A New Approach of Hetero-Cladding Using Ferroelectric BaTiO₃ and SiO₂ for Design of Compact Si Photonic Tunable Directional Coupler

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Abstract— The present work proposes a new approach of hetero-cladding for silicon photonic directional couplers and outlines its contributions towards realization of a compact, tunable and energy efficient directional coupler. 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 (PICs). The proposed concept could also be utilized to design compact, low loss and energy efficient phase shifters and other types of couplers.

Index Terms—Integrated Photonics, Programmable Photonic Integrated Circuit, Integration Density, Small footprint, Energy efficient, Identical coupling length

I. INTRODUCTION

SILICON based integrated photonics has paved its way towards several cutting edge technological applications such as data centers, high performance computing, and sensing, owing to its number of advantages like low loss, good confinement, CMOS-compatibility, etc. [1-9]. In spite of all such benefits, relatively large size of photonic devices compared to its electronic counterparts poses a major limitation for high density integration of photonic ICs (PICs). Other than consuming much space, large size of photonic devices also increases energy consumption and cost of the PICs. Thus, there have been tremendous efforts by researchers across the globe to address this challenge of reducing size of photonic devices and components to exploit the full benefit of photonics towards design of low footprint and energy efficient PICs [10-12].

Besides, now-a-days, to face the increasing complexity of photonic circuits, programmable PICs have drawn immense research interest to make the PICs multi-functional [13,14]. Being a new generation PIC, these facilitate post-fabrication manipulation and on-demand reconfiguration of PICs with a variety of functionalities, by avoiding custom chip fabrication

[15]. It is now possible to fabricate complex interferometric systems on a chip, by incorporating architectures and algorithms within it, for its programming and control. Among these, some architectures even allow for self-configuration, adapting arbitrary matrix operations to solve real time optical problems, without going for high-level calculations [16,17].

Programmable PICs have often been reported in literature by employing two-dimensional meshes of Mach-Zehnder (MZ) couplers as their fundamental building elements. These couplers are usually arranged in a square, triangular, or hexagonal pattern, defining unit cells of programmable PICs. [13,14,18-20]. Connectivity of these unit cells (design of mesh), determines the way in which the PIC can be configured, and behave. Since the size of currently used MZ couplers is large (few 10's of μm), their assemble in a huge number contributes to the extremely large size of programmable PICs. To reduce the footprint of programmable PICs and turning them into compact, energy efficient and cost-effective PICs, it is essential to design compact MZ couplers. The present study focuses on implementation of a new hetero-cladding technique in directional coupler, anticipating for compact and tunable silicon photonic coupler.

Ferroelectric BTO is being widely used in silicon photonics industry for design of several successful photonic devices [21-24]. On application of an appropriate electric field, refractive index (n) of BTO changes from its ordinary axis value ($n_o = 2.41$) to its extraordinary axis value ($n_e = 2.36$) with the orientation of ferroelectric domains from in-plane (a -axis) to out-of-plane (c -axis) [25]. This huge modulation of the refractive index, i.e., $\Delta n = 0.05$, is fast (takes few tens of microseconds) and quite non-volatile in nature (lasts more than a week) [26,27]. This makes BTO suitable for being used as a cladding material for the silicon photonic waveguides and helps in realization of fast, non-volatile, and energy efficient optical components such as photonic phase shifters. In this paper, 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 with

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availing more light in the coupling region.

Section-2 discusses in detail the aim and engineering involved in the structure with proposed cladding concept and in section-3 numerical results and selection of structure parameters are discussed. Section-4 shows the study for bias dependent coupling length and discusses the advantages of this study over the conventional system. Section-5 gives the conclusion of this work.

