

On the Optimum Design for 1xN Multimode Interference Coupler based Beam Splitters

Amir Hosseini*, David N. Kwong, Yang Zhang, Yazhao Liu, and Ray T. Chen*

Microelectronics Research Center, Electrical and Computer Engineering Department, University of Texas at Austin, Austin, TX, 78758, USA

*Corresponding authors: ahoss@mail.utexas.edu, raychen@uts.cc.utexas.edu, Fax: +1-512-471-8575

Abstract: An analytical formula for optimum 1xN multimode input/output channel width is derived for improved performance based on the insertion loss and output uniformity. Experimental investigation of a SOI based 1x12 MMI confirms the analytical results.

©2010 Optical Society of America

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). 1xN MMI-based beam splitters have been theoretically and experimentally investigated. The resolution and contrast of the images formed in the multimode waveguide determine the uniformity and insertion loss of MMI splitter devices [1]. Analyzing the phase errors due to deviations of the high order modes dispersion relations from those required for ideal self-imaging, it has been shown that MMI couplers with large number of outputs (N) normally result in poor output uniformity and high insertion loss [2]. There have been two major techniques proposed to enhance MMI performance: optimizing the index contrast [2, 3] and increasing the input/output channel width [4]. Other approaches, such as using genetic algorithm [5] and tuning the input taper angle [6], have been also investigated.

Among the abovementioned techniques, tuning the index contrast may not be an option based on the choice of the substrate and geometry of the splitter. Also, use of generic algorithm or input taper angle tuning does not provide insights into the nature of the poor MMI performance at large N values. Increasing the input/output channel width to enhance the self-imaging quality proposed in [2] is a practical approach especially for cases such silicon-on-insulator (SOI) based devices, where the index tuning is a challenge. In this study we investigate the effect of the input/output channel width on the MMI performance and derive an analytical relation for the optimum channel width for lowering the insertion loss and enhancing the output uniformity. Experimental results for a 1x12 MMI based on a slab SOI substrate confirms the analytical conclusions.

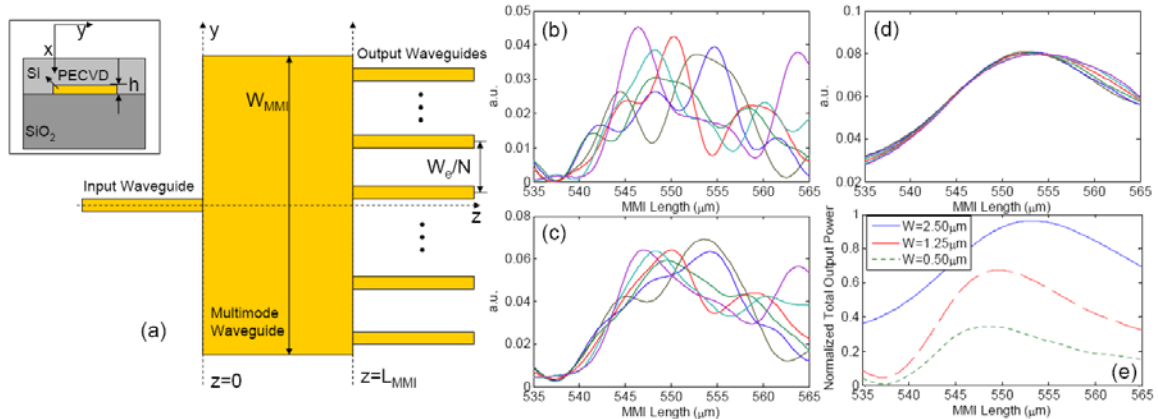


Figure 1 (a) A schematic of a 1xN MMI beam splitter. Inset is a cross section schematic of the SOI waveguiding structure. (b), (c) and (d) Variations of the output channel power (fundamental mode norm) normalized by the input power versus MMI length for $W_w=0.5\mu\text{m}$, $W_w=1.25\mu\text{m}$ and $W_w=2.5\mu\text{m}$, respectively. The MMI is 1x12 (only 6 curves are visible due to the symmetry), $W_{MMI}=60\mu\text{m}$, $h=230\text{nm}$. (e) Variations of the total output power normalized by the input power versus MMI length for $W_w=0.5\mu\text{m}$, $W_w=1.25\mu\text{m}$ and $W_w=2.5\mu\text{m}$. $n_{Si}=3.47$, $n_{SiO_2}=1.45$, $n_{PECVD}=1.46$.

