Fabrication and Characterization of Radial and Azimuthal Polarization Converters with Photoaligned Liquid Crystals

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Abstract

Radially and azimuthally polarized beams have applications in laser technology, such as material processing and microscopy. Radially and azimuthally polarized beams have been produced using liquid crystal polarization converters created through the photoalignment of a coumarin-based photopolymer. In devices assembled with two substrates and nematic liquid crystals in the intersubstrate gap, the nematic liquid crystal molecules align along dimers produced by photoalignment at the surface of each substrate. Radial alignment is achieved by inducing a radial dimerization on one substrate by rotation of the polarization during UV exposure. A defect in the way the liquid crystals align themselves alters the final polarization state by 180° across the disclination line. A π phase step plate compensates for this defect, producing useful radially and azimuthally polarized fields. This investigation focused on integrating this π phase step plate into the polarization converter. Devices with integrated internal and integrated external phase step plates were fabricated and characterized. Characterization data were taken on a transmission set-up at 1053 nm. Far field and near field measurements were taken. The expected properties of radial polarization were seen in the far field of devices with an integrated external phase plate. The expected properties of azimuthal polarization were seen in the far field of devices with an integrated internal phase plate.

I. Introduction

The polarization state of light is determined by the direction of the electric field component of light. Laser light, which is coherent, is usually linearly polarized. In this case, the polarization vector of light oscillates in a fixed direction (Figure 1).

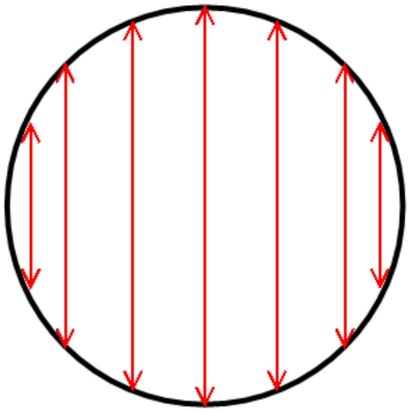

Figure 1: *The direction of the polarization vector in linearly polarized light. The polarization vector remains the same in all parts of the beam.*

Radially polarized beams and azimuthally polarized beams are both cylindrical vector beams — beams where the polarization is locally linear, but where the overall polarization depends on the position in the beam. Radial polarization occurs when the polarization vector points toward the center of the beam. In azimuthal polarization, the polarization vector is tangential to the beam (Figure 2).[1] In both types of polarization, the polarization of the beam is not defined at the center of the beam.

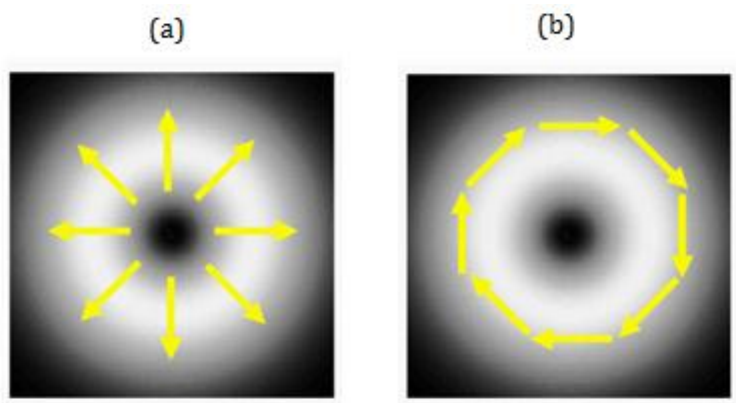

Figure 2: *The direction of the polarization vector in radially polarized (a) and azimuthally polarized (b) beams.*[1]

Cylindrical vector beams have been experimentally demonstrated to have advantages in laser technology. Radially and azimuthally polarized laser beams have been determined to be preferable in materials processing, optical trapping, electron acceleration, optical lithography, and microscopy.[2]

The generation of cylindrical vector beams, however, is cumbersome. Beams have been generated by inserting specially designed elements into a laser resonator, which is not practical for laser systems with limited space.[3] They have also been generated by superimposing two orthogonally polarized Laguerre-Gaussian modes.[3] An advantageous alternative to these approaches is the generation of radially and azimuthally polarized beams thorough patterned liquid crystal cells. This process has previously been demonstrated to be feasible.[4] This concept is illustrated in Figure 3.

Liquid crystals are in a mesophase — a state of matter between a liquid and a solid. Liquid crystals flow as a liquid would, but retain order reminiscent of a crystalline solid. Liquid crystals can be in several different phases. The phase used in figure 3 is the nematic phase, where the liquid crystals have directional order, but not positional order. A thin layer of this nematic liquid crystal, specifically E7 liquid crystal, was used to fabricate radial and azimuthal polarization converters. This liquid crystal was aligned through the irradiation of a coumarin-based photopolymer coated on fused silica substrates with polarized broadband UV light. This process, known as photoalignment, causes dimers to form parallel to the polarization of the light. One substrate was patterned with linear dimers. The other substrate was patterned with radial dimers. These substrates were then affixed together, and E7 was inserted in the inter-substrate gap. The liquid crystals aligned themselves along the dimers that were patterned on each substrate.

