Demonstration of Compact 2x2 Multimode Interference Coupler on Silicon Nanomembrane

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Abstract: We designed and fabricated a 2x2 tapered multimode interference coupler on silicon-on-insulator with dimensions of 12.88μm×3μm. The device keeps a 50/50 splitting ratio over a 50nm bandwidth. To our best knowledge this is the most compact 2x2 MMI demonstrated.

OCIS codes: (130.3120) Integrated optics devices; (130.2790) Guided waves

1. Introduction

Multimode interference (MMI) devices based on self-imaging are key components in photonic integrated circuits (PICs) as they provide different NxM couplers with different output power distributions [1, 2, 3]. Since the MMI length is proportional to the square of the MMI width, the MMI length can be shortened by a factor of three to four in width-tapered MMIs [4, 5, 6, 7]. Linear and parabolic tapers were investigated and it was shown that while linear tapers result in shorter devices, the power splitting ratio deviates from 50/50 due to induced phase differences in the images formed at the middle of the multimode sections [4]. Parabolic 2x2 MMIs have been used as beam splitters [1, 4, 5], optical switches [8], and all-optical flip flops [9].

Previously, a parabolically tapered 2x2 using air-cladded SU-8 rectangular waveguides was demonstrated [6]. Despite the advantage of polarization independent waveguide structure, optical coupling imposed a lower limit on the separation between the excess waveguides at the input and output, and therefore it increased the size of the MMI coupler (34.2μm x 5.3μm). In this paper we present a 2x2 MMI designed and fabricated on silicon nanomembrane. The high index contrast enables realization of ultra-short MMIs by reducing the proximity limitations [4] through large light confinement inside the silicon waveguide structure. Using eigenmode decomposition based simulations, we fine tune the device length from theoretical calculation. The device is 12.88μm x 3μm, which is the smallest tapered 2x2 MMI presented to date. Experimental investigation results show large bandwidth over 50nm.

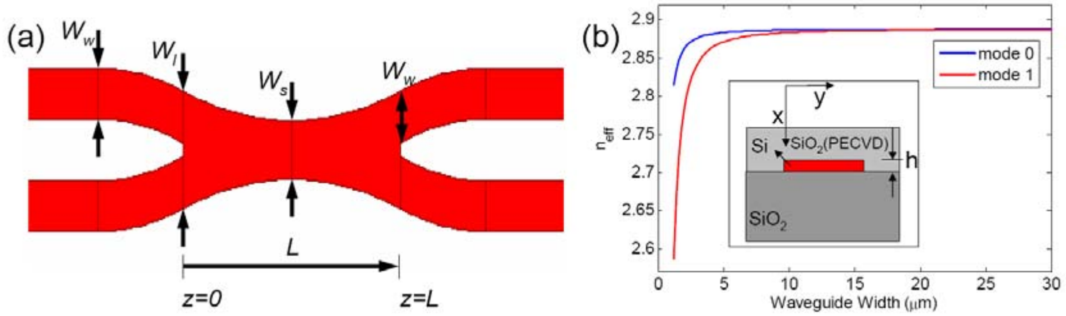

Fig. 1 (a) a schematic of the parabolically tapered 2x2 MMI. (b) Variations of the effective refractive indices of the zeroth and first order modes versus waveguide width for the waveguide structure shown in the inset. The refractive indices of the silicon, the buried oxide and the top cladding PECVD oxide are 3.47, 1.45 and 1.46, respectively. h=230nm and λ=1550nm.

