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Minimally invasive optical beam profiler

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Abstract: Proposed and demonstrated is a minimally invasive optical beam profiler using a non-pixelated liquid crystal spatial light modulator. The profiler features high detection sensitivity in the visible band, high 50 lines/mm spatial resolution, beam observation zone 100 % fill factor and magnification flexibility, and video rate operations. Applications for this beam profiler includes plug and test beam measurements with minimal interruptions and feedback effects introduced into the optical beam system under test.

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1. Introduction

The use of optical beams in a wide variety of applications has led to the need for beam analyzers or spatial power profilers capable of producing detailed beam intensity profile information [1-13]. Today, there are two dominant commercial techniques for beam spatial analysis. For high power optical beams, mechanical profilers based on the motion of a moving spatial sampling element such as a knife edge coupled with a large area optical power meter accumulate data that is turned into the desired spatial profile via computer processing. Mechanical profilers, although possessing high spatial resolution (e.g., 4 microns), require moving parts, leading to none real-time operations with bulky frontend optics. Moreover, complete two dimensional (2-D) spatial profiling increases the complexity of the moving part samplers. For example, two orthogonal slits may be required, adding to the hardware requirements of the frontend optics. The second dominant profiling technology that is mainly suited for low power beams is based on 2-D array sensor technology such as Charge Coupled Devices (CCDs). Profilers using CCDs are chip-based economical systems that have compact frontends and operate in real-time (e.g., video rates). Both mechanical profilers and CCD image capture devices are optically intrusive instruments as the light beam under measurement interacts with an optical/mechanical structure in the frontend of the profiler instrument that causes effects such as diffraction and back reflection that can enter the optical system whose beam is undergoing the test. For instance, the knife edge in a mechanical profiler will cause edge diffraction effects that can produce stray light entering the optical system under test. Similarly, CCDs are pixelated devices with fine optical features that cause severe diffraction effects.

Thus there exists a need to enable beam profiling without effecting the operations of a given optical system whose beam requires spatial monitoring. In addition, this beam profiler should be able to provide real time, high dynamic range, 2-D large area beam profiles with a high degree of spatial accuracy and intensity resolution, preferably with no dead space in the beam profile spatial sampling zone. This paper proposes such a minimally invasive beam profiler. In particular, the proposed profiler is achieved by uniquely exploiting the features of an optically addressed liquid crystal (LC) 2-D spatial light modulator (SLM). The rest of the paper describes the operational principles of the proposed profiler and its proof-of-principle demonstration.

2. Minimally invasive beam profiler design

Figure 1 shows the proposed minimally invasive beam profiler design encased in the dotted enclosure. The profiler front-end is translated into the optical beam path under test. The beam profiler contains a partially reflecting beam splitter (BS) that acts as a beam tap and directs a small percentage (e.g., 5%) of the test beam power into the spatial measurement optics. The remaining test beam power (e.g., 95 %) travels as a bypass beam within the optical system under test. In such a way, the optical system under test can continue its optical functions while its beam undergoes spatial monitoring. More importantly, the entrance to the spatial beam profiler is an anti-reflection coated optically absorbing non-pixelated SLM that does not cause pixelation based diffraction effects that would otherwise produce unwanted feedback optical noise into the optical system under test. Hence, the proposed beam profiler forms a minimally to non-invasive beam profiler that can be used to test optical beam spatial performance within active optical systems that require continuous beam monitoring such as in high power laser designs.