This process of photoalignment is a non-contacting process, which leaves no scratches or embedded particles on the substrates that would disrupt liquid crystal alignment.[6] It is easily scalable and cost effective, and produces devices with a high laser damage threshold — 60 J/cm^2 at 1053 nm.[7]

As light propagates through a nematic liquid crystal medium, its polarization rotates with the liquid crystal chain, changing the initial polarization. As shown in Figure 3a a horizontally polarized input field results in a radially polarized output field. In Figure 3b a vertically polarized input field results in an azimuthally polarized output field.

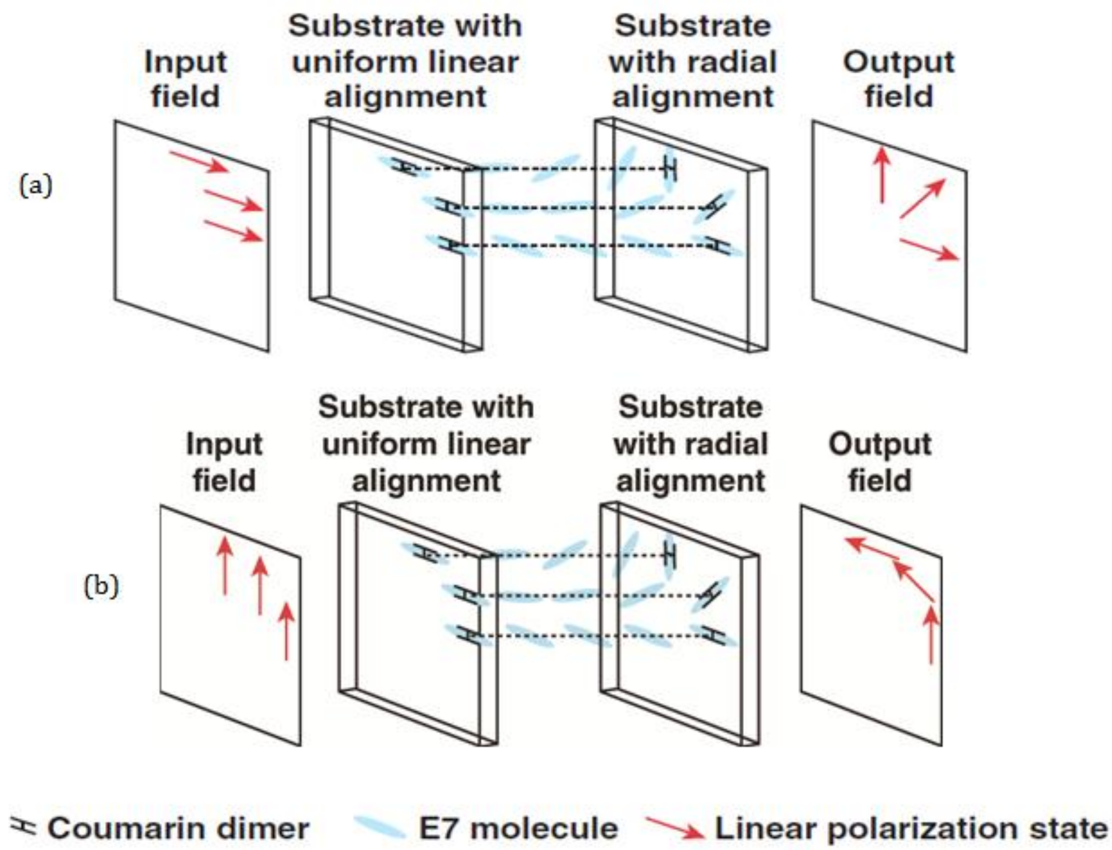

Figure 3*:* *A schematic of an assembled cell. (a) Radial polarization converter. Horizontal linearly polarized light enters the radial polarization converter through a linearly patterned substrate, propagates through a layer of E7 liquid crystal and emerges through a radially patterned substrate to have an output field of radial polarization. (b) The cell becomes an azimuthal polarization converter when the input polarization is vertical.*

Figure 4 depicts the result of a defect in the way the liquid crystals align themselves within the cell. On the horizontal line between points A and B in the figure, the polarization state does not change because the liquid crystals are aligned along the light path. The liquid crystal rotates the polarization at other points due to the patterning of the liquid crystals. Directly through the center of the device a disclination line forms — indicated by the dashed line in Figure 4 — where the nematic liquid crystals are twisting in opposite directions. This causes a π phase shift, altering the final polarization state by 180°, as seen in Figure 4b. This causes the output field of radial or azimuthal polarization to not be useful in laser technology applications. This π phase shift can be compensated with a phase step applied to half the cell, so a useful polarization state is achieved, as seen in Figure 4c.

