Holographic beam-shaping diffractive diffusers fabricated by using controlled laser speckle

Kevin Murphy
*Technological University Dublin*, kevin.murphy@tudublin.ie

Vincent Toal
*Technological University Dublin*

Izabela Naydenova
*Technological University Dublin*, izabela.naydenova@tudublin.ie

Suzanne Martin
*Technological University Dublin*, suzanne.martin@tudublin.ie

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Holographic beam-shaping diffractive diffusers fabricated by using controlled laser speckle

KEVIN MURPHY,† VINCENT TOAL, IZABELA NAYDENOVA, AND SUZANNE MARTIN

Centre for Industrial and Engineering Optics, School of Physics and Clinical and Optometric Sciences, College of Science and Health, Dublin Institute of Technology, Dublin 8, Ireland

†kevin.murphy@dit.ie

Abstract: A method for fabricating diffractive holographic optical diffusers is reported, allowing a high degree of control of the resulting diffuser characteristics. The method consists of recording a laser speckle pattern using a single carrier beam, with controlled speckle size and shape, in an acrylamide-based volume photopolymer. The multiple interferences that create the speckle pattern form the hologram. Results are presented verifying the diffusers are volume holographic in nature and the speckle pattern is recorded accurately in the photopolymer. Diffusers recorded by this method are analysed to characterise the optical performance of the diffusers and to illustrate their beam-shaping capabilities, particularly in producing asymmetric beam outputs.

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References and links
1. Introduction

Holography is a well-established process that captures both the phase and intensity information of a wavefront propagating from an illuminated object [1]. The standard technique involves recording an interference pattern from two beams, a reference beam and the object beam, into a recording material. The intensity and phase of the object beam can then be retrieved by probing the hologram with a beam of light at a known angle. Holograms can be recorded and used in both reflection and transmission mode.

Volume phase holograms are holograms where the recording of the features takes place entirely within the volume of the recording material, rather than through creating surface structures. They offer advantages over surface holograms in having a higher efficiency and a resistance to any surface contaminants. Commonly used recording materials for volume holograms include silver halide, dichromated gelatin and photopolymer [2]. Self-developing photopolymer formulations have been developed which provide for the cost-effective mass-production of stable holograms for long-term use, with high repeatability [3, 4].

One application of holography is for the development of diffractive holographic optical elements (HOEs) including lenses, filters, beam splitters, gratings and diffusers. Traditional refractive optics, while being optically efficient, are bulky, heavy and expensive to produce which are disadvantages for applications requiring small form factors and lightweight technologies. HOEs produced as volume holograms in photopolymer have the potential to be thin, efficient, lightweight and flexible, which makes them an attractive solution. Examples of applications which could benefit from HOEs include solar arrays [5, 6] and astronomical measurement [7].

Optical diffusing elements are used in photography to soften illuminating light and laser applications to reduce hotspots, while beam shaping diffusers are utilised in machine vision. Various optical elements are used as diffusers including ground and opal glasses and roughened surfaces. More recently engineered surfaces and surface holographic elements have been utilised [8, 9]. There are a large number of diffusers commercially available, the vast majority of which employ one of these fabrication methods. Both methods require the initial creation of an expensive master, from which diffusers of specific characteristics are mass-produced cheaply. This is an indirect process which inhibits the inexpensive availability of custom designed diffusers.

Volume holographic diffusers have been reported where an in-line hologram of an optical glass diffuser is directly recorded using a two-beam method with multiplexing [10] and by a contact-copying method [11], however these methods do not offer control over the diffusivity of the hologram. Scattering Optical Elements (SOEs), consisting of a volume holographic photopolymer layer and a traditional diffusive layer, which control the beam output have been achieved [12]. This method optimises a wavefront pattern on an SLM, records it in photopolymer, and then exploits the multiple scattering effects of the diffuse layer to produce the desired wavefront. This approach has challenges in being computationally exacting, requiring an SLM, necessitating extremely precise alignment between the two layers and not being a direct holographic method. Historically, reflective diffusers with different scattering properties have been fabricated in photoresist by exploiting speckle theory and the variations in speckle patterns [13]. Fabrication of holographic diffusers by controlling speckle patterns has been suggested [14] and carried out in a photoresin layer for creating holographic masters [15]. However we are not aware of any work directly fabricating beam-shaping diffusers in a single volume photopolymer layer.

In this paper a direct method of fabricating customizable and controllable holographic diffusers in an acrylamide-based volume photopolymer [4] is experimentally examined. To the best of the
authors knowledge this is the first time volume holographic diffusers have been directly formed through control of laser speckle statistics.

