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; TE00-TE01, TE00-TE00 and TM00-TM00 SOI direction couplers are designed with symmetrical and asymmetrical configurations to couple with TE00, TE01 and TM00 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.

Keywords: Multimode waveguide, Directional coupler, Guided optics, Ring resonator, Optical devices.

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](#_ENREF_1), [2](#_ENREF_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 SiO2 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](#_ENREF_1)]. A high index difference is produced by a symmetrical (Δ≈2) or an asymmetrical (Δ≈2.47) SWG for 1550nm wavelength. Therefore, a high power transmission (around 1000 times larger than a single mode fiber, Δ ≈ 0.001) and lower bending loss (< Si-rib WG, fiber, etc.) is achieved [[2](#_ENREF_2), [3](#_ENREF_3)]. SWG is used for many optical devices such as micro ring resonators[[4](#_ENREF_4), [5](#_ENREF_5)], array-WG-gratings (AWG) [[6](#_ENREF_6)], switches [[7](#_ENREF_7)], wavelength converters [[8](#_ENREF_8)], filters [[9](#_ENREF_9), [10](#_ENREF_10)], logic gates[[11](#_ENREF_11)], optical amplifiers [[12](#_ENREF_12)], modulator [[13](#_ENREF_13)], photonic crystal lens[[14](#_ENREF_14)] and splitter [[15](#_ENREF_15), [16](#_ENREF_16)], etc. The WG based Direction Coupler (DC) is a basic component of many optical systems like passive polarizer rotators [[17](#_ENREF_17)], polarizer independent couplers [[3](#_ENREF_3)], optical switches, multiplexers [[18](#_ENREF_18)], etc. DCs are usually made from semiconductor, silica, lithium niobate based optical fibers and so on [[2](#_ENREF_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](#_ENREF_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](#_ENREF_19)]. Due to the small dimension, maintaining the same polarization is an important factor for Si-wire DC. The polarization independent DC for around 278nm 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](#_ENREF_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](#_ENREF_20)]. Symmetrical WGs with different materials (InP/InGaAsP and Si/SiGe) were also used to design wavelength splitters by C. W. Lee [[21](#_ENREF_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](#_ENREF_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](#_ENREF_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 region of a slot WG has gained much attention due to light-material interaction enhancement, modification and tailoring of Si-wire WG properties. Higher 3dB bandwidth of 250nm and more than 72% peak-efficiency was demonstrated in 2013 by Wong *et al* [[24](#_ENREF_24)]*.* Similarly, SWG and slot WG were used as a coupler for the passive polarization converter between fundamental TM-TE [[17](#_ENREF_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](#_ENREF_25)]. Light coupling from fiber to SWG is enabled through grating coupler and is able to couple higher order modes efficiently [[5](#_ENREF_5), [26](#_ENREF_26)] by using grating coupler for mode multiplexing systems [[27](#_ENREF_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 TE00-TE01 (Coupler-1), TE00-TE00 (Coupler-2) and TM00-TM00 (Coupler-3) are designed to couple TE00, TE01 and TM00 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](#_ENREF_28)].

SWG consisted of a Si core, SiO2 as a bottom cladding and SiO2 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-SiO2 / BCB-Si-SiO2) or symmetrical (SiO2-Si-SiO2) based on top and bottom materials as shown in Fig. 1 [[29](#_ENREF_29), [30](#_ENREF_30)].



Fig.1: (a) Si-Wire Waveguide and (b) Directional Coupler.

The simulations were done by considering symmetrical and asymmetrical configurations, Si (n=3.47) was used as a core material; SiO2 (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](#_ENREF_31), [32](#_ENREF_32)]. The computational area was meshed using triangular domain elements [[33](#_ENREF_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](#_ENREF_34), [35](#_ENREF_35)].

Table 1: Number of Modes with different WG Dimensions

|  |  |
| --- | --- |
| WG Width [nm] | Number of Modes |
| <380 | 1 (TE00) |
| <600 | 2 (TE00, TM00) |
| <900 | 3(TE00, TE01, TM00 ) |
| <1000 | 4(TE00, TE01, TM00, TE02) |
| <1200 | 5(TE00, TE01, TM00, TE02, TM01) |

For the mode analysis, two different WG (core) dimensions of 500220 nm2 and 800220 nm2 were considered. Additionally, upper and lower cladding dimensions for the asymmetrical Air-Si-SiO2 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 500220 nm2 WG (core) dimension allows only TE00 and TM00 modes with different effective indexes. Similarly, TE00, TE01 and TM00 modes were exist for the dimension of 800220 nm2 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.



