Generation of Radially Polarized Beams Using Optically Patterned Liquid Crystals

Michael Statt

School of the Arts

Advisors: Dr. Christophe Dorrer & Kenneth L. Marshall

University of Rochester

Laboratory for Laser Energetics

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Abstract

Radially polarizing liquid crystal (LC) devices aligned optically were investigated for applications in laser technology. Presently, radially polarized beams are generated through complex laser resonator configurations or buffing of LC alignment layers. Optically aligned LC devices offer several advantages over these methods, including their simple fabrication, low cost, high laser damage threshold, and scalability. This project researched the fabrication of the LC devices using a high-damage-threshold coumarin-based photopolymer irradiated with polarized UV light on a rotating stage coupled with a slit. Radially polarizing LC devices have been fabricated and characterized. This will lead to more research to improve the fabrication technique and make larger devices.

Introduction

Polarization is an important aspect of light. The polarization state locally describes the vibration of the electric field. This affects the propagation of optical beams and their interaction with matter. Laser beams are usually linearly polarized (the electric field is oriented in one particular direction across the entire beam) or circularly polarized (the electric field locally rotates at a rate given by the optical frequency at each point in the beam). However, new research has been done on the generation and use of cylindrical vector beams, such as radially and azimuthally polarized beams: the polarization is locally linear, but its orientation depends on the position in the beam. This leads to many interesting properties[1].

Radially polarized beams have many potential uses in laser technologies. In laser cutting, radially polarized beams have shown potential for large increases in efficiency. The orientation of the polarization to the plane of incidence heavily affects laser cutting efficiency. When the polarization is parallel to this plane it is called p-polarization. When the polarization is perpendicular to this plane, it is called s-polarization. For laser cutting, p-polarization is much more efficient. Presently, circularly polarized light is used for laser cutting because it is an average of s-polarization and p-polarization and therefore makes uniform cuts. However, p-polarization yields a much higher absorption coefficient, meaning that the surface absorbs much more of the light of the beam when it is p-polarized than when it is s-polarized. The use of radially polarized light instead shows promise because it's p-polarized relative to the edge of the hole being drilled across the entire beam and could increase efficiency by 1.5 to 2 times.[1] Radially polarized beams can also be focused to a significantly smaller focal spot than linearly polarized light, 0.16λ compared to 0.26λ, due to the strong longitudinal component of the beam. This tighter focusing has uses in higher resolution microscopy.[1] Radially polarized beams also have uses in optical trapping due to the doughnut-shaped intensity distribution in the far field (i.e., when focused).[1] This intensity distribution is due to the destructive interference between the opposite polarizations on either side of the center of the beam.

