Ultra-low Loss Silica-based Waveguides with Millimeter Bend Radius

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Abstract *We characterize an approach to make compact low loss silica on silicon waveguides and achieve good agreement with theory. Record low losses of 8 dB/m for 0.5-mm bend radius down to 3 dB/m for 2-mm bend radius were achieved.*

Introduction

Photonic integration is important for advanced optical networks with increased requirements on performance, cost, functionality and reliability. Photonic integrated circuits offer increased stability, smaller footprint and have the potential to drastically reduce energy consumption.

Achieving ultra-low loss waveguides is a critical next step in the roadmap towards high performance, large scale, low cost PICs. The most promising and wide-spread technology platform for ultra-low loss planar lightwave circuits (PLC) is silica-on-silicon. Adar et al. reported 0.85 dB/m propagation loss at 30-mm bend radii, using P-doped silica[1]. More recently Kominato et al. reported an average loss of 0.3 dB/m in a PLC including bend radii of 5 mm, using a multi-mode, large-core Ge-doped silica waveguide[2]. These ultra-low propagation losses are beneficial for large scale integrated PLCs, but also open up opportunities for integrating very long optical delay lines on a chip. Optical buffer technology[3] and fiber-optic gyroscopes[4] will greatly benefit from the increased stability and low-cost that ultra-low loss PLCs offer.

There are three requirements for a feasible and practical low loss waveguide technology platform. Firstly, PIC footprint is a key metric for many circuits and applications. The bend radii and corresponding bend losses are key factors limiting the performance-footprint tradeoff. Secondly, to meet demands on functionality, it should be possible to integrate the waveguide with other passive components such as splitters or combiners. Lastly, the fabrication of a PLC should be uniform and reproducible.

In this paper we report the use of a silica based single-mode Si_3N_4-core strip waveguide that achieves ultra-low losses. The waveguide characteristics are determined by structural design, utilizing stoichiometric and stable SiO_2 and Si_3N_4 glasses for repeatability of the fabrication. We report record-low waveguide propagation losses in the regime of bend radii ranging from 0.5 mm up to 4 mm. Measurements were done using two different techniques for verification. Furthermore we report the realization of a multi-mode interference coupler (MMI) in this technology, which shows the feasibility of this approach as a platform for ultra-low loss and highly integrated PLCs.

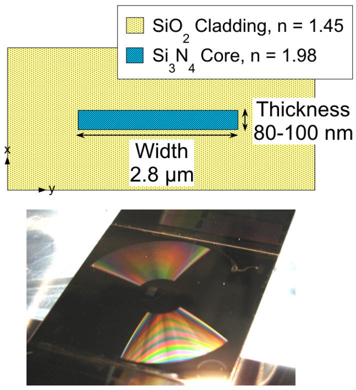

Fig. 1: (top) Schematic cross-section of waveguide (bottom) Top-down view of 20-m spiral delay having a footprint of 9 cm^2.

Waveguide Structure

In silica-based waveguides, scattering at the core-cladding interface dominates over scattering due to irregularities in the bulk core and cladding materials' refractive indices. So to reduce waveguide scattering losses for a given material system, the geometry of the core should be designed such that the modal field amplitude at the core-cladding interface is minimized.

To achieve this, the optical mode can be "buried" in a large multi-mode waveguide core[2], but the possible excitation of higher-order modes then limits the applications. At the other extreme the mode can be "squeezed out" using a core of sub-wavelength dimensions. However the low mode confinement then limits the

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minimum achievable bend radius, and a trade-off between bend radius and loss has to be found. This approach is explored in this paper.

Since sidewall roughness, which is caused by lithography and etching, is typically larger than surface roughness, which is caused by the deposition, the optimal core geometry is elongated in the horizontal direction as pictured in Fig 1. This elongation leads to differences in propagation constants for the TE and TM polarized modes, yielding a waveguide with better polarization-maintaining qualities. The waveguides in this work have been realized by LioniX BV using the TriPleXTM fabrication technology described in ref. 5.

