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Demonstration of ultra-broadband single-mode and single-polarization operation in *T*-Guides

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Silica-based anchored-membrane waveguides (*T*-Guides) are fabricated and characterized from the visible to infrared with streak imaging. It is numerically shown that the *T*-Guides can have wideband single-mode and single-polarization (SMSP) properties over a span of 2.6 octaves. Experimentally, a polarization-dependent loss difference of up to 89±19 dB/cm is measured between orthogonal polarizations and a record SMSP window of >1.27 octaves is observed, limited only by the available measurement equipment. These measurements make a strong case for *T*-Guides for SMSP photonics, particularly in high-index materials such as those in our previous demonstration on silicon.

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The modal properties of waveguides can strongly affect their performance in many important application sectors. In telecommunications, modal dispersion leads to pulse distortion, and coupling into higher-order modes during bends results in power loss. In the context of supercontinuum generation, operating with multimode waveguides can result in poor beam quality of the output, which limits the brightness achievable. It is also desirable to achieve a highly polarized output without simply rejecting orthogonally polarized light. Polarization is a key concern for on-chip optical gyroscopes, which can suffer from performance degradation through polarization-fluctuation-induced noise [1]. One means of averting these issues is through single-mode and single-polarization (SMSP) waveguides. SMSP waveguides should be designed to maximize the SMSP "window" over which one mode and one polarization can propagate with sufficiently low loss. Any other mode or polarization is either completely unsupported, or made to be strongly attenuated. The specific means of achieving this may vary, but in general, asymmetric geometries or material anisotropy is employed [2].

To date, SMSP waveguiding has been primarily investigated in fibers [3–7]. However, the bandwidth of fabricated fibers to date has reached only 0.23 octaves, with a polarization-dependent loss (PDL) of ~2.8 dB/cm [7]. For compact and low-cost photonics, an integrated SMSP solution with much stronger attenuation for the undesired polarization and higher-order modes is desirable.

Recently, we have proposed a novel geometry known as "anchored membrane" waveguides (or the *T*-Guide) [8] and demonstrated it on a silicon platform [9]. The variations on silica (SiO_2), as well as the simplified fabrication method on silicon substrates, are depicted in Fig. 1. It is numerically and experimentally shown in this Letter that these silica *T*-Guides possess SMSP windows significantly larger than those in the previous reports on integrated waveguides and optical fibers.

The *T*-Guide consists of a membrane (or "slab") bonded over two trenches and separated by a narrow post, which acts to confine the optical mode at the junction of the "T"; its asymmetric and semi-infinite geometry (due to the continuity of its features into the substrate) enable extremely broad SMSP windows [8]. The direct connections to the substrate in all directions distinguish the *T*-Guide from other *T*-shaped

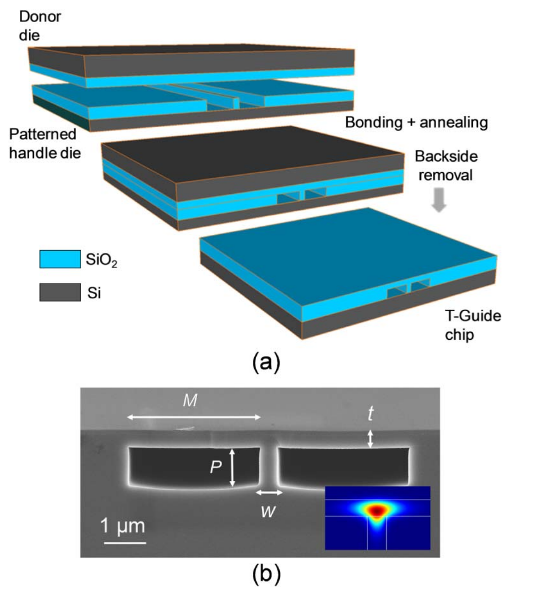

Fig. 1. (a) Simplified fabrication method for *T*-Guides; (b) scanning electron microscopy cross-section of a fabricated silica *T*-Guide on silicon substrates (inset: simulated intensity profile of the mode).

geometries, such as those in Ref. [10]. Only the fundamental transverse-electric mode is permitted for most T-Guide designs and wavelength regions. Silicon T-Guide designs were theoretically investigated and shown to exhibit up to 2.75 octave-wide SMSP windows [8], spanning nearly the entire material transparency window of silicon [11].

