Sharp Bending of On-Chip Silicon Bragg Cladding Waveguide With Light Guiding in Low Index Core Materials

Yasha Yi, Shoji Akiyama, *Student Member, IEEE*, Peter Bermel, Xiaoman Duan, and Lionel C. Kimerling, *Member, IEEE*

***Abstract*—A novel on-chip Bragg cladding waveguide is designed and fabricated using conventional CMOS techniques. This optical waveguide has a low refractive index core surrounded by high index-contrast cladding bilayers. Polysilicon ($n = 3.5$) and silicon nitride ($n = 2.0$) are used for high index-contrast Bragg layers, where index difference is as high as 1.5. Our simulation shows that sharp bending in low index core materials can be achieved, which is not possible using index guiding mechanism. Within our approach, various on-chip applications are expected such as optical integration, high power transmission, biosensor/microelectromechanical system and so on.**

***Index Terms*—Bragg layers, low index core, optical waveguide.**

I. Introduction

INTEREST in achieving light guiding and sharp bending in low-index materials (including air) has increased, with new devices that use a photonic band gap (PBG) [1]–[4] or Bragg reflection [5]–[9] to confine light. Specific examples include two-dimentional (2-D) photonic crystal fibers [10]–[12] and anti-resonant reflecting optical waveguides (ARROW) [13]. Another example, the omniguide fiber, uses high index-contrast concentric dielectric layers to enhance the mode confinement in a relatively simple structure [14]–[18]. It is difficult to fabricate this structure on a silicon chip. However, the same principle of using one-dimentional (1-D) omnidirectional mirrors can be applied to an alternative structure that can be fabricated with current microelectronics technology processes (CMOS compatible processes). Toward that end, an on-chip silicon-based Bragg cladded waveguide is designed with low refractive index material for the core, and stratified high index-contrast dielectric layers as the cladding [19]. Due to the high index contrast of these materials with each other, they have a large PBG, and may act as omnidirectional reflectors, which means light of all incident angles and polarizations is reflected within a specific range of wavelengths (e.g., near 1550 nm). In contrast with an index-guided waveguide, it is possible to confine light to a low index core (possibly air). The high index contrast allows the cladding thickness to be less than 2 μm, which is much thinner than the conventional silica optical bench waveguide. This structure can also be used to efficiently transmit light about bends much tighter than that found in low index contrast index-guided waveguides.

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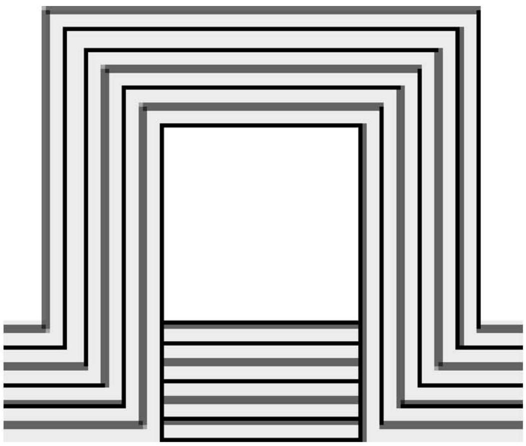
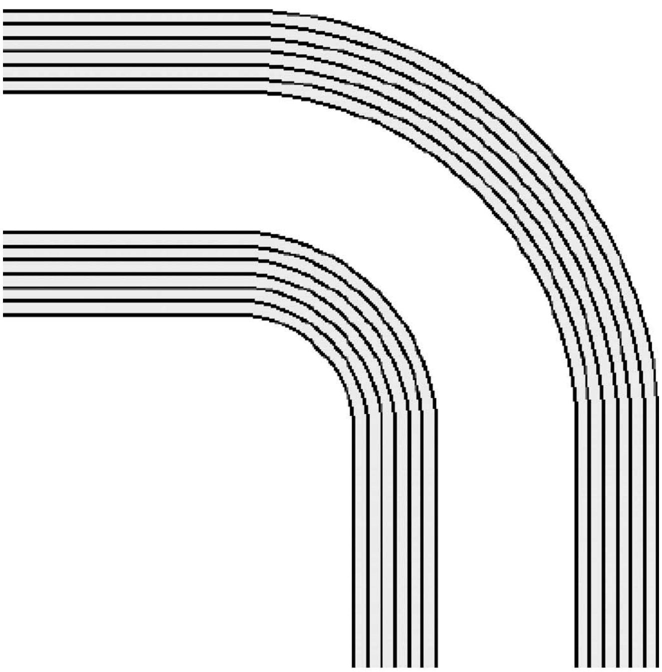
II. Design and Simulation for Sharp Bending

