Transmittance performance of 90°-bend optical waveguides fabricated in fused silica by femtosecond laser inscription

JING LV,1,2 JING BAI,2 KAIMING ZHOU,2,3 XUESONG MEI,1 KEDIAN WANG,1 MING LI,1,2 AND GUANGHUA CHENG,2,*

1State Key Laboratory for Manufacturing Systems Engineering, School of Mechanical Engineering, Shaanxi Key Laboratory of Intelligent Robotics, Xi'an Jiaotong University, Xi'an 710049, China
2State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China
3Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, UK
*Corresponding author: gcheng@opt.ac.cn

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The L-shape waveguide was written in fused silica using femtosecond laser with beam shaping. The guiding structure supports good light turning, 0.88 dB/turn was achieved at the silica-air interface. By using finite-different time-domain (FDTD) method, the turn loss due to the turning structure and refractive index of the L-shape waveguide has been simulated. The results show that the proposed method has unprecedented flexibility in fabricating 90°-bend waveguide. © 2017 Optical Society of America

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Nowadays, the direct femtosecond-laser writing technique, which is effectively three-dimensional (3D) micromachining method in transparent materials, has been regarded as a powerful tool in the field of integrated photonic [1,2]. The trend of miniaturization of photonic devices has revolutionized the deployment regimes of most optical devices. As the basic optical components, waveguides with bending structures are expected to shrink the device size and have significant applications. For instance, 90°-bend waveguides have been encouraged to use for deformed ring cavity [3] and optical interconnection [4]. However, there remains challenging on the end product of 90°-bend waveguides, especially femtosecond-laser-written waveguides. Bend waveguides made by femtosecond laser are restricted in size due to the weaker confinement of guided light caused by the low refractive index contrast (on the order of 10^{-2} - 10^{-4}[5-7]). Recently, though s-curve waveguides with the radii of more than 10 mm were fabricated and reported [8], no bending efficiency mentioned. For low-index waveguides, waveguide loss increases exponentially inversely with the bend radius [9]. To overcome these problems, the method of internal total reflection (ITR) on an interface is proposed to allow a drastic reduction in the bending size and ensure low turn loss. However, etching the air trench as a mirror is a complex and expansive process [10]. Thus, we attempt to directly utilize the refractive index contrast between the substrate with special shape and air media to achieve light turning.

In this letter, we report on for the first time to the best of our knowledge the fabrication of femtosecond-laser-written 90°-bend, namely, L-shape waveguides in fused silica based on the ITR principle at silica-air interface. Applying FDTD method to several two-dimensional (2D) bend structures, we demonstrate theoretically the feasibility to write bend waveguides by femtosecond laser inscription technique, thus showing an intriguing potential as compact integrated optical devices such as splitters, optic gyro, and so on. The waveguides were inscribed into the fused silica glass (Corning 7980-5F) which was a right prism with a height of 5 mm and a base of isoceles right triangle whose leg length was 10 mm. The experiments were performed using a Ti:Sapphire regenerative amplifier femtosecond laser system (Phidia, Uptek Solutions) emitting 50 kHz repetition rate Gaussian laser pulses of pulse width τp=150 fs, centred at 780 nm. The pulse energy was attenuated by a half-wave plate in front of a polarizer. The new combination of a slit [11] and couple of cylindrical lenses [12] was used for beam shaping to produce waveguides with circular cross sections. Because the laser power is severally attenuated if a slit is only used, even though it allows free adjustment to the required beam shape; however, the cross section of the waveguide cannot be optimized when the special cylindrical lenses are used alone without too much energy loss. Therefore, this combination can flexibly adjust the cross section of the waveguide on the premise of low-loss incident laser. The samples were moven transverse to the incident laser beam by a computer-controlled 3D translation stage (ANT130, Aerotech) which can provide deep sub-micron scale precision over the cubic centimeter scale workspace. The combination of a positive optical phase-contrast microscopy
(PCM) system and a charge coupled device (CCD) connected to a computer was employed to reveal the morphological characteristics of structures in real time. The schematic of experimental setup is shown in Fig. 1.

![Schematic of the experimental setup.](image)

Fig. 1. Schematic of the experimental setup.