Fig. 2: Effective index vs. width for TE00 and TM00 modes for 500×220 nm2 SWG.

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](#_ENREF_36)]. The SWG can act as a single mode up to the <380nm width. The most dominant TE00 mode faces interference with different higher order modes (like TE01, TM00, 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 (Bbrif =neffTE – neffTM) 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, ΔBbrif**/** Δw = 1.07375 µm-1 was found for asymmetrical (Air-Si-SiO2) 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.



Fig. 3: SWG (500×220 nm2) sensitivity w.r.t (a) height, (b) width variation and (c) Birefringence properties.

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-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 but also on stress and temperature variations, with a minor change in the level of stress or temperature the effective index of SWG will alter causing polarization change. The refractive index variation with temperature and stress was reported to be: 1.9 x10-4 / K and 1.4 x10-8 / kPa respectively [[37](#_ENREF_37)].

An important application of the SWG is to design the passive TE and TM coupler. A WG coupler is a significant part of many optical components such as the ring-resonator, mach-zehnder interferometer (MZI), power splitter or combiner, add-drop multiplexer switching, etc. [[2](#_ENREF_2)]. The optical power transfer through the parallel (Pa) and cross port (Pb) can be expressed as [[3](#_ENREF_3), [28](#_ENREF_28)]:

 (1)

 (2)

For a symmetrical WG, the coupling efficiency is F=1 whereas, normalized distance is qz=πL/2Lc. The transmission and coupling intensity with coupler length, L is shown in Fig. 4. The TE modes need a larger coupler length, L compared to TM modes. The maximum transmission and coupled power to the parallel and cross port can be described with coupling efficiency, . 100% of light coupling from one WG to another depends upon the coupler length known as coupling length, Lc and is a function of effective index differences between even and odd modes, .



Fig. 4: (a) Transmitted / Coupled power for TE & TM modes, (b) Asymmetrical and (c) symmetrical SWG (500×220 nm2).

For the symmetrical WG (same dimension), propagation constants are β2 = β1 and δ = (β2 – β1)/2 = 0, therefore coupling efficiency is: F =1. In this case, maximum power will be at the point of the coupling length, Lc= π / 2k and k = π / (βeven – βodd), there will be no coupling loss for the symmetrical WG i.e. Pa + Pb=1. However, for the asymmetrical WG (different dimension) configuration, β2 β1, δ = (β2 – β1)/20 with the coupling efficiency: F < 1, there also exits some coupling loss and Pa + Pb< 1 [[28](#_ENREF_28)]. For the 3 dB coupler design, the coupling distances of (π / 2) and (0 - π /2) were used to design an arbitrary coupler. The simulated transmitted power, Pa and the coupled power, Pb with the symmetrical WG and asymmetrical WGs are shown in Fig. 4(b-c).

A noteworthy observation is that in the symmetrical WGs there was no coupling loss at N\*(π / 2) where N= 1, 2, 3… (Integer value) but in the asymmetrical WG coupling losses were observed. The loss was then calculated from the difference between transmitted and coupled power, Pa(z)-Pb(z). The losses for the asymmetrical WGs were found to be higher for WG with greater difference in dimensions which is due to the phase miss-matches between the interference waves.



Fig. 5: (a) Effective index Vs. WG width; Effective Vs. coupling Gap for (b) TE and (c) TM mode of Si-Wire WG (500×220 nm2).

Asymmetrical WGs are required for the passive modes conversion and for the coupler design with different WG dimensions and effective indexes (Fig. 5(a)). Another important issue that needed to be taken under consideration for the coupler design was that the TM modes required less coupler length than TE modes (Fig. 4(a)). The reason is that the effective index differences, eff between the even and odd modes for the TM modes have higher values than the TE modes (Fig. 5(b-c)). The designing of WG coupler is not straightforward due to the existence of different modes with in the same WG width. For example, TE00, TE01, and TM00 modes is existed within the same WG width of 800 nm. Therefore, index of the WG is responsible for one particular mode. As an example, if we need TE00 mode then a 395 nm WG with an effective index, neff = 2.1 will be required. But the TE01 mode with 800 nm WG (having neff = 2.1) is also excited at the lower order modes (TE00) at the same time. Therefore, this effective index approach is not always suitable. It only works best for small WG widths when there would be no other modes to excite within the same effective index. There needs to be an appropriate approach that will be suitable for coupler design. One of the important parameter may be the coupler length, L or more specifically, coupling length, Lc for coupler design.

