

Electro-Optical Switching Characteristics of Holograms Recorded in Polymer Dispersed Liquid Crystals

L. V. Natarajan, R. L. Sutherland*, V. P.Tondiglia**
T. J. Bunning and R. M. Neal*
Materials Directorate, Wright Laboratory, Wright-Patterson AFB, OH
** Science Applications International Corporation, Dayton, OH*

Abstract

Electro-optical switching of the diffraction efficiency in volume holographic gratings offers the possiblity of real-time control and programmability of diffractive optic components. We have recently demonstrated recording of transmission holographic Bragg gratings in a material system consisting of a photoinitiator dye, coinitiator, a chain extender, a multifunctional acrylate and a low molecular weight nematic liquid crystal. Low voltage scanning electron microscopy studies have shown that the gratings consist of periodic polymer dispersed liquid crystal (PDLC) planes. Electrical switching of a first order Bragg diffracted beam into the zero-order with an applied field of 10V/µm was observed. Addition of a surfactant to the pre-polymer syrup reduces the switching field to ~ 5 V/µm. Fast response times of the order of microseconds were observed for switching and relaxation. We have also demonstrated storage and electrical switching of holographic image data in PDLC material. The image hologram can be reversibly erased and restored repeatedly by the application of the field (10-15V/µm). Switchable reflection gratings were also made in this material system.

Introduction

Volume holograms which respond to electrical field have high potential for developing new photonic devices like switchable notch filters for reconfigurable optical interconnects in optical computing, fiber optic switches, beam steering in laser radar, and tunable diffractive filters for color projection displays. Recently, we have developed an unique material combination for recording of volume holographic gratings which consist of periodic polymer-dispersed (PDLC) liquid crystal planes formed in situ by a single step photopolymerization reaction. We have demonstrated high diffraction efficiency,narrow angular selectivity, low voltage switching (<10V/µm) and microsecond switching speeds in transmission grating (1-3). Morphology studies of the gratings have shown that very small LC droplets(20 to 200 nm) occupy well defined periodic channels. The polarization properties and sharp threshold switching of the diffracted light may be explained by the unique shape and consequent ordering of the LC droplets. Preliminary NMR studies indicate a possible homeotropic ordering with a dominant defect comparable in size to the droplet itself (4).

Experimental

The material combination consists of a multifunctional acrylate monomer, a chain extender monomer, a photoinitiator, a co-initiator, and a commercially available low moecular weight nematic liquid crystal. We employed rose bengal as photoinitiator dye, n-vinyl pyrrolidone as the chain extender and n-phenyl glycine as the co-initiator. The pre-polymer syrup containing the above constituents were mixed to form a viscous syrup. The syrup is then sheared between ITO glass plates containing a 15µm spacer. In some samples a surfactant is added to the receipe. A CW Argon ion laser was used to write transmission gratings. Rose bengal dye was used to photoinitiate the polymerization at laser wavelengths 458, 478 and 514 nm. Standard holographic techniques involving combining two beams on the sample were used. In another technique, a prism was placed before the sample to overlap the beams. We recorded transmission gratings with spacing ~ 0.5µm and 0.8 µm. The gratings are essentially formed in a single step process. Real time monitoring of the diffraction efficiency during recording indicated that gratings are fully formed in approximately 60s after a brief induction period. We also made reflection gratings by placing a mirror at the back of the sample and also by prism coupling technique.. Morphology of the gratings was studied by low voltage high resolution scanning electron microscopy. For this study the films were peeled and the liquid crystal in the sample was removed. Edge, surface and in-plane views of the pictures were analysed.

Salient Features of PDLC Gratings

1. Angular Selectivity

The angular selectivity for different Bragg spacings showed little variation and also the gratings exhibited narrow angular dependence (<20). The efficiencies are measured for a He-Ne beam with p polarization. The samples had 30% loading of E7 liquid crystal. We also found that the DE (diffraction efficiency) values for p probe beam were usually higher than the s-beam. Our electro-optical studies have shown that the grating is not over-modulated, and the coupling coefficient for p-polarization is much larger than for the s-polarization.

2. Electrical field switching of Bragg Gratings

Figure 1 illustrates the electrical control of the diffraction efficiency of a sample containing 34% E7. The grating was read with a p-polarized beam. The first order Bragg DE and transmittance (Trans) are plotted as functions of rms voltage. The sum of these data has a small positive slope, indicating that there is a clearing of the film due to decrease in random optical scattering. As the electrical field is applied, there is a progressive decrease in the values of DE with increase of transmittance thus demonstrating transfer of energy from the diffracted beam to the transmitted beam. The DE values reach an actual minimum at 55 V rms equivalent to ~ 5V/µm. We also noticed that addition of a surfactant octanoic acid lowered the switching voltage.