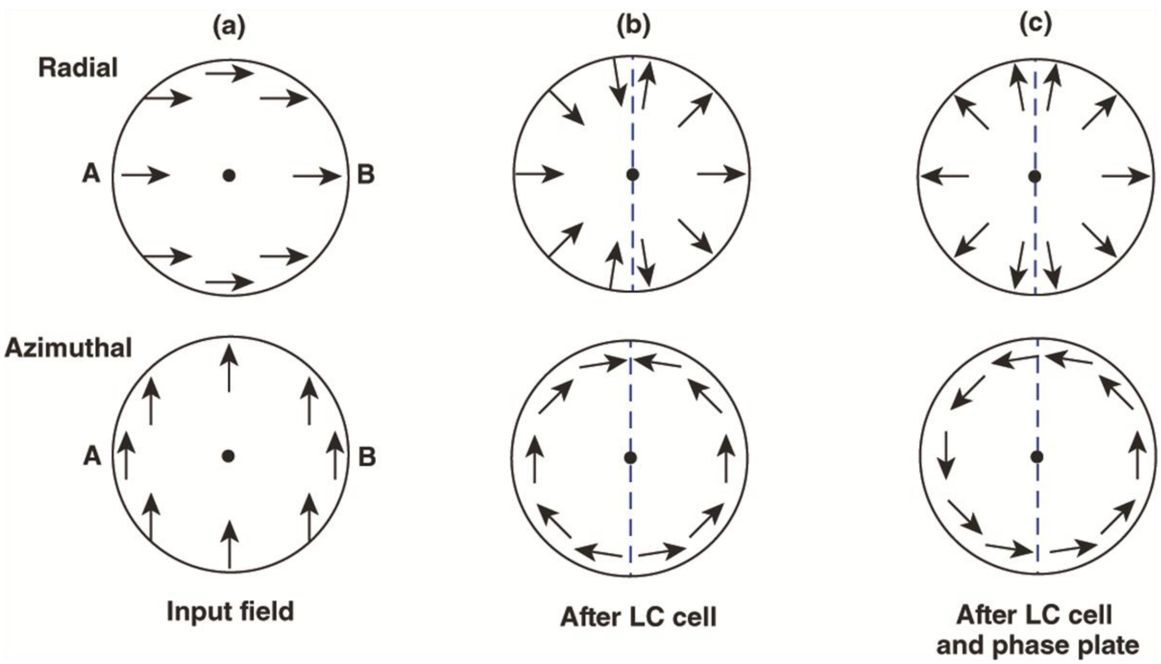

Figure 4: *Change in polarization state due to a disclination line formed by liquid crystals in a polarization converter. The input to the devices is linear polarization (a). After propagating through a device without a phase step (b) the polarization state is shifted 180° across the disclination line (shown dashed). With the addition of a π phase plate to the left half of the cell (c) useful radial or azimuthal polarization is achieved.*

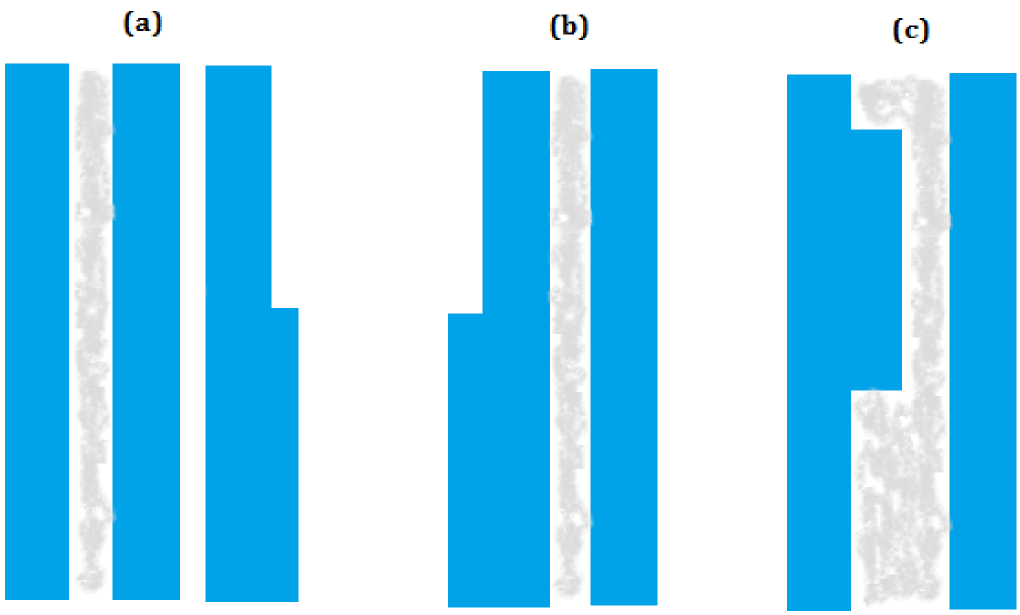

Figure 5: *Three types of phase steps used to correct for disclination lines . Phase steps can be separate external (a), integrated external (b), or integrated internal (c). This research investigated integrated external (b) and integrated internal (c) phase steps .*

