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Development of a photopolymer holographic lens for collimation of light from a green light-emitting diode

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A holographic optical element (HOE) was developed to collimate a monochromatic light-emitting diode (LED). The fabrication was achieved by the interference of collimated and diverging beams from a 532 nm laser to produce the required photonic structure in a self-developing photopolymer material. The experimental values of diffraction efficiency and spatial period across the HOE were compared with their expected theoretical values. Good agreement was found for the spatial period; however, the diffraction efficiency varied significantly across the lens. In this paper, two approaches have been taken to address this variation: (1) modification of recording geometry and (2) optimization of recording intensity and exposure time at constant energy. The performance of an optimized HOE (cylindrical holographic lens) was then demonstrated using a 532 nm laser beam. The optimized conditions for the cylindrical holographic lens were used to fabricate a spherical holographic lens of the same numerical aperture for LED applications. This type of lens has the potential to be used in combination with LED sources. © 2018 Optical Society of America

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1. INTRODUCTION

Photopolymers have many appealing qualities as holographic recording materials, including high diffraction efficiency, linear response, high sensitivity, high dynamic range, low noise, mechanical stability, long shelf lifetime, low toxicity, and low cost of production [1]. The self-developing capability of photopolymer materials presents significant advantages for mass production processes and could enable development of low-cost holographically recorded optical elements for many applications. However, there are certain challenges in adapting recording methods and materials to produce photopolymer holographic optical elements (HOEs) that perform well in specific applications.

The low-cost production and flexible format of photopolymer HOEs have potential to play a valuable role in lighting applications if integrated with solid-state lighting. In comparison to refractive optical elements (ROEs), HOEs are lightweight and compact, and have the potential to be used to tailor the light output to specified shapes and directions [2]. However, the challenge of re-directing light from light-emitting diodes (LEDs) using diffraction is significant, since the LED is an extended source, emitting broadband, nonpolarized light,

and the desired output is a homogenous uniform-intensity beam with directional characteristics [3]. Studies have been done in the area of diffractive elements for LED applications, such as fabrication of binary diffractive lenses to control the intensity distribution of LED light [4]. In addition to this, volume holographic gratings have been fabricated for use with unpolarized RGB light [5]. Holographic lenses have also been fabricated for solar energy applications [6]. Work has also been carried out in thin-film light management systems for large-area LED luminaires by designing diffractive diffusers [7] or gratings [8] that combine RGB light as well as multiplexed gratings which split collimated white LED light into focused RGB beams [9] at different positions.

All the work listed above describes elements that are either non-focusing, such as gratings and diffusers, or have long focal lengths unsuitable for directly shaping the light output from non-collimated LEDs. Results have also been reported on reflection photopolymer HOEs, used to narrow the output beam of an LED, which could be useful for some lighting applications [10]. Recently developed transmission focusing holographic elements for solar applications were used to achieve a doubling of the output from a solar cell [11]. Further work

is needed to develop holographic optical elements suitable for LED applications. To the best of our knowledge, no work has been reported to date on fabricating holographic devices that can collimate a diverging LED beam with good uniformity in diffraction efficiency across the beam.

This paper focuses on the fabrication of cylindrical and spherical holographic lenses with uniform intensity across an output beam. Photopolymer is used as recording material. The preparation method and composition of the photopolymer used in this paper are previously described by Akbari *et al.* [12]. The optimization and analysis are initially performed for the cylindrical holographic lens, which contains the full range of spatial frequencies and slant angles that occur in the equivalent spherical lens but only along one axis. These optimized conditions are used to fabricate a spherical holographic lens to collimate a diverging monochromatic LED.

In this paper, first the principles of volume phase holograms and fabrication of HOE lenses are outlined. Second, the fabricated HOE is characterized and optimized. Third, the optimized HOEs are tested with a monochromatic diverging laser and a single-color LED. In the last section, the summary of the paper is presented.