Our proposed structure is briefly outlined in Fig. 1(a). The core is surrounded with Bragg cladding layers, which consists of polysilicon and silicon nitride. The core is uniformly wrapped with PBG layers except bottom corners. This structure is realized by conventional planar CMOS techniques. The thickness of Bragg cladding layers is obtained simply from $\lambda_c/4n$ rule, where λ_c is 1.55 μm. Therefore, the target thickness of polysilicon and silicon nitride is 110 and 194 nm, respectively. For core material, silicon dioxide (SiO_2) is employed as an example. For bends, the inner radii are varied from 2 to 40 μm. Waveguide bending is an important issue, which needs to be addressed if we want to utilize the light propagation in low index core materials. It has been shown that a constant cross section waveguide with a bend maps onto a 1-D quantum problem with a potential well. In 1-D, an arbitrarily weak attractive potential will always create a bound state. It is easy to show that a resonance will occur when a half-integer number of wavelengths are contained within the potential well. In principle, this leads to perfect transmission. Our system is based on the straight on-chip Bragg cladding waveguide, but with a smooth 90° bend, as illustrated in Fig. 1(b). The transmission is calculated by comparing the total integrating Poynting flux going into the bend is compared to the total coming out, for a Gaussian pulse centered around $\omega = 0.203$ $(2\pi c/a)$ and $k_z = 0.191$ $(2\pi/a)$, with a core of $10a \times 10a$ (a is the periodicity of Bragg cladding layers), which is meant to correspond to the parameters for the TM11 mode. The calculation was done for inner turning radii of $8a$, $15a$, and $22a$. The results indicated a transmission of 91.6% for the smallest inner radius, corresponding to a value of 2.4 μm for $a = 0.3$ μm, and 92.9% for the largest inner radius, corresponding to a value of 6.6 μm. As illustrated in Fig. 2(a) and (b), despite our attempt to choose a $\boldsymbol{k}$-vector corresponding to a resonant mode in the waveguide, it is found that the transmission as a function of frequency is relatively flat.

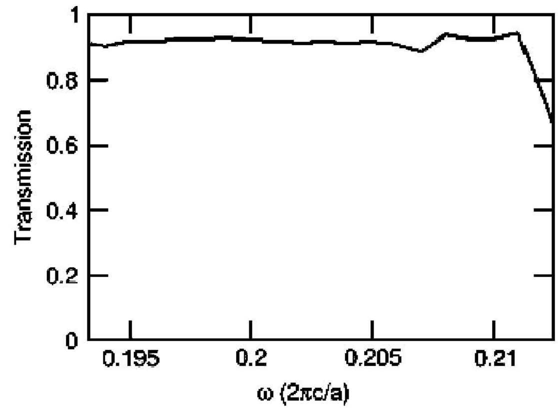


(a)

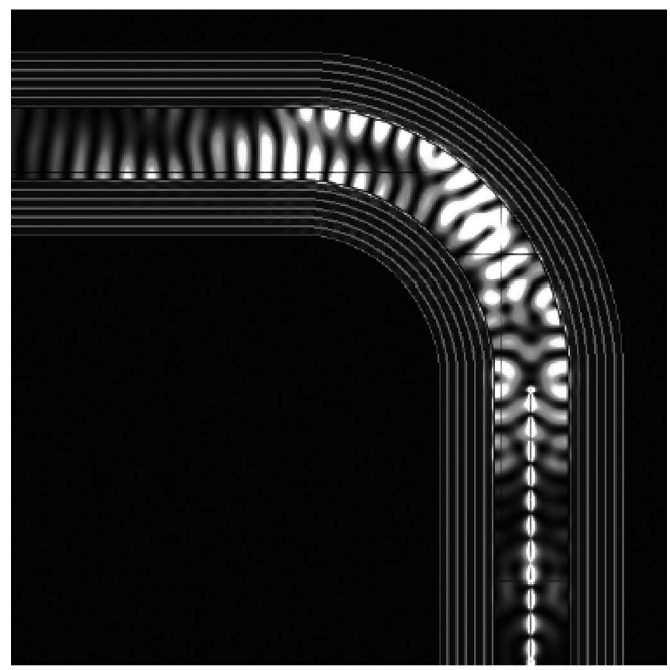


(b)

