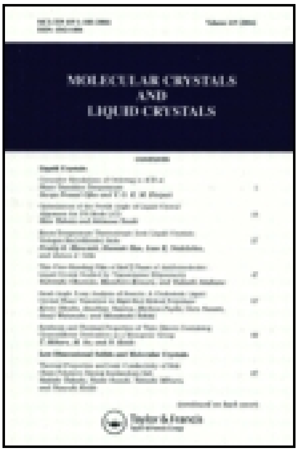

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Optically Controlled Alignment of Liquid Crystals: Devices and Applications

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OPTICALLY CONTROLLED ALIGNMENT OF LIQUID CRYSTALS: DEVICES AND APPLICATIONS

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Abstract Optically controlled homogeneous-to-homogeneous alignment of liquid crystal molecules using polarized light is discussed. Applications of this technology and experimental results that support these applications are presented.

INTRODUCTION

In 1991, we published the results of our efforts on the homogeneous-to-homogeneous alignment of liquid crystal molecules using polarized light and specially designed optically controlled alignment polymers.[1] Since then similar work has been published by other researchers using different optically controlled alignment materials.[2-4]

The optically-induced alignment process demonstrates high spatial and angular resolution of the local alignment of liquid crystals. With the proper design of the alignment material, the process is reversible allowing for the potential of real-time write/rewrite control of the local liquid crystal director.

An immediate application is to use this noncontact method to align liquid crystal displays. For display applications, issues such as the pretilt angle and the dielectric properties of the optically controlled alignment polymer must be addressed. By combining the high spatial and angular resolution of this process with the birefringent and electro-optical properties of liquid crystals, the generation of novel liquid crystal binary phase devices can be realized. In addition, an erasable, optical data storage medium based on liquid crystals is possible when reversible optically controlled alignment polymers are used.

We will present an overview of the optically controlled alignment of liquid crystals and discuss the application of this process to display manufacturing, binary phase devices and optical data storage.

OPTICALLY CONTROLLED ALIGNMENT OF GUEST-HOST NEMATIC LIQUID CRYSTALS

The initial experiment that demonstrated optically controlled alignment of liquid crystals was serendipitous and simple. A liquid crystal cell, assembled from two mechanically buffed polyimide-coated glass substrates with buffing directions mutually parallel, was filled with a conventional liquid crystal (host) containing a dichroic poly(azo) dye (guest).[5] When viewed through a polarizer, the filled cell had the expected uniform planar alignment along the rubbing direction.

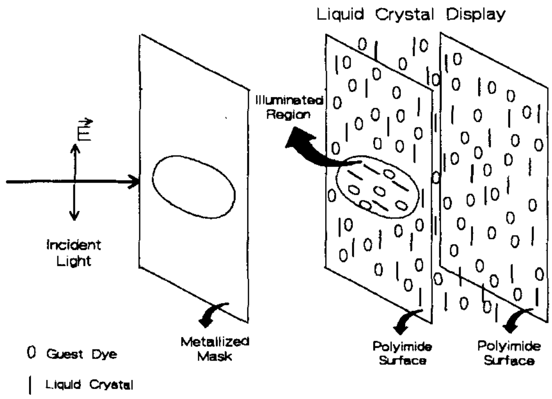

Figure 1. Guest-host cell illumination geometry.

A portion of the masked cell was irradiated with plane polarized laser light (514.5nm) within the absorption band of the poly(azo) dye as depicted in Figure 1. The polarization of the light was parallel to the original alignment direction. After irradiation, alignment of the irradiated area was found to be that of a conventional 90° twisted nematic cell. The portion of the front plate irradiated directly with plane polarized light took on an alignment 90° to the polarization direction. Due to attenuation of the light across the cell, the back plate maintained the original direction, thus, generating the observed twisted nematic cell.

Figures 2a and 2b are photographs of the cell as viewed through a single polarizer oriented 0 and 90 degrees to the initial rubbing direction, respectively. In this case, the metallized mask was a resolution target.

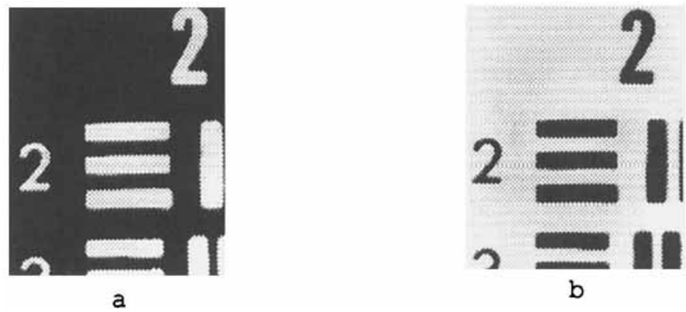

Figure 2. Guest-host cell with polarizer a) 0° and b) 90°.

