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A New Approach of Hetero-Cladding for Design of Compact Si Photonic Directional Coupler

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Abstract— In this letter, we propose a new approach of hetero-cladding for realization of compact CMOS compatible silicon photonic directional couplers. The proposed hetero-cladding comprises ferroelectric BaTiO₃ (BTO) and SiO₂ to control the evanescent mode within the structure. The results show very small and identical coupling length for both TE and TM modes with reduced device cross-section, which promises for a huge reduction in the footprint of both conventional and programmable photonic integrated circuits. The concept can also be utilized to design compact, low loss and energy efficient phase shifters, other types of couplers, sensors etc.

Index Terms—Photonic Integrated Circuit, Reduced footprint, Programmable PIC, Directional coupler.

I. Introduction

CMOS compatibility is an important driving force for increased interest in silicon based integrated photonic devices [1-4]. This, along with useful properties of light lead to numerous applications of cutting edge Si photonic technology [5-10]. However, large size of photonic devices compared to the state-of-the-art electronic counterparts leads to larger footprint of Si photonic integrated circuits (PICs). This severely limits the number of on-chip device integration, hence leads to less functionality of the PICs. To avoid it up to a certain extent, recently, programmable PICs have been developed to facilitate post-fabrication manipulation and on-demand reconfiguration of PICs with variety of functionalities [11-13]. These employ two-dimensional meshes of Mach-Zehnder (MZ) couplers as their fundamental building elements with a square, triangular, or hexagonal pattern as their unit cell [11,12,14]. However, since the size of currently used on-chip conventional MZ couplers is large (few 10's of μm), their assembly in a huge number again contributes to extremely large footprint of programmable PICs. To reduce the footprint and making those energy efficient, cost effective and multi-functional, it is very essential to design compact MZ couplers.

In search of ultra-compact couplers, researchers have made use of plasmonics, photonic crystals and other techniques [15-21]. However, most of those follow unconventional design rules with abundant structural modifications. Realization of

ultra-compact MZ couplers without manipulating the cores of regular on-chip conventional bus waveguides is still a major concern. Using ferroelectric BTO as cladding material has been shown to be useful in reducing length of the switching device. BTO is being widely used in Si photonics due to its low loss, high quality growth on Si and its very high Pockels coefficient ($\sim 1000 \text{ pm/V}$) etc. [22-26]. It's refractive index (n) varies from 2.41 (n_o) to 2.36 (n_e) tracing the orientation of its ferroelectric domains from in-plane (a -axis) to out-of-plane (c -axis) with application of suitable amount of electric field [27,28]. This huge modulation (i.e., $\Delta n = 0.05$) is fast (takes few tens of microseconds) and quite non-volatile in nature [29-31]. In the proposed approach to tailor only the cladding material, BTO is used as one of the materials for the hetero-cladding, the other being SiO₂. This creates an asymmetry in the dielectric mirror around the cores, which enhances the coupling process by allowing more light in the coupling region.

II. SCHEMATIC STRUCTURE WITH PROPOSED DESIGN

The schematic of the device structure with a new approach to design using SiO₂-BTO-SiO₂ hetero-cladding of thickness ' t ' is shown in Fig. 1(a). The coupling gap is taken as 200 nm to ensure it doesn't violate the minimum experimental limit. In this concept of hetero-cladding, our aim is to gather more light in the cladding which take part in coupling and reducing the light spreading in other cladding region. At the same time, the hetero-cladding also includes the technique of releasing more light from core to cladding without modifying the core structure unlike the slotted/trenched core structure [32]. The whole cladding region of the hetero-cladded coupler is hence divided into two parts, named "Region-1" and "Region-2" (indicated in figure). *Region-1* contributes for light guiding, while *region-2* is involved in coupling process. Fig. 1(b) shows the schematic of the refractive index profile of the given structure. The idea here is to keep *region-1* with a cladding material of high refractive index contrast (w.r.t core) and to replace *region-2* with a low refractive index contrast material, to help the mode evanescent gather there to enhance the coupling as shown later. Moreover, the two additional dielectric interfaces formed at the junction of both the claddings (indicated as dashed orange lines in Fig. 1(b)), will prevent spreading of the mode evanescent in

