Design of 2 × 2 SOI MMI couplers with arbitrary power coupling ratios

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Proposed is a new method for implementing multimode interference couplers with arbitrary power splitting ratios on silicon on insulator technology. The devices are verified and optimised using the three dimensional beam propagation method.

Introduction: Coupling elements having arbitrary power splitting ratios are needed for a number of optical communication, sensing and signal processing functions. Multimode interference (MMI)-based devices have advantages of low losses, wide fabrication tolerances and ease of fabrication [1]. However, conventional 2 × 2 MMI couplers are only capable of providing a limited number of power splitting ratios (defined as the cross output power divided by the bar output power) of 85/15, 72/28, 50/50, 27/73, 15/85 and 0/100 [2]. The purpose of this Letter is to outline a new method for achieving arbitrary power splitting ratios for MMI couplers using silicon on insulator (SOI) channel waveguides. Previous approaches for realising MMI couplers with arbitrary splitting ratios [2–5] are generally not suitable for the SOI platform because our simulations show that they have relatively high excess loss. The proposed method does not require complicated device geometries but still has the advantage that it enables a free choice of splitting ratios.

Device design: The proposed method uses a generalised Mach-Zehnder interferometer (MZI) structure as shown in Fig. 1. An ideal 2 × 2 restricted interference MMI coupler [1] with a length $L = L_\pi/2$ has a transfer matrix given by:

$$M = \frac{e^{j\phi_0}}{2}\begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}\begin{bmatrix} e^{j\phi_1} & 0 \\ 0 & e^{j\phi_2} \end{bmatrix}\begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \qquad (1)$$

where L_π is the beat length [1] between the two lowest order modes, ϕ_0 is a constant phase shift, and ϕ_1 and ϕ_2 are the phase shifts of the interstitial linking arms. Equation (1) can be rewritten in the form:

$$M = \exp(j\Phi)\begin{bmatrix} \tau & \kappa \\ \kappa & -\tau^* \end{bmatrix} \qquad (2)$$

where, $\Phi = \phi_0 + \pi/2 + \Delta\phi/2$, $\Delta\phi = \phi_1 - \phi_2$, $\tau = \sin(\Delta\phi/2)$ and $\kappa = \cos(\Delta\phi/2)$.

The power coupling coefficient $|\kappa|^2$ is:

$$|\kappa|^2 = 1 - |\tau|^2 = |\cos(\Delta\phi/2)|^2 \qquad (3)$$

Hence by varying the phase difference $\Delta\phi$ over the range from 0 to π, any coupling ratio should be possible.

The phase difference $\Delta\phi$ can be implemented by using a multimode section in one of the linking waveguides. The multimode section can be viewed as a 1 × 1 symmetric interference MMI coupler [1]. The width W_2 of the multimode linking section must be large enough to support at least three guided modes, but not so wide as to introduce significant crosstalk with the other linking waveguide.

The field $\Psi(y,z)$ at distance z along the multimode section can be ideally written as [1]:

$$\Psi(y, z = L) \simeq \exp(-j\beta_{0M}z)\sum_{\nu=0}^{M-1} c_\nu \phi_\nu(y)\exp\left[j\frac{\nu(\nu+2)}{3L_{\pi M}}\right] = \exp(-j\beta_{0M}z)\Psi(y, z=0) \qquad (4)$$

where $L_{\pi M}$ is the beat length of the multimode section, ν is the mode number and M is the number of modes supported by the multimode linking section. c_ν is the excitation coefficient and $\phi_\nu(y)$ is the mode field profile for the guided modes of the multimode linking section. Radiation modes have been neglected in the above result. The phase difference between the two arms of the MZI is $\Delta\phi = \frac{2\pi}{\lambda}\Delta n L_M$, where Δn is the difference between the effective refractive index of the fundamental mode of the multimode section (β_{0M}) and that of waveguide 1. L_M is the length of the multimode linking section, and λ is the operating wavelength. The symmetric interference theory can be used to estimate the length L_M of the 1 × 1 multimode linking section. A more accurate representation of the variation of L_M with width W_2 can be found numerically.