3. DC Design and Performance Analysis

For coupler design a semi-triangular ring resonator configuration has been considered based on the 800x220 nm2 multimode WG that supports the TE00, TE01 and TM00 modes. The access WG is either single or multimode. Different widths of the bus and ring WG would support different modes. With the same width, mode coupling depends on the coupling lengths (Lc) of the couplers and this sparks the interest to design three 3dB couplers as these are commonly used in telecommunication applications. Each coupler has different distances between WGs (d), coupling lengths (Lc) and coupler lengths (L). The aim of the coupler design is to build up the TE00, TE01 and TM00 modes in the ring WG. Bus WGs support the TE00 and TM00 modes which is shown in Fig. 6.

The aim of the coupler-1 design is to couple the TE01 modes in the ring WG and TE00 mode in the bus WG. Mode conversion is needed in this coupler design therefore, asymmetrical WGs (different WG widths) are chosen. The ring WG should be large enough to support the multimode modes (TE00, TE10 TM00). Hence, we must optimize the width of the two WGs so that one WG support the TE00 mode and the other WG supports the TE01 modes. We kept one WG (ring WG) constant and varied the access WG’s width to get the suitable mode confinement to the ring WG. For a width of 800nm the ring WG can support the TE00, TE01 and TM00 modes and also need another WG which only supports the TE00 modes and acts as a passive mode converter. For this, the effective index of both WGs should have be identical.



Fig. 6: (a) Proposed three couplers for a semi-triangular ring-resonator configuration, (b) couplers design to couple three different modes, TE00, TE01 and TM00 to detect three different analyte layers in the ring WG.

From Fig. 5(a), the middle dotted horizontal line which crosses the TE00 and TE01 curves has same effective refractive index, neff  2.1. Indicating, that another WG can be  390nm width. This was an approximation from the curve but the optimized value for the WGs was found from the JCMwave simulation results. For the simulation, the right WG (ring) was fixed to be 800nm and left WG (Bus or access WG) was varied from 380nm, 385nm, 390nm, 395nm to 400nm respectively. The optimum result was observed for the left-WG= 395nm and right-WG=800nm as shown in Fig. 7. To design a coupler the coupling length (Lc)is an important parameter. Coupling length (Lc) indicates the required length to couple maximum power from the excited access WG to the ring WG. The coupling length (Lc) depends upon the coupling coefficient, k and propagation constant’s differences, .Coupling length(Lc) can be also measured from the effective index of odd and even modes of the WG:

Lc  (3)

In this case the left-WG and right-WG considered to be 395nm and 800nm, respectively. The separation width is 200nm providing neven = 2.1077 and nodd = 2.0815 and therefore the coupling length, Lc130 µm. It is known that,  and for a 3dB coupler. Therefore, the coupler length for the coupler-1 is obtained: L= 65 µm.



Fig. 7: (a1-a3) Cross-section of the proposed Coupler-1, 2, 3 and (b1-b3) Mode profiles using JCMwave simulation tools.

Next, the coupler-2 was designed to couple the TE00 both in the bus WG and ring WG. In this case, mode conversion is not required and symmetrical WG (same width) is enough to meet the goal. The ring WG was fixed at 800nm as in the previous case so that the bus WG can be close to the 800nm width. With 800nm width both WG support the TE00, TE01 and TM00 modes. But we are interested in coupling the TE00 mode into both the WGs so the bus WG width was varied from 795nm 798nm, 800nm, 802nm to 805nm respectively. The best result was observed with the left-WG= 800nm and right-WG=800nm with the distance of 200nm and the coupling length, Lc 3.67 mm. Here the larger Lc value was found with WG with distance, d = 200nm. In order to reduce this value, simulation was done with the WG distance, d = 90nm which is the feasible distance in terms of fabrication and as a result different even (2.6677) and odd (2.6624) values for the TE00 modes were obtained. The coupling length also reduced to 1038.57µm. For, 3dB coupler, coupler length is about, LTE00 =519.2854 µm. In the same way, for the TE01 and TM00 modes, the even and odd pairs of indexes (neven ,  nodd ) found in (2.1282, 2.0785) and (1.7723, 1.6828) and 3db coupler lengths are LTE01  90.36 µm and LTM00 = 24.15 µm. A similar procedure was used in order to design the coupler-3 to couple the TM00 both in the bus WG and ring WG. As done previously, both bus and ring WG were fixed to be 800nm, this way the TE00, TE01 and TM00 modes were excited at the same time but TM00 mode needed to be coupled in both ring and bus WG based on coupling length, . For the even-odd pairs of index values, 36.55µm, 2200.45µm and 119.48 µm and coupler lengths for the 3dB coupler were LTM0018.27µm, LTE0159.74µm and LTE001100.23 µm.

