

On the Design of 1xN Multimode Interference Coupler for Photonic Integrated Circuits

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Abstract—We derive an analytical relation for the maximum number of output channels for high performance (power transmission and uniformity) multimode interference (MMI) based 1xN optical beam splitters. Eigenvalue-expansion based simulation results confirm the analytical relation.

INTRODUCTION

On-chip optical interconnections are being considered as a solution for the looming interconnection bottlenecks. Such interconnections network and the associated integrated photonic circuits (PICs) require efficient optical beam splitters as a building block. The self-imaging properties of multimode interference (MMI) based couplers have been used to realize 1xN optical beam splitters. The theory of self-imaging in multimode optical waveguides has been the subject of several studies [1, 3, 4, 5, 6]. The resolution and contrast of the images formed in the multimode waveguide determine the uniformity and insertion loss (or equivalently the total transmitted power) of MMI splitter devices [1]. It has been shown that MMI couplers with large number of outputs (N) normally result in poor output uniformity and high insertion loss [2].

In this paper, by analyzing the phase errors due to deviations of the high order modes dispersion relations from those required for ideal self-imaging, we derive a relation for the maximum number of output channels for a given MMI width that can still result in an acceptable MMI performance.

DERIVATION OF MAXIMUM NUMBER OF OUTPUT CHANNELS

Figure 1 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 [4]. The multimode section can support

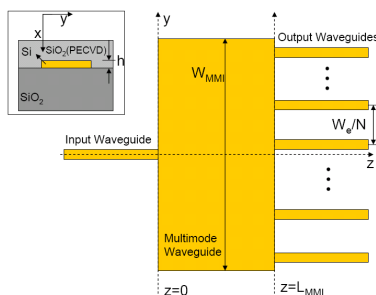


Fig. 1. A schematic of a 1xN MMI beam splitter. Inset is a cross section schematic of the SOI waveguiding structure. $n_{Si}=3.47$, $n_{SiO_2}=1.45$, $n_{SiO_2(PECVD)}=1.46$.

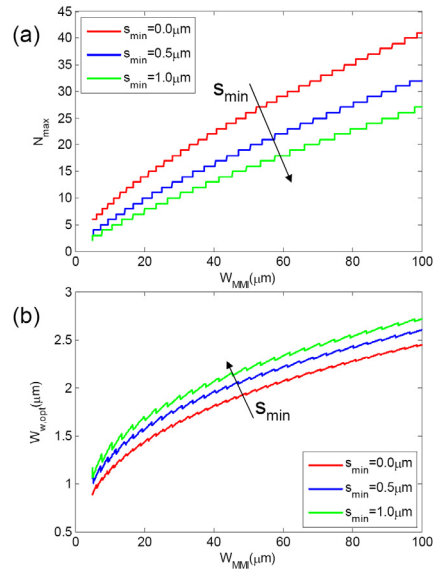


Fig. 2. (a) Variations of the maximum number of the output channel versus MMI width. (b) Variations of the optimum channel width for 1xN_{max} MMIs versus MMI width.

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 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 including the penetration depth due to the Goos-Hänchen shift [4]. n_c is the core index in a 2D problem and the effective index ($n_{eff,1D}$) of the fundamental mode of an infinite slab waveguide in a 3D problem (with same thickness and claddings). In 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.

When using Equation (2), the error in the calculated propagation constant 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 modal phase errors at the output 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

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

We also note that the output channel-to-channel spacing is W_e/N . Therefore, we can derive an upper bound on the maximum number of channels for which the image quality is still acceptable by $W_{w,opt} < W_e/N$ given as

$$N_{max} = \sqrt[3]{\frac{2n_c^2 W_e^2}{\lambda_0^2}}. \quad (5)$$

The result is quite general and gives an optimistic N_{max} . For more realistic N_{max} one needs to consider $W_{w,opt} < W_e/N - s_{min}$, where s_{min} depends on the waveguiding structure and is the minimum required side-to-side spacing between the output waveguides to avoid channel-to-channel coupling and/or required by the geometrical restrictions of the devices connected to the MMI's output channels, as well as the limitations of the fabrication technique. Figure 2(a) Shows N_{max} as a function of W_{MMI} for $s_{min}=0$ [Equation (5)], $s_{min}=0.5\mu\text{m}$ and $s_{min}=1.0\mu\text{m}$. $n_c = n_{eff,1D} = 2.85$, which corresponds to $h=230\text{nm}$ at $\lambda_0=1.55\mu\text{m}$ in Figure 1 inset. Figures 2(b) demonstrates variations of $W_{w,opt}$ versus W_{MMI} for an MMI with N_{max} output channels.

