Optics and Laser Technology 100 (2018) 7–11

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Experimental demonstration of a broadband two-mode multi/demultiplexer based on asymmetric Y-junctions

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A R T I C L E I N F O

Article history:
Received 7 April 2017
Received in revised form 23 August 2017
Accepted 26 September 2017

Keywords:
Integrated optics
Waveguide
Multiplexing

A B S T R A C T

A broadband two-mode multi/demultiplexer using asymmetric Y-junctions is designed and experimentally demonstrated on a silicon-on-insulator platform for on-chip mode-division multiplexing applications. Within a bandwidth from 1513 to 1619 nm, the fabricated device, which consists of a two-mode multiplexer, a multimode straight waveguide, and a two-mode demultiplexer, exhibits demultiplexing crosstalk of less than −9.1 dB. The demultiplexing crosstalk as low as −42.1 dB, lower than −12.8 dB over the C band can be obtained. The measured insertion loss varies from 0.40 to 0.56 dB at a wavelength of 1550 nm. A transmission experiment of 10 Gbit/s electrical signals carried on TE_0 and TE_1 modes is successfully achieved with open and clear eye diagrams.

1. Introduction

Silicon-based optical interconnects are regarded as a promising solution for future massively parallel chip multiprocessors [1–3]. In order to keep up with the increasing capacity demand, several techniques have been employed, such as wavelength division multiplexing (WDM) [4], polarization division multiplexing (PDM) [5], and multilevel modulation formats [6]. Mode division multiplexing (MDM) utilizing each orthogonal mode waveguide as a separate data channel is attracting much attention for further expanding the link capacity [7].

To realize MDM transmission, a mode multi/demultiplexer (mux/demux) which can combine/separate optical signals conveyed in different mode channels is one of the key components. In recent years, various types of muxs/demuxs with different structures have been proposed and experimentally demonstrated on the silicon-on-insulator (SOI) platform, including asymmetrical directional couplers (ADC) [8–10], tapered directional couplers (TDC) [11–14], adiabatic couplers (AC) [15,16], and densely packed bent waveguide arrays[17]. The asymmetric Y-junction is an useful mode-evolution-based element. Using asymmetric Y-junctions, the device can be designed to act as a mode (de)multiplexer [18,19], mode splitter [20], mode (de)interleaver [21], wavelength multiplexer [22], or polarization splitter[23]. Previously, silicon two-mode muxs/demuxs using asymmetric Y-junctions have been characterized with demultiplexing crosstalk as low as −30 dB, lower than −9 dB over the C band [18].

In this paper, an optimized design of a broadband two-mode mux/demux based on asymmetric Y-junctions for transverse-electric (TE) mode operation is presented. The properties of the two-mode mux/demux are numerically studied using the three-dimensional beam propagation method (3D-BPM). To verify the design, the device composed of a two-mode multiplexer, a multimode straight waveguide, and a two-mode demultiplexer is fabricated on the SOI platform. Our measurements show that demultiplexing crosstalk of the fabricated device lower than −9.1 dB can be achieved in a broad wavelength range of 106 nm. In the whole C band, the demultiplexing crosstalk is less than −12.8 dB. The insertion loss ranges from 0.40 to 0.56 dB, which depends on the I/O ports. Additionally, open and clear eye-diagrams at 10 Gbit/s are obtained.

2. Design and analysis

The asymmetric Y-junction transform optical modes by the junction. The mutual conversion between the *i*-th-order mode in the stem waveguide and the fundamental mode in the narrow arm can be achieved, when the propagation constants of the modes in the two arms satisfy the relationship given below [19]:

$$\beta_{w,i} < \beta_{n,0} < \beta_{w,i-1} \tag{1}$$

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https://doi.org/10.1016/j.optlastec.2017.09.043
0030-3992/

where $\beta_{n,0}$ and $\beta_{w,i}$ are respectively called the propagation constant of the fundamental mode in the narrow arm and the propagation constant of the *i*-th-order mode in the wide arm. In addition, the performance of a two-mode multiplexer based on an asymmetric Y-junction can be evaluated quantitatively by utilizing the mode conversion factor (MCF) [24]:

$$\mathrm{MCF} = \frac{|\beta_{\mathrm{n},0} - \beta_{w,0}|}{\theta\gamma_{nw}} \tag{2}$$

where θ is the branching angle between the two output arms. γ_{nw} is defined as $\gamma_{nw} = 0.5\sqrt{(\beta_{\mathrm{n},0} + \beta_{\mathrm{w},0})^2 - (2k_0 n)^2}$, where k_0 is the free-space wavenumber and n is the cladding refractive index.