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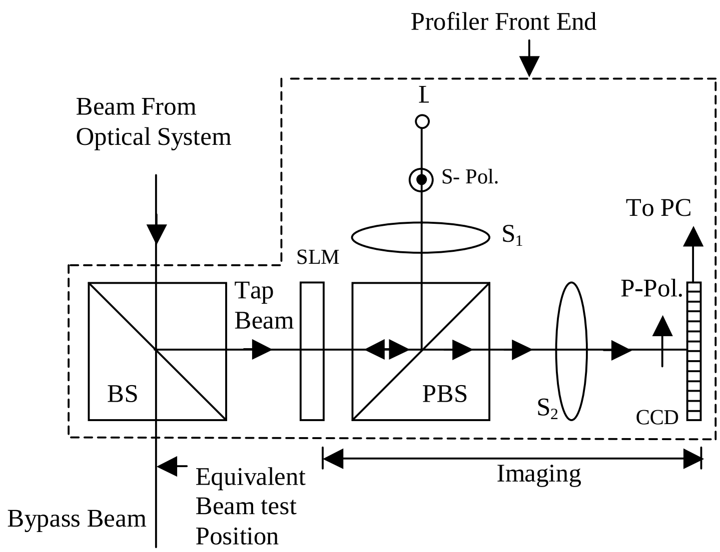

Fig. 1. The proposed minimally invasive beam profiler design using an optically addressed SLM.

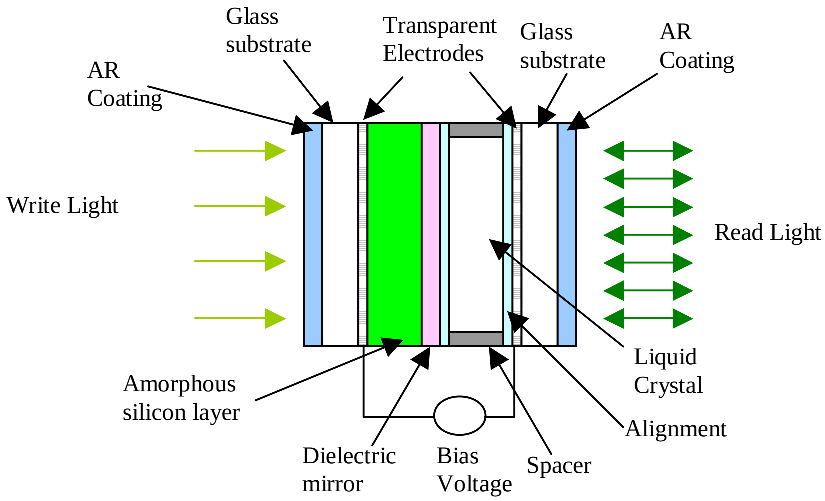

Fig. 2. Schematic of the Hamamatsu PAL-SLM

The location of the SLM amorphous silicon layer indicates the beam plane position under test. The equivalent beam test plane outside the profiler is indicated in Fig. 1 as an equivalent symmetric distance position on the straight path of the BS where a majority of the light passes in the system. The SLM used is a special type; namely, an optically addressed SLM where the SLM side facing the test beam absorbs the light intensity map while the opposite side of the SLM converts this intensity map to an optically read phase modulation map produced via light reflection and electro-optic phase modulation. One such device appropriate for the proposed profiler is the Hamamatsu Parallel Aligned Nematic Liquid Crystal Spatial Light Modulator (called PAL-SLM) [14,15] shown in Fig. 2 that uses parallel aligned liquid crystals to shift the phase of one linear polarization of incident light relative to the other polarization. The SLM has a layer of photoconductive amorphous silicon on the write side

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where the test beam strikes the profiler. When no light is incident on the write side of the SLM, the silicon has an impedance Z of infinity (i.e., Write Light Intensity of Test Beam I_w =0, Z = ∞). As I_w increases, Z decreases and current flows between the two transparent electrodes (see Fig. 2). This current creates a finite voltage drop across the liquid crystal sandwiched between the electrodes. When there is a voltage drop across the parallel aligned liquid crystal, the alignment of the molecules changes from parallel to the light propagation direction to perpendicular to it. The layer of silicon and the liquid crystal have no pixelation leading to an SLM fundamental spatial resolution limited by the sheet resistivity of the photoconductor.

