Robust Directional Couplers for State Manipulation in Silicon Photonic-Integrated Circuits

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Abstract—Photonic integrated circuits play a central role in current and future applications such as communications, sensing, ranging, and information processing. Photonic quantum computing will also likely require an integrated optics architecture for improved stability, scalability, and performance. Fault-tolerant quantum computing mandates very accurate and robust quantum gates. In this work, we demonstrate high-fidelity directional couplers for single-qubit gates in photonic integrated waveguides, utilizing a novel scheme of detuning-modulated composite segments. Specific designs for reduced sensitivity to wavelength variations and real-world geometrical fabrication errors in waveguides width and depth are presented. Enhanced wavelength tolerance is demonstrated experimentally. The concept shows great promise for scaling high fidelity gates as part of integrated quantum optics architectures.

Index Terms—Coherent control, directional couplers, integrated quantum photonics, quantum electronics, silicon photonics.

I. INTRODUCTION

PHOTONIC-INTEGRATED circuits (PICs) are essential for present and future data center communications [1]. PICs are also widely regarded among the most promising platforms for the realization of quantum technologies in computation, information processing, and sensing [2]–[5]. The advancement of quantum integrated photonics would critically depend on the reduction of errors [2], [4]. Compared with classical applications, quantum technologies are far less tolerant to possible uncertainties associated with the fabrication of PICs [6].

The directional coupler is among the most fundamental and widely employed building blocks of PICs [5]. Quantum photonic applications require that the splitting ratios of directional couplers comply with a target design to the fourth decimal point [6]. This requirement places stringent tolerances on process parameters such as etching depth, waveguides widths, etc., which are difficult to meet in practice. Geometrical errors are often correlated: they affect both constituent waveguides in the directional coupler in the same manner. In addition, quantum-photonic integrated circuits would need to operate over ranges of wavelengths and temperatures, leading to further variations in their transfer functions. Unfortunately, standard directional couplers with uniform waveguide sections do not exhibit sufficient tolerance to inevitable fabrication and spectral uncertainties [5].

Much effort has been dedicated in recent years to the design and realization of robust photonic-integrated couplers and quantum gates [2], [7]–[9]. For example, several works have reported wavelength insensitive couplers in silicon-on-insulator (SOI) photonics [10]–[13]. However, fewer works addressed tolerance to geometrical errors in fabrication. Recently, some of us have proposed a design concept for fault-tolerant directional couplers based on waveguide sections of different widths [14]. The approach is based on the principles of composite pulse sequences used in atomic physics [15], [16]. The so-called composite-sections couplers are simple to realize, and they do not require modifications to the fabrication protocols. The design approach is generic and can be optimized for the mitigation of errors in wavelength or geometry.

In this work, we report composite-sections directional couplers in the standard SOI platform, the workhorse of PICs. One specific design addresses wavelength variations, whereas another provides enhanced tolerance to real-world geometrical fabrication errors in the widths and etching depth of both coupler waveguides. Improved spectral stability is demonstrated experimentally: the coupling ratios of hundreds of microns-long uniform and composite-sections couplers are characterized across the C-band wavelengths. The spectral sensitivity of the composite-sections couplers splitting ratio is reduced by over an order of magnitude. The composite-sections couplers may serve as a fundamental building block of practical quantum silicon photonics.

II. DESIGN OF COMPOSITE-SECTION DIRECTIONAL COUPLERS

According to the coupled-mode theory, the propagation of the pair of electrical fields $E_{1,2}$ in a directional coupler of a fixed coupler waveguide sections and the design parameter $\gamma$ are chosen such that the splitting ratio $S$ is a function of the geometrical parameters of the coupler waveguides. The approach is based on the principles of composite pulse sequences used in atomic physics [15], [16]. The so-called composite-sections couplers are simple to realize, and they do not require modifications to the fabrication protocols. The design approach is generic and can be optimized for the mitigation of errors in wavelength or geometry.

