



Short and broadband silicon asymmetric Y-junction two-mode (de)multiplexer using fast quasiadiabatic dynamics

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Abstract: A short and broadband silicon asymmetric Y-junction two-mode (de)multiplexer is proposed and simulated. An adiabaticity parameter suitable for high index-contrast silicon waveguides is defined. The fast quasiadiabatic dynamics protocol is used to homogeneously distribute adiabaticity over the device length. This protocol limits the power coupled into the unwanted waveguide eigenmode under a fixed value along the propagation. A 16 μm long mode (de)multiplexer with crosstalk < -34 dB is obtained. Simulations show that the optical bandwidth is as large as 300 nm (1400 nm \sim 1700 nm). The design is also fabrication tolerant.

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1. Introduction

As high performance computing continues the shift towards parallel architecture with massive numbers of processing cores, the demand for high-capacity on-chip communication has become an important challenge [1, 2]. Silicon photonic optical interconnects, with its compatibility with commercial complementary metal-oxide-semiconductor process, has emerged as an promising solution for on-chip communications [3]. To further increase the bandwidth of optical interconnects, on-chip wavelength-division multiplexing (WDM) technology has been used to demonstrate over 1 Tbit/s transmission through a silicon waveguide [4]. Besides the WDM technology where multiple laser sources with different wavelengths are required, mode-division multiplexing (MDM) technology [5] has been developed as a feasible solution for very short-reach on-chip interconnects. It can also be used alongside WDM to further increase the communication bandwidth [6]. In MDM systems, the multiple propagating modes in the system provide the extra degrees of freedom for potential capacity increase. To avoid intermodal dispersion, one

needs to be able to excite and detect the spatial modes independently in MDM systems. A major challenge in MDM is thus the development of high-performance mode (de)multiplexers with low crosstalk and large bandwidth to selectively excite/extract the modes in a communications link.

Many mode (de)multiplexer schemes have been developed using silicon-on-insulator (SOI) platforms, including asymmetric directional couplers (ADCs) [6, 7], multimode interference couplers (MMIs) [8, 9], tapered directional couplers [10–12], and asymmetric Y-junctions [13, 14]. The ADCs are resonant coupling based devices, meaning that they require precise phase matching for device operation and are susceptible to fabrication errors and wavelength shifts. The MMI based devices require phase shifters that are sensitive to fabrication error as well. On the other hand, the tapered directional couplers and asymmetric Y-junctions are adiabatic devices, and are therefore inherently broadband and less sensitive to fabrication errors. The tapered directional couplers are more complicated than asymmetric Y-junctions because they require control over both the width and spacing of the waveguides. In asymmetric Y-junctions, two diverging single-mode arms with different widths are joined to a two-mode stem waveguide. When the junction satisfies the adiabatic criterion, a mode in the stem waveguide would evolve into the mode of the output arm with the closest effective index, with very little or no excitation of the other arm [15–17]. However, this smooth evolution can only occur when the variation at the junction is slow enough such that the evolution is adiabatic. So, the adiabatic devices are conventionally very long ($> 100 \mu\text{m}$) compared to other schemes. The challenge in asymmetric Y-junction mode (de)multiplexer design is thus to reduce the device length while minimizing the crosstalk between the arms.

In quantum control, the speed up of slow adiabatic process while maintaining robustness has attracted a lot of attentions. In particular, a family of protocols called shortcuts to adiabaticity (STA) [18] has found applications in manipulating Bose-Einstein condensate (BEC) [19], electron spin control [39], and optics [21–30]. The applications of the STA protocols in optics are largely based on the analogy between quantum mechanics and wave optics, which allows one to manipulate light in waveguide structures based on their analogies with coherent quantum phenomena [31]. So far, the optical STA has largely been limited to finite-dimensional systems where the dynamics of light transport can be reduced to coupled-mode equations, allowing a direct adaptation of STA protocols already developed in quantum mechanics. However, the coupled-mode theory, based on the perturbation methods, is limited in its application to high index-contrast SOI waveguides [32]. Moreover, the previous application of STA to asymmetric Y-junction design based on the coupled-mode theory formalism requires control of both the waveguide separation and branching arm widths along the device [23], which might be challenging in terms of fabrication. Recently, a new protocol, the fast quasiadiabatic dynamics (FAQUAD), has been applied to the design of a low index-contrast polymer mode sorting asymmetric Y-junction [33]. The FAQUAD protocol works by homogeneously distributing adiabaticity over the device using a single control parameter. By driving a control parameter as close to the adiabatic limit as possible during the evolution, slow adiabatic evolution in the device can be significantly sped up [34]. In this paper, we define an adiabaticity parameter that is suitable for high index-contrast SOI waveguides and use the FAQUAD protocol to redistribute the adiabaticity of a conventional linearly separating Y-junction. A short and robust Y-junction mode (de)multiplexer is obtained and verified with rigorous eigenmode expansion (EME) method simulations, showing that suitable STA protocols can be successfully applied to silicon photonics.