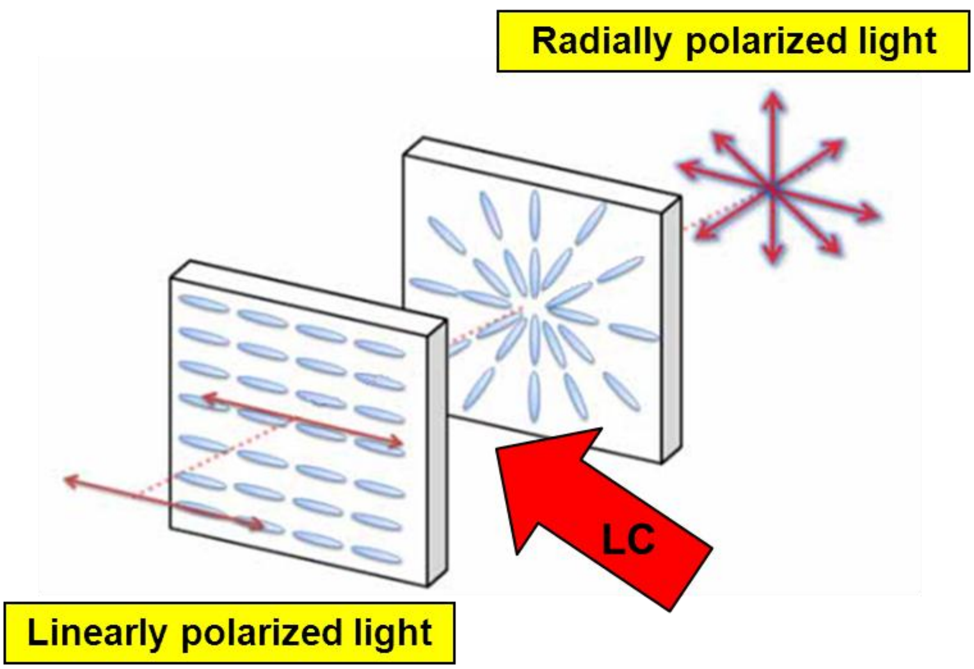

Figure 1: Schematic of a radially polarizing LC device. It consists of a linearly patterned substrate (left) and a radially patterned substrate (right), put together and filled with a twisted nematic liquid crystal

Presently, radially polarized beams are generated through complex resonator configurations or the superposition of Gaussian beam modes.[2] These methods, however, are cumbersome and not applicable to laser systems that cannot be specifically designed for radially polarized beams or where space is limited. Another method to generate radially polarized beams is with a segmented spatially variable $\lambda/2$ wave plate, but this method is not very accurate due to the distinct cuts between each segment.[3]

The generation of radially polarized beams using a radially patterned liquid crystal (LC) has been investigated as an alternative to the previously stated methods (Fig. 1). Liquid crystal devices are more advantageous than previous methods thanks to their simplicity, low cost, and ease of fabrication. Once fabricated, these devices are very easy to install into existing laser systems. As shown in Figure 1, all that is needed to convert incident polarized light to radially polarized light is to put the LC devices in front of a linearly polarized beam. They are also spatially continuous, unlike the segmented wave plate that consists of several pieces of glass put together. Finally, LC optical devices fabricated with patterned alignment layers generated by irradiation with polarized UV light have previously demonstrated a damage threshold higher than 30 J/cm^2 at 1053 nm in the nanosecond regime. Using such LC device technology allows the generation of radially polarized beams in high-energy and high-power laser systems.

There are two methods to align LC molecules: (1) by mechanical buffing of a polymer alignment layer and (2) by irradiating a photosensitive polymer layer with polarized UV light ("photoalignment".) The mechanical buffing process makes use of a polymer alignment layer deposited on a glass substrate and buffed by a machine so as to create a preferred direction for the LC molecule to align along. This process is inherently "dirty" in that it requires physical contact between the buffing roller and the coating, which generates particles and can produce large scratches in the alignment coating. Photoalignment, however, is a very clean, non-contacting process that uses polarized UV irradiation to align the LC molecules. Photoalignment was used to radially pattern the devices in this experiment. The UV irradiation causes a coumarin-based photopolymer, synthesized at the Laboratory for Laser Energetics, to dimerize parallel to the polarization of the UV light. The LC molecules align themselves parallel to the dimers creating uniform alignment.[4] The radial pattern is possible through the use of a rotating stage coupled with a slit.

Experimental Device Fabrication

All processes except for cleaning and irradiation were done in Class 100 or better hoods inside a Class 10,000 clean room facility. Borofloat™ windows (25mm x 25mm, Edmund Optics® part number NT48-542) were used for the radially polarizing devices. The glass was wetted with deionized (DI) water, scrubbed with 0.05 μm Masterprep® Polishing Suspension micropolish and then rinsed with DI water. The substrates were subjected to a seven-second water break test where the surface tension of the water on the glass was examined: if a continuous sheet of water was unable to remain on the surface of the substrate for seven seconds without beading or pulling up from the surface (e.g. "breaking"), then more cleaning was necessary. If the substrates passed the water break test, they were placed in a substrate holder and then placed in a small glass container that was filled with DI water. This container was then placed in an ultrasonic bath at 69°C for 60 minutes with approximately 3 mL of Extran detergent added to the water in the container and just enough water added to the ultrasonic machine so as to not spill over the sides of the container. After cleaning in the ultrasonic bath the substrates were rinsed with DI water for approximately five minutes and dried with a nitrogen air gun. They were then placed on a hot plate set at 130°C for 30 min. to completely dry the substrates before depositing the photoalignment layer.