2. PRINCIPLE OF VOLUME PHASE HOLOGRAPHY

When two beams interfere, they form a grating in the recording medium. The orientation of the grating's index modulation is determined by the angle and wavelength of the two interfering beams, which can be manipulated to produce the desired pattern. During the exposure step, this pattern creates a spatially varying change in refractive index inside the photosensitive medium. The refractive index modulation is approximately sinusoidal [5] and is given by Eq. (1):

$$n(x) = n_o + \Delta n \cos\left(\frac{2\pi x}{\Lambda}\right), \quad (1)$$

where n_o is the average index of refraction of the photopolymer material, Δn is the amplitude of the index modulation, and Λ is the spatial period of refractive index modulation, which is the fringe spacing in the interference pattern. In thicker photosensitive materials such as photopolymers, the refractive index modulation continues through the depth of the material creating a volume phase hologram (VPH).

A VPH works on the principle of Bragg's law [13] and has the advantage of producing a single diffracted order, so volume holograms are highly advantageous for applications in which the percentage of light in the diffracted beam should be high. Volume holograms are defined by Q parameter given by Eq. (2):

$$Q = \frac{2\pi\lambda d}{n_o\Lambda^2}, \quad (2)$$

where λ is the wavelength of the recording beam, d is the thickness of the recording medium, n_o is the average refractive index of the recording medium, and Λ is the period of refractive index modulation. For a large value of Q parameter (greater than 10), the hologram is considered as a volume hologram [14]. When a light beam passes through any grating, it obeys the classical grating equation [15] given by Eq. (3):

$$k_i \sin \alpha + k_d \sin \beta = \frac{2\pi m}{\Lambda}, \quad (3)$$

where k_i and k_d are the propagation vectors for the incident and diffracted beams, m is an integer (order of diffracted beam), Λ is the period of refractive index modulation, α is the angle of incidence in air, and β is the angle of diffraction in air. In volume gratings, the Bragg condition must be satisfied, so that the angle of incidence equals the angle of diffraction (relative to the fringe planes) and the diffracted beam propagates in a direction determined by the Eq. (4):

$$m\lambda = 2\Lambda \sin \beta. \quad (4)$$

All the parameters are the same here as in Eqs. (2) and (3). The Bragg angle is an important parameter for diffraction by VPH gratings, because it determines the direction of the output beam and can be set by the fringe spacing in the recorded interference pattern. The percentage of energy diffracted by the desired (diffraction efficiency) VPH depends primarily on the refractive index modulation, the thickness of the medium, wavelength, and the angle of incidence of the light beam. The diffraction efficiency in the volume grating can be calculated by using Kogelnik's coupled wave theory (KCWT) [16]. Kogelnik's equation for diffraction efficiency is given by Eq. (5):

$$\eta = \frac{\left[\frac{\sin(\nu^2 + \xi^2)^{1/2}}{(1 + \frac{\xi^2}{\nu^2})^{1/2}}\right]^2}{}, \quad (5)$$

where the modulation parameter ν and deviation parameter ξ are given by Eqs. (6) and (7):

$$\nu = \frac{\pi n_1 d}{\lambda \cos \theta_o}, \quad (6)$$

$$\xi = \frac{\Delta\theta 2\pi n_o d \sin \theta_o}{\lambda}, \quad (7)$$

where n_1 is the depth of refractive index modulation, d is the thickness of the hologram, n_o is the average refractive index of the medium, λ is the wavelength of the reconstructing light beam, θ_o is the Bragg angle, and $\Delta\theta$ is the deviation from the Bragg angle.

By arranging the appropriate interference pattern to be recorded, the diffraction characteristics of a VPH can be used to collimate a diverging light beam. Figure 1 is a schematic showing the re-direction and collimation of a diverging beam

Fig. 1. Schematic of a HOE lens collimating a diverging light beam with inset showing typical fringe structure (not to scale).

using a volume phase holographic optical lens. The angle of diffraction of the output light beam depends on the angle of incidence, the wavelength of the light beam, and the orientation and spacing of the grating in the medium.

