Waveguides fabricated by femtosecond laser exploiting both depressed cladding and stress-induced guiding core

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Abstract: We report on the fabrication of stress-induced optical channel waveguides and waveguide splitters with laser-depressed cladding by femtosecond laser. The laser beam was focused into neodymium doped phosphate glass by an objective producing a destructive filament. By moving the sample along an enclosed routine in the horizontal plane followed by a minor descent less than the filament length in the vertical direction, a cylinder with rarified periphery and densified center region was fabricated. Lining up the segments in partially overlapping sequence enabled waveguiding therein. The refractive-index contrast, near- and far-field mode distribution and confocal microscope fluorescence image of the waveguide were obtained. 1-to-2, 1-to-3 and 1-to-4 splitters were also machined with adjustable splitting ratio. Compared with traditional femtosecond laser writing methods, waveguides prepared by this approach showed controllable mode conduction, strong field confinement, large numerical aperture, low propagation loss and intact core region.

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1. Introduction

Over the past decade, repeated attempts using femtosecond laser as a tool to inscribe optical waveguides into passive [1], active [2] and nonlinear [3] transparent dielectrics have accumulated fruitful results. Compared with planar lithography approaches, this method predominates itself in single-step 3D processing flexibility. So far, two basic fabrication manners, including type I laser-induced index enhancement with low energy pulses and type II double filaments sandwiched waveguides at higher energy [4], have emerged to achieve waveguiding in versatile materials with desirable optical quality. However, despite of their outstanding availability in particular applications, these methods contain irreconcilable contradictions. For example, type I method is only realizable for some materials since structure damage and density rarefaction upon laser irradiation prevail in most crystals, ceramics and some glasses [5–7], besides the laser modified region tends to show tailored nonlinear [8], electro-optical [9], fluorescent properties [7] or unstable thermal stability [10]; the double filaments waveguide not only inherently possesses one-dimensional compression that would introduce birefringence through piezo-optical effect [11], but also lacks 3D processing prospects.

As the most defining property of a waveguide, the refractive index profile directly determines the number of its supported transverse modes, the coupling efficiency to fiber and polarization-dependent guiding properties. Unfortunately, both the above mentioned approaches are vulnerable to insufficient control of the cross-sections. On the one hand, the astigmatic spot of the focused laser and self-focusing would produce tear-drop modified structure inside bulk materials [12], which is unfavorable for type I waveguides. Accordingly, elaborate beam shaping measures, including slit beam shaping [13] and multi-scan technique [14], have to be taken to alleviate the deformed spatial distribution of the refractive index. Even so, the profile is very tough to be modulated merely by adjusting focusing. On the other hand, type II double filaments waveguides are characterized by approximate step-index distribution in the direction vertical to writing laser beam while graded-index in the parallel direction. Reports of polarization selected guiding phenomena further prove the limitation of index profiling feasibility of the double filaments approach [5, 15–17].

Phosphate glass has been widely used in high power laser system and optical communications due to its high solubility of rare earth ions, low nonlinear coefficient and
excellent thermal-physical properties [15]. Previous reports have revealed that phosphate glass is intractable for type I method to write waveguides therein [6, 16], since the refractive index change of directly exposed region by femtosecond laser tends to be negative even under modest energy just like some crystalline materials behave and highly depends on glass composition.

Therefore, we demonstrated a 3D waveguide machining approach, which exploited both index-depressed cladding and stress-induced refractive index increase in the core to achieve light guiding in phosphate glass while preserved its initial merits. The cross-section of the fabricated waveguide was readily to be regulated and maintained high symmetry with the guiding region free from laser damage. The laser energy was chosen to be high enough to cause ablation filaments and consequently density rarefaction in laser exposed area. The outward expansion shock wave during the ultra-short and highly nonlinear process gave rise to stress-field gradient around the irradiated region, resulting in index-depressed or even void center surrounded by a compressed and index-enhanced surrounding area due to piezo-optical effect. Encompassing squeezed area with laser damaged shell would likely result in marked refractive index contrast capable of guiding light.

Similar to the double filaments procedure, current method is applicable to materials that are formidable for the type I method in principle. However, unlike double filaments practice, which adopts transverse writing scheme, we employ longitudinal scheme that the resulted waveguide is parallel to the writing laser beam. Only with longitudinal scheme, the stressed center column, which is encompassed by laser-induced cylindrical shell, can be stacked along certain routine with well defined cross-section. As a result, the waveguide consists of dozens of sequentially overlapping tubular segments produced by scanning the vertically elongated laser spot in horizontal direction along an enclosed path.

In contrast to traditional waveguide machining approaches, the transverse mode distribution can be tailored by changing the enclosed routine that the stage moved along. The independence of cross-section controlling from refractive index engineering ensures more freedom of processing. In principle, the refractive index contrast between core and cladding can be greatly increased that permits larger numerical aperture and thus more powerful coupling capability, since the cladding arising from laser damage can be very rarified or even void. Moreover, the additional cladding exerts tighter mode confinement, which enables more localized evanescent wave, thereby reduces crosstalk between adjacent channels and is a valuable feature for fabrication of compact waveguide devices. The central core is merely subject to mechanic pressure without substantial structure damage and re-arrangement, therefore it preserves faithful optical properties to the substrate, including low propagation loss, similar luminescent spectrum and nonlinear coefficients.