After cooling for 30 minutes, the substrates were placed one at a time on the circular stage of a spin-coater. A small crystallizing dish was then placed over the substrate; the dish had ventilation holes which were taped over prior to use. Covering the ventilation holes allows for the atmosphere which the substrate is in to become saturated with the vapor of the chloroform-based coatings. 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 chloroform on the surface of one substrate to precondition the surface before coating (approximately 3 mL was used to completely flood one substrate.) The substrate was then spun at 4000 RPM for 60 seconds to spin off the chloroform. A second 2-cc glass syringe fitted with a 0.45-µm PTFE 13-mm hydrophobic syringe filter and syringe needle was used to deposit the photoalignment material (coumarin Polymer 3) as a 0.1 wt% solution in chloroform onto the substrate. It was then spun for 4000 RPM for 120 seconds. Each coated substrate was then air-dried under a Class 100 clean hood for 30 minutes.

Radial patterning of the dried photoalignment layer was achieved with a rotating-stage setup inserted in a photolithographic system emitting non-polarized UV light (Fig. 2). The setup consists of a 500-watt broad-band xenon light source equipped with a dichroic mirror and lenslet array configured to deliver collimated 325 nm UV light to a pile-of-plates polarizer set at Brewster's angle that produces linearly polarized UV light. The polarized UV light then passes through an adjustable slit set to restrict the width of the beam to 0.6 mm. A cylindrical lens reimages the beam onto a substrate previously coated with the photopolymer set on a rotating stage. During this irradiation process, the rotating stage was driven by a computer program that sets the rotation speed and the number of revolutions. The substrate was rotated at 10° per second for 30 minutes to align the dimer molecules in a radial pattern. Another substrate was then placed directly below the pile-of-plates polarizer on top of the closed slit and illuminated without rotation for 1 minute to induce parallel alignment.

The substrates were assembled into cells using an epoxy and spacer mixture prepared by mixing EPO-TEK® OG 154-1 UV-curing epoxy with a quantity of 10 µm glass microsphere spacers. A very small amount of the mixture was then applied to the corners of one linearly patterned substrate using a needle. A radially patterned substrate was then placed on top of this substrate and this resulting cell was irradiated under a 365 nm UV lamp for 5 minutes to cure the epoxy. The assembled cell was then heated to 100°C on a hot plate so as to raise its temperature above the nematic-to-isotropic phase transition temperature (or "clearing point") of the E7 LC (58°C). Filling the device above the clearing point of the LC material improves the final alignment quality of the device and speeds up the filling process due to the reduced viscosity of the LC material at elevated temperatures. 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 LC (Manufactured by Merck.) Once filled, the cell was cooled at 10°C an hour until it reached room temperature.

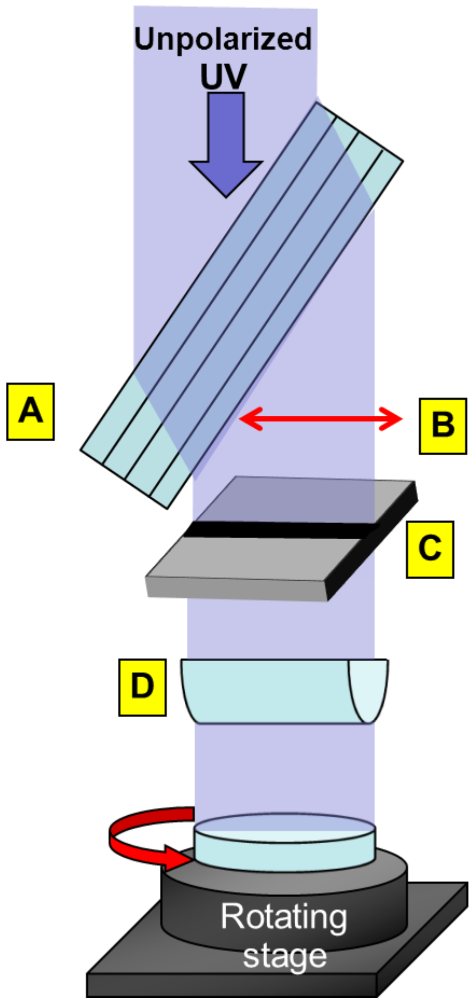

Figure 2: Schematic of the rotating-stage setup.