2. Method

2.1. Speckle theory

The theory governing laser speckle size and distribution has been well established for many years in fields such as electronic speckle pattern interferometry, holographic interferometry and speckle imaging [16, 17]. Assuming the phase of the light has first been randomized (e.g. by a rough surface) the intensity distribution of a laser speckle pattern at a particular distance depends only on the wavelength of the light and diameter of the illuminated area. However in the case of subjective speckle where a speckle pattern is imaged by a lens the (finite) lens aperture determines the minimum size of speckle that is displayed in the focal plane of the lens. The minimum size of speckle in the subjective speckle case is, \( \sigma \), given by

\[
\sigma = \frac{2.44 \lambda f}{a}
\]

where \( f \) is the focal length of the lens, \( a \) its aperture diameter and \( \lambda \) the wavelength of light.

By controlling the lens pupil diameter using a variable aperture, precise control can be exercised over the range of speckle sizes in the subjective speckle pattern at the lens focal plane. Placing a photopolymer layer at the focal plane will result in the speckle pattern being recorded holographically in the photopolymer volume. Varying the speckle size recorded will vary the feature size in the photopolymer, giving a change in the level of diffraction through the material. Adjusting the spatial symmetry of the aperture will change the shape of the recorded speckles. In this way a spatial asymmetry may be introduced in the light diffracted through the photopolymer material, when the HOE is probed by beam of light.

2.2. Recording of the diffusers

Figure 1 is a schematic of the optical setup used to control and record the speckle pattern in the photopolymer material. An Ar-Ion (\( \lambda = 514 \text{nm} \)) laser beam, passes through a spatial filter (SF). A lens (CL) is used to collimate the beam which is then propagated through a ground glass diffuser (1500 grit polish). This diffuser was chosen as it maximises the amount of light which propagates through the diffuser, while still randomising the phase. The speckle pattern at the pupil plane of a focusing lens (FL, \( f = 10 \text{cm} \)) is translated onto the photopolymer layer (PP), placed at the focal plane of FL. An adjustable aperture at the pupil of FL controls the speckle size and shape.

![Fig. 1. Schematic of setup used to record laser speckle diffusers in photopolymer. SF = Spatial Filter, CL = Collimating Lens, FL = Focusing Lens, PP = Photopolymer Layer.](image)

Photopolymer layers (\( \approx 70 \mu\text{m} \) thick) are prepared on a 450 \( \mu\text{m} \) thick plastic substrate. A 50 \( \mu\text{m} \) cover film is used to prevent the formation of surface structures during polymerisation, which
have been previously observed to form at the spatial frequencies studied [18]. Laser energy of $\approx 65 \text{mJ/cm}^2$ is delivered to the samples, as $1 \text{mW/cm}^2$ for 65s for the circular aperture diameters between 6mm and 18mm, as $0.65 \text{mW/cm}^2$ for 105s for a 4mm diameter and as 0.175mW/cm$^2$ for 390s for a 2mm diameter, to allow for longer monomer diffusion distances for larger feature sizes. When slit apertures were substituted for circular ones, the exposure energy $\approx 65 \text{mJ/cm}^2$ was delivered as $1 \text{mW/cm}^2$ for 65s. Any residual dye remaining from the recording process was bleached out under ambient light before testing. It should be noted that what is recorded in the volume hologram is a 70$\mu$m thick slice of the speckle field and thus it will not record the full thickness of the speckle in the z-direction (typically $> 100\mu$m). In addition, due to the size and random nature of the features recorded it is not believed there will be any polarisation dependence for these elements.

2.3. Testing methodology

In order to measure the recorded speckle size, for comparison and verification with speckle theory, the recorded patterns are imaged microscopically. This is achieved using an Olympus BX51 phase contrast microscope, with a DP72 camera and a 40X magnification. Three images are taken per sample at various points across the sample. These images are subjected to image processing in MATLAB, in which a row-by-row (column-by-column) autocorrelation is carried out in the x-direction (y-direction). The results for all rows (columns) are averaged to give an autocorrelation function in each direction. The outputted averaged autocorrelation function describes the shape and size of an average speckle in two orthogonal directions. The diameter of the speckle can then be calculated and is shown in the results section.

To verify that the speckle pattern formed by the system is accurately recorded in the photopolymer layer observations of the speckle patterns were made with a camera. A camera, without lenses, was placed in the focal plane of FL and the speckle patterns formed, using the different aperture sizes and shapes, on the CCD array were recorded. The images obtained were then subjected to the same MATLAB program as the phase contrast microscope images and the speckle sizes determined. The results are then compared to both theory and the microscope images of the diffusers recorded holographically.