3. FABRICATION METHOD

The experimental setup used to fabricate the cylindrical holographic lens is shown in Fig. 2. A green laser (532 nm, Ventus 532, Laser Quantum) beam passes through a shutter, a neutral density filter, a half-wave plate, a spatial filter, a collimating lens and an aperture, producing a collimated beam of 14 mm diameter, which then gets divided into two optical paths (reference and object beam) by a non-polarizing beam splitter. In the reference beam, a neutral density filter is used to equalize the intensities of the two beams. A refractive cylindrical lens ($f = 5$ cm) is inserted in the object beam path to form a diverging beam that interferes with the reference beam and creates the desired fringe pattern.

Table 1 shows the composition of photopolymer material. Dry photopolymer layers are prepared from this formulation by coating glass substrates as described in previous publications [12]. In this work, layers have thickness of $75 \mu\text{m} \pm 5 \mu\text{m}$ unless otherwise stated. The refractive index for the polymer layer is approximately 1.5, and absorbance is 0.76. The grating angle inside the photopolymer depends on the incident angle of both reference and object beam during recording. Each position in the cylindrical holographic lens acts as a local grating [6,17].

Here, all calculations for angles corresponding to the spatial frequency have been done in air. Snell's law is then used to find

the angles inside the material. Unless otherwise stated, the total intensity of recording was kept constant at $1 \text{ mW}/\text{cm}^2$, and exposure time was 60 s. The diameter and focal length of the fabricated lenses were 14 mm and 50 mm, respectively. To measure the angular selectivity curve, a He-Ne (633 nm) laser was used to probe the HOE perpendicular to the sample surface. Using a Newport M-URM100ACC rotation stage (resolution 0.001 deg), controlled by a LabVIEW program, the HOE was rotated while the diffracted beam intensity was measured by a Newport 818-SL Optical Power Meter (Model 1830-C). This produced data on the diffracted beam's intensity as a function of the incident beam angle, which is used to characterize the diffraction behavior at the location where the incident beam probes the sample. The photopolymer material used is sensitive to green light, so a wavelength of 633 nm is convenient for probing the grating directly after recording without affecting the grating structure. It should be kept in mind that this results in a small decrease in the diffraction efficiency (4%–5%) due to the longer wavelength.

4. CHARACTERIZATION OF CYLINDRICAL HOLOGRAPHIC LENS

A. Grating Spatial Period Across the Diameter of the Lens

Phase contrast microscope images of the local gratings were captured (Fig. 3) at three different positions (center of the lens, +3 mm from the center and -3 mm from the center). The spatial period was measured by imaging the layer. The sample was moved laterally between measurements in order to compare the pattern observed in the photopolymer at each of three different positions across a horizontal line through the center of the HOE. The length of 10 fringes around these positions was measured to find the spatial period. The results are $26.5 \mu\text{m} \pm 0.7 \mu\text{m}$ at +3 mm from the center, $39.0 \mu\text{m} \pm 1.0 \mu\text{m}$ at the center, and $66.6 \mu\text{m} \pm 1.7 \mu\text{m}$ at -3 mm from the center of the cylindrical lens.

The grating is slanted at the -3 mm and +3 mm positions, so a slant correction factor of 2.21° is included in the above measurement. The theoretical calculation of the local spatial period at each point across the HOE lens was made by substituting the inter-beam angle during recording, at that specific location, into Eq. (4). The inter-beam angle at each location was estimated from the geometry of the recording setup using the known divergence of the beam from the cylindrical lens (5 cm focal length), the position of the photopolymer layer, and the angle between the two arms of the optical setup. The calculated values are $2.66 \mu\text{m}$, $3.37 \mu\text{m}$, $6.96 \mu\text{m}$ at +3 mm from the center, at the center, and at -3 mm from the center, respectively. Agreement between the theoretical and experimental value of the spatial period is within 1% except for the central measurement. This is likely due to the difficulty in accurately locating the “center” of the holographic lens.