The single-scan waveguide writing was investigated for the experimental setup. The waveguide performances depend sensitively on materials characteristics and laser processing parameters [13]. Therefore, the pulse train was focused inside the glass sample to a depth of 150 μm below the polished surface using a 20× microscope objective with a numerical aperture of NA=0.42. Cylindrical lenses pair with the focus of 150 mm and 50 mm were used. A slit width of 500 μm was set in the following experimental works. In order to obtain the optimum parameters for this material, a range of pulse energy from 1.0 to 2.0 μJ and writing velocity from 25 to 500 μm/s were investigated. Assisted by the 3D stage, the intersecting point of the two waveguides (L-shape waveguide) which are perpendicular to each other was placed on the hypotenuse of glass cross-section. This configuration achieved total internal reflection so that the beam can be easily bended 90°. Waveguides were illuminated using a fiber laser of 976 nm. The near field of the guided modes was imaged with a 5× microscope objective on the sensor of a CCD camera.

Propagation losses were measured for all the fabricated waveguides by coupling fiber laser to the waveguides with pitch and yaw adjustment carefully. The output power after propagation through the waveguide with different lengths was measured based on the cut-off method. It was found that for single-scan waveguides, in general, the propagation loss decreased first and then increased as both the velocity and pulse energy increased. As a result, the optimal single-scan waveguide with the lowest propagation loss about 0.6 dB/cm at 976 nm was fabricated using a translation velocity of 100 μm/s and a pulse energy of 1.6 μJ. It is important to note that the pulse energy was measured before focusing. The mode field of this waveguide was symmetrical with a horizontal diameter (full width at half maximum) of 7.5 μm and a vertical diameter of 7.7 μm, as shown in Fig. 2. The propagation loss was 2.6 dB/cm at a pulse energy of 2.0 μJ and a velocity of 100 μm/s. Results indicate that the waveguide with good performance can be fabricated only within a narrow energy window. For a given pulse energy, as the scanning velocity increased, the refractive index contrast in irradiated region became smaller due to the decrease of accumulated energy per unit area.

![Near-field mode image of the waveguide written under optimal conditions at 976 nm.](image)

Fig. 2. Near-field mode image of the waveguide written under optimal conditions at 976 nm.

Next, we employed the optimized process parameters to fabricate L-shape waveguides. It is worthy of noting that the writing direction must be consistent with the axes of the slit and cylindrical lenses. Therefore the slit and cylindrical lenses had to be rotated by 90° for fabrication of the second waveguide which is perpendicular to the first one. Hypotenuse of glass cross-section, where the two arms of the L-shape waveguide intersect, was polished as aftermath-treatment to improve the interface smoothness. Characterizations of the L-shape waveguide are shown in Fig. 3. The near-field mode was remarkably similar to the straight waveguide’s (horizontal diameter of 7.3 μm and a vertical diameter of 7.9 μm), unlike a shift of the mode profile observed in Ref. 8, where higher order modes were excited especially for the waveguides with R ≤ 60 nm. A larger refractive index change at the inner curve of the outer track resulted in the observed mode shift as well as the deformation [8]. This phenomenon becomes obvious with smaller radius and also be observed in bent fibers [14].

![Fig. 3. (a) The definition of the parameter ΔW in L-shape waveguide structure; (b) the morphology of L-shape waveguide captured by PCM; (c) near-field distribution of guided laser at 976 nm.](image)

Fig. 3(a) shows the schematic diagram of the experimentally established structure. The refractive index of glass substrate $n_g$ is 1.458 at the wavelength $\lambda=976$ nm. The maximum refractive index change induced by femtosecond laser system is on the order of $10^{-3} - 10^{-4}$. Therefore, it is considered to be a single-mode waveguide. The refractive index contrast is gradual. Because the beam spot intensity is Gaussian distribution. The excitation of the fundamental mode of light intensity for weak-guide optical waveguides can be described by scalar wave equation [15].
\[ \nabla^2 \psi(x, y) + \left[ k^2 n^2(x, y) - \beta^2 \right] \psi(x, y) = 0 \quad (1) \]

Where \( \psi(x, y) \) is electric field intensity which is proportional to the square root of light intensity \( I(x, y) \); \( \beta \) is the propagation constant; \( k \) is the wavenumber which equals \( 2\pi/\lambda \), and \( n(x, y) \) represents the refractive index of the waveguide. We deduce the equation to calculate the refractive index change \( \Delta n(x, y) \) of laser-irradiated areas,

\[ \Delta n(x, y) = -\frac{\lambda^2}{16\pi^2 n_y I} \left[ \nabla^2 I - \frac{1}{2f} (\nabla I)^2 \right] \quad (2) \]

It should be noted that the effective index used in the formula derivation is approximately equal to \( n_e \). The Gaussian fitting of the calculated value of the refractive index contrast \( \Delta n(x, y) \) of single axis was used in numeric calculation.

