Title

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Journal
Optical Fiber Communication Conference (OFC), Los Angeles, California March 6, 2011

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Publication Date
2011-03-06

Peer reviewed

Fabrication and Demonstration of a Pure Silica-Core Waveguide Utilizing a Density-Based Index Contrast

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Abstract: We report a novel approach for creating a dopant-free pure silica-core waveguide (PSCW) for chip-scale waveguides with the goal of reaching fiber-like losses on-chip. Stoichiometric silica films were used as both the cladding and core material for buried channel waveguides, with the required index contrast generated by a difference in physical density. The bulk densities of the thin-films were measured with X-Ray Reflectometry, and these density values were compared with the expected change in refractive index using the Lorentz-Lorenz (Clausius-Mosotti) relation. We found the difference in density of 5.29% to correspond with the difference in refractive index of 1.17%, and measured propagation losses of 2.119 to 2.660 dB/cm.

OCIS codes: (130.2755) Glass waveguides; (310.4925) Thin-Films: Other Properties

Sponsored By:
Defense Advanced Research Projects Agency, Microsystems Technology Office (MTO)
Program: Integrated Photonic Delay (iPhoD), Issued by DARPA/CMO under Contract No. HR0011-09-C-0123
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1. Introduction

Low loss optical fibers to date exhibit losses of 0.15 dB/km [1], 4 to 6 orders of magnitude lower than typical planar waveguide losses, which today are on the order of a few dB/meter for silica-based waveguides and a few dB/cm for semiconductor waveguide platforms [3-6]. Optical fibers, drawn from a boule rather than etched into a thin-film, are typically not limited by the roughness of the core/cladding interface, while the losses of integrated (planar) waveguides are dominated by waveguide roughness [3, 5]. A survey of the history of optical fiber loss reduction (Figure 1) reveals that as silica waveguide roughness losses are reduced the next major loss contributions will be due to OH- concentration and impurities/dopants. In particular, we observe that the lowest loss fibers currently utilize Pure-Silica Core Fiber (PSCF) designs [1,2] .

In this paper we report on a method of fabricating Pure-Silica-Core Waveguides (PSCW) using no dopants. This is of particular interest because commonly used dopants (Ge, P) have been shown to increase the transmission loss of fibers by increasing the capacity of a material to bond to diffused Hydrogen [7].

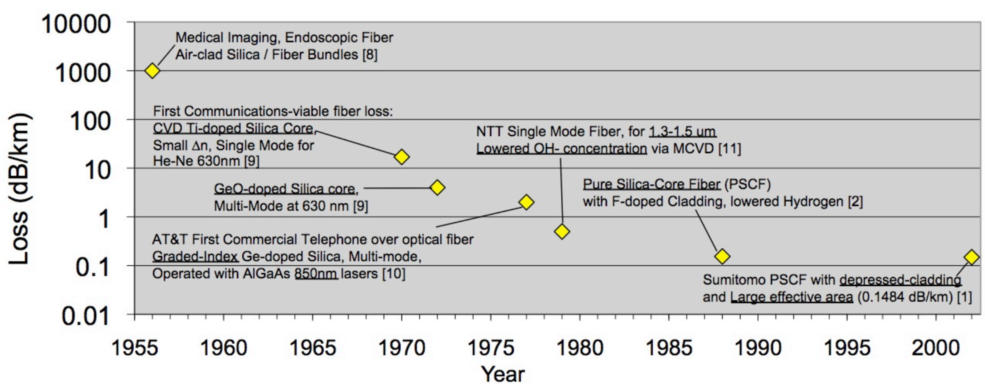

Figure 1: History of Fiber Loss Reduction. The trend is to move towards fewer impurities and dopants near the optical mode, with pure silica-core fibers (PSCF) holding the records for lowest propagation loss.

The Lorentz-Lorenz (or Clausius-Mosotti) relation describes the dependence of a material's refractive index on its physical density. Due to the difficulty of modifying the physical density of a deposited material while maintaining high quality, this relation has not been utilized (to our knowledge) to create an integrated waveguide.

Ion-Beam-Assisted Sputter Deposition (referred to here as IBD) is commonly used for optical coatings due to the high uniformity, quality and purported high density of the dielectric films, increasing the shelf lifetime of optical coatings by reducing absorption of atmospheric water vapor [12]. In this paper we report results on the measurement of the physical density of IBD and ICP-PECVD (Plasma Enhanced Chemical Vapor Deposition with an Inductively Coupled Plasma source) silicon dioxide films and use this disparity to create a density-based index contrast for use in a pure silica-core waveguide.

The use of IBD silica as a waveguide core not only enables a dopant-free PSCW, but has the added benefit of being nearly Hydrogen-free when compared to CVD methods, which utilize Hydrogen-based precursor gasses that introduce O-H absorption losses in the near infrared [13]. This eliminates the need for high temperature annealing, and is thus CMOS compatible. The method is characterized by low deposition rates, and this limitation is somewhat alleviated through the use of an "Assist" ion beam which oxidizes the deposited film, as illustrated in Figure 2.