B. Diffraction Efficiency Across the Diameter of the Lens

A 633 nm is used to probe the cylindrical holographic lens at the three positions studied above to obtain angular selectivity curves, shown in Fig. 4(a). These angular selectivity curves are

Fig. 2. Experimental setup for the recording of the cylindrical holographic lens. NDF, neutral density filter; HWP, half-wave plate; SF, spatial filter; CL, collimator lens; A, variable aperture; BS, beam splitter.

Table 1. Composition of Photopolymer Material

Constituents	Amount
Acrylamide	0.6 g
Methylene-bis-acrylamide	0.2 g
Polyvinyl alcohol	10 mL
Triethanolamine	2 mL
Erythrosine B dye	4 mL

Fig. 3. Microscopic image of the surface of the cylindrical holographic lens at position (a) +3 mm, (b) center, and (c) -3 mm taken using Olympus BX51 phase contrast microscope, with a DP72 camera (scales are not the same due to changes in magnification).

compared with KCWT [16] by calculating the theoretical curve of diffraction efficiency versus angle of incidence in the air. The theoretical curves were generated using a probe 633 nm, grating thickness of 75 μm , and refractive index modulation values of 0.0012, 0.0026, and 0.0030. The refractive index modulation value used in the theoretical curve is obtained from the experimental angular selectivity curve. The agreement between experimental and theoretical curves demonstrates that the expected volume diffraction is occurring and that the spatial period at these different locations in the element is close to that predicted from the recording geometry. This also confirms that any shrinkage that may have occurred in the layer during recording has not significantly distorted the photonic structure.

Fig. 4. (a) Comparison of experimental angular selectivity curve with angular selectivity curve obtained from Kogelnik coupled wave theory. (b) Theoretical variation of the spatial period for different central frequencies: 264 lines/mm, 300 lines/mm, and 500 lines/mm.

A small amount of broadening is observed in the experimental curves, probably due to the size of the probe beam. It is also noted that at the +3 mm position, the diffraction efficiency is significantly higher ($\approx 80\%$) compared with the center ($\approx 65\%$) and -3 mm ($\approx 20\%$) positions, as can be seen from Fig. 4(a). The theoretical analysis of the variation of the spatial period across the cylindrical lens is shown in Fig. 4(b) for three different “central” spatial frequencies. It shows that the lower spatial frequencies (larger spatial periods) in each lens occur towards the negative side. This is the region where the recording beams have a lower angle between them.

In addition to the expected change in angular selectivity, significantly lower diffraction efficiency is observed here. In a previous publication, it was shown that the diffraction efficiency response to exposure dose is reduced at low spatial frequencies [12]. This causes non-uniform efficiency across the lens, which is not desirable for a collimated beam. The Gaussian profile of the recording beam could also contribute to lower diffraction efficiency at the two outer edges of the holographic lens. However, the effect is not significant here, and the positive side

of the cylindrical lens is observed to have higher diffraction efficiency.

5. OPTIMIZATION OF CYLINDRICAL HOLOGRAPHIC LENS

Higher and more uniform diffraction efficiency across the holographic lens is required if a HOE is used to collimate a diverging beam. In lighting applications, minimal losses and uniformity in the intensity of the re-directed beam are required. Here, two methods [18] to increase the overall diffraction efficiency of the lens and to improve the spatial uniformity of the diffraction efficiency are presented.

A. Improvement of Uniformity by Avoiding Low Spatial Frequencies

Since significant non-uniformity in the lens efficiency had been attributed to the low spatial frequency components in the fabricated lens, one solution was to shift the spatial frequency range to avoid such problems. Holographic cylindrical lenses were fabricated in the same manner described in Sections 3 and 4 but with different angles between the interfering beams, so that one had a central spatial frequency of 300 lines/mm (only slightly higher than the previous example) and the other had a central spatial frequency of 500 lines/mm. The fabricated lenses were then probed with a He–Ne laser at different positions along the lens diameter, and the angular selectivity curves are shown in Figs. 5(a) and 5(b).