2. Parabolically tapered 2x2 MMI design

A 3-dB MMI device is shown in Figure 1(a). The width of the MMI at the input and output is W_l. The MMI width is parabolically tapered down to W_s in the middle of the MMI according to [4]

$$W(z) = W_s + (W_l - W_s)(L/2 - z)^2 / (L/2)^2 \tag{1}$$

where z and L are the direction of the propagation and the MMI length, respectively. A 2x2 MMI is designed to have a general interference (GI) two-fold self imaging at $z=L$. For a GI two-fold self imaging, the difference in the accumulated phases of the zeroth (φ_0) and the first (φ_1) order modes is $3\pi/2$ at the MMI output ($z=L$) given by [5]

$$\Delta\varphi_1(L)=\varphi_0(L)-\varphi_1(L)=\int_0^L[n_{eff0}(z)-n_{eff1}(z)]k_0dz=3\pi/2 \tag{2}$$

where n_{eff0} and n_{eff1} are the effective indices of the zeroth and the first order modes, respectively, $k_0=2\pi/\lambda_0$ and λ_0 is the free-space wavelength. We design a tapered 2x2 MMI based on the silicon-on-insulator (SOI) waveguide structure as shown in the inset of Figure 1(b). We assume the transverse electric polarization (TE). The variations of n_{eff0} and n_{eff1} for silicon thickness h=230nm at λ=1550nm for changes in the waveguide width are shown in Figure 1(b) calculated from Rsoft's FIMSIM simulations. We select W_l=3µm and W_s=1.5µm, for which we find L=12.98µm. The input and output access waveguides are designed to match the local taper angle at the two end sides of the tapered MMI as shown in Figure 1(a). We select the access waveguide width W_w=1.3µm, which is wide enough to minimize the accumulated modal phase errors at the end of the multimode region [10, 11]. Avoiding the accumulated phase errors is the key to realize high transmission and high uniformity [11].

We model the designed 2x2 MMI using the eigenmode decomposition based PhotonDesign's FIMMPROP simulations. In order to fine-tune the device length we excite both input waveguide with the same input power and maximize the total transmission. Figure 2(a) shows the field profile (Ey) for the designed tapered MMI. Figure 2(b) shows the transmission versus L. The maximum transmission is found to be 97% at L=12.88µm, which is very close to the theoretically calculated value (12.98µm). Therefore, the multimode region dimensions are 12.88µm x 3µm, which are the smallest experimentally demonstrated to date.

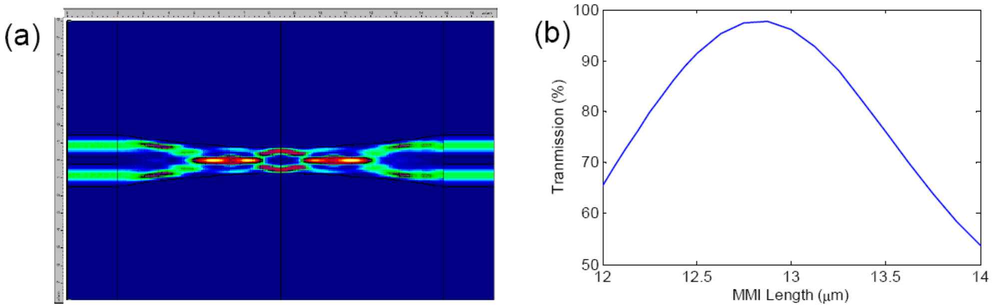

Fig. 2, eigenmode decomposition based FIMMPROP simulations for W_l=3µm, W_s= 1.5µm and W_w=1.3µm, (a) field profile (Ey) for L=12.88µm, (b) variations of the total output power to the total input power ratio versus MMI length, while both input waveguides are excited by the same power.

3. Experimental measurement and characterization

The MMIs are fabricated on a silicon-on-insulator (SOI) substrate with 3µm buried oxide layer (BOX). The MMIs are patterned using electron beam lithography, followed by reactive ion etching (RIE) and plasma-enhanced chemical vapor deposition (PECVD) of a 1µm thick silicon dioxide film for the top cladding. The details of the fabrication process will be reported separately. All the input channels are tapered to 2.5µm to match the input coupling lensed fiber and are fanned out for 60µm center-to-center separation. Figures 3(a) and (b) show top-down and tilted SEM images of the fabricated compact tapered 2x2 MMI.