A) Pile-of-plates polarizer

B) Direction of polarization axis

C) Adjustable slit

D) **Cylindrical lens**

E) **Rotating stage**

The rotating stage was connected to a computer program that allowed the speed and number of revolutions to be controlled. Later, the rotating stage was put on a translation stage to allow movement perpendicular to the slit direction.

Experimental Results

Radially polarized beams were successfully generated through the use of an optically patterned LC device. The fabrication process and setup were optimized so as to align the slit with the rotation axis of the stage and to determine the speed of rotations that would yield the highest quality devices.

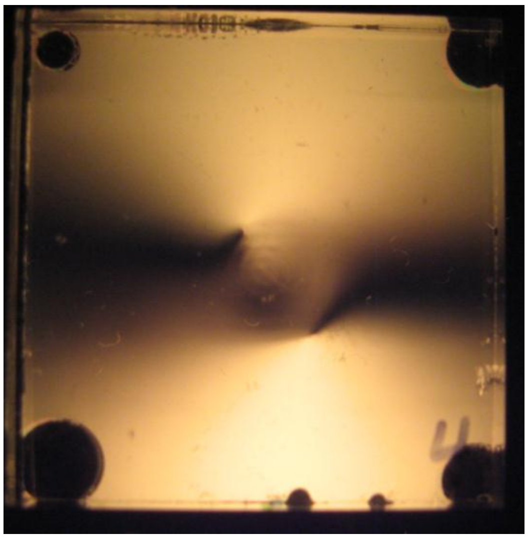

Figure 3: A LC device that was irradiated using one slow 180° turn, and incorrect relative alignment of the slit and rotation axis. Viewed through crossed polarizers.

The optimal rotation speed of the stage during irradiation was determined based on experimental trials. In early trials, inconsistencies in the width of the slit proved to be a major contributor to the poor quality of the devices. Devices that were irradiated with one 180° turn over a period of 15 minutes had large centers of undefined alignment (Fig. 3). After changing the rotation speed to 25 rotations over a period of 15 minutes, a much clearer and higher quality device resulted (Fig. 4a). The multiple rotation cycles produced by the increase in rotation speed helps to minimize the effect of the inconsistencies of the slit on LC alignment uniformity.

Even with multiple rotations, a large artifact in the center of the device that resembled a miniature radially polarizing device 90° out of phase with the rest of the device was produced (Fig. 4a). This artifact was found to be caused by the slit and rotation axis of the stage not being aligned. To correct this problem, the rotation stage holding the substrate was set on a translation stage to allow the position of the rotation axis to move relative to the fixed illumination from the slit. The alignment of the slit and the rotation axis of the stage were optimized using a calibration process. The process consisted of making an LC device by irradiating a substrate under the slit so as to make three lines at 45, 135°, and 225° when assembled and filled with LC material (Fig. 4b). If the slit and rotation axis were aligned properly, the 45°