II. DEVICE STRUCTURE

The schematic of the device structure with proposed cladding concept is shown in Fig. 1(a). The structure consists of two identical silicon cores of 300 nm height, sitting on a SiO_2 substrate and covered with a SiO_2 -BTO- SiO_2 hetero-cladding of thickness ' t '. As shown in the figure, extensions of outer walls of both the cores are continued up to the device boundary with a height of 90 nm, on which the side electrodes are deposited. The top electrode is deposited covering the BTO portion of the cladding. Unlike the conventional structures which use a uniform cladding concept, the proposed structure focuses on a concept of hetero-cladding, with a proper distribution of the whole cladding region into two parts, named "Region-1" and "Region-2" (indicated in figure). *Region-1* covers the cladding region which mainly contributes for guiding the light within the device, while *region-2* covers the region, which is involved in coupling process. The schematic of the cross sectional view of refractive index profile of the structure is shown in Fig. 1(b). 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 (See Fig. 2). Moreover, the two additional dielectric mirrors formed at the interface of both the claddings (indicated as dashed light orange lines in Fig. 1(b)), will help the mode evanescent not to spread easily to *region-1*. Again, employing a ferroelectric material in *region-2*, the coupler could turn into tunable one by exploiting its electro-optic effect. As it is shown in Fig. 1(a), BTO is used as cladding for *region-2*, by keeping *region-1* as SiO_2 . This kind of cladding design creates a strong dielectric mirror at the outer walls of the cores (red lines in Fig. 1(b)), whereas a weak mirror at the inner wall and top of the cores (solid orange lines in Fig. 1(b)). This asymmetry in dielectric mirror helps pushing the mode shape more towards the BTO cladding (See Fig. 2), without seeking for any modification in the core, unlike the uniform cladding concept. This makes the intensity distribution of the mode in cladding to be pushed into the central region of cladding (*region-2*). Weak dielectric mirror 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.

To exploit the electro-optic effect of ferroelectric BTO cladding, the structure needs application of an external electric field. For this to happen, the proposed structure uses three independent ITO electrodes (one top and two bottom electrodes) prepared to be employed as two biasing configurations, say "biasing-1" and "biasing-2". *Biasing-1* is aimed to polarize the ferroelectric domains of BTO along z -axis

by converting the n of BTO from n_o to n_e , and *biasing-2* is aimed to polarize the ferroelectric domains of BTO along y -axis by reverting n from n_e to n_o . In case of *biasing-1*, both the bottom electrodes are connected to positive potential and the top electrode to ground; whereas, in case of *biasing-2*, the left and right bottom electrodes are connected to positive potential and ground respectively, leaving the top electrode floating. The initial refractive index of BTO is taken as n_o . Both the cores are considered as n -doped with a concentration of 10^{18} to act as the part of bottom electrodes in addition to the ITO electrodes sitting upon them.

(a)

(b)

Fig. 1. (a) Schematic of the device structure using ferroelectric hetero-cladding with its coordinate axis, and (b) Schematic of the refractive index distribution and asymmetry in dielectric mirror around the core. The refractive index of core, cladding *region-1* and *region-2* are n_{co} , n_{cl} and n respectively. The red marked interface is the most reflective one while the orange and dashed orange marked interfaces are less reflective. The light propagation occurs along the x -axis within the coupler.

III. NUMERICAL RESULTS AND SELECTION OF STRUCTURE PARAMETERS

In this part of study, we have used FEM based simulator (COMSOL) to obtain the numerical results. Based on the results obtained, the structure parameters are finalized to their optimum values. The estimation of these parameters are explained below.

A. Estimation of Core Width and Coupling Length

At first, the study shows a comparison between the mode shapes of the structure with proposed cladding concept and the

conventional structure. Fig. 2 shows the mode distribution of structure with uniform BTO cladding and SiO₂-BTO-SiO₂ hetero-cladding. Fig. 2(a) and (b) compare for TM mode and (c) and (d) compare for TE mode profiles. It can be clearly seen from Fig. 2(a) and (b) that, the presence of TM mode evanescent in the central BTO cladding region is more for the proposed design than for the uniform cladding, for both even and odd modes. It is because of the two-fold benefit of SiO₂ side cladding layers, which not only reduces the presence of mode evanescent in *region-1* (indicated with red rectangle), but also push the mode evanescent towards the coupling region by creating a high reflective dielectric mirror at the outside wall of both the cores. This also helps in release of more light from core to clad as indicated by black circles in both Fig.2 (a) & (b); due to asymmetric reflectivity around the cores. Similar things happen in case of TE modes too (Fig. 2 (c) & (d)). Because of the strong asymmetry in reflectivity of both the side walls of the cores (Fig. 1(b)), the mode shape is pushed more towards the BTO cladding region, than in case of TM modes. As a result, power release from cores (indicated by black and red marks in Fig.2(c) & (d)) into the cladding increases. This, will affect the coupling length of TE mode prominently. The variation of refractive index (Δn) and absorption ($\Delta \alpha$) of cores as a function of doping density is considered as follows [28].

$$\Delta n(\lambda) = -3.64 \times 10^{-10} \lambda^2 \Delta N - 3.51 \times 10^{-6} \lambda^2 \Delta P^{0.8} \quad (1)$$

$$\Delta \alpha(\lambda) = 3.52 \times 10^{-6} \lambda^2 \Delta N + 2.4 \times 10^{-6} \lambda^2 \Delta P \text{ [cm}^{-1}\text{]} \quad (2)$$

where, ΔN and ΔP are the n -type and p -type doping concentrations respectively. Since we have considered the cores as n -doped, ΔP is kept zero throughout the study.

