Ultra-Low-Loss (< 0.1 dB/m) Planar Silica Waveguide Technology

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Abstract: We demonstrate record low (0.045 ± 0.04 dB/m) total propagation loss in silica-on-silicon planar waveguides fabricated with wafer-bonded thermal oxide upper claddings.

1. Introduction

Planar waveguides with ultra-low loss are essential in applications requiring long propagation distances or high quality factor resonators. In [1], we reported the lowest *single-mode* propagation loss to date, 0.7 dB/m, in a planar waveguide with a high aspect ratio Si_3N_4 core design. In this work, we present a novel and improved approach where we replace the deposited PECVD top cladding with a high quality thermal oxide by means of wafer bonding. We investigate the spectral dependence of the propagation loss, and we show that these waveguides with bonded oxide upper claddings have record low propagation loss below 0.1 dB/m, short fabrication time, mitigated absorption loss, and low dielectric film stress.

2. Waveguide fabrication

The waveguides are fabricated on Si substrates with 15 microns of SiO_2, n = 1.45, thermally grown on top. In the first step, 40 or 50 nm of stoichiometric Si_3N_4, n = 1.98, are deposited using low pressure chemical vapor deposition (LPCVD). The waveguide cores are then defined with a dry etch that extends fully through the Si_3N_4 layer. A total of 3.1 μm of SiO_2 is then deposited in three steps using tetraethylorthosilicate based LPCVD. The surface is planarized with a chemical mechanical polishing step that consumes 200 nm of the top SiO_2. The waveguides are then completed with either PECVD or bonded thermal oxide upper cladding. In the PECVD upper cladding process, 12 μm of PECVD SiO_2 are deposited, and the waveguides are annealed for three hours at 1150 °C. In the bonded thermal oxide process, the waveguide wafer and another Si substrate with 15 μm of thermal oxide are treated with O_2 plasma before spontaneous bonding at room temperature and pressure. The bond is strengthened by a three hour anneal at 950 °C. The wafer bonding process is faster and cheaper than the PECVD process due to the immediate availability of 15 μm thermal oxide wafers (which can be batch-oxidized), whereas the PECVD deposition takes more than 20 hours. Data in the next section confirm our hypothesis that the wafer-bonded process produces lower residual stress in the dielectric waveguide films, while the thick PECVD upper cladding alters the index contrast significantly due to the stress-optic effect.

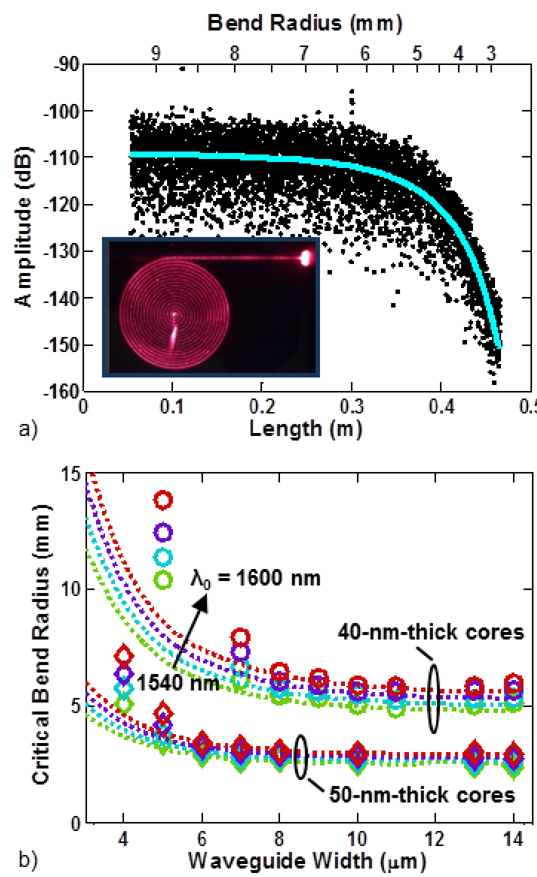

Fig. 1. a) OFDR data used to measure the bending capabilities of planar waveguides. The top horizontal axis shows the dependences of backscatter amplitude on bend radius. The solid line is a nonlinear fit to the data. Data is taken from a spiral structure shown with red laser light in the inset. b) Critical-bend-radius vs. waveguide width for waveguides with 40 and 50 nm thick cores fit at 1540, 1560, 1580, and 1600 nm wavelengths. Dashed lines are simulated values.

3. Waveguide characterization

Coherent optical frequency domain reflectometry (OFDR) is used to measure the optical power loss in waveguides with respect to propagation distance [2]. Spiraled planar waveguide structures are used to characterize the propagation loss as a function of bend radius (inset to Fig. 1a). Twelve waveguides with core widths ranging from 3 to 14 μm are tested. All waveguides begin at a single mode core width before linearly tapering out over the first 22 mm of propagation to the final core width in order to excite only the fundamental mode.