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cross-section is described by the following unitary propagator:

\[
\begin{bmatrix}
E_1(z) \\
E_2(z)
\end{bmatrix} =
\begin{bmatrix}
\cos(A) + \frac{i\Delta\beta}{\kappa_g} \sin(A) & -\frac{i\kappa}{\kappa_g} \sin(A) \\
\frac{i\kappa}{\kappa_g} \sin(A) & \cos(A) - \frac{i\Delta\beta}{\kappa_g} \sin(A)
\end{bmatrix}
\begin{bmatrix}
E_1(z_0) \\
E_2(z_0)
\end{bmatrix}
\]

(1)

Here \(\kappa\) is the coupling coefficient between the two waveguides, determined mainly by the distance between the cores, \(\Delta \beta = \frac{\beta_2 - \beta_1}{2}\) denotes the detuning, or the phase mismatch parameter, which is determined by the propagation constants \(\beta_{1,2}\) in the two constituent waveguides when uncoupled. Also, in (1), \(z\) represents the axial coordinate in the direction of propagation, \(z_0\) is the point of entry into the coupler, \(\kappa_g = \sqrt{\kappa^2 + \Delta \beta^2}\) is the generalized coupling coefficient, and \(A = \int_{z_0}^{\infty} \kappa_g dz = \kappa_g(z - z_0)\) is the integral of the generalized coupling coefficient, also referred to as the 'pulse area'.

In the design of robust composite-section directional couplers, several segments of uniform waveguides widths and uniform gaps are concatenated together, such as to achieve better robustness for a specific error model. Each uniform section is described by its own unitary matrix. We relate to variations in the operating wavelength first. To realize couplers with reduced spectral sensitivity, we utilize the first-order scheme [14], in which the second-order derivative with respect to pulse area error is nullified, as defined in equation (2):

\[
\frac{\partial^2}{\partial A^2} \left( \prod_i \hat{U}_i \right) = 0
\]

(2)

The solution of (2) for two segments, \(i = 1, 2\), with full power swap (\(\hat{U}_{12} = 1\)), yields the following relations: \(\kappa_1 = \kappa_2 = \kappa\), and \(\Delta \beta_1 = -\Delta \beta_2 = \kappa\). The extraction of waveguides widths and lengths in each segment is detailed in Appendix A.

A two-section composite directional coupler is illustrated in Fig. 1. The coupler comprises one uniform waveguide and a second waveguide of position-dependent width. The second waveguide consists of repeating sections of widths \(W_{1,2}\) and length \(L_{1,2}\). The lateral separation \(g\) between the centers of the two waveguides remains constant. To reduce scattering and reflection losses at abrupt width changes, a 1 \(\mu m\) long tapering region is inserted in each width transition.

To verify our design, a three-dimensional finite difference time domain (FDTD) simulation was performed with Lumerical, a commercially available solver. The simulation compared between uniform and composite-sections directional couplers of SOI ridge waveguides, designed nominally for complete power swap. The thickness of the silicon device layer is 220 nm and that of the buried oxide layer is 2 \(\mu m\). The exact dimensions of waveguides within the couplers were taken from atomic force microscope measurements of fabricated devices (see next section). The depth of partial etching is 77 nm between the two ridge waveguides and 85 nm to their sides. The lateral separation between the centers of the two waveguides is fixed at 1 \(\mu m\). Examples of the results of the field propagation are displayed in Fig. 2(a)–2(b).

The wavelength dependence of both couplers is shown in Fig. 2(c). The blue trace presents a 32.9 \(\mu m\)-long uniform coupler between waveguides of 750 nm widths. Corresponding results for a composite-sections coupler (\(W_1 = 660 nm, W_2 = 890 nm, L_1 = 24.39 \mu m, L_2 = 21.83 \mu m\), overall length of 46.22 \(\mu m\)) are shown in orange. The composite-sections design reduces wavelength dependent errors in the coupling ratio from 10.6% to 2.4%. In addition, the propagation constants \(\beta_{1,2}\), the
coupling coefficient $\kappa$ and the mismatch parameter $\Delta \beta$ were calculated numerically for each waveguide segment, and the power splitting ratios of the directional couplers were found by applying (1) to each section. These approximate calculations were found to be in good agreement with the full FDTD simulation.