Transverse-electric field from an external cavity tunable laser source is coupled into one of the input waveguides through a tapered and lensed polarization maintaining fiber (PMF). A CCD camera captured top-down images of the scattered light at the cleaved output waveguide facets. Figure 3(c) shows the experimental setup and the image of the output facet from the CDD camera when one of the input waveguides is excited by a single wavelength laser (λ=1550nm). In order to investigate the bandwidth of the tapered 2x2 MMI, a broad-band laser diode was used to excite one the input waveguides. The output transmission spectrum, the difference of the two output channel normalized to the input spectrum, is shown in Figure 3(d). The bandwidth over which the deviation in the splitting ratio is less than 3dB is over 50nm.

In summary, we designed and fabricated a compact tapered 2x2 MMI coupler on SOI. High output uniformity demonstrated over a large bandwidth prove the device's potential for use as a passive or active component in integrated photonic circuits.

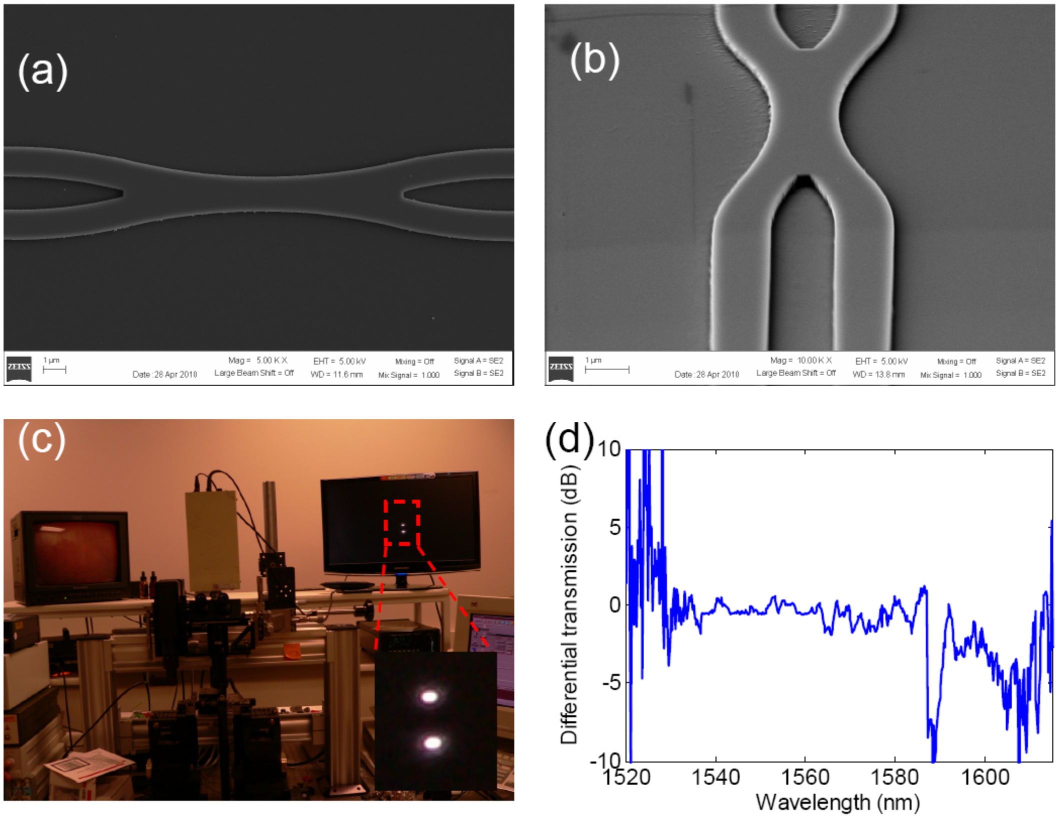

Fig. 3, SEM images of the fabricated compact tapered 2x2 MMI coupler (a) top-down image, (b) titled-angle image. The SEM pictures are taken before the deposition of the top silica cladding layer. The SEM pictures show the device before the disposition of the top cladding layer. (c) The experimental setup and the image of the output facet from the IR CCD camera. (d) Measured difference of the two output channels' power normalized to the input excitation spectrum. In (c) and (d) only one of the input waveguides is excited.

4. References

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