The optically controlled twisted alignment was observed to be stable for long periods of time (>1 year) at room temperature. These data indicate that the guest-host liquid crystal/aligning layer interface was "permanently" altered by the polarized light and that the liquid crystal medium is sensitive to these changes.

OPTICALLY CONTROLLED ALIGNMENT OF NEMATIC LIQUID CRYSTALS

The guest-host experiments showed that the dichroic dye and the liquid crystal/aligning layer interface were important for the observed effect. As a result, cells were constructed that had a dichroic dye incorporated in the aligning layer instead of the liquid crystal. Localization of dye near the interface allows exposures in the absence of the liquid crystals and, thus, the process is not limited to guest-host liquid crystal systems.

An experiment was performed to demonstrate the concept of optical buffing. Prior to cell assembly, a polyimide/dye aligning layer[1] was scanned with linearly polarized laser light. A subsequent exposure was made through a metallized mask of a Hercules Logo and with the linearly polarized light rotated 90° to the first exposure. A cell was assembled with the exposed polyimide/dye and polyimide only coated substrates. The cell was filled with the guest-host mixture described previously.[5] The photograph of the cell as viewed through a single polarizer is depicted in Figure 3. It is important to reiterate that no electric field is applied to the cell and the background alignment and image were done optically. In addition, this example demonstrates the write/rewrite capability of this alignment process (background then image). The uniformity of the optically buffed background and subsequent image is comparable to or better than the quality of mechanical buffing techniques.

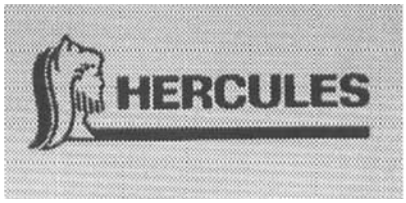

Figure 3. Optical buffing and realignment.

The high resolution of the optically controlled alignment technique is demonstrated in Figure 4. As with the Hercules Logo, a cell was assembled and, prior to filling, it was exposed with a linearly polarized optical interference pattern with a 10μm period.[1] After filling the cell with nematic liquid crystals, the cell was placed between crossed polarizers and viewed with a microscope. As shown in Figure 4, the local alignment of the liquid crystals was periodic and, as with the exposing beam, the period of the alignment was 10μm. This would be difficult, if not impossible, to achieve using conventional alignment techniques.

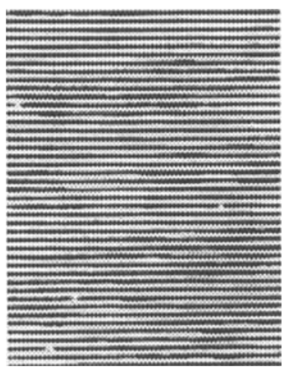

Figure 4. Liquid crystal grating.

ADVANTAGES OF OPTICALLY ALIGNED LIQUID CRYSTAL DEVICES

The overview of the optically controlled alignment of liquid crystals points out several advantages of this technology over the existing techniques for aligning liquid crystals. These advantages include

- Noncontact method of inducing macroscopic alignment;
- High resolution angular control of alignment;
- Reconfigurable by changing the linear polarization of the incident light;
- Potential for submicron resolution;
- Potential for real-time optical control of device.

As a consequence of these advantages, improved performance of traditional liquid crystal devices and some new applications can be envisaged. One important application of this technology is in the macroscopic alignment of liquid crystal displays. Other applications include liquid crystal diffractive optics and holographic elements, optical memory/data storage, adaptive optics, and real-time optical signal processing.

REQUIREMENTS FOR APPLICATIONS

The aforementioned applications require an optically controlled alignment polymer that will improve on the performance of existing alignment polymers while preserving the desirable dielectric, thermal, uniformity, and thin film processing properties of existing alignment polymers. Another important property (particularily for liquid crystal displays) is the alignment polymer's ability to create a pretilt angle to eliminate reverse tilt disclinations in twisted nematic applications.

In addition, the optically controlled alignment polymers must demonstrate good optical stability in the operating wavelength range (usually visible) and low optical energy densities for the alignment process. For some applications such as optical data storage, the ability to have multiple write/rewrite cycles with minimal fatigue is of critical importance.

Some of these requirements are discussed in more detail and related to particular applications in the following sections.

OPTICAL ALIGNMENT OF LIQUID CRYSTAL DISPLAYS

The alignment materials used for demonstrating the optical alignment of liquid crystal displays and subsequent applications include a standard Huls America polyimide as a control, polyimide with 33wt% diazodiamine[1], and a proprietary polymer with the active moieties covalently bonded to the backbone of the polymer.