A significant improvement was observed in the lens with higher spatial frequencies [Fig. 5(b)], where diffraction efficiency was maintained in the range of 65%–85%. In comparison, the lens with central spatial frequency 300 lines/mm [Fig. 5(a)] showed a marked decrease in the diffraction efficiency as the spatial frequency moved below 223 lines/mm. This happens because at low spatial frequencies, where fringe spacing is large, the diffusion time is long and the mass transport of monomers is limited, which decreases the diffraction efficiency. At higher spatial frequencies the fringe spacing decreases, and thus diffusion time becomes shorter and mass transport of monomers is more effective [11,17]. Similar fall-off in efficiency at low spatial frequency has been observed in other photopolymer materials [19].

This result provides a solution for elements where the lower spatial frequencies can be avoided without compromising the function of the lens element but will not suffice, e.g., for on-axis elements; therefore, other solutions are also needed.

B. Uniformity Improvements by Optimization of the Recording Intensity

This approach involves recording the holographic lens at lower intensities and longer exposure times while keeping the overall exposure energy constant [11,20]. The optimum recording conditions depend on physical parameters, such as the thickness of the layer and spatial frequency of recording. Slower recording at lower spatial frequencies allows more time for the monomer to diffuse from dark to bright regions during recording and will increase the diffraction efficiency [17].

By decreasing the recording intensity, the efficiency achieved in the lower spatial frequencies region becomes comparable to the diffraction efficiency in the higher spatial frequencies

Fig. 5. Angular selectivity curve for different positions (different spatial frequency) on the cylindrical holographic lens. (a) Lens recorded with central frequency 300 lines/mm and (b) lens recorded with central frequency 500 lines/mm.

region of the lens. Six cylindrical lenses (central frequency 300 lines/mm) with different recording intensities and exposure times (keeping energy constant for all six lenses) were fabricated. These six lenses were probed with a He–Ne (632.8 nm) laser at three positions (+3 mm, center, –3 mm). The angular selectivity curves for these six lenses at the three positions (+3 mm, center, –3 mm) are given in the Fig. 6.

Figure 6 shows differences in the peak diffraction efficiencies across a single lens ranging from 30% at high intensity recording to 7% as the recording intensity is lowered (and exposure time increased accordingly). For best device performance, this difference should, of course, be minimized while the diffraction efficiency is maximized.

The mean of peak diffraction efficiency for each position with its standard deviation (three lenses were fabricated for each recording intensity) is shown in Fig. 7. As the thickness of the

Fig. 6. Slow recording of a cylindrical holographic lens with a central spatial frequency of 300 lines/mm: (a) intensity -1.5 mW/cm^2 with 40 s exposure time, (b) intensity -1.25 mW/cm^2 with 48 s exposure time, (c) intensity -1 mW/cm^2 with 60 s exposure time, (d) intensity -0.75 mW/cm^2 with 80 s exposure time, (e) intensity 0.5 mW/cm^2 with 120 s exposure time, and (f) intensity -0.25 mW/cm^2 with 240 s exposure time.

layers was not constant in this particular set of samples, the diffraction efficiencies in Fig. 7 have been normalized to the central (0 mm) peak efficiency in each case in order to remove the influence of individual layer thickness variations from the graph.

6. COLLIMATION OF DIVERGING LIGHT BEAMS USING HOE

From the above discussion, it is found that 0.5 mW/cm^2 with 120 s exposure time is the optimized condition to produce a cylindrical holographic lens (central frequency 300 lines/mm),

Fig. 7. Normalized average diffraction efficiency (with standard deviation) at +3 mm, center, and -3 mm for three samples with the same recording parameters as a function of recording intensity.

which gives spatially uniform diffraction efficiency. In the next section, the optimized fabricated lens has been used in front of a diverging laser and LED to produce a collimated beam.