2. Waveguide Design

With variable-angle spectroscopic ellipsometry (J.A. Woolam EC-400) the refractive index of the stoichiometric IBD SiO_2 film was measured to be 1.4708 ± 2.379E-3 at 1550 nm, which is higher than that of fused silica or thermally oxidized silicon due to higher density of the film (see section 3). Depositing ICP-PECVD SiO_2 at 100°C in a Unaxis VLR system produces a cladding index of 1.4538 ± 4.056E-4 (Table 1). For this index contrast, we fabricated channel waveguides with IBD SiO_2 core thicknesses of 760 nm and widths of 5, 6 and 7 microns, with 10µm ICP-PECVD SiO_2 upper and lower claddings (Figure 3). Waveguide fabrication was performed via contact lithography and a Chromium Hard-Masked ICP-RIE etch of the core silica.

Table 1: Properties of the three SiO_2 thin-films used in the PSCW process

Waveguide Function	Deposition Tool & Method	Film Thickness	Refractive Index @ λ = 1550 nm	Density
Upper/Lower Cladding	Unaxis VLR ICP-PECVD, 100°C	10 µm	1.4538 ± 4.056E-4	2.27 ± 0.052 g/cm^3
Core	Veeco Nexus IBD-O Ion-Beam Assisted Sputter	760 nm	1.4708 ± 2.379E-3	2.39 ± 0.051g/cm^3

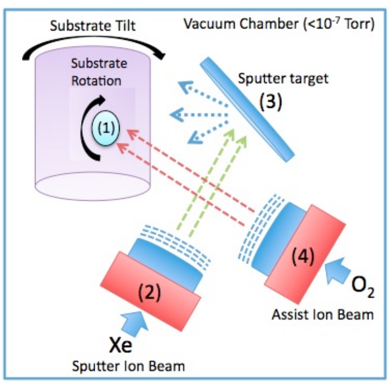

Figure 2: Schematic of the Ion Beam Assisted Sputter Deposition system (Veeco Nexus IBD-O) – a top-down view of vacuum chamber. Sample (1) is tilted at 40° relative to the view-plane, and rotating at 40rpm. The "Depo" ion beam source (2) is focused on the Sputter target (3), sputtering Silicon particles using a Xe ion-beam. The "Assist" ion beam source (4) oxidizes the film with an Oxygen ion-beam.

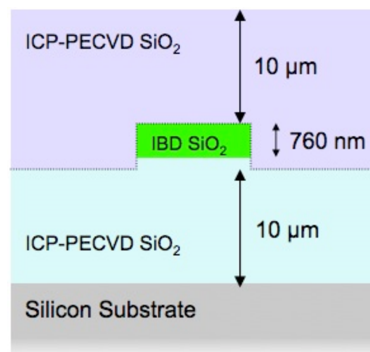

Figure 3: Waveguide structure chosen to minimize scattering and bend radiation losses for 9.8mm bend radius. Widths of 5, 6 and 7µm were fabricated.

3. Density-Based Index Contrast

The theoretical reason that an IBD film has the potential to exhibit higher physical density is due to the ionization of sputtered silicon particles with ion energies greater than that of electrons on the sample surface. X-Ray Reflectometry (XRR) allows us to probe the electron density of the deposited thin-film by measuring x-ray reflection intensity at a range of very shallow incidence angles and subsequently locating the "critical angle" at which the x-ray beam penetrates the film surface. To ensure a distinct disparity between the densities of the deposited silica films and the bulk substrate, sapphire wafers were used as substrates for the XRR measurements.

We measured deposited films of 55 nm of IBD SiO_2 and 53 nm of ICP-PECVD SiO_2 on Al_2O_3 substrates, and obtained density values of 2.39±0.051 g/cm^3 and 2.27±0.052 g/cm^3, respectively.

For transparent materials, the Lorentz-Lorenz relation may be expressed as $(n^2-1)/(n^2+2) = \rho\ (N_A/M)\ (4\pi\ \alpha_m/3)$

where n is the refractive index, ρ is density, N_A is Avogadro's number, M is the molecular mass and α_m is the mean polarizability [14,15]. With a known percentage difference in refractive index of 1.17 ± 1.45E-5%, and using the density-dependent mean polarizability from [16], $\alpha_m = (4.4742- \rho*0.6934)*1e-24\ cm^3$, we solve for a theoretical density difference of 6.27 ± 0.31%, which corresponds relatively well with our measured density difference of 5.29 ± 0.24%. Thus we can say that the majority of the index contrast is due to the difference in physical density.

4. Experimental Loss Measurements

A Luna Optical Backscatter Reflectometry (OBR) system was used to measure the decay in optical backscattering versus distance in a set of 10 cm long straight waveguides, as discussed in [3] and [17]. The optical loss measured by OBR was 2.66 ± 0.123 dB/cm, 2.43 ± 0.0832 dB/cm and 2.12 ± 0.0452 dB/cm for the 5, 6 and 7 micron wide waveguides, respectively.

5. Summary and Conclusions

We have demonstrated the first use of a density-based index contrast to produce a dopant-free pure-silica core planar waveguide, with both cladding and core composed of undoped SiO_2. The measured density difference of 5.29% and index contrast of 1.17% was found to correlate with the Lorentz-Lorenz law. This correlation may be improved via a more accurate method of density determination. We measured propagation losses of 2.12 to 2.66 dB/cm, which may be reduced by further optimization of the lithography and etching processes [18].

Waveguides utilizing a density-based index contrast could be fabricated in other dielectric materials, as long as a tool such as ion-beam sputtering can be employed to increase the density of said film. For example, our IBD system is also able to produce thin-films of Si_3N_4, Al_2O_3, TiO_2 and Ta_2O_5, each of which may have a lower-density analogue produced via other deposition methods such chemical vapor deposition or electron-beam evaporation.

6. References

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