Photoaligned Liquid Crystal Wave Plate

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Abstract

Liquid crystal (LC) wave plates were produced using a photosensitive polymer to generate alignment. Currently, alignment of liquid crystals is achieved through the use of mechanical buffing, although this process is relatively imprecise and inherently generates particulate contamination. Photoalignment of LC wave plates using a coumarin-based photopolymer resolves many of these fundamental problems with buffing. Because photoalignment of LC wave plates is a non-contact process, it provides high-quality LC alignment without introducing particulate contamination on to the substrate. For the low-birefringence LC materials used for wave plate fabrication, the alignment quality produced using coumarin-based photopolymers is most greatly impacted by the surface quality and optical uniformity of the substrates. When substrates with relaxed scratch/dig, wedge and flatness tolerances were used, LC alignment was poor with numerous disclinations (alignment defects). When substrate quality was improved, the number of disclinations was vastly reduced. Small-

aperture prototype photoaligned wave plates produced had retardance values well within the allowable specifications for buffed waveplates deployed in OMEGA.

Introduction

Wave plates are an important part of the OMEGA laser system. As a laser beam passes through the system, the high intensity and optical uniformity of the beam must be maintained. This is accomplished using a wide variety of lenses, amplifiers, and beam shapers that form and amplify the original beam. However, each of these devices will only operate correctly with a certain polarization state of light. Wave plates are used to change the polarization of the laser beams, ensuring that each element in the system receives the correct polarization.

The polarization shift in wave plates is accomplished using liquid crystals (LCs). This is possible because the observed properties of liquid crystals are dependent on orientation, making them anisotropic. Figure 1 shows the molecular orientation in an isotropic liquid. The molecules are arranged randomly, with a very low orientation order. An isotropic liquid has only one refractive index, which is independent of the direction in which the liquid is viewed. Liquid crystals are anisotropic, and are not arranged randomly but possess some orientation order. Anisotropic materials have different properties based upon the orientation in which they are viewed. This anisotropy allows them to shift the polarization of light. Rather than being aligned randomly, the molecules align generally in the same direction (Fig. 2). Because of this orientation order, liquid crystals have more than one refractive index, typically two. The difference between the two indices of refraction is called

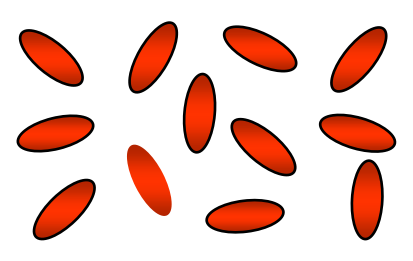

Figure 1: Molecular ordering in an isotropic liquid

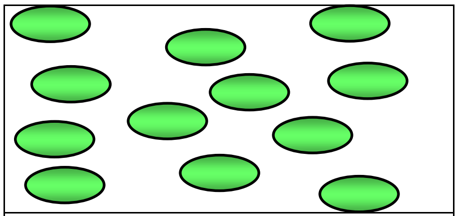

Figure 2: Anisotropic molecular ordering in a nematic liquid crystal

birefringence. It is birefringence that causes the change in polarization when light is passed through an anisotropic liquid.

When light enters a birefringent material, it breaks into two components with perpendicular directions of polarization. These are called the ordinary ray and the extraordinary ray. The refractive index is a measure of how fast light moves through the material. Because LCs are birefringent and have two refractive indexes, these components move through the LC at different speeds. The phase shift between the components caused by the difference in speed at which they propagate determines the polarization direction of the light. By varying the phase shift, different polarizations of light can be created. When the components are completely in phase, the light is linearly polarized. However, circular and elliptical polarizations can be produced by varying the phase shift. A phase shift of π/2 will convert linearly polarized light into circularly polarized light.