(a) *(b)*

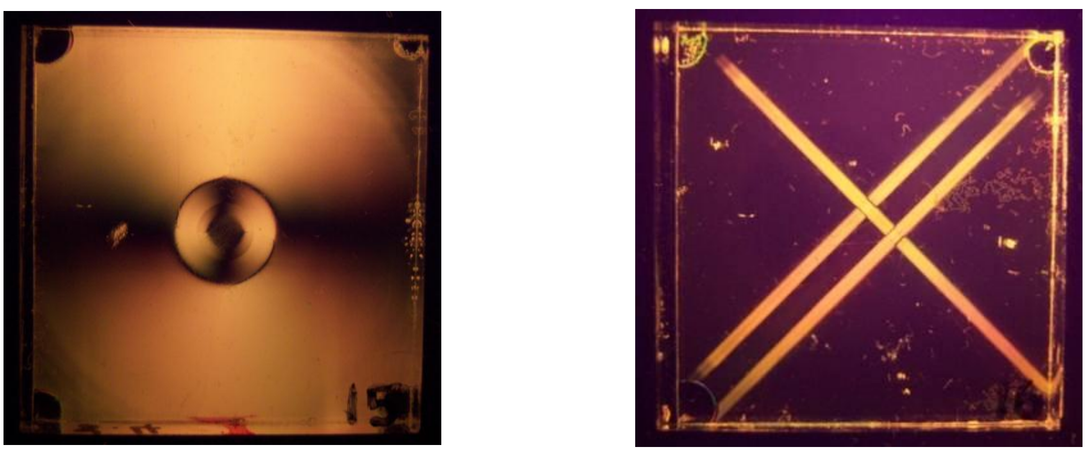

Figure 4: (a): Artifact found in center of devices with unaligned slit and rotating-stage. (b): A calibration cell. 3 lines at 3 discrete angles (45°, 135°, and 225°) were made using the slit in the rotating-stage setup. Proper alignment of the rotation axis and slit produces only two lines. Viewed through crossed polarizers.

and 225° lines would be indistinguishable; if misaligned, two separate lines were generated. The distance between the rotation axis and the illumination from the slit is half the distance between the centers of the two lines; this distance was determined using a *Leica*® DMRX polarizing microscope equipped with ImagePro microscope measuring software. The direction in which to move the stage was determined by using the 135° line and the knowledge of the order in which the lines were irradiated. This calibration yielded a much better device and a significantly smaller artifact in the center that had a diameter that was approximately 0.6 mm (Fig. 5a). This device comes very close to a computer-generated image of an ideal device (Fig. 5b).

(a) **(b)**

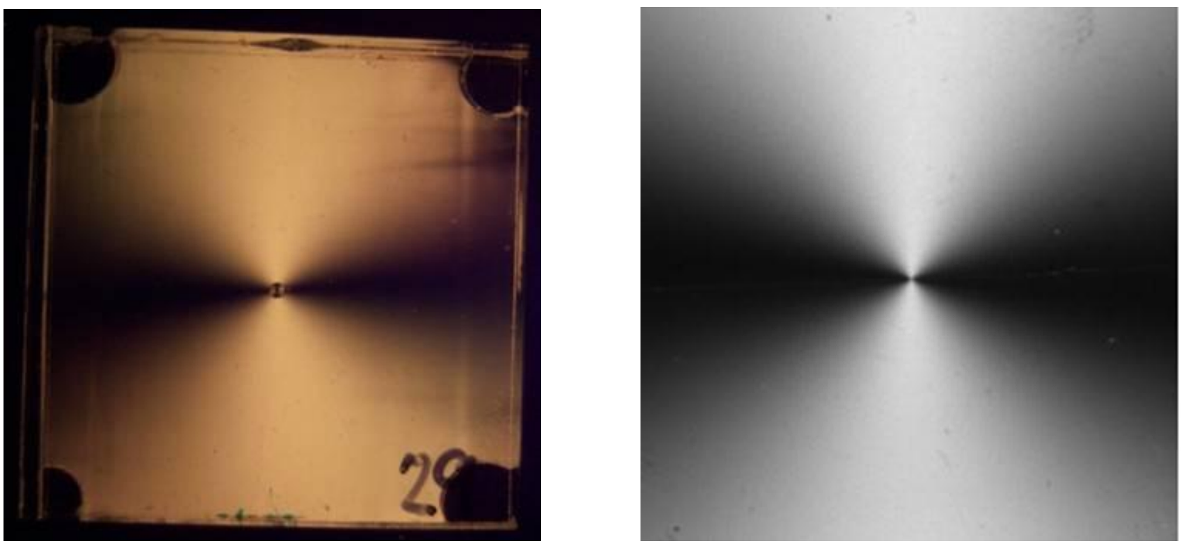

Figure 5: (a) -Fabricated device after alignment process (b) - Computer generated image of an ideal device. Viewed through crossed polarizers.