To characterise the optical performance of the diffusers two systems were used. The first probes the diffusers with a laser (633nm) to determine the efficiency of the diffusers, over a range of input angles and the power in the zero order is measured by a power meter, with an iris ($\approx 2\text{mm}$) placed over it. The diffuser efficiency is defined by Eq. (2) and is analogous to the haze factor.

$$\text{Diffuser Eff.} = \left(1 - \frac{\text{Zero Order Intensity}_{\text{Diffused}}}{\text{Zero Order Intensity}_{\text{Control}}} \right) \times 100\%$$ (2)

The control zero order intensity is measured by illuminating a control sample of a bleached photopolymer layer, with no hologram recorded on it. If the diffuser efficiency is dependent on the input angle it indicates the diffuser to be volume holographic in nature. In addition by measuring the light emission across a large range of angles an angular selectivity/acceptance angle map of each diffuser can be constructed.

The second test system propagates laser light through the diffusers and the output is measured in terms of the angular spread of the light, which allows for the output beam shape to be quantified. This is achieved by placing a DPSS laser diode module ($\lambda = 532\text{nm}$) on a rotation stage. The diffusers are held almost in contact with the laser diode module, also on the rotation stage. A stationary optical power meter, with an iris of $\approx 2\text{mm}$ placed over it, is placed at a distance of $\approx 11\text{cm}$ from the diffuser. The rotation stage is rotated in a stepwise fashion over the desired angular range and the intensity of the output light is measured.
3. Experimental results

3.1. Verification of photopolymer recording of speckle

The verification of the accurate recording of the speckle patterns in the photopolymer layers begins with the images obtained of the diffusers using phase contrast microscopy. In the case of a circular aperture the speckles generally have a rounded shape and their average size should be determined by Eq. (1). Two examples of the kind of images produced are shown in Fig. 2, where the aperture diameter \( a = 18 \text{mm} \) [Fig. 2(a)] and \( a = 5.5 \text{mm} \) [Fig. 2(b)]. Visually it can be seen that the larger aperture diameter gives a smaller speckle size, as predicted by theory.

In the case of a slit aperture the speckles have an elongated shape, with the length of the elongated speckle changing with the width of the slit, due to diffraction. The width of the elongated speckle stays constant on account of an unchanging slit length. This is visually evident from microscope images, in Fig. 2(c) the slit width \( = 0.5 \text{mm} \) and in Fig. 2(d) slit width \( = 2 \text{mm} \).

![Fig. 2. Phase contrast microscope images of various speckle patterns recorded in photopolymer to create diffusers: (a) circular aperture \( \phi = 18 \text{mm} \), (b) circular aperture \( \phi = 5.5 \text{mm} \), (c) slit width \( = 0.5 \text{mm} \) and (d) slit width \( = 2 \text{mm} \). Scale bar \( = 50 \mu\text{m} \).](image)

The autocorrelation method described in Section 2.3 returns the speckle size in both the x- and y- directions for each microscope image. Three images are taken and processed in the MATLAB program for each sample and three samples for each aperture size were examined. In the case of the circular aperture the results for the x- and y- directions are averaged together. In the case of the slit aperture only the y-direction is considered to determine the speckle length.

![Fig. 3. Speckle size predicted by theory and the measured speckle size (by camera and microscope methods) for (a) a range of circular aperture diameters and (b) a range of slit aperture widths.](image)

The results for the speckle size for a range of circular apertures are presented in Fig. 3(a) and for a range of slit widths in Fig. 3(b). This figure shows the minimum theoretical speckle size, as obtained from Eq. (1), and the speckle size calculated by the autocorrelation of the microscope images. Both of these use the distance between the minima of the speckle to define the diameter. Also shown is the speckle as seen directly by the camera, which defines the speckle diameter as the distance between the \( 1/e^2 \) points on the speckle, due to noise effects in the camera images.

Results for speckle size obtained from the CCD camera and the theory in Fig. 3(a) confirm that the speckle patterns generated in the optical setup conform to theory. The deviation from the theory for the camera results seen at the small aperture sizes is easily explained by the definition
of the speckle diameter between the $1/e^2$ points on the speckle. This will underestimate the size of the speckles, particularly for larger speckles. The slight deviation from theory at the larger apertures is due to the speckles approaching the size of the CCD pixels ($6\mu m$). The speckle size of the recorded diffusers (measured from the microscope images) also follow the theoretical trajectory, indicating that the speckles are recorded accurately in the photopolymer. There are deviations from the theory for larger speckle sizes which is due to the photopolymer being less well able to record low spatial frequency features [19], due to the large monomer diffusion distance required to form the features. It may be possible to improve the fidelity of recording these larger speckle sizes by optimising the recording conditions at these sizes.

