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Grating assisted MDM-PDM hybrid (de)multiplexer for optical interconnect application

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ABSTRACT

In this paper, a grating assisted MDM-PDM hybrid (de)multiplexer based on the silicon-on-insulator (SOI) platform has been proposed and analyzed using coupled mode theory with effective index method (EIM). The proposed device consists of a multimode wide waveguide and five single mode narrow waveguides. The quasi-TE/TM modes of the wide waveguide are phase matched with the respective contra-propagating fundamental quasi-TE/TM modes of the single mode narrow waveguides. The phase matching conditions are satisfied by using different period gratings, which are surface corrugated on the wide waveguide. The proposed device structure exhibits good crosstalk, insertion loss, and return loss values.

Keywords: Coupling, grating, multiplexing, silicon photonics

1. INTRODUCTION

The ever increasing data traffic due to technological advancements as well as increase in the number of users has ignited tremendous interest in the research and development of high performing computing systems. This has resulted in miniaturization of the feature size while increasing the number of transistors in order to increase the performance of the system. As per the Moore's law, the number of transistors in an integrated circuit doubles every 18-24 months.[1] However, the performance increase is limited by the usage of electrical interconnects, as it suffers from high power dissipation and propagation delay (known as interconnect bottleneck caused due to increase in parasitic capacitances and resistances).[2] To overcome these issues optical interconnect has emerged as a viable solution owing to its low power consumption and potential for link capacity improvement with various multiplexing techniques such as wavelength division multiplexing (WDM), polarization division multiplexing (PDM), and mode-division multiplexing (MDM).[3] Silicon photonics platform has attracted a lot of attention as it has enabled monolithic integration of photonics and microelectronics due to its compatibility with the standard complementary metal oxide semiconductor (CMOS) technology.[4]

MDM and PDM have emerged as cost-effective solutions to improve the link capacity of the on-chip optical networks. As compared to the WDM based systems, which is expensive and power hungry due to requirement of multiple wavelength sources, tuning, and stabilization; MDM and PDM systems can improve the link capacity even with a single wavelength source.[5] WDM has been employed and developed for long-haul fiber communication systems and data center applications, where different wavelength of light act as data channels.[6] In MDM systems different eigenmodes of the bus waveguide are treated as data channels, whereas in case of PDM each polarization of the mode can carry separate data.[7,8] Many MDM devices have been reported using adiabatic couplers,[9] assymetric Y-junction,[8] multimode interferometers,[10] grating assisted couplers;[11] PDM devices using subwavelength gratings[12] and slot waveguides.[13] However, to meet the future demands of high data capacity and to develop next generation on-chip data communication systems, a hybrid MDM-PDM that can improve the link capacity with a single wavelength source has become essential.

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In this paper, a hybrid MDM-PDM (de)multiplexer has been introduced, which can (de)multiplex four quasi-TE modes and two quasi-TM modes at 1550 nm. The proposed device consists of a multimode wide waveguide and five single mode narrow waveguides. Contra-directional power coupling between the quasi-TE/TM modes of wide and narrow waveguide is achieved by employing surface corrugated gratings on the wide waveguide. The proposed MDM-PDM hybrid (de)multiplexer is analyzed using coupled mode theory and EIM method.

2. DEVICE STRUCTURE AND PRINCIPLE OF OPERATION

The top view of the proposed device structure is illustrated in Figure 1, which is composed of a wide wavguide WG_w and five narrow waveguides (WG_{n1}, WG_{n2}, WG_{n3}, WG_{n4}, and WG_{n5}). The width of WG_w is denoted by w_w and the widths of WG_{n1}, WG_{n2}, WG_{n3}, WG_{n4}, WG_{n5} are equal and denoted by w_n. WG_w is a multimode waveguide, which supports four quasi-TE (three quasi-TM) modes namely TE_w^0, TE_w^1, TE_w^2, and TE_w^3 (TM_w^0, TM_w^1, and TM_w^2) and WG_{n1}, WG_{n2}, WG_{n3} (WG_{n4} and WG_{n5}) are single mode waveguides, each supporting a fundamental quasi-TE (quasi-TM) mode denoted as TE_{n1}^0, TE_{n2}^0, TE_{n3}^0 (TM_{n4}^0 and TM_{n5}^0) respectively. Superscript in the notation denotes the order of the respective mode. To couple the modes of the wide and narrow waveguides, surface corrugated gratings are used on WG_w. Contra-directional coupling is achieved between TE_w^1 and TE_{n1}^0, TE_w^2 and TE_{n2}^0, TE_w^3 and TE_{n3}^0, TM_w^0 and TM_{n4}^0, TM_w^1 and TM_{n5}^0 by employing the surface corrugated gratings sg_1, sg_2, sg_3, sg_4, sg_5 respectively to satisfy the phase matching condition defined as:[14]

$$\beta_a + \beta_b = \frac{2\pi}{\Lambda} \tag{1}$$

where β_a and β_b are the propagation constants of the two coupled modes, Λ is the period of the respective surface corrugated grating.