A phase step is a substrate with a slight step built into it. Figure 5 shows three types of phase step. Previous fabrication methods[4] involved creating polarization converters with a separate external phase step, as shown in Figure 5a. This is burdensome because alignment of the device and phase step needs to be performed each time the device is used. Figure 5b shows an external phase step that is integrated into a device — the external phase step is on the non-coated side of the substrate. In Figure 5c the phase step is internal — on the side of the substrate that will be coated with the coumarin-based photopolymer necessary for photoalignment. The index of refraction difference between the air and fused silica, for an external step, or between the liquid crystal and fused silica, for an internal phase step, is used to calculate the phase step height for a particular wavelength of light. Devices with an integrated internal phase step can only be used with one input polarization; therefore they cannot be rotated to produce both radial and azimuthal polarizations because the refractive index of the liquid crystal depends on the input polarization. Internal phase steps are preferred, because they lead to a cleaner device.

In this study, two devices with an integrated phase step (Figure 5b and c) were fabricated and characterized. The external phase step height was 1.17 µm in the first device and the internal phase step height was 2.03 µm in the other device, calculated to produce azimuthal polarization.

II. Fabrication Procedure

Polarization converters were fabricated with 5-cm diameter fused silica substrates. One substrate was a blank; the other substrate had a phase step, either external or internal. Blank substrates and phase step substrates were cleaned, dried, and spin coated identically.

II.1 Substrate Preparation

Substrates were rinsed with deionized water (DI water) and then polished with 0.05 µm Masterprep® polishing suspension.[8] Substrates were polished for three to four minutes, with care taken to ensure that all parts of the substrate were scrubbed an equal amount. After polishing, substrates were rinsed again with DI water until they passed a water break test, which tested whether hydrophobic surface contaminants were present. To perform a water break test, substrates were wetted with DI water and held horizontally for seven seconds. If the water did not form a continuous sheet for the duration of seven seconds, hydrophobic contaminants were present, and more cleaning was necessary. After passing this test, substrates were cleaned with nanopure water for one minute. Substrates were then placed in an ultrasonic bath with three milliliters of Extran detergent added, and set to 69° C for 60 minutes. After being cleaned in the ultrasonic bath, the substrates were rinsed for five minutes with DI water to ensure that no residual polish or detergent was left behind. All water was blown from the substrates using a nitrogen air gun. The substrates were then placed under a crystallizing dish on a hotplate set to 130°C for thirty minutes. This was to assure that no water remained on the substrates. The substrates were then set under a crystallizing dish for thirty minutes in a class-10 clean hood to cool.

After cooling, the substrates were spin-coated in a class-10000 clean room. One substrate was placed on a small circular spin-coating stage. A crystallizing dish was placed so that it encapsulated the stage and substrate. This crystallizing dish had ventilation holes that were taped over prior to use; this allowed for the air to be saturated with photoalignment materials, but also for an easy means of depositing the material. A substrate was first flooded with chloroform, which served as a preconditioning layer for the photoalignment material. A 2-cc glass syringe fitted with a 0.45-μm PTFE 13-mm hydrophobic syringe filter and a syringe needle was used to deposit approximately 3 mL of chloroform onto the substrate. The substrate was then spun at a speed of 4000 rpm for one minute. After this, the substrate was coated with 0.1% wt coumarin polymer 3 in a chloroform solution. A 2-cc glass syringe fitted with a 0.45-μm PTFE 13-mm hydrophobic syringe filter and a syringe needle was used to deposit the photoalignment material onto the substrate. The substrate was then spun at 4000 rpm for two minutes. Subsequent to spin coating, the substrate was placed under a crystallizing dish in a class 10 clean hood to dry for ten minutes. The spin-coating process was then repeated for all remaining substrates.

II.2 Photoalignment

Substrates were removed from the class-10000 clean room to a class-1000 clean hood for irradiation. The irradiation setup (Figure 6) was a photolithographic system emitting non-polarized UV light. This system consists of a broadband xenon light source equipped with a dichroic mirror and lenslet array configured to deliver UV light to a pile-of-plates polarizer at Brewster’s angle, which produces linearly polarized UV light. The polarized light passes through a 0.6 mm slit, and then through a cylindrical lens which images the slit onto the substrate placed on the rotation stage, as seen in Figure 6. The rotation stage is necessary to produce radial patterning. A fixed stage, not shown in Figure 6, is used to produce linear patterning.