The nematic liquid crystals were purchased from E. Merck and are given in Table 1 with the relevant optical and physical parameters.

Table 1

Material	**n_e**	**Δn**	**N→I (°C)**
ZLI1982	1.640	0.14	91
ZLI2452	1.6368	0.1366	110

Table 2 summarizes the energy density requirements for the two optically controlled alignment polymers discussed in this paper. The desired value is ≤3 J/cm^2 which is compatible with existing photopolymers and automated machinery. For example, if the energy density were 0.5 J/cm^2, ten 14inch X 14inch substrates can be optically aligned per minute using a 100 Watt source. Mechanical buffing techniques are limited to 5 to 6 14inch X 14inch subtrates per minute and require an additional cleaning step after buffing.

Table 2

Alignment Material	**Energy Density (J/cm^2)**
Polyimide/Diazodiamine	50-2500
Proprietary Polymer	2

The energy density for the polyimide/diazodiamine material is strongly dependent on the processing conditions (cure temperature, atmosphere, etc.) of the thin film after spin casting onto a glass substrate. Table 2 demonstrates that the energy density values can be controlled by the material chemistry as well as the processing conditions of the material.

Optical "buffing" of the alignment layer was performed using a scanning technique as depicted in Figure 5. The laser can be operated in a single or multiline mode depending on the energy density requirements of the alignment material. The polarized laser beam was focussed to a line and the substrate was scanned at rates of 0.5-30mm/s (depending on the material). To ensure high uniformity of the alignment, a step size of 1.5mm was used for each successive scan line.

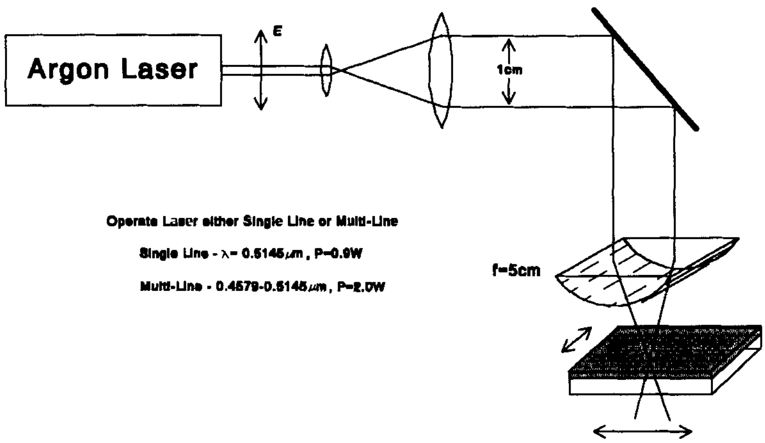

Figure 5. Scanning geometry for optically "buffing" alignment materials.

Liquid crystal displays (LCD) require a pretilt angle of the liquid crystals to eliminate reverse tilt disclinations in twisted geometrys. Ninety degree twisted nematic displays give adequate performance with pretilt angles of approximately 1-5 degrees. For supertwisted nematics, pretilts of approximately 8-12 degrees are required. To be useful for LCD applications, optical "buffing" techniques should allow for the creation of uniform pretilt angles. Table 3 provides pretilt data on the alignment polymers as function of process conditions and alignment technique. Pretilt angles were measured using the method described in Reference 6.

It is clear from Table 3 that optical "buffing" can provide pretilt angles in properly designed materials and with certain exposure conditions. However, it is unclear what physical mechanisms control the uniformity and magnitude of the pretilt angle. These parameters are currently being investigated. Please note that the pretilt angle of the polyimide/diazodiamine alignment material was 0° for all optical "buffing" geometries tried to date. However, it was measured to be -4° when buffed with a cloth (mechanical buffing).

Table 3			
Material	**Buffing Technique**	**Liquid Crystal**	**Tilt Angle (°)**
Polyimide	Rubbed with cloth	ZLI1982	-1.5
Polyimide/ Diazodiamine	"	ZLI1982	-4.0
Polyimide/ Diazodiamine	Optical 0.75-12mm/s	ZLI1982 ZLI2452	0.0
Proprietary Polymer	Optical 5mm/s	ZLI2452	-1.5
"	Optical 10mm/s	"	-0.8
"	Optical 1.5mm/s, different thin film processing	"	-1.5

We also observed that the proprietary polymer gave different values for the pretilt angle as a function of scan speed as well as thin film processing conditions. Higher pretilt angles were achieved (≤15°) with faster scan rates and different thin film processing but the uniformity of these cells was poor.