2. Experimental details

The sample, an $1 \times 1 \times 1$ cm$^3$ Nd$^{3+}$ doped phosphate glass cube (N31) [17] from Shanghai Institute of Optics and Fine Mechanics, was mounted on a 3D translation stage (PriorScan), with inscribing laser incident from its top surface to the bottom. The stage moved along an enclosed route including square, polygon and circle in the horizontal plane, followed by a minor descent of 20-40 $\mu$m in the vertical direction. The stage moved at a speed of 1 mm/s and 10 mm/s in the horizontal and vertical direction, respectively. For 3D processing, the movement of the stage was controlled by a computer and worked along with a mechanical shutter. The sample was irradiated by a regeneratively amplified femtosecond Ti: sapphire laser (Spectra-Physics Ltd.), which supplied 1 kHz, 120 fs, mode-locked laser pulses centered at a wavelength of about 790 nm. The polarization of the laser beam was adjusted to be circular with a $\lambda/4$ wave plate to avoid any non-reciprocal exciting possibility [18]. The power of the laser was tuned with a $\lambda/2$ wave plate and a Glan-Thompson polarizer. The laser pulses with 90 mW average power were focused by a $10 \times$ objective with a numerical aperture of 0.3 and working distance of 17.3 mm into the substrate glass. The laser produced an ablation line about 200 $\mu$m in length. The schematic diagram of the experimental setup is shown in Fig. 1. The arrow labels in the figure illustrate the motion sequence of the stage.
Fig. 1. Schematic diagram of the experimental setup.

For waveguide characterization, He-Ne laser was used for end-fire coupling into the waveguides. Both the output near- and far-field mode of the waveguide was measured. We employed Fabry-Perot resonance method [19] to measure the waveguide propagation loss, during which the sample was heated to about 350 °C and the intensity curve of the transmitted light versus temperature was recorded. The refractive index contrast of the waveguide was estimated by its numeric aperture (NA) and far-field divergent angle. We also simulated the output mode distribution using commercial software BeamPROP© based on the finite difference beam propagation method assuming a step-index profile. For better understanding of the waveguide formation, we fabricated a type II waveguide and examined its micrograph under white light illumination. We also took the confocal fluorescence microscope images of the waveguide cross-section using a confocal laser scanner fluorescence system (Thorlabs).

To further demonstrate the 3D processing capability of current waveguide machining approach, we fabricate 1-to-2, 1-to-3 and 1-to-4 splitters with fan-out arms tilting against the input arm. Each branch was comprised of concentrically stacked segments in entrance and exit port and gradually centrifugal cascaded segments in central part. For equal splitting of energy among output ports, arms were located following wheel hub geometry with input port at the nave. Their near-field output distribution from the splitters was measured.

3. Results and discussion

Waveguide cross-sections in shape of triangle, square, polygon and circle with center-to-vertex distance (or radius for circle) of 18 μm and cladding thickness of about 6 μm are shown in Fig. 2. Depending on cross-section geometry, the feature size of center region varies from 10 to 20 μm. The guiding property (multi- or mono-mode) can be accommodated by adjusting cross-section size and writing laser energy. Since damaged tracks produced by larger energy pulses are usually accompanied by more powerful laser driven micro-explosion and more strained neighboring periphery. The minimum core dimension is limited by the precision of the positioning system and the diameter of the focused beam. Thanks to the multiple photon absorption of the femtosecond laser, the incident femtosecond laser penetrates the sample without remarkable loss. The spherical aberration introduced at the phase interface can be relieved using loose focusing. For waveguides as long as 1 cm in our experiment, an objective with long working distance has to be used, whereas shorter
waveguides permit tighter focusing and thus more slender and better located filaments. Since multimode waveguides are much easier to machine for current approach, we adopted a cross-section size so that all waveguides operated under single mode condition, thereby exporting similar mode profile. Therefore, we only present results of the square waveguide for convenience and clarity.

![Fig. 2. Resulted waveguides with cross-section in shape of (a) triangle, (b) square, (c) pentagon, (d) hexagon and (e) circle.](image)

As can be seen from Fig. 2, the laser ablated cladding turns to be dark under optical microscope inspection, which can be ascribed to the decrease of light transmission in the rarified or even void structure in the cladding upon laser irradiation [20].

Multimode He-Ne laser was coupled into the waveguide by a 20 × objective. The numeric aperture (NA) of the waveguide, which described its maximum half angle for light collecting, was estimated by measuring the maximum incidence angle without substantial output loss and far-field divergent angle. The former and the latter measurement gave a result of 0.022 and 0.017, respectively. We take the mean value of 0.02 for estimation. As a result, the refractive index increase was calculated to be $1.3 \times 10^{-4}$ assuming step-index profile according to the following equation:

$$
\Delta n = n_{\text{core}} - n_{\text{cladding}} = \frac{NA^2}{2n},
$$

where the substrate index $n$ equals to 1.53. The normalized waveguide parameter $V$ was calculated to be 1.99 (<2.405) for 20 μm diameter, suggesting single mode operation for He-Ne laser. The propagation loss of the waveguide was measured to be 0.5 dB/cm using the Fabry-Perot method. Degraded performance of the waveguides was not detected after repeated heating processes during loss measurement.

