Adaptive slit beam shaping for direct laser written waveguides

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We demonstrate an improved method for fabricating optical waveguides in bulk materials by means of femtosecond laser writing. We use an LC spatial light modulator (SLM) to shape the beam focus by generating adaptive slit illumination in the pupil of the objective lens. A diffraction grating is applied in a strip across the SLM to simulate a slit, with the first diffracted order mapped onto the pupil plane of the objective lens while the zeroth order is blocked. This technique enables real-time control of the beam-shaping parameters during writing, facilitating the fabrication of more complicated structures than is possible using nonadaptive methods. Waveguides are demonstrated in fused silica with a coupling loss to single-mode fibers in the range of 0.2 to 0.5 dB and propagation loss <0.4 dB/cm.

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Photonic waveguides may be written in bulk glasses by means of a femtosecond laser [1]. Under tight spatial focusing, structural modifications arising from nonlinear absorption of the incident light generate a permanent local increase in the refractive index, leading to the formation of an optical guide, which may be used in a wide range of applications [2].

Because of the nonlinear character of the interaction between the writing laser pulses and the medium, it is vital to have precise and accurate control of the laser beam focusing. For example, because the sample is translated transverse to the writing beam to form the guide, the waveguide cross section is related to the shape of the focal volume. Typically, the focal intensity distribution of a beam focused into a planar glass substrate is several times larger in the axial direction than the transverse directions, potentially resulting in highly asymmetric waveguides.

To obtain an appropriate waveguide profile, one can employ multiple scans of the writing beam across the substrate, shifting the beam transversely between each pass [3]. This multiscan approach is well suited to systems where the fabrication beam has a pulse repetition frequency (PRF) $\gtrsim$100 kHz, enabling high scan speeds [4]. However, when applied to systems with a lower PRF of ~1 kHz, as considered here, fabrication times become impractically long. Therefore, low-PRF systems benefit greatly from shaping the writing beam to achieve the desired waveguide cross section in a single pass.

Several methods have been used in the past to shape the writing beam's focal volume. The simplest of these is to use a physical slit (PS) before the objective, effectively reducing the NA in one dimension [5]. Although simple to implement, a PS requires mechanical adjustment to change the beam focus during writing [6]. Alternatively, an astigmatic writing beam has been used by several groups, but adjusting the focal ellipticity requires adjusting bulk optics [7] or varying the distance between the objective and an adaptive optical element (AOE) [8]. AOEs have also been employed in low-PRF systems for other static beam-shaping methods [9] and in high-PRF writing to provide adaptability during the writing process [10,11].

In this Letter, we demonstrate the use of a spatial light modulator (SLM) for adaptive slit beam shaping in the creation of waveguides. The slit is mapped perfectly onto the pupil plane of the objective and can be easily adapted during fabrication to alter the ellipticity and orientation of the focus and vary the writing power. This enhanced control of the focal volume facilitates the fabrication of more elaborate structures.

Figure 1 shows a schematic of the experimental setup. The output of a regeneratively amplified titanium sapphire laser (Solstice, Newport/Spectra Physics, 100 fs, 1 kHz, 790 nm) was attenuated using a rotatable half-wave plate and a Glan-Laser polarizer. The expanded beam was directed onto a reflective LC phase-only SLM (Hamamatsu, X10468-02). The SLM and the pupil plane of the objective were mapped together by a $4f$ system, composed of two achromatic doublet lenses. A pinhole on an adjustable mount was inserted into the Fourier plane of the SLM. The beam fully illuminated the back aperture of a Zeiss Plan-Neofluar 20 × 0.5 NA objective, with internal correction for a 170 μm coverglass. The substrate was

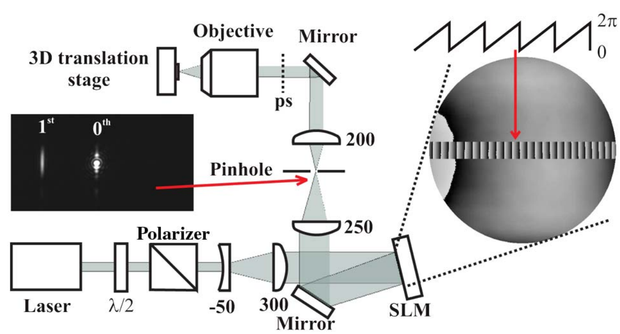

Fig. 1. (Color online) Experimental setup for the adaptive slit beam shaping. Inset, example SLM phase pattern.