Prior to study of hetero-cladded structure, the comparison of coupling length for uniform SiO₂ and BTO cladded structure is shown in Fig. 3 for three different core widths ($W_c = 400$ nm, 450 nm & 500 nm). It can be clearly seen from Fig. 3 (a), (b) and (c) that, for conventional SiO₂ cladding, the coupling length of TE mode is substantially higher. On the other hand, in case of uniform BTO cladding (with $n = n_o$) the coupling length reduces drastically (by $\approx 60\%$). However, with uniform BTO cladding, in some cases (TM modes for $W_c = 400$ nm and 450 nm), the variation of coupling length remains significant even for high values of t . A change in refractive index of BTO ($n = n_e$), reduces the coupling length further (by ~ 1 μ m) for all three core widths and reduces the variation of L_c of TM mode for higher t . The plots also show that, the coupling length for both the modes are reasonably low and close to each other for $W_c = 450$ nm, unlike the results for other two core widths. However, the TM mode coupling length is still sensitive to higher value of cladding thickness (up to $t \approx 1600$ nm). The reduction in coupling length due to change in n is also small in this case.

Now we show results for the coupler using the hetero-cladding technique in Fig. 4. It can be seen that, saturation of coupling length for both the modes occurs at much lower t (for $t \approx 1000$ nm) than in case of uniform BTO cladded structure. Again, when n of BTO changes from n_o to n_e , the coupling lengths of both the modes undergo further reduction and finally

converge into an identical value. This reduction in L_c could be recovered by switching n back from n_e to n_o . Thus, by altering the refractive index of BTO, the coupling length can be tuned both in forward and backward direction. This tunability is high in case of narrower cores. For example, for $W_c = 400$ nm, 450 nm and 500 nm, the corresponding tunability for both TE and TM modes are 5 μ m & ~ 2 μ m, 4 μ m & ~ 2 μ m, and 2 μ m & ~ 0 μ m respectively. Though L_c is small for $W_c = 500$ nm, the tunability being very low, it is inadequate for tuning purpose. Among the rests, $W_c = 450$ nm (Fig. 4(b)), shows promising behavior with smaller L_c and equal range of tunability for both the states of BTO (for $n = n_o$ and n_e) as compared to $W_c = 400$ nm (Fig. 4(a)).

Fig. 2. Even and odd mode profiles of directional coupler for (a) TM even and odd modes for uniform BTO cladding, (b) TM even and odd modes for SiO₂-BTO-SiO₂ hetero-cladding (c) TE even and odd modes for uniform BTO cladding, and (d) TE even and odd modes for SiO₂-BTO-SiO₂ hetero-cladding.

Moreover, both the modes have an identical coupling length of 7.1 μ m, which is almost half micron less than $W_c = 400$ nm, that is shown in Fig. 4(a). Thus, this study found $W_c = 450$ nm as the suitable waveguide width for further investigation.

Fig. 3. Coupling length of directional coupler with conventional uniform SiO₂ cladding and uniform BTO cladding for both $n = n_o$ and $n = n_e$ for waveguide widths of (a) 400 nm, (b) 450 nm, (c) 500 nm.

B. Estimation of Transverse Dimension

We have clearly seen that, the proposed hetero-cladding concept offers the benefits of small and identical coupling length for both TE and TM modes. Besides, the mode plots show that, the presence of light is mainly in *region-2*, while in *region-1* is negligible. This helps in huge reduction in 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. Closeness of electrodes towards the cores also makes themselves closer, which increases the possibility of less consumption of applied voltage.

The amount of loss experienced by the structure is shown in Table 1. The table shows results for three different values of core to side electrode gap (d_{el}) and three values of t (also core to top electrode gap) with a doping concentration of 1×10^{19} . In general, loss (Δw) can be calculated using the following formula:

$$\Delta w = \ln\left(\frac{P_o}{P_{in}}\right) = \alpha L_c, \quad (3)$$

where, P_{in} and P_o are the input and output powers respectively and α is the attenuation constant. Here α can be calculated as:

$$\alpha = \frac{4\pi n_{im}}{\lambda}, \quad (4)$$

where, n_{im} is the imaginary part of refractive index, and obtained from effective refractive index of the TE (TM) fundamental mode of the structure, and $\lambda = 1550$ nm, is the wavelength of the light propagating through the device. Since

Fig. 4. Coupling length of directional coupler with SiO₂-BTO-SiO₂ hetero-cladding with BTO for $n = n_o$ and $n = n_e$ for waveguide widths of (a) 400 nm, (b) 450 nm and (c) 500 nm.

both even and odd modes together contribute to L_c for TE (TM) mode, loss of the device has been calculated using n_{im} of even and odd modes, and combined together to obtain the total loss for TE (TM) mode.