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region-1. As it is shown in Fig. 1(a), BTO is used as cladding for region-2, by keeping region-1 as SiO₂. This kind of cladding design creates a strong reflection of light at the outer walls of the cores (red lines in Fig. 1(b)), whereas a weak reflection at the inner wall and top of the cores (solid orange lines in Fig. 1(b)). This asymmetry in reflection helps pushing the mode shape more towards the BTO cladding i.e. to region-2, without seeking for any modification in the core. Weak reflection at inner side wall and top of the cores could also help the device become less sensitive to roughness at the core-coupling region interface.

The proposed structure can be fabricated using the procedures indicated in literature [26, 29, 33-35]. For example, after the growth (/patterning) of the doped Si-core waveguide, BTO layer can be deposited around the Si-cores using pulsed layer deposition technique [29]. A mask can be used along with a photoresist to etch out the BTO from the sides using inductively coupled plasma (ICP) etching technique leaving BTO cladding only on the top [35]. It may be mentioned here that a slight misalignment of the BTO edge and Si-core edge won't affect the performance reported in this study. The side cladding now can be filled with growth of SiO₂.

To exploit the electro-optic effect of ferroelectric BTO, three independent ITO electrodes could be employed (Fig. 1(a)) in two biasing configurations, say "biasing-1" (to set n to n_e) and "biasing-2" (to set n to n_o) (Fig. 1(c)) as reported earlier [28,36]. Initially n is taken as n_o . Also, both the cores are n-doped ($\sim 10^{18}$) to behave as a part of bottom ITO electrodes.

III. NUMERICAL RESULTS AND SELECTION OF STRUCTURE PARAMETERS

This part of study employs FEM based simulator (COMSOL) to optimize the structure parameters as follows.

A. Estimation of Core Width and Coupling Length

Fig.2 shows a comparison between the mode shapes of the proposed hetero-cladding and the uniform (BTO) cladding structure. Comparing Figs. 2(a) and (b) it can be seen that, the presence of TM mode evanescent in the central BTO cladding

is more in the case of hetero-cladding structure, for both even and odd modes as anticipated in section-II. This also happens for TE modes (Fig. 2 (c) & (d)), but with the mode shapes pushed more towards the BTO cladding region. This, helps reducing the coupling length (L_c) of TE mode prominently.

Fig. 2. Mode profiles of directional coupler for (a,c) uniform BTO cladding, and (b,d) SiO₂-BTO-SiO₂ hetero-cladding (core width=450 nm).

Results for estimated coupling length for proposed hetero-cladding structure as a function of cladding thickness (t) for three values of core width ($W_c = 400, 450$ and 500 nm) are shown in Fig. 3. Considering the intermediate W_c , (Fig. 3(b)), L_c is now of only ~ 11 μm and 9 μm (dashed lines) for TE and TM mode respectively, which saturates at a cladding thickness of only $t \approx 1300$ nm. We have seen from our simulation study that, this L_c is $\sim 60\%$ smaller than traditional uniform SiO₂ cladding case (for TE mode) and $\sim 40\%$ smaller than uniform BTO cladding case, which occurs at a t which is only $< 30\%$ of the t needed in uniform BTO cladding case (where $t > 3000$ nm). As indicated in figure, on changing n from n_o to n_e , L_c for both TE and TM modes undergo further reduction and finally converge into an identical value (solid lines in figure). That means, for a fixed value of L_c (i.e. of a fabricated structure), both the modes get fully coupled. Moreover, switching n back and forth between $n_e - n_o$, the power coupling can also be tuned.

