Ultra-low-loss Single-mode Si_3N_4 Waveguides with 0.7 dB/m Propagation Loss

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Abstract: We report an approach to make ultra-low-loss waveguides using fixed-index-contrast stoichiometric Si_3N_4. A record low single-mode propagation loss of 0.70 ± 0.02 dB/m was achieved while multi-mode designs have fundamental mode loss as low as 0.43 ± 0.04 dB/m.
OCIS codes: (130.2755) Glass Waveguides; (230.7390) Waveguides, planar.

1. Introduction

In order to meet the increasing technological demands of many photonic applications with integration, the performance advantages of optical fiber must be brought to the chip scale. In particular, communication network filters [1], rotational velocity sensors [2], optical buffers [3], true-time-delay beam-steering networks [4], and other applications requiring long propagation distances and high-Q resonators can benefit from ultra-low propagation loss. One approach to realizing low-loss waveguides on a chip emulates the glass technology of optical fibers in planar fabrication processes in order to deposit low-index-contrast (often < 1%) phosphorus-doped, germanium-doped, and undoped silica cores [5-7]. Another approach utilizes the various stable compositions of silicon oxynitride (SiON) to offer a wide range of index contrasts [8]. To date, the lowest-loss waveguides at $\lambda = 1550$ nm are the single-mode phosphorus-doped waveguides reported by Adar, et al. and the "quasi-single-mode" germanium-doped waveguides reported by Kominato, et al. with 0.85 ± 0.03 dB/m and 0.3 dB/m propagation losses, respectively [5,6].

In [9], we demonstrated how stable stoichiometric Si_3N_4 films, with a fixed index contrast of ~25%, can be used to achieve record low single-mode propagation losses from 8 down to 3 dB/m in the bend radius regime extending from 0.5 up to 4 mm. Sidewall scattering was identified as the dominant loss mechanism in these waveguides. Using a loss model that optimizes waveguide core geometry with respect to lowest combined bend and interfacial scattering losses at $\lambda = 1550$ nm, we projected that single-mode propagation loss on the order of 1 dB/m could be realized at larger bend radii through an increase in the aspect ratio (width:thickness) of the Si_3N_4 core. In this work we present SiO_2/Si_3N_4 waveguides with such optimized geometry. We report better-than-projected low-loss performance due to an improvement in etched sidewall roughness resulting from a photoresist reflow process.

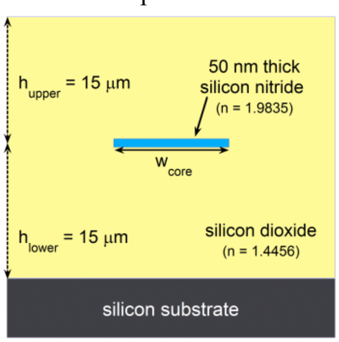

Fig. 1. Waveguide structure (not to scale). Core widths of 5.3, 6.5, 8.5, 9.0, 9.5, 12.5, 13.0, 13.5, 14.0, and 14.5 µm were fabricated.

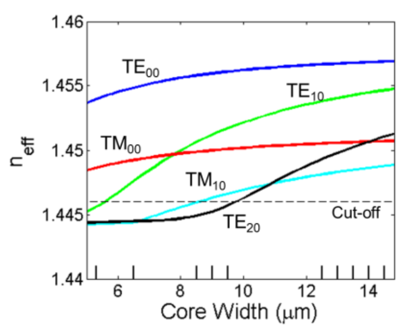

Fig. 2. Simulated (λ = 1550 nm) effective index vs. core width for the first 5 modes in a 50-nm-thick-core waveguide. Longer tick marks along the bottom axis indicate fabricated core widths.

Fig. 1 shows the structure of the waveguides fabricated and characterized in this work. The 50-nm-thick cores were deposited via low-pressure chemical vapor deposition (LPCVD) and etched to ten widths ranging from 5.3 to 14.5 µm. A 15 µm lower cladding was grown using wet thermal oxidation of the silicon substrate, while the 15 µm upper cladding was deposited with LPCVD and plasma-enhanced chemical vapor deposition processes. Fig. 2 shows the simulated evolution of the first five modal indices with increasing core width. The 5.3-µm-wide cores are single-mode at $\lambda = 1550$ nm, while wider cores support at least one higher-order mode. Cores wider than 12 µm support two higher-order TE-like modes as well as a higher-order TM-like mode with multiple intensity lobes along the horizontal. In these waveguides, polarization maintaining operation results from the high birefringence [10].

