Short and robust silicon mode (de)multiplexers using shortcuts to adiabaticity

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Abstract: Compact silicon mode (de)multiplexers based on asymmetrical directional couplers are designed using shortcuts to adiabaticity. The coupling coefficient and propagation constants mismatch are engineered to optimize the device robustness. Simulations show that the devices are broadband and have large fabrication tolerance.

OCIS codes: (130.3120) Integrated optics devices; (060.1810) Buffers, couplers, routers, switches, and multiplexers; (230.7370) Waveguides.

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1. Introduction

Optical interconnects have emerged as a very promising technology for on-chip data communication. Current photonic integrated circuits operate almost exclusively in the single-mode regime, and wavelength-division multiplexing (WDM) provides a straightforward approach to increase the transmission capacity by scaling up the number of wavelengths in the interconnect link. However, WDM may be too costly for short-reach interconnects due to the requirement of multiple laser sources. For fiber communications, multimode communications utilizing space-division multiplexing (SDM) in multi-core fibers [1] or mode-division multiplexing (MDM) in few-modes fibers [2] have been exploited as an effective approach to increase the capacity of a single wavelength carrier. Recently, on-chip optical communication using MDM has also attracted lots of attentions. One of the key components to realize on-chip MDM is an mode (de)multiplexer with low crosstalk, broad bandwidth, small footprint and large fabrication tolerance. Several schemes have been proposed to realize mode (de)multiplexers, including microrings [3], asymmetric Y-junctions [4, 5], multimode interference (MMI) [6, 7], adiabatic couplers (ACs) [8, 9], and asymmetrical directional couplers (ADCs) [10–12]. For microring and Y-junction based devices, very precise fabrication are usually required to obtain the desired ring size and the ultrasmall gaps in Y-branches. MMI-based devices, on the other hand, are less flexible for incorporating more channels. AC-based devices are usually broadband but associated with long device lengths. ADC-based devices usually require accurate control of the coupling length and waveguide width, unless the adiabatic scheme is employed [10], which inevitably leads to long device length.

Conceptually, the problem of power coupling between a spatial mode in a multimode bus waveguide and a single-mode access waveguide in a mode (de)multiplexer is analogous to the problem of coherent quantum system state control with laser pulses, with the goal of performing precise and robust state transfer in a short time. In this framework, a family of protocols called shortcuts to adiabaticity (STA) [13] has been developed to optimize quantum state transfer, providing design rules to shape the profile and phase of the laser pulses to achieve the desired transfer properties. Using the analogies between quantum mechanics and wave optics in weakly-coupled waveguides [14], we have recently proposed a series of coupled-waveguide devices using the STA protocols including directional couplers [15–17], mode-sorting asymmetric Y-junctions [18], and polarization rotators [19]. These devices are efficient and broadband, and have large fabrication tolerance and short length. While these earlier works are focused on weakly-guided waveguide platforms with small refractive index contrasts, there is interest to extend the concept of quantum-optical analogy in coupled waveguides and STA into the design of silicon-based high index contrast photonics for the purpose of dense integration of optical components on chip. In this paper, we apply the STA theory to the design of ADC-based mode (de)multiplexers on silicon-on-insulator (SOI) technology, which can be easily integrated with CMOS circuitry for on-chip data communication.

2. Asymmetrical directional coupler (ADC) and shortcuts to adiabaticity (STA)

In an ADC consisting of a single-mode access waveguide and a multimode bus waveguide as shown in Fig. 1, the evolution equation for the changes in the guided-mode amplitudes in the individual waveguides $|\Psi\rangle = [A_0, A_m]^T$ (A_0 denotes the amplitude of the fundamental mode in the access waveguide, and A_m denotes the amplitude of the m-th propagating mode in the bus waveguide) is [20]

$$\frac{d}{dz}|\Psi\rangle = -i \begin{bmatrix} \Delta & \Omega \\ \Omega & -\Delta \end{bmatrix} |\Psi\rangle, \tag{1}$$

where Ω is the coupling coefficient, and $\Delta = (\beta_0 - \beta_m)/2$ describes the difference between propagation constants of the fundamental mode and the m-th mode of the corresponding waveguides. In conventional ADCs with constant Ω and Δ, the coupling efficiency F is described by $F = 1/[1 + (\Delta/\Omega)^2]$. Selective mode coupling is achieved by selecting appropriate access and bus waveguide widths W_1 and W_2 such that the resulting Δ for the corresponding modes is zero (phase-matching). The scheme is equivalent to exact resonant coupling between two quantum states by a Rabi π pulse [21], which provides the fastest transition but is not robust against pulse parameter variations. In other words, the conventional ADC mode (de)multiplexers are typically compact but lacks other desired properties such as broadband and large fabrication tolerance.

