Detuning Modulated Composite Segments for High Fidelity Directional Couplers in Integrated Photonic Devices

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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.

Introduction

Photonic-integrated circuits (PICs) are regarded among the promising platforms for the realization of quantum technologies in computation, information processing, and sensing. The advancement of quantum integrated photonics would critically depend on the reduction of errors. The directional coupler is among the most fundamental and widely employed building blocks of PICs. Quantum photonic applications require that the splitting ratios of directional couplers comply with target design to very high fidelity. This requirement places stringent fabrication tolerances on process parameters such as etching depth, waveguides widths, etc., which are difficult to meet in practice.

Light inside a directional coupler exhibit the same dynamics as two-level atomic systems, so it makes sense to adopt robust schemes from atomic physics. For example, Composite pulses are used in NMR for decades, and provide a robust scheme to perform atomic operations. Traditionally, on resonance pulses are used, with complex control over the coupling. Coupling in waveguides systems is always real valued, so we can solve this by controlling the detuning of off-resonance segments instead.

Design

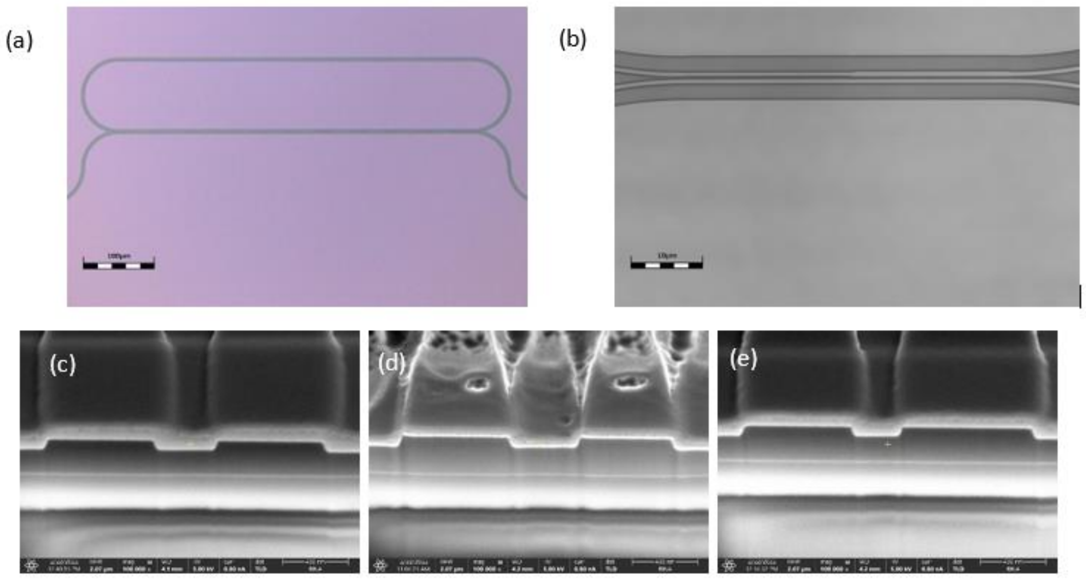
According to the coupled-mode theory, the propagation of the pair of electrical fields $E\_1,2$ in a directional coupler of a fixed cross-section is described by the following unitary propagator:

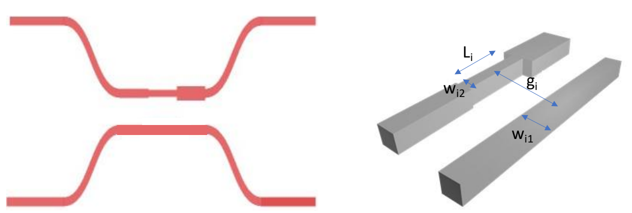
$$\begin{bmatrix} E_1(z) \\ E_2(z) \end{bmatrix} = \begin{bmatrix} \cos\left(\frac{A}{2}\right) + \frac{i\Delta\beta}{\kappa_g}\sin\left(\frac{A}{2}\right) & -\frac{i\kappa}{\kappa_g}\sin\left(\frac{A}{2}\right) \\ -\frac{i\kappa}{\kappa_g}\sin\left(\frac{A}{2}\right) & \cos\left(\frac{A}{2}\right) - \frac{i\Delta\beta}{\kappa_g}\sin\left(\frac{A}{2}\right) \end{bmatrix} \begin{bmatrix} E_1(z_0) \\ E_2(z_0) \end{bmatrix} = \hat{U} \begin{bmatrix} E_1(z_0) \\ E_2(z_0) \end{bmatrix}$$

The idea behind composite segments is to concatenate several such fixed cross-section segments to create a final unitary propagator. While controlling the different cross sections in the segments, one can implement the required Unitary with additional robustness requirements.

