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Multimode waveguide based directional coupler

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ABSTRACT

The Silicon-on-Insulator (SOI) based platform overcomes limitations of the previous copper and fiber based technologies. Due to its high index difference, SOI waveguide (WG) and directional couplers (DC) are widely used for high speed optical networks and hybrid Electro-Optical inter-connections; TE_{00}–TE_{01}, TE_{00}–TE_{00} and TM_{00}–TM_{00} SOI direction couplers are designed with symmetrical and asymmetrical configurations to couple with TE_{00}, TE_{01} and TM_{00} in a multi-mode semi-triangular ring-resonator configuration which will be applicable for multi-analyte sensing. Couplers are designed with effective index method and their structural parameters are optimized with consideration to coupler length, wavelength and polarization dependence. Lastly, performance of the couplers are analyzed in terms of cross-talk, mode overlap factor, coupling length and coupling efficiency.

1. Introduction

Silicon(Si)-photonics is a well-developed technology which enables us to fabricate a myriad of optical devices such as light emitters, photo-detectors, switches, passive or active devices, and nonlinear optical devices [1,2]; this technology is also used for nanoscale monolithic integration with Si substrates. Likewise, Si-wire WG (SWG) which is based on a Si core and SiO_2 or air as a cladding material is a promising technology. The limitations of the conventional Si-rib WGs which have dominated the field for over a decade can successfully be overcome by the SWG [1]. A high index difference is produced by a symmetrical ($\Delta \approx 2$) or an asymmetrical ($\Delta \approx 2.47$) SWG for 1550 nm wavelength. Therefore, a high power transmission (around 1000 times larger than a single mode fiber, $\Delta \approx 0.001$) and lower bending loss ($<$ Si-rib WG, fiber, etc.) is achieved [2,3]. SWG is used for many optical devices such as micro ring resonators [4,5], array-WG-gratings (AWG) [6], switches [7], wavelength converters [8], filters [9,10], logic gates [11], optical amplifiers [12], modulator [13], photonic crystal lens [14] and splitter [15,16], etc. The WG based Direction Coupler (DC) is a basic component of many optical systems like passive polarizer rotators [17], polarizer independent couplers [3], optical switches, multiplexers [18], etc. DCs are usually made from semiconductor, silica, lithium niobate based optical fibers and so on [2].

A lot of research has been carried on SWGs and DCs. The fabrication of SWG based DC and its basic characteristics, coupling in micrometer range and multiplexing functionalities have been studied by Yamada et al. in 2005 [2]. SWGs show two major issues of propagation and connection loss. To address these problems, Itabashi et al. in 2006 proposed a low-loss WG using silica ($n = 1.5$) as upper cladding to get 40% of the refractive index contrast [19]. Due to the small dimension, maintaining the same polarization is an important factor for Si-wire DC. The polarization independent DC for around 278 nm WG width was proposed by Passaro et al. in 2008. The effect of Si-wire side-wall inclination on birefringence properties is also discussed [3]. Many applications and a large number of experiments have been done with WG but comparatively less attention is given to the coupling of light into SWGs. Costa et al. in 2007 proposed TE–TM coupling from standard fiber to SWG; their proposed vertical coupler shows polarization independent coupling efficiency of up to 72% [20]. Symmetrical WGs with different materials (InP/InGaAsP and Si/SiGe) were also used to design wavelength splitters by Lee [21]. The use of multi-mode wave-guides has several advantages compared to single-mode WGs such as low loss, polarization-independency, fabrication-simplicity and suppress higher order modes are also possible to get single mode [22]. Slotted four-port metal-on-metal WG was demonstrated as a quasi-optical circulator to achieve high-transmission and isolation. The linear relationship was found between the wavelength and WG length or refractive index of insulator [23]. Multi-mode WGs can also be used to couple multi-modes for multi-analyte sensing. Moreover, couplers designed with asymmetrical WGs are also required for the mode conversion. Recently, the coupling of light from a Si-wire WG into the low index slotted

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region of a slot WG has gained much attention due to light-material interaction enhancement, modification and tailoring of Si-wire WG properties. Higher 3 dB bandwidth of 250 nm and more than 72% peak-efficiency was demonstrated in 2013 by Wong et al. [24]. Similarly, SWG and slot WG were used as a coupler for the passive polarization converter between fundamental TM–TE [17]. Multi-mode WG was used as an optical circulator to selectively couple lower order modes through WG tips. The radiation characteristics from microwave simulation shown an extinction ratio of more than 18 dB with WG interval of about 1λ. The lower- to higher-order mode coupling for the forward direction, and lower- to lower-mode coupling for the backward direction was also demonstrated [25]. Light coupling from fiber to SWG is enabled through grating coupler and is able to couple higher order modes efficiently [5,26] by using grating coupler for mode multiplexing systems [27].

The aim of this study is to design passive couplers or mode converters using symmetrical and asymmetrical configurations. A simple approach has been proposed to design passive WG coupler and mode converter; considering effective index, coupler and coupling length to couple proper modes, dependency of coupling length on the width and air gaps. Three different couplers TE_{00}–TE_{01} (Coupler-1), TE_{00}–TE_{00} (Coupler-2) and TM_{00}–TM_{00} (Coupler-3) are designed to couple TE_{00}, TE_{01} and TM_{00} modes to a semi-triangular ring resonator (multi-modes) configuration in which can be useful to sense three different analytes. This paper is structured to cover a basic introduction, presents the properties of SOI WG based DC, design and performance analysis and has an overview in the conclusion section.