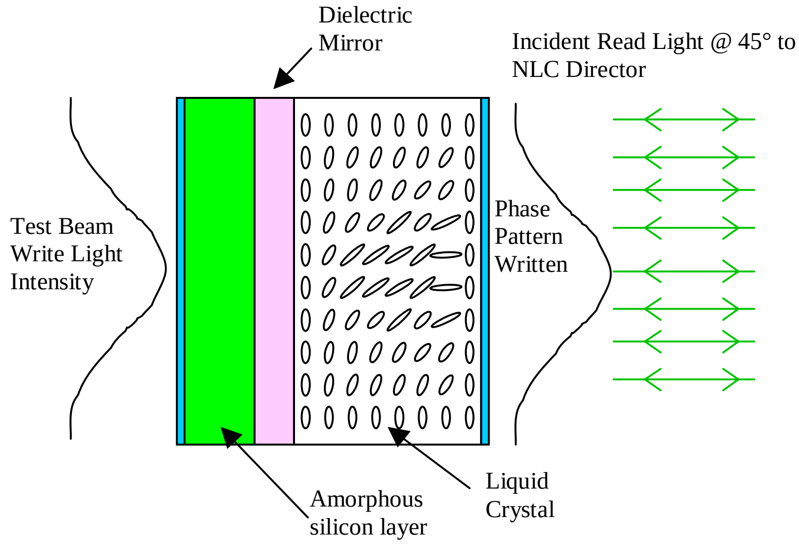

Fig. 3. Liquid Crystal Operation within the PAL LC-SLM in the Fig. 1 profiler.

As shown in Fig. 3, the liquid crystals in the profiler PAL LC-SLM have a different refractive index n depending upon their orientation. When the LC molecules are aligned parallel to the direction of propagation, they have a refractive index n_o and when they are aligned normal to the direction of propagation they have refractive index n_e. The effective refractive index n_{eff} of a row of liquid crystals is due to the combined effects present for a given write light intensity. In Fig. 1 showing the proposed beam profiler, collimated light (using sphere S1) from the read laser L (shown vertically or s-polarized) is reflected by the cube polarization beam splitter (PBS) to strike the SLM. The SLM nematic liquid crystal (NLC) director is oriented such that it is at 45 degrees with respect to the incoming s-polarized light. Hence, the incoming light at the (x,y) coordinates of the SLM has one polarization that is oriented along the molecular rotation direction (this optical field sees the index n_{eff}) while the other orthogonal linear polarization sees the fixed refractive index n_o. After reflection from the SLM, the net retardation that the read light wave experiences at the SLM coordinates (x,y) is given by:

$$\phi(x,y) = (4\pi\, d/\lambda)\,[\; n_{eff}(x,y) - n_o \,], \tag{1}$$

where d is the thickness of the liquid crystal layer and λ is the wavelength of the read light. Note that the PBS produces a crossed polarizer setup for the reflected light, mapping the phase modulation on the PAL LC SLM to intensity modulation of light picked up by the Fig. 1 CCD imager. Specifically, using spherical lens S2 as a 1:1 imaging lens, the read side of the SLM is imaged on to the CCD. This CCD image map indirectly contains the spatial optical power distribution information of the test beam incident on the write side of the SLM. Hence, the video signal from the CCD is sent to a digital processor for image processing and beam profile image generation. Note that traditionally, the Hamamatsu PAL LC SLM has been used in the opposite way; namely, light of a known intensity profile is written on the write side to generate a desired all-optical phase modulation for a read beam that is engaged in some sort of optical signal processing. In the proposed beam profiler, an unknown spatial power distribution incident on the write side of the SLM is determined by measuring the phase modulation induced in the device. Hence, proposed is a novel application for the PAL LC SLM that takes full advantage of the non-pixelated nature of the write side of the SLM that also engages the beam under spatial test; thus not introducing unwanted pixel-based diffraction effects on this test beam optical system. Also note that as needed, the imaging system magnification/demagnification between the SLM read-side and the CCD plane can be adjusted to meet specific spatial profiling resolution and test beam capture area requirements, adding to the versatility of the proposed instrument.