Comparing Fig. 3(b) with (a) and (c) shows that, Fig. 3(a) gives larger L_c and Fig. 3(c) shows negligibly small tuning with L_c values for TE and TM modes. At the same time, Fig. 3(b) ($W_c = 450$ nm) shows promising behavior with smaller and identical L_c and equal range of tunability for both $n = n_o$ and n_e , as compared to $W_c = 400$ nm (Fig. 3(a)). Thus, this study found $W_c = 450$ nm as the optimum waveguide width.

Fig. 3. Coupling length of directional coupler with hetero-cladding for both $n = n_o$ (dashed line) and $n = n_e$ (solid line) for wave guide widths of (a) 400 nm, (b) 450 nm, (c) 500 nm.

B. Estimation of Transverse Dimension

As shown in Fig.2, light in cladding is mainly present in *region-2*, with its negligible presence in *region-1*. This greatly reduces the transverse dimension and power loss of the device. Absence of mode evanescent beyond few 100's of nanometers from outside wall of the cores allows the side electrodes sit closer to them without any significant contribution to insertion loss. This leads to the need of less applied voltage.

The amount of loss experienced by the structure (with optimized core-to-side electrode gap (d_{el}) of 500 nm and thickness t of 1300 nm) for TE and TM modes are around 0.052 dB and 0.057 dB respectively with $n = n_o$, and is 0.035 dB and 0.040 dB for $n = n_e$. The estimated loss for uniform BTO cladding case for same structure parameters are around 0.135 dB and 0.179 dB respectively for TE and TM modes with $n = n_o$, and is 0.138 dB and 0.14 dB with $n = n_e$; thus showing 3-4 times improvement in the proposed hetero-cladding structure.

Finally, the optimized parameter values are summarized in Table I. It can be seen that, the values of minimum L_c may be kept $\sim 7.1 \mu\text{m}$ for both TE and TM modes, which may further reduce if coupling assisted by bending is considered as in an actual design, discussed in the following sub-section.

TABLE I
OPTIMIZED PARAMETER VALUES OF THE PROPOSED STRUCTURE

Symbol	Structure Parameters	Optimized Values
t	Thickness of cladding	1300 nm
d_{el}	Core to side electrode Spacing,	500 nm
W_c	Width of core	450 nm
L_c	Minimum coupling length for TE and TM mode for $n = n_o$	11 μm (TE) 9 μm (TM)
L_c	Minimum coupling length for TE and TM mode for $n = n_e$	7.18 μm (TE) 7.12 μm (TM)

C. Optical Design

Using suitable dimensions as discussed above, the schematic of optical design and the power coupling plot are shown in Fig.4. As shown in Fig. 4(a), the structure uses a bending radius (b_r) of $8 \mu\text{m}$ with hetero cladding only in the straight coupling region. Fig. 4(b) shows the light coupling (seen to be $\sim 97\%$ from simulation) with an insertion loss of about 0.14 dB. Thus, high power coupling can be achieved with this design for reduced footprint. This L_c is less than the minimum L_c mentioned in Table I because of the bending arms. Fig. 4 (c) shows power coupling assuming 50 nm of under-filling at the bottom of coupling gap (assuming any fabrication constraint).

Fig. 4. (a) Schematic of coupler (b) power coupling for $n = n_e$ without under filling and (c) with 50 nm of under filling.

Simulations show that the power coupling here is 2 % less. It may be mentioned here that the power coupling can be tuned to some extent by applying a suitable bias as reported earlier [41].

IV. CONCLUSION

A new approach of hetero-cladding (BTO/SiO₂) has been proposed for realization of compact silicon photonic devices through realization of compact directional coupler. The design is capable to make the coupler more than 60% smaller compared to traditional uniform SiO₂ cladded structure. An optical design shows high power coupling using the designed small coupling length. The concept of hetero-cladding could also be used to improve the performance of other type of couplers, sensors, phase shifter, switches, power splitters etc.

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