1 × 12 even fanout using multimode interference optical beam splitter on silicon nanomembrane

D. Kwong, Y. Zhang, A. Hosseini, Y. Liu and R.T. Chen

A compact silicon nanomembrane based 1 × 12 multimode interference coupler (MMI) fabricated on silicon-on-insulator is presented. The strip waveguide structure provides the smallest device size for a single stage MMI with 12 output channels. The MMI exhibits high uniformity up to 0.72 dB and has low loss of 1.13 dB using tranverse-electric (TE) polarised light at 1550 nm wavelength.

Introduction: Efficient optical beam splitters are a key component in photonic integrated circuits (PICs). Multimode interference (MMI) couplers have the advantages of compact size, low loss, stable splitting ratio, large optical bandwidth, and good fabrication tolerances [1, 2]. One of the major applications of MMI couplers is power splitters. To date, high performance in output uniformity is difficult to achieve for MMIs with a large number of output ports N owing to the modal phase errors, which have been shown to scale with N [3]. Acoleyen *et al.* have shown a 16 port optical phased array but this is achieved by cascading 1 × 2 MMI couplers, thereby creating multiple stages of MMIs [4].

The majority of MMI couplers based on silicon-on-insulator (SOI) have used a ridge waveguide structure. Until recently, few devices employing a strip waveguide structure for the input and output have been presented. Using strip waveguides, submicron cross-sectional areas of the waveguide core are possible while still maintaining singlemode operation at 1550 nm wavelength owing to the large refractive index contrast between silicon ($n_{Si} = 3.5$) and silicon dioxide ($n_{SiO2} = 1.45$) which provides excellent light confinement. In addition, the strong lateral confinement of strip waveguides allows the bending radius to be shrunk down to the micron range [5], whereas the slab region of ridge waveguides does not provide such confinement and thus requires large bending radius to achieve low loss propagation. Ultimately, the overall device size is increased by using ridge waveguides and this limits their use in ultracompact photonic integrated circuits, such as on-chip optical interconnects. In this Letter, we demonstrate a single stage optical beam splitter with a large number of outputs that avoids multiple insertion loss by using a 1 × 12 MMI on SOI with a rib waveguide structure, which shows the smallest device size for a 1 × 12 waveguide beam splitter at a wavelength of 1550 nm.

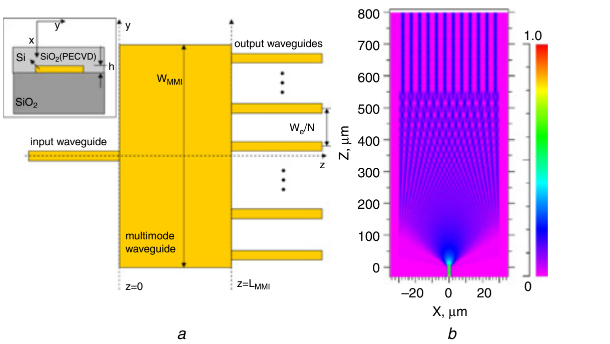

Fig. 1 *Schematic of 1XN MMI beam splitter (Fig. 1a). Inset: cross-section schematic of SOI based waveguiding structure. $n_{Si} = 3.47$, $n_{SiO2} = 1.45$, $n_{PECVD(SiO2)} = 1.46$. BeamPROP simulation of 1 × 12 MMI beam splitter showing equal power distribution at singlemode output after tapering (Fig. 1b)*

Operation principles: MMI devices operate based on the phenomenon of self-imaging in multimode waveguides whereby an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide [6, 7]. From Fig. 1*a*, the multimode waveguide consists of a core with refractive index n_c and width W_{MMI}, length L_{MMI}, and N output ports. The MMI length is given as $L_{MMI} = n_{eff}W_e^2/\lambda_0 N$, which is $L_{MMI} = 553.4$ µm for a $W_{MMI} = 60$ µm. Here, n_{eff} is the effective refractive index of the fundamental mode in the multimode section, W_e is the effective width including the penetration depth due to the Goose-Hahnchen shift, and λ_0 is the wavelength, which is 1550 nm in this Letter. The input/output access waveguide width is $W_W = 2.6$ µm. At this width, the modal phase errors are greatly reduced, thereby enhancing the output uniformity of our MMI. The derivation of the optimum MMI access waveguide width will be presented separately. We performed a simulation of our MMI device using Rsoft's BeamPROP software based on the beam propagation. As can be seen from Fig. 1*b*, our simulation shows good output uniformity when using TE polarised light at 1550 nm.