Couple proper modes on the WG coupler depends on the different parameters such as distances or gap, width, coupling lengths, operating wavelengths, etc. Fig. 5(a) shows the TE00- TE00, TE00-TE01 and TM00-TM00 mode coupling was possible with effective index of neff  2.7, 2.1 and 1.78 which is consistent with the simulation results shown in Fig. 7(b1-b3). With the numerical calculations, coupling length, Lc were calculated for the three couplers and found in agreement with simulation results shown in Fig. 8. The TM00-TM00 mode coupler required a lower coupling length (Fig. 8(c)) than others. Due to higher effective index difference of odd and even modes, the TE00- TE00 mode had a higher coupling length and lower effective difference than the others. Therefore, coupling proper modes depends on the coupling lengths which were controlled by the WG distance, width, index differences and wavelengths. Important notes from the results is that the coupling lengths are different for the various modes with same widths and distance between WGs. Thus, coupling the right modes to the correct WG strongly depends on the chosen coupler lengths. At the same times other modes exist along with the desired modes.



Fig. 8: Simulation results of (a) Coupler-1: TE00-TE01, (b) Coupler-2: TE00-TE00, and (c) Coupler-3: TM00-TM00.

By using the same coupling length, one mode coupled is maximized and the other modes will be minimized but neglecting minor modes is a difficult task. This can be explained by an example for the TE00 3dB (50% coupled power) coupler; for different modes (say TE00, TE01, and TM00) having different coupling length, Lc (100% power couple) and there may also exist coupler length, L for which TE00 having 45% coupling power but nearly 100% transmission for the TE01 and TM00. Transmitted and coupled power through the parallel WG like sine and cosine curves (Eq.1-2) and coupling length, Lc changed with operating frequency (Fig. 9).

Therefore, proper coupled modes also depends on the wavelength. If wavelength altered then coupled modes will also change, this is because the effective index of the odd and even modes is a function of wavelength and coupling lengths for modes are inversely related to the index differences. Therefore, keeping the wavelength fixed is also desired for the proper coupled modes. But unwanted modes are coupled unconsciously with the desired mode, this undesired mode coupling is considered as a cross-talk and is expressed as a ratio of unwanted-power and desired-power, expressed in dB [[21](#_ENREF_21)]:

WGs Cross-talk (dB) = 10 log [pu/pd]

≈10 log [cos2 (qz)] (4)

Here, Pu and Pd are unwanted however, desired for coupled power at the cross port. Considering the unwanted coupled power from the parallel port to the cross port, the value of symmetrical WGs is F=1 and the total desired coupled power is Pd =1. Cross- talk is true for both cross and parallel ports; for the TE and TM modes similar results was found in ref. [[21](#_ENREF_21)] but no results were found for cross-talk that prove its function in coupler length. Therefore, a study was performed for WG cross-talk as a function of wavelength and coupler length, L. With the decrease of wavelength from 1.55 µm to 1.30 µm the curves moved to the right for the TE00 mode. In Fig. 9(a), region-A shows a lower cross talk with wavelength, *λ*= 1.35 µm however, it was found to be higher with region-B. Larger coupler lengths show higher cross-talk for smaller wavelengths than *λ*= 1.55 µm. With higher wavelengths and more suitable coupling length, lower cross-talk is achievable and the case was similar with ref [[21](#_ENREF_21)] but the cross-talk up-to -20 dB was considered as an acceptable range. Therefore, WG width and coupler lengths should be further studied for performance analysis. Also sharp resonance peaks were found due to the high index difference with silicon core (n=3.44).



Fig. 9: (a) Cross-talk and (b) power overlap factor as a function of coupler length for symmetrical WG (neff = 2.75, TE mode) having 1000nm width and 200 nm spacing while Si (n=3.44) as a core, H20 (n=1.311) as a top cladding and SiO2 as a bottom cladding material. (Results are shown for TE00 modes with WGs effective index, neff = 2.75; similar results also possible for other TE and TM modes with different WG widths and effective indexes).