Fig. 2 shows the calculated overlap factors of the optical mode with the sidewall and surface respectively. The modes are simulated via film mode matching, and the overlap of each surface with the modal field squared is calculated according to Payne and Lacey's formula[6]. It can be seen that by decreasing the waveguide thickness the sidewall overlap factor is reduced. As the thickness is reduced, the core width is increased in order to maintain high enough mode confinement for low bend loss operation at reasonably small bend radii. For this work we have designed waveguides with core widths of 2.8 µm to guarantee single-mode operation. We study core heights of 80 nm, 90 nm and 100 nm.

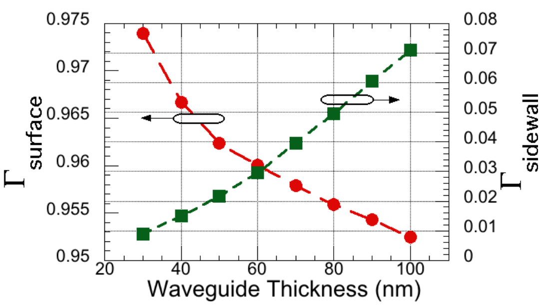

Fig. 2: Dependence of overlap factors on core geometry

Measurement Procedures and Results

In order to separate bend loss from other contributions, waveguide loss was first extracted from the transmission spectra of ring resonators measured using a wavelength tunable laser. Rings with 0.5, 1, 1.5, 2, and 4-mm radii were measured around a central wavelength of 1550 nm. Each ring resonator has a single two-port coupling waveguide with a coupling region offset by ~2 µm. The transmission spectrum of such a resonator can be fit according to ref. 12. The three waveguide core thicknesses measured were chosen to have negligible bend loss at a bend radius of 2 mm, the minimum bend radius of the 20-m spiral delay pictured in Fig. 1.

In Fig. 3, it can be seen that the loss is indeed unchanged for the 2-mm and 4-mm resonators. Furthermore it can be observed that losses increase exponentially for decreasing bend radius below around ~1 mm. In this regime the radiation losses dominate. Our measurements show that propagation losses using the approach reported in this paper can be 8-9 dB/m for 0.5-mm radius and 100-nm core height, decreasing down to 3 dB/m for 2-mm radius and 80-nm core height. These values are well below state of the art as indicated in Fig. 3.

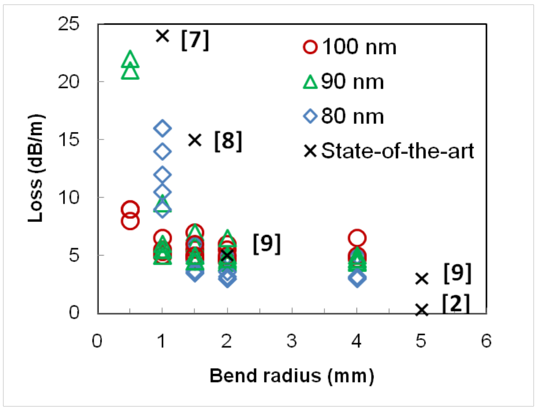

Fig. 3: Propagation losses measured using ring resonators as a function of bend radius. The best results from literature are also shown (black)

To confirm the values extracted from ring spectra, optical backscatter reflectometery[10] (Luna OBR 4400) was used to obtain the loss in a 6-m length spiralled waveguide. The OBR laser sweeps the wavelength range of 1525.00-1610.47 nm in order to obtain time and frequency domain reflected amplitude information with a spatial resolution of 10 µ m across a distance of up to 30 m and with an accuracy of ±0.1 dB. Fig. 4 shows how the decrease in backscattered optical power can be fit in order to extract waveguide loss. Because the slope of the linear fit is a measure of the decrease in backscattered optical power, it must be divided by a factor of 2 to yield the waveguide loss in dB/m, i.e. the return-loss is measured. With the OBR, waveguide loss is measured at 2.91, 4.21, and 5.32 dB/m for the 80, 90, and 100 nm thick waveguides, respectively, confirming the ring measurements.

