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# Experimental Study of Tunable Layout Printed Fresnel Lens Structure Based on Dye Doped Liquid Crystal

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***Abstract*—**In this article, we present a layout printing way for producing Fresnel zone on 1294-1b doped liquid crystal with Methyl-Red azo dye. We made a Fresnel zone mask with 25 zones and radius of 5 mm using lithography technique. With layout printing way, we recorded mask's pattern on cell with λ=532 nm solid-state diode pump laser. By recording Fresnel zone pattern on cell and making Fresnel pattern on the surface of cell, odd and even zones, will form. The printed pattern, because of Azo dye's photoisomerization, was permanent. Experimentally, we saw focal length tunability from 32 cm to 43 cm.

***Keywords*—**Liquid crystal, lens, Fresnel zone, diffraction, Fresnel lens.

## I. INTRODUCTION

OPTICAL lenses have wide usage in our nowadays life and in applications like sunglasses, microscopes, etc. [1]. Fabricating a lens is based on shaping an optical material such as a glass. The nodes of such lenses are increasing its thickness with reducing focal length, and from the other side, fabricating costs are very expensive. In addition, the quality of lenses typically decreases with increasing size. One of the most interesting solutions for these problems is using diffractive lenses such as Fresnel [2] and Photon Sieve lenses which are relatively thin. In fact, Fresnel lenses are collapsed version of normal lenses, and their range of work is based on focusing light through diffraction instead of refraction [1]. Binary phase in Fresnel lenses leads to focusing light only when the difference between two adjacent zones is equal to an odd multiple of $\pi$ . Most interesting ability of liquid crystals is their ability for modulating light application for both phase and amplitude. Because of this property, liquid crystals are one of the most promising candidates for various optical applications like: 3-D displays, optical communications, surgeries, optical information processing, and space navigations [3]. One of liquid crystals trait is supporting external manipulation of optical beams via an external electric field. The optical birefringence of liquid crystals is most important for the optical applications in millimeter wave devices, displays, and spectroscopic systems [4]. Development of this kind of lenses which can be controllable with electrical field and making variable focal lengths, are of great importance for a wide range of applications, from smart eyeglasses with adjustable focal length to fast no mechanical zooming devices [5], confocal microscopy systems, electrically controlling optical systems, and CD/DVD pickup head [4]. The Fresnel lens based on liquid crystal property is the simple fabrication process with large aperture size. There are two common ways for fabricating Fresnel lens based on liquid crystals. The first one, deploys patterned electrodes for generation special electric field distribution to localize controlling liquid crystals director, and the second one deals with reorient directions of liquid crystal molecules for making a special refractive index distribution that includes patterned polymer relief, polymer dispersed liquid crystals, polymer stabilized liquid crystals, dye doped liquid crystals, and UV modified alignment films [3], [6].

## II. THEORY

A Fresnel lens, which is called Kinoform lens [4], is consisting of $n$ concentric rings with same area and radial symmetry. In fact, each part of the Fresnel zones of Fresnel lens collects the optical beams and diffracts them to one focal point [4]. For studying a Fresnel lens, first we choose a plain wave front, which irradiates to the lens. In the first zone with a distance equal to $r$ from center of the lens, there is a point whose name is source point on the plain of Fresnel lens. Therefore, we can call $l$ as maximum travelled length in first zone to focal point, which can br calculated as:

$$l = \sqrt{r^2 + f^2} \tag{1}$$

For calculating the radius of the $n$th zone ($R_n$), we have:

$$R_n^2 = nR_1^2 \tag{2}$$

where $R_1$ is the radius of the first zone. Focal length of the fabricated Fresnel lens depends on the first zone, which can be calculated as:

$$f = R_1^2 / \lambda \tag{3}$$

where $\lambda$ is the wavelength of input light [7]. The difference

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between odd and even zones of the Fresnel lens pattern is $\pi$. First order diffraction efficiency for an individual phase binary Fresnel zone plate can be reachable as:

$$\eta_1 = \left[\sin\left(\frac{m\pi}{2}\right) / \left(\frac{m\pi}{2}\right)\right]^2 \tag{4}$$

where $m$ shows the order of diffraction. By looking at (4), we can find out that diffraction efficiency of the primary focus theoretically is 40.5%. In addition, experimental diffraction efficiency can be calculated by:

$$\eta = \frac{P - P_0}{P_t} \tag{5}$$

where $P$ is the light intensity at the focal point, $P_0$ is the environment noise, and $P_t$ is the light intensity before cell [4].