Further studies were performed in order to understand the dependence of wavelength on the coupler length. For this, power overlap factor was plotted as a function of coupler length with different wavelengths ranging from 1.3 to 1.55 µm for the TE00 mode. Power overlap factor indicates that the overlap fields or modes between the WG ports have a similarity with coupling power and so, overlap factors are always less or equal to the coupling power [[38](#_ENREF_38)]. Here, the overlap factor is equal to the coupling power because of the same effective index of symmetrical WG. Therefore, the overlap factor indicates the ratio of input power coupled to the output port and was found less in unity. For-example the overlap of 0.5 for the wavelength of 1.3 µm means that 50% of the power is distributed to leaky modes of the single mode, or to higher modes of the multimode WG; with lower frequency level, the power overlap factor is also lower due to the smaller effective index difference between odd and even modes which gives lower confinement. The power is spread at a lower frequency and hence needs a longer coupling length. Therefore, wavelength modulates the output power to pass through the particular port. This wavelength dependency of coupling length phenomena is used for wavelength de-multiplexing or splitting [[21](#_ENREF_21)].

It has been observed that the proper modes coupling depends upon the WG dimension, effective index difference between odd and even modes and coupling, coupler length, etc. The performance of the coupler also depends on the WG’s width and distance. Therefore, to study coupling length as a function of WG distance, d; the WG widths were fixed to be 800nm and the distance d was changed for the coupler-3 (TM00-TM00). Coupling length (Lc) was increased linearly with the distance (d) and lower coupling lengths were found for all the small distances. This is because the power factor increases with a small gap and it requires a shorter coupler length to transfer the maximum amount of power to the output ports. Moreover, lower distance values give higher differences between odd-even index pairs and reduce the coupling length. Similarly, linear relation properties were found for the coupler-1 (TE00 – TE01) and coupler-2 (TE00 – TE00). The coupling length also depends upon the WG width; now, the WG distances (200nm, 250nm, and 300nm) kept fixed and the WG widths were changed. It was found that the smaller widths and distances give lower coupling lengths but are increased for higher widths. Smaller widths have a lower loss for the single mode and most of the power coupled to the WG with small coupling length [[38](#_ENREF_38)].



Fig. 10: Coupling length as a function of WG (a) distance and (b) width; (c) Coupling efficiency Vs. WG distances.

The performance of the coupler depends upon the coupling efficiency (F) which is defined as a ratio of power between outgoing modes to the incoming mode at a particular coupling length, LC. Maximum coupling efficiency (F=1) is found for the symmetrical DC due to the mode matching conditions. This may be due to the reason that no coupling losses were found from the transmitted and coupled power with equal WG dimension (Fig. 4(c)). But for the asymmetrical DC, F was always <1 and it was found that more than 50% of the coupling efficiency was due to mode miss-match. Curves become flat after WG distances, this indicates a little dependency on the WG distance, d for the larger WGs pairs. Due to high index difference between odd and even modes, smaller width and distances of WGs pair provide power coupling more efficiently even with lower coupling length. For this reason, the smaller WG pairs (w1 = 300 nm, w2 = 400 nm) show a higher coupling efficiency than the larger WG pairs (w1= 400 nm, w2= 600 nm). A small width also indicates less leakage loss for the single mode. However, a wider width has multiple modes and this mixture of the modes reduces the coupling efficiency and increases the cross-talks [[38](#_ENREF_38)].

4. Conclusion

Numerical analysis is performed to observe the Si-wire WG and DC properties, needed for the coupler design. For this purpose, modes confinement and polarization dependency is also found with WG width and effective index. The transmitted and coupled power with coupler length, L = 600 nm is investigated and it is found that the TM mode is dominant over the TE. A semi-triangular ring resonator configuration is considered to design three coupler for the three different modes (TE00, TE01 and TM00). A unique novel effective index approach with coupling length is used to design a passive asymmetrical and symmetrical coupler, mode converter with FEM and hard-wall boundary conditions. A simple procedure with coupling length consideration is used to design both TE and TM couplers. However, designing the TM coupler is more complex as compared to the TE and also is less efficient: a more enhanced TM coupler is still being studied. The coupler performance is investigated with cross-talk, mode overlap factor, coupling length and coupling efficiency. An improved coupling length is found for lower WG widths and distances. The coupling efficiency is found to have strong dependent upon WG dimensions, and smaller WG pairs are more efficient than larger WG pairs. Therefore, a high index difference, small dimension Si-wire WG and coupler is suitable for the small scale integrations and can be employed as an attractive platform for nano-optical devices.

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