

On-chip beam rotators, polarizers and adiabatic mode converters through low-loss waveguides with variable cross-sections

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Abstract

Photonics integrated circuitry would benefit considerably from the ability to arbitrarily control waveguide cross-sections with high precision and low loss, in order to provide more degrees of freedom in manipulating propagating light. Here, we report on a new optical-fibres-compatible glass waveguide by femtosecond laser writing, namely spherical phase induced multi-core waveguide (SPIM-WG), which addresses this challenging task with three dimensional on-chip light control. Precise deformation of cross-sections is achievable along the waveguide, with shapes and sizes finely controllable of high resolution in both horizontal and vertical transversal directions. We observed that these waveguides have high refractive index contrast of 0.017, low propagation loss of 0.14 dB/cm, and very low coupling loss of 0.19 dB coupled from a single mode fibre. SPIM-WG devices were easily fabricated that were able to perform on-chip beam rotation through varying angles, or manipulate polarization state of propagating light for target wavelengths. We also demonstrated SPIM-WG mode converters that provide arbitrary adiabatic mode conversion with high efficiency between symmetric and asymmetric non-uniform modes; examples include circular, elliptical modes and asymmetric modes from ppKTP waveguides which are generally applied in frequency conversion and quantum light sources. Created inside optical glass, these waveguides and devices have the capability to operate across ultra-broad bands from visible to infrared wavelengths. The compatibility with optical fibre also paves the way toward packaged photonic integrated circuitry, which usually needs input and output fibre connections.

Introduction

Low-loss integrated optical waveguides have indispensable roles in wide range of significant modern technologies, such as integrated photonic chips¹⁻³, quantum applications⁴⁻⁹, and topological photonics¹⁰⁻¹⁴. In recent years, these research areas have underpinned some of the most remarkable advances in modern applied physics. The waveguides produced with silica-on-silicon technology (silica waveguides on a silicon chip, or SoS) hold significant future promises for both high-performance photonic chips² and also quantum computing^{4,6-9}. Thousands of integrated components can be fabricated on a single wafer using a similar technological process as employed in industrial micro-electronic chips, with availability to robustly control the phase of single element rendering the chip re-programmable. In a complementary manner, waveguide created by femtosecond laser (fs-laser) writing^{15,16} has found its unique position

for producing rapid prototypes and three-dimensional (3D) waveguide arrays. Laser written waveguides have been demonstrated to have significant potential in areas of such as topological photonics^{10-14,17}, as well as quantum technology applications^{7,18-23}.

For most current applications, based simply on light guiding or cross-coupling, the waveguide transection remains fixed along the propagation direction, primarily because it is very difficult to find an existing fabrication method that has the ability to arbitrarily transform cross-section shape and size along a waveguide with high resolution while maintaining low loss. Silica-on-silicon waveguides are normally fabricated through etching on a two-dimensional (2D) plane, where it is non-trivial to transform the transection in 3D. Precise cross-section deformation is also an open challenge for low loss fs-laser written waveguides in glass. Existing reported flexible cross-section transformation in glass substrate waveguides employed the powerful “classic multi-scan” technique²⁴⁻²⁶, where fine control is possible in one transversal direction with resolution of $\sim 0.4 \mu\text{m}$, but accompanied by a typical coarse resolution, for an example, $8 \mu\text{m}$ in the other transversal direction. The coarse resolution lies along the direction of the fs-laser propagation, where the extended focal volume creates a complicated refractive index (RI) structure in the glass with both positive and negative regions of index change, making it difficult to build precisely controlled RI structures along this direction from a simple stack of multi-scans when they are spatially too close with each other. In comparison, a 3D stack of closely spaced multi-scans is much easier in some other materials where the fs-laser helps to create a much simpler positive refractive index region²⁷. However, since the waveguide has to be created in material other than optical glass, the propagation loss is typically increased. For example, in recent works demonstrating waveguides by two-photon polymerisation of SU-8 resin, various complicated cross-section structures²⁸ could be produced and transformed along beam propagation direction²⁹. An exceptional high polarization conversion efficiency of $>90\%$ was achieved by twisting the shape of SU-8 resin waveguides, while a high propagation loss of 7.5 dB/cm was also observed.

Many applications in integrated optics would benefit from waveguides whose transection could be arbitrarily transformed in order to have much more versatile light control. The polarization state of light carries important information in most photonic chip-based applications, such as polarization encoding for quantum information³⁰, polarization division multiplexing in optical communications³¹, and polarization sensors³². Though implementing polarization manipulation in free space is easy, arbitrary on-chip polarization control using integrated waveguides remains an open challenge. Existing on-chip polarization rotation technologies are mostly based on etching and deposition³³⁻³⁹, with high performance devices operating with a bandwidth up to $100 - 200 \text{ nm}$. Created on a planar layer, the devices sometimes require high design precision and accuracy in fabrication. On the other hand, by using femtosecond laser writing, it was reported that the waveguide’s birefringence could be finely tuned in fused silica^{40,41}. Osellame’s group reported excellent work with polarization conversion in glass to create rotated waveplates in optical waveguides⁴². By controllably rotating the birefringence axis, the waveguides were demonstrated for quantum state tomography.

Mode conversion is another well-known concept in integrated photonics, typically used to transform the size of the guided mode to suit different parts of the device via tapered waveguides⁴³⁻⁴⁶. For efficient mode conversion, it is desired that the transition is gradual such that the process is adiabatic. Existing mode converters are mostly based on similar etching and deposition technique, seeing limitations in operating bandwidth, spatial dimension and fabrication complexity. There have been reports in femtosecond laser written waveguides, where the power of the fabrication laser was continuously tuned to vary the size of the guided mode^{47,48}. Conversion between different symmetric guided LP_{0x} modes is also possible through more complex structuring⁴⁹. However, there is still lack of flexible mode shape and precise size control, and there is yet to be a solution to address mode conversion between the asymmetric guided modes with high precision.

Considering these limitations, it is beneficial to find a universal solution to address these outstanding challenges in waveguide-based integrated photonic circuits. In this paper, we firstly demonstrate the concept of spherical phase induced multi-core waveguides (SPIM-WGs), which enables glass waveguides with high refractive index contrast and high precision in arbitrary 3D cross-section shape control. We then characterize loss properties with varying waveguide parameters and demonstrate arbitrary on-chip beam rotation. Following these, we present SPIM-WGs’ capability in

manipulating the polarization state of light. Finally, we demonstrate high efficiency arbitrary adiabatic mode conversions including asymmetric modes together with advanced mode matching.

Results

Spherical Phase Induced Multi-Core Waveguides (SPIM-WGs)

Historically, fs-laser written waveguides operate with two different fabrication regimes: non-heating regime with low laser repetition rate (< 10 kHz); and heating regime with high laser repetition rate (> 500 kHz). These two fabrication regimes involve different processes to create the RI profile in glass^{15,50} (Supplementary Note 1). We develop our technology based on the latter, which has much higher fabrication efficiency, reducing processing time from several hours to 1-2 minutes. Higher refractive index contrast (refractive index difference between waveguide core and substrate) can also be obtained which helps in our applications.

In the rest of this paper, we refer to a common Cartesian coordinate system (Fig. 1 (a) and inset of Fig. 2 (a)) in which the waveguide was written along the y direction. The z axis (vertical direction) points along the optical axis of the laser-writing system. The x axis (horizontal direction) is perpendicular to the y and z axes. As briefly mentioned above, the “classic multi-scan” technique^{24–26} is a powerful method for creating rectangular shape waveguides in glass. The fabrication laser focus is scanned multiple times through the glass substrate with a x axis separation of about $0.4 \mu\text{m}$ between each pass to build up the waveguide RI profile. As shown in Fig. 1 (a), in the vertical z axis dimension, control over the cross-section is challenging since the z axis separation is limited (to $\sim 8 \mu\text{m}$, depending on objective NA). To enable fine control of sizes, and ultimately achieve arbitrary deformation of cross-section, it is essential to find a solution to reduce the step size along the z direction, without affecting the uniformity of overall refractive index profile.