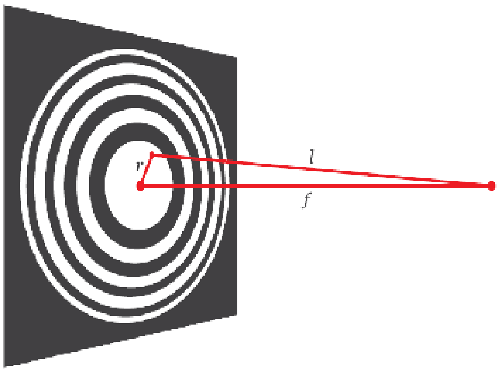

Fig. 1 Source point on first zone with focal length of *f* and maximum travelled length

With this information, we fabricate a binary Fresnel liquid crystal lens. For controlling the phase difference between odd and even zones, we apply an electric field to the Fresnel liquid crystal lens by using a function generator. With reorienting liquid crystal molecules, the focal point and diffraction efficiency can be modulated [4].

Doping liquid crystal with azo dyes will cause interesting light induction process in this material. Azo compound is a kind of materials consisting of R-N=N-R' groups where R and R' are the alkyl groups. Because of decomposition of $\pi$ linking of azo groups (N=N), molecular shape of azo dyes can change. Therefore, this combination can appear in two isomers whose names are *Trans* and *Cis*. With irradiating beam in range of absorption wavelength of dyes, occurring probability of trans-cis-trans photo isomerization takes place. In each period, location and direction of molecules are paste randomly. So, after occurring this cycle for many times, molecules getting far from irradiance beam polarization direction (getting perpendicular) and will show less likely to absorb beam and participation in the cycle. Systematically, the number of molecules increases, and molecular directions are perpendicular to irradiance beam polarization. With doping liquid crystal with azo dye, dyes in effect of liquid crystal reorientation will arrange. Because of light field, with high induction effect, azo dyes will reorient. This reorientation will apply torque on liquid crystal molecules, which causes reorientation on liquid crystal. With recording Fresnel zone pattern on the surface of the cell, odd and even zones are forming. In fact, in the areas with exposure with light, molecules will be perpendicular to the initial order of cell and because of high birefringence, this will create refractive index difference between odd and even zones. In addition, in light zones, with resulting enough energy of light, ionization inherent impurities will be added and with applying external electric field, the created ions will be separated and due to direction of the applied field, will reorient. In effect of separation in charges in different zones, an electric field whose name is spatial charge field will be form. If this field is in direction opposite from external electric field, it will cause reorientation in molecular director and refractive index modulation, and so, it causes changing in diffraction efficiency [8]. Fig. 2 shows reorientation of liquid crystal molecules after recording Fresnel zone pattern on cell.

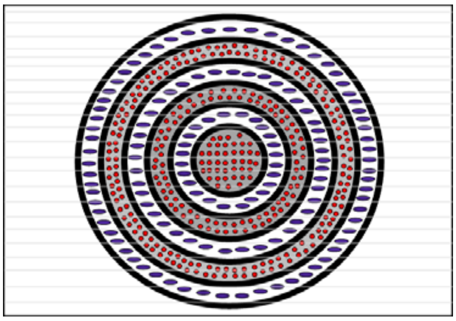

Fig. 2 Reorientation of liquid crystal molecules after recording Fresnel zone pattern

## III. EXPERIMENTAL WORKS

For making tunable layout printed Fresnel lens structure based on dye-doped liquid crystal (DDLC), we used a 50 $\mu m$ HG cell with ITO layer indicated. Our liquid crystal was 1294-1b with 1.501 ordinary refractive index and 1.813 extraordinary refractive index [9]. We used 1% azo methyl red as dye, which was doped with liquid crystal. The transition temperature of this liquid crystal is about 103 °C. After preparing cell, because of gradually cooling process and better positioning of LC molecules, we put it into oven in 70 °C for about 1hr and 16 hours in 40 °C. The characteristics of the produced mask according to the active zone of our cell (5x5 mm$^2$) are:

TABLE I
DEVELOPED MASK PROPERTIES

| | |
|---|---|
| *$n=25$* | *Number of zones* |
| *$r_1=0.0005$ m* | *Radius of first zone* |
| *$r_{24}=0.002449$ m* | *Radius of 24th zone* |
| *$r_{25}=0.002500$ m* | *Radius of 25th zone* |
| *$d_{25}=51$ $\mu m$* | *Thickness of 25th zone* |
| *$R=1.22*d_{25}= 62.22$ $\mu m$* | *Rayleigh's diffraction resolution* [10] |

According to the above values and using the following equation, the focal length of our Fresnel lens can be calculated [4]:

$$f = 39.5\ cm$$

Fig. 3 shows developed mask under polarized microscope.