2. Optimum Channel Width Derivation

The theory of self-imaging in multimode optical waveguides has been the subject of several studies [1, 7, 8, 9]. Figure 1(a) shows a schematic of a 1xN MMI splitter. The multimode waveguide section consists of a W_{MMI} wide

and L_{MMI} long core with refractive index n_c . In the case of 3D waveguides, an equivalent 2D representation can be made by techniques such as the effective index method or the spectral index method [7]. The multimode section can support maximum $M + 1$ number of modes. For each mode p , the dispersion relation is given as

$$\beta_p^2 + \kappa_{yp}^2 = \left(\frac{2\pi n_c}{\lambda_0} \right)^2, \quad (1)$$

where, β_p is the propagation constant of the the p^{th} mode, λ_0 is the free-space wavelength. κ_{yp} is the lateral wavenumber of the p^{th} mode given as $\kappa_{yp} = (p+1)\pi/W_e$, where W_e is the effective width for mode m including the penetration depth due to the Goose-Hahnchen shift [7]. n_c is the core index in a 2D problem and the effective index ($n_{\text{eff},1D}$) of the fundamental mode of an infinite slab waveguide in a 3D problem (with same thickness and claddings). In the MMI theory, β_p is approximated from Equation (1) as

$$\beta_p \approx \beta_0 - \frac{p(p-2)}{3L_\pi}, \quad (2)$$

where, $L_\pi = \pi/(\beta_0 - \beta_1) \approx 4n_c W_e^2 / 3\lambda_0$. In the case of symmetric excitation, such as a 1xN coupler excited by the fundamental mode of the input waveguide, using the approximation in Equation (2) one can show that the required length for such a coupler is $L_{MMI} = 3rL_\pi/4N$, where r is an integer.

However, MMIs with length derived using the approximation in Equation (2) suffer from insertion loss and poor output uniformity as discussed in [2]. The approximation in Equation (2) becomes increasingly inaccurate for large mode numbers (p), which results in large accumulated phase errors of the modes in the multimode section at the output with regard to the values required for ideal self-imaging. Increasing the input/output waveguide width (W_w) improves the image quality by reducing the overlap integral of the input field at $z=0$ with modes with large p values [4]. However, the maximum W_w is limited by the geometry as well as the coupling between the output waveguides. Also larger W_w results in longer tapers when output channels are tapered down for single mode operation. Our goal is to find the minimum W_w for an acceptable MMI performance.

The error in the calculated propagation constant when using Equation (2) can be estimated by the third term in the Taylor Expansion of β_p given by Equation (1) as $\Delta\beta_p \approx 2(\kappa_{yp}\lambda_0/4\pi n_c)^4$. After propagating along the MMI the resulting phase errors are given as

$$\Delta\phi_p = \Delta\beta_p L_{MMI} = \frac{\pi\lambda_0^2(m+1)^4}{64Nn_c^2W_e^2}. \quad (3)$$

For a high quality image, we restrict the maximum $\Delta\phi_p$ to $\pi/2$, which gives q , which is the maximum allowed mode number (p). We choose W_w so that highest order mode excited in the multimode region can satisfy this restriction. To do so, we pick W_w to be equal to the lateral wavelength ($2\pi/\kappa_{yq}$) of the highest allowed mode given by $\Delta\phi_p < \pi/2$. This also guarantees negligible excitation of all higher order modes since several periods of these modes fall within the input excitation field and the resulting overlap integrals are thus small. By equating $W_{w,opt} = 2\pi/\kappa_{yq}$ we get

$$W_{w,opt} = \frac{1}{\sqrt[4]{2N}} \sqrt{\frac{\lambda_0 W_e}{n_c}}. \quad (4)$$