One might test the idea, illustrated in Fig. 1 (b)-Scheme I, where all laser spot scans closely stack together both along x and along z . However, as shown by the LED-illuminated transmission microscope image in Scheme I, the fabricated feature includes two large dark areas surrounded by bright regions, indicating a complicated structure of both positive and negative refractive index, which is most likely due to local thermal accumulation during processing^{15,50}. During heating regime fs-laser fabrication, the high repetition rate laser creates a localized region of high intensity plasma. If the multiple scans are chosen to be too close with each other (e.g., $0.4 \mu\text{m}$ in both the x and z directions), the high intensity plasma generated by a newer scan melts the nearby feature created by existing scans, producing complicated structures. As shown in Fig. 1 (b)-Scheme I, when the waveguide is tested with laser transmission, a non-uniform multi-mode profile was observed.

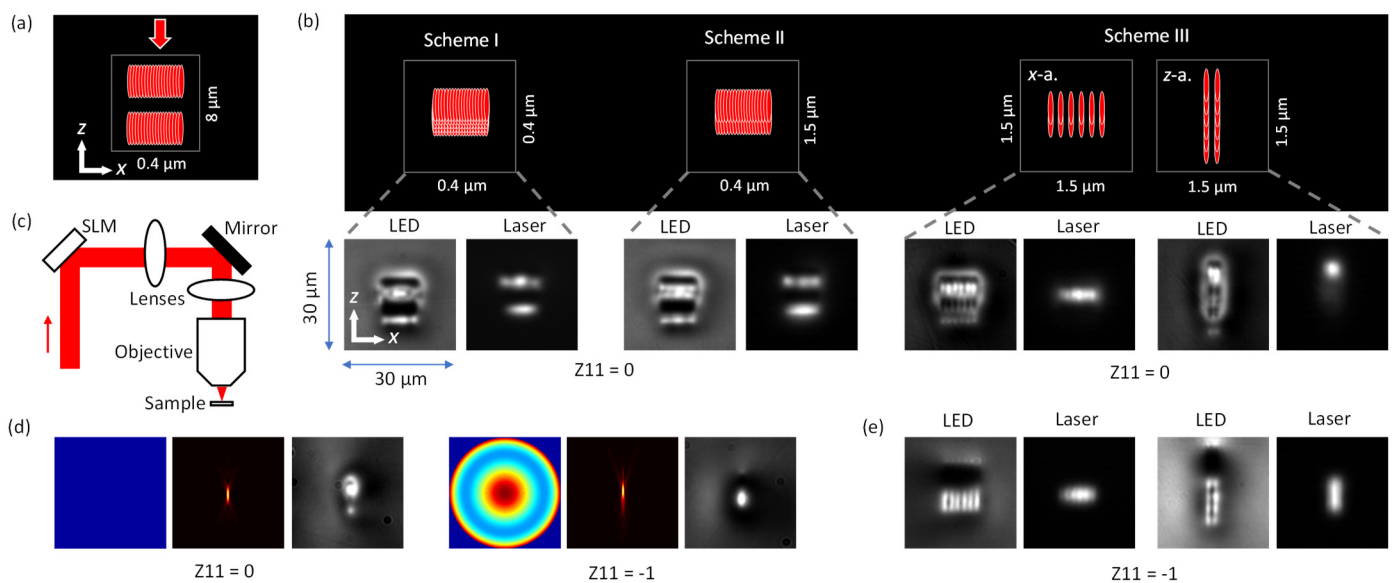


Figure 1. **Enabling fine control of waveguide cross-section shape and sizes by SPIM-WGs.** All images (LED, laser, simulation) excluding phase pattern have the same frame size of $30 \times 30 \mu\text{m}$. (a) Classic multi-scan laser fabrication technique has a large z step resolution ($8 \mu\text{m}$ in this case). The red arrow marks laser propagation direction. Distances of core spacing along x axis (Δx), and z

axis (Δz) are presented beside the diagram. (b) Three proposed new fabrication schemes and the corresponding fabricated waveguides. In experimental demonstrations, Scheme I had $\Delta x = \Delta z = 0.4 \mu\text{m}$, with 20 horizontal and 6 vertical scans. Scheme II had $\Delta x = 0.4 \mu\text{m}$, $\Delta z = 1.5 \mu\text{m}$, with 20 horizontal and 2 vertical scans. Scheme III had $\Delta x = \Delta z = 1.5 \mu\text{m}$, with 6 horizontal and 2 vertical scans for the *x-aligned* rectangular waveguide, 2 horizontal and 6 vertical scans for the *z-aligned* rectangular waveguide. Labels: “LED” – images obtained with LED illuminated microscope; “Laser” – 785 nm laser transmission mode profile imaged at the waveguide output facet; “Z11” – manually induced primary spherical aberration⁵¹ (corresponding to Zernike mode 11 phase aberration) applied to spatial light modulator (SLM). “*x-a.*” - *x-aligned* rectangular waveguides. “*z-a.*” - *z-aligned* rectangular waveguides. (c) Simplified diagram of laser fabrication system with phase control. SLM is imaged to objective pupil with a 4f telescope system. SLM: spatial light modulator; Objective: objective lens. (d) Manually induced additional spherical beam shaping phases to SLM and their effects on laser focus and single scan waveguides. Note that these phases are not used to correct spherical aberration caused by refractive index mismatch between air and sample, which was pre-corrected in all our experiments (please refer to “Methods- Phase pattern for SLM” section for details). Left: beam shaping phase applied to SLM in addition to aberration corrections. Middle: simulated focal intensity distribution (enlarged images in Supplementary Fig. S1). Right: LED illuminated microscopic image of single scan waveguides. (e) Scheme III fabrication with negative spherical beam shaping phase (Z11 = -1), demonstrating significant improvement of cross-section control.

Observed from a single laser scan in Fig. 1 (d), we noticed that the refractive index asymmetry only exists along *z* direction but not *x* direction (which is consistent with existing reports^{48,52,53}). We therefore explored the fabrication in Scheme II to see whether increased *z* scanning step of $1.5 \mu\text{m}$ from $0.4 \mu\text{m}$ could help. While there was a slight improvement, as shown in Fig. 1 (b)-Scheme II, where positive RI region become wider along *x* direction, the transmitted laser mode was still far away from design. We therefore relaxed both horizontal and vertical scanning steps to $1.5 \mu\text{m}$ in Scheme III, and fabricated both *x-aligned* rectangular and *z-aligned* rectangular waveguides. As shown by the images in Fig. 1 (b), Scheme III gave us better processed features. Comparing the laser mode profiles of all the three schemes in Fig. 1 (b), waveguides fabricated by Scheme III presents a confined one-lobe laser guiding region instead of two laser guiding regions shown in Scheme I and II. We explored varying fabrication parameters (pulse energy 50-150 nJ, scanning speed 1-12 mm/s) and cross-section sizes, however neither Scheme I nor Scheme II was able to fabricate a feature close to the design.