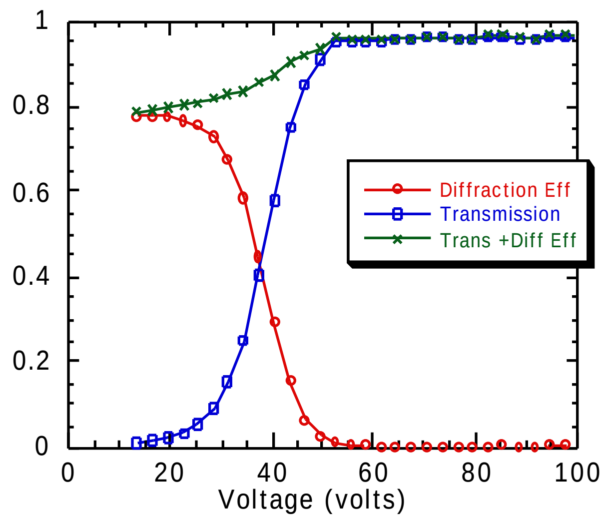

Figure 1: Elelectric field switching of a transmission grating studied by appling a square wave across the PDLC grating.

We measured the thickness of the sample from SEM as 15µm. The physics associated with the electrical switching of the gratings is similar to the electro-optical switching observed in PDLC systems used in display applications(5). In our PDLC gratings, there is a separation of phase separated liquid crystal regions and pure polymer regions. We will illustrate this in a later section of the paper. The LC microdomains form into some nematic director configuration depending on the anchoring of the LC molecules at the polymer-liquid crystal interface. The incident light sees a mixture of the ordinary (n0) and extraordinary (ne) refractive indices of the liquid crystal. This average index differs from the polymer index np and hence produces an index modulation producing a phase grating. When a strong electric field is applied normal to the plane of the film, the LC domains try to reorient in a direction parallel to this field, causing incident light to see an index approximately equal to n0. The result of this is to reduce the index modulation, assuming, np~no, thereby decreasing the DE values. The gratings can also be switched thermally by heating the sample above the nematic to isotropic transistion temperature of E7. Cooling the sample restores the original value of DE. We also measured the switching speed of the gratings. The switching times were of the order of ~50µs for the response and ~100 µs for relaxation.

3. Morphology of holographic gratings

The morphology of the PDLC gratings studied by low voltage high resolution SEM is shown in Figure 2 The sample consisted of 30%E7. Figure 2 is an edge view of the gratings.

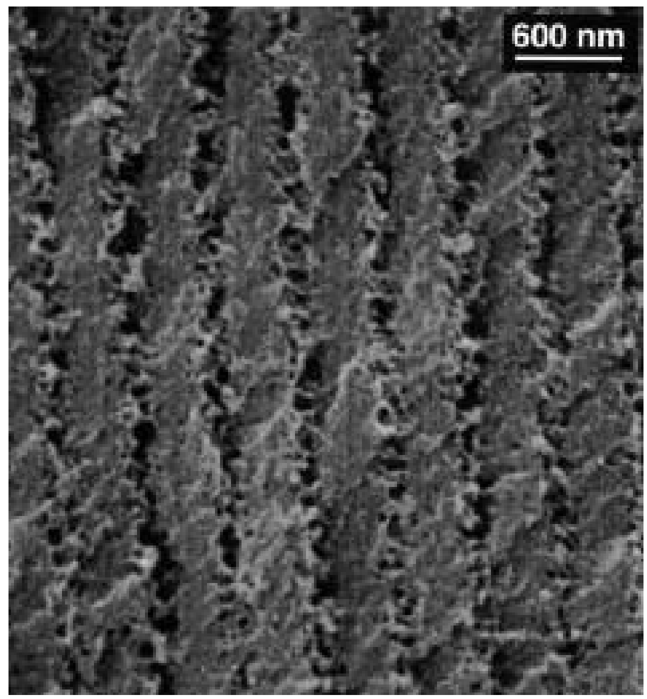

Figure 2: Morphology of a PDLC transmission grating(edge view).

The SEM picture confirm the volume nature of the gratings and demonstrate that the grating consists of periodic PDLC planes.The LC rich region contains 30-40% of the grating spacing while the polymer region is homogeneous and featureless. There are very few LC droplets in the polymer region. The size of the droplets are in the range of 100-200nm. We have also seen that there is a significant difference in the LC droplet sizes between 30% and 16% LC loadings in the sample. In low LC content samples, the LC -rich regions are narrow(`100 nm) with small, discrete droplets(20-40 nm). In higher LC loadings as shown in the figure above, samples have large LC-rich channels with lower polymer content.

4. Holographic reflection gratings

We have also shown electric field switching of reflection holographic gratings with this polymer-liquid crystal composite material system.