Another area of interest for liquid crystal displays are the dielectric properties of the optically controlled alignment layers and the effect it has on the threshold voltage and switching speed of the display. Figure 6 is a plot of the transmission vs. voltage of a standard mechanically buffed polyimide cell and an optically buffed polyimide/diazodiamine cell. It is encouraging that there is little difference between these two cells. Switching speeds are currently being investigated.

We have not demonstrated that the optically controlled alignment polymers satisfy all the requirements of liquid crystal display manufacturing. However, the preliminary data we have shown indicate that the potential for use in LCDs is good for these materials. The potential simplification of the alignment process with lower defect frequency and increased throughput could aid in increased yields for the LCD manufacturer. This is particularly important for active matrix LCDs where low yield affects the competitiveness of this product. Another advantage of this alignment technology is the ability to perform repairs on poorly aligned regions of the display after it has been assembled, thus, further increasing the manufacturing yield.

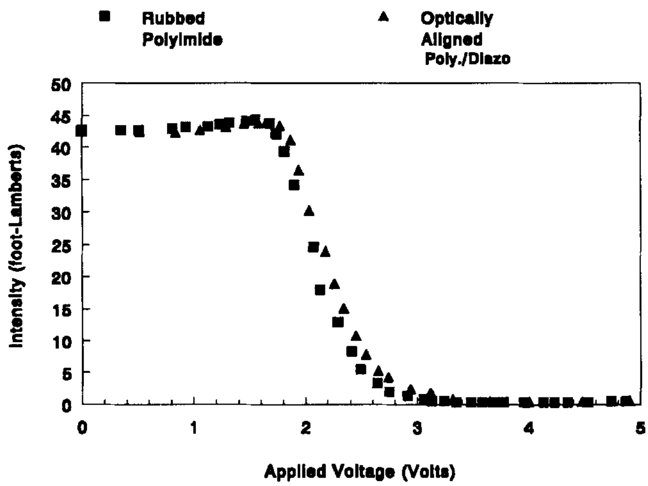

Figure 6. Voltage behavior of a standard polyimide cell and an optically buffed liquid crystal cell.

OPTICAL DATA STORAGE

The optical control of liquid crystals has the potential for use as an optical data storage medium. The high resolution of this process combined with the high birefringence of the liquid crystals make it a prospective candidate. A small optically controlled change in liquid crystal orientation will result in a large change in birefringence of the written spot. This would significantly improve the signal-to-noise ratio over the existing optical data storage media (e.g., magneto-optic media).

Another advantage is that the manufacturing technology for a liquid crystal optical data storage disk would be nearly identical to existing LCD manufacturing technology. LCD manufacturing has been researched extensively and, thus, the expertise is available to make low cost liquid crystal optical data storage disks. It is also possible to exploit the electro-optic properties of liquid crystals. For example, advanced data encryption schemes could be realized where certain areas of the data storage disk are electrically "activated" during the read cycle.

Key to the usefulness of this technology to optical data storage is the minimum time required to write/rewrite the information into the alignment material. Although the response of the liquid crystal to the change in alignment material may be on the order of several milliseconds, this should not be a problem since the need to read information within several milliseconds after it is written is unlikely to occur. Figure 7 is a schematic of the experimental set-up used to study the write times of the alignment materials.

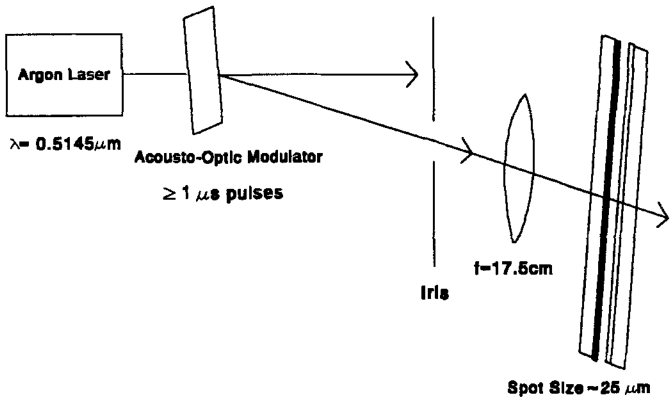

Figure 7. Schematic of experimental set-up for measuring write times.

For these experiments the liquid crystal cell had only one optically active alignment layer. The alignment layer on the back plate was standard mechancally buffed polyimide. The data for these experiments are summarized in Table 4.

Table 4

Material	Minimum Pulsewidth (μs)			
	P=125mW	250mW	500mW	950mW
Polyimide Diazo.	100	50	5	5
Prop. Polymer	1	1	1	1

The polyimide/diazodiamine generated 90 degree reorientation with a 5μs pulse but required laser powers in excess of 500mW. The proprietary polymer with its lower energy density requirements reoriented the liquid crystal with 1μs pulses regardless of the powers tried. Limitations of the acousto-optic modulator and the laser prevented further testing at shorter pulsewidths and lower powers.

