Mechanical Deformation of a Liquid Crystal Diffraction Grating in an Elastic Polymer

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ABSTRACT: We demonstrate the tuning of the diffraction efficiency in a polymer-dispersed liquid crystal (PDLC) diffraction grating by mechanical shear deformation. We chose a photocurable thermoset with elastic mechanical properties as the host material to demonstrate the tuning effect. Raman–Nath gratings were prepared by anisotropically curing a mixture of commercial photopolymer doped with liquid crystal. The mixture was contained between glass slides which were mounted in a simple shearing device. During the photopolymerization, the liquid crystal phase separated into 2-μm droplets organized into channels with 3.8-μm spacing. Gratings were deformed by shearing the samples in a direction perpendicular to the channel orientation. The diffraction intensity and morphology were monitored as a function of shear strain. Reversible tuning was observed due to the elastic nature of the matrix. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci 68: 523–526, 1998

Key words: shear; polymer dispersed liquid crystal; diffraction grating; hologram; elastic

INTRODUCTION

Holographically recorded diffractive optical materials are useful for a variety of applications which include sensor systems, head-up displays, optical data storage, and optical interconnects for optical computing. One class of materials that is being used to make these diffractive elements is made up of polymer-dispersed liquid crystals (PDLC). The system consists of a photocurable polymer which has been mixed with a liquid crystal. During the holographic writing process, the mixture is irradiated with a spatially periodic intensity which initiates photopolymerization. The polymerization induces the liquid crystal to phase-separate from the polymer into droplets (0.1–1 μm in diameter) which are confined to relatively well-defined channels. Due to the refractive index difference between the polymer-rich channels and the liquid crystalline-rich channels, a constructive Bragg diffraction interference pattern is produced when a laser probes the grating. PDLC optical gratings operating in the Bragg[1–5] and Raman–Nath[1] regime have been reported.

Many optical devices require that the diffraction efficiency of gratings be tunable or switchable. Previous studies on PDLC gratings report tuning by altering the liquid crystal orientation within the droplet by electric fields[1–5] or by thermal methods.[3] These earlier investigations produced phase-separated liquid crystal droplets within rigid polymer matrices. Here, we report our observations of PDLC droplets formed in an elastic polymer matrix. We demonstrate a mechanical method of tuning diffraction efficiency of elastic PDLC films recorded in the Raman–Nath regime by deforming the phase-separated grating struc-

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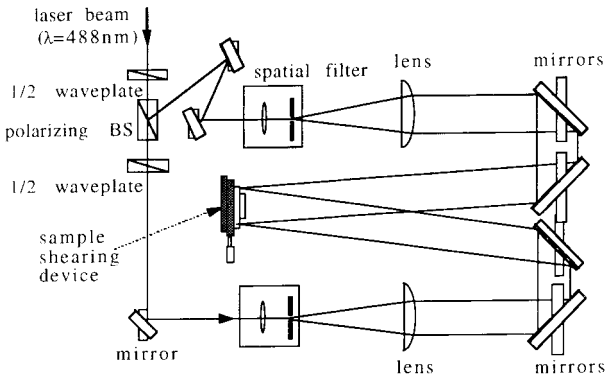

Figure 1 Holographic PDLC grating recording setup. The shearing device with the film sample is placed in the beam path.

ture. We employed a controlled plane shearing deformation to the thin films and examined the morphology and diffraction efficiency in the strained and unstrained states.

EXPERIMENTAL

Materials and Recording Process

PDLC syrups consisted of 1.0 g of NOA 65 photocurable thermoset (Norland Products, Inc.), 0.11 g of ethanol, 0.036 g of camphorquinone (photoinitiator), and 25–30 wt % of the liquid crystal E7 (EM Industries, Inc., Hawthorne, NY). When fully photocured, NOA 65 becomes a transparent film with rubbery mechanical properties at room temperature, which makes it possible to mechanically distort the grating structure of the holographic film.

The components of the syrup were homogeneously mixed by ultrasonicating for 1 min in a glass vial in the dark. A few drops of the liquid syrup were placed between glass microscope slides separated by 15-μm spacers. The glass slide sandwich was mounted in a specially designed shearing device which was then placed on an optical table in the beam path for the holographic recording process (see Fig. 1). The grating was written by exposing the sample for 10 min with 26 mW of total energy at 488 nm. The grating spacing was determined to be 3.8 μm. Large spacing was used so that we could observe changes in the morphology with a polarized optical microscope during shear.

Morphology and Diffraction Measurements

The morphology of the PDLC films was examined by placing the shearing device on the stage of a polarizing microscope (Nikon Optihot-POL). Shear strain was applied in a direction perpendicular to the grating channel direction. Photographs of the strained and unstrained states were taken at a magnification of 400×.