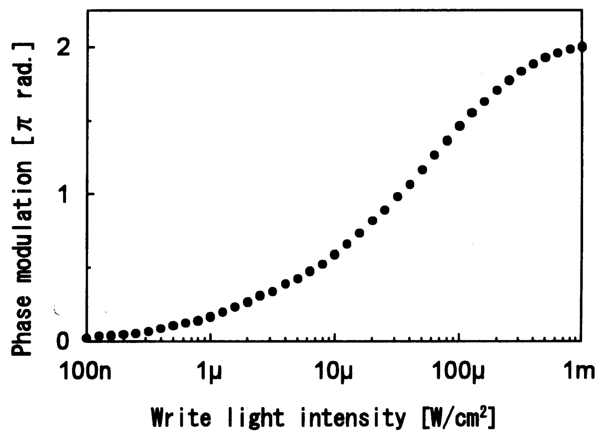

Fig. 4. Manufacturer Provided Experimental Phase Response at 633 nm Read Light versus 633 nm Write Light Intensity for Hamamatsu PAL LC SLM. [14]

For the Hamamatsu device, n_{eff} is not directly proportional to the write light intensity. Specifically as shown in Fig. 4, the SLM exhibits a logarithmic phase response to write light intensity over a 100 nW/cm^2 to 1 mW/cm^2 ratio or a 40 dB dynamic range. For a given read light beam with optical intensity distribution $I_0(x,y)$, assuming zero loss from the SLM, imaging lens S2, and PBS, and a 1:1 imaging from SLM to CCD plane, the optical intensity distribution on the CCD in the Fig. 1 beam profiler is given by:

$$I(x,y) = I_0(x,y) \sin^2(\phi/2). \quad (2)$$

Equation (2) indicates that the intensity should vary from 0 to $I_0(x,y)$ with a maximum intensity at $\varphi = (2n+1)\pi$. By combining Eq. (2) with the Phase/ Intensity plot of the SLM (Fig. 4) at the specific phase reading wavelength of 633 nm, the logarithmic plot of Fig. 5 is theoretically generated assuming $I_0(x,y)$ to be a constant intensity level. From Fig. 5 it can be seen that a one-to-one relationship can be achieved between the 633 nm read light intensity and the 633 nm write light intensity if the intensity of the write light remains between either 0 and ~30 μW/cm^2 or ~30 and 1000 μW/cm^2. A desired BS tap ratio in Fig. 1 or the use of a

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variable light attenuator before the SLM write face can be used to make sure that this condition holds.