For all the waveguide fabrications in this paper, system induced aberrations were corrected by a wavefront sensorless adaptive optics method using a liquid crystal spatial light modulator (SLM) integrated into the laser fabrication system^{54,55}. We experimentally verified the correction by the imaging of laser focus before each fabrication session. The spherical aberration that arose from refractive index mismatch between immersion and sample, was also pre-corrected by using the SLM⁵⁶. It was important to ensure these aberrations were well corrected before our exploration (more details in Method section). For the convenience, we expressed this situation as “Zernike mode 11 equals 0” or “Z11 = 0”, as the 11th Zernike polynomial mode corresponds to the lowest order spherical aberration.

While Scheme III looked to give best results for fabrication strategy (Fig. 1 (b)), there were however still large areas of complicated refractive index structure around the waveguide core. For the *z-aligned* rectangular waveguide, only the top region could guide light (bottom right images in Fig. 1 (b)). Again, the problem was due to the fact that asymmetric complicated refractive index structure of single-scan waveguide was along the *z* direction⁵³. To resolve this problem, we introduced additional wavefront shaping, allowing us to gain a powerful capability to simplify and precisely control the fs-laser modified refractive index structure. The primary spherical aberration Zernike mode⁵¹ was chosen, as it can change laser focal shape along the *z* axis, while maintaining circular symmetry in the *x-y* plane (more analysis in supplementary Fig. S1). We found that by deliberately introducing a negative spherical aberration phase, we were able to relocate more energy to the bottom half of the laser focus, shifting heat distribution along the *z* direction, thus producing a considerably simplified refractive index structure (Fig. 1 (d), Supplementary Fig. S1). It was found empirically that an amplitude of -0.8 to -1.3 radians rms for Z11 worked well, so we chose negative one radian rms (Z11 = -1) for subsequent fabrication. As shown in Fig. 1 (d), fabrication with Z11 = -1 greatly simplified the single scan generated refractive index structure. Applying fabrication with Z11 = -1 to multi-scan *x-aligned* and *z-aligned* rectangular waveguides of Scheme III, we were able to produce structures which were well-matched to the original waveguide design (Fig. 1 (e), more results in Supplementary Fig. S2). The guided mode profiles showed well-confined elliptical modes.

Using manually induced spherical phase, we fabricated waveguides with core distances down to $0.3\ \mu\text{m}$ and saw negligible difference in loss and mode properties. The distance of core spacing should be chosen based on practical applications. Larger spacing greatly increases fabrication efficiency and can be more suitable for longer wavelength applications. Smaller spacing gives higher resolution in controlling over cross-section shape and size and may be used for shorter wavelengths. As we targeted the design of devices to be optimized at the wavelength of $1550\ \text{nm}$, $1.5\ \mu\text{m}$ was chosen for the core distance of most waveguides in this paper.

We named the waveguides fabricated by this new technique as spherical phase induced multi-core waveguides (SPIM-WGs). We experimentally compared an alternative solution - to simply adopt a high NA objective lens in "classic multi-scan" (Fig. 1 (a)), which could bring down the vertical separation down to $\sim 3\ \mu\text{m}$ with a 1.3NA oil objective lens. However, our experimental results suggested that SPIM-WGs still hold several competitive advantages, including much higher fabrication efficiency (an order of magnitude reduction in fabrication time), better organized refractive index profile, and lower propagation loss. Some details of these will be analysed further in this paper.

Twisted waveguides

Using the capability to finely control cross-section size along all transversal axes, we created waveguides with cross-section shape and size that varied along the length. The concept of these waveguides is illustrated in the schematics of Fig. 2 (a), where a single waveguide is composed of a straight *z-aligned* rectangular waveguide region at the input, twisted waveguide region at the middle, and *x-aligned* rectangular waveguide region at the output. To realize the concept in experiment, waveguides were fabricated with 9×2 multiple scans, with each scan translating continuously through the entire sample. The transition in the twisted region from *z-aligned* rectangular to *x-aligned* rectangular was achieved by a smooth rotation of the 9×2 array by 90 degrees along a length of $1.4\ \text{mm}$. A transmission microscope image viewing from top of the fabricated sample (2D projection) shows the clear change in transverse waveguide dimension in the twisted region.

To demonstrate the laser mode transition efficiency, we tested the twisted waveguide with both $785\ \text{nm}$ and $1550\ \text{nm}$ lasers. As shown in Fig. 2 (b), when laser light was coupled from a *x-aligned* rectangular facet (right side of waveguide), the mode profiles obtained at the output of waveguide were rotated 90 degrees to become *z-aligned*. Similarly, when light was coupled from the *z-aligned* rectangular facet, the output mode profiles were rotated 90 degrees to be *x-aligned* (more results in Supplementary Fig. S2).

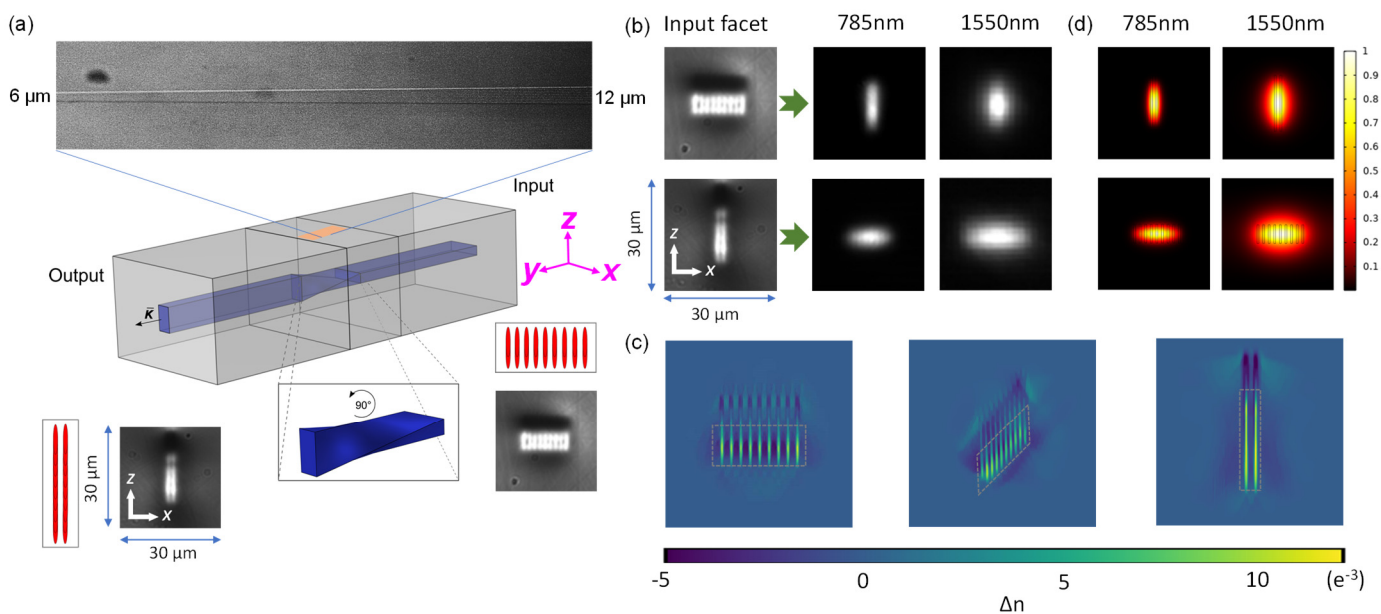


Figure 2. **Characterization of twisted shape SPIM-WGs.** All images (LED, laser, simulation) have the same frame size of $30 \times 30\ \mu\text{m}$. (a) Composition of a twisted waveguide. The lengths of *z-aligned* rectangular, twisted, *x-aligned* rectangular regions were $9.3\ \text{mm}$,

1.4 mm, 9.3 mm, respectively for the studied waveguide. LED microscopic image top view of the fabricated sample is included, where a transition from 6 μm width to 12 μm width is clearly seen from the top 3D to 2D projection. Multi-scans of the laser spot at waveguide facets are shown as schematics. Coordinates: x/z transversal axis, y longitudinal axis. (b) Rectangular beam rotation can be achieved by a twisted waveguide, with 785 nm laser and 1550 nm laser tested respectively. Top: light guided from x -aligned rectangular input facet was converted to z -aligned rectangular modes. Bottom: light guided from z -aligned rectangular input facet was converted to x -aligned rectangular modes. (c) Measured refractive index profiles by a 3D tomographic microscope. Dashed boxes highlight positive refractive index regions which was able to guide laser light. Refractive index contrast was measured as high as 0.017. (d) COMSOL simulations of mode intensity distribution for 785 nm laser and 1550 nm laser. The simulations were conducted based on measured refractive index data in the positive region from tomographic microscope (highlighted by dashed boxed).

