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Proton beam writing for producing holographic images

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ABSTRACT

This work reports on the writing of computer generated hologram diffraction patterns using focused 2 MeV proton beam irradiation. These patterns were designed using a ray tracing algorithm and written directly into a thick polymethylmethacrylate layer. When the developed holographic pattern was illuminated with a 650 nm laser it produced a good reconstructed image. This work provides means of forming high-resolution, high aspect ratio holographic images in polymers for applications in data storage using switchable holography.

1. Introduction

1.1. Review of holography

Holography is a technique that records the wave-front information based on light which is scattered from an object into a hologram and produces a reconstructed image from it. Unlike conventional photography in which only light-intensity information is recorded, a hologram records both intensity and phase information, thus has the ability to reconstruct three-dimensional images. As the position of the viewer changes, the reconstructed image from a hologram changes exactly the same way as if the object were still present.

A simple conventional hologram is created from the superposition of waves from a single, highly-coherent beam of light, usually a laser. A portion of the light from the light source, known as the 'object' beam, is reflected/scattered off from the object which one wants to record and hits at an angle on a light-sensitive recording medium, such as high-resolution photographic film. Another portion of the light from the light source, known as the 'reference' beam, is simultaneously sent directly to the recording film without any interaction with the object. The object and the reference waves interfere to form an interference pattern and their relative phase differences are recorded across the photographic film as fringe patterns.

After developing the photographic film, a hologram is formed and object 'reconstruction' is achieved by illuminating the hologram with a laser, as shown in Fig. 1. The fringe patterns act as diffraction gratings and the light incident upon the photographic film is partly diffracted into the angle which the original object beam was incident. The transmitted waves would thus appear to originate from the object and a virtual image of the object is formed. In Fig. 1, the first lens focuses the reconstructed image into a projection lens which then enlarges the image onto a viewing screen. A few of the many applications of holography include storage of digital data and images [1–3], precise interferometric measurements [4,5], pattern recognition [6,7] and data encryption [8,9].

1.2. Computer generated holography (CGH)

CGH are holograms in which the recording process is not performed optically as described above, but instead by computing the wave propagation produced by an object using mathematical algorithms. The advantage of CGH over holograms produced by optical means is that the object used for recording the CGH does not need to exist if it can be described mathematically. Therefore, arbitrary object geometries can be holographically reproduced, which is important for example for producing holographic security features.

There are several ways of calculating a CGH, including ray tracing [10,11] and a Fourier transform method [12,13]. In this work, CGHs were designed with a simple ray tracing method [14], in which calculation of the difference between the path length that a virtual 'reference beam' and a virtual 'object beam' travel is carried out which then gives the relative phase of the scattered object beam. Fig. 2(a) inset shows a simple example of an object which comprises the letters 'NUS' and its holographic diffraction pattern in the form of a 1024×1024 black and white pixel image is shown at different magnifications in Fig. 2. The reconstruction process is the same as that of conventional optical holography shown in

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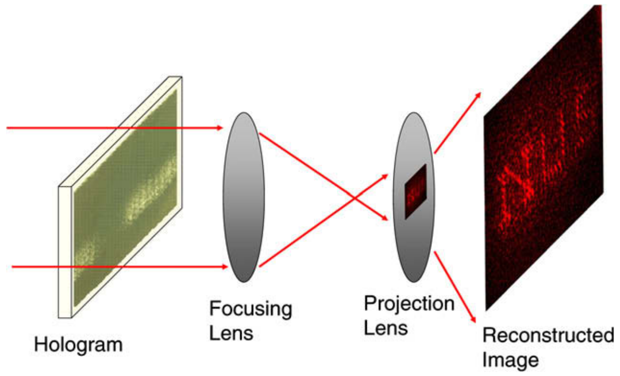

Fig. 1. Schematic of holographic reconstruction set-up.

Fig. 1, where the CGH is illuminated by a laser and the reconstructed image is formed by diffraction.

1.3. Switchable CGH

A switchable CGH using polymer-dispersed liquid crystals (PDLC) and LC cell with patterned electrode was recently reported [15]. An optical path length difference was achieved because of the difference in refractive indices in the polymer-rich and LC-rich regions. Upon application of an external voltage, reorientation of the LC directors in the PDLC or LC cell results in a change in the refractive index of the LC-rich regions. When the indices of the LC and polymer are matched, the reconstructed image is erased.

