Optics Communications 340 (2015) 26–32

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Design and fabrication tolerance analysis of multimode interference couplers

P.E. Morrissey [a,*], H. Yang [a], R.N. Sheehan [a], B. Corbett [a], F.H. Peters [a,b]

[a] *Tyndall National Institute, Lee Maltings, Cork, Ireland*
[b] *Physics Department, University College Cork, College Road, Cork, Ireland*

ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form
17 November 2014
Accepted 26 November 2014
Available online 28 November 2014

Keywords:
Waveguide devices
Optical couplers
Planar lightwave circuits

ABSTRACT

This paper examines the sensitivity of InP multimode interference couplers (MMIs) to fabrication errors caused by over or under exposure during device processing. MMIs are modelled using modal propagation analysis, which provides a rapid means of simulating the performance of such couplers across a large design space with varying structural parameters. We show for the first time that when MMIs are anlaysed with fabrication errors in mind, there exists an optimal set of design parameters for a given input waveguide width which offer the best tolerance to fabrication errors while maximising optical throughput and ensuring compact size. Such MMIs are ideally suited for use in photonic integrated circuits, where robust performance and smallest possible device footprint are required.

1. Introduction

Multimode interference couplers (MMIs) have found widespread application in photonic devices [1–3], where they can be used in a range of configurations with single and multiple input and output ports to act as efficient optical splitters or combiners. The advantages of using MMIs are many-fold, with the main benefits being their ability to operate over a wide wavelength range [4], insensitivity to polarization and refractive index variations, ease of fabrication and compact size [5]. The basic structure of a 1 × 2 MMI is shown in Fig. 1. Input and output waveguides of width W_{input} couple light to and from the MMI. Light from the fundamental mode of the input waveguide propagates in the MMI region of width W_{MMI} and is self-imaged periodically along the length of the structure. In the case of Fig. 1, two self-images are formed at a distance L_{MMI} along the MMI, which can be decoupled from the MMI using the output waveguides spaced MMI_{Sep} apart at this length. The integration of MMIs with semiconductor lasers has previously been demonstrated [6] and was shown to offer excellent potential for future photonic devices. The advantages of photonic integration are many-fold, with perhaps the greatest benefit being the dramatic reduction in device footprint when multiple structures are combined on a single chip. To this end, each element of any photonic integrated circuit (PIC) must be as compact as possible while maintaining satisfactory performance.

As the size of MMIs continues to be reduced, the need to understand their behaviour becomes increasingly important. The tolerance of MMIs to variations around their optimised parameters becomes a key concern for compact MMI structures, where typical fabrication deviations can significantly impact on device performance. In particular, variations associated with over or under exposure of the lithographical mask used during fabrication and over or under etching of the waveguiding structure are the two main sources of errors during device processing.

The optical bandwidth and fabrication tolerance analyses of MMIs have been examined analytically by Besse [7], where a series of design rules were found to improve the tolerance of MMIs to variations around the main structural design parameters. Recently, this has been further developed by Hill [8] where the imbalance between the arms of an MMI with fabrication errors has been shown to be significantly reduced by suitable choice of the access waveguide width. Work on silicon-on-insulator (SOI) couplers [9] has described the design procedure for MMIs with low loss and high fabrication tolerances. In particular, it focuses on how tight the exposure and over/under etching tolerances must be in order to ensure low loss performance. However, it does not describe how the performance of MMIs can be improved by varying its design parameters to compensate for fabrication errors. For silicon based devices this is less of a concern due to the highly sophisticated, precise and well developed fabrication systems used [10]. However, this is an issue with InP and III–V processing where larger fabrication errors of ≤0.5 μm can be encountered. The work presented in this paper confirms the results presented by Besse using

---

[*] Corresponding author.
E-mail address: padraic.morrissey@tyndall.ie (P.E. Morrissey).

http://dx.doi.org/10.1016/j.optcom.2014.11.083
0030-4018/

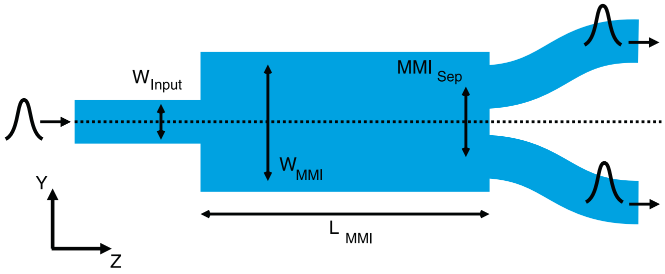

Fig. 1. General structure of a multimode interference coupler (MMI).

simple and fast computational methods, before investigating in practice how compact and efficient MMIs can be designed where fabrication errors are included. The results of our computational analysis have shown that when fabrication errors are incorporated into the design of MMIs, there exists a specific value of W_{MMI} where the MMI becomes most tolerant to these errors. Remarkably, MMIs optimised for larger values of W_{MMI} show higher losses. From this analysis, the most compact MMI design can be found which offers low loss performance for a particularly known fabrication error. The results of this work are most applicable to the design of robust and low loss InP based MMIs.