To accurately characterize the waveguide refractive index profile at various points along the device, measurements were made using 3D tomographic microscopy⁵⁷. From the profiles in Fig. 2 (c), we can see that the multi-core waveguides along the z axis were well combined and formed a smooth transition of positive refractive index regions along z (the vertical bright lines). The positive refractive index in each single core was highly uniform, significantly reducing scattering to achieve low waveguide loss. The shape and size of those positive refractive index regions were highly consistent across the whole multi-core cross-section. The light guiding region is highlighted with a dashed box; and there are surrounding areas of negative refractive index, which could further enhance mode confinement. As one of the SPIM-WGs' advantages, the refractive index contrast was measured to be 17×10^{-3} , which is higher than that of most glass waveguides¹⁵. We believe this benefitted from both spherical phase control and partial overwriting (more details in Supplementary Fig. S3). Compared to a classic multi-scan technique, the refractive index distribution of SPIM-WGs is better organized and highly predictable, contributing to much better waveguide qualities, especially low losses, which will be discussed later.

In order to investigate the waveguiding properties from spatially separated regions of positive index change, we conducted simulations using the experimentally measured refractive index data. As shown in Fig. 2 (d), the guiding modes at both wavelengths were uniform without any evidence of deterioration. We note that the mode profile was dependent on spacing of multi-core as well as refractive index contrast. In our design, choosing 1.5 μm core distance with 17×10^{-3} refractive index contrast was sufficient to produce a uniform laser guiding mode with excellent confinement for both the 785 nm and the 1550 nm laser. As seen from Fig. 2 (b) and (d), the mode size was smaller for the shorter wavelength, which is expected. Based on a large number of simulations for varying waveguide cross-sections, we found by appropriate design that these periodic positive-negative refractive index transection profiles were well able to produce mode profiles similar to a homogeneous step index waveguide, and had negligible impact to waveguide losses, which will be discussed in the following text.

Light guiding performance

It is essential to evaluate waveguide losses to inspect whether the multi-core structure or the twisted region may introduce additional coupling and/or propagation losses to the waveguide. In order to have a comprehensive understanding of losses, we fabricated several sets of waveguides with different cross-section shapes and sizes, as illustrated in Fig. 3 (a). As the basis for comparison, we here used waveguides fabricated with a single pass of laser focus¹⁵ (referred to here as "classic single-scan waveguide"). Loss measurements were conducted by a cut-back method (details in Methods section) with 785 nm wavelength. We first evaluated whether the multi-core structures introduced additional loss compared to the classic single-scan waveguide. The averaged measured waveguide transmission efficiencies (proportion of light transmitted per centimetre of waveguide) are summarized in Fig. 3 (b). The numbers were averaged by several waveguides in each set with same configuration to improve reliability. Except for the x -aligned rectangular waveguide with $10 \times 4 \mu\text{m}$ cross-section, all the other SPIM-WGs had higher transmission efficiencies than that of classic single-scan waveguide. We therefore concluded that overall, SPIM-WGs had better transmission efficiency, or in other words lower propagation losses, than that of classic single-scan waveguides. We believe this is due to higher refractive index uniformity and contrast of SPIM-WGs.

We then investigated whether the twisted region inside SPIM-WGs introduced additional losses compared to the straight region. In the measured results of Fig. 3 (b), we found twisted waveguides have on average transmission efficiency lies between that of *x-aligned* rectangular waveguides and *z-aligned* rectangular waveguides. It was therefore concluded that additional loss induced by twisting should be negligible. On the other hand, SPIM-WGs with twisting demonstrated even lower propagation loss than classic single-scan waveguides in Fig. 3 (b).

We evaluated the coupling efficiency for all types of waveguides, with results summarised in Fig. 3 (c), by coupling laser light from a 785 nm wavelength single mode fibre (core diameter around 5 μm). We found the three sets of waveguides with input cross-section of $20\times 4\ \mu\text{m}$ were able to couple more laser light from the fibre. This is easily understandable as a much bigger waveguide facet had a larger overlap with a single mode fibre, therefore reducing coupling losses even in the presence of mode mismatching. The reason that *x-aligned* rectangular waveguides have higher coupling efficiency than that of *z-aligned* ones is due to the *x-aligned* facet having slightly larger area (Fig. 2 (b)). The *z-aligned* $10\times 4\ \mu\text{m}$ waveguide had slightly lower coupling efficiency than single-scan waveguides, where we think this is due to the fact that *z-aligned* $10\times 4\ \mu\text{m}$ waveguide had multimode behaviour at the wavelength of 785 nm, hence causing a single-to-multiple mode mismatch. There is no evidence that the facet of multi-core structure in SPIM-WGs causes significant additional coupling loss. In the following context, we experimentally demonstrated that the coupling loss of SPIM-WGs can be significantly reduced by advanced mode matching.

We conducted experiments to evaluate how the fabrication parameters affected the performance of twisted waveguides. Fig. 3 (d) summarized how the twisted waveguide's propagation loss could be optimized by changing laser scanning speed. It appeared that with pulse energy of 78nJ, a scanning speed around 4 mm/s was optimal. A waveguide fabricated with these parameters was measured with propagation loss as low as 0.14 dB/cm, which is close to the limit of EAGLE glass absorption at 785 nm⁵⁸. During our experiments, we constantly measured propagation losses in the range of 0.13-0.2 dB/cm for twisted shape SPIM-WGs fabricated with 4 mm/s scanning speed, further confirming these low propagation losses were easily repeatable.