Furthermore, the geometry provides superior mechanical stability, thanks to its post feature, while allowing for compact dimensions due to the large index contrast achievable between the core material and the air cladding. In this Letter, we experimentally demonstrate that T-Guides can exhibit ultrabroadband SMSP operation as predicted.

We have recently demonstrated Si T-Guides in the mid-infrared [9]. However, in order to measure their SMSP properties, it is desirable to implement T-Guides such that accurate loss measurements can be made over a very broad bandwidth. Furthermore, since the magnitude of losses for the "rejected" polarization is expected to be on the order of >50 dB/cm for much of the spectrum, the measurement setup must be capable of resolving this value over very short distances. This loss is too high for resonator-based loss measurement or for cut-back measurements. An alternative can be found in top-view streak imaging [12], in which a digital image is captured from the top view of light scattering from the top surface of a waveguide. The intensity of scattered light is fitted to an exponential curve, allowing for accurate loss measurements over a wide range, limited only by the detector sensitivity and the magnification optics. Therefore, they should be implemented in a material transparent in the visible to near-IR range, where suitable cameras and optics are readily obtained. To this end, we chose to explore T-Guides constructed of silica rather than silicon. It is noted that silica exhibits wideband material transparency [13] and can be processed using techniques similar to silicon.

First, the theoretical SMSP operation of silica-type waveguides is considered in order to understand what can be expected of various designs. Accordingly, eigenmode simulations of silica T-Guide geometries were conducted in COMSOL over a wide spectrum. Scattering boundary conditions were used to approximate leakage to the substrate [14], and a cutoff condition of 10 dB/cm from leakage losses was employed. Generally, the cutoff is chosen to correspond to the length scale of interest; in fibers, values on the order of dB/m have been used as a cutoff in the past [3,4]. The SMSP window is thus determined by the spectrum in which transverse magnetic (TM) losses are above this limit and transverse electric (TE) losses are below this limit (in an asymmetric structure, the TE mode will cut off when a sufficiently long wavelength is reached). The simulated structure in this case used a membrane width M of 5 μm, slab thickness of $t = 350$ nm, post height P of 2.5 μm, and post widths w varying from 250 to 450 nm. The geometrical definitions of these parameters are provided in Fig. 1(b).

The effective index for TM and TE modes are plotted for varying post widths in Fig. 2(a), and the corresponding window of operation for the mode for each post width and polarization is shown in Fig. 2(b). The observed results are similar to those observed in the theoretical investigations of silicon T-Guides [8], where both polarizations are guided only at short wavelengths, and increasing the post width beyond the slab thickness results in broader SMSP windows. This occurs because the TM mode begins to leak to the substrate through the post as it is widened. In Fig. 2(a), this is reflected by the disappearance of