For this type of application, one needs a CGH pattern fabricated in a reasonably thick layer of several micrometers. However, it is difficult to achieve high spatial resolution pattern with high aspect ratio on thick layers using conventional photolithography-based processes. This limited the spatial resolution in the above switchable CGH pattern, which was fabricated using a photo-polymerization process, to about 50 μm.

2. Proton beam writing

Proton beam writing (PBW) is a direct write process which uses a focused beam of MeV protons to pattern thick polymer resist materials at lateral dimensions of micrometers. Since MeV protons have much higher momentum compared with keV electrons, they have a deeper penetration in resist materials with little lateral scattering, enabling PBW to fabricate high aspect ratio microstructures with vertical, smooth sidewalls and low line edge roughness. While various modes of direct-writing in polymers using high energy focused ion beams have been available for many years [16,17], it is only recently that it has achieved resolutions of about 50 nm with uniform irradiations owing to use of high resolution nuclear microprobes coupled to high stability megavolt accelerators [18,19].

PBW has many similarities to electron beam lithography, which offers unparalleled lateral resolutions of several nanometers in thin resist layers. This makes electron beam lithography the ultimate tool for fabricating CGH patterns, capable of writing up to 10,000 lines per mm, which is needed for the highest fidelity reconstructed images. However, it is not ideal for producing high-resolution patterns in thick layers suitable for switchable CGH. PBW gives the ability to produce patterns in thick resist layers potentially several thousand lines per mm, and this paper considers the formation of CGH patterns in resist layers suitable for producing switchable CGH patterns when filled with liquid crystals.

3. Results

A 5 μm thick layer of polymethylmethacrylate (PMMA) was first prepared on a 1 mm thick glass slide by spin coating. The CGH pattern in Fig. 2(a) and (b) was converted into a binary file format which fully specifies the pattern in terms of coordinates which can then be read by the IONSCAN code [20] which controls the scanned irradiation pattern. Black pixels are exposed to the focused 2 MeV proton beam while the white pixels are 'blanked'. In this manner, the CGH diffraction pattern may be transferred to the PMMA. This form of PBW is demanding since it requires frequent beam blanking due to the many changes from black to white pixels typically found in CGH patterns.

The CGH pattern in Fig. 2 was transferred to PMMA by irradiating over an area of 2×2 mm^2 containing 1024×1024 pixels, giving a pixel size and resolution of approximately 2×2 μm. The proton beam current of 70 pA was focused to a spot size to match that of each pixel. The fluence required for PMMA to be removed for subsequent development is 140 nC/mm^2 ($\sim 10^{14}$ ions/cm^2) for 2 MeV protons [21] which gives a total irradiation time of approximately 2.2 h. Removal of irradiated PMMA was done using a solution of isopropanol and water in the ratio of 7:3 for 10 min at room temperature. The IPA based solution was used as a developer as its effect on unexposed/un-irradiated PMMA resist is less aggressive [21] than that of the conventional GG developer. This ensures that the structural precision of the structures is determined by the size of the focused proton beam, rather than arising from the etching of un-irradiated resist. The developed PMMA patterns contain the CGH diffraction pattern and are shown in Fig. 3 at the same magnification as the original generated CGH images in Fig. 2 for a direct comparison. Good pattern transfer from the image file into the PMMA layer is achieved.

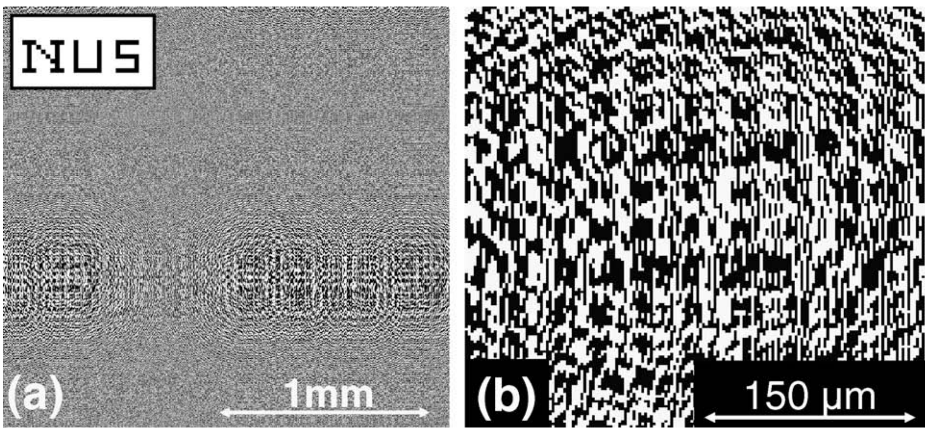

Fig. 2. (a) Inset shows NUS input file, comprising 30 by 15 pixels. (a) and (b) Corresponding CGH pattern at different magnifications.