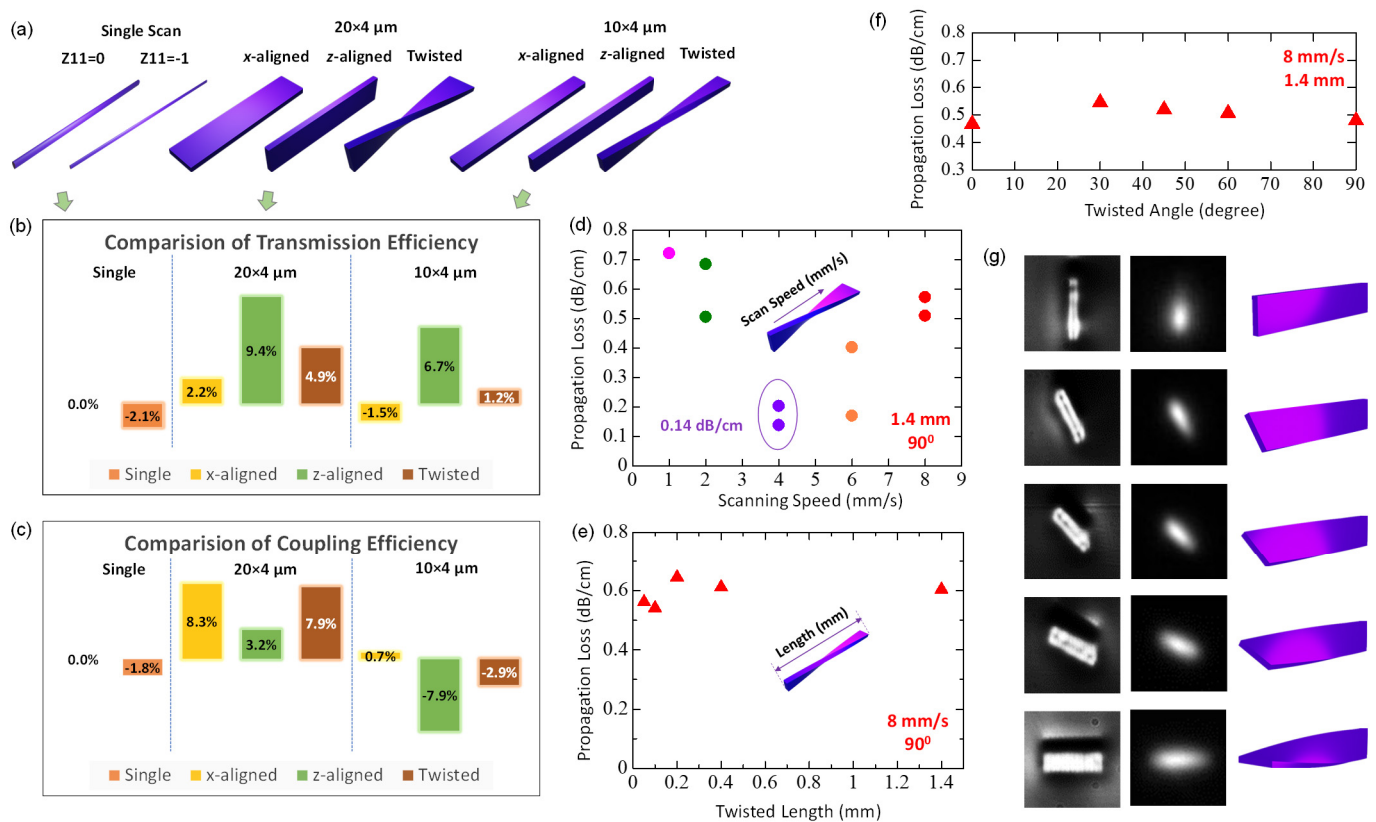


Figure 3. **Light guiding performance of SPIM-WGs.** All images (LED, laser) have the same frame size of $30\times 30\ \mu\text{m}$. (a) Sets of waveguides were fabricated with different cross-section shapes and sizes. Classic single-scan, *x-aligned*, *z-aligned* waveguides were two waveguides per set, while twisted waveguides (twisted length of 1.4 mm) were four (two *z-aligned* input facet, two *x-*

aligned input facet) per set. Cross-section images are included in Supplementary Fig. S2. (b) Comparison of laser transmission efficiency (proportion of light transmitted per centimetre of waveguide) for classic single-scan, *x-aligned*, *z-aligned* and twisted waveguides, in relation to classic single-scan waveguide with $Z_{11}=0$. Higher transmission efficiency means lower propagation loss. Each number presented in the figure is an average of 2 measured waveguides for single-scan, *x-aligned*, and *z-aligned* sets; an average of 4 waveguides for twisted sets. (c) Comparison of laser coupling efficiency for classic single-scan, *x-aligned*, *z-aligned* and twisted waveguides, in relation to classic single-scan waveguide with $Z_{11}=0$. Higher coupling efficiency means lower coupling loss. Twisted waveguides were a set of four waveguides with two *z-aligned* inputs and two *x-aligned* inputs. (d) Twisted waveguides propagation losses versus laser focal spot scanning speed. Cross-section size was $20 \times 4 \mu\text{m}$, twisted length was 1.4 mm, twisted angle was 90° . (e) Twisted waveguides propagation losses versus twisted region length. Cross-section size was $10 \times 4 \mu\text{m}$, laser scanning speed was 8 mm/s (sacrificing loss to gain fabrication efficiency), twisted angle was 90° . (f) Twisted waveguide propagation losses versus twisted angle. Cross-section size was $20 \times 4 \mu\text{m}$, laser scanning speed was 8 mm/s (sacrificing loss to reduce fabrication time), twisted length was 1.4 mm. (g) Demonstration of beam rotation by several sets of twisted waveguides with varying twisted angle. Left: LED transmission microscopic images of waveguide facet. Middle: measured 1550 nm laser mode profile images. Right: diagrams of twisted SPIM-WGs with different angles.

We fabricated waveguides with different twisted region lengths to evaluate how this parameter affects the overall performance. As shown in Fig. 3 (e), the total propagation losses (straight plus twisted regions) remained almost constant when reducing the length of twisted region, which means the SPIM-WGs with twisted region as short as 0.05 mm had similar overall loss to one with a 1.4 mm twisted region. Moreover, we found that the waveguides with different twisted lengths had comparable performance in *z-aligned* to *x-aligned* mode conversion. It is notable that waveguides in Fig. 3 (e) were fabricated with higher scanning speed of 8 mm/s, which reduced fabrication time by half. Optimizing scanning speed could easily bring down the losses as indicated in Fig. 3 (d).

Finally, we demonstrated SPIM-WGs' flexibility in controlling the twisted angles, providing versatile beam rotation capability. We fabricated twisted waveguides starting from a *z-aligned* rectangular shape into twisted angles of 0° , 30° , 45° , 60° , 90° . Fig. 3 (g) includes both LED illuminated microscopic images and 1550 nm laser transmission mode profiles, showing not only good control over cross-section shape, but also the flexibility to rotate the orientation of elliptical laser guiding modes. Moreover, as demonstrated in Fig. 3 (f), varying the twisted angle did not have noticeable effects on SPIM-WGs' propagation losses.

On-chip Polarization Manipulation

In this section, we demonstrate the capability of SPIM-WGs in manipulating the polarization state of guided light. To prove this concept on a chip, we constructed polarization-controlled experimental apparatus (details in Methods section). Either monochromatic or broadband supercontinuum generation light sources passing through the linear polarizer were used to illuminate the waveguide. SPIM-WGs were studied to evaluate their polarization conversion efficiency (PCE) for propagated light, which is defined as,

$$PCE_{TE \rightarrow TM} = \frac{P_{TM}}{P_{TE} + P_{TM}}$$

$$PCE_{TM \rightarrow TE} = \frac{P_{TE}}{P_{TE} + P_{TM}}$$

in which, $P_{TE(TM)}$ is the power in the TE (TM) polarization at the waveguide output facet.

We investigated 90° twisted waveguides with varying twisted length and total length (diagram in Fig. 2 (a)). When tested with $0^\circ/90^\circ$ linear polarized 1550 nm monochromatic laser, we found that appropriately designed twisted waveguides were able to rotate the polarization of transmitted laser light. Fig. 4 (a) compared two twisted waveguides with same total length of 30 mm, but different twisted length of 25 mm (top) and 15 mm (bottom). As seen in the mode images, the twisted waveguide with 25 mm twisted length maintained the same polarization state of guided laser light at 1550 nm with less than 10% polarization state lost. In comparison, the twisted waveguide with 15 mm length was able to convert up to 65% of a TE mode into a TM mode, or a TM mode into a TE mode, as demonstrated

in bottom images of Fig. 4 (a). With a TE input, TM mode was strongly observed at the output of twisted waveguide, while a similar case was seen for TM mode conversion into TE mode.