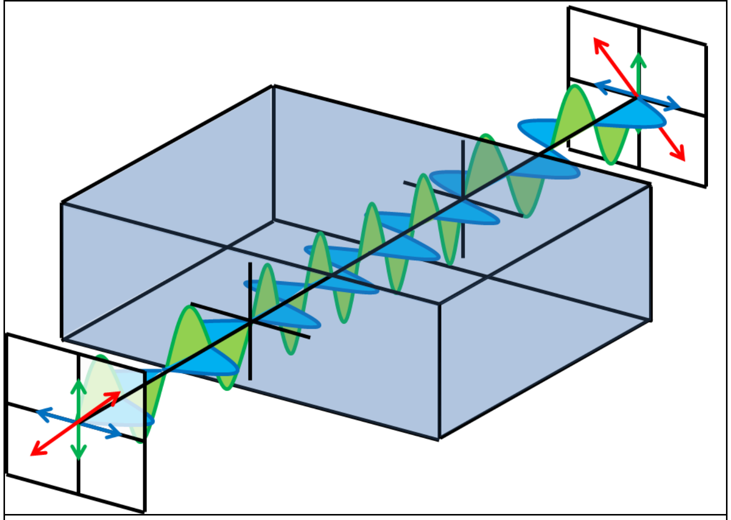

Figure 3: Rotation of the polarization of linearly polarized light through an anisotropic medium(e.g, a LC wave plate)

Figure 3 shows light passing through a half wave plate (shown as the blue box). Prior to moving through the wave plate, the light is linearly polarized. As the light passes through the wave plate, the ordinary and extraordinary ray, represented by the green and blue waves, gradually move out of phase, eventually rotating the polarization by 90°. The amount of phase shift is dependent on both the birefringence of the liquid crystal and the thickness of the wave plate, as governed by this equation:

$$\tau = \frac{2\pi\,\Delta n\,L}{\lambda} \qquad 1.$$

where τ is the phase shift (retardance), Δn is the birefringence, L is the thickness, and λ is the wavelength of light passing through the plate. By varying the thickness of the wave plate, the retardance can be adjusted.

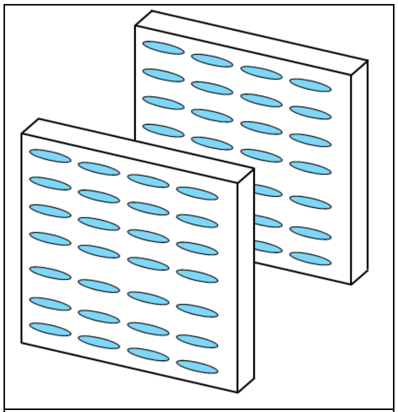

Figure 4: Uniform molecular alignment in an LC waveplate containing a molecular alignment layer on the substrate surfaces

However, in order to produce a viable wave plate, the LC molecules must be uniformly aligned in the cell. This can be accomplished in two different ways. Previously, liquid crystal alignment was generated using mechanical buffing. In this process, the glass substrate is first coated with a polymer alignment coating, then placed under a rotating cylinder, which gradually moves across the entire substrate. The rotation of the cylinder creates microscopic ridges along the surface of the polymer. The liquid crystals then align themselves along these ridges. If both substrates are buffed and positioned correctly, the LC molecules will be aligned parallel to each other (Fig. 4). Although the buffing process works well for information display and other low incident energy applications, it has many drawbacks for high peak power laser applications.[1] Because the buffing cylinder is physically scraping over the coated substrate, it can leave many embedded particles behind. These particles not only disrupt the LC alignment, but can also act as sites for laser-induced damage. Furthermore, it becomes more difficult to scale up the buffing process as the substrate size increases.

Photoalignment can be used instead of buffing to generate LC alignment by coating the substrate with photo-reactive coumarin monomers and exposing it to linearly polarized UV light. This UV exposure causes the coumarin monomers to dimerize and align themselves perpendicular to the polarization direction of the UV light[2,3] (Fig. 5). When the LC molecules come into contact with the photo-dimerized coumarin layer, the LC molecules will then align themselves parallel to these dimers, producing uniform alignment[4]. Because the photoalignment process is non-contacting and leaves no scratches or embedded particles, it is inherently clean-room compatible and readily scalable to much larger substrate sizes. As a result, photoaligned devices have a much higher damage threshold (30-60 J/cm^2 at 1054 nm, 1ns, than do buffed LC devices with the upper damage threshold of the device limited primarily by the LC material.