2. Si-wire waveguide and directional coupler

The light propagation through the WG is based on the ray optics and its propagation is due to the reflections and refractions at the boundary mediums. The reflection of light is based on the critical angle and above which total internal reflection will occurs. Therefore, light will be confined in the inner core of the WG. The polarization (TE and TM mode) of the light is based on the field components along the propagation direction, the light propagation through the WG is responsible for the guided modes (particularly TE and TM field configurations) depending upon the WG structure. Different modes can be radiated and may be used for sensing applications. The WG supports single mode or multi-mode based on its dimensions (Table 1). The number of WG modes increases as the width of WGs is increased; each guided mode of the WG is based on the propagation constant and their field distribution. Guided modes are independent and maintain the orthogonal condition. This condition has proven to be useful for determining the mode matching and coupling efficiency between WGs [28].

SWG consisted of a Si core, SiO_2 as a bottom cladding and SiO_2 or air as a top cladding material. The DC was considered as a two-wave guide with a close proximate to each other so that the power transfer from one WG (parallel-port) to another (cross-port) can take place. The configuration can either be asymmetrical (Air–Si–SiO_2/BCB–Si–SiO_2) or symmetrical (SiO_2–Si–SiO_2) based on top and bottom materials as shown in Fig. 1 [29,30].

Table 1
Number of modes with different WG dimensions.

WG width [nm]	Number of modes
< 380	1 (TE_{00})
< 600	2 (TE_{00}, TM_{00})
< 900	3 (TE_{00}, TE_{01}, TM_{00})
< 1000	4 (TE_{00}, TE_{01}, TM_{00}, TE_{02})
< 1200	5 (TE_{00}, TE_{01}, TM_{00}, TE_{02}, TM_{01})

The simulations were done by considering symmetrical and asymmetrical configurations, Si (n=3.47) was used as a core material; SiO_2 (n=1.44) was used as a bottom cladding and air (n=1) or Benzocyclobutene, BCB (n=1.63) was used as a top cladding. The numerical analysis was performed with JCMwave software based on the Finite Element Method (FEM) [31,32]. The computational area was meshed using triangular domain elements [33]. The hard-wall boundary's (electric–magnetic) conditions were used to calculate the leaky-modes in SWG. Here, modes were calculated while considering only the real values. Therefore, it was faster, simpler and a more efficient method compared to the perfectly matched boundary conditions (using complex values). Convergence test was also carried out to optimize computational mesh size in order to improve the results accuracy [34,35].

For the mode analysis, two different WG (core) dimensions of 500×220 nm^2 and 800×220 nm^2 were considered. Additionally, upper and lower cladding dimensions for the asymmetrical Air–Si–SiO_2 configurations were considered to be fixed. The WG supports different TE, TM modes based on its dimensions; if the width of the WGs was increased, the number of modes also increased. For larger widths, both lower and higher order modes were exist. For example, for a 500×220 nm^2 WG (core) dimension allows only TE_{00} and TM_{00} modes with different effective indexes. Similarly, TE_{00}, TE_{01} and TM_{00} modes were exist for the dimension of 800×220 nm^2 WG. Similar polarized modes (TE or TM) can exist for same dimensions but with different effective indexes. It is also possible to have similar polarized modes and same effective indexes but different parallel wave guides dimensions. This property is used for producing the passive polarization rotator/converter, effective coupler design and will be discussed in the WG coupler design section. The real part of the effective index as a function of WG width is shown in Fig. 2.

Different TE and TM modes were found with 2D simulations for the different dimension of SWG. For the same WG widths TE modes were found more confined than TM modes due to higher effective indexes. Therefore, a good application of the TM modes can be done on sensing because of the evanescent fields that can interact easily with the surrounding analytes and provide higher sensing response. Furthermore, maximum hybrid modes were found for the square WGs [36]. The SWG can act as a single mode up to the < 380 nm width. The most dominant TE_{00} mode faces interference with different higher order modes (like TE_{01}, TM_{00}, and so on) as the width is increased.

Both the TE or TM modes of the WG strongly depend on the WG width and it is difficult to design a polarization- independent WG. Birefringence properties of the WG i.e. difference of effectives index of the TE and TM modes ($B_{brif} = \eta_{eff}^{TE} - \eta_{eff}^{TM}$) have also shown strong dependency on the WG width. This is true for both the asymmetrical and symmetrical configurations. The birefringence change for the small change of width, $\Delta B_{brif} / \Delta w = 1.07375\ \mu m^{-1}$ was found for asymmetrical (Air–Si–SiO_2) SWG. Fig. 3(c) shows birefringence properties for different upper cladding materials. Higher birefringence properties were observed for air as a top cladding materials, due to larger index difference than others.

Therefore TE or TM modes of the SWG can be varied by controlling the width. Even a minor change of dimension due to inaccuracy may cause mode change. This can be easily realized from the effective index sensitivity, in response to the variations in SWG height and width as shown in Fig. 3(a and b). The change of effective index is found to be very sensitive to the width and height variations on the nano-scale, this is true for both asymmetrical and symmetrical SWG. Improved value of sensitivity is found with smaller widths. Moreover, sensitivity is inversely related to the mode confinement and smaller widths provide higher sensitivity but lower confinement of light. Polarization changes in SWG not only depend on the width and height variations