Another artifact found on all devices was a thin black line running straight up and down each device (Fig. 6). This disclination line, which is a region of undefined alignment of the LC, is caused by the LC twisting in opposite directions on either side of the line. These disclinations were measured, using ImagePro, to be 5-μm wide. Previous research into radially polarizing LC devices has obtained a similar disclination line, but in those devices the disclination lines were substantially larger (approximately 20 μm wide).[5]

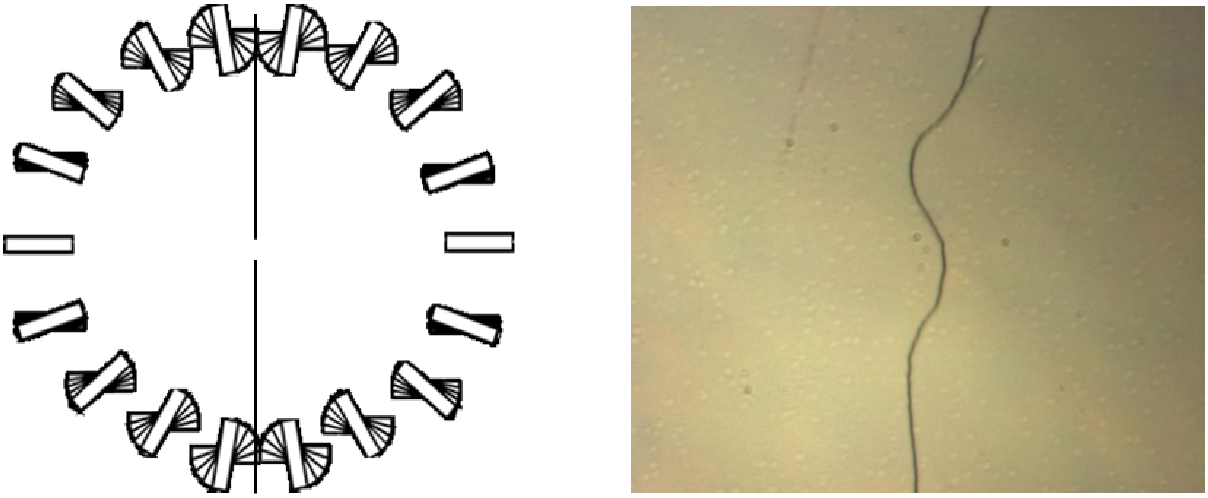

Figure 6: **Left- Twisting of the LC throughout the device. Right- Disclination line under 100X magnification (viewed with unpolarized light)**

The opposite twist directions also result in a π phase shift at the disclination line. This affects the focusing properties of the beams that pass through the devices, also called far-field properties. A transmission setup was used to characterize the devices. The setup included light passing sequentially through a polarizer, the device, and then a second polarizer that was rotated throughout the characterization. The light source used was amplified spontaneous emission around 1053 nm obtained from a fiber amplifier. The near field, or the properties of an unfocused beam, demonstrates the expected properties, as the polarizer selects a fraction of the beam polarized along its transmission axis (Fig. 7, first row). In the far field a radially polarized beam would be expected to yield a pattern that would rotate as the second polarizer rotated. However, when the radially polarized beams were characterized in the far field a pattern was observed that changed considerably as the polarizer rotated instead of simply rotating (Fig. 7, second row). A radial beam is expected to yield the desirable doughnut shaped beam in the far field, when no polarizer is present. The correct far field measurements were not observed due to the π phase shift at the disclination. This phase shift disrupts the destructive interference at the center of the beam that causes the doughnut-shaped intensity distribution. Investigation into this problem has yielded several promising methods of compensating for this phase shift, such as the use of an extra substrate to induce another π phase shift to cancel out the first one. The feasibility of this approach was demonstrated later using a fused silica plate to induce the required phase shift on one side of the beam. After propagation through the LC device and this phase plate, the expected far field distribution patterns, without and with a polarizer, have been obtained for a radially polarized beam (Fig. 7, third row).