2. Fast quasiadiabatic dynamics in high index-contrast waveguides

In integrated optics, adiabaticity in a spatially varying device is usually achieved by keeping the coupling between the local eigenmodes (supermodes) below a certain level using the coupled-mode formalism [35], which could be problematic when dealing with high index-

contrast waveguides. In quantum control, the "slowness" of the evolution of a system can be characterized by [36]

$$\left| \frac{\langle m | \dot{n} \rangle}{\beta_m - \beta_n} \right| \ll 1, \quad (1)$$

where the dot denotes derivative with respect to t , and $\beta_{m,n}$ is the eigenvalue associated with eigenstate $|m, n\rangle$. By recognizing that the inner product in Eq. (1) is the same as the mode orthogonality check of guided modes in optical waveguides; that is

$$\langle m | n \rangle \equiv \int [\mathbf{E}_{mt} \times \mathbf{H}_{nt}^*] \cdot \hat{\mathbf{z}} dS, \quad (2)$$

where \mathbf{E}_{mt} and \mathbf{H}_{nt} are the transverse components of the electric field and magnetic field associated with the m th and n th eigenmode of the optical waveguide, and S is the entire waveguide cross section; an adiabaticity parameter for vectorial fields in an optical waveguide can be obtained using Eq. (2) in Eq. (1)

$$c(z) = \left| \frac{\int [\mathbf{E}_{mt} \times \frac{\partial}{\partial z} \mathbf{H}_{nt}^*] \cdot \hat{\mathbf{z}} dS}{\beta_m - \beta_n} \right|, \quad (3)$$

where $\beta_{m,n}$ is now the propagation constant associated with the m, n th eigenmode (we change t to z in subsequent analysis to account for wave propagation in optics).

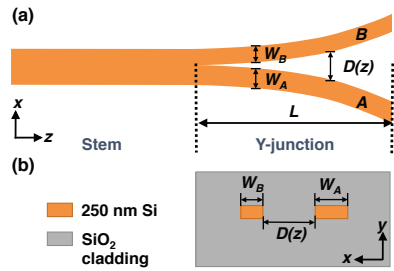


Fig. 1. Schematic of the asymmetric Y-junction silicon mode (de)multiplexer. (a) Top view. (b) Cross-sectional view.

The FAQUAD protocol homogenizes the adiabaticity during the evolution with a single control parameter $D(z)$ (in this work the branch separation shown in Fig. 1) by imposing

$$\left| \frac{\langle m | \dot{n} \rangle}{\beta_m - \beta_n} \right| = \left| \dot{D} \frac{\langle m | \frac{\partial}{\partial D} | n \rangle}{\beta_m - \beta_n} \right| = \varepsilon, \quad (4)$$

where the dot denotes now derivative with respect to z , ε is a small number and using the chain rule $\frac{\partial}{\partial z} |n\rangle = \frac{\partial}{\partial D} \frac{\partial D}{\partial z} |n\rangle$. The scalar and paraxial wave equation, which is essential in quantum optical analogies and subsequent applications of quantum control protocols to optics, is not a priori in the application of the FAQUAD protocol. This makes FAQUAD highly suitable for silicon waveguides. To obtain the control parameter, we first calculate the adiabaticity parameter $c_{lin}(z)$ in Eq. (3) for a device of length L with a linearly varying control parameter

$$D(z) = \alpha z + D_i, \quad (5)$$

where $\alpha = (D_f - D_i)/L$ and D_i and D_f are the initial and final conditions of the control parameter. The control parameter that homogenizes the adiabaticity can be obtained following [33] as

$$D_{FAQUAD}(z) = \alpha \varepsilon \int_0^z \frac{dz}{c_{lin}(z)} + D_i, \quad (6)$$