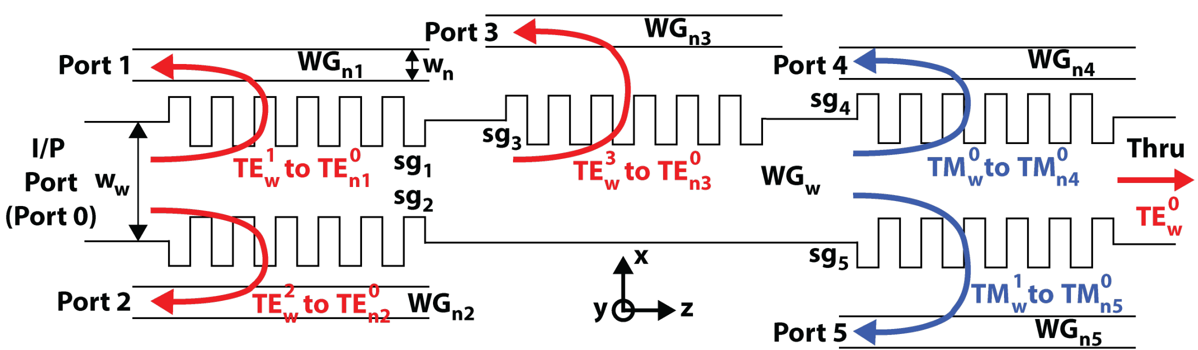

Figure 1. Top view of the proposed device structure.

The energy is transferred between the coupled modes when different modes of the wide waveguide WG_w are excited at the input port. The fundamental mode of WG_w (TE_w^0), when given as input, keeps propagating in the same waveguide without any power leakage to the adjacent single mode narrow waveguides. The periods of the gratings sg_1, sg_2, sg_3, sg_4, and sg_5 are calculated from Eqn. (1) and thus are responsible for coupling a particular pair of coupled modes while other input modes propagate unaltered through the grating structure.

The proposed device structure is based on the buried strip SOI platform, where Si is used as the waveguide core material and SiO_2 is used as the upper and lower cladding materials. The grating structures are corrugated on the sidewalls of the wide waveguide (WG_w) with center of the grating width positioned at the sidewall of WG_w. The duty cycle of all the grating structures are taken as 50%. The separation distance between the waveguides WG_w and WG_{n1}, WG_w and WG_{n2}, WG_w and WG_{n3}, WG_w and WG_{n4}, WG_w and WG_{n5} are denoted by g_1, g_2, g_3, g_4, and g_5 respectively.

The coupled mode theory in conjunction with EIM has been used to study the energy transfer between the coupled modes in the proposed device structure. The thickness of the strip waveguide is taken as 220 nm to make it compatible with the CMOS technology. The 220 nm thickness ensures single mode operation (fundamental TE and TM) in the vertical direction. To analyze the response to the quasi-TE (quasi-TM) mode injection, the 3D structure is transformed to an equivalent 2D structure by replacing the refractive index of the core with the effective index of the fundamental TE (TM) mode obtained from performing TE-analysis (TM-analysis) on the strip thickness. Then in the resulting 2D structure, TM (TE) modes are calculated and with the help of coupled mode theory transmission/reflection spectrum are obtained.

3. SIMULATION RESULTS

The refractive indices taken for Si and SiO_2 are 3.473[15] and 1.444[16] respectively. A modechart is given in Figure 2 which depicts variation of effective indices of the modes with the varying waveguide core width at the operating wavelength of 1550 nm. The waveguide attains single mode condition at 320 nm, and thus w_n is taken as 320 nm. The width of WG_w, w_w, is taken as 1300 nm for which WG_w supports four quasi-TE modes (TE_w^0, TE_w^1, TE_w^2, and TE_w^3) and three quasi-TM modes (TM_w^0, TM_w^1, and TM_w^2). To prevent any co-directional coupling between WG_w and the single mode waveguides, the widths are appropriately chosen such that effective refractive indices of the wide and narrow waveguide modes are not matched. TM_w^2 is the unused mode as it is less confined to the core of the waveguide, which leads to longer coupling length and wider separation distance between the waveguides.