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mounted on a three-axis translation stage (Aerotech, ABL10100 and ANT95-3-V).

The pinhole position was adjusted so that when a vertical grating of period 420 μm (21 pixels) was displayed on the SLM, the first diffracted order passed completely through the pinhole while the zeroth order was blocked. A blazed grating with a modulation depth (MD) of 2π rad ensured maximum diffraction of light into the first order. Only the light diffracted by the grating was imaged onto the objective pupil. Hence the shape of the grating region in the SLM defines the effective slit aperture in the pupil, as demonstrated by the phase pattern shown in the inset of Fig. 1. It is important that the writing focus is a diffracted order to avoid interference effects with light unmodulated by the SLM. In the phase pattern shown in Fig. 1, the grating is added to a background phase profile, which corrects any system aberrations including the initial flatness correction for the SLM. For comparison, guides were also fabricated with a PS of adjustable width placed a distance approximately 5 cm before the objective (the position marked "ps" in Fig. 1). In this configuration, the pinhole was removed and the SLM was set to produce a flat wavefront.

Waveguides were written using the SLM slit and the PS, for comparison, at a translation speed of 25 μm/s and a depth of 170 μm in fused silica (Schott Lithosil Q1). The slit width needed to obtain a symmetric waveguide cross section was estimated as 800 μm [5]. Using this slit width, uniform straight waveguides were written with a pulse energy of 0.14 μJ and the beam was passed five times along an identical trajectory.

The local structure of the fabricated features was characterized by third-harmonic generation (THG) microscopy [12]. The THG microscope is sensitive to nonuniformity in the third-order susceptibility [$\chi^{(3)}$], which typically coincides with regions where there is a change in the local refractive index. The nature of the THG process dictates that the signal is only generated at the focus of the excitation beam, allowing three-dimensional resolution of the waveguide structure [12]. THG images of the written waveguides are shown in Figs. 2(a) and 2(b), demonstrating the similarity of guides fabricated with the SLM slit and PS respectively. The THG images of the guide cross sections appear "hollow" as the signal decreases in regions where the refractive index is uniform, as expected in the center of the guide [12].

The written waveguides were coupled to single-mode fibers in V-groove arrays (VGAs), where index-matching gel was used to minimize Fresnel reflection losses. Near-field images of the waveguide modes were taken using an 825 nm source, microscope objective and CCD camera, with results shown in Figs. 2(c) and 2(d). An overlap integral, assuming a flat phase, between these mode images and similar ones from the VGA fibers then gives a lower bound on the coupling loss at each fiber–silica chip interface. By measuring the insertion loss of the fiber-coupled system, and knowing this bound on the coupling loss, an upper limit to the waveguide propagation loss can be obtained. Conversely, one can assume the propagation loss is zero and use the insertion loss to place an upper bound on the coupling loss achieved. These loss results for both the PS and SLM slit are summarized in Table 1 and demonstrate that SLM beam shaping produces low insertion-loss waveguides comparable to conventional beam-shaping methods [5].

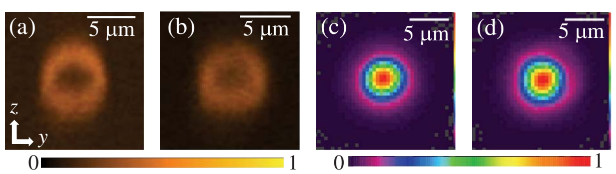

Fig. 2. (Color online) THG images showing cross sections through waveguides written in fused silica using (a) SLM and (b) PS beam shaping. (c), (d) Near-field profiles of the guided mode associated with (a) and (b) for an 825 nm source.

Having demonstrated the equivalence of our technique to existing methods, we explore its true strength as the ability to adaptively shape the writing beam. For example, writing low-loss curved waveguides will be important for more complex circuits. Ideally, the guide cross section should be uniform along this curve, which has recently been demonstrated using spatiotemporal focusing to create a spherical focal intensity distribution [13]. Alternatively, in our system, a rotation of the writing focal disk is required such that it is always orthogonal to the waveguide axis, demanding a rotation of the effective slit on the SLM. Figure 3(a) displays a differential interference contrast (DIC) image and THG cross sections of a (nonguiding) circular structure written in glass. A fixed slit on the SLM was used for fabrication of the right-hand side, while the slit orientation was varied with the sample translation direction during fabrication of the left-hand side. The difference is most striking when comparing points A and B. At point A, the slit is parallel to the translation, as desired, while at point B the slit is perpendicular. Thus a circular cross section is maintained at point A, while at point B it is strongly elliptical.