Next, we propose a composite-sections coupler design with increased tolerance to real-world geometric fabrication errors. The most commonly encountered deviations from design parameters are in the partial etching depth of ridge waveguides and in their widths. Both types of deviations are likely to be the same for the two constituent waveguides of a directional coupler, along its entire length. Errors in width and depth are statistically uncorrelated. Numerical analysis of modal solutions suggests that the detuning parameter $\Delta \beta$ is the most sensitive to geometrical errors. We therefore expanded (1) in terms of a Taylor series with respect to detuning errors $\delta \Delta \beta$. The composite-sections coupler was designed to nullify the detuning error $\delta \Delta \beta$ to the first order, while keeping the constraint for complete power swap, $|\tilde{U}_{12}| = 1$. These considerations result in a three-section design, with the following relations among parameters:

$$\begin{align*}
\kappa_1 &= \kappa_2 = \kappa_3 = \frac{\Delta \kappa}{\kappa} \\
-\Delta \beta_1 &= \Delta \beta_3 = \kappa, \quad \Delta \beta_2 = 0
\end{align*}$$

(3)

Fig. 3 shows the calculated splitting ratios at 1550 nm wavelength of two directional couplers, designed again for a complete power swap, as functions of width and etching depth errors. Panel (a) presents a standard coupler of uniform cross-section, whereas panel (b) shows the results for a three-sections composite coupler (for details of sections lengths and waveguides widths, see Fig. 3). Eta etching depth errors $\delta h$ between $\pm 8$ nm and width errors $\delta w$ within $\pm 80$ nm were considered. The analysis suggests that the composite-sections coupler is more robust to geometrical fabrication errors. The mean splitting ratio across all error values is 97.6% with deviations of $+2.4\%$ and $-3.2\%$ in the uniform coupler, compared to a mean 99.1% with deviations of $+0.9\%$ and $-2.0\%$ in the composite-sections coupler.

This design approach described above is suitable to arbitrary power splitting ratio, by setting the requirement for the propagator element as $|\tilde{U}_{12}|^2 = \eta$. For example, a 50:50 power splitter ($\eta = 0.5$) with enhanced wavelength insensitivity can be obtained with the choice of [14]:

$$\begin{align*}
\Delta \beta_1 &= -5.52 \kappa, \quad \Delta \beta_2 = 0.69 \kappa \\
A_1 &= A_2 = \frac{\pi}{2}
\end{align*}$$

(4)

III. DEVICE FABRICATION AND TESTING

To compare between uniform and composite-section couplers, test patterns of racetrack resonators were fabricated in standard SOI substrates. The lengths of the resonators were 1.3 mm. The widths of waveguides within the directional couplers forming the resonators, the separation between the waveguides, and the etching depths were the same as those in Fig. 2 above. A reference resonator device was based on a uniform coupler of 350 $\mu$m length. A second device included a composite-sections coupler with ten repeating periods. Following the ten periods, another composite section was added to provide critical coupling into the resonator. That section comprised of two segments, with the width of one waveguide fixed at 750 nm. The width of the other waveguide was 486 nm in the first section and 690 nm for 101 $\mu$m. The separations between the centers of the two cores is again fixed at 1550 nm. The calculations suggest that the composite-sections coupler is more robust to real-world geometrical fabrication errors.

Light was coupled between the bus waveguides of resonator devices and standard single-mode fibers using vertical grating couplers. The coupling losses were 10 dB per facet.Fig. 5(a)
Fig. 4. Fabricated devices (a): Top-view optical microscope image of a silicon-photonic racetrack resonator device used in the comparison between uniform and composite-sections directional couplers. The scale bar represents 100 µm. (b): Top-view optical microscope image of one period within a long composite-sections directional coupler. The scale bar represents 10 µm. (c)-(e): Scanning electron microscope images of focused ion beam cross-sections of directional couplers. The scale bars represent 400 nm. (c): Uniform coupler with two identical waveguides, each 750 nm wide. (d): The first section of a composite-sections coupler, in which the width of the right waveguide is reduced to 660 nm. (e): The second section of a composite coupler, in which the width of the right waveguide is increased to 890 nm.