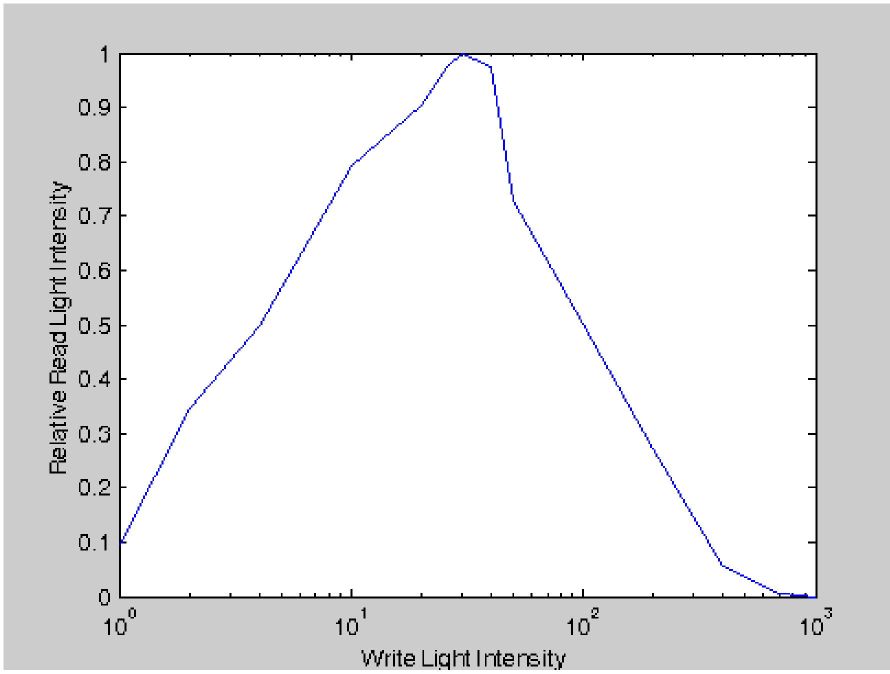

Fig. 5. Calculated Logarithmic 633 nm Read Light Relative Intensity vs. 633 nm Write Light Intensity Plot for the PAL LC SLM. The write light axis units are in μW/cm2 while the read light axis units are relative units scaled to 1.

The logarithmic nature of the PAL LC SLM provides several features for the beam profiling application. First, the analog nature of the liquid crystal makes the SLM-based beam profiler capable of providing a near continuous 40 dB processing dynamic range. In addition, by varying the external bias drive voltage of the PAL SLM, the phase response curve (Fig. 4) can be manipulated. Through this manipulation, a Gaussian beam can be analyzed with a high resolution in certain intensity ranges. As the PAL NLC SLM is more responsive to lesser intensities, it can be used to analyze the portion of a beam that lies on the outside of the $1/e^2$ beam waist. Because of its digital nature, the CCD must assign one of a limited number of values to each intensity level. For example, if the intensity of the input beam is between 1-1000 $\mu W/cm^2$ and the CCD encoded each pixel with 8 bits for 256 values, then the intensity image would be encoded with a resolution of ~4 $\mu W/cm^2$. However, since the PAL SLM is analog, it transfers the information of the write beam without loss. The logarithmic nature of the SLM also means that when the 1000 $\mu W/cm^2$ beam information reaches the CCD, it can be encoded with 150 values corresponding to 1-75 $\mu W/cm^2$ and 106 values for 76-1000 $\mu W/cm^2$. This would give a much better resolution of ~.5 $\mu W/cm^2$ in the lower 1-75 $\mu W/cm^2$ range.

The non-pixelated structure of the PAL SLM in the beam profiler means that no diffraction or reflection effects occur that could create optical noise in the beam being tested, hence making the beam profiler minimally invasive. As there are no inter-pixel dead gaps on the write side of the SLM, this also means that the test beam intensity information is completely transferred to the non-pixelated SLM read side of the beam profiler for further high spatial resolution processing. The PAL SLM also has an anti-reflection (AR) coated mirror on the write side, thus reducing back-reflections into the optical system under test.

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Read laser light intensity is arbitrary, and by increasing the read beam intensity and using multiple beam splitters and multiple CCDs with pixels in different relative locations, arbitrary spatial resolution can be achieved. Without the interfacing PAL LC SLM, the input beam intensity may not be sufficient to be distributed to multiple CCDs to achieve the proposed high resolution spatial sampling.

The proposed beam profiler design also has advantages over knife-edge based beam profilers that are mechanical scanners with intensity sensors that scan the beam. The proposed beam profiler provides arbitrary spatial resolution, while the knife-edge beam profiler can only resolve down to the motion sensitivity of the mechanical elements. Using all electrical and electro-optical devices, the proposed beam profiler also provides real-time analysis with no moving parts.