![Fig. 3. Measured near-field profile for horizontally and vertically polarized He-Ne laser.](image)

The near-field profile of guided He-Ne beam was obtained with an objective and a CCD detector. Horizontally and vertically polarized light yielded similar near-field distribution ($HE_{11}$ and $HE'_{11}$), as shown in Fig. 3. The simulated transverse mode distribution assuming a step-index profile is show in Fig. 4. Due to mono-mode propagation, the output is nearly circularly Gaussian distribution. The effective refractive index of the waveguide is shown on the title. The simulated mode was not subject to polarization since it adopted an isotropic core model. Compared with the simulated mode distribution, the slightly asymmetric distribution of measured profile was probably caused by irregular scattering on the guide boundary and non-perfect step-index profile.
To better understand the role of laser affected and its surrounding area for waveguiding, we employed multi-scan technique [21] to write a rectangular cylinder in Nd$^{3+}$ doped phosphate glass using the same femtosecond laser as above. In order to achieve that, the stage moved in line direction in the horizontal plane so that the filament was scanned across the sample producing a laser damaged sheet. This step was repeated for several times with the resulted sheets aligned side by side. Since laser induced structure is largely elongated vertically, the outward expelling force is more powerful in the horizontal plane than in the vertical.

Figure 5 shows the output end facet of laser modified structure with white light illumination from the other side. The laser scanned region turned to be pitch-dark sandwiched by bright regions that appeared to function as waveguides with their dividing boundary remained unambiguous and sharp. It can be inferred that the laser damaged area acted as a steep and high barrier to effectively curb the light propagation and \textit{in situ} laser depression of index was present, for which the laser damaged tubular shell could be utilized as index depressed cladding in current method. However, index enhancement in the neighboring area cannot be ruled out since unilateral barrier cannot support guiding, which can be illustrated by the comparison of the upper and lower region with the right and left region, since only the more compressed latter region can support light guiding. It seemed that the comet-like white light profile plunging towards the central region was outlining or mapping the refractive index increase in the neighboring area, which was consistent with the stress field distribution upon shock impact. For current method, stress field enveloping the damage tube was constructively balanced to be nearly uniform distribution in central core capable for light guiding and gradually faded in the outside. Thus it can be seen that the laser depressed tubular shell of waveguides functioned as cladding and the encompassed and compressed column served as guiding core.
The confocal fluorescence microscope images of the waveguide cross-section were obtained using an excitation wavelength of 405, 488, 532 and 642 nm, respectively. The 405 nm excitation laser induced the most distinct red fluorescence in laser modified region as shown in Fig. 6. As excitation wavelength increased, the fluorescent signal weakened. Color center formation has been considered to be the reason for fluorescence and index depression [22]. The core region and the substrate didn’t emit obvious fluorescence under these excitation wavelengths, which proved, at least partially, the integrity of core area in terms of fluorescence.

The micrograph of a 1-to-2 splitter is illustrated in Fig. 7, with a center-to-center separation of 600 μm between output ends and a tilting arm length of 8 mm, corresponding to a full branching angle of 4 degrees. Compared the total output with that of single waveguide, the 1-to-2, 1-to-3 and 1-to-4 splitter suffered additional loss of 1 dB, 1.5 dB and 2.3 dB, respectively. Branching point surely contributed to the additional loss as visible stray light appeared there during experiment, which was probably correlated with bending loss, cross between cladding and core and positioning errors.

The output distribution from the splitters is shown in Fig. 8. The splitting ratio was determined by the incident angle as well as the branching configuration (splitting angle, bending curvature and cross-section profile). Fine tuning of the incident angle was an efficient way to adjust the splitting ratio among output ports. The Gaussian output profile was deteriorated with stray light between peaks. More splitting branches can be fabricated following the similar procedure.

**4. Summary**

In summary, mono-mode waveguides with controllable cross-section were longitudinally written in phosphate glass by femtosecond laser with the laser modified shell acting as cladding and the encompassed and compressed column as core. The propagation loss of the
waveguide was measured to be 0.5 dB/cm with Fabry-Perot method. The refractive index increase of the core region in respect to the cladding was estimated to be $1.3 \times 10^{-4}$ according to the measured numeric aperture. The confocal fluorescence microscopy of the waveguide cross-section revealed that color center formed in the laser-affected area but the core region remained immune. The similar near-field output distribution of waveguide was obtained for orthogonally polarized input light, suggesting symmetric index profile. 1-to-2, 1-to-3 and 1-to-4 splitters were also fabricated with the adjustable splitting ratio, indicating the prospects of current approach for fabrication of complex optical functional devices with high packaging density.

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