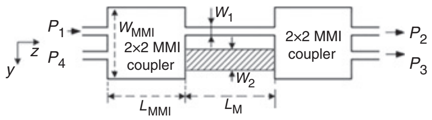

Fig. 1 *Variable coupler using MZI structure*

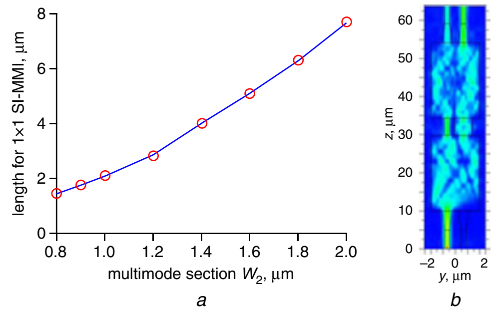

Fig. 2 *MZI with multimode section for arm*

a Optimised length of MMI section
b 3D-BPM simulation when width of 1.5 µm is used for MMI section

Device simulation: The dependence of the length L_M of the 1 × 1 MMI coupler for various multimode section widths W_2, as calculated using a transverse electric (TE) mode three dimensional beam propagation method (3D-BPM) simulation, is shown in Fig. 2*a*. The parameters used in this simulation are the refractive index of the silicon core $n_{Si} = 3.45$, the refractive index of the silica cladding $n_{SiO_2} = 1.46$ at the operating wavelength, $\lambda = 1550$ nm, the waveguide thickness $h = 220$ nm and the upper waveguide width $W_1 = 450$ nm. Silica is used as the upper cladding. Fig. 2*b* shows the 3D-BPM simulation result for the whole MZI SOI structure, having a linking multimode section width of $W_2 = 1.5$ µm. The width of each larger MMI coupler (3 dB MMI coupler) is chosen to be $W_{MMI} = 4$ µm to limit crosstalk between the two access waveguides. The optimised length of the MMI coupler is found to be $L_{MMI} = 20$ µm. The access waveguide is tapered to a width of W_{tp} 800 nm to improve device performance. The calculated excess loss is 0.4 dB.

Fig. 3 shows the normalised output powers against the multimode section width W_2 for different lengths of the multimode section. The result was calculated by using the 3D-BPM. It is clear that variations in the width and length of the multimode section have the strongest effect on the output powers when a splitting ratio of 50/50 is desired at the outputs. The simulation shows that for fabrication tolerances of the multimode section of ±10 nm, the output power tolerances are ±0.1%. Our 3D-BPM simulations also show that fabrication tolerances of the multimode section width of ±10 nm will allow for the output power variations to be ±4.3% and for fabrication tolerances of waveguide 1 of ±10 nm, the output power variation will be in the range of ±8.5%. The simulation shown in Fig. 3 demonstrates that it is possible to achieve almost a full range of splitting ratios by varying the width of the multimode section from 1.3 µm to around 1.8 µm and optimising the length L_M.

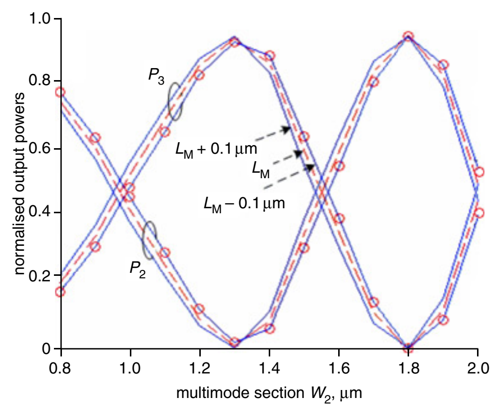

Fig. 3 *Normalised output powers against multimode section width for different MMI linking section lengths*