3. Experimental demonstration

An experiment is conducted to demonstrate a proof-of-principle minimally invasive optical beam profiler. A 532 nm wavelength laser with its given diffraction limited beam profile is expanded, collimated, and passed through a polarizer to strike the write side of a Hamamatsu PAL-SLM. Rotation of the polarizer is used to control the power level incident on the SLM. For the read laser L, another 532 nm wavelength s or vertically polarized laser is used whose beam is passed through a spatial filter and a collimating lens S1 to strike a cube PBS. The light beam reflects off the PBS to enter the SLM. The SLM reflected horizontal or p-polarized light component passes via the PBS to be imaged via lens S2 on to the CCD. The resultant image on the CCD is read by a computer with a frame grabber. The SLM read and write side active areas are 2 cm x 2 cm. The SLM response time is 40 ms with a resolution of 50 line pairs/mm. The write and read sides of the SLM are designed to operate for a broad visible band (e.g., 400-800 nm), adding to the spectral flexibility of the proposed spatial beam profiler. For the experiment, chosen is a 532 nm write side beam with an arbitrary spatial intensity distribution from the ~25 $\mu W/cm^2$ level to below the 1000 $\mu W/cm^2$ level obtained by rotation of a polarizer acting as a variable spatially uniform attenuator. In this manner the phase modulation of the SLM due to the arbitrary spatial distribution test beam was restricted between π and 2π, creating a one to one inverse proportionality between the write light and read light intensities.

To retrieve the intensity pattern of the input beam, used is the PAL SLM wavelength calibrated read/write data plot and a function is written for Matlab that can recreate the intensity distribution of the write side from the matrix that represents the intensity distribution read by the CCD. Specifically, using two 532 nm beams, one for write light and one for read light, and two power meters to detect specifically set incident light levels and measured reflected light levels, a data plot is generated that indicates the SLM modulation curve at the 532 nm experimental wavelength. This wavelength calibration step is important to do as on the photoconductor side, amorphous silicon is more sensitive to 632 nm red than 532 nm green and on the LC side, the birefringence is higher for the green than the red light. First the computer program converts the image from an RGB image into a grayscale image. It then uses the Matlab function 'histeq' to broaden the distribution of intensities so that it will cover the entire 0-255 range. Once it has produced the expanded grayscale image, the program uses an intensity matrix that maps each value of the intensity from 0-255 on the read side to a corresponding intensity value from 0-255 on the write side. Once the function has mapped the read image into a write image, it uses the Matlab function again to distribute the intensities across the entire range. Since it is known that the write intensities lie between 25 $\mu W/cm^2$ and 1000 $\mu W/cm^2$, the intensity distribution can be scaled by a factor of (1000 – 25) / 256 to find the true intensities.

The proposed minimally invasive beam profiler is put to test for a given input laser beam. Figure 6 shows the CCD measured beam profile of this test beam incident on the write side of the SLM. This data is used for comparison purposes. A careful review of Fig. 6 shows some

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image artifacts present within the true beam image due to CCD window-based multiple back reflections (CCD has no AR coating) of the original beam from optical surfaces of the beam splitter in Fig. 1. Specifically, two smaller replicas of the original beam exist towards the right side of the central true beam lobe. When the proposed SLM beam profiler is used, these backreflections do not occur as the PAL LC SLM has AR coatings and device is designed to eliminate back reflections. Next, the read light data from the CCD is processed via a computer to produce the experimentally calculated test beam write light pattern shown in Fig. 7. Comparison of the Fig. 7 and Fig. 6 images indeed show the correct recovery of the desired test beam spatial power map, indicating the proof-of-concept working principles of the proposed minimally invasive spatial beam profiler. Figure 8 shows the CCD output from the beam profiler in Fig. 1, indicating the measured read light spatial power map. As expected, this Fig. 8 image does not look like the original input write light beam image as it reflects the logarithmic mapping between the input and output optical ports of the proposed profiler.