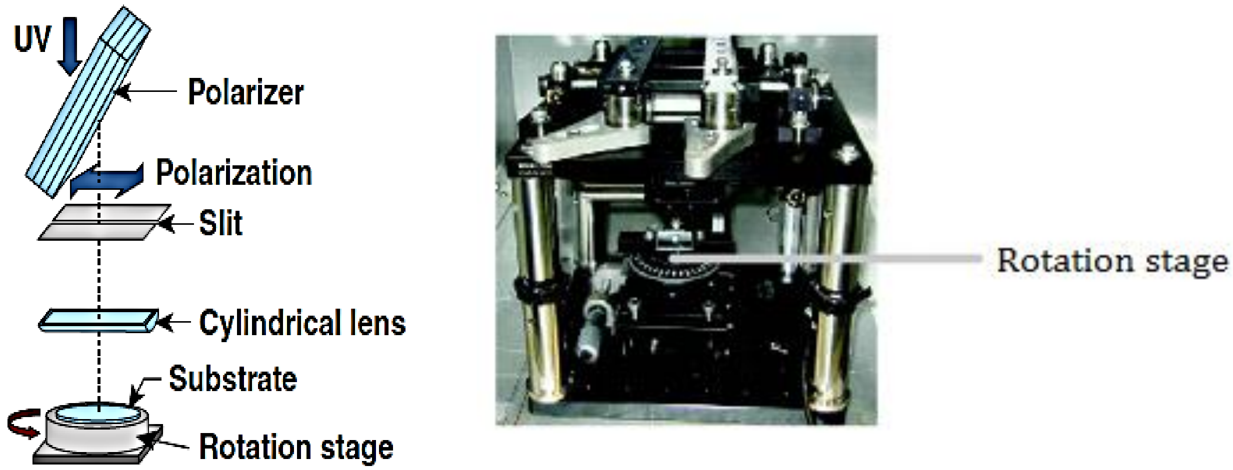

Figure 6: *Rotation stage set-up used for irradiation of the substrates of polarization converters. Substrates are placed on a rotation stage which is controlled by LabView software*

The phase step substrate was irradiated first (the irradiation process was the same for internal and external phase step substrates). The substrate was tilted so that the phase step line was clearly defined; a line was then drawn along the phase step on the uncoated side of the substrate using a permanent marker. Markings for 0°, 90°, and 270° were made along the edge of the substrate. The substrate was then transferred to the fixed stage used for linear patterning in the irradiation chamber, so that the phase step line was horizontal and the coated side of the substrate was facing upward. The dimers form parallel to the polarization of the UV light. The irradiation chamber was then sealed and the substrate was irradiated for one minute. After the irradiation was completed, the phase step substrate was set aside. The blank substrate was marked similarly to the phase step substrate: 0°, 90°, and 270° were marked along the edge of the substrate. The substrate was then placed on the rotation stage setup, which was controlled by a LabView program that dictated the rotation stage speed and the number of revolutions of the rotation stage. To induce radial patterning, the substrate was irradiated for one hour at a speed of 10° per second. More time is needed for this irradiation because less of the substrate is exposed.

II.3 Assembly

After irradiation, substrates were assembled in the class-10000 clean room. UV-curing epoxy was mixed with a small quantity of 10 μm glass microsphere spacers. The phase step substrate was placed into a fixed rotation stage, so the 0°, 90°, and 270° markings on the substrate were aligned with 0°, 90°, and 270° on the stage. Three very small dots of the mixture were placed on the coated side of the radially patterned phase step, as shown in Figure 7. The placement of the epoxy was very important for internal phase step devices — if the epoxy was not properly placed on the phase step substrate a wedge would result, and interference fringes would occur. These interference fringes would be an indication that the blank substrate and the phase step substrate were not parallel, which would mean that the π phase shift would not be properly compensated for.

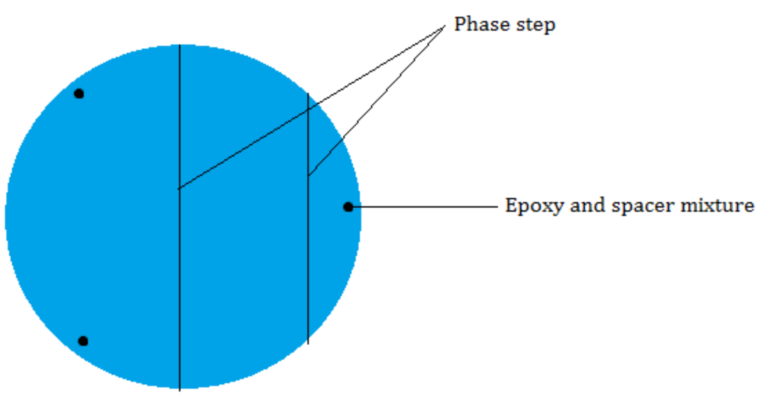

Figure 7: *Correct placement of epoxy and spacer mixture for assembly of internal phase step devices*

The phase step substrate was then lowered, as flat as possible, onto the radially patterned substrate, with the coated sides facing each other (Figure 8). Considerable care was taken so that the 0°, 90°, and 270° markings were aligned. Misalignment would mean that the phase step and the disclination line would not be aligned, and the desired radial alignment pattern would not be achieved.