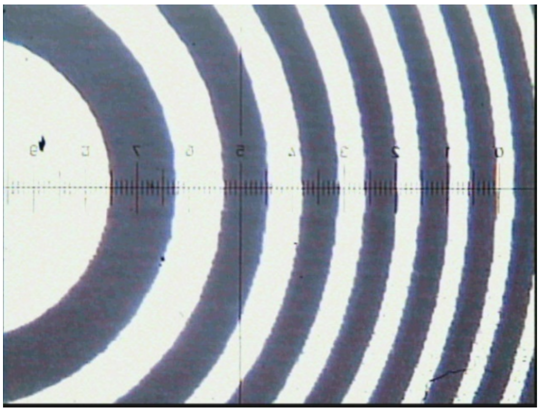

Fig. 3 Developed mask under polarized microscope

In order to record the Fresnel zone pattern on the cell [8], we used a 100-mW green diode pump solid state laser (DPSSL) with λ=532 nm wavelength and *S* polarization (electrical field parallel to cell's furrow). Fig. 4 is showing the recorded Fresnel zone pattern on DDLC.

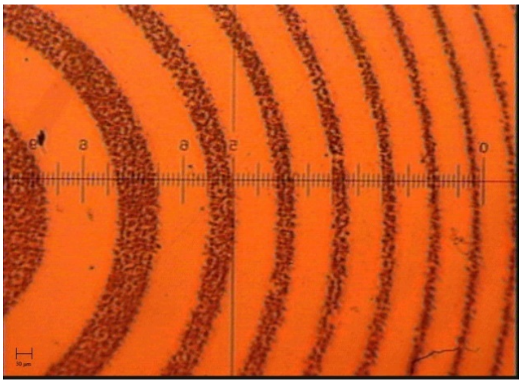

Fig. 4 Recorded Fresnel zone pattern on DDLC under polarized microscope

It seen that by increasing the voltage, orientation of molecules changes along the field course (molecules oriented perpendicular to the cell surface), gradually resulting in a difference in refractive index between the odd and even areas. At the maximum field, molecules will reorient in the same way of beam polarization. Therefore, lens like effect of cell will be destroyed.

## IV. Assessment of Fresnel Lens Based on DDLC

To assess lens focal point changes, we used a 1-mW *He-Ne* laser with *P* polarization. A 1.5-kHz square-frequency voltage was applied to the cell. In the absence of voltage, maximum intensity of diffraction by a power meter at 32 centimeters was observed. This is the focal point in non-voltage situation. By increasing the voltage up to 20 $V_{r.m.s}$, the focal length was changed to 42 cm. Fig. 5 shows the movement of the focal length by changing the electric field.

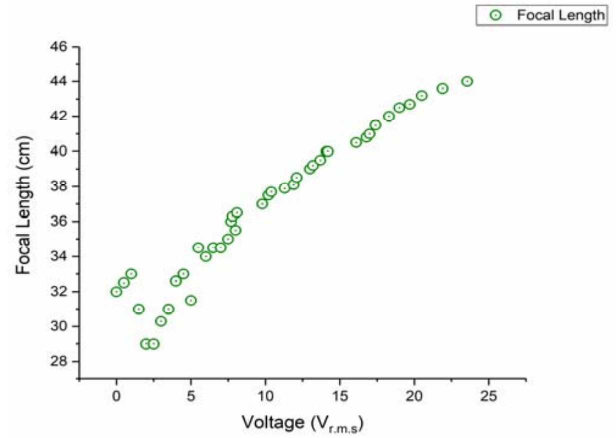

Fig. 5 Movement of the focal length by changing the electric field

## V. Results

In this work, we studied a way for fabrication Fresnel lens based on DDLC and its specifications. By observing changes in focal lengths with applying electrical field, tunability property of lens clearly was observed. This lens depends on polarization. It shows that if the irradiated beam polarization is parallel with the cell slots (S polarization) in the presence or absence of voltage, focalization process will not appear, so the environment shows a homogeneous behavior. It arises from the same refractive index of different areas of Fresnel zone with reading by P polarization. Tunable Fresnel lenses based on liquid crystal have applications on devices such as spectrometers, switches, and optical modulators.

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