Inverse-designed low-loss and wideband polarization-insensitive waveguide crossing

Student Paper

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ABSTRACT

Polarization-insensitive waveguide crossings are desired because photonic networks usually involve light with different polarizations. Here, we propose a polarization-insensitive waveguide crossing on a 250-nm silicon-on-insulator platform by using an inverse-design method. In simulation, the designed waveguide crossing can maintain insertion loss below 0.18 (0.25) dB in the wavelength range of 1440‒1640 nm for the TE0 (TM0) mode and achieve the minimal insertion loss as small as 0.08 (0.07) dB at the wavelength of 1550 nm. The crosstalk maintains below −32 dB and −35 dB for the TE0 and TM0 modes, respectively. Experimentally, the fabricated waveguide crossing achieves measured insertion loss less than 0.20 (0.25) dB for the TE0 (TM0) mode with the minimal insertion loss as small as 0.1 dB. The measured crosstalk is below −28 dB and −31 dB for the TE0 and TM0 modes, respectively. Therefore, our proposed waveguide crossing can be widely applied in photonic integrated circuits to construct photonic systems with the capabilities of polarization control and mode (de)multiplexing.

Keywords: optical devices, integrated photonics, silicon photonics.

1. INTRODUCTION

Photonic systems are becoming more and more complicated and the number of devices integrated on a single chip is also increasing exponentially. In a planar photonic circuit, waveguide crossings with negligible influence on the propagating light are indispensable. Many waveguide crossings have already been demonstrated and some of them have shown negligible insertion loss and crosstalk for light with TE polarization [1, 2]. A complex photonic system usually needs to control and process light with different polarizations, so waveguide crossings which can transport light perfectly for different polarizations are highly desired. However, a polarization-insensitive waveguide crossing connecting wire waveguides with compact sizes and negligible insertion loss and crosstalk is yet to be realized. Photonic inverse design is a generic and robust design method which explores the full parameter space of device structures. Devices with complicated functions can be designed by using this method. Numerous devices have been proposed and demonstrated including polarization rotator [3], reflector [4], waveguide bend [5-7], etc.

Here, we propose a low-loss and wideband polarization-insensitive waveguide crossing by using an inverse-design method. The simulated insertion loss and crosstalk maintain less than 0.18 (0.25) dB and −32 (−35) dB in the wavelength range of 1440‒1640 nm with the minimal values reaching 0.08 (0.07) dB and −37 (−38) dB, respectively, at the wavelength of 1550 nm for the TE0 (TM0) mode. Experimentally, the fabricated waveguide crossing maintains low insertion loss less than 0.20 dB (TE0 mode) and 0.25 dB (TM0 mode), and the crosstalk maintains less than −28 dB (TE0 mode) and −31 dB (TM0 mode) in the wavelength range of 1440‒1640 nm. At the wavelength of 1550 nm, the insertion loss and crosstalk can reach as small as 0.10 (0.10) dB and −35 (−32) dB for the TE0 (TM0) mode. Therefore, the inverse-designed and experimentally demonstrated waveguide crossings have great potential as a standard module in the silicon photonic integrated circuitry for constructing high-density photonic integrated networks.

2. DEVICE DESIGN METHOD

The devices were designed on a silicon-on-insulator (SOI) wafer with a 250-nm-thick silicon layer embedded inside silicon oxide. Figure 1(a) shows the conventional waveguide crossing, where the purple and gray regions denote silicon and silicon oxide, respectively. Figure 1(b) is a conceptual illustration of our proposed waveguide crossing. We take the waveguide crossing structure shown in Fig. 1(c) as an example to illustrate the design process. The design optimization region is restricted within a circle of 3 μm radius denoted by the blue line. Four continuous lines are used to delineate the borders of the waveguide crossing, and these lines are fitted from the discrete green dots by the triple spline interpolation. The position of each discrete dot is described by the radial and angular coordinates (ri and θi). Due to the rotational symmetry, we only need to optimize 1/8 of the entire structure as shown in Fig. 1(c). During the optimization, the black dots which are used for connecting the waveguides were fixed. The angular coordinates θi of the discrete dots were also fixed. The greedy optimization method was
adopted to determine the radial coordinates \( r_i \) of the discrete dots. We first generated a random value for each dot, then optimized them in series. During the serial optimization, we varied the individual \( r \) and restricted the dot within the blue circle, while fixing all the other dots. The best \( r_i \)'s were obtained after comparing the structural transmission of all attempted values.