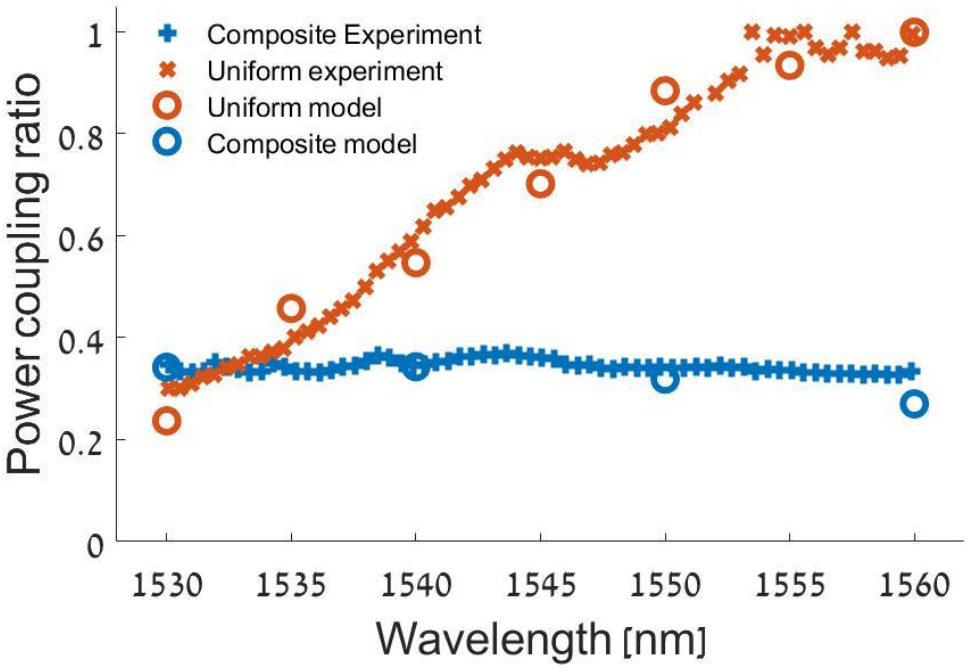
For example, we've shown numerically increased geometrical error robustness of single photon gates. We also demonstrated, experimentally, considerable increase in robustness to wavelength variation of complete population transfer, by demanding robustness of the following matrix element: : $\frac{\partial^2}{\partial A^2}\left(|\hat{U}_{1,2}|\right)$.

We have also shown, numerically, increased geometrical error robustness of single photon gates.

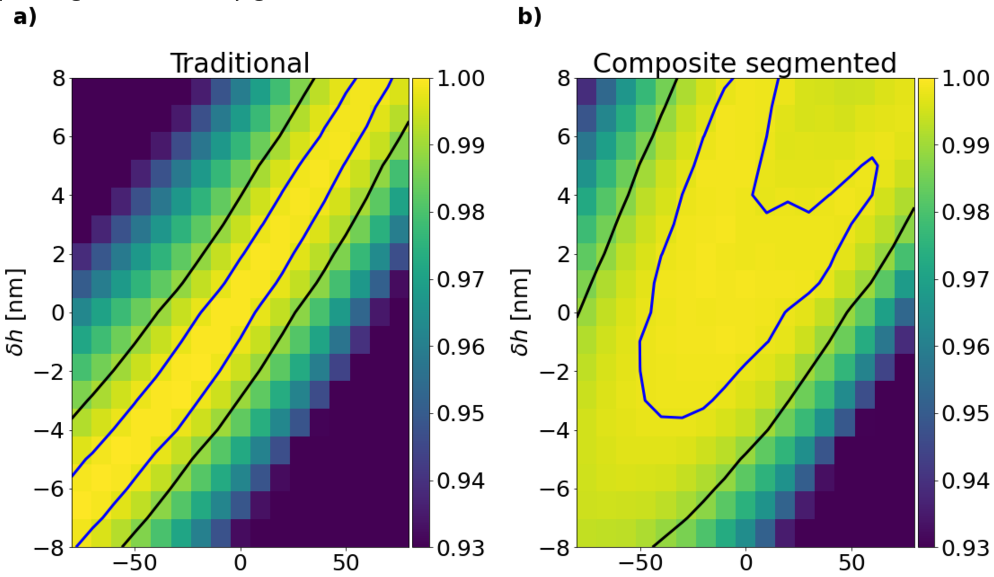




Results



Power splitting ratios of the two couplers as functions of wavelengths. 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. Agreement between models and measurements of splitting ratios is very good.



Comparison between splitting ratios of traditional, as well as composite segmented, directional couplers, designed for a complete power swap, as functions of width and etching depth errors. Etching depth errors δh between ±8 nm and width errors δw within ±80 nm are considered. The analysis suggests that the composite-sections coupler is more robust to geometrical fabrication errors. Compared with the uniform coupler, the splitting ratio remains above 99% over δh and δw values that are two times larger (black contour lines). 99.8% Fidelity contour lines are shown, as well, in blue.