Femtosecond laser written embedded diffractive optical elements and their applications

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ABSTRACT

Femtosecond laser direct writing (FLDW) has been widely employed to create volumetric structures in transparent materials that are applicable as various photonic devices such as active and passive waveguides, couplers, gratings, and diffractive optical elements (DOEs). The advantages of fabrication of volumetric DOEs using FLDW include not only the ability to produce embedded 3D structures but also a simple fabrication scheme, ease of customization, and a clean process. DOE fabrication techniques using FLDW are presented as well as the characterization of laser-written DOEs by various methods such as diffraction efficiency measurement. Fresnel zone plates were fabricated in oxide glasses using various femtosecond laser systems in high and low repetition rate regimes. The diffraction efficiency as functions of fabrication parameters was measured to investigate the dependence on the different fabrication parameters such as repetition rate and laser dose. Furthermore, several integration schemes of DOE with other photonic structures are demonstrated for compact photonic device fabrication.

Keywords: Femtosecond laser direct writing, Diffractive optical elements, Fresnel zone plates

1. INTRODUCTION

Diffractive optical elements (DOEs) such as Fresnel zone plates (FZPs) and gratings are important components in manufacturing compact and multifunctional integrated optical devices such as micro-sensors, communication systems, and optoelectronic devices [1-6]. They serve as planar and compact alternatives to refractive optics. The current demand in optical device fabrication requires 3-D volumetric and integrated structures to reduce device size. Conventional manufacturing techniques such as e-beam lithography are not capable of producing 3-D structures because they are basically planar processes, optimized for 2-D structures limited to the sample surface. Thus, a multistep process is required to fabricate volumetric structures using a 2-D based technique. Furthermore, this multistep process is not cost effective nor time efficient when custom design is required for frequent revision and low-volume production. Although holographic recording is available to generate 3-D structures with a single step process, it may be limited to low laser power applications because it requires photo-sensitive materials that exhibit low laser damage thresholds.

Femtosecond laser direct writing (FLDW) is a powerful technique to generate truly 3-D features in transparent bulk materials [7-11]. It provides a unique 3-D fabrication protocol creating embedded structures with a single step process. Hence, it is advantageous over conventional techniques based on 2-D structures described above. In addition, FLDW is a suitable technique for fast, custom-designed fabrication, as its direct writing scheme does not require any pre-designed masks and preparation process. Therefore, it has a great advantage in custom-design optical device fabrication involving photonic structures such as DOEs and waveguide channels. Femtosecond laser-written Fresnel zone plates have been demonstrated in fused silica by several research groups [12-14]. However, they have suffered so far from low diffraction efficiencies and long fabrication times that may prevent the practical use of femtosecond laser-written DOEs in photonic device manufacturing.

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In this paper, femtosecond laser-written single/multi layer binary type phase FZPs are generated in borosilicate glass with multi-hundred kHz pulses in order to increase the diffraction efficiency and reduce the fabrication time. Their diffraction efficiencies are investigated as functions of fabrication parameters. Integration of FZPs with laser-written waveguides is also demonstrated and their beam propagation properties are investigated through near field images.

2. EXPERIMENT

2.1 Laser direct writing

In this study, a Yb-doped fiber laser (FCPA μJewel D-400-VR, IMRA America, Inc.) was used to investigate the effect of fabrication parameters such as the laser repetition rate, laser dose, and writing speed. This laser has a center wavelength at 1043 nm and a pulse duration of 400~450 fs. It provides pulses at a variable repetition rate that ranges from 100 kHz to 5 MHz. The laser system was integrated with a direct writing station consisting of a computer controlled 3-D stage (Aerotech, ALS130), a CCD camera (Pixelink) and a focusing objective. Fig. 1 (a) shows the laser writing and custom-built pulse characterization setups. Fig. 1 (b, c) shows a custom-built intensity-autocorrelation setup and the autocorrelation of a pulse, emitted from the laser at 1 MHz. The autocorrelation pulse width is measured to be <510 fs.
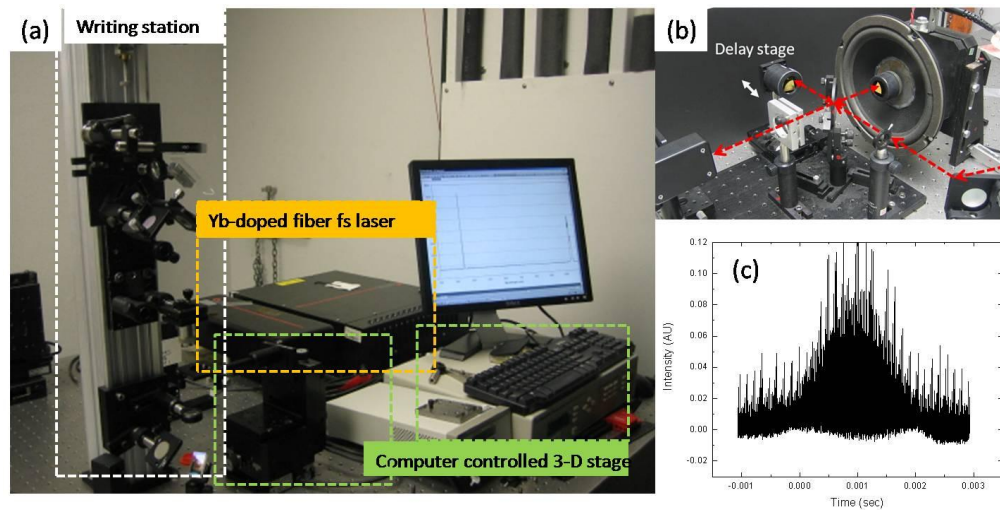