Fig. 1. (a) Bragg cladding waveguide schematic: Bragg cladding layers surrounds low index core. Bragg layers consist of polysilicon ($n = 3.5$) and silicon nitride $n = 2.0$). (b) Cutaway view of 3-D bend, which locally has an on-chip Bragg cladding channel waveguide cross section everywhere.



(a)



(b)

Fig. 2. (a) Transmission spectrum around a 90° bend for a Bragg cladding channel waveguide structure with an inner radius of $8a$. (b) Distribution of electric field power for light being guided around a 90° bend. The source is the narrow array of bulges in the lower right. Virtually no power is observed to leak from the waveguide suggesting that most losses about the bend are a result of reflection.

III. Fabrication

In contrast to lithographic approach, where photonic structures are fabricated by fine lithography such as e-beam lithography and successive dry etching, a simple and conventional CMOS technique is employed in our case. The fabrication scheme is outlined in Fig. 3. Polysilicon and nitride were chosen as high index contrast materials. Both materials were deposited using low pressure chemical–vapor deposition (LPCVD) process. Polysilicon was deposited using 150-sccm SiH_4 at 625 °C under 200-mtorr pressure with 98-Å/min deposition rate. Silicon nitride was deposited using 250-sccm SiH_2Cl_2 and 25-sccm NH_3 at 775 °C under 200-mtorr pressure with 23-Å/min deposition rate. Oxide was deposited using 150-sccm SiH_4 at 400 °C under 200 mtorr. By employing LPCVD technique, a good step coverage is expected due to its long diffusion length, in addition to good film quality, which is because of its high reaction temperature as compared to plasma-enhanced CVD (PECVD), where the reaction temperature is around 400 °C or other physical vapor deposition techniques such as sputtering, where the substrate temperature is as low as room temperature. The thickness for polysilicon and silicon nitride are 110 and 194 nm, respectively. The deposition was done using SVG/Thermco 7000 series. Using the above conditions and parameters, six pairs of polysilicon/silicon nitride Bragg layers were deposited as well as a 4–6-μm-thick oxide core [(Fig. 4(a) and (b)]. The oxide is densified at 800 °C in N_2 ambient for 4 h to obtain stoichiometric oxide, and chemomechanical polishing (CMP) was applied to

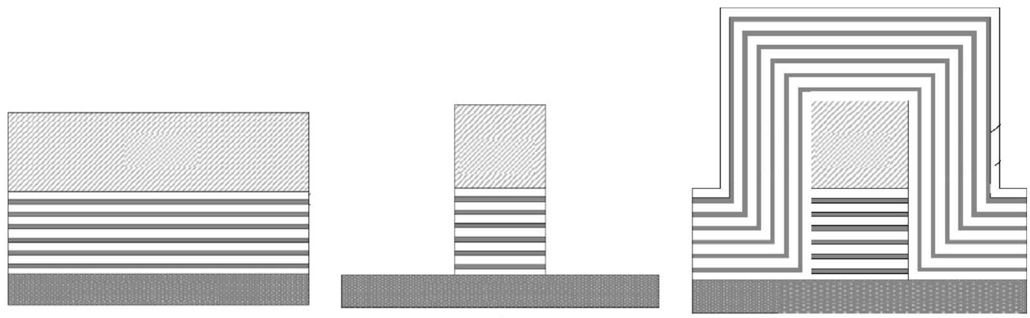


Fig. 3. Waveguide fabrication schematic. All steps are done by conventional CMOS process. (a) Deposit thick oxide (LTO) on Bragg under-cladding layers and densify it. (b) Lithography and dry etch patterning. (c) Deposit top cladding layers using LPCVD process (not to scale).