The capability of broadband polarization manipulation of twisted waveguides is demonstrated in the results of Fig. 4 (b) and (c). We observed that the polarization conversion had periodical variation across a broad range of wavelengths. We think the oscillations can be the consequence of excitation and interference of higher order modes in our waveguides. With the definition of modal group index⁵⁹ $n_g = -\frac{\lambda^2}{2\pi} \frac{d\beta}{d\lambda} = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda}$, where β is the propagation constant, λ is the wavelength of transmitted laser light and n_{eff} is effective refractive index, we obtained the following expression for the period of spectral oscillations in wavelength (more details in Supplementary Note 2):

$$\Delta\lambda = \pm \frac{\lambda^2}{(n_{g1} - n_{g2})L}$$

n_g has relatively weaker dependence over λ , so that $\Delta\lambda$ is almost a function of λ^2 and L . The obtained expression explains faster oscillations for waveguides with longer total length (larger L , comparing Fig. 4 (b) and (c)), and narrowing of the wavelength period at shorter wavelengths. The period of the observed oscillations may indicate that the interference occurs between modes of different order rather than between polarization modes of the same order. On the other hand, twisted waveguides can be treated as effective optically active media whose eigenmodes are, in general, elliptically polarized. Interference of such modes in general leads to the rotation of polarization and, in turn, to PCE oscillations across broadband wavelengths.

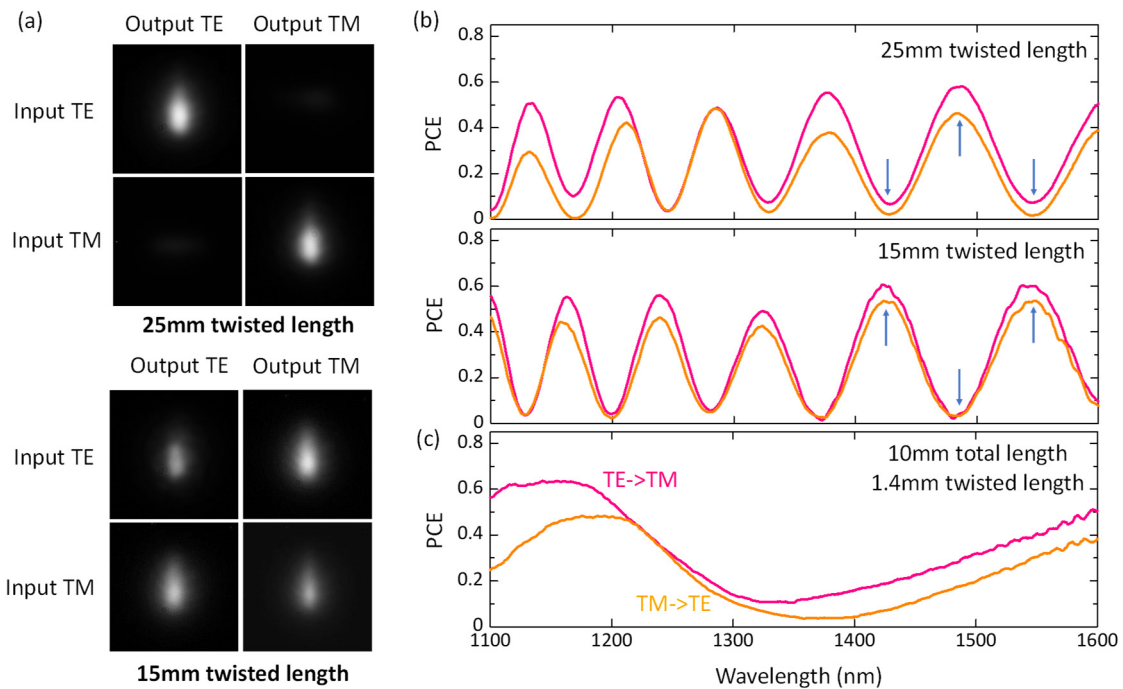


Figure 4. **Demonstration of ultra-broad band on-chip polarization manipulation of SPIM-WGs.** All images (LED, laser) have the same frame size of $30 \times 30 \mu\text{m}$. (a) Results of polarization-controlled experiments at 1550 nm wavelength laser. Top: twisted waveguide with 25 mm twisted length. Bottom: twisted waveguide with 15 mm twisted length. Images are waveguide mode profiles observed for particular output polarization state, with input laser light of either pure TE or pure TM polarization. Both waveguides have total length of 30 mm. (b) Measured broadband polarization conversion efficiency (PCE) for twisted waveguides with total length of 30 mm, different twisted lengths of 25 mm and 15 mm. PCEs are controllable for any target wavelength by modifying twisted length while fixing total length. (c) Measured broadband polarization conversion efficiency (PCE) for twisted waveguides with total length of 10 mm, twisted lengths of 1.4 mm. In Fig. 4, Waveguide cross-section sizes are $20 \times 4 \mu\text{m}$ for all. Twisted waveguides are with 90 degrees twisting angle.

Modification of the total waveguide length makes it possible to adjust the period of PCE variation, which provides a useful tool for on-chip polarization manipulation. When the total waveguide length was fixed, but the length of the

twisted region was changed, we found that the periodical variations can shift, as shown in Fig. 4 (b). Fixing the total length and controlling the length of twisted region thus becomes a second method for tunable polarization manipulation. Based on these observations, it is possible to design a waveguide which provides high polarization conversion at several target wavelengths while maintaining original polarization state at the other wavelengths. For an example, as shown as middle figure of Fig. 4 (b), the waveguide with 15 mm twisted length has high polarization conversion at 1550 nm (telecom. C band) and 1420 nm (telecom. E band), but maintains original polarization state at 1490 nm (telecom. S band). Conversely, the waveguide with 25 mm twisted length (top figure) maintains the original polarization state at 1550 nm (telecom. C band) and 1420 nm (telecom. E band), but has high polarization conversion at 1490 nm (telecom. S band). It is thus possible to design and achieve a desired polarization conversion efficiency (with any target value between 0% to 65%) for any particular target wavelength. The maximum polarization conversion efficiency almost stays the same for waveguides with different twisted lengths in the studied range of 1.4 - 25 mm. One could further increase the maximum conversion efficiency possibly through reduction of the spacing between multiple cores (from 1.5 μm to 0.5 μm) to produce a more uniform refractive index cross-section. We also note another capability of the twisted SPIM-WGs, where they are able to rotate the laser intensity profile with 90° orientation, without rotate the polarization state. These cases are effectively, polarization-maintaining beam rotator, shown in Fig. 4 (b) and (c) where the PCE approaches zero.

Adiabatic Mode Converters with Advanced Mode Matching

We demonstrate that SPIM-WGs enable flexibly creation of mode converters that can arbitrarily transform modes regardless of their symmetry. There are many photonic chip applications that require mode manipulation, for example, when mode matching is needed. We highlight two common application cases to demonstrate this capability. In most optical chips, couple laser light in/out of a single mode fibre is important³. In terms of direct laser written waveguides, researchers have adopted methods to control the fabrication laser power to achieve higher coupling efficiency^{47,48}. Based on SPIM-WGs, the converters were created by us so that cross-sections are transformed between circular and rectangular shapes (Fig. 5 (a) left). The mode conversion performance is demonstrated in Fig. 5 (a), where the mode intensity plots indicate a clear transition between circular and elliptical modes. Both the circular or rectangular shapes and sizes can be flexibly and precisely controlled. In our experiments, the circular facet of the mode converter was designed to have the same physical dimensions as the core of the 1550 nm single mode fibre (a diameter of 8 μm). This provided excellent mode matching; we observed that 95.7% light was coupled from the fibre tip to the circular facet of SPIM-WGs mode converter. This represents a significant decrease of coupling loss after advanced mode matching, from 1.69 dB in the case of rectangular facet to 0.19 dB in the case of circular facet based on our measurement with 1550 nm laser. The total loss (coupling + propagation) of a mode converter with length of 1.32 cm was as low as 0.59 dB, where the waveguide was fabricated with scanning speed of 6 mm/s. During our experiments, the total losses of 10 converters fabricated in the same configuration were measured to be in the range of 0.59 - 0.75 dB, confirming high consistency of light guiding performance.