Fig. 1. Femtosecond laser writing facilities: (a) Yb-doped fiber laser, FCPA μJewel D-400-VR, integrated with a 3-D stage and a CCD monitoring system, (b) a custom-built autocorrelator, (c) autocorrelation of a pulse (τ < 510 fs at 1 MHz).

A borosilicate substrate (thickness ~1.1 mm) was mounted on a 3-D computer controlled translation stage to be exposed to a tightly focused laser beam through a microscope objective. Various microscope objectives were used in order to produce appropriate modification lengths and cross-section profiles required for each application. A low NA microscope objective (NA 0.15) was used to generate a long modification length for FZPs and a medium NA microscope objective (NA 0.4) was used to fabricate waveguides for reasonably round waveguide cross-section and millimeter range working distance. Mounted samples were translated perpendicular to the beam propagation direction to produce the 2-dimensional Fresnel zone plate patterns 300 μm underneath the surface. The writing scheme using FLDW is shown in Fig. 2. An integrated structure consisting of a binary type FZP and a waveguide were combined via a single writing process. First, a FZP was created on the facet of the incident probe beam, then the substrate was rotated to allow for the writing of a waveguide. The input and output facets of the borosilicate substrates were polished prior to the irradiation that generated the FZPs to ensure low loss at the interface. The distance between the FZP and the waveguide was set equal to the primary focal length of the zone plate, so that the incident light can be focused and coupled into the waveguide whose end is located at the focal point of the FZP.
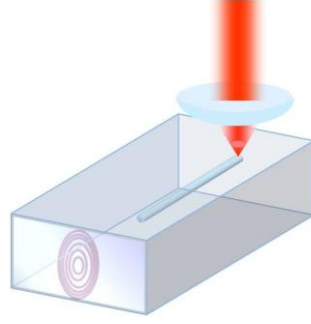
Fig. 2. Schematic diagram for writing integrated structures consisting of a FZP and a waveguide.

2.2 Diffraction efficiency and propagation measurement

The laser-written samples were characterized by measuring the diffraction efficiency and propagation properties through near field image observation. A 5-axis manual stage was used to mount and translate the sample and tweak the incident angle of the probe beam. A HeNe laser (λ= 543 nm, $2w_0$~1 mm) was used as a probe beam. Fig. 3 depicts a schematic of the diffraction efficiency measurement setup. The FZP focused HeNe beam was coupled into a waveguide and finally the propagation was imaged on a CCD beam profiler (Spiricon Inc., SP-980M). The diffraction efficiency η of the FZP was estimated by measuring the ratio between incident power and the power of the first diffracted order beam. The total propagation efficiency was determined as the ratio between the incident power and the power transmitted by the waveguide through the FZP. The diffraction efficiency η was measured separately and taken into account for the estimation of total propagation.
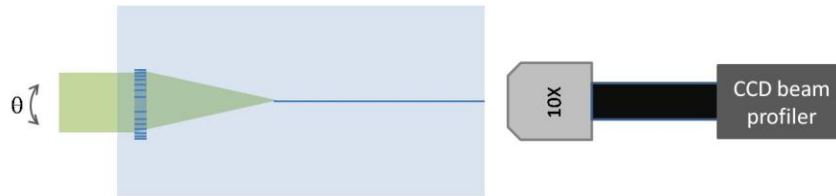

Fig. 3. Schematic diagram of the propagation measurement through near-field image setup