Two methods were used to observe the intensities of diffracted orders as the gratings were sheared. In both methods, the film-shearing device was rotated at an angle to the incident probe beam which maximized the Bragg diffraction intensity. This was the initial unstrained state. The gratings were then sheared from this initial maximum Bragg condition while measuring the diffraction intensity.

The first characterization method involved probing the grating with an argon ion laser. The diffracted beams were projected onto a flat white screen at a distance of 1 m from the sample. A video camera recorded the center and the first two side order (the 0, +1, and −1 diffracted orders) intensities as the grating were being sheared. Three or more diffracted orders were observed; however, the camera's field of view was limited to capturing only the 0, +1, and −1 orders. An optical density filter placed in the center beam kept the camera from saturating and improved the contrast between the diffracted orders.

The second technique measured the relative diffraction intensities of the 0 and +1 diffracted orders as a function of shear strain. In this setup, an encoded linear actuator controlled the shearing distance, a 1-mW polarized HeNe laser probed the sample, and silicon detectors monitored the power in each of the diffracted beams. The shear strain was slowly increased and then decreased as the intensities of the diffracted beams were recorded. The samples were cycled three to seven times and tested with the HeNe probe in both *s* and *p* polarizations.

RESULTS AND DISCUSSION

Figure 2(a) shows the morphology of the PDLC grating in the unstrained state. The liquid crystal droplets are approximately 2 μm in diameter and are confined to well-defined channels in the matrix. Figure 2(b) shows the morphology of the sample in the shear strained state after a shear displacement of 210 μm (14.3 shear units) in a direction perpendicular to the channel direction. In the strained state, the droplets maintain their spherical shape; however, they no longer appear in aligned rows of droplets as in the unstrained state. The process of deforming the channel drop-