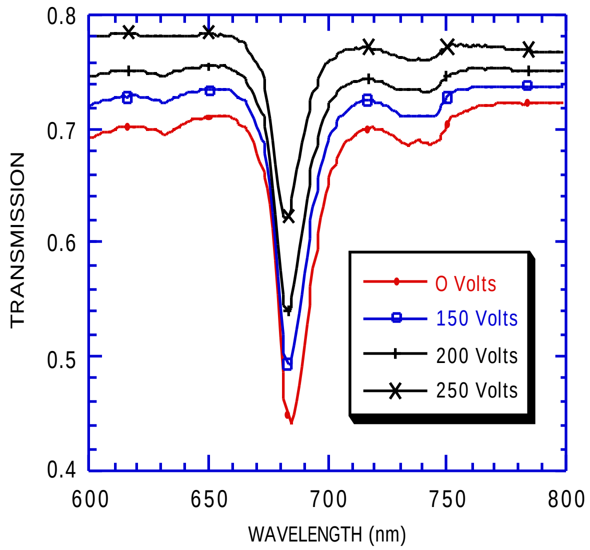

Figure 3: Transmittance of a PDLC reflection hologram.

Figure 3 shows a spectral transmission plot for a reflection grating at different applied electrical fields. The grating was written with 514 nm laser line on a sample with 30% E7 content. High laser intensity of the order of 50-100 mW/cm2 was used for writing this grating. The grating has a very narrow reflection width (<20 nm) and high efficiency. The grating is stable for months, and morphology studies show that the grating consists of very small LC droplets of the order of 50 nm size. Presently, we are studying the electrical switching of reflection gratings.

5. Holographic Image Storage and Electro-optical readout

We have demonstrated image storage and and an electro-optical readout of information in PDLC holograms.

Figure 4 is the holographic image of an elephant figure. We employed the 514 nm line of an Argon-ion laser for recording. The beam was split and expanded to form the reference and object beams. The object beam was obtained by reflection from the elephant figure. The two beams made an angle of 30 at the sample. The total exposure was approximately 5mW/cm2 for 5 minutes. The image was read with 632.8 nm from a He-Ne laser. The hologram was projected onto a white screen as shown in the photograph. The resolution and the optical quality of the image are excellent. With the application of 150V rms (2kHz, no dc bias) to the ITO plates, the image is effectively erased. We can repeatedly erase and restore the image by tuning the external field on and off.

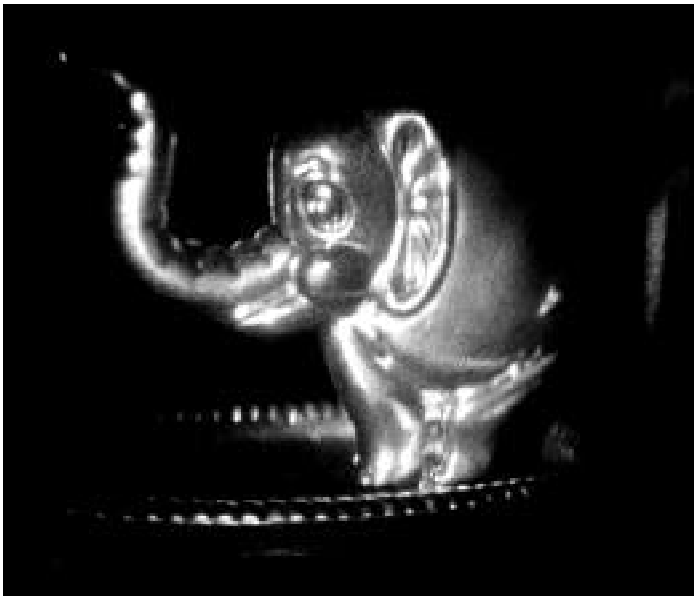

Figure 4. Volume holographic image made by transmission gratings.

Conclusions

We have developed device prototypes based on the progress made in switchable transmission grating. One is a fiber optic switch for the 1.3mm telecommunications wavelength. This device is useful as a robust fiber communication switch since it has no mechanically movable parts. Another device recently demonstrated is a switchable focus holographic lens. The focus may be switched between infinity and a finite value with a contrast ratio of 100:1. Such lenses may be useful for digital zoom camera lenses, or in the reart head of volumeoptical data storage devices.

References

1. R. L. Sutherland, L. V. Natarajan, V.P. Tondiglia and T. J. Bunning, *Chemistry of Materials*, **5**, pp1533-38(1993).
2. R. L. Sutherland, Proc. SPIE, *Liquid Crystal Chemistry, Physics and Applications*, Vol. **1080**, pp83-90(1989).
3. R. L. Sutherland, V. P. Tondiglia, L. V. Natarajan, T.J. Bunning and W. W. Adams, *Applied Physics Letters*, **64**, pp303-12(1994).
4. G. S. Iannacchione, D. Finotello, L. V. Natarajan, R. L. Sutherland, V. P. Tondiglia, T. J. Bunning and W. W. Adams, *Euro.Phys. Letts*, **36**, pp425-30(1996).
5. J. W. Doane, N. A. Vaz, B. G. Wu, and S. Zumer, *Applied Physics Letters*, **48**, pp269-71(1986).