where the constant adiabaticity parameter in Eq. (4) is now

$$\varepsilon = \frac{L}{\int_0^L (1/c_{lin}(z)) dz}. \quad (7)$$

The fact that the average value of $1/c_{lin}(z)$ is used instead of $c_{lin}(z)$ may seem counterintuitive here. The reason is that the FAQUAD protocol aims to homogenize the adiabaticity, so when calculating for the control parameter $D_{FAQUAD}(z)$ using Eq. (6), the local variation of $D_{FAQUAD}(z)$ has to be inversely proportional to $c_{lin}(z)$; i.e., when $c_{lin}(z)$ is small, the variation is big, and vice versa. So, it's not the adiabaticity parameter $c_{lin}(z)$ that is summed and redistributed; rather the variation of $D(z)$, which is inversely proportional to $c_{lin}(z)$, that is summed and redistributed; and in the process, adiabaticity is homogenized.

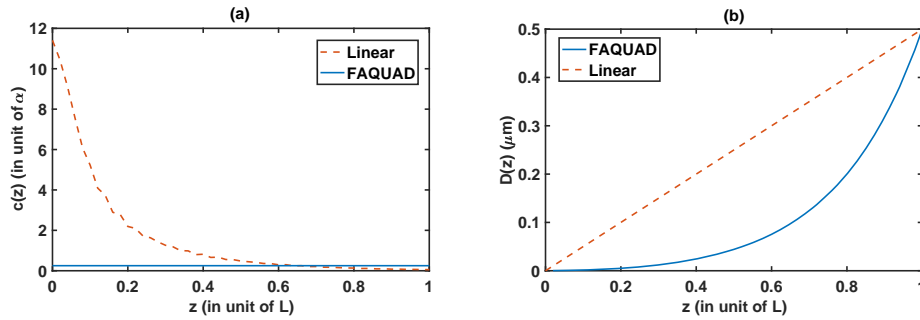


Fig. 2. (a) Device adiabaticity [Eq. (3)] for the linearly separating (dashed) and the FAQUAD (solid) Y-junctions. (b) Branch separations $D(z)$ for the FAQUAD (solid) and linearly separating (dashed) Y-junctions. L is the device length.

3. Structure and design

To illustrate the application of FAQUAD to silicon asymmetric Y-junctions using the branch separation as the control parameter $D(z)$, we choose a rectangular silicon wire structure in Fig. 1 consisting of silicon core and silica cladding with the following parameters for design and simulation: $250 \text{ nm} \times 550 \text{ nm}$ ($h \times w$) for branching arm A, $250 \text{ nm} \times 450 \text{ nm}$ for arm B, and $250 \text{ nm} \times 1 \mu\text{m}$ for the two-mode stem. A finite-difference three-dimensional vectorial mode solver is used to solve for the first two modes of the Y-junction for different branch separations from 0 to $0.5 \mu\text{m}$ in steps of 10 nm . The calculation window in the transverse direction is $1.95 \mu\text{m} \times 6 \mu\text{m}$ ($h \times w$) and discretized into 650×650 uniform rectangular grids. The quasi transverse electric (TE) modes TE_0 and TE_1 are considered. Using the obtained mode data, we can calculate the adiabaticity parameter $c(z)$ in Eq. (3) for a linearly separating Y-junction by assuming $D(z)$ varies linearly with z . The resulting adiabaticity as a function of z for the conventional linearly separating Y-junction of length L is shown in Fig. 2(a). We can observe that at lengths close to L , which corresponds to a branching separation of $0.5 \mu\text{m}$, the adiabaticity is small ($c(L) = 0.054\alpha$), indicating negligible coupling between the eigenmodes. So, we target a final branch separation of $D_f = 0.5 \mu\text{m}$ for the Y-junction and the initial separation $D_i = 0$. Using the calculated linear adiabaticity $c_{lin}(z)$ in Eqs. (6) and (7), we obtain $\varepsilon = 0.25\alpha$ and the FAQUAD branching separation $D_{FAQUAD}(z)$ as shown in Figs. 2(a) and (b). It is enough to find the FAQUAD protocol for one particular device length L , since the protocol for any other length is simply obtained by scaling. The $D(z)$ for the linearly separating Y-junction is also plot in the same figure. Looking at Fig. 2, it is clear that FAQUAD works by redistributing the

control parameter depending on the adiabaticity parameter. When the adiabaticity is large, the variation of $D(z)$ is slowed down; and when the adiabaticity is small, the variation of $D(z)$ is sped up.