As the closeness of electrodes towards the cores increases, possibility of their interaction with the available mode evanescent also increases. This gives rise to an increment in the device loss. However, since we are studying a hetero-cladded structure, it can be seen from Table. 1 that, though d_{el} becomes

very small i.e., 500 nm, the device shows very less insertion loss even at the cladding thickness (t) of 1000 nm. Although $d_{el} > 500$ nm and $t > 1000$ nm show further reduction in insertion loss, however, it will need a higher voltage to get the whole BTO cladding change its refractive index from n_o to n_e (See Fig.6 in Section-4). Hence $d_{el} = 500$ nm and $t = 1000$ nm are taken as the optimum values for the given structure. On the other hand, for uniform BTO cladding case, the loss of the structure is much higher considering the same parameter values (Table. 2). From Table. 2, it can be seen that, loss with uniform BTO cladding is twice (for TE mode with $n = n_o$), thrice (for TM mode with $n = n_o$) and more than thrice (for both TE & TM modes with $n = n_e$), as compared to the proposed hetero-cladded structure. Finally, based on the above discussion, the optimized parameter values for the proposed ferroelectric hetero-cladding based directional coupler are summarized in Table. 3.

TABLE I
EXCESS LOSS DUE TO ITO ELECTRODES AND DOPED CORES FOR HETERO-CLAPPED STRUCTURE

d_{el} (nm)	t (nm)	Loss (Δw) in dB			
		For $n = n_o$		For $n = n_e$	
		TE	TM	TE	TM
2000	900	0.0908	0.0802	0.0448	0.0580
	1000	0.0718	0.0630	0.0395	0.0457
	1200	0.0556	0.0531	0.0350	0.0401
1000	900	0.0908	0.0802	0.0448	0.0580
	1000	0.0718	0.0627	0.0395	0.0457
	1200	0.0556	0.0531	0.0350	0.0386
500	900	0.0933	0.0877	0.0472	0.0627
	1000	0.0739	0.0702	0.0417	0.0503
	1200	0.0577	0.0603	0.0372	0.0433

TABLE II
EXCESS LOSS DUE TO ITO ELECTRODES AND DOPED CORES FOR UNIFORM BTO CLAPPED STRUCTURE

d_{el} (nm)	t (nm)	Loss (Δw) in dB			
		For $n = n_o$		For $n = n_e$	
		TE (12 μm)	TM (10.5 μm)	TE (11 μm)	TM (9 μm)
500	900	0.1390	0.2438	0.1428	0.1869
	1000	0.1358	0.2081	0.1389	0.1608
	1200	0.1352	0.1839	0.1383	0.1447

TABLE III
OPTIMIZED PARAMETER VALUES OF THE STRUCTURE

Structure Parameters	Optimized Values
Thickness of cladding (t)	1000 nm
Core to side electrode spacing (d_{el})	500 nm
Width of Core (W_c)	450 nm
Minimum Coupling length (L_c) for TE and TM mode before tuning ($n = n_o$)	11 μm (TE Mode) 9 μm (TM Mode)
Minimum Coupling length (L_c) for TE and TM mode after tuning ($n = n_e$)	7.18 μm (TE Mode) 7.12 μm (TM Mode)

IV. SIMULATION STUDY FOR VOLTAGE DEPENDENCE OF COUPLING LENGTH

Voltage dependence of coupling length appears through the variation of change in n of BTO with applied bias. The variation in n is simulated using a semi-empirical model reported in ref [29]. Using that study, the coercive field of BTO cladding is found to be 27.7 kV/cm, for a cladding thickness of $t = 1000$ nm. When the local electric field of BTO exceeds the coercive field, the refractive index of the particular region of BTO changes from n_o (n_e) to n_e (n_o). Fig. 5 shows the z -component of refractive index profile (n_z) of BTO cladding with respect to different applied voltages for both the biasing configurations. Fig. 5(a) shows the change in refractive index profile from n_o (2.41) to n_e (2.36) for *biasing-1*. As it can be seen from the figure, upon increment of the applied voltage, the refractive index change initiates with a small patch of n_e (blue patch in Fig. 5(a)) and tends to cover almost the whole BTO cladding. It has been seen that, this increment in n_e patch occurs up to increasing voltage of 30V. In fact, the effective change is seen to occur up to 24V of applied voltage. This change in n of BTO cladding retains for a period of more than a week [26, 27]. Similarly, Fig. 5(b) shows the refractive index profile for

