$, when an incident angle is zero, where $m$ is an integer corresponding to the diffraction order, and $\alpha_m$ is the corresponding angle of diffraction. It is seen that the maximum efficiency is attained to be 30 %, and the diffraction efficiency of 0.5 % can be observed at 4 µm.

Since the liquid crystal molecules are aligned along the rubbing direction (grating line direction) in the polymer/LC grating, the polarization dependence of the diffraction properties has been observed. Diffraction light intensity of the 0th-order and the 1st-order as a function of applied voltage are shown in Fig. 7 (a) and (b), respectively. When an extraordinary ray is incident upon the polymer/LC grating, the intensity of the 0th-order increases and that of the 1st-order decrease as the applied voltage increases.

When the applied voltage is high enough, the saturated diffraction intensity is obtained. The applied voltage at which the cell shows 90 % of its maximum intensity is about 10 V, and the
threshold voltage is about 4 V. When no electric field is applied, the diffraction efficiency of the 1st-order is maximum, and is about 30%. The transmittance is about 80% for the 0th-order at the applied voltage of 20V.

The extinction ratios are about 46:1 and 12:1 for the 0th-order and the 1st-order at 10V, respectively. They become over 60 for both the 0th-order and first-order under the applied voltage of 20 V.

On the other hand, When an ordinary ray is incident upon the polymer/LC grating, the intensity of the 0th-order and the 1st-order do not change with applied voltage, because an effective refractive index of the liquid crystal does not change as the applied voltage increases.

3.3 Response Property

Figure 8 shows the measured response property. The voltage of 10 V is applied at the time t=0, and is switched off at the time t=100ms. The response time (t_{on}) is defined as t_{on} = t_0 + t_R , where t_0 and t_R are delay time and rise time, respectively. The recovery time (t_{off}) is defined as decay time (t_D). In this case, the rise time (t_R) is about 9 ms, and both of the response time (t_{on}) and the recovery time (t_{off}) are about 15 ms.

Figure 9 shows applied voltage dependence of rise and decay times which have been measured between 5 V and 20 V. The rise times decrease rapidly as the applied voltage increases. The rise time vs. applied voltage curve can be fitted by a inverse square curve. It is seen that the rise times are inversely proportional to the square of the applied voltage. On the other hand, the decay times slightly increase with increasing the applied voltage.

4. Conclusion

We have fabricated the polymer/LC grating in various conditions and their electrooptical properties have been measured.

The groove depth can be controlled by varying the energy of UV irradiation, and the experimental results show that the diffraction efficiency is strongly dependent on the groove depth.

The polarization dependence of diffraction properties have been investigated. For the extraordinary ray, high diffraction efficiencies about 30% for the 1st-order have been obtained, and the transmittance for the 0th-order is 80%.

Their extinction ratios are over 60 both for the 0th-order and the 1st-order diffraction at applied voltage of 20 V. The applied voltage at which the cell shows 90% of its maximum intensity is about 10 V, and the threshold voltage is about 4 V.

The rise time and the decay time are about 9 ms and 15 ms under 10 V, respectively. The rise times are depend strongly on the applied voltage, and the decay times depend slightly on the applied voltage.

The polymer/LC grating, which can be fabricated with a single process, is a useful device for beam steering and switching device
because of their high diffraction efficiency and a lower driving voltage.

References