A 2D waveguide model with perfectly matched layer condition is applied. The source with TE fundamental mode is injected into the input waveguide. Due to dramatic change of the electromagnetic field in the turn region, it needs to improve the accuracy of simulation using the thinning grids method. Maybe some higher-order modes would exist in the output field of L-shape waveguides, but can be theoretically consumed up if the length of the waveguide is infinite. Therefore, the bend efficiency is lower than a power ratio of the output to the input. We compute the fraction of the power from mode-in that can propagate in mode-out based on the overlap method between the output field and input field.

In this section, we evaluate the impact of \( \Delta w \) in the waveguide structure, which is determined by the intersecting position as unclearly shown in Fig. 3(b), to the bend performance and the results are in Fig. 4(a). The field distribution from the output waveguide has almost no changes compared to that of the input waveguide as displayed in Fig. 4(b). The L-shape waveguide has great optical performance without obvious mode shift even though its size is on the order of microns. The maximum bending efficiency is \( \sim 97.3\% \) at \( \Delta w = 8.29 \mu m \), which can compensate the Goos-Hanchen shift at the interface. It is worth noting that bending efficiency is larger than 80.0% when \( \Delta w \) is in the range from 6.11 to 10.40 \( \mu m \), i.e. \( \sim 2 \mu m \) from the optimized position. Bending efficiency becomes \( \sim 50.0\% \) when \( \Delta w \) is 12.39 \( \mu m \). The lower bending efficiency of 81.6% in the experiment than the global maximum point of \( \Delta w = 8.29 \mu m \) with index contrast \( \Delta n_1 \).

The two waveguides are not completely intersected taken into consideration the Goos-Hanchen shift in our case. The lengths of their extensions (\( \Delta H \) in Fig. 5(a)) range from 0 to 150 \( \mu m \) herein. Fig. 5(b) shows the dependence of the bending efficiency on \( \Delta H \). Initially, small \( \Delta H \) (\( \Delta H \) for waveguides with index contrast of \( \Delta n_1, \Delta n_2 \) and \( \Delta n_3 \) are \( 30, 50 \) and 20 \( \mu m \), respectively) has little impact on the bending efficiency. As the extended line increases, the bending efficiency decreases monotonically. Declining is accelerated when index contrast increases. During the length of 150 \( \mu m \), the bending efficiencies are \( \sim 93\% \) and 66\% for smaller and larger index contrasts, respectively. These phenomena can be explained as follows. The emergence of the incident light from the optical waveguide has Gaussian divergent beam, which beam waist is at its port. Using \( NA = (n_1^2-n_2^2)^{1/2} \), the numerical aperture can be estimated with knowledge of the refractive index of the waveguide region \( n_1 \) and the unmodified glass \( n_2 \). The bigger refractive index of the waveguide core causes higher NA and smaller mode field diameter. Rayleigh length is proportional to the square of the beam waist radius. Therefore, the flattening part of the efficiency curve in the early stage roots in the distribution of modal field out from the waveguide. The light from the waveguide with smaller index contrast has less divergence angle and less loss. It is obvious that the influence of \( \Delta H \) on bending efficiency is less than the parameter of \( \Delta w \), because of dramatic change of the electromagnetic field and its strong intensity distribution in the turn region. Femtosecond laser inscription is suitable for achieving higher bending efficiency for the L-shape waveguide structure. Because the index contrast induced by femtosecond laser is small and controlled with process parameters.
In summary, the straight single-scan waveguides and L-shape waveguides were fabricated in fused silica by the shaped femtosecond laser beam. The good mode-field distribution and low transmission loss were obtained. The guiding structures support good light confinement with a translation velocity of 100 μm/s and a pulse energy of 1.6 μJ, yielding propagation loss of ~0.6 dB/cm at 976 nm. Bending efficiency of L-shape waveguide was measured to be ~81.6%. Using 2D waveguide models, the bending efficiency is strongly dependent on device geometry, especially the intersecting position. That is, ±2 μm deviating from the optimized position can lead to ~20% reduction in bending efficiency. The acceptable range of the extensions is within 30 μm. It is feasible for femtosecond laser precision machining to satisfy the demand of micro-meter accuracy. Our novel approach will facilitate the integration of high-density optical circuits. Future effort will be writing mirror inside materials so that beam turning is no longer dependent on the shape of samples and can be at a more arbitrary position.

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