3.2. Holographic optical diffuser performance

The performance of a series of diffusers produced using a circular aperture during recording were tested using the first test setup described in Section 2.3. The aperture diameter ranged from 2mm to 18mm, which corresponds to a theoretical minimum speckle size varying from $\approx 63\mu m$ to $\approx 7\mu m$. These diffusers were found to have a typical total transmission of $88.6\%$ ($\sigma = 1.0\%$). This compares with a control sample of exposed photopolymer with typical transmission of $89.2\%$ ($\sigma = 1.1\%$), indicating that very little additional reflection or absorption is caused by the diffractive features.

Figure 4(a) shows the diffuser efficiency, defined in Eq. (2), for six diffusers in the range described above, over a 50° angular spread, with an angular step size of 0.25°. It illustrates that the efficiency of the diffusers is greater for a smaller speckle sizes, with a peak diffuser efficiency of > 97% reached by a diffuser recorded with an 18mm aperture diameter. However the diffusers with smaller speckle sizes exhibit peak efficiency over a narrower angular input range than diffusers with larger speckle sizes. Figure 4(a) highlights that a suite of diffusers can be manufactured using this technique, with a span of diffuser efficiency characteristics.

Figure 4(b) uses the second test setup defined in Section 2.3 to characterise the beam-shape outputted from diffusers over a range of 30°, with an angular step size of 0.25°. The intensity of the detected light is plotted on a log scale. The output of the holographic diffusers is compared to the beam-shape obtained from two grades of ground glass. The beam profile of the laser diode used to probe the samples is shown for comparison in green. The black and orange lines represent ground glass diffusers of 120 grade (considered a coarse diffuser) and 660 grade (considered a fine diffuser; with similar characteristics to a 1500 grade) grit polish respectively. The ground glass diffusers show a beam-shape with a very strong decrease in the zero order and a spreading of the transmitted light over a wide angle, with an irregular pattern. The red and blue lines represent the two extremes of the fabricated holographic diffusers shown in Fig. 4(a), 18mm and 2mm apertures respectively, and illustrate how the HOEs can be used to control the diffusion.
characteristics of a beam.

The zero order terms which remain in the HOE diffusers (the zero order and diffused terms are merged for the 2mm sample due to the small diffraction angle) are typical of the speckle pattern produced by having a small number of scatterers relative to the beam size \[17\]. The zero order could be further suppressed by reducing the speckle sizes recorded to closer to the wavelength of playback; this will also increase the angular output of the beam. The photopolymer used has the capability to record sub-wavelength feature sizes \[20\], indicating this can be achieved using the methods described here.

### 3.3. Visual beam-shaping performance of holographic optical diffusers

Figure 5 illustrates two types of beam shape output possible from the holographic diffusers depending on the aperture proportions. Figure 5(a) shows the output of a diffuser recorded with a circular aperture illuminated with a laser diode; the central spot is the residual zero order term seen and discussed previously in Fig. 4(a). Figure 5(b) is the output of a diffuser recorded with a slit aperture diffuser. These images depict the visual beam-shaping effects of the diffusers.

The beam shaping exhibited by these diffusers is in contrast to previous volume holographic diffusers \[10\], in that the diffusers described here have specific and controllable speckle dimensions. The speckle dimensions recorded determine the diffraction through the diffuser and hence the output beam shape. It should also be noted that although the diffusers were recorded at a single wavelength (\(\lambda = 514\) nm), they are capable of diffusing at other wavelengths.

![Output beam shapes produced when a laser diode probes (a) a diffuser recorded with a circular aperture and (b) a diffuser recorded with a slit aperture.](image)

**Fig. 5.** Output beam shapes produced when a laser diode probes (a) a diffuser recorded with a circular aperture and (b) a diffuser recorded with a slit aperture.

### 4. Discussion and conclusions

A straightforward, effective and controllable method for recording holographic optical diffusers with known speckle statistics, in a volume photopolymer, is presented. The diffusers characteristics can be tuned by controlling the speckle size and shape, therefore the diffractive feature size, which in turn will regulate the output beam-shape and angular size. The speckle sizes produced are shown to conform to theory and are recorded with a high degree of fidelity into the photopolymer medium. The diffusers are established to be holographic in nature through the recording of an interference pattern (speckle) and the dependency they have on the incidence angle of a probe beam. The recorded diffusers can be used to diffuse and beam shape (including asymmetric beam shapes) the output of single wavelength laser sources. This technique therefore could have applications in the machine vision and laser manufacturing fields.

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