The schematic of the proposed two-mode mux/demux using asymmetric Y-junctions is illustrated in Fig. 1(a). As shown in Fig. 1(a), the asymmetric Y-junction consists of a stem waveguide with a width of W, a narrow arm with a width of W_0, and a wide arm with a width of $(W - W_0)$. The access waveguide with a width of W_a supports just the fundamental mode. Between the arms of the asymmetric Y-junction and the access waveguides, adiabatic tapers are used to link them. Fig. 1(b) shows the calculated effective indices of the first three TE modes as a function of the waveguide width at an operating wavelength of 1550 nm. In the simulation, an SOI wafer with a 220-nm-thick top silicon layer is considered. The refractive indices of SiO_2 and Si are respectively set to be 1.444 and 3.467. The width of the access waveguide is selected to be $W_a = 0.45$ µm. The optimal widths for the stem waveguide and the narrow arm are chosen as $W = 0.9$ µm and $W_0 = 0.4$ µm under the constraint condition of the propagation constants. According to the definition of MCF, if the propagation constants and the cladding refractive index are given, the branching angle will be a critical factor. L is the length of the wide arm and W_s is the gap between the narrow arm and the wide arm. L and W_s are related to the branching angle θ. The length L and the width W_s dependence of the optical transmission of the proposed two-mode mux/demux are shown in Fig. 2.

As depicted in Fig. 2(a) and (b), as the width W_s increases, the calculated output power at the unwanted output port is first reduced, and then significantly increased. There is an inflection point. In addition, the calculated output power at the unwanted output port shows a periodic oscillation with increasing length L. In order to reduce the footprint and improve the extinction ratio, the width W_s and the length L are respectively set to be 1.3 µm and 60 µm in the simulation. The mode extinction ratios of the fundamental modes at different output ports can exceed 41.3 dB at the wavelength of 1550 nm.

Fig. 3 shows the simulated light propagation in the designed two-mode mux/demux, when the fundamental mode at the wavelength of 1550 nm is launched into different input ports. As is shown, when the fundamental mode is launched into the input$_1$

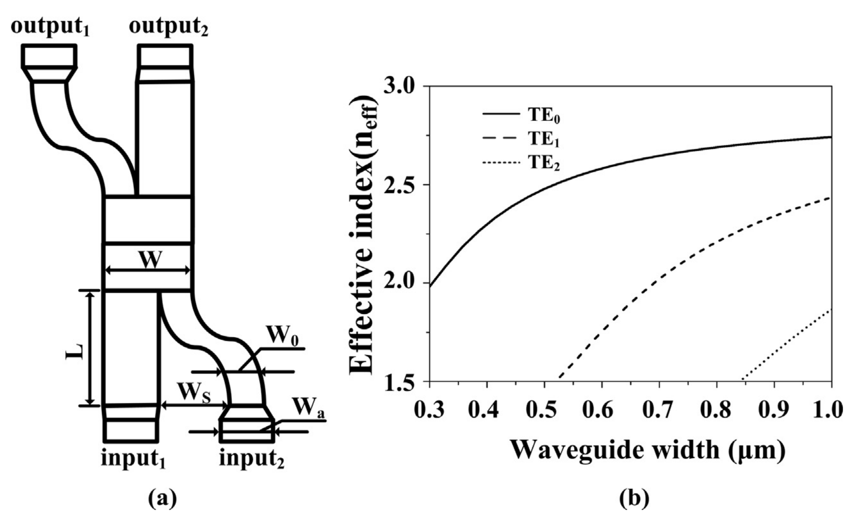

Fig. 1. (a) The schematic drawing of a two-mode mux/demux using asymmetric Y-junctions, (b) variations of the calculated effective indices of the TE_0, TE_1 and TE_2 modes with the waveguide width for a waveguide height of 220 nm.

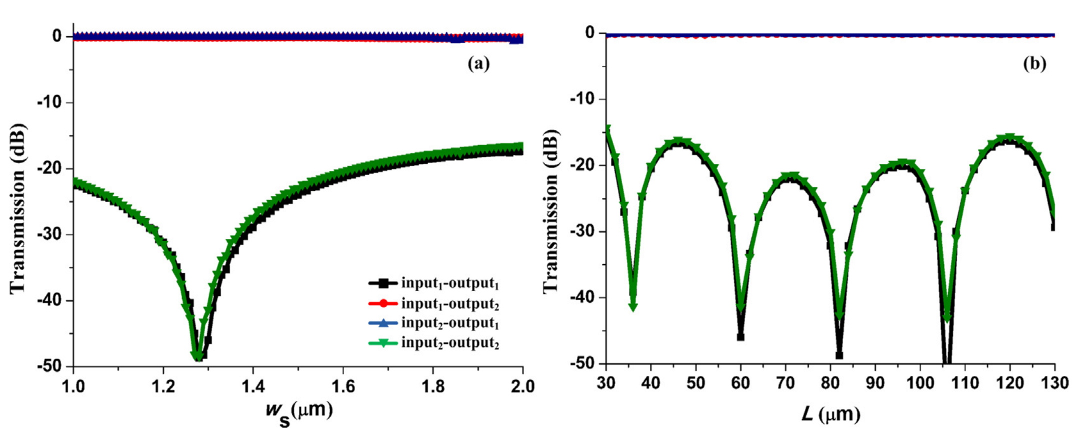

Fig. 2. Optical transmission responses at ports output$_1$ and output$_2$ as a function of W_S in (a) (L = 60 µm used) and L in (b) (W_S = 1.3 µm used), when the fundamental modes are launched into ports input$_1$ and input$_2$ of the designed mode mux/demux.