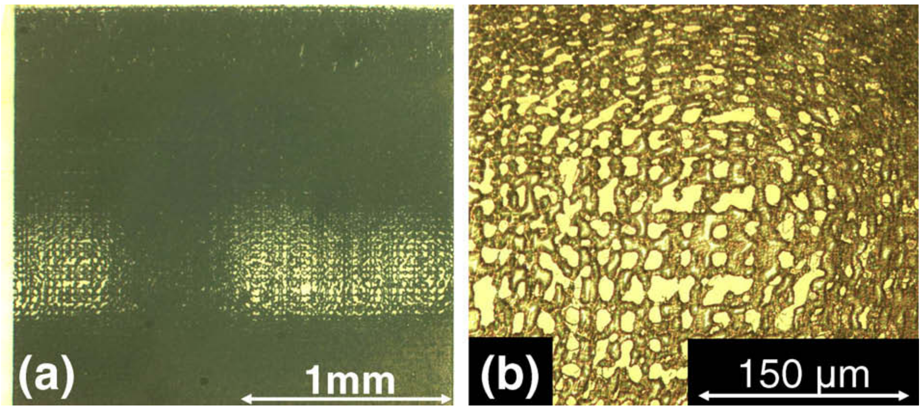

Fig. 3. The developed PMMA structures of the CGH pattern shown in Fig. 2.

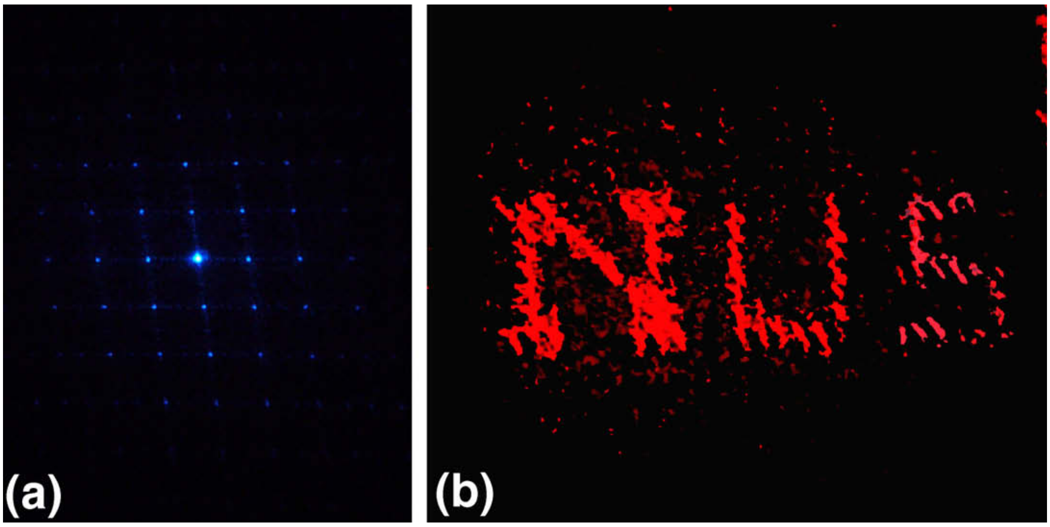

Fig. 4. (a) Diffraction pattern, and (b) reconstructed holographic image of NUS CGH pattern.

Fig. 4(a) shows a diffraction pattern formed by shining a blue laser (473 nm) through the developed PMMA CGH pattern, with no lenses present. A blue laser is used here as it is more intense than the available red laser, so producing a wider range of visible diffraction spots. The bright spots are produced by the many orders of diffraction from the high resolution CGH pattern. Fig. 4(b) shows the CGH image reconstructed using a red laser pointer (650 nm, 5 mW power) with the set-up shown in Fig. 1. When illuminated with the laser, the CGH pattern on the PMMA produced a good reconstructed image of the original pattern.

4. Conclusions

We have demonstrated the ability to transfer a CGH diffraction pattern onto PMMA using a focused 2 MeV proton beam. The transferred CGH on PMMA was able to reconstruct a relatively good image upon illumination by a laser. This work provides means of forming high-resolution, high aspect ratio holographic images in polymers for applications in data storage using switchable holography.

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