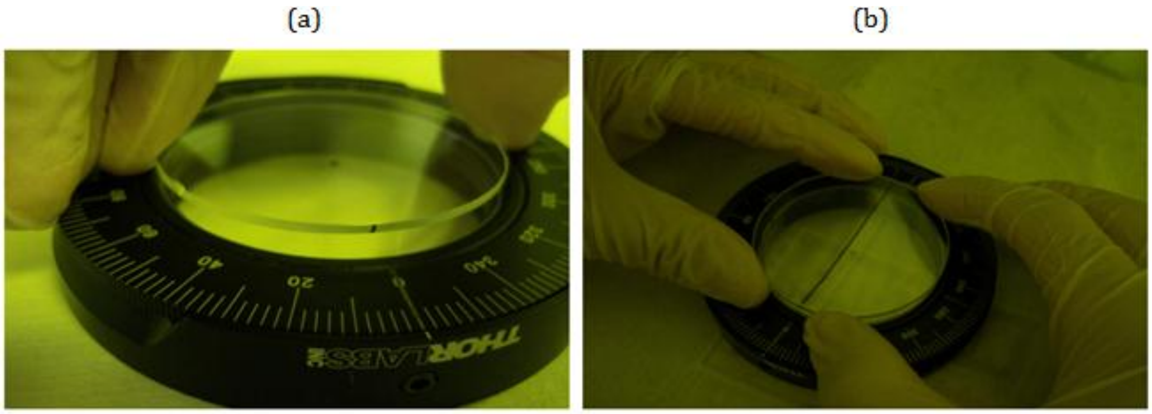

Figure 8: *Assembly of polarization converters. (a) A flat, radially patterned substrate is lowered onto a rotation stage so that the fiduciary markings are aligned at 0°, 90°, and 270° . (b) The phase step substrate is lowered onto the radially patterned substrate so that the fiduciary markings are aligned and the phase step is straight between 0° and 180°.*

Once the device was affixed together, it was placed under a UV lamp for five minutes to cure the epoxy. After curing, the assembled cell was transferred to a hot plate heated to 70°C. A 1-mL plastic syringe fitted with a 0.45-μm PTFE 4-mm hydrophobic syringe filter and syringe needle was used to fill the assembled cell with E7 liquid crystal in the intersubstrate gap. After filling, the substrate was cooled to 25° at a rate of ten degrees per hour.

III. Characterization

Characterization data were taken on a transmission set-up at 1053 nm, where the light source is spontaneous emission obtained from a fiber amplifier and collimated by a lens. Near and far field data were taken for both devices. The near field of a light source is at the aperture of the beam—right after light passes through the cell. The far field is the light at the focus of a lens.

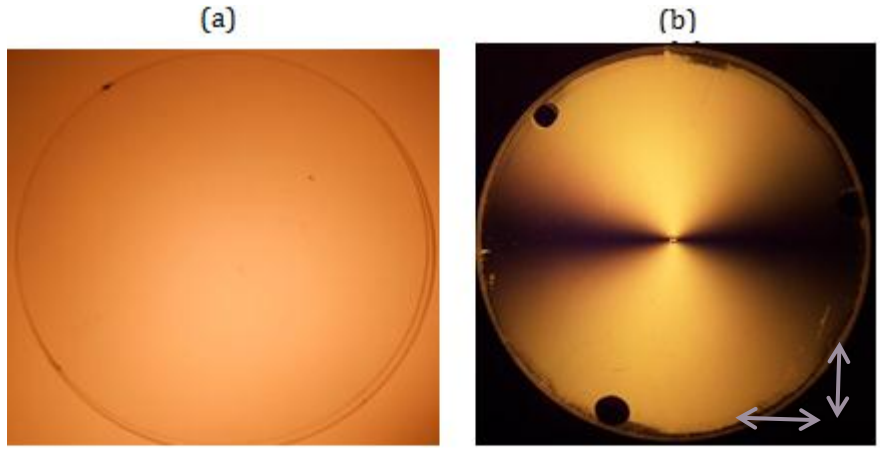

Figure 9: *5 cm polarization converter with an integrated external phase step viewed in broadband light without a polarizer (a) and viewed through crossed polarizers (right).*

Characterization data were taken for a polarization converter with an integrated external phase step (Figure 9). In Figure 9a, the cell is seen alone. Figure 9b depicts the device through crossed polarizers and shows good alignment, indicated by a surface free from defects. In the near field without a polarizer, two lines were seen (Figure 10). The straighter of the two is the integrated phase step; the other line is the disclination line. These lines need to be close together in order for the π phase shift to be compensated for. Figure 10 shows good alignment of the disclination line and phase step line.