Fig. 1a shows OFDR data taken for a waveguide with a 40-nm-thick by 5-μm-wide core and bonded thermal oxide upper cladding. The solid line is a nonlinear fit of $R_{dB}(z) = -20\log(e)\left[\alpha_1 + \alpha_2(z)\right]z + R_{offset}$ to the reflectivity data, where α_1 is a propagation loss constant that accounts for radius independent scattering and absorption losses and α_2 is a radius dependent bend loss coefficient. The fit to α_2 allows one to determine the bending capabilities of the waveguide. Fig. 1b shows critical bend radius data for waveguides with 40 and 50 nm thick cores and bonded thermal oxide upper claddings. For our purposes, the critical bend radius is defined as the radius at which bend loss equals 0.1 dB/m. For the wider cores, critical bend radius values simulated with refractive indices measured during fabrication, shown as dashed lines in Fig. 1b, fit well to the data. This indicates a minimal change to the refractive index due to the stress-optic effect [3].

Fig. 2 shows the spectral dependence of propagation loss. Data are obtained from OFDR measurements of 1.0 m spiral delays, utilizing a narrowed spectral window and scan of the central wavelength to obtain OFDR data at each wavelength. The lower central axes show a large wavelength range, allowing one to see the spectral dependence of the fit molecular absorption and interfacial scattering loss contributions. The absorption loss peaks are fit to Gaussian functions, the center wavelengths of which are given in the figure color keys, while the scattering loss is fit to a function shape obtained from numerical simulation of the spectral dependence of interfacial scattering loss [1]. The upper left and right figures show the OFDR data (circles) taken around wavelengths near 1.3 and 1.56 μm. The minimum propagation loss measured in the 1.3 μm regime is (0.33 ± 0.03) dB/m. The flatness of the spectral dependence for the bonded thermal waveguides in this regime suggests a mitigation of OH absorption loss for these waveguides. The minimum propagation loss measured in the 1.58 μm regime, obtained at the longest measurement wavelengths furthest from the absorption peaks, is (0.045 ± 0.04) dB/m. Again, absorption losses are mitigated in the bonded thermal waveguide, which has lower propagation loss by about 0.5 dB/m at a wavelength of 1.54 μm as compared to the waveguides in [1]. Reductions in hydrogen impurity concentration in the waveguides should be possible with the appropriate process changes, resulting in lower loss throughout the C band.

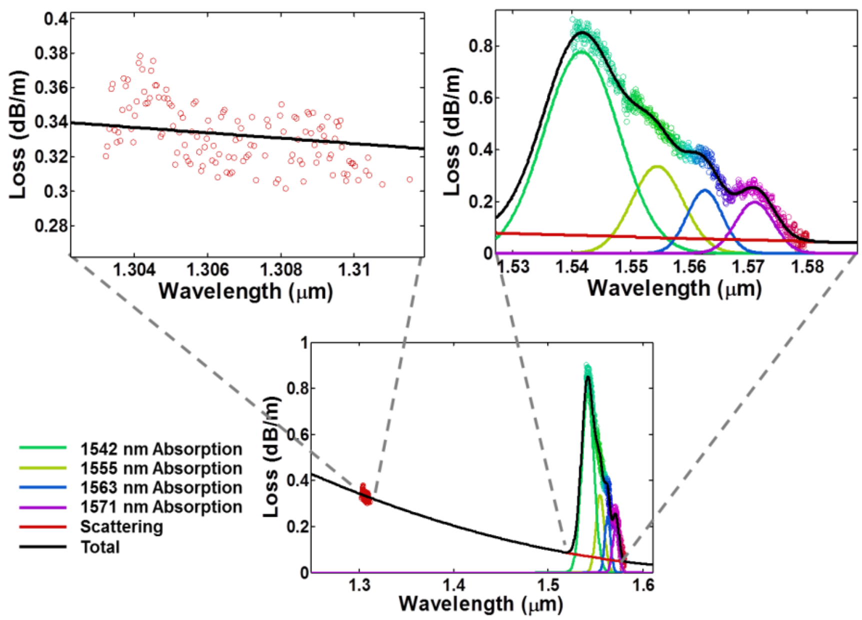

Fig. 2. Propagation loss vs. wavelength for a waveguide with a 40-nm-thick by 13-μm-wide core and bonded thermal oxide upper cladding. OFDR data are averaged over a 50 nm spectral window centered at each marker. The large spectral window reduces the error in measurement, but it also increases averaging of the actual spectral dependence of propagation loss.

4. Conclusions

We have demonstrated a silica-on-silicon planar waveguide platform with propagation loss as low as 0.045 dB/m near 1580 nm. Though propagation loss increases away from this wavelength due to hydrogen impurity absorption losses, we have shown how these loss contributions may be decreased using a wafer-bonded thermal oxide upper cladding. The bonded thermal oxide upper cladding process has the further advantages of shorter fabrication time and low residual dielectric film stress compared to the PECVD oxide upper cladding process. Further reductions in hydrogen impurity concentration should also be possible through processes used in optical fiber manufacturing.

5. Acknowledgements

This work was supported by DARPA MTO under iPhoD contract No: HR0011-09-C-0123. The authors thank Scott Rodgers, Bill Jacobs, Jim Adleman, Justin Klein, and Di Liang for helpful discussions.

6. References

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