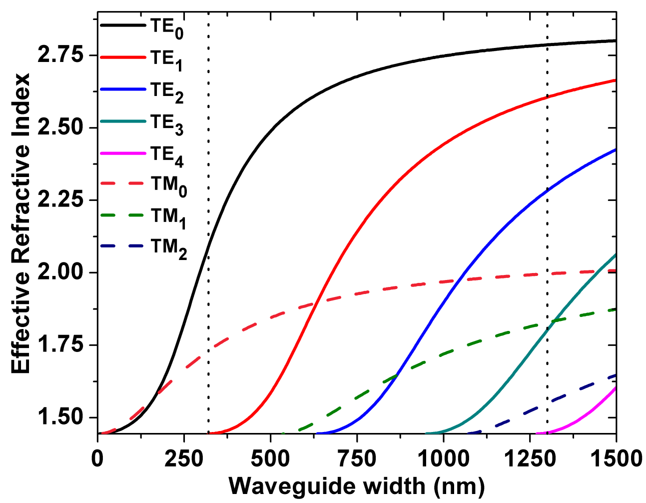

Figure 2. Modechart at 1550 nm wavelength with Si and SiO_2 as core and cladding materials.

The coupled mode theory has been used to analyse the mode propagation and power coupling between the modes. The coupled mode equations can be given as:[14]

$$\frac{\partial A^+}{\partial z} = -i[B^-(z)\kappa_{ab} + A^+(z)\kappa_{aa}] \tag{2a}$$

$$\frac{\partial B^-}{\partial z} = i[A^+(z)\kappa_{ba} + B^-(z)\kappa_{bb}] \tag{2b}$$

where A and B are the slowly varying amplitudes of the coupled modes of multimode wide waveguide and single mode narrow waveguide respectively. The superscripts + and − denote forward and backward propagation in the z-direction. κ_{ab} and κ_{ba} are the coupling constants which represent power exchange between the two modes, whereas κ_{aa} and κ_{bb} are the coupling coefficients which result from the dielectric perturbation caused due to the presence of other waveguide. κ_{aa} and κ_{bb} serve as correction terms for the propagation constant. This results in a small modification in Eqn. (1), which can be expressed as:[14]

$$(\beta_a + \kappa_{aa}) + (\beta_b + \kappa_{bb}) = \frac{2\pi}{\Lambda} \tag{3}$$

Appropriate values for the separation distance between the waveguides and grating widths are taken such that any unwanted power leakage is avoided and sufficient power exchange between the coupled modes is observed, whereas the corresponding grating periods are calculated from Eqn. (3). The grating lengths of sg_1, sg_2 are 300 μm and for the rest 400 μm. The coupled mode equations are solved using OptiGrating and the spectral responses are obtained for each input mode of WG_w. To assess the performance of the device insertion loss (IL), return loss (RL), and extinction ratio (ER) have been calculated, which are defined as:

$$IL = 10\ log_{10}\Big(\frac{P_t}{P_i}\Big) \tag{4a}$$

$$RL = 10\ log_{10}\Big(\frac{P_{ir}}{P_i}\Big) \tag{4b}$$

$$ER = 10\ log_{10}\Big(\frac{P_t}{P_r}\Big) \tag{4c}$$

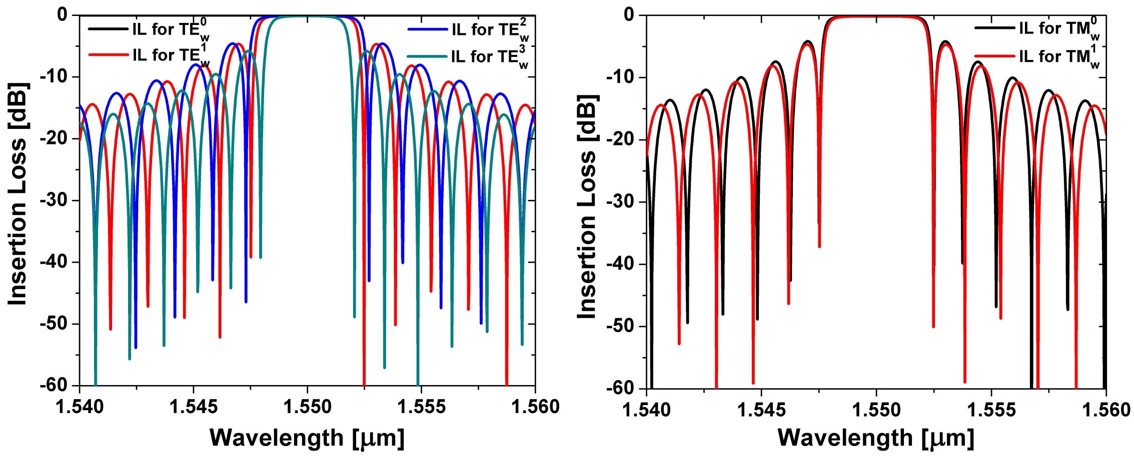

Figure 3. Insertion loss values at different wavelengths for TE and TM mode inputs.