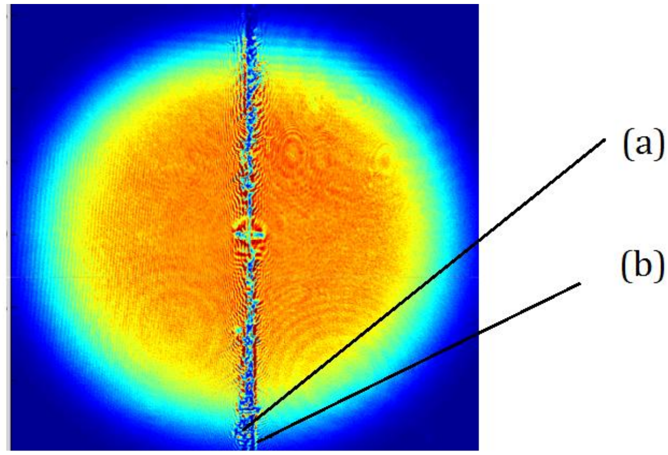

Figure 10: *Near field of a polarization converter with an integrated external phase step characterized at 1053 nm. Two lines can be seen; (a) is the disclination line and (b) is the phase step.*

In the near field, when viewed with a polarizer that selects the part of the beam polarized along the transmission axis of the polarizer, properties of radial polarization are seen, illustrated by the first row of Figure 11. The pattern produced by the radial polarization converter rotates as the polarizer rotates along its transmission axis. These characteristics seen in the near field are confirmed in the far field (bottom row of Figure 11). In the far field, viewed without an output polarizer, a doughnut beam is characteristic of a beam produced by a radial polarization converter .

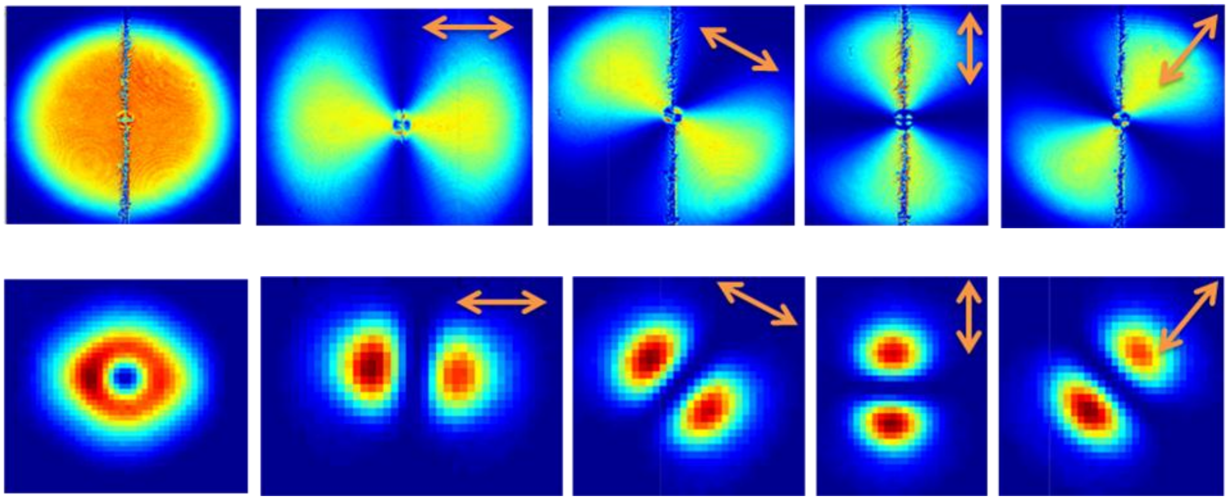

Figure 11: (First Row) *Near field of a radial polarization converter with an integrated external phase step. From left, near field without an output polarizer, polarizer at 0 °to the horizontal, polarizer at 45°, polarizer at 90°, polarizer at 135°.* **(Second row)** *Far field of the radial polarization converter. From left, far field without an output polarizer, polarizer at 0 ° to the horizontal, polarizer at 45°, polarizer at 90°, polarizer at 135°. Input polarization was horizontal.*

An azimuthal polarization converter with an integrated internal phase step was characterized. As in Figure 10, the disclination line and phase step are seen in the near field without an output polarizer (Figure 12). The alignment is not as good as in Figure 10, due to an error in the fabrication process. Currently, there is a slight lip on the edge of the stage used to secure the radially patterned substrate when aligning the substrates, as previously seen in Figure 8, that makes it difficult to properly align the phase step substrate. The phase step line is not perfectly in the center of the device. In order for the substrates to be perfectly aligned, the blank substrate needs to be placed slightly left of center, but the lip causes the blank substrate to be higher than the phase step substrate, making the blank substrate prone to slipping. A way to address this would be to eliminate the use of the stage. Instead, substrates could be placed flat on the surface of the clean hood, so utmost care could be taken to align the substrates properly. There is also a large center defect in this device, which was due to misalignment of the slit used to produced radial patterning during photoalignment.