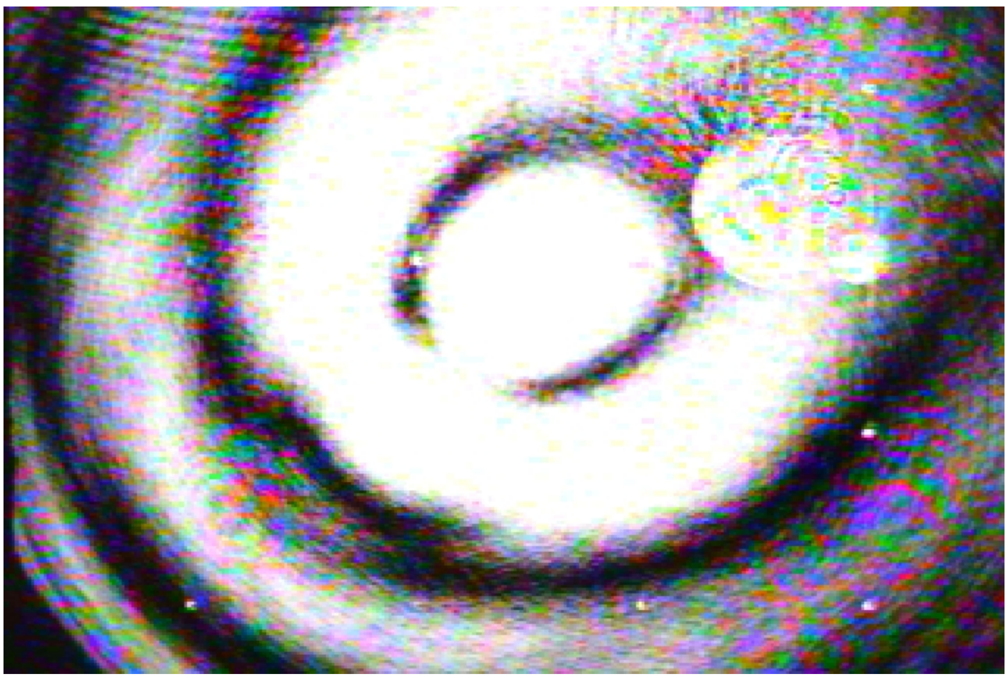

Fig. 6. Original Beam Intensity Pattern Measured by a CCD on the Write Side location of the SLM. Due to back-reflections, this image also contains two unwanted smaller versions of the original beam towards the top right corner of the image.