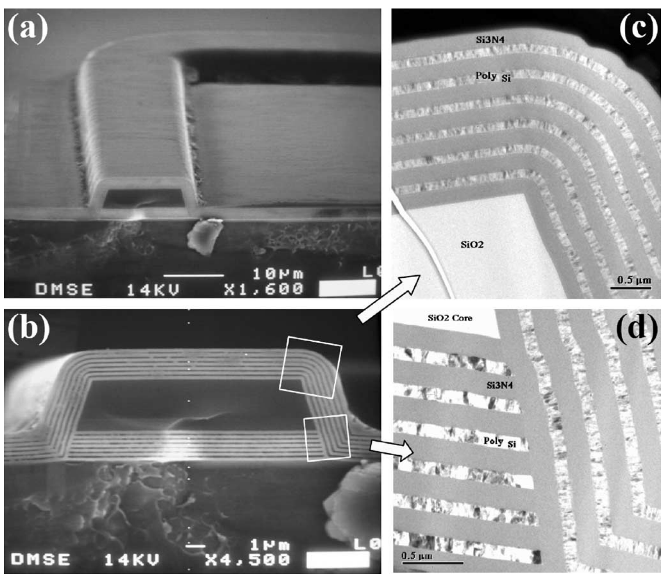


Fig. 4. SEM and TEM images of Bragg cladding waveguide. (*left*) SEM images of PBG waveguide. (a) 1600 × . (b) 4500 × . (*right*) TEM images for top corner and bottom corner. (c) 5000 × . (d) 8000 × .

planarize the top surface in order to suppress the scattering loss. A Strasbaugh Harmony 6EC was used for CMP. Then, the oxide core and Bragg undercladding are patterned and dry-etched by Applied Materials AME5300 using 17.9-sccm C_2 F_6 and 12.1-sccm CH_3F with 1800 W source RF. Then, six pairs of polysilicon/silicon nitride bi-layers are deposited as top-cladding. TEM images for fabricated Bragg waveguides are shown in Fig. 4(c) and (d). It is shown that a good step coverage and uniformity are achieved by this approach.

IV. Waveguide Measurement Results

For waveguide loss measurement, conventional cutback method was employed since these waveguides are multimoded. The Fabry–Perot resonance method, which is considered to be a better approach for accurate measurement, is not available in this case. Due to waveguides' larger core sizes, it can be expected that the alignment between the waveguide and the fiber is relatively easy. Propagation loss of waveguide (α_T) is defined as

$$\alpha_T = \frac{10}{d}\,\log_{10}\left(\frac{P_{\mathrm{in}}}{P_{\mathrm{out}}}\right)$$

where P_{in} and P_{out} are the input and output powers, respectively. d is the length of the waveguide (the chip length). Since P_{in} cannot be measured directly, several lengths were chosen to obtain propagation losses. To suppress scattering losses at the input and output facets and achieve good coupling between the fiber and the waveguide, both facets were polished using a Buehler ECOMET3. The measurement shows that 3 dB/cm loss and 2 dB/90° turn for a 4×20 μm Bragg cladding waveguide have been achieved. Larger losses are observed for thinner waveguides. The observed higher loss than simulation can be attributed to fabrication imperfections such as sidewall roughness, which was introduced during dry-etching step.

V. Discussion and Summary

In this paper, a SiO_2 core is used as the example of on-chip Bragg cladded waveguide structure. However, fabrication need not be restricted to SiO_2—a hollow core could also be fabricated with a slight change in the procedure. This so-called "core freedom" would give rise to multiple applications, for example, transmission of high intensity beams (e.g., for a CO_2 laser) through a hollow core without absorption or nonlinearity or to trap light—or even modify the rate of emission—from an optically active material. It also has unique group-velocity dispersion characteristics, which can be modified with changes to the core. Finally, the on-chip Bragg cladded waveguide has the advantage of relatively small dimensions, including a tight turning radius compared to low-contrast index-guided fibers.

VI. Conclusion

A new low-index core optical waveguide with sharp bending, whose fabrication is fully compatible to the current CMOS technology, is developed. Si and Si_3N_4 are deposited using LPCVD method and high quality Bragg cladding layers are realized. Light guiding and sharp bending in the low-index core is demonstrated. A thin PBG cladding, made possible by the large index contrast between the Si and Si_3N_4 layers, indicates the advantage of this device over traditional silica optical bench waveguides.

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