As a second example, we consider ppKTP (periodically-poled potassium titanyl phosphate) waveguides⁶⁰⁻⁶⁴, which are used in nonlinear optics, in particular for frequency conversion and quantum light sources. The waveguiding mode is defined via a rubidium ion-exchange process beginning at the surface of the material and penetrating below with gradually reduced concentration. This typically leads to a skewed-Gaussian mode profile⁶⁵⁻⁶⁷, inducing high coupling losses to single-mode fibre due to mode mismatch, which is a major hurdle for effective integration of these devices. We demonstrate that our SPIM-WGs technique can easily create a converter to transform between a ppKTP waveguide mode and a circular mode from an external single mode fibre. We designed a refractive index profile, presented in Fig. 5 (b), that was able to generate a mode profile matched to the mode from a typical ppKTP waveguide. The designed refractive index profile was created by fine tuning the size and shape with feedback from COMSOL simulation. We fabricated this type of mode converter from an 8 μm diameter circular shape (matching to the core size of single mode fibre) to the designed ppKTP refractive index with sizes of 8×8 μm , 6×6 μm , and 4×4 μm . A typical mode converter with length of 1.38 cm was measured to have total loss as low as 0.65 dB, with coupling loss of 0.24 dB (94.6% light coupled). In total, 18 converters were fabricated, and their total losses were measured in the range of 0.65-0.8 dB.

The mode profiles of one converter with mock ppKTP waveguide of $8 \times 8 \mu\text{m}$ size are presented in Fig. 5 (c), where the mode shape transition is clearly seen. In practical applications, mode converters could be cut to be shorter (e.g., ~ 0.5 cm), easily reducing the propagation loss and raising overall efficiency to be $> 90\%$.

We found that the adiabatic transitions of these converter cross-sections introduced negligible additional loss. This was verified by comparing the losses of mode converters to SPIM-WGs of fixed circular shape cross-section. When they were created with same circular diameters and total waveguide lengths, there were no observable difference in their total losses. The capability of SPIM-WGs in creating adiabatic mode converter is also not restricted to above two examples.

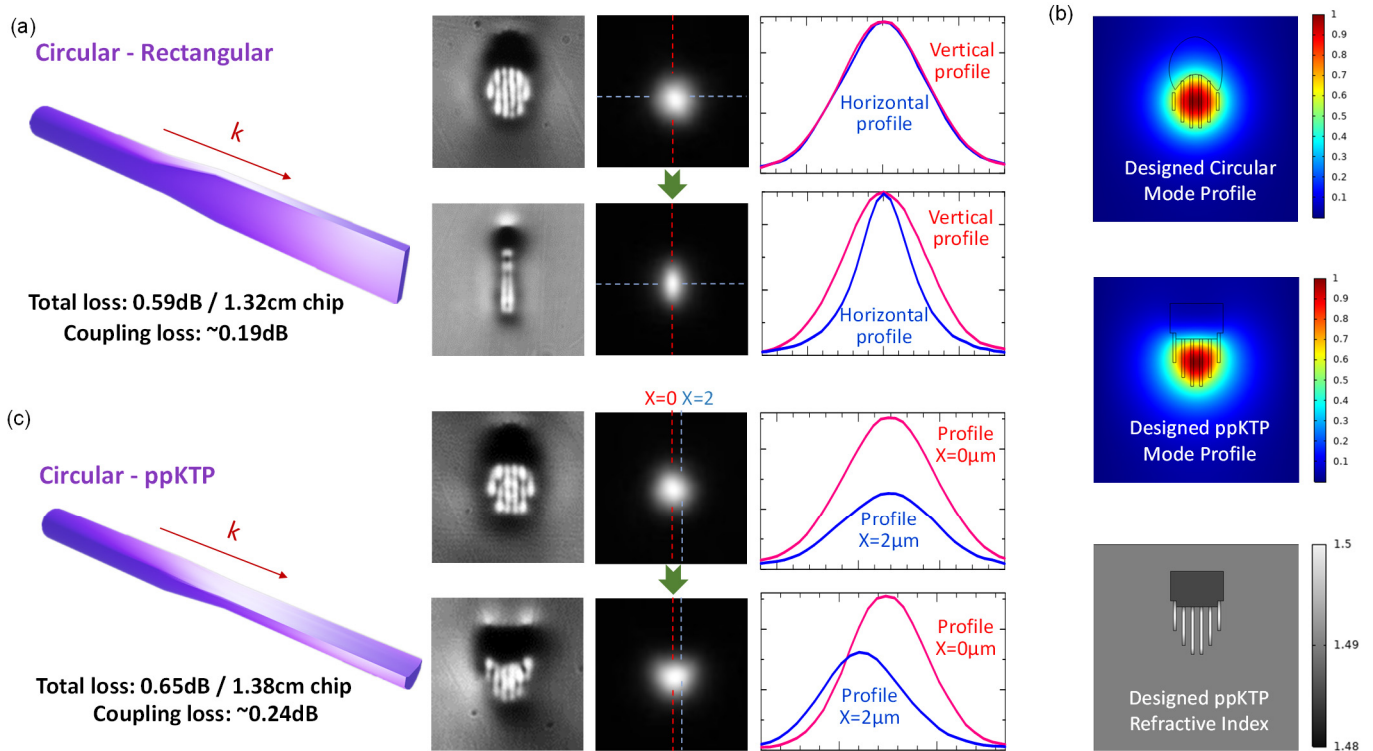


Figure 5. **Adiabatic mode converters with advanced matching of arbitrary modes.** All images (LED, laser) in (a) and (b) have the same frame size of $30 \times 30 \mu\text{m}$. (a) Left: Circular-Rectangular mode converter that couples single mode fibres (circular shape mode) to rectangular shape waveguides (elliptical shape mode). A waveguide with length of 1.32 cm was measured to have ultra-low total loss of 0.59 dB (coupling + propagation). The coupling loss was calculated to be as low as 0.19 dB (95.7% light coupled). Middle: LED illuminated microscopic image and 1550 nm laser guiding profiles for circular-rectangular mode converter. Right: plots of intensity versus distance for corresponding circular and elliptical mode profiles. Position of plotting lines are indicated in mode profiles in the middle. (b) Top: COMSOL simulated field distribution of circular shape mode profile with our design to match a single mode fibre. Middle: COMSOL simulated field distribution of mode profile with our design to match ppKTP waveguide. Bottom: designed refractive index profile to match ppKTP waveguide mode. (c) Circular-ppKTP mode converter that couples single mode fibres to ppKTP waveguides. A waveguide with length of 1.38 cm was measured to have ultra-low total loss of 0.65 dB (coupling + propagation). The coupling loss was calculated to be as low as 0.24 dB (94.6% light coupled).