3.   RESULTS

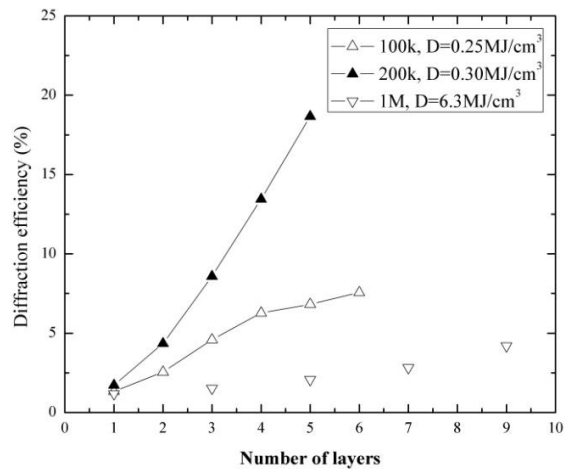## 3.1 Investigation of diffraction efficiency

The binary type phase FZPs were produced and characterized. The theoretical diffraction efficiency of the FZP is known to be 40.5%. The diffraction efficiencies η of laser-written binary FZPs were investigated as functions of the fabrication parameters to improve the fabrication process so that optimized FZPs could be prepared for each application, which will be described in the next section. First, η of a single track FZPs was investigated as a function of the pulse energy and number of layers. Laser repetition rates of 0.1, 0.2 and 1 MHz were used to compare the effect on η. Various writing speeds, ranging from 0.05 to 2 mm/s, were investigated as well as varying the pulse energy from ~1 to ~ 2 μJ. Fig. 4 (a) shows η as a function of the laser pulse energy using a NA 0.15 objective lens. As shown in the figure, the increase of η is linear, which implies that the pulse energy range is under the saturation threshold of this material with regard to the laser-induced refractive index change **Δn**. It also confirms that the higher laser dose, obtained by a slower writing speed, produced FZPs with higher η. Second, the multilayer scheme was investigated to increase the overall η. The effect of increasing the number of layers on the total phase shift **Δφ** was investigated. To stack layers effectively in the substrate, the gaps between successive layers were minimized. However, the gaps were made sufficiently to avoid overlaps between layers. Fig. 4 (b) shows the relation between the number of layers and diffraction efficiency of FZPs at each repetition rate. Interestingly, 200 kHz pulses fabricated higher η compared to 100 kHz although similar (volumetric) laser doses were used. The result at 1MHz

exhibited the lowest η. This is due inadequate pulse energy from the laser at 1 MHz for a 0.15 NA objective lens to induce sufficient modification.

For a normal Fresnel zone plate, the fabrication time T and η were investigated as a function of the reciprocal spacing between irradiation tracks, which determines the density of laser-induced modification. Fig. 4 (c) shows T and η as a function of reciprocal spacing between irradiation tracks. The increase of diffraction efficiency per layer is seen as the reciprocal spacing is increasing. In the figure, it is noticed that the slope of the increase of η became slower at the reciprocal spacing about ~2 or higher, corresponding to the spacing around ~500 nm or smaller. Therefore, the effective spacing can be chosen as to be larger than 500 nm. The multilayer scheme can be then simultaneously be used to obtain higher efficiency. In this way, the optimal density of modification (or number of tracks) in a zone and appropriate fabrication time can be determined.
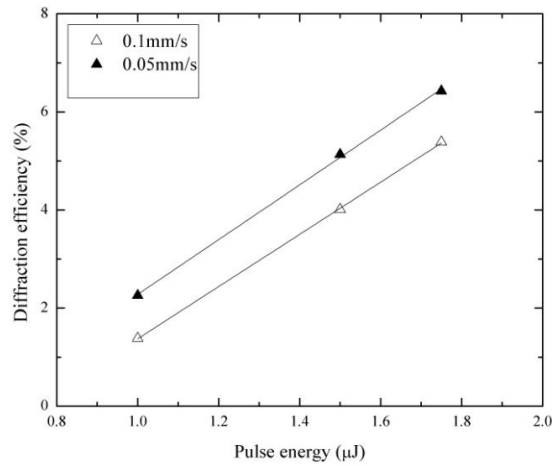
(a)

(b)
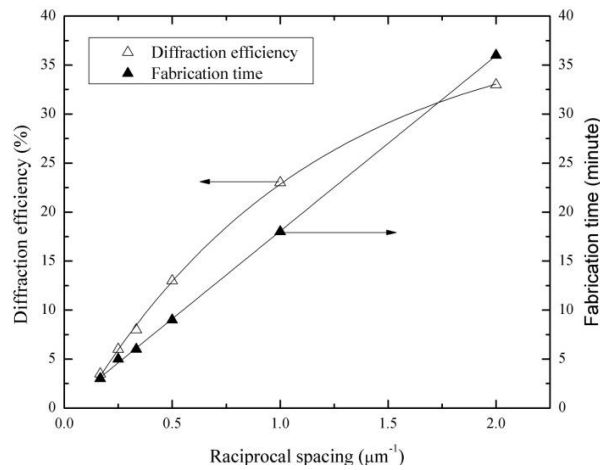
(c)