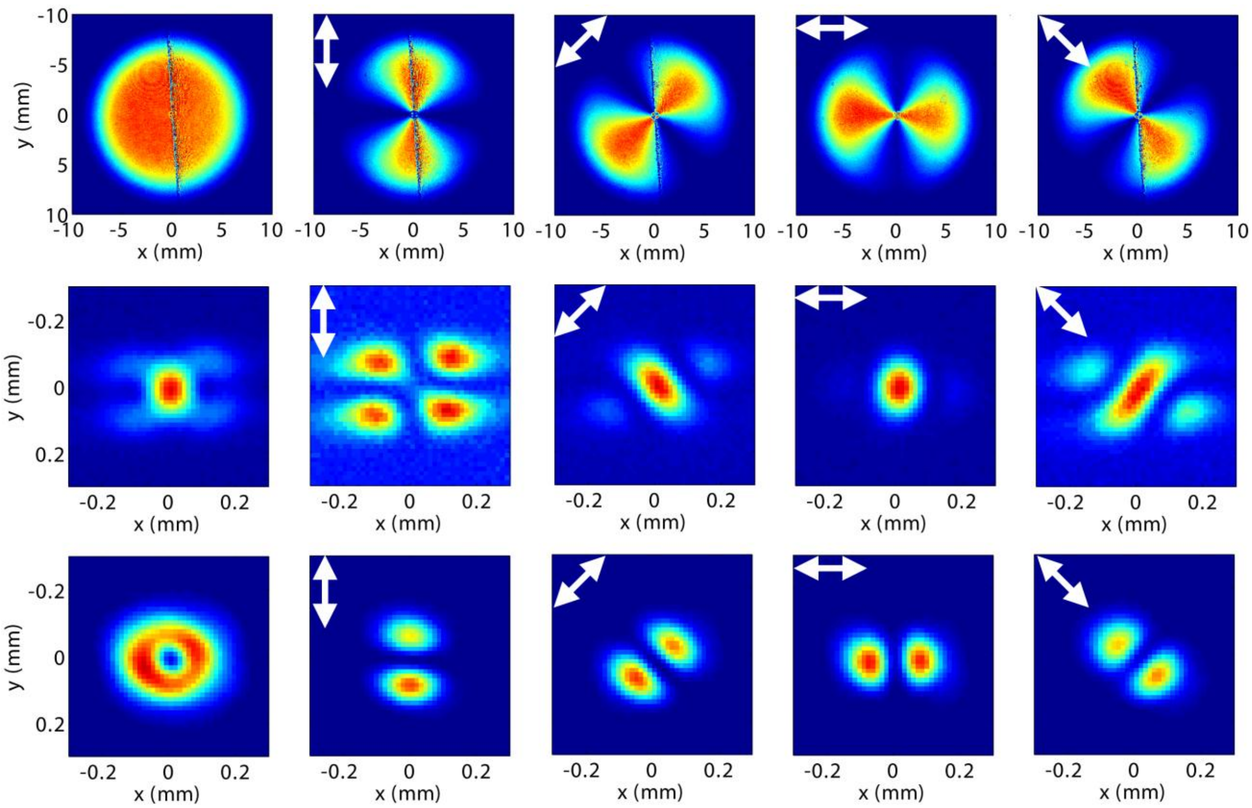

Figure 7: First row (from left to right): near field of the beam without a polarizer, and with a polarizer oriented in four different directions. **Second row** (from left to right): far field of the beam after the LC cell without a polarizer and with a polarizer oriented in four different directions. **Third row** (from left to right): far field of the beam after the LC cell and a corrective π phase plate without a polarizer and with a polarizer oriented in four different directions. In all cases, the white arrows indicate the transmission axis of the polarizer.

Conclusion

This investigation resulted in the successful fabrication and testing of radially polarizing LC devices. A setup was designed and constructed for radially patterning the photoalignment polymer layer used to generate the required LC alignment. Larger aperture devices for use in larger laser systems could be made in the future by scaling up the process and equipment used to fabricate the 25 mm devices reported here. More research could also be done to optimize methods aimed at compensating for the π phase shift without needing to add additional substrates or optical elements. These devices are a promising and simple way of generating radially polarized beams.

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