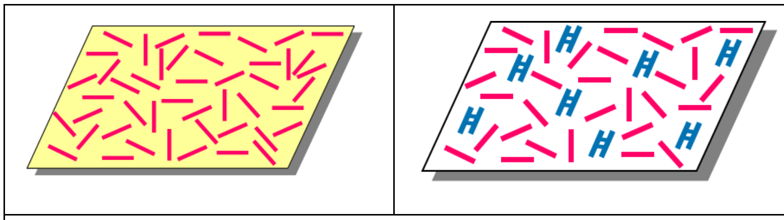

Figure 5: Representation of the coumarin photopolymer coating before and after UV irradiation. (Red lines are monomers, double blue lines are dimers)

Experimental

For most experiments, either 1” dia. BK7 round substrates with a surface flatness of one quarter-wave at 1054 nm or 1” x 1” Borofloat squares were used. The 1” x 1” Borofloat squares were used for early process development experiments, as they are much less expensive due to their poorer scratch-dig and wedge specifications. The higher quality BK7 round substrates were used for the final wave plate prototype fabrication.

Both the substrates and the synthetic wipers used to clean the substrates were rinsed with deionized (DI) water, to remove any large particles. The substrates were then scrubbed with the synthetic wipers using 0.05 µm Masterprep® Polishing Suspension, and rinsed again with DI water. The substrates were inspected using a water break test to reveal surface contaminants. In this test, substrates were rinsed with water and tilted. If the surface is sufficiently clean, water will stay spread as a continuous film on the substrate surface and not bead up or be pulled to the edge of the substrate. Substrates that passed the water break test were placed in an ultrasonic bath filled with DI water and detergent at 69°C for 60 minutes. After the ultrasonic bath cleaning, the substrates were rinsed with DI water, then visible water droplets were removed from the substrates using a nitrogen air gun. The cleaned substrates were then placed on a hotplate at 130°C for 30 minutes to ensure that all absorbed water was evaporated.

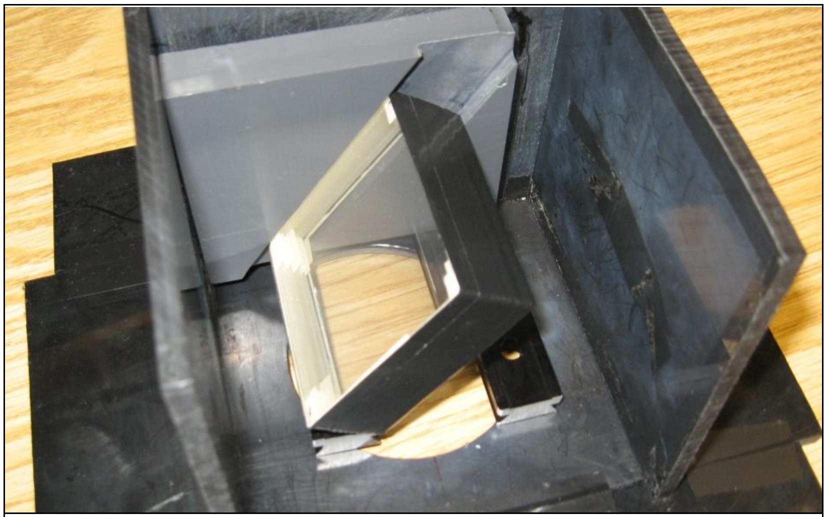

Figure 6: "Pile of plates" polarizer and polarizer holder

After drying, the substrates were placed on a spin-coater and covered with approximately 0.3 mL of chloroform. The spin-coater was covered with a glass crystallizing dish to prevent evaporation and ensure that the air was saturated with chloroform. Excess chloroform then was spun off at 4000 rpm for 60 seconds. Using a 0.45 µm PTFE 13 mm dia. hydrophobic syringe filter and glass syringe, approximately 0.3 ml of 0.1wt% coumarin Polymer 3 in chloroform was