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2. Measurement Method and Results

Fig. 3 shows $\lambda = 633$ nm light propagating through one of the ten waveguides that make up the interleaved spiral loss test structure. Since scattering loss scales by λ^{-4} [11], the small decrease in relative intensity with propagation for the red laser light serves as an indicator of low scattering loss. As shown in Fig. 4, light in each waveguide traverses a range of bend radii from ~30 mm to ~20 mm that changes almost linearly with respect to propagation distance before reaching the abrupt ~10-mm-radius s-bend section of the spiral. The inset of the figure shows how the seemingly continuous transition in bend radii over one round-trip is actually discretized into 20 sections of waveguide, each with a constant bend radius. The total loss due to bend mode mismatch at these interfaces, not including the s-bend, is simulated to be 0.001 dB for the TE_{00} mode in the 5.3-μm-wide waveguides using PhotonDesign's FIMMPROP software. This loss is negligible when distributed over the 3.18 meters of propagation.

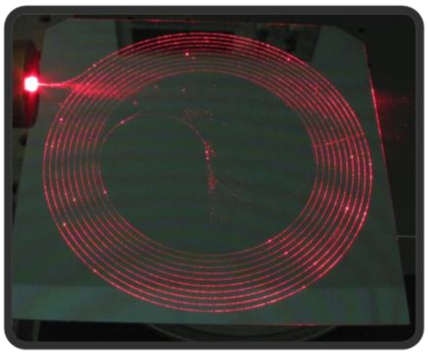

Fig. 3. 3.18 meters of spiraled waveguide with 10 waveguides of different core widths interleaved.

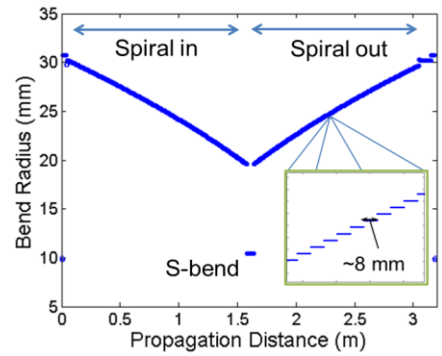

Fig. 4. Bend radius vs. propagation distance for the waveguide shown in Fig. 3.

As in [9], propagation loss in the spiraled waveguides is measured using optical frequency domain reflectometry (OFDR). In OFDR, the return loss amplitude measured from a small section of waveguide is proportional to the optical intensity reaching that point. Assuming a waveguide structure and modal excitation that is invariant with propagation distance, the return loss amplitude decreases linearly (on a dB scale) with a slope that is equal to twice the propagation loss of the waveguide (in dB/m). For the 5.3-μm-wide waveguides, fitting this slope yields a record low single-mode propagation loss of 0.70 ± 0.02 dB/m. To illustrate other interesting phenomena observable with OFDR, Fig. 5 shows data for a multi-mode waveguide. Two ordinary least squares fits were performed on either side of the spiral s-bend in order to extract the propagation loss. The fit region is not extended to regions near large reflections since the phase noise of the OFDR source could influence the fit there [12]. Furthermore, return loss data falling outside of the typical Gaussian distribution of the waveguide backscatter (shown in the inset) are not included in the fit. Such points indicate an abrupt change in the backscatter proportionality factor, i.e. a local scatterer, which violates the required condition of a structure that is invariant with propagation distance when relating the backscatter slope to distributed propagation loss.