Discussion

We have made several breakthroughs by introducing this new kind of SPIM-WGs. Firstly, we open the capability to create waveguides in glass not only with precisely organized refractive index and low propagation loss, but also have arbitrarily variable cross-section in any shape and size (to the limits of writing laser spot), with high resolution precision control along both horizontal and vertical axis. Secondly, with advanced mode matching capability of SPIM-WGs, we achieved very high coupling efficiency (95.7%) from an external single mode fibre to an on-chip device. The optical fibre compatibility of SPIM-WGs could be an important solution for future packaged photonic integrated circuitry.

Thirdly, this new kind of waveguide enabled the easy creation of adiabatic mode converters that can handle complicated asymmetric modes, for which significant difficulties remain using existing technologies. Together with the broadband applicability from visible to near-infrared, these breakthroughs constitute a significant development in integrated waveguide technology that will open new interesting applications in on-chip photonics, quantum technologies and a lot of other related areas.

Materials and methods

Femto-second laser fabrication system

The laser waveguide fabrication system used a regenerative amplified Yb:KGW laser (Light Conversion Pharos SP-06-1000-pp) with 1MHz repetition rate, 514 nm wavelength, 170 fs pulse duration. A Spatial Light Modulator (SLM, Hamamatsu Photonics X10468) was aligned and imaged by a 4-f lens system to the pupil of objective lens. The power of the laser beam was controlled with a motorized rotating half waveplate together with a Polarization Beam Splitter (PBS). The laser beam at objective lens focus was circularly polarized. The glass sample was fixed on a three-axis air bearing stage (Aerotech ABL10100L/ABL10100L/ANT95-3-V) to control the movement to inscribe waveguides.

The results presented in this paper were fabricated in borosilicate glass (Corning EAGLE 2000) samples, as we found high repetition laser fabrication in heating regime works better in this glass compound. SPIM-WGs fabrications in fused silica glass have slightly greater complexity, likely due to the difference in material properties between these two glass compounds⁶⁸.

In this paper, if not specified, the waveguide fabrication parameters were: 0.5NA objective lens, waveguide depth of 120 μm from surface of glass sample, scanning speed of 8mm/s, pulse energy of 87nJ for fabrication with Z11 = 0, and 78nJ for fabrication with Z11 = -1. For all the fabrications in this paper, the primary spherical aberration, arising from the refractive index mismatch between immersion and sample, was corrected⁵⁶.

Phase pattern for SLM

For all the waveguide fabrications in this paper, the phase pattern applied to SLM was,

$$\begin{aligned} \text{SLM Phase Pattern} \\ &= \text{Compensation of system induced aberrations} \\ &+ \text{Compensation of refractive index mismatch aberration} \\ &+ \text{Manual induced Z11 beam shaping phase for SPIM_WGs} \end{aligned}$$

where “Z11” represents the first order Zernike polynomial mode for spherical aberration. For the convenience, we expressed the situation, that first two aberration terms (system induced + RI mismatch) were pre-corrected, as “Zernike mode 11 equals 0” or “Z11 = 0”.

Waveguide characterizations

After direct laser fabrication, waveguide samples were polished by using a sequence of 30 μm , 9 μm and 3 μm polishing films. A layer of at least 200 μm glass were polished off both input and output facets of the glass. A self-built LED-illuminated widefield transmission microscope was used to check waveguide cross-sections after polishing. To image laser guiding mode profiles, single mode fibres were used to guide 785 nm or 1550 nm laser light into the input facet of a waveguide. The fibre output was mounted and adjusted in a six-axis stage (three spatial axes plus three angle adjustment). A custom-built microscope was used to image the output facet of a waveguide in order to capture guided laser mode profile.

To analyse the propagation loss and coupling loss of the waveguides, a cut-back approach was adopted. A power meter was placed at camera position of microscope to measure laser powers: 1) direct at fibre tip without waveguide sample (P_{fiber}); 2) at waveguide output facet after full-length waveguide (P_{output_long}); 3) at waveguide output facet after cut waveguide with shorter length (P_{output_short}), where the lengths of waveguide were measured in centimetres. The waveguide coupling efficiency ($E_{coupling}$) is defined as proportion of laser light coupled from waveguide to the other waveguide. The propagation efficiency per centimetre ($E_{propagation}$) is defined as proportion of laser light transmitted after one centimetre length of waveguide. These two measurements of longer and shorter waveguides can be resolved by:

$$P_{output_long} = P_{fiber} \cdot E_{coupling} \cdot E_{propagation}^{Length_long}$$

$$P_{output_short} = P_{fiber} \cdot E_{coupling} \cdot E_{propagation}^{Length_short}$$

In the system to demonstrate polarization manipulation, the coupling-in was performed via the focusing objective. The light was collected from the output facet via objective and split into two paths by 50:50 beam splitter. Concurrently to the imaged-on camera (VIS-SWIR Ninox-640) mode profiles of twisted and reference-straight waveguides, the spectrum was collected by optical spectrum analyser (OSA Yokogawa 6370D). Two polarizers were placed before and after the waveguide sample in order to conduct the polarization conversion measurement. The two polarizers were placed with relative angle of 0° to characterize the polarization maintaining, and with relative angle of 90° to characterize the polarization conversion.

Simulations

A Fourier optics model was adopted to simulate (in Matlab) the focal intensity distribution of an objective lens focussing into glass⁶⁹⁻⁷¹. The focal intensity distribution was calculated by solving the Rayleigh-Sommerfeld diffraction integral from the pupil illumination. The spherical phase was added into the model by a phase function φ in the pupil of the objective lens (Fig. 1 (d), Supplementary Fig. S1). To simulate waveguide mode profiles, we used finite element method (COMSOL Multiphysics) to create complicated refractive index structures which approximated the measured refractive index profiles from 3D tomographic microscope. When multiple modes existed, we presented the major mode.

Refractive index profile measurement

Refractive index profiles were measured by a self-built 3D tomographic microscope⁵⁷. The imaging system records many intensity images of a waveguide at different illumination angles ranging between about -45° and 45° . The light source was a collimated blue LED (460 nm). A two-dimensional refractive index cross section of the waveguide was then reconstructed from the image stack using an error reduction algorithm based on gradient descent and simulated beam propagation.

Acknowledgements

B.S. is grateful for the valuable experimental assistance from Dr. Mohan Wang and helpful discussion with Dr. Chao He. This project was partially supported by the European Research Council Advanced Grants AdOMiS (695140), UK Engineering and Physical Sciences Research Council grants EP/T001062/1, EP/R004803/01, EP/T00326X/1, Austrian Science Fund (FWF) I3984-N36. A.K. acknowledges Israel Innovation Authority KAMIN #69073 'Development of mode converters technology with twisted waveguides on a chip'.

Author contributions

B.S. conceived the idea of SPIM-WGs, developed the technique, and oversaw the project. B.S. designed and fabricated all the waveguides and devices for beam rotators, polarizers and adiabatic mode converters, characterized laser guiding performance, obtained microscopic images and conducted loss analysis. A.K., F.M., A.H., A.Kat., A.N. conceived the concept of twisted shape waveguides, conducted analytical description, modelling, measurements of twisted waveguide's polarization conversion properties. S.M., N.B. and A.J. developed the tomographic microscopy, measured and analysed refractive index profiles. I.W., R.P., P.S., M.B. and B.S. conceived and developed the concepts of adiabatic mode converters. Z.P. and B.S. conducted COMSOL simulations. B.S. performed laser focus simulations. B.S. and A.H. drew the waveguide diagrams. J.F. assisted with waveguide characterization. B.S. drafted the manuscript and constructed all the figures. B.S. and M.B. co-wrote the paper, with great contribution from P.S. and A.K., and valuable comments from A.J., R.P. and I.W. All authors discussed the results and reviewed the manuscript.

Conflict of Interest

The authors declare no competing interests.

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