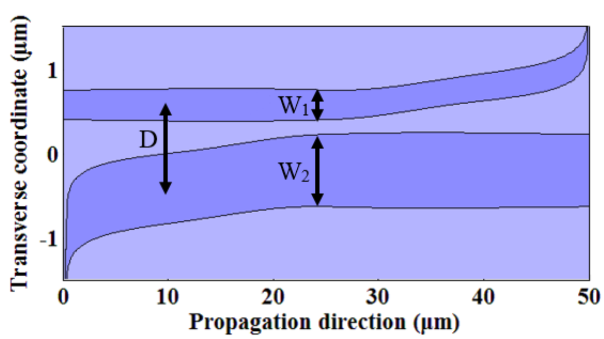

Fig. 1. Schematic of an asymmetric directional coupler mode (de)multiplexer.

The STA approach [13] provides protocols for the design of $\Omega(z)$ and $\Delta(z)$, allowing for high coupling efficiency, robustness against variations in fabrication and/or input wavelength, and short device length. The solution of Eq. (1) can be described by the following decoupled

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system state [17]

$$|\Psi_z\rangle = \begin{bmatrix} \cos(\theta/2)e^{i\phi/2} \\ \sin(\theta/2)e^{-i\phi/2} \end{bmatrix} e^{i\gamma}, \tag{2}$$

where

$$\begin{aligned} \dot{\theta} &= \Omega \sin\phi \\ \dot{\phi} &= \Delta + \Omega\cos\phi\cot\theta \\ \dot{\gamma} &= \dot{\theta}\tfrac{\cot\phi}{\sin\theta} \end{aligned} \tag{3}$$

Different from the traditional adiabatic approaches where the evolution of Ω and Δ are designed to satisfy the adiabatic criterion, the STA approach described here designs the system evolution using Eq. (2). In adiabatic designs, the system evolution follows the eigenstates of the matrix in Eq. (1) (the adiabatic states) approximately; while in STA, the system evolution follows Eq. (2) exactly. The STA protocols provide alternative fast processes which reproduce the same final state as the adiabatic approach in a shorter distance, without the need to satisfy the adiabatic criterion. For example, to describe 100% excitation of the m-th mode in the bus waveguide by the access waveguide using Eq. (2) in a (de)multiplexer with length L, the initial and final states of the system are set as $|\Psi_z(0)\rangle = [1,0]^T$ and $|\Psi_z(L)\rangle = [0,1]^T$ respectively. The boundary conditions

$$\theta(0) = 0 \quad \theta(L) = \pi, \tag{4}$$

guarantee the desired initial and final states. If in addition

$$\dot{\theta}(0) = 0, \quad \dot{\theta}(L) = 0, \tag{5}$$

this guarantees $\Omega(0) = \Omega(L) = 0$, meaning no coupling at the beginning and the end of the waveguides. So, the waveguides are well-separated at the beginning and the end of the coupling region. Because the system evolution follows Eq. (2) exactly, the above conditions thus ensure perfect excitation of the m-th mode in the bus waveguide. There is still much freedom to design the coupling coefficient and mismatch except for the boundary conditions. The freedom allows one to engineer stable or robust system evolution against different errors. To find the optimal sets of $\Omega(z)$ and $\Delta(z)$ which are robust against errors, we can nullify the derivatives of the coupling efficiency F at $z = L$ with respect to the considered errors [22–24].