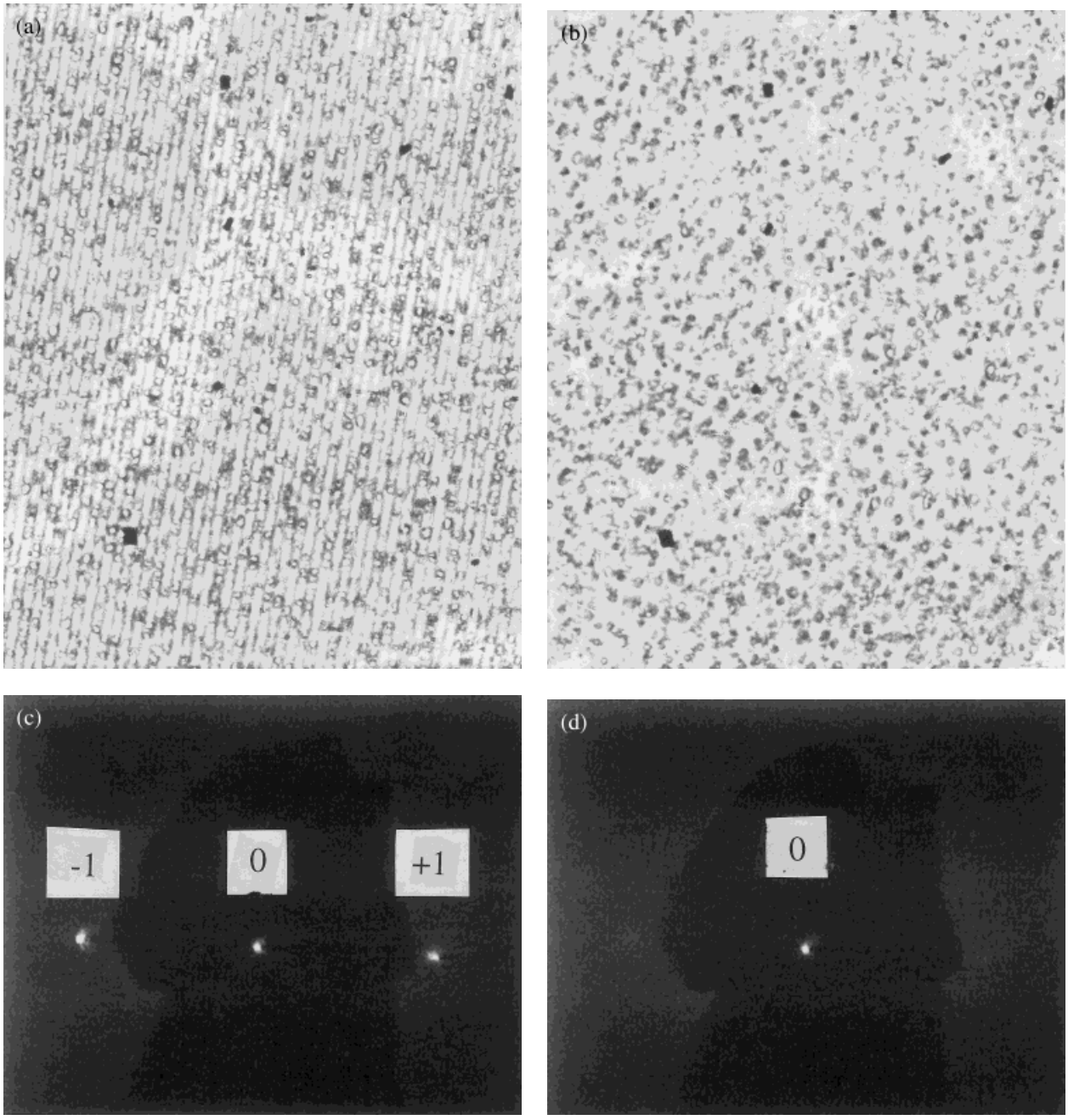

Figure 2 (a) PDLC transmission grating at 400× magnification in the unstrained state. (b) PDLC grating in the shear strained state after top plate was displaced by 210 μm. (c) Diffraction pattern of the grating in the unstrained state. The figure shows the 0-order center beam along with the −1 and +1 diffracted orders. (d) Diffraction pattern of the grating in the strained state. Only the center probe beam is seen. The −1 and +1 orders are no longer visible.

let morphology was reversible due to the elastic nature of the polymer matrix. Figure 2(c) shows the image of the diffraction pattern corresponding to the sample in the unstrained state. As the sample is strained, the intensity of the diffracted orders is attenuated to almost complete extinction as is shown in Figure 2(d).

Figure 3 shows the relationship between the relative diffraction intensity of the +1 order and the shear strain. The attenuation of the signal is

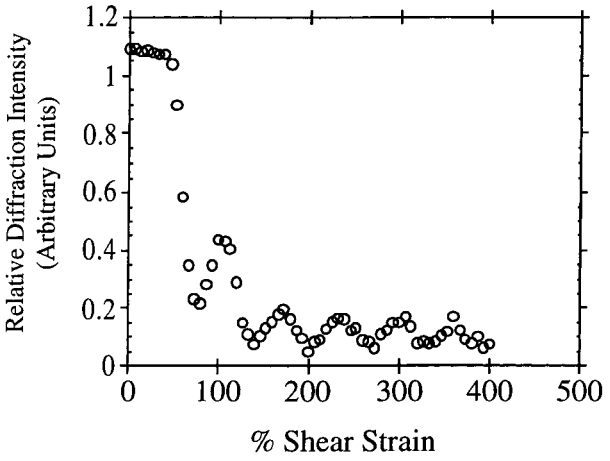

Figure 3 Relative diffraction intensity of the +1 diffracted beam as a function of percent shear strain.

quite sensitive to shear strain and decreases by more than 80% at 80% strain (i.e., 12-μm displacement). Here, we see that the attenuation of the signal exhibits a damped sinusoidal oscillation with a period of 0.8 shear units (80% strain). The damped oscillating signal is very similar to the intensity function produced by a stationary grating as it is replayed in the off-Bragg angle condition.[6] This phenomenon has also been observed in holographic gratings recorded in thick films of bleached photographic emulsions which were processed with a fixed tilted structure.[7,8]

We attribute the attenuation of the signal to the tilting of the grating channels during shear deformation. This tilting disrupts the alignment of the droplet channels which initially were stacked directly on top of each other in the unstrained state. The well-defined stacking and spacing of the droplets allows constructive interference to be maximized and thus produce the multiple diffracted orders. By mechanically deforming the matrix, the droplets are moved out of alignment and thus maximum constructive interference is suppressed, causing a dramatic decrease in the diffraction intensity. When viewing the deformation process in real time under the microscope, one can see droplets in the plane closest to the moving glass slide gliding past droplets which are stationary near the bottom immobile glass slide.

In addition to Raman–Nath gratings, we also observed shear tuning diffraction effects in PDLC films recorded in the Bragg regime. In both the Bragg and Raman–Nath elastic gratings, mechanical tuning of the diffraction efficiency was reversible for many repeated cycles of strain deformation. We observed slight hystersis effects; however, we have not studied this phenomenon in detail.

CONCLUSIONS

We have demonstrated the mechanical tuning of the diffraction efficiency in coarse PDLC transmission gratings recorded in the Raman–Nath regime. Reversible mechanical deformation of the grating morphology is possible due to the elastic nature of the polymer matrix. Tuning occurs by tilting the grating channels by imposing a shear strain perpendicular to the channel orientation which creates an off-Bragg condition and, consequently, attenuates the signal. Such a technique could lend itself to optical applications where a tilted grating structure is desired. Our method allows one to control the grating shear angle reversibly and could be advantageous to use instead of holographic gratings recorded with fixed angles. In the future, we plan to explore this shearing effect further and assess its potential for practical applications.

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