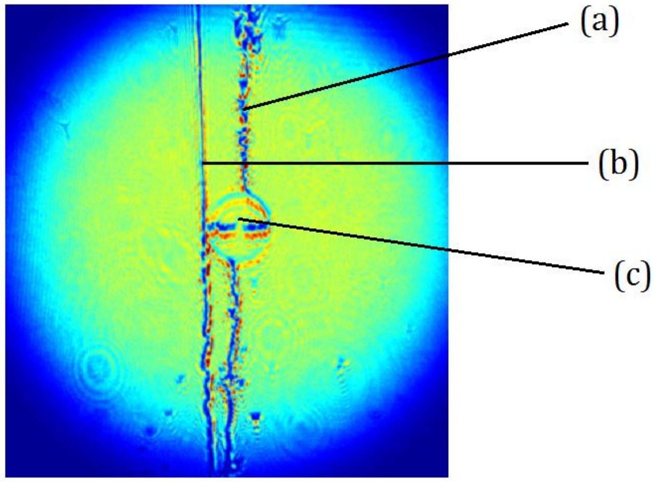

Figure 12: *Near field of an azimuthal polarization converter with an integrated internal phase step. Two lines can be seen; (a) is the disclination line and (b) is the phase step. (c) is a center defect caused by misalignment of the slit used to produced radial patterning during photoalignment.*

Azimuthal polarization characteristics were confirmed in the near and far fields (Figure 13). In Figure 13, the near and far field characterizations are shown. The patterns are very similar to those seen in Figure 11. As in Figure 11, the beam pattern also rotates with the rotation of the transmission axis of the polarizer; this is characteristic of both azimuthal polarization and radial polarization. In the far field, the azimuthally polarized beam is a doughnut beam, which is seen in the bottom left corner of Figure 13. The doughnut beam in Figure 13 is not as good as the doughnut beam in Figure 11, due to the fabrication error depicted in Figure 12.

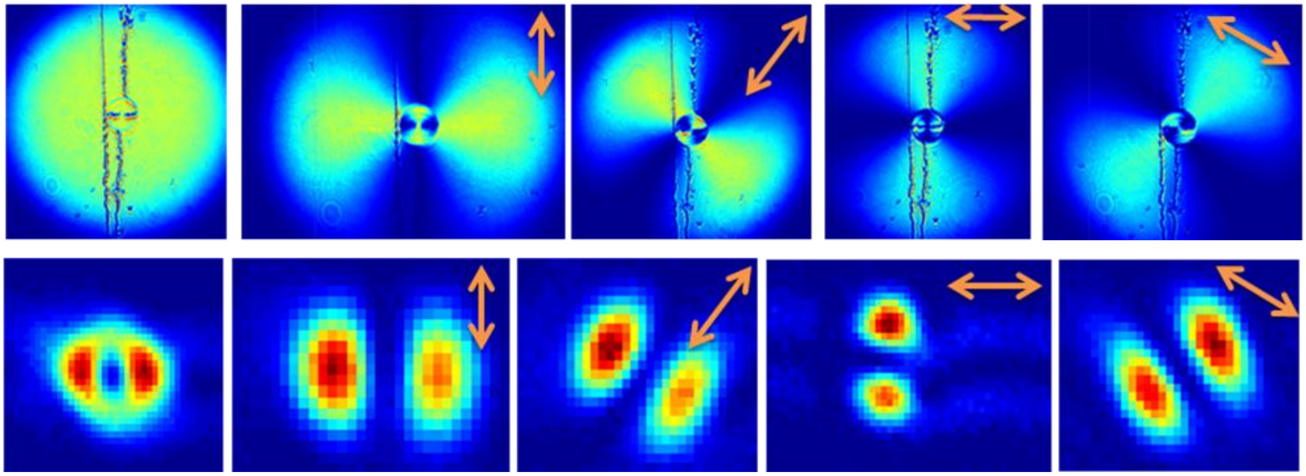

Figure 13: (First Row) *Near field of an azimuthal polarization converter with an integrated internal phase step. From left, near field without output polarizer, polarizer at 0 °to the vertical, polarizer at 45°, polarizer at 90°, polarizer at 135° .* **(Second row)** *Far field of the azimuthal polarization converter. From left, far field without output polarizer, polarizer at 0 °to the vertical, polarizer at 45°, polarizer at 90°, polarizer at 135°. Input polarization was vertical.*

Conclusion

5 cm diameter radial and azimuthal polarization converters with integrated phase steps were successfully fabricated. The integration of phase steps successfully compensated for the π phase shift caused by the disclination line. Radial polarization converters were fabricated using an integrated external phase step. Azimuthal polarization converters were fabricated using an integrated internal phase step. In both devices, the phase step line and disclination lines were aligned. In some cases, such as Figure 10, this alignment was very accurate. In other cases, the alignment was less good due to fabrication errors. However, despite these alignment problems, cylindrical vector beams were produced.

This method of generating cylindrical vector beams is easier to use than previous methods, needs less space, and does not require alignment of a separate phase step. This is a promising way of producing radially and azimuthally polarized beams for a variety of different applications in laser technology.

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