A. Collimation of a Diverging Laser Beam Using a Cylindrical Holographic Lens

A holographic cylindrical lens of 5 cm focal length, fabricated with 0.5 mW/cm^2 and 120 s exposure time, was used to demonstrate the collimation of a diverging (532 nm) laser beam. For the reconstruction of the diverging beam (one axis diverging), a setup as shown in Fig. 8 (schematic diagram) is used. The intensity profile of the input beam (position A) in steps of 1 mm is mapped. The HOE was positioned 5 cm away from the input beam (diverging beam) and tilted at an angle of 4.56° to the beam propagation. The output beam is mapped at 10 cm, 15 cm, and 20 cm (Position B) from the HOE.

Figure 9 shows the intensity profile of the reference input (position A) and collimated output (position B at 10 cm, 15 cm, and 20 cm) beams. The beam profile and intensity of the first-order collimated beam is maintained over 20 cm from the HOE, demonstrating a well-collimated output beam. The intensity profiles of the input beam and output collimated beam in Fig. 9 are similar; however, there is a drop in the intensity of the output collimated beam as compared to the input reference beam measured at position A. This is due to losses at

Fig. 8. Mapping of the intensity of beam A and beam B at 10 cm, 15 cm, and 20 cm away from HOE (schematic).

Fig. 9. Mapping of the beam intensities at Positions A and B—as shown in Fig. 8.

the HOE as well as some reflection and losses at the cylindrical lens surfaces.

By making direct measurements of the input and collimated output beam using a photodetector, it was estimated that 66.4% of total energy has been transferred to the collimated beam by the HOE. Figure 10(a) shows an image of the input beam diverging from a refractive cylindrical lens, and

Fig. 10. (a) Cylindrically diverging laser beam without HOE lens and (b) off-axis collimation of a cylindrically diverging beam using the fabricated HOE lens.

Fig. 10(b) shows the output when the HOE is placed in front of the diverging beam, showing the weak zero order and strong collimated first order.

The cylindrical lens can collimate only a beam that diverges in one axis; however, the light emitted from an LED diverges in two dimensions, thus requiring a spherical lens to collimate it.

B. Collimation of a Diverging LED Beam Using a Spherical Holographic Lens

A similar experimental setup as shown in Fig. 2 was used to fabricate the spherical holographic lens. In the object beam, the cylindrical lens is replaced by a spherical lens of 5 cm focal length. The optimized recording conditions as found in Section 5.B (0.5 mW/cm^2 with 120 s exposure time) were used to fabricate the spherical holographic lens. These optimized conditions will maximize uniformity in the diffraction efficiency in both horizontal and vertical axes of the lens.

The holographic spherical lens was tested with an LED source (534 nm, viewing angle = 120° , spectral bandwidth FWHM = 33 nm, Osram Opto LTE-SG-AABB-35). The same setup as described in Section 6.A is used here with an LED at the position of the beam focus. An aperture is used to block light that bypasses the perimeter of the HOE. Three output beams were observed when the HOE was placed at 5 cm from the LED with a tilt angle of 4.56° . A weak beam (zero order) continues to diverge in the original direction of propagation; however, most of the light is diverted by the HOE into a new collimated beam (+1st order). Some light is also redirected into a focused beam (−1st order), which is the conjugate of the diverging beam.

Figure 11 shows images of LED beams captured on a screen for three separate cases: first, without any lens present, Fig. 11(a), second, with the spherical HOE lens in place, Fig. 11(b), and third, with the equivalent refractive spherical

lens in place, Fig. 11(c). In all three cases, images are taken at distances of 10 cm, 15 cm, and 20 cm, respectively, from the HOE and ROE. The ROE used here has 5 cm focal length. It is clear in Fig. 11 that when the HOE is placed in the diverging beam path, 5 cm from the LED, at an angle of 4.56° , a collimated beam is produced. The high efficiency is demonstrated by the very small amount of light remaining in the original beam. In this weak beam, some non-uniformity is observed, and this is due to the small variations in efficiency that remain across the lens as well as variations in Bragg angular selectivity. The ROE performs the same collimation without the losses resulting from the other two beams.