Fig. 5. Refractive index profile (n_z) with respect to applied voltage for *biasing-1* (a), and *biasing-2* (b) for cladding thickness of 1000 nm.

biasing-2, which tries for reverting the refractive index change occurred during *biasing-1*. This time, there is a need of fairly little voltage ($\sim 4V$) for complete recovery of the initial value. The y -component of refractive index (n_y) can also be plotted with n_o and n_e values of Fig. 5 swapped.

The variation of coupling length with voltage is shown in

Fig. 6. The figure shows results for two values of t (1000 nm and 1200 nm), to show the comparison between the behavior of voltage dependent coupling length for both the cladding thicknesses. As predicted from Fig. 5(a), for $t = 1000$ nm case, the variation in coupling length is noticeable up to 24 V and remains almost unchanged after 30 V of biasing voltage. It can be noticed that, the device requires a higher voltage for $t = 1200$ nm than for $t = 1000$ nm to get both the coupling lengths reach their minimum values. For $t = 1200$ nm, the variation in coupling length also continues even at a voltage of 40 V. It may further be noticed that, for both the TE and TM modes the switching length decreases at a rapid rate for $t = 1000$ nm, compared to $t = 1200$ nm. Results shown in Fig. 6 are in well agreement with the expected coupling length of $\sim 7.1 \mu\text{m}$, indicated in Fig. 4(b). It is also seen from Fig. 6 that, at the cost of small increment in L_c ($7.1 \mu\text{m} \rightarrow 7.5 \mu\text{m}$), there is a benefit through significant reduction in applied bias ($40 \text{ V} \rightarrow 25 \text{ V}$).

Fig. 6. Variation of TE & TM mode coupling length with respect to applied voltage (*biasing-1*) for cladding thickness of 1200 nm and 1000 nm.

After application of *biasing-1*, application of *biasing-2* is needed to revert the initial coupling length of the device before completion of its retention period. The response of coupling length to the applied voltage of *biasing-2* is shown in Fig. 7. In this case of biasing, since the electrodes (doped cores) are sitting very close to each other, the biasing voltage needed for reverting the coupling length is very small. The change in L_c start to appear at a value of 2 V and return completely to their initial values at a voltage of 4 V.

Fig. 6 and Fig. 7 are well in accordance with Fig. 5, and support the results for expected coupling length with $n = n_e$ and n_o , as shown in Fig. 4(b). Coupling lengths can simultaneously be tuned to any intermediate value within the tuning range by application of respective bias voltage (Fig. 6 and 7). The voltage required for reverting the initial coupling length is very small and is due to the doped cores, which act as electrodes. Other than BTO, the proposed hetero-cladding concept could also employ any other suitable cladding material (dielectric or ferroelectric) for *region-2*, to engineer the coupler for a desired coupling length.

Fig. 7. Variation of TE & TM mode coupling length with respect to applied voltage (*biasing-2*) for $t = 1000$ nm.

V. CONCLUSION

A new approach using hetero-cladding (BTO/SiO₂) has been proposed for realization of compact, tunable and energy efficient silicon photonic directional coupler. The structure also offers an identical coupling length of $7.1 \mu\text{m}$ for both TE and TM modes. The proposed design shows more than 50 % reduction in coupling length compared to traditional uniform SiO₂ cladding structure, and thus is a promising solution for effective reduction of the footprint of programmable PICs. Use of BTO in hetero-cladding has made the device energy efficient through non-volatile refractive index switching, while use of SiO₂ helps reducing loss through lowering of mode spreading. All these attributes also lead to significant reduction in coupling length. The concept of hetero-cladding could also be used to improve the performance of photonic sensors and to design other fundamental photonic devices such as a phase shifter, and other type of couplers such as waveguide-to-ring and ring-to-ring couplers which are also vital building blocks of PICs. Further, by suitably adjusting the asymmetry in dielectric mirror around the core (also incorporating more layers in hetero-cladding if needed), the evanescent modes around the core can be controlled to meet one's design requirement.

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