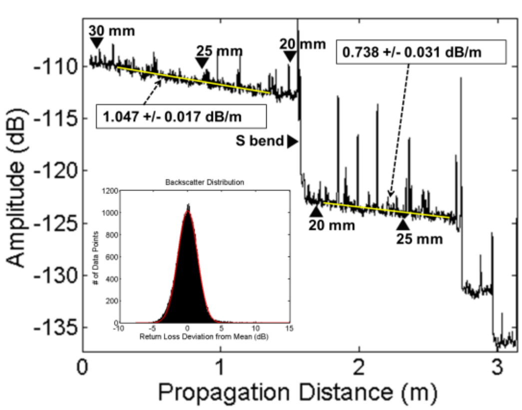

Fig. 5. Example Luna OBR 4400 trace from a multi-mode 12.5-μm-wide waveguide. Arrows indicate the local bend radius. Inset shows backscatter distribution around the mean.

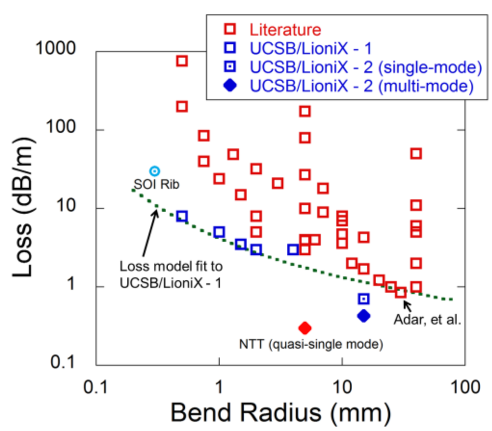

Fig. 6. A comparison of this work (blue) with various state-of-the-art technologies found in the literature (red). Single-mode waveguides have square markers while others have a diamond.

Large reflections at the s-bend and the asymmetry in loss slope before and after the s-bend imply that the s-bend behaves as a higher-order mode filter in multi-mode waveguides. Before the s-bend, higher-order modes in the waveguide propagate with greater loss, likely due to increased bend and substrate leakage loss for these less-confined modes. After the s-bend, the field is primarily composed of the fundamental TE-like mode, which has reduced total loss in this structure. This conclusion is supported by the observation of a similar change in loss slope when switching the input and output ports of the measurement. The lowest fundamental mode loss measured in a multi-mode waveguide structure is 0.43 ± 0.04 dB/m. More interesting features from the OFDR traces for various waveguide widths will be presented orally.

Fig. 6 plots loss values for this work along with those reported in the literature versus waveguide bend radius. The plot includes loss values from [5-9], as well as those references included in the text of [9]. The downward slope of the loss values with increasing bend radius illustrates the bend vs. scattering loss trade-off common to a wide range of single-mode waveguide technologies including Ge-doped SiO_2, P-doped SiO_2, SiON, polymer, and Si_3N_4 cores. For clarity, the previous single-mode low-loss record reported by Adar et al. is indicated with an arrow. In [9], our loss model was fit to loss data obtained at various bend radii using 80, 90, and 100 nm-thick Si_3N_4 cores. RMS roughness values of 14 and 0.1 nm were extracted for the core sidewall and surface, respectively. As can be seen from the green dashed line in Fig. 6, those roughness values yield an expected single-mode scattering-limited loss around 1 dB/m for the bend radii of 20-30 mm in our spiral test structure. In this work, atomic force microscope measurements were performed on Si_3N_4 cores after etching and before upper cladding deposition. A slightly higher RMS surface roughness of 0.175 nm was measured, while a lower measured RMS sidewall roughness of 4.75 nm indicates an improvement due to the photoresist reflow process. Putting these RMS deviation values into our loss model along with roughness correlation lengths of 30 and 50 nm for the surface and sidewall, a total scattering loss of 0.51 dB/m is obtained for the fundamental TE-like mode of the 5.3-μm-wide waveguides. This indicates that scattering loss remains the primary contributor to loss in these waveguides.

3. Summary and Conclusion

We have demonstrated an ultra-low-loss planar waveguide technology fabricated using stable and stoichiometric Si_3N_4 films deposited with LPCVD. Record low single-mode propagation loss in these waveguides was measured with OFDR to be 0.70 ± 0.02 dB/m, while the lowest fundamental mode loss in a multi-mode structure was 0.43 ± 0.04 dB/m. The spiral test structures measured include bend radii in the 10-30 mm range. The single-mode loss is lower than projected because of a decrease in sidewall roughness resulting from an intentional photoresist reflow.

4. Acknowledgements

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