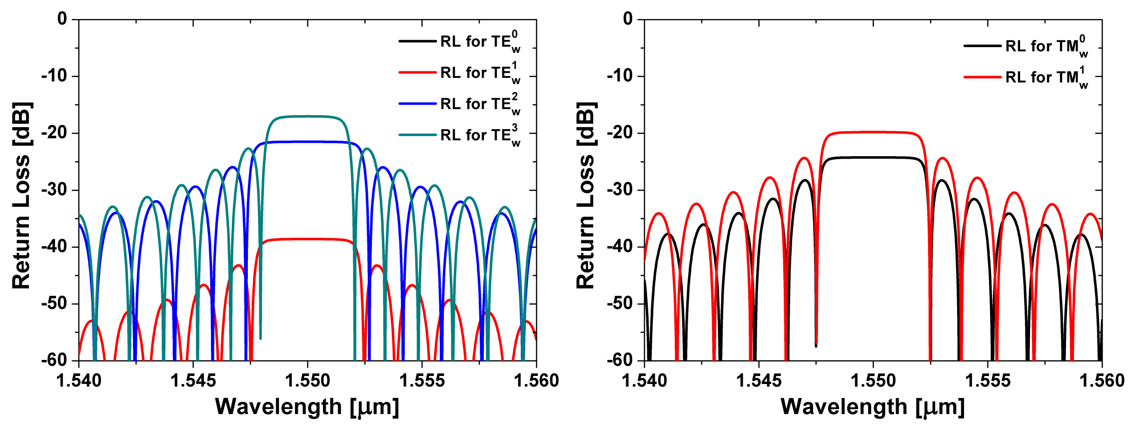

Figure 4. Return loss values at different wavelengths for TE and TM mode inputs.

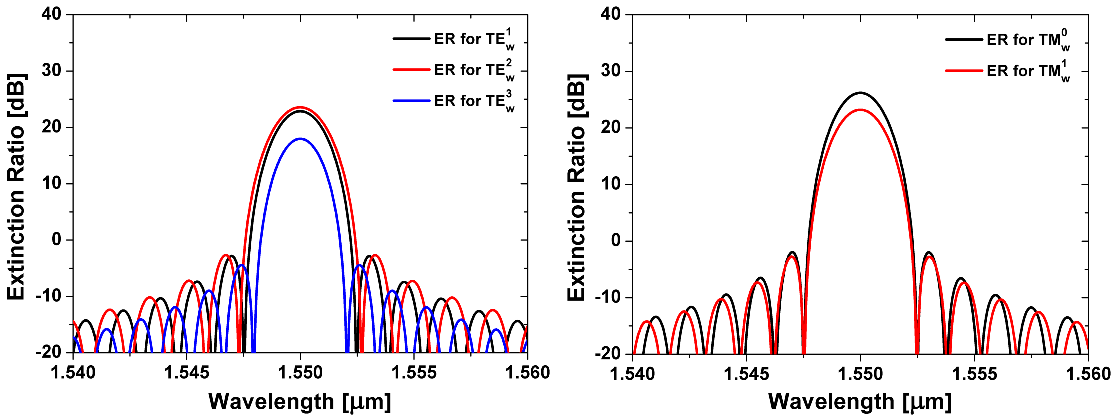

Figure 5. Extinction ratio values at different wavelengths for TE and TM mode inputs.

Table 1. Results

Input Mode	ER (dB)	RL (dB)	IL (dB)
TE_w^0	-	-90	0.00
TE_w^1	22.86	-38.60	-0.03
TE_w^2	23.56	-21.47	-0.10
TE_w^3	17.97	-17.02	-0.10
TM_w^0	26.19	-24.24	-0.14
TM_w^1	26.19	-19.80	-0.14

where P_i is the input power, P_t is the output power at the target port, P_{ir} is the reflected power at the input port, and P_r is the output power at the thru port.