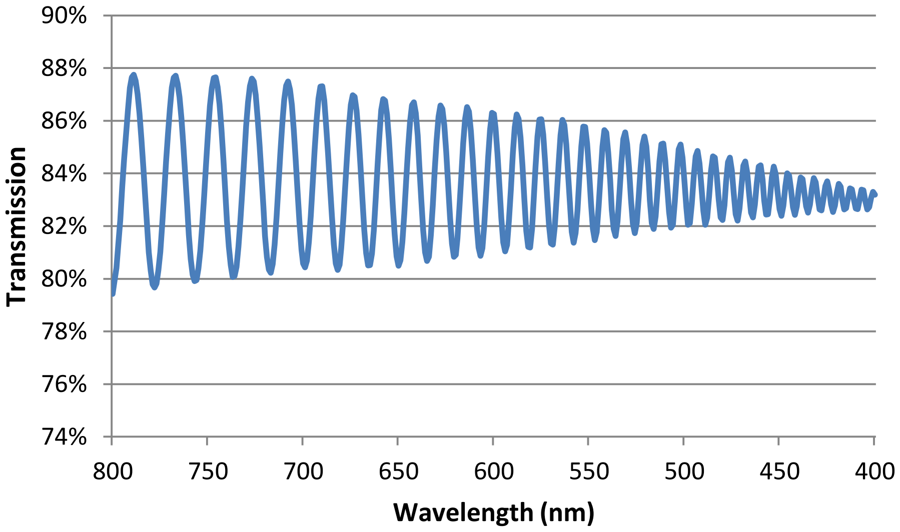

Figure 7: Interference fringes measure on an empty LC wave plate device. This data is used to accurately determine the cell gap before filling with LC.

deposited on the substrate. The substrate was immediately spun at 4000 rpm for 120 seconds. The substrates were then removed from the spin-coater to air-dry before being irradiated.

Photoalignment was achieved by irradiating the substrates for one minute with a broad-band 500-watt mercury xenon UV lamp equipped with a dichroic mirror and lenslet array to produce collimated UV light at 325 nm. To polarize the UV light, the substrates were placed under a “pile of plates” polarizer oriented at Brewster’s angle (Figure 6). To assemble the cell, a capillary tube was first dipped in OG-142-13 UV-curing epoxy. The tip of a metal spatula was used to pick up a very small amount of 14 μm glass fiber spacers, which were mixed with the epoxy and applied to the corners of the substrates. The substrates were then assembled so that the alignment direction of the photoalignment layers was parallel to each other. The substrates were placed under a 365 nm low-intensity UV lamp to cure the fiber-filled epoxy spacers for 5 minutes. The cell gap (distance between the substrates) was measured using a Lambda 900 spectrophotometer. As shown in Fig. 7, the transmission of the empty cell followed a damped sinusoidal pattern as the wavelength of light being passed through the cell was decreased from 800 to 400 nm. This pattern could be used to calculate the cell gap[6] from the following equation:

$$t = \frac{\lambda_1 \lambda_2}{2n(\lambda_2 - \lambda_1)} \qquad 2.$$

where t equals the cell gap, λ_1 equals a wavelength of peak transmission, λ_2 equals the next wavelength of peak transmission, and *n* equals the refractive index of the material between the substrates (air). Once the cell gap was calculated, the LC material could be correctly blended and added to the device.

Using equation 1, the required birefringence of the LC mixture could be calculated after the cell gap was known. In order to obtain this birefringence, a blend of two commercial low-birefringence LC fluid mixtures (BDH 18523 and 14627) was prepared. These fluids were mixed at room temperature, then placed on a hot plate set at 60° C. The mixture was stirred with a magnetic stir bar at 500 rpm for two hours. Because the two LC mixtures have different birefringence values, the birefringence of the final mixture could be adjusted by varying the percentages of 18523 and 14627. Although the exact proportion of LC used varied in each cell, the mixture consisted of between 49% to 52% 18523 by weight. Once this mixture was made, the cell was placed on a hot plate set to 80°C. The LC was drawn into a 1 mL plastic syringe, and a 0.45 μm PTFE 4 mm hydrophobic syringe filter was fitted on the end of the syringe. A small syringe needle was fitted to the end of the syringe filter and the cell was filled slowly with the needle tip contacted to the space between the two substrates. Once filled with LC and partially sealed with epoxy, the cells were cooled at 10°C per hour until they reached room temperature. This slow cooling rate avoids rapid LC fluid contraction that could cause alignment defects.

Discussion

Small-aperture prototype photoaligned wave plates had retardance values well within the allowable specifications for buffed waveplates already deployed in OMEGA. To meet this specification, a wave plate must have a high uniformity and contrast, as well as a retardance that

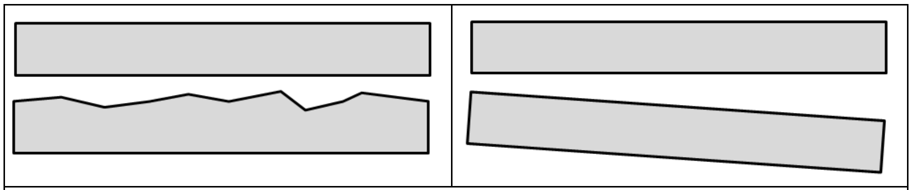

Figure 8: A cell with high scratch-dig (left) and high wedge (right)