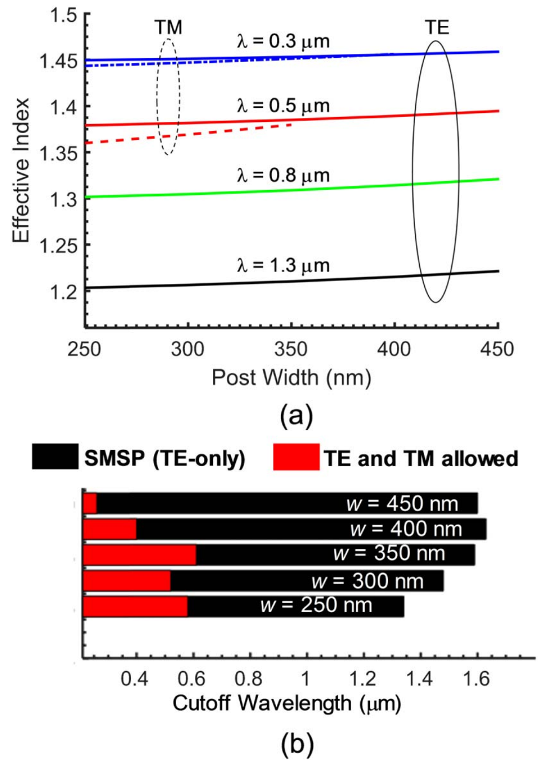

Fig. 2. (a) T-Guide post width versus modal effective index for different wavelengths (slab thickness fixed at 350 nm). Dashed lines are TM modes and solid lines are TE modes; (b) transmission windows (defined by >10 dB/cm loss threshold) for the TE and TM guided modes, with black corresponding to SMSP operation and red to bi-polarized operation.

the dashed lines corresponding to the TM modes above a minimum post width. An SMSP window from 260 to 1600 nm (2.6 octaves) is possible for a post width of 450 nm with silica T-Guides, but smaller post widths also produce extremely broad SMSP operation.

The bending performance of T-Guides is also important to consider for their use in complex integrated photonic systems. We used axially symmetric 2D eigenmode simulations in COMSOL to analyze the losses in bent T-Guides of different radii. Perfectly matched layers were incorporated into the horizontal boundaries to allow proper estimation of bending-induced radiation losses. The bending losses at $\lambda = 633$ nm for T-Guides with a fixed slab thickness of 350 nm and post width of 450 nm are plotted versus bending radius in Fig. 3. A bent propagation loss of ~0.5 dB/cm is feasible for a radius of 190 μm.

Silica T-Guides were fabricated according to the illustration in Fig. 1(a). A thermally oxidized (2500 nm thick) silicon die was patterned with trenches to form isolated posts between 250 to 400 nm wide. This die was then contacted and spontaneously bonded with a thermally oxidized (300 nm thick) piece of silicon (the "donor" die) approximately 3 × 5 cm^2 after activation in oxygen plasma, a 15 second dip in deionized water, and drying in nitrogen. A low-temperature anneal up to 250°C for 30 minutes was performed with no applied pressure. Next, the die was annealed at 1000°C for 1 hour without applied pressure. The backside of the donor die was removed by dry etching, followed by wet etching with tetramethylammonium

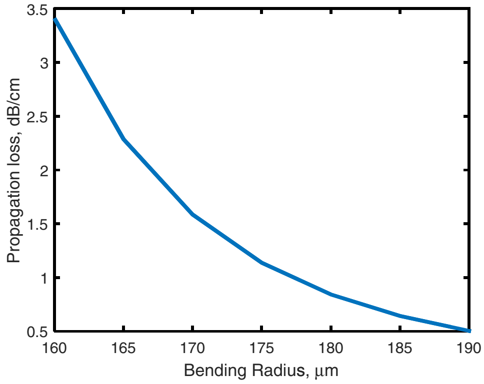

Fig. 3. Propagation loss in a bent T-Guide plotted against the bending radius, for a fixed post width of 450 nm and a slab thickness of 350 nm.