3. Device design and simulation

In this paper, we use a SOI wafer with a 340 nm thick top silicon layer for device design. The design wavelength is set at 1550 nm, and the refractive indices of Si and SiO_2 are 3.5 and 1.45. The devices are air-cladded with a refractive index of 1. The effective indices of the first four TM modes in the waveguides are calculated for different widths with a full-vectorial finite-element method mode solver and shown in Fig. 2. Phase-matching condition for the TM_m mode in the bus waveguide can be satisfied by choosing W_1 and W_2 such that $n_{\text{eff}0}(W_1) = n_{\text{eff}m}(W_2)$, where $n_{\text{eff}0}$ and $n_{\text{eff}m}$ are the effective indices of the fundamental TM_0 mode of the access waveguide and TM_m mode of the bus waveguide, respectively. The waveguide spacing D and widths W_1, W_2 are then adjusted along the propagation direction to satisfy the following set of $\Omega(z)$ and $\Delta(z)$ functions for robustness [16]

$$\Omega(z) = -\dot{\theta}\sqrt{1+4M^2\sin^2\theta}, \tag{6}$$

$$\Delta(z) = 2\dot{\theta}\cos\theta\left[M + \frac{1-4\alpha+6\alpha\cos(2\theta)}{1+4M^2\sin^2\theta}\right], \tag{7}$$

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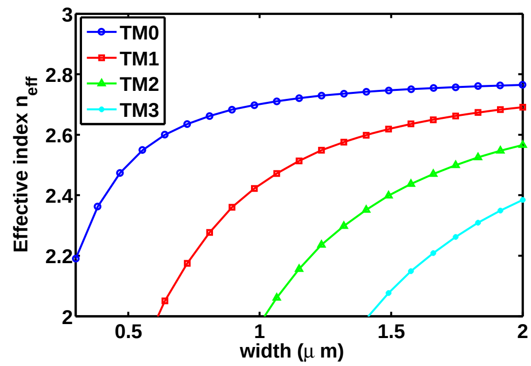

Fig. 2. Effective indices of the first four TM modes of 340 nm thick SOI waveguides.

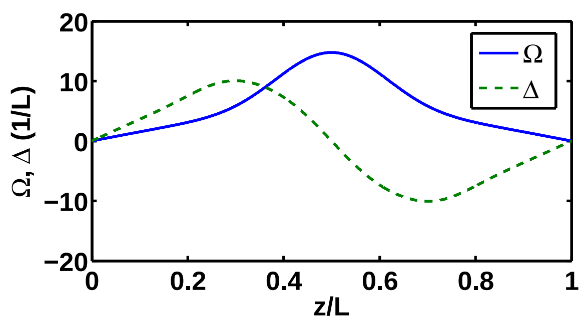

Fig. 3. The chosen set of coupling coefficient Ω and propagation constants mismatch Δ in Eqs. (6) and (7) for the design of mode (de)multiplexers. L is the device length.

with $\theta = (\pi/2)\{1-\sin[\pi(2z-L)/2L]\}$, $M = 1+2\alpha\cos(2\theta)$, and $\alpha = -0.206$. The coupling coefficient and propagation constants mismatch in Eqs. (6) and (7) are shown in Fig. 3.

We design mode (de)multiplexers for TM-polarization operation. The width of the access waveguide W_1 is fixed at 0.3 μm for single-mode operation. We set the device length L at 50 μm, further reduction of L results in large values in Ω, which would lead to small gap between the access and bus waveguides that is difficult to fabricate. Using the exponential relation between Ω and D (details can be found in [16]) and the relation between Δ and the width difference calculated from Fig. 2, we obtain the corresponding (de)multiplexers for TM$_m$ (m=1, 2, and 3) modes as shown in Fig. 4. The corresponding design parameters (W_1, W_2, and D) for these devices are shown in Fig. 5. A commercial software (FIMMPROP, Photon Design) employing an eigenmode expansion method [25] is used to simulate light propagation in these devices. The calculated light propagation in the designed (de)multiplexers are also shown in Fig. 4. It can be seen that higher-order modes in the bus waveguide are efficiently excited by input light in the narrow access waveguides.