Figure 3 shows the insertion loss for different TE and TM mode excitation of WG_w. The excited TE and TM modes of WG_w are coupled to their respective single mode waveguide with an IL ranging from -0.14 dB to -0.03 dB. The 3 dB bandwidth range for TE modes is 3.5–5 nm, whereas for TM modes it is about 4.5 nm. Figure 4 shows return loss incurred for each TE and TM mode input. The ER is plotted with varying wavelength in Figure 5.The ER, RL, and IL as observed in the above figures at 1550 nm are tabulated in Table 1.

4. CONCLUSIONS

In this paper, a 6 channel (4 quasi-TE modes and 2 quasi-TM modes) MDM-PDM hybrid (de)multiplexer has been presented in SOI platform using coupled mode theory and EIM. The demultiplexing operation has been demonstrated, where the demultiplexing is accomplished by coupling the quasi-TE/TM modes of the multimode wide waveguide and the fundamental quasi-TE/TM mode of the respective single mode narrow waveguide with the help of grating structures. The grating stuctures are surface corrugated type, which are patterned on the side walls of the multimode waveguide. The dimensions of the gratings are appropriately chosen such that power is transferred between coupled modes. The fundamental quasi-TE mode of the wide waveguide is not phase matched to any other mode and thus power leakage to the other adjacent single mode waveguides is prevented. The coupled mode analysis shows that the proposed MDM-PDM hybrid (de)multiplexer has achieved an ER of > 17.97 dB, RL of < -17.02 dB, and IL of > -0.14 dB.

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REFERENCES

[1] Schaller, R. R., "Moore's law: past, present and future," *IEEE spectrum* **34**(6), 52–59 (1997).

[2] Dhoedt, B., Baets, R., Van Daele, P., Heremans, P., Van Campenhout, J., Hall, J., Michalzik, R., Schmid, A., Thienpont, H., Vounckx, R., et al., "Optically interconnected integrated circuits to solve the cmos interconnect bottleneck," in [*1998 Proceedings. 48th Electronic Components and Technology Conference (Cat. No. 98CH36206)*], 992–998, IEEE (1998).

[3] Dai, D. and Bowers, J. E., "Silicon-based on-chip multiplexing technologies and devices for peta-bit optical interconnects," *Nanophotonics* **3**(4-5), 283–311 (2014).

[4] Jalali, B. and Fathpour, S., "Silicon photonics," *Journal of lightwave technology* **24**(12), 4600–4615 (2006).

[5] Dai, D., "Silicon nanophotonic integrated devices for on-chip multiplexing and switching," *Journal of Lightwave Technology* **35**(4), 572–587 (2016).

[6] Paniccia, M. J., "A perfect marriage: optics and silicon: Integrated silicon-based photonics now running at 50 ggps, with terabit speeds on the horizon," *Optik & Photonik* **6**(2), 34–38 (2011).

[7] Yadin, Y. and Orenstein, M., "Parallel optical interconnects over multimode waveguides," *Journal of lightwave technology* **24**(1), 380 (2006).

[8] Doerr, C. and Taunay, T., "Silicon photonics core-, wavelength-, and polarization-diversity receiver," *IEEE Photonics Technology Letters* **23**(9), 597–599 (2011).

[9] Xing, J., Li, Z., Xiao, X., Yu, J., and Yu, Y., "Two-mode multiplexer and demultiplexer based on adiabatic couplers," *Optics letters* **38**(17), 3468–3470 (2013).

[10] Uematsu, T., Ishizaka, Y., Kawaguchi, Y., Saitoh, K., and Koshiba, M., "Design of a compact two-mode multi/demultiplexer consisting of multimode interference waveguides and a wavelength-insensitive phase shifter for mode-division multiplexing transmission," *Journal of Lightwave Technology* **30**(15), 2421–2426 (2012).

[11] Minz, M. and Sonkar, R. K., "Numerical design and analysis of a 3-channel grating assisted mode-division (de) multiplexer," *Optik* **187**, 272–277 (2019).

[12] Chen, S., Wu, H., and Dai, D., "High extinction-ratio compact polarisation beam splitter on silicon," *Electronics Letters* **52**(12), 1043–1045 (2016).

[13] Xu, Y., Xiao, J., and Sun, X., "Design of a compact polarization demultiplexer for silicon-based slot waveguides," *Applied optics* **53**(35), 8305–8312 (2014).

[14] Yariv, A. and Yeh, P., [*Photonics: optical electronics in modern communications*], Oxford Univ. (2006).

[15] Chrostowski, L. and Hochberg, M., [*Silicon photonics design: from devices to systems*], Cambridge University Press (2015).

[16] Safa, K., [*Optoelectronics and Photonics: Principles and Practices*], Pearson Education India (2009).