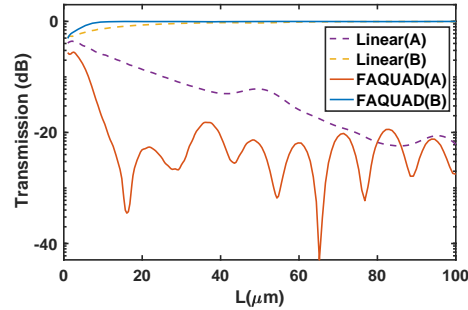


Fig. 3. Simulated transmission in waveguides A and B of the FAQUAD and linearly separating Y-junctions using the 2nd mode (TE_1) of the stem waveguide as the input as a function of device length.

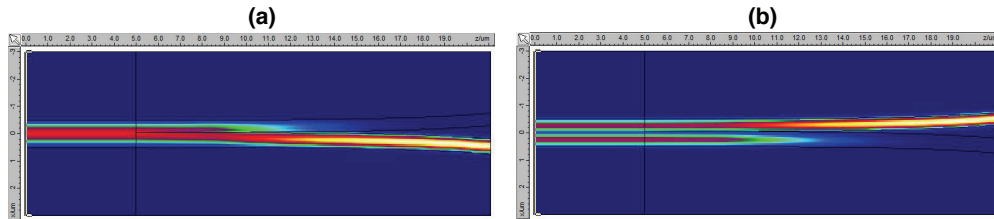


Fig. 4. Simulated field distributions in the asymmetric Y-junction mode (de)multiplexer using the (a) TE_0 and (b) TE_1 modes of the stem as the inputs. The length of the stem waveguide is $5 \mu\text{m}$ and the Y-junction is $16 \mu\text{m}$.

4. Device simulations

Next, we use a commercial software (FIMMPROP, Photon Design) employing a full vectorial eigenmode expansion method (EME) [37] to simulate light propagation in the designed Y-junction. The device is simulated at $1.55 \mu\text{m}$ input wavelength and the quasi TE polarization. In Fig. 3, we show the simulated transmission in branches A and B using the second mode (TE_1) of the stem waveguide as the input as a function of device length L for both the FAQUAD and linearly separating designs. As expected, the FAQUAD design provides shortcut at a shorter device length (it achieves a mode crosstalk below -34 dB at a length of $16 \mu\text{m}$). On the other hand, the conventional linearly separating design can only achieve a mode cross talk of -22 dB even at a length of $100 \mu\text{m}$. The oscillatory behavior of the FAQUAD protocol (see Fig. 3) is due to the quantum interference among jumps from A to B at different locations. This is quantitatively explained in [34], where the oscillation period is identified using adiabatic perturbation theory, $T = \frac{2\pi}{\phi_{AB}}$ where $\phi_{AB} = (1/L) \int_0^L \omega_{BA}(z) dz$ and $\omega_{BA}(z) = \beta_B(z) - \beta_A(z)$.

The corresponding FAQUAD Y-junction geometry for a $L = 16 \mu\text{m}$ Y-junction and the EME simulation results using the TE_0 and TE_1 modes of the stem as the inputs are shown in Fig. 4. In Fig. 4(a), the simulation result shows that the TE_0 mode has evolved to branch A at the output, and the evolution of the TE_1 mode to branch B is shown in Fig. 4(b).

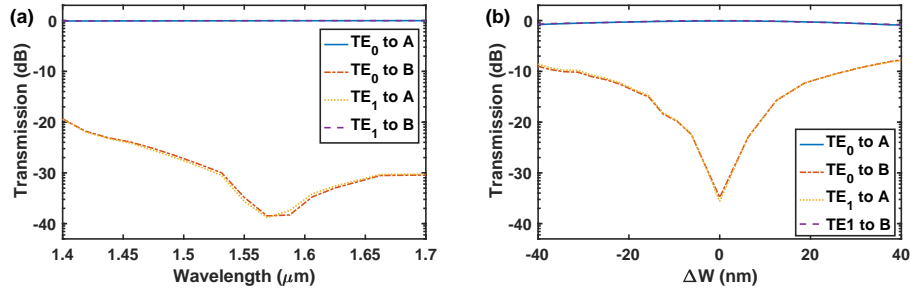


Fig. 5. Simulated transmission as a function of (a) wavelength and (b) fabrication error in waveguide widths for the 16 μm Y-junction.