Device fabrication: We fabricated 1 × 12 MMIs ($W_{MMI} = 60$ µm, $L_{MMI} = 553.4$ µm) with $W_W = 2.6$ µm. The output waveguides were tapered down from 2.6 to 0.5 µm for singlemode operation. The MMIs were fabricated on commercially available SOI from SOITEC with 3 µm buried oxide layer (BOX) and 250 nm top silicon layer. The silicon was first oxidised to create a 45 nm-thick top oxide layer which serves as a hard mask for the silicon etch. This oxidation consumes 20 nm of silicon, leaving a final silicon thickness of 230 nm.

The MMIs were patterned using a JEOL JBX600 electron beam lithography system. A nickel liftoff step was used to invert the pattern, and subsequently transferred to the top silicon layer via an HBr/Cl_2 based reactive ion etching (RIE). A subsequent piranha clean has the dual purpose of providing a clean sample, but more importantly, removing the nickel etch mask that would cause large absorption loss from penetration of the electromagnetic tail into the metal layer. A schematic of this process flow is shown in Fig. 2. SEM pictures of the fabricated 1 × 12 MMI at this stage are shown in Figs. 3*a* and *b*. Afterwards, a 1 µm film of plasma-enhanced chemical vapour deposition (PECVD) silicon dioxide was deposited using the Plasmatherm 790 system for top cladding as well as passivation. The refractive index of the PECVD SiO_2 film was found to be $n_{PECVD(SiO2)} = 1.46$.

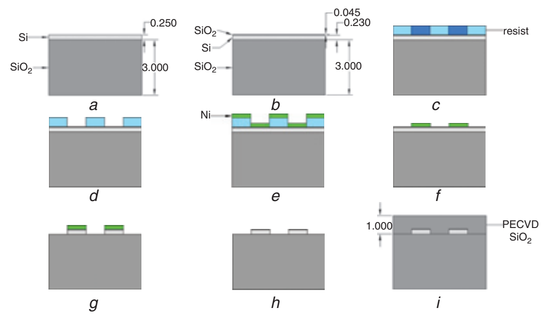

Fig. 2 *Fabrication process flow*

a Start with SOI wafer
b Light oxidation for oxide etch mask
c E-beam lithography
d Develop
e Nickel deposition
f Liftoff for pattern inversion
g RIE etch
h Piranha clean
i PECVD silicon dioxide deposition

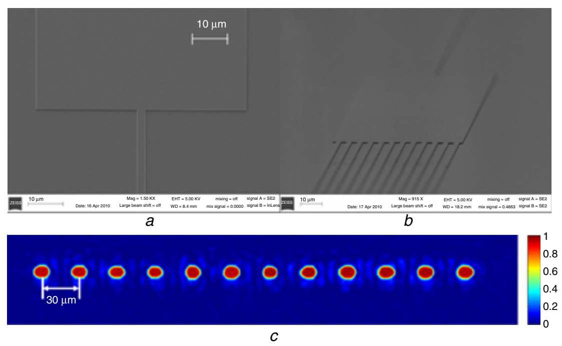

Fig. 3 *Top-down SEM picture of 1 × 12 MMI at input (Fig. 3a); tilted view of entire MMI (Fig. 3b); intensity profile of 12-channel MMI output with top-down near-field imaging (Fig. 3c)*

Experimental results: A six-axis automated aligner system with a 50 nm precision in movement was used to couple TE polarised light at 1547 nm from a polarisation maintaining lensed fibre (PMF) with a 2.5 µm output mode diameter into the input. A CCD camera connected to a variable objective lens captured the top-down near-field images of the cleaved output waveguides' facets.

To clearly resolve the 12 spots in the near-field image, a fanout design was used to increase the separation of each channel to 30 μm. Fig. 3*c* shows the top-down intensity profile of the near-field image. In addition, we used a singlemode lensed fibre (SMF) to scan each output channel to determine the output power of each channel and evaluate the performance of our MMI. To determine the uniformity we used $10\log(I_{max}/I_{min})$, where I_{max} and I_{min} are the maximum and minimum intensities of the MMI output channels, respectively. The insertion loss of an MMI is defined as $-10\log[(\Sigma I_i)/I_{in}]$, where I_i is the intensity of each output channel, and I_{in} is the output power of a straight waveguide. The device has an insertion loss of 1.13 dB, and a uniformity of up to 0.72 dB.

Conclusion: An optical beam splitter with a large number of outputs has been successfully demonstrated using a 1 × 12 MMI fabricated on a silicon nanomembrane on an SOI wafer with a rib waveguide based structure. This MMI has high uniformity of 0.72 dB and exhibits low loss of 1.13 dB using TE polarised light.

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One or more of the Figures in this Letter are available in colour online.

D. Kwong, Y. Zhang, A. Hosseini, Y. Liu and R.T. Chen (*Microelectronic Research Center, Department of Electrical and Computer Engineering, University of Texas, Austin TX 78758, USA*)

E-mail: diddykwong@gmail.com

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