Figure 12 provides a quantitative analysis of the images in Fig. 11. Image-J software has been used to obtain intensity profiles from the images shown in Fig. 11. It can be clearly seen from Fig. 12(a) that the LED beam is diverging, as the intensity profile broadens and decreases in intensity. The results depicted in Fig. 12(b) highlight the improvement in collimation that occurs when the spherical HOE lens is introduced in the beam path. This can be seen by the similar intensity profiles observed at the three different distances. The intensity of the conjugate focused beam decreases rapidly having very little effect at 20 cm, while the strong collimated +1 order remains almost unchanged. The ROE results are presented in Fig. 12(c) for comparison, and its intensity profile is relatively constant over these distances. At the 20 cm point, there is a slight change in the intensity profiles, and a slight decrease in the intensity levels, which occurs with both the HOE and ROE, perhaps as an artifact of the LED extended source structure. Using the area under the curves in Fig. 12 to estimate an approximate efficiency (% energy transferred into the collimated beam) values of 44%, 42%, and 41% were obtained for the HOE and values of 53%, 48%, and 43% were obtained for the ROE, at 10 cm, 15 cm, and 20 cm, respectively.

Fig. 11. (a) Diverging LED beam with no lens present, (b) collimated LED beam observed with HOE in place and (c) collimated LED beam observed with ROE in place. Images taken at Positions B (see Fig. 8) 10 cm, 15 cm, and 20 cm from the HOE/ROE, respectively.

Fig. 12. (a) Diverging LED beam profile at 15 cm, 20 cm, and 25 cm from LED, (b) collimated beam profile of LED using HOE, and (c) collimated beam profile of LED using ROE at 10 cm, 15 cm, and 20 cm from HOE and ROE, respectively.

7. SUMMARY

Two types of volume phase holographic lenses for collimating diverging light beams were fabricated in a photopolymer material; a cylindrical lens and a spherical lens. Phase contrast microscope images were used to obtain the spatial period of the diffractive features, and the results were consistent with theory. A He–Ne laser was used to probe the HOEs at different positions on the fabricated lenses to obtain angular selectivity curves, and the results were validated with KCWT. The diffraction efficiency varied across the cylindrical HOE lens due to the different spatial frequencies at each location, however, for LED applications, there is a need for uniform and high diffraction efficiency. Two methods of improving the diffraction efficiency uniformity in a fabricated lens were presented. It was demonstrated that by increasing the angular offset so that all the spatial frequency components of the recorded pattern were greater than 200 lines/mm, uniform, high diffraction efficiency was achieved. The second method involved optimizing recording conditions to allow more time for the monomer to diffuse during recording and thus increase diffraction efficiency. This method produced impressive results even for lower spatial

frequencies, and an overall diffraction efficiency of 66.4% in collimating a diverging laser was demonstrated. As a cylindrical lens is capable of collimating a diverging beam only in one axis, a spherical HOE lens was also produced using the same method. This spherical HOE lens had the same focal length and numerical aperture as the cylindrical lens. This lens was tested with a single-color LED as the diverging source and was found to provide good collimation. This was demonstrated and the results captured on a screen at 10 cm, 15 cm, and 20 cm from the HOE. In LED applications, imaging quality optics is not the goal, and so the aberrations within the HOE are not a critical factor, with the exception of chromatic aberration. Future work will involve addressing the issue of chromatic aberration [21] and fabricating a holographic lens capable of collimating a white light LED source by utilizing a stack of HOEs fabricated in a manner similar to that described here.

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