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

Jared F. Bauters, Martijn J. R. Heck, Demis D. John, Jonathon S. Barton, Daniel J. Blumenthal, and John E. Bowers
Engineering Science Building, University of California, Santa Barbara, CA 93106, U.S.A.
jbauters@ece.ucsb.edu

Christiaan M. Bruinink, Arne Leinse, and René G. Heideman
LioniX BV, P.O. Box 456, 7500 AH, Enschede, the Netherlands

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 Si₃N₄ 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 SiO₂, n = 1.45, thermally grown on top. In the first step, 40 or 50 nm of stoichiometric Si₃N₄, 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 Si₃N₄ layer. A total of 3.1 μm of SiO₂ is then deposited in three steps using tetraethyloxysilicate based LPCVD. The surface is planarized with a chemical mechanical polishing step that consumes 200 nm of the top SiO₂. The waveguides are then completed with either PECVD or bonded thermal oxide upper cladding. In the PECVD upper cladding process, 12 μm of PECVD SiO₂ 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 O₂ 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.

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. 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. Dashed lines are simulated values.
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 \( R_{\text{dB}}(z) = -20 \log(e)\left|\alpha_1 + \alpha_2(z)\right|z + R_{\text{offset}} \) to the reflectivity data, where \( \alpha_1 \) is a propagation loss constant that accounts for radius independent scattering and absorption losses and \( \alpha_2 \) is a radius dependent bend loss coefficient. The fit to \( \alpha_2 \) 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.

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.

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6. References