3. Simulations and Discussions

In order to investigate the effect of W_w on the image quality we used the 3D bi-directional and full vectorial eigenmode expansion simulator in the FIMMPROPTM module from Photon Design. We calculated MMI outputs from the transfer matrix coefficients of the fundamental mode in the output channels. We assumed SOI substrate as shown in Figure 1 inset, where the thickness of the silicon slab is $h=230\text{nm}$ ($n_{\text{eff},1D}=2.85$). In this paper $\lambda_0=1.55\mu\text{m}$. Let's consider a 1x12 MMI with $W_{MMI}=60\mu\text{m}$. The theoretical prediction is that $L_{MMI}=553.4\mu\text{m}$. Figure 1(b), (c) and (d) show the individual channel mode norm versus L_{MMI} excited by an input fundamental mode for $W_w=0.5\mu\text{m}$, $W_w=1.25\mu\text{m}$ and $W_w=2.5\mu\text{m}$, respectively. Figure 1(e) shows the total output power normalized to the input power for varying L_{MMI} and for different W_w values. In the case of $W_w=0.5\mu\text{m}$, $W_w=1.25\mu\text{m}$, the channel outputs uniformity is poor at $L_{MMI}=553.4\mu\text{m}$. As proposed before, the length of the MMI can be tuned to achieve better uniformity. However, best uniformity does not occur at the highest output power (or lowest insertion loss) and the resulting optimized MMI length is different from the theoretical predictions. For $W_w=2.5\mu\text{m}$, the optimum length is very close to $L_{MMI}=553.4\mu\text{m}$ at which the total output power is also much higher than that for $W_w=1.25\mu\text{m}$ and $W_w=2.5\mu\text{m}$. Figure 2(a) and (b) show the total output power and the uniformity, respectively, for 1x3, 1x6 and 1x12 MMIs versus W_w at the predicted MMI lengths for each case. Uniformity is calculated as $10\log(P_{\text{max}}/P_{\text{min}})$, where P_{max} and P_{min} are the maximum and minimum power of the MMI output channels, respectively. Using Equation (4), the corresponding $W_{w,opt}$ is $1.81\mu\text{m}$, $2.15\mu\text{m}$ and $2.56\mu\text{m}$ for 1x3, 1x6 and 1x12 MMIs, respectively. One can easily see

that these numbers correspond to the points of diminishing returns in both the total output power and uniformity versus W_w .

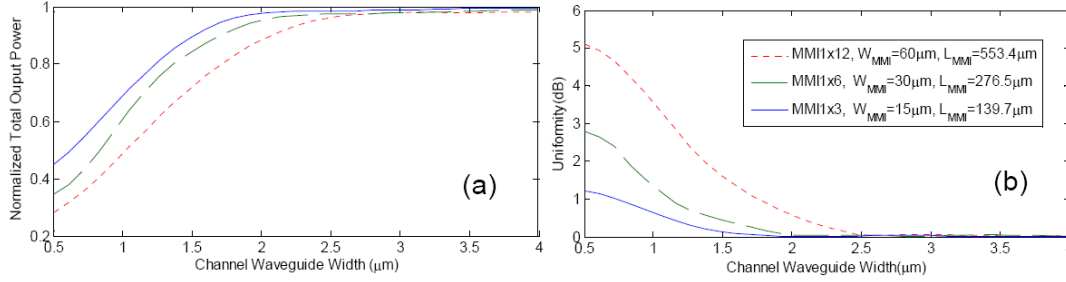


Figure 2 (a) and (b) variations of the total output power normalized by the input power and output channel uniformity, respectively, versus W_w for 1x3, 1x6 and 1x12 MMIs.

4. Experimental Results

We fabricated 1x12 MMIs ($W_{MMI}=60\mu\text{m}$, $L_{MMI}=553.4\mu\text{m}$) with $W_w=0.5\mu\text{m}$ and $W_w=2.5\mu\text{m}$. In the case of the $W_w=2.5\mu\text{m}$ MMI, the output waveguides were tapered down to $0.5\mu\text{m}$ for single mode operation [See Figure 3(a)]. The MMIs were fabricated on SOI from SOITEC with $3\mu\text{m}$ buried oxide layer (BOX) and 250nm top silicon layer. The silicon was oxidized to create a top oxide layer that serves as a hard mask for the silicon etch. The MMI were patterned using a JEOL JBX600 electron beam lithography system. The pattern was inverted by using a nickel liftoff step, and subsequently transferred to the top silicon layer via reactive ion etching (RIE) and piranha cleaning. Afterwards, a $1\mu\text{m}$ film of plasma-enhanced chemical vapor deposition (PECVD) silicon dioxide was deposited for the top cladding using the Plasmatherm 790 system.