Finally, we characterized an array of 1 x 2 MMIs with varying multi-mode waveguide lengths. The best performing on-mask MMI design is 375.5 µm long and 15 µ m wide with corners angled 67.7°. The waveguides are spaced 2.35 µ m apart at the MMI output before separating to a final spacing of 25 μm. The power imbalance of the MMI is 0.1 dB, and the insertion loss compared to a reference waveguide is 0.3 dB.

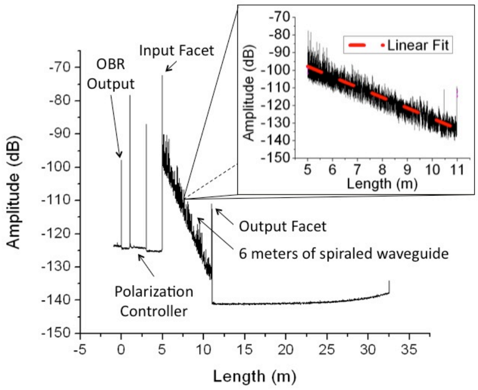

Fig. 4: Reflected power data from Luna OBR (inset) linear fit used to determine loss

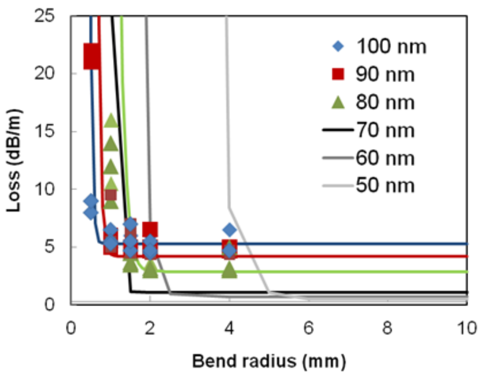

Fig. 5: Measured propagation losses (markers) compared to calculated radiation losses (lines) for waveguides having a width of 2.8 μm. The scattering-loss dominated floor is fitted to the data. The 50-70 nm data are simulation results.

Fig. 5 shows how the measured losses fit with theory. The bend loss is simulated in CAMFR using perfectly matched layers along with a conformal mapping of the bent waveguide index[11]. The simulated radiation loss data agree well with the experimental data. The scattering loss due to roughness has been added to the model and was fitted to the experimental results using a two-parameter equation that includes the surface and sidewall overlap factors,

$$\alpha_{total} = \Gamma_{surface}\alpha_{surface} + \Gamma_{sidewall}\alpha_{sidewall}$$

yielding $\alpha_{surface}$ = 0.2 +/- 0.2 and $\alpha_{sidewall}$ = 64 +/- 5 dB/m. Because $\Gamma_{surface}$ is about one order of magnitude greater than $\Gamma_{sidewall}$ for the waveguides studied in this paper and the ratio of $\alpha_{sidewall}$ to $\alpha_{surface}$ is at least two orders of magnitude, the sidewall contribution to scattering loss is an order of magnitude greater than that of the top and bottom surfaces.

This model can then be used to simulate waveguides with different geometry and predict propagation losses based on the current fabrication technology. In Fig. 5, we show the results of this simulation for core heights of 50-70 nm, having a core width of ~5 μm. These waveguides are single-mode and show losses of 0.5 to 1.1 dB/m at bend radii above 6 down to 1.5 mm for the 50-70 nm core heights respectively.

Conclusions

In summary we have shown ultra-low waveguide losses of 8-9 dB/m for 0.5-mm bend radius down to 3 dB/m for 2-mm bend radius. These losses are the lowest reported for this range of bend radii. The trade-off between bend radius and waveguide loss can be optimized by changing the waveguide height in the design. The waveguide design is by geometry only, using stoichiometric glasses, and hence presents a robust and reproducible fabrication technology.

Investigation of the loss contributions shows that the loss is dominated by scattering due to sidewall roughness. Hence by decreasing the core height we expect a significant decrease of the propagation loss, albeit at larger minimum bend radii. With our model, a loss of 0.5 dB/m at 6 mm radius is predicted for this technology.

Furthermore we have shown the low insertion-loss realization of an MMI coupler in this platform, which means that this platform is very promising for highly integrated and ultra-low loss PLCs.

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