Realistically, the liquid crystal need not be rotated a full 90 degrees for optical data storage applications. A few degrees change in orientation should be more than sufficient to detect written spots. As a consequence, shorter pulsewidths and lower powers could be used to write data into the disk. However, longer pulses and/or higher powers may be needed to erase the information and provide uniform alignment.

ACTIVE LIQUID CRYSTAL BINARY PHASE DEVICES

Optically controlled alignment of liquid crystals allows for applications that were difficult to achieve with standard alignment techniques. These new applications include active binary phase devices for use in holography, interconnection technology, adaptive optics and optical signal processing.

The concept of active binary phase devices can be demonstrated using simple liquid crystal phase gratings written using the optical alignment technique. Figure 8 is a schematic of the two types of liquid crystal gratings studied.

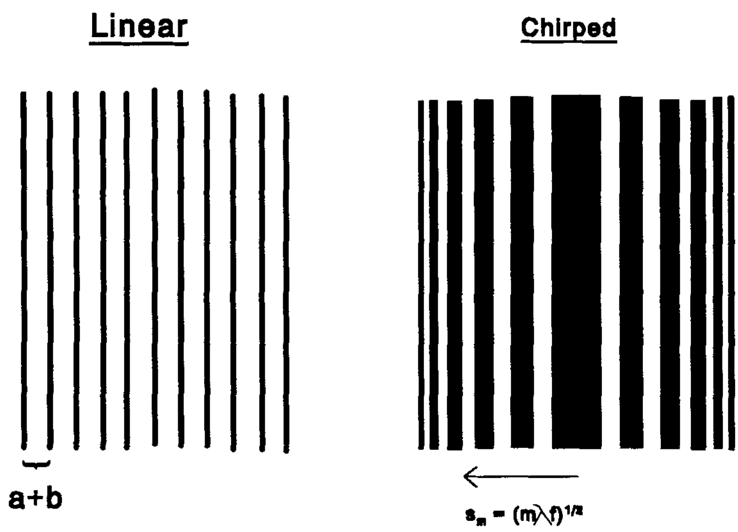

Figure 8. Grating types studied with optically aligned liquid crystals. Here a is the line width, b is the spacing, s_m is the distance from the center, m is an integer, λ is the design wavelength, and f is the primary focal length.

Linear gratings diffract the incident light beam into higher order multiple beams, and chirped gratings provide focussing properties to the diffracted beams (much like a cylindrical lens). Linear liquid crystal gratings were formed via interference or scanning techniques (see Figure 9). The liquid crystal chirped gratings were only made by scanning. Also included in Figure 9 are the interference and scan parameters used in manufacturing the liquid crystal gratings.

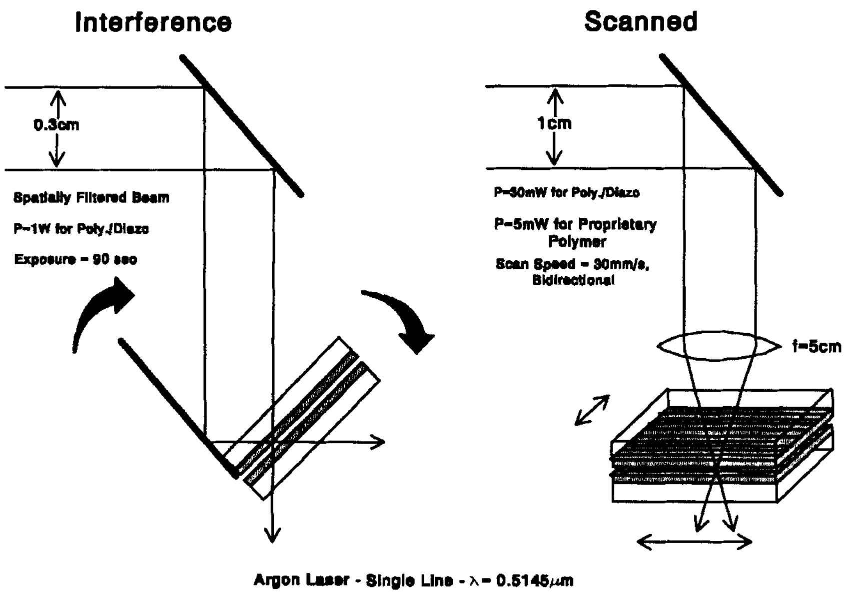

Figure 9. Exposure geometries for creating liquid crystal gratings.