A six-axis automated aligner system was used to couple TE polarized input light from a polarization maintaining lensed fiber (PMF) into the input waveguide by a precision in movement of 50nm . A CCD camera connected to a 100X lens captured the top-down near field images of the cleaved output waveguides' facets. Figure 3(b) and (c) show the pictures of the output waveguides (after tapering down to $0.5\mu\text{m}$) for $W_w=0.5\mu\text{m}$ and $W_w=2.5\mu\text{m}$ respectively. In the case of the $W_w=2.5\mu\text{m}$ MMI, the average output intensity is about 3 times higher and the uniformity is about 2dB better than those of the $W_w=0.5\mu\text{m}$ MMI.

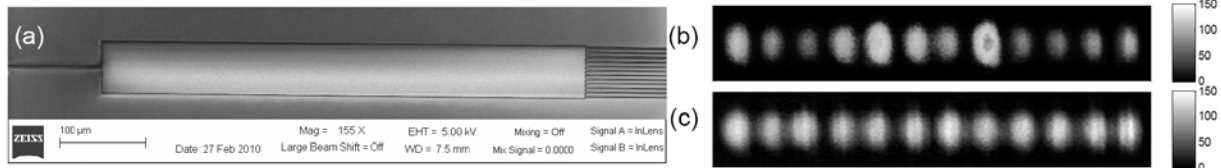


Figure 3 (a) SEM picture of a 1x12 MMI with $W_{MMI}=60\mu\text{m}$, $L_{MMI}=553.4\mu\text{m}$ and $W_w=2.5\mu\text{m}$. (b) And (c) near field images of 1x12 MMIs output for $W_w=0.5\mu\text{m}$ and $W_w=2.5\mu\text{m}$, respectively.

5. References

- [1] R. Ulrich and T. Kamiya, "Resolution of self-images in planar optical waveguides," J. Opt. Soc. Am. **68**, 583-592 (1978).
- [2] J.Z. Huang, R. Scarmozzino, and R.M. Osgood Jr. , "A new design approach to large input/output number multimode interference couplers and its application to low-crosstalk WDM routers ," Photonics Technology Letters, IEEE **10**(9), 1292-1294 (1998).
- [3] R. Yin, J. Yang, X. Jiang, J. Li, and M. Wang, "Improved approach to low-loss and high-uniformity MMI devices," Optics Communications **181**(4-6), 317-321 (2000).
- [4] Y. Shi, D. Dai, and S. He, "Improved performance of a silicon-on-insulator-based multimode interference coupler by using taper structures," Optics Communications **253**(4-6), 276-282 (2005).
- [5] Q. Wang, J. Lu, S. He, "Optimal design of a multimode interference coupler using a genetic algorithm," Optics Communications **209**(1-3), 131-136 (2002).
- [6] R. M. Lorenzo, C. Llorenle, E. J. Abril, and M. López, "Improved self-imaging characteristics in 1xN multimode couplers," Proc. Inst. Elect.Eng. Optoelectron. **145**(1), 65-69 (1998).
- [7] L. Soldano and E. Pennings, "Optical multi-mode interference devices based on self-imaging: principles and applications," J. Lightwave Technology **13**(4), 615-627 (1995).
- [8] M. Rajarajan, B.Rahman, T. Wongcharoen, and K. Grattan, "Accurate analysis of MMI devices with two-dimensional confinement," J. Lightwave Technology **14**(9), 2078-2084 (1996).
- [9] A. Hosseini, D. N. Kwong, C.-Y. Lin, B. S. Lee, and R. T. Chen, "Output Formulation for Symmetrically-Excited one-to-N Multimode Interference Coupler," IEEE Journal of Selected Topics in Quantum Electronics **6**(1), 53-60 (2010).