The flexibility of SLM slit beam writing also enables adjustment of the writing power. Reducing the SLM grating MD from 2π decreases the proportion of light directed to the first order, and hence the objective, in a controllable manner. This enables modulation of the writing intensity along the length of the guide, as shown in Fig. 3(b), which presents an alternate strategy for Bragg grating fabrication [14,15].

Finally, the slit width and length can be changed during fabrication to modify the major and minor axes of the resulting structure. For example, the slit width could be altered while keeping the slit length constant to produce guides of increasing ellipticity. Alternatively, the slit width and length could be simultaneously adjusted to produce a mode size converter. In parallel, the grating MD must be adjusted to maintain a constant fabrication fluence. Figure 3(c) demonstrates a structure where the cross section smoothly changes along the writing direction. Such a structure, if manufactured over a longer distance, could permit adiabatic conversion between

Table 1. Losses for Physical and SLM Slit Beam Shaping

	Coupling Loss (dB)	Propagation Loss (dB/cm)
PS	$0.2 < \alpha_{\mathrm{coupl}} < 0.8$	$\alpha_{\mathrm{prop}} < 0.4$
SLM	$0.2 < \alpha_{\mathrm{coupl}} < 0.5$	$\alpha_{\mathrm{prop}} < 0.4$

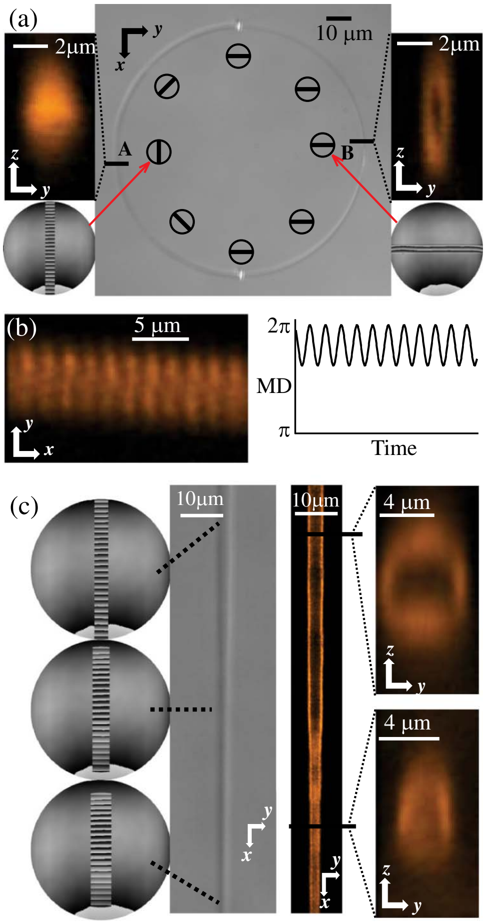

Fig. 3. (Color online) (a) DIC image of a circular structure, written with and without variation of the slit orientation during fabrication. The THG images show cross sections of the structure at points A and B, while the circular insets indicate the slit orientation at each point. (b) THG image of a structure written changing the MD of the grating on the SLM, thereby altering the writing beam intensity during fabrication. (c) DIC and THG images of a structure created with a smoothly varying cross section by modification of the slit dimensions during fabrication.

different mode states confined by waveguides of differing cross section, as has been successfully demonstrated using the multiscan technique in a high PRF system [4].

To conclude, we have demonstrated an SLM-based adaptive slit beam-shaping method for the fabrication of direct written waveguiding structures. Uniform single-mode waveguides are demonstrated with a propagation loss of <0.4 dB/cm, which is comparable to reported values for fused silica using static PS beam shaping [5]. Moreover, using this single component, it is possible to vary the writing intensity, the slit orientation and width, and the effective NA of the objective lens during fabrication. Such attributes will be useful in the fabrication of curved waveguides, Bragg grating waveguides, and mode converters.

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