Figure 4 is an example of a liquid crystal grating created via interference. The scanned gratings were similar but usually of lower resolution (16μm periods or higher due to focussed beam size). In both scanned and interfered gratings, the alignment on the front and back aligning layers differed slightly from each other due to attenuation, focussing, and interference effects in the cell. As a consequence, the liquid crystal demonstrated a small twist in the optically aligned regions. This resulted in reverse tilt disclinations which caused increased scattering of light passing through the grating.

Liquid crystal gratings have been generated by patterning electrodes which periodically control the liquid crystal orientation with an applied voltage and, thus the diffraction efficiency of the grating. One advantage of optically patterning active liquid crystal gratings is the reduced processing of the switching electrodes. In the case of optical patterning, single electrodes on each substrate can be used to control the liquid crystal orientation. The experimental setup for studying the electro-optical properties of the gratings is sketched in Figure 10.

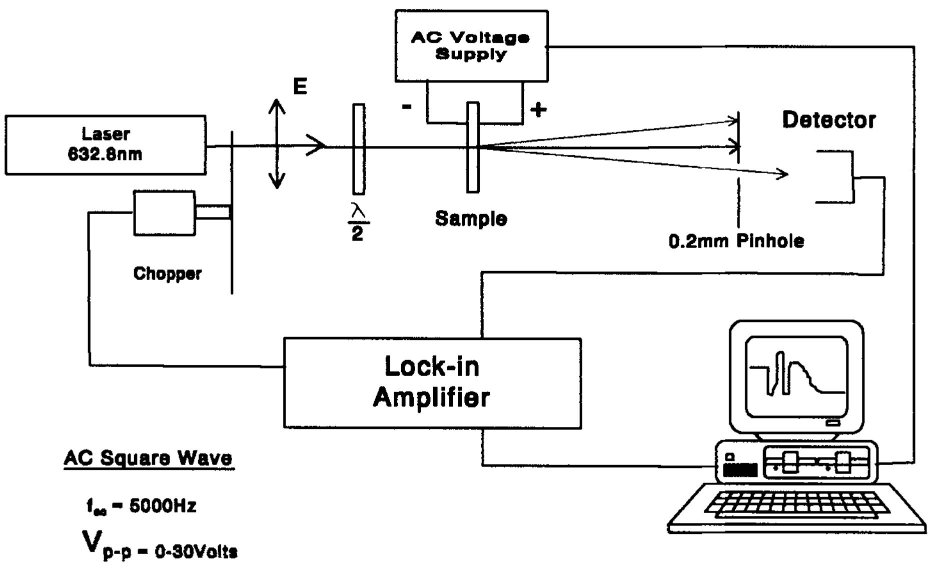

Figure 10. Schematic of set-up to measure electro-optical properties of optically aligned gratings.

The voltage was ramped on the grating and the amount of light transmitted through the pinhole detected as a function of applied voltage. By rotating the $\lambda/2$ plate the input polarization could be varied. Figure 11 is a plot of the data for the linear interference grating described in Figure 4. The cell thickness is 11μm and the liquid crystal is ZLI1982.

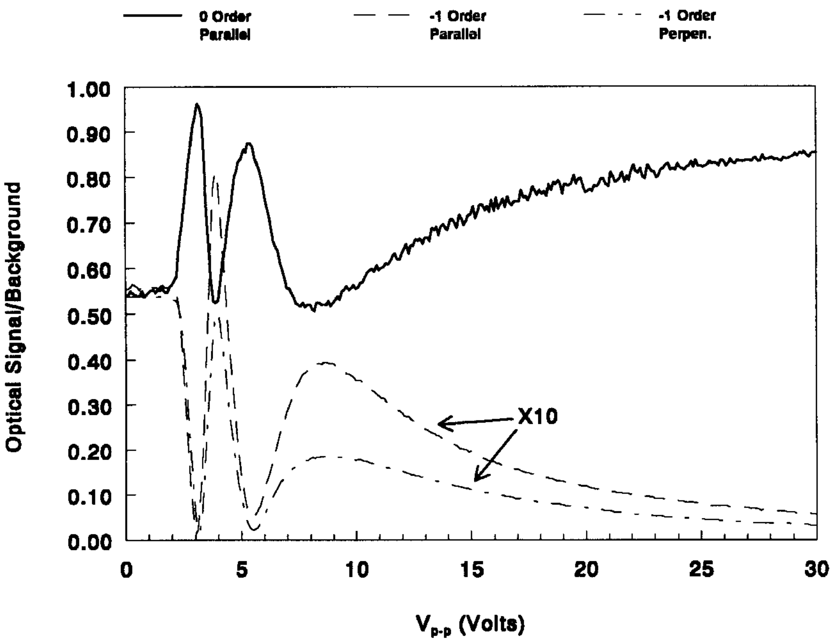

Figure 11. 10µm Grating formed via interference. Polyimide/diazodiamine alignment layers, ZLI1982 liquid crystal, 11µm thick cell, cell mechanically buffed prior to optical alignment of grating. Parallel and perpendicular means light polarized along and orthogonal to the grating lines, respectively.