We then look at the device robustness against wavelength variations. Figure 5(a) shows the simulated wavelength dependence of the conversion efficiency for the FAQUAD Y-junction at a $L = 16 \mu\text{m}$ using the TE₀ and TE₁ modes of the stem as the inputs. It can be seen that for a wide range from 1.4 to 1.7 μm , the coupling efficiency is larger than 98 % and the crosstalk into the undesired branch is lower than -20 dB.

Next, the fabrication tolerance is investigated at the operating wavelength of 1550 nm by changing the waveguide widths to $W_A \pm \Delta W$ and $W_B \pm \Delta W$ in the simulation, where ΔW is the width deviation due to fabrication error. The simulation result is shown in Fig. 5(b). It can be seen that for width variation of ± 40 nm, the coupling efficiency into the desired branch is greater than 80 %. Our numerical simulation also shows that the crosstalk is lower than -20 dB for ΔW from -10 nm to +10 nm. The good robustness of the device indicates that the adiabaticity of the device is indeed achieved with FAQUAD at a much shorter device length than the conventional design. The robustness can be further improved in longer devices. For example, we find in our simulations that a $L = 54 \mu\text{m}$ device shows mode crosstalk lower than -25 dB from 1.4 to 1.7 μm as shown in Fig. 6(a), as well as mode cross talk lower than -20 dB for ΔW from -10 nm to +40 nm as shown in Fig. 6(b).

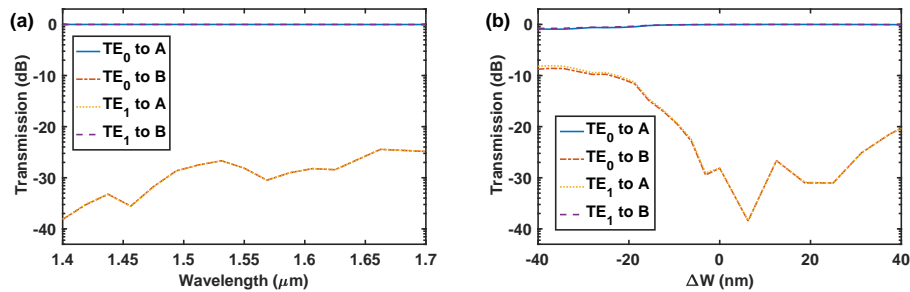


Fig. 6. Simulated transmission as a function of (a) wavelength and (b) fabrication error in waveguide widths for the 54 μm Y-junction.

We then look at the fabrication tolerance for branch separation variations ΔD with the waveguide widths W_A and W_B held as constants. The considered starting separation $D_i = 0$ is difficult to obtain in fabrication. Here, we add a constant ΔD to $D(z)$ in branch separation, corresponding to a starting gap of ΔD , to reflect more realistic situations in fabrication, and the results are shown in Fig. 7(a). It can be seen that the crosstalk is lower than -20 dB for ΔD smaller than

10 nm. The deterioration in performance for starting gaps larger than 10 nm is due to the abrupt change in mode profiles from the multimode stem to the branches, which is not adiabatic. The FAQUAD approach optimizes the adiabatic evolution in the branches but not the transition from the stem to the branches. For a multimode stem consisting of two closely placed waveguides such as the one in Ref. [10], the FAQUAD algorithm can be suitably applied by changing the initial condition D_i in Eq. (5) to account for the non-zero starting gap. The performance of the device against junction location deviation is also investigated. The junction location is moved on the x axis at the stem and branch junction in the simulations. As shown in Fig. 7(b), the crosstalk is lower than -25 dB for junction deviation up to 100 nm in the positive x direction. On the other hand, as the junction is moved in to the negative x direction, the width difference between the branching waveguides decreases and reaches zero at -50 nm, when $W_A = W_B = 500$ nm. It can be seen that the Y-junction now functions as a 3-dB beam splitter with both input modes being equally divided into the two arms. Further deviation in the negative direction results in the switch of arms A and B.

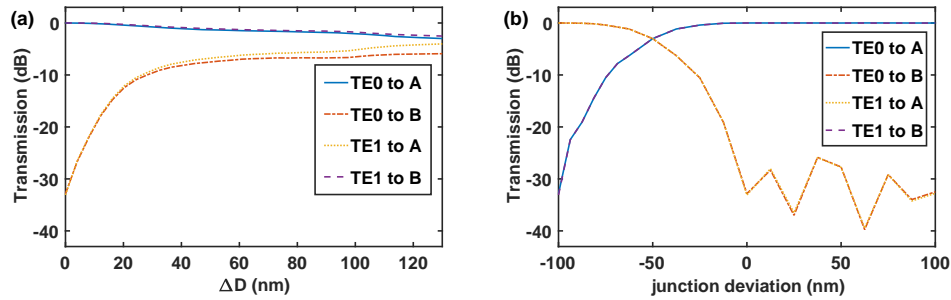


Fig. 7. Simulated transmission as a function of (a) branch separation deviation and (b) junction deviation in waveguide widths for the 16 μm Y-junction.