shows optical vector network analyzer measurements of the normalized transfer functions of optical power through the two devices. The wavelength resolution was 3 picometers. The transfer functions consist of multiple periods with a free spectral range of 0.5 nm. The Q factors of both resonators are 30000. The use of composite-sections couplers did not lead to measurable excess losses. The extinction ratios of the periodic transmission notches of the uniform-coupler device vary strongly across the C-band wavelengths range, between 0.25 dB and 20 dB. By contrast, the extinction ratios of the resonator with the composite-sections coupler remained within 16 ± 3 dB over the entire wavelength range.

Fig. 5(b) presents the power splitting ratios of the two couplers as functions of wavelengths, as calculated from the observed extinction ratios of the two transfer functions [5]. The splitting ratio of the long, uniform coupler varies between 0.3 and 1, whereas that of the composite-sections coupler remains within 0.34 ± 0.02. The results illustrate the superior robustness of the composite-sections design with respect to wavelength changes, in agreement with analysis [14]. Fig. 5(b) also presents the calculated splitting ratios of both directional couplers as functions of wavelengths, based on (1). Contributions of transition regions leading the two waveguides to and from the coupling region were accounted for as well. Agreement between models and measurements of splitting ratios is very good.

IV. SUMMARY

In this work, we have proposed and demonstrated fault-tolerant directional couplers comprised of sections with different waveguide widths. The design concept is inspired by the principles of composite pulses in atomic physics [15], [16], which were recently expanded by the detuning modulated composite sequence scheme to tackle errors in PICs [14]. This study shows that the scheme developed for a general quantum system is also applicable to integrated optics. The results suggest a considerable improvement in the robustness of single-qubit state manipulation in the common path encoding of photonic qubits.

We have experimentally demonstrated the enhanced wavelength insensitivity of a full swap coupler. Compared with a reference uniform device, splitting ratio variations of a long composite-sections coupler across the C-band were reduced fifteen-fold. Measurements and calculations were in good agreement. The results suggest a large potential benefit in the cascaded operation of multiple couplers in series within larger processing layouts. A second design targeted common errors in both waveguides width and etching depth within the coupler. The width and depth errors for which the splitting ratio remains above 99% were calculated for a reference uniform coupler and a composite coupler. The composite coupler design tolerates geometrical errors that are twice larger.

The design concept shows great promise for enabling and scaling integrated photonic quantum information processors, which will require many single-qubit operations in every architecture. While this design can eliminate errors to the first order, the concept can be extended to mitigate second and higher-order errors as well. Additional extensions of this scheme
would address the design of robust single- and two-qubit unitary gates.

APPENDIX A – INVERSE DESIGN FOR COUPLED WAVEGUIDES

The general framework presented in this work is valid for every two-level system that exhibits the same dynamics as given in (1). The first-order solution presented in this paper, \( \kappa_1 = \kappa_2 = \kappa \) and \( \Delta \beta_1 = -\Delta \beta_2 = \kappa \), would nullify the second-order derivative of the transfer function and result in robust population transfer for each such system. In this appendix we address the problem of inverse design: calculating the required waveguides widths, gaps, and lengths of coupler segments that realize the required values of \( \kappa, \Delta \beta \).

According to the coupled-mode theory, the detuning \( \Delta \beta \) equals half the difference between the propagation constants of the uncoupled modes in each waveguide. Since there is no analytic solution for the propagation constant as a function of width for ridge waveguides, we performed a numerical simulation using Lumerical, a commercially available solver, and extracted the propagation constant as a function of width for ridge waveguides. The width of the second waveguide \( w_2 \) was varied to obtain \( \Delta \beta_1 = -\Delta \beta_2 = \kappa \). The pulse area for a uniform section is given by \( A = \int z \kappa_g \, dz = \kappa_g L \), where \( \kappa_g = \sqrt{\kappa^2 + \Delta \beta^2} \). The length of the section is chosen by dividing the required pulse area by the generalized coupling coefficient \( \kappa_g \).

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