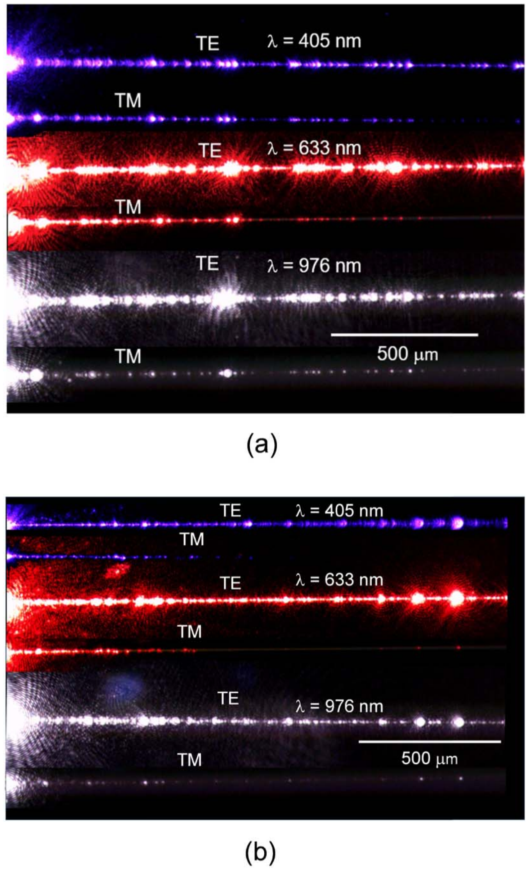

Fig. 4. Streak images of T-Guides: (a) $w = 250$ nm; (b) $w = 300$ nm. Single-polarization operation is observed by the much-longer length of TE-mode streaks compared to those of the TM mode.

hydroxide to expose the silica membrane without damage. The thickness of the transferred membrane was adjusted after this step from 300 to 350 nm using plasma-enhanced chemical vapor deposition to compensate for width reduction of the posts during trench etching. These processing steps resemble our approach for our demonstration of all-Si suspended-membrane waveguides [15] and, of course, the aforementioned silicon T-Guides [9].

Cleaved waveguides were characterized to assess their SMSP window. Three different lasers were utilized: blue (diode, 405 nm), red (helium neon, 633 nm), and near-infrared (diode, 976 nm). Light was coupled into the T-Guides through an aspheric lens and a top-view of scattered light from the waveguides was imaged onto a silicon camera module with 2048 × 1536 resolution through a microscope with 4.5 × magnification. A linear polarizer was placed in front of each laser to image the TE and TM mode streaks separately for comparison. The corresponding streak images for T-Guides with widths of 250 and 300 nm are collected and shown in Figs. 4(a)–4(b). The case of $w = 300$ nm showed stronger attenuation for the TM polarization, a result consistent with the expected behavior of TM light leaking to the substrate through the wider post. It can be seen that for all wavelengths and for both widths the TM mode is severely attenuated compared to the TE mode, as evidenced by the short length of the streak. Fitting the measured intensity along the streak to an exponential decay function, the propagation loss was examined for $w = 250$, 300, and 350 nm. The length was accurately calibrated using the known spacing between adjacent waveguides. A high degree of particle scattering was observed during the measurements, evidenced by the bright dots in Figs. 4(a)–4(b); this results from particles trapped between the slab and the handle wafer during bonding. Inspection of the waveguides under higher magnification confirmed this issue. This discrete scattering thus obscured most measurements of the TE mode propagation loss. Nevertheless, two TE mode-loss cases could be accurately analyzed despite the scattering: $w = 300$ nm at $\lambda = 405$ nm with 12±4 dB/cm, and $w = 250$ nm at $\lambda = 976$ nm with 19±3 dB/cm. Next, the TM mode propagation losses (the rejected polarization) were examined at $\lambda = 405$ nm; the corresponding TM mode propagation losses for $w = 250$, 300, and 350 nm were 49, 101, and 387 dB/cm, respectively. For $\lambda = 633$ nm, the TM losses were 116, 181, and 234 dB/cm. The propagation loss for the TM mode at $\lambda = 976$ nm was too large to measure accurately; however, since the largest measurable loss in this experiment was 387 dB/cm, the attenuation is expected to be even greater. The uncertainty in all TM loss measurements is estimated to be $\pm 15\%$. All loss uncertainties were obtained after repeated curve fittings of similar streak sections. The earlier onset of single-polarization operation at shorter wavelengths here than that predicted by simulations can be explained by the slightly rounded top corners of the fabricated post [Fig. 1(b)], which significantly increase the rate of leakage through the post for the TM mode.

The intensity streaks in the case of $\lambda = 405$ nm and $w = 300$ nm are plotted in Figs. 5(a)–5(b) for the TE and TM modes, showing the form of the fitted function and the curve-fitting parameters. With vendor-supplied thermal oxide donor wafers (instead of films grown in-house, which accumulated particles during oxidation), the loss can be greatly reduced in the future by reducing the density of these defects. Future work may also include mode-field adapters to improve the coupling efficiency on- and off-chip.