The threshold voltage for ZLI1982 is 1.9 volts. The curve shows little change in diffraction until this voltage is exceeded and electro-optical reorientation begins to occur. As can be seen in Figure 11, there are two peaks and valleys corresponding to the case when the phase difference between every other grating line is some odd integer multiple of π (maximum diffraction) and when the phase difference is some integer multiple of 2π (minimum diffraction), respectively. For the given thickness, birefringence and measuring wavelength two peaks and two valleys are expected in the output. The diffraction into the ±1 orders is less than 10% for this grating. Note the difference in diffraction for the two input polarizations. This indicates that the optically aligned regions have a slight twist and are not oriented 90° to the background as explained earlier in the text.

Figure 12 depicts the electro-optic response of a 20µm scanned grating. The liquid crystal in this cell is ZLI2452 which has a higher threshold voltage of 2.6 volts.

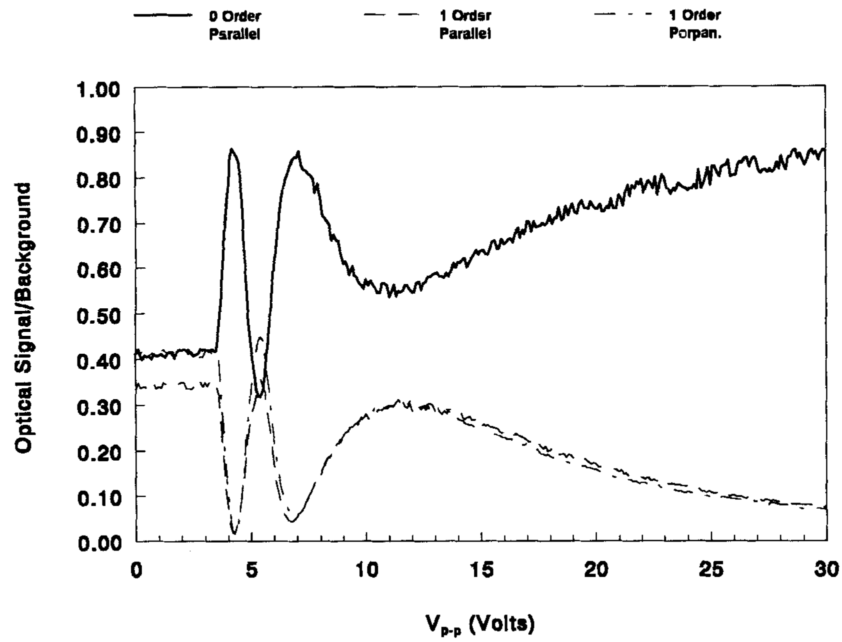

Figure 12. 20µm Grating formed via scanning. Polyimide/diazodiamine alignment layers, ZLI2452 liquid crystal, 11µm thick cell, cell optically buffed prior to optical alignment of grating. Parallel and perpendicular means light polarized along and orthogonal to the grating lines, respectively.

The higher threshold voltage of ZLI2452 results in a higher voltage requirement for electro-optical realignment of the liquid crystals. This is reflected in Figure 12. The scanned grating diffracts more of the incident beam into the the higher orders than the interference grating. Also note, the smaller difference between the two polarizations. These differences are consistent with the lower resolution requirements of the scanned grating and the higher intensity beam writing the grating lines. As a consequence, effects due to absorption, scattering, and interference are less likely to cause a difference in optical realignment between the back and front alignment layers of the cell.

A chirped grating was scanned in polyimide/diazodiamine cell and subsequently filled with ZLI2452. The design wavelength and primary focal length of the chirped grating were 0.6328μm and 10cm, respectively. The electro-optic response of the chirped gratings were studied by placing the pinhole depicted in Figure 10 at the primary focal point. The amount of light passing through the pinhole was monitored as function of applied voltage. Figure 13 gives the electro-optical response of this grating.