5. Discussion

The constant adiabaticity achieved by the FAQUAD protocol leads to a mode (de)multiplexer that is only 16 μm long as compared to previous adiabatic devices which are hundreds of microns in lengths [10–14]. The constant adiabaticity scheme has been found to be an optimal approach in adiabatic passage [38]. The merit of constant adiabaticity can be understood using adiabatic perturbation theory. In the paraxial limit and assuming that only the n th eigenmode is excited initially, $a_n(0) = 1$, it can be shown using adiabatic perturbation theory that the derivative of the modal amplitude of the m th eigenmode a_m with respect to z is [34, 35]

$$\frac{da_m}{dz} = -\langle m|\dot{n}\rangle \exp[-i \int_0^z B(z') dz'], \quad (8)$$

where $B(z) = \beta_m - \beta_n$. Substituting the FAQUAD condition Eq. (4) into Eq. (8) and integrate, we obtain

$$a_m = -i\varepsilon[e^{-i \int_0^z B(z') dz'} - 1], \quad (9)$$

where $a_m(0) = 0$ is used. We can then conclude that $|a_m| \leq \varepsilon$. Despite the paraxial limit in the preceding discussion, we can understand FAQUAD conceptually as a protocol that works by limiting the power coupled into the unwanted mode $|m\rangle$ below a fixed value ε along the propagation. For the other protocols, the adiabaticity varies along the propagation, so a longer device length than FAQUAD is required to keep the power in the unwanted mode below the

same fixed value. In Fig. 8, we show the evolution of mode amplitudes $|a_1|$ and $|a_2|$ of the first and second eigenmodes $|1\rangle$ and $|2\rangle$ of the $16\ \mu\text{m}$ Y-junction mode (de)multiplexer when the TE_1 mode of the stem is excited. Clearly, the power in the unwanted eigenmode $|1\rangle$ is kept under 0.015 along the propagation, which is expected from Eq. (7).

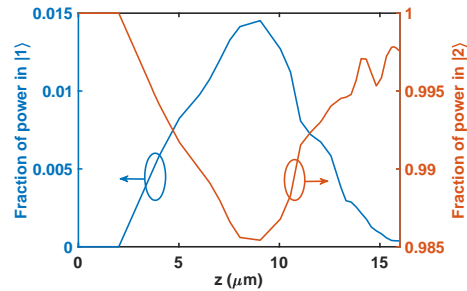


Fig. 8. Simulated evolution of the fraction of power in the eigenmodes of the Y-junction for a $L = 16\ \mu\text{m}$ device.

So far, most of the Y-junction designs in the literature focus on linearly separating designs [13–17] due to its simplicity. What we show here is that by varying a single control parameter (branch separation $D(z)$), the device length can be significantly reduced while maintaining its robustness. The physics behind the improvement is also explained. While optimization techniques are aplenty for the design of efficient devices, e.g. Ref. [39, 40], they normally require multiple parameters and could pose further difficulties in fabrication. Also, the invariant-based inverse engineering STA techniques have also been successfully applied to silicon (de)multiplexers [27, 30], resulting in short and robust devices. The STA techniques need to work in the weak coupling regime where the coupled-mode theory is valid, and both the waveguide widths and separation need to be controlled. The FAQUAD technique here provides a simple and efficient alternative using a single control parameter and provides the robustness of adiabatic designs without the need of coupled-mode and perturbation calculations.

6. Conclusion

We have demonstrated that the FAQUAD approach in quantum control can be applied successfully to the design of high index-contrast silicon asymmetric Y-junction mode (de)multiplexers. By defining an adiabaticity parameter appropriate for vectorial fields in waveguides, the FAQUAD approach is used to homogeneously distribute device adiabaticity along the propagation. We show that it has the effect of limiting the power coupled into the unwanted eigenmode during propagation. We use the approach to design a mode (de)multiplexer that is compact, broadband, and has good fabrication tolerance. This approach is highly suitable for high index-contrast silicon waveguides and could find applications in various components.

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