It should be noted that the modal cutoff condition of 10 dB/cm propagation loss used in the simulations cannot be straightforwardly applied to these measurements since the performance of scattering boundary conditions is inherently different from substrate leakage. Regardless, it is clear from the streak measurements that extremely high attenuation values are achieved

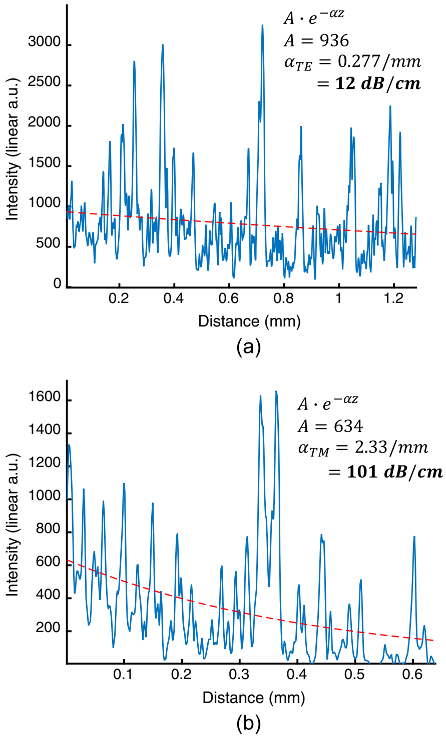

Fig. 5. Measured (solid) and fitted (dashed) intensity of scattered light for $w = 300$ nm at $\lambda = 405$ nm for (a) TE and (b) TM modes.

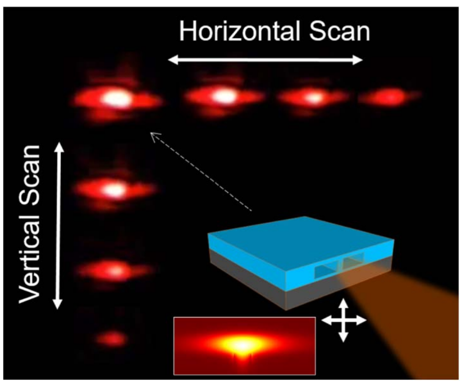

Fig. 6. Images of the optical mode collected from a T-Guide during horizontal and vertical misalignment of the focused input beam onto the facet. The faint lines above and below the mode are a result of aberrations in the imaging optics used. Inset: simulated intensity profile of the mode. A video of the complete scan is available in Visualization 1.

for the TM mode in comparison to those of the TE mode, thus demonstrating strong single-polarization operation over a span of more than 1.27 octaves (405–976 nm) in the case of $w = 300$ nm, limited by the lasers available for the measurement and the camera's spectral sensitivity. A maximum PDL of 89±19 dB/cm was observed in the case of $\lambda = 405$ nm for $w = 300$ nm (based on 12 dB/cm loss for the TE mode and 101 dB/cm loss for the TM mode). The 1.27 octave SMSP window is significantly higher than the previous record of 0.23 octaves in optical fibers [7].

Although the single-mode behavior of T-Guides is derived from the same well-understood mechanism as for shallowly etched ridge waveguides [16], it is nevertheless desirable to provide an experimental confirmation of this. To this end, the tightly focused input beam at 633 nm wavelength was scanned both horizontally and vertically across a T-Guide facet (with $w = 300$ nm) while the output mode profile was imaged with a camera (Fig. 6). The existence of higher-order modes would be evidenced by a change in the spatial distribution of the intensity during the scan. However, the mode retains its shape and only changes in absolute intensity, confirming that only one transverse mode is permitted in the T-Guides.

In conclusion, the SMSP properties of silica-based anchored-membrane (T-Guide) waveguides were numerically and experimentally investigated. Silica T-Guides were fabricated and characterized from the visible to infrared using streak imaging. Polarization-dependent losses of up to 89±19 dB/cm were measured with minimum TE-mode losses of 12±4 dB/cm, and an SMSP window >1.27 octaves was experimentally observed, limited only by the measurement equipment available. These results support the expected broadband SMSP behavior of these structures and establish T-Guides as a promising candidate for high-quality on-chip nonlinear photonics.

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