Figure 6 shows the simulated wavelength dependence of the coupling efficiency from the access waveguide to TM$_m$ (m=1, 2, and 3) modes in the bus waveguide. It can be seen that for a wide range from 1.45 to 1.60 μm, the coupling efficiency is larger than 90 %. We note that the coupling efficiency at 1550 nm is not at the maximum, this can be attributed to the fact that the simple coupled mode theory in Eq. (1) only approximately describes light propagation in high index contrast waveguides [26]. Our result shows that the approximation works very well and

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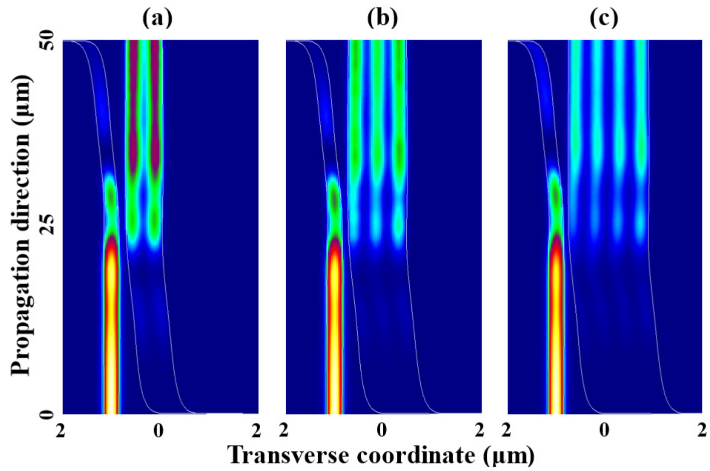

Fig. 4. Designed mode (de)multiplexers using STA and the corresponding light propagation simulations for coupling in to the TM_m mode in the bus waveguide: (a) m=1, (b) m=2, and (c) m=3. White lines indicate the waveguide boundaries.

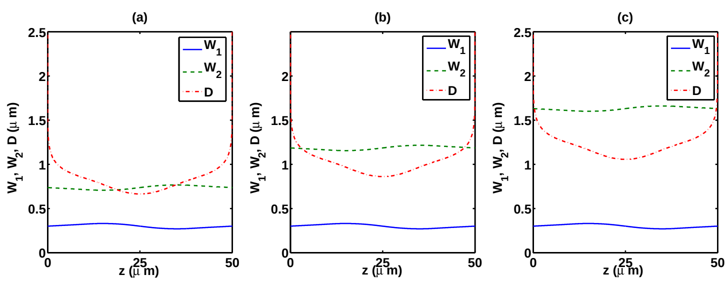

Fig. 5. Device parameters for the mode (de)multiplexers in Fig. 4. (a) m=1, (b) m=2, and (c) m=3.

that the concept of quantum-optical analogy in coupled waveguides and STA can indeed be applied to high index contrast photonics. Figure 7 shows the transmission from the access waveguide into the guided modes of the bus waveguide for the designed (de)multiplexers. Clearly, our numerical simulation has shown that the crosstalk into the unwanted modes is lower than -40 dB from 1.45 to 1.60 μm for all three (de)multiplexers.

Next, the fabrication tolerance is investigated at the operating wavelength of 1550 nm by changing the waveguide widths to $W_1 \pm \Delta w$ and $W_2 \pm \Delta w$ in the simulation, where Δw is the width deviation due to fabrication error. The simulation result is shown in Fig. 8. It can be seen that for width variation as large as $\pm$ 40 nm, the coupling efficiency is greater than 80 %. Our numerical simulation also shows that the crosstalk into the unwanted modes is lower than -30 dB for Δw from -40 nm to +40 nm in all three (de)multiplexers as shown in Fig. 9.

We note that the chosen $\Omega(z)$ and $\Delta(z)$ in Eqs. (6) and (7) are optimized for broadband operation to the third order variation in Δ [16, 23]. Optimization to higher-order robustness and the inclusion of Ω variation could further improve the fabrication tolerance and bandwidth [24]. While the width variation Δw considered in this work is assumed to be unvaried along the device

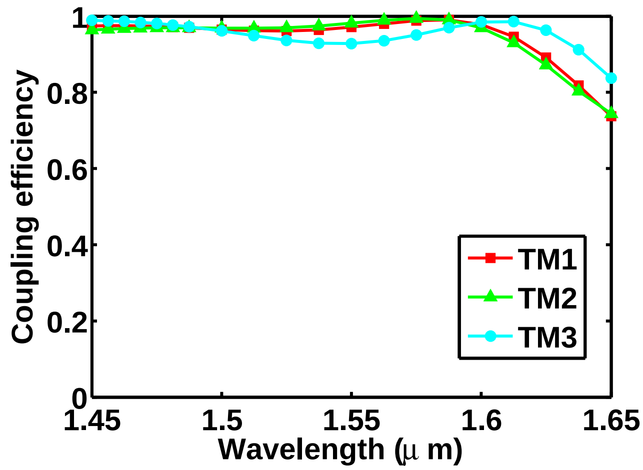

Fig. 6. Simulated wavelength dependence of the coupling efficiency from the access waveguide to the TM_m mode (m=1, 2, and 3) in the bus waveguide.