Fig. 4. Diffraction efficiency of single track FZPs as functions of (a) pulse energy at 200 kHz with different writing speeds and (b) the number of layers. (c) Diffraction efficiency and fabrication time of a normal FZP as a function of the reciprocal spacing at 200 kHz with a writing speed of 1 mm/s

3.2 Integration of multiple photonic structures with FZPs

As described above, laser direct writing is capable of producing custom-designed, multiple photonic structures in a substrate with great convenience via a single step fabrication process. With this approach, two different integration schemes are demonstrated in searching for a fabrication protocol for multifunctional photonic devices. The first approach is multiplexing by integrating multiple identical photonic structures in a substrate. Fig. 5 shows an example of multiplexing, which is a microlens array composed of laser-written embedded FZP lenslets, produced in a borosilicate substrate. The input beam is divided into many outputs with reduced power. Each lenslet has a diameter of 600 μm. As a micro-FZP can replace a single convex micro-lenslet, this can be used as a convex microlens array for micro-imaging system. The advantage of the technique can be the "in-situ" customization of each lenslet without suffering from preparing new masks. Therefore, the specification of each micro-lenslet such as focal length and diffraction efficiency can be simply adjusted by changing fabrication parameters including writing patterns and laser doses during the fabrication process.
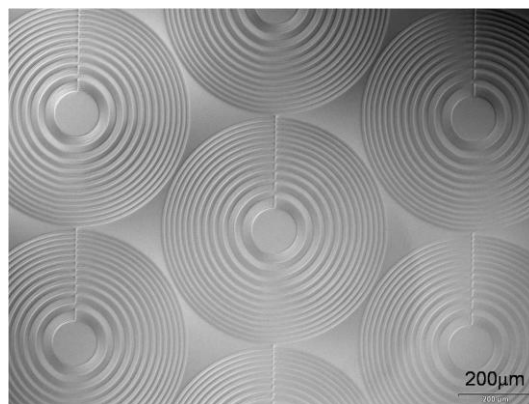

Fig. 5. The DIC optical microscopic image of the top view of a laser written FZP array in borosilicate glass. The diameter of a single lenslet is ~600 μm.

Another type is the integration of different photonic structures. Two or more optical elements are integrated in a single substrate to demonstrate multifunctional performance. Fig. 2 shows a schematic diagram of this type of

integration. As shown in the picture, a FZP and a waveguide are produced in a single substrate. Therefore, the FZP works as a built-in coupler to deliver the input beam into the waveguide. This coupling structure is free from misalignment from any environment fluctuation such as mechanical shock or temperature change. Fig. 6 shows the near-field image of the propagation of a probe HeNe laser beam through a waveguide array. The focal length of the FZP was designed as $f = 10$ mm, thus the waveguide was generated 10 mm away from the FZP. In the picture, the cross-section image of the waveguide is elliptical and revealed that the waveguide exhibits a multimode propagation. This type of structure can be utilized for applications such as chemical sensors or micro-fluidics that require large area photon collecting and delivery from a reservoir to the output end facet of the device.
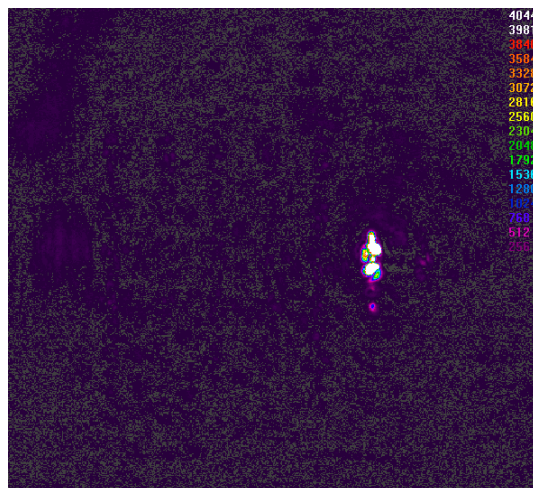

Fig. 6. A near-field image of the beam propagation ($\lambda = 543$nm) through a laser-written waveguide coupled by an embedded FZP.

4. SUMMARY

In this paper, the diffraction efficiency of laser-written FZPs in borosilicate glass was investigated as a function of different fabrication parameters. Repetition rate of 200 kHz induced a higher phase shift that allows improved diffraction efficiency with similar laser dose and fabrication time. The density of the irradiation (or number of irradiation tracks) in a zone of a FZP was also optimized to reduce the fabrication time. A micro FZP lenslet array and integration of a FZP with a waveguide were also demonstrated. The integrated structure was also characterized by the near-field image beam propagation. It revealed that an incident beam through the FZP was successfully coupled into a waveguide. It implies that the integrated structure can be applied to custom-designed integrated optical devices for applications such as signal collecting and delivery,

ACKNOWLEGEMENTS

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