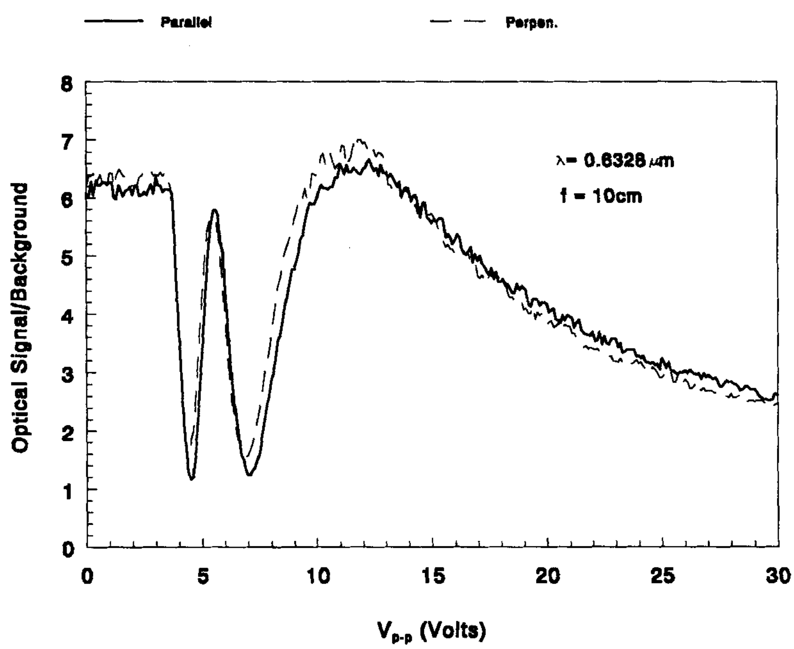

Figure 13. Chirped grating formed via scanning. Polyimide/diazodiamine alignment layers, ZLI2452 liquid crystal, 11μm thick cell, cell optically buffed prior to optical alignment of grating. Parallel and perpendicular means light polarized along and orthogonal to the grating lines, respectively.

There is little difference between the parallel and perpendicular polarization of light for this grating. The resolution requirements of the chirped grating were much less than that required for the linear gratings. Note that approximately 6X more light passes through the pinhole due to the focussing effect of the grating. The foccussing of the grating is destroyed when the proper phase conditions are met between grating lines. The leakage light corresponds to the unfoccused beam incident onto the pinhole. Improvements in the grating quality and the grating design should lead to higher contrast ratios.

Two chirped gratings of focal length 10cm and 20cm were written into a proprietary polymer cell. The electro-optic response of these gratings is shown in Figure 14.

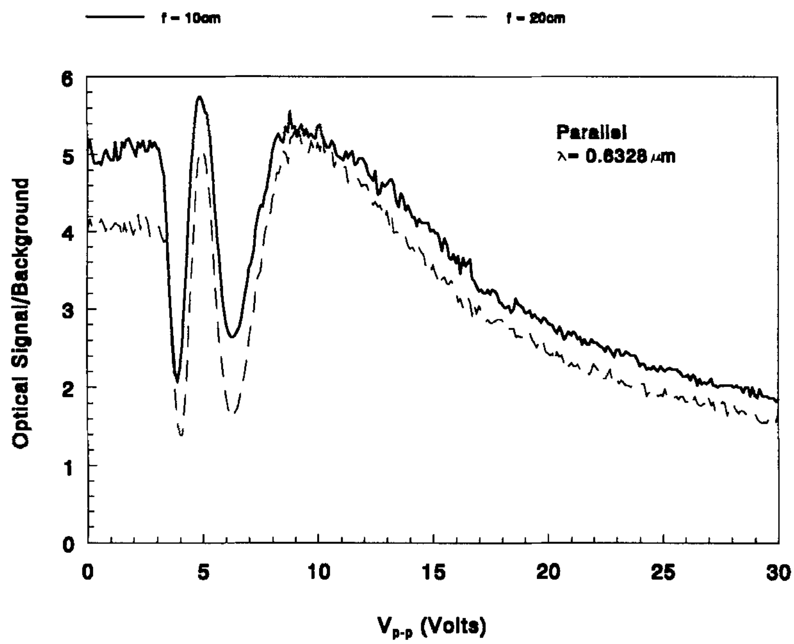

Figure 14. Chirped gratings formed via scanning. Proprietary polymer alignment layers, ZLI2452 liquid crystal, 11μm thick cell, cell optically buffed prior to optical alignment of grating. Parallel means light polarized along the grating lines.

The quality of the proprietary polymer chirped gratings were not as good as the polyimide/diazodiamine gratings. This resulted in more background scatter and, thus, the lower contrast in the electro-optical response. We would expect a tighter focus for the 10cm focal length versus the 20cm focal length. This could account for the larger diffracted signal for the f=10cm chirped grating.

SUMMARY

We have provided an overview of the optical alignment technology and discussed its potential applications to LCDs, optical data storage, and binary phase devices. The optical alignment process does produce a pretilt angle with the proper material choice and process conditions. The optically aligned binary phase gratings can be tuned electronically with simple single electrode configurations. Although more work is needed to refine the aligning polymers and the process conditions, it is clear that this technology can have a significant impact on existing applications as well as create new applications for liquid crystals.

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