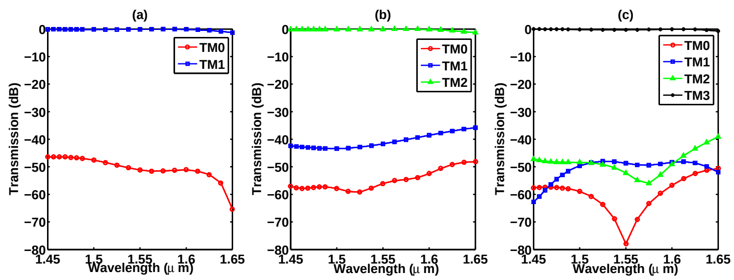

Fig. 7. Simulated transmission from the access waveguide into the guided modes of the bus waveguide as a function of wavelength for the mode (de)multiplexers in Fig. 4. (a) m=1, (b) m=2, and (c) m=3.

to account for a uniform deviation in device width, the STA approach in fact allows one to optimize $\Omega(z)$ and $\Delta(z)$ against various types of fabrication errors, for example, Δw varies with z [27]. In other words, STA provides a versatile toolbox for the design of devices depending on the type of error encountered in fabrication. An exhaustive discussion on possible designs is, however, beyond the scope of this work.

4. Conclusion

In conclusion, we have demonstrated that the STA approach can be applied successfully to the design of high index contrast silicon mode (de)multiplexers. By engineering the coupling coefficient and propagation constants mismatch variation, we use the approach to design mode (de)multiplexers that are compact, broadband, and have large fabrication tolerance. This opens the door to applying STA protocols to the design of compact and robust waveguide devices for dense integration of optical components on chip.

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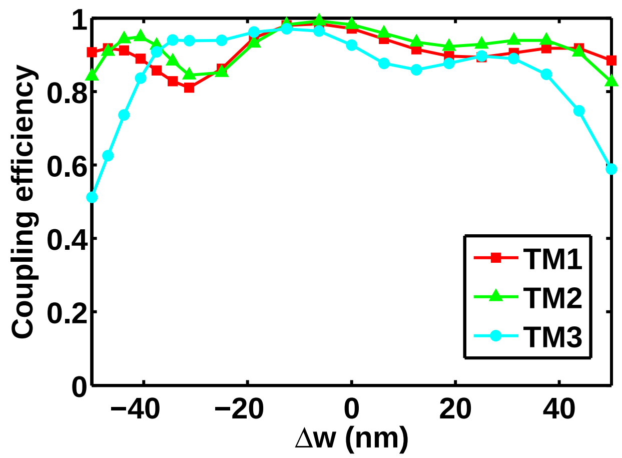

Fig. 8. Simulated coupling efficiency from the access waveguide to the TM_m mode (m=1, 2, and 3) in the bus waveguide as a function of width deviation Δw.

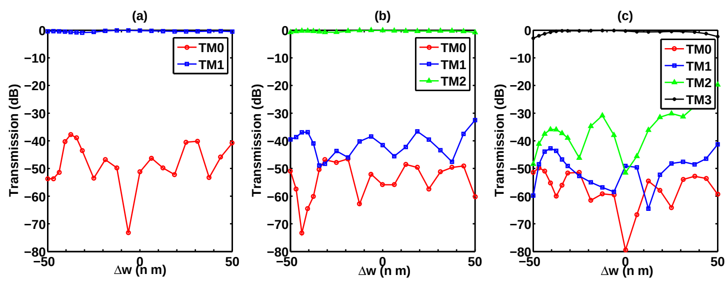

Fig. 9. Simulated transmission from the access waveguide into the guided modes of the bus waveguide as a function of width deviation Δw for the mode (de)multiplexers in Fig. 4. (a) m=1, (b) m=2, and (c) m=3.

Acknowledgments

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