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 assumed SOI substrate as shown in Figure 1 inset, where the thickness of the silicon slab is $h=230\text{nm}$ ($n_{eff,1D}=2.85$). Throughout this paper $\lambda_0=1.55\mu\text{m}$.

Let's consider MMIs with $W_{MMI}=30\mu\text{m}$ with required $s_{min}=0.5\mu\text{m}$ with different N (See Table I). The maximum number of output for which [Figure 2(a)] high quality self-imaging of the input is possible is $N_{max}=13$. For any $N>13$ the condition $W_{w,opt} < W_e/N - s_{min}$ can not be fulfilled. In other words, W_w is forced to be smaller than the $W_{w,opt}$ value from Equation 4 as indicated in Table I.

Figures 3(a-d) show the output field [$\text{abs}(E_x)$] profile of 1x10, 1x12, 1x14, and 1x16 MMIs, respectively. One can note the poor uniformity for the $N>13$ cases. Figure 3(e) and (f) show the total output power (normalized to the input power) and the output uniformity, respectively. Uniformity is calculated as $10\log(P_{max}/P_{min})$, where P_{max} and P_{min} are the maximum and minimum power (norm of the fundamental mode) of the MMI output channels, respectively. As N increases and W_w becomes increasingly smaller than the required $W_{w,opt}$, the MMI

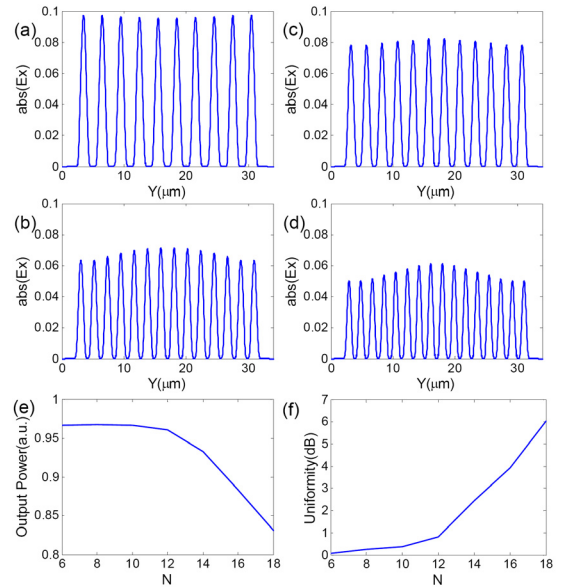


Fig. 3. (a-d) $\text{abs}(E_x)$ at the MMIs' outputs in the middle of the output channel (height-wise). (e) Total (all channels) output power normalized with respect to the input power versus the output channel number (N). (f) Output uniformity versus output channel number.

performance is rapidly degraded due to increasing phase errors discussed before.

In conclusion, for high performance MMI design and a given number of output channels, the multimode section width needs to be wide enough to accommodate channel width not smaller than $W_{w,opt}$. Equation (5) can be used as a guideline for high performance MMI beam splitter design.

Table I. 1xN MMI based optical beam splitters' and channel width dimensions for $h=230\text{nm}$ at $\lambda_0=1.55\mu\text{m}$. L_{MMI} values are calculated using $L_{MMI}=3rL_p/4N$.

N	W_{MMI} (μm)	L_{MMI} (μm)	$W_{w,opt}$ (μm)	W_w (μm)
6	30	276	2.16	2.16
8	30	207	2.02	2.02
10	30	166	1.91	1.91
12	30	138	1.82	1.82
14	30	118	1.76	1.64
16	30	104	1.70	1.38
18	30	92	1.65	1.17

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