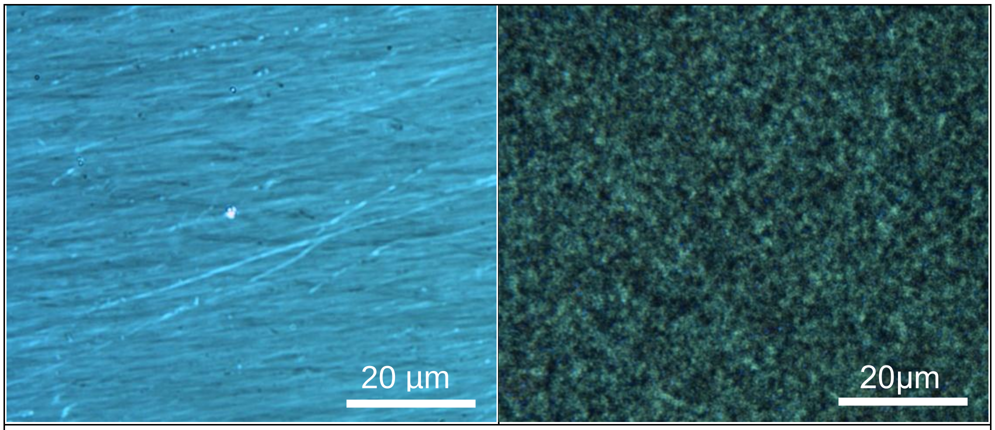

Figure 9: Comparision of liquid crystal alignment of buffed (left) and photoaligned (right) wave plates as viewed in transmission using a polarizing microscope with crossed polarizers.

deviates < 5% from the OMEGA device specification. It was determined that the most important factors impacting the quality of the photoaligned waveplate prototypes were the scratch-dig specification of the substrates and the wedge of the completed cell. A substrate with a high scratch-dig will have numerous alignment defects, while a cell with high wedge in its cell gap will cause the retardance to vary across the device clear aperture (Fig 8). Such a device would be unsuitable for use in operation in OMEGA, as a consistent retardance across the entire clear aperture is necessary to maintain beam uniformity. Photoaligned devices employing substrates with low scratch-dig and a small variance in cell gap thickness can produce waveplates with properties superior to those of buffed devices. As shown in Fig. 9, the buffed wave plate has multiple scratches and embedded particles, and readily visible buffing lines, while the photoaligned wave plate is free of embedded particles and has a more uniform alignment. This uniform alignment and cell gap allows cells to be created with nearly ideal retardances (Table 1).

Cell	**Thickness**	**Retardance**	**% Error**
A	14.08 μm	522.7 nm	0.82%
B	13.87 μm	530 nm	0.57%
C	14.10 μm	540 nm	2.47%
D	14.14 μm	543 nm	3.04%

Table 1: Measured retardance values for the small aperture photoaligned LC wave plate prototypes. The error is measured relative to the ideal retardance of 527 nm

The quality of the cell was also impacted by the spacers used to separate the substrates. Originally, 10 μm or 8 μm glass spheres were mixed with the OG 154-1 epoxy and applied to the corners of the substrate. However, cells produced with this method had extremely variable cell gaps. This problem was eliminated by using 14 μm glass fibers mixed into the epoxy instead of the glass beads. A combination of higher quality substrates and fiber spacers produced the most accurate and precise cells.

Conclusions

Experiments have shown that photoaligned wave plates of equal or superior quality to buffed wave plates can be created if substrates with low scratch-dig and wedge are used along with precise photopolymer application.

If the quality of photoaligned waves can continue to be improved, there will be many applications for photoaligned devices. Photoaligned wave plates could be used on the OMEGA and OMEGA EP laser systems to replace the currently used buffed wave plates. The repeatability, precision, and inherent cleanliness of the photoalignment process will offer vast improvements over buffing. Experiments in the future will explore scaling up the photoalignment process to larger wave plates and apertures. This is a requirement for use on the OMEGA system and will ensure that photoalignment is successful on large scale devices. As part of the scale-up process, large-aperture photoaligned waveplates will need to be tested for their laser damage resistance, both by small-aperture testing and on one OMEGA beamline to qualify then for full deployment in OMEGA or OMEGA EP as replacements for buffed LC wave plate technology.

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