After several rounds of \( r \) optimization from the first dot to the last, the process was stopped when the insertion loss of both the TE0 and TM0 modes at 1550 nm could not be reduced in additional optimization runs. Based on the structure obtained from the greedy optimization method, we subsequently adopted a random-walk method to further improve the performance of the waveguide crossing. The radii \( r_i \)'s of all dots were given a slight random variation. If the resulting insertion loss reduced, the change was accepted; otherwise, the change was discarded. This process was stopped when the insertion loss was below 0.1 dB. After ~48 hours of optimization by using a normal 16-core desktop computer, we obtained the final design of polarization-insensitive waveguide crossing as shown in Fig. 1(c). Figures 1(d) and 1(e) plot the normalized transmission spectra of the optimized and conventional waveguide crossings. The insertion loss of the TE0 (TM0) mode can maintain less than 0.18 (0.25) dB in the wavelength range of 1440–1640 nm and reach as small as 0.08 (0.07) dB at the wavelength of 1550 nm. The crosstalk of the optimized waveguide crossing maintains below −32 (−35) dB for the TE0 (TM0) mode. By contrast, the minimal insertion loss of the conventional waveguide crossing is higher than 1.35 (0.84) dB, and the crosstalk is higher than −16 (−19) dB for the TE0 (TM0) mode in the same wavelength range.

3. EXPERIMENTAL RESULTS

The waveguide crossing devices were fabricated on a SOI wafer with 250-nm Si device layer on 3-μm buried oxide. The device patterns were defined along with the input and output waveguides and grating couplers in a single step of electron-beam lithography with ZEP520A resist. Then, the patterns were transferred to the top silicon layer by inductively coupled plasma reactive-ion etching with SF6/C4F8 gas chemistry. Last, a 2.5-μm-thick silicon oxide layer was deposited on the top as an upper cladding by plasmon-enhanced chemical vapor deposition. Figures 2(a) and 2(e) are the optical microscope images of the fabricated devices for characterizing the insertion loss and crosstalk of the optimized and conventional waveguide crossings, respectively. We adopted on-chip grating couplers to couple light from an optical fiber into and out of the devices, because grating couplers can work not only as power couplers but also as mode selectors to couple light with the desired polarization into and out of the devices. Devices composed of a pair of grating couplers connected by straight waveguide were used to extract the insertion loss and crosstalk without waveguide crossings. We cascaded multiple optimized waveguide crossings in a single device in order to measure the small insertion loss. Figures 2(b) and 2(f) are the scanning electron microscope (SEM) images which are zoomed in at the optimized and conventional waveguide crossings, respectively.

We characterized the fabricated devices by spectroscopic measurement of their optical transmission. A tunable semiconductor laser was used to measure the wavelength dependence of the waveguide crossings in the wavelength range of 1440–1640 nm. The light was sent over a single-mode fiber with its polarization state adjusted by a fiber polarization controller and then coupled into the device under test via the input grating coupler. A photodetector was used to collect the light coupled out of the output grating coupler. For the TE0 mode, the normalized transmission spectra measured from the through and cross ports of the optimized and conventional waveguide crossings are plotted in Figs. 2(c) and 2(g), respectively. The measured insertion loss and crosstalk of the optimized waveguide crossing maintain below 0.20 dB and −28 dB in the wavelength range.
of 1440–1640 nm. As a comparison, the insertion loss and crosstalk of the conventional waveguide crossing are higher than 1.00 dB and −16 dB in the same wavelength range. For the TM₀ mode, the normalized transmission spectra measured from the through and cross ports of the optimized and conventional waveguide crossings are plotted in Figs. 2(d) and 2(h), respectively. The measured insertion loss and crosstalk of the optimized waveguide crossing maintain below 0.25 dB and −31 dB in the wavelength range of 1440–1640 nm. As a comparison, the insertion loss and crosstalk of the conventional waveguide crossing are higher than 0.65 dB and −25 dB in the same wavelength range. It should be noted that previous demonstrated waveguide crossings were designed for only one polarization and could not achieve low insertion loss for both the TE₀ and TM₀ modes simultaneously [8, 9]. Although some optimized crossings considered both the TE₀ and TM₀ modes, they suffer from larger insertion loss and narrower operating bandwidths [10, 11].

Figure 2. (a),(e) Optical microscope images of the fabricated optimized (a) and conventional (e) waveguide crossing. (b),(f) Scanning electron microscope (SEM) images of the fabricated optimized (b) and conventional (f) waveguide crossing. (c),(g) Experimental insertion loss (blue lines) and crosstalk (red lines) spectra of the optimized (c) and conventional (g) waveguide crossing for the TE₀ mode. (d),(h) Experimental insertion loss (blue lines) and crosstalk (red lines) spectra of the optimized (d) and conventional (h) waveguide crossing for the TM₀ mode. The scale bars represent 20 μm in (a) and (e), and 1 μm in (b) and (f).

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