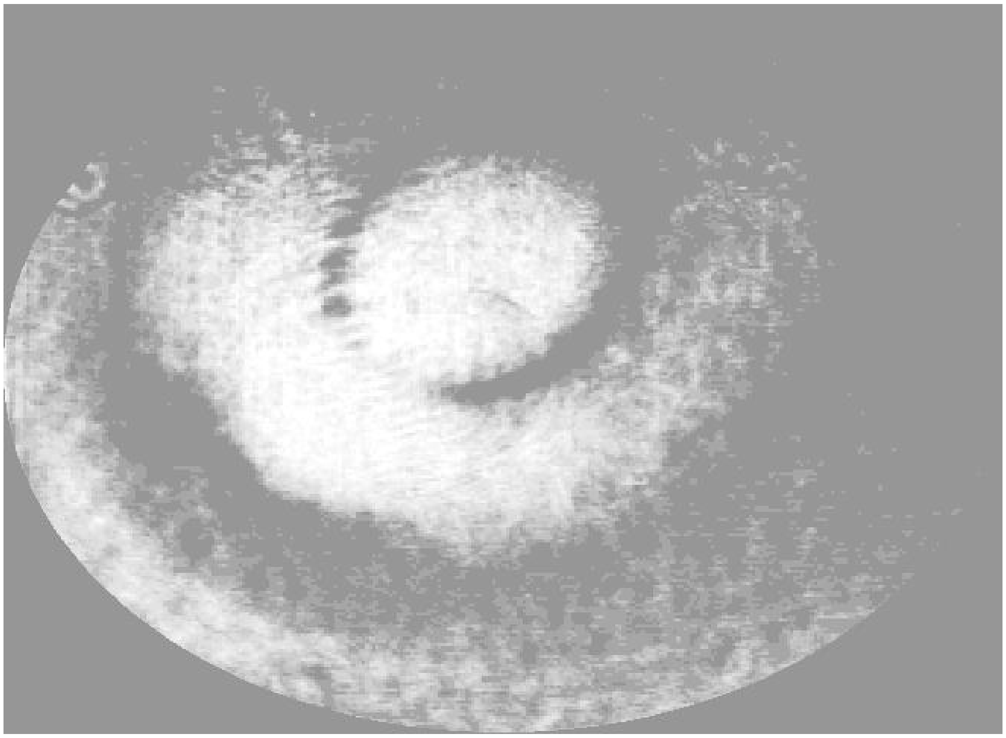

Fig. 7. Experimentally produced and the post-processed power profile image of the test beam generated via the minimally invasive beam profiler instrument.

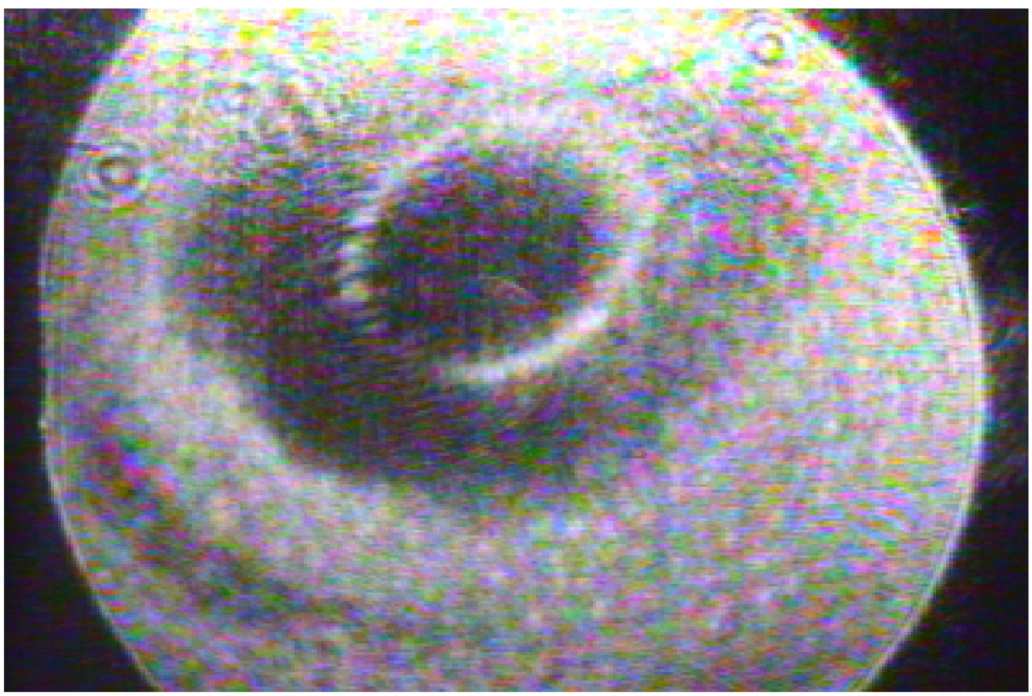

Fig. 8. Read Light Direct Image from the Beam Profiler CCD.

4. Conclusion

A minimally invasive optical beam profiler using an optically addressed liquid crystal SLM has been proposed. A proof of concept experiment using a Hamamatsu PAL LC SLM operating in the visible light band verifies the profiler operational principles of recovering the input intensity spatial pattern from an indirect mapping of input intensity to optical phase modulation of non-pixelated liquid crystals. The profiler possesses a 2 cm x 2 cm test beam tap area for beam measurements at real-time with flexibility in spatial resolution processing via adjustment of output imaging optics (i.e., lens S2 position, focal length, and CCD pixel size and count) and SLM bias drive voltage.

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