2. Design of multimode interference couplers

2.1. MMIs and modal propagation analysis

Several methods exist for simulating MMIs. These include using hybrid methods [11] and beam propagation methods (BPM) [12]. A full description of self-imaging in multimode waveguides can be explored using Modal Propagation Analysis (MPA) techniques developed in [13] and particularly [14], where the principles of self-imaging and MPA are examined. With MPA, the input field in an optical waveguide can be decomposed into the guided modes of the waveguide itself. These individual supported modes can then be propagated along the structure where the field at any point can be determined by the superposition of the guided modes to that point. MPA provides an efficient means of modelling MMIs without the need for extensive computational analysis. In effect, the electric field distribution in an MMI can be determined fully once the guided modes in the input and MMI waveguide regions of the structure have been accurately calculated.

By considering a typical InP based ridge waveguide structure, as shown in Fig. 2, the waveguide modes can be determined using a number of different means. These include numerical techniques such as BPM [15–17], Finite Difference Method (FDM) [18–20] and Finite Element Method (FEM) [21,22] when highly accurate solutions are required. Approximate methods also exist, which allow for rapid solutions for a given waveguide mode at the expense of accuracy. Similar to Kumar's [25] and Marcatili's method [26], the Effective Index Method (EIM) provides an estimate of the propagation constants of waveguide modes, which can in turn be used to determine the field distribution of the waveguide mode. With the EIM, a two-dimensional waveguide structure shown in Fig. 2 is reduced to a series of equivalent one-dimensional waveguides which approximate the original structure and can be solved analytically. The EIM provides accurate solutions for strongly confined waveguide modes but breaks down in weakly confined structures. As a result, it has excellent applicability when modelling deeply etched waveguides.

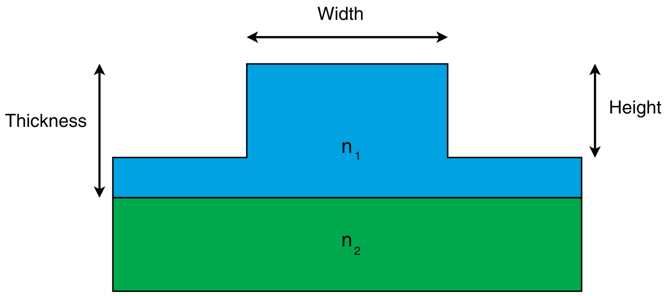

Fig. 2. Typical rib waveguide structure used for the MMIs modelled using modal propagation analysis (MPA).

For the MMI analysis developed in this work, two different implementations of MPA have been considered. The first technique uses the EIM to determine the propagation constants and modes of an MMI waveguide structure before applying MPA to determine its electric field distribution. We refer to this technique as *effective index method modal propagation analysis* (EIM-MPA) and relies on the EIM reducing the original two dimensional waveguide structure to a one dimensional equivalent, which can be solved analytically. The second implementation of MPA uses a scalar finite element [21,22] solver to calculate the modal properties of a waveguide structure in two dimensions and is referred to as *scalar finite element method modal propagation analysis* (SFEM-MPA). The SFEM-MPA method provides more accurate solutions than the EIM-MPA by solving the structure directly in two dimensions rather than reducing the dimensionality of the structure. However, this comes at the cost of extra computational complexity and simulation time. More accurate MMI analysis can be performed using full-vectorial methods [23,24] which are commercially available. In this work, the SFEM-MPA method was used to confirm that the EIM-MPA technique provided sufficiently accurate waveguide modal solutions while allowing MMIs to be designed with a high degree of computational efficiency. In the following section MMIs are designed using both the EIM-MPA and SFEM-MPA methods, where we show that there is good agreement between the two.

2.2. MMI analysis using EIM-MPA and SFEM-MPA

The EIM-MPA and SFEM-MPA techniques were both used to model MMIs based on the waveguide structure shown in Fig. 2 at a wavelength of 1.55 μm with parameters summarised in Table 1. Computational routines were developed to determine the optimum length, L_{MMI}, of an MMI where it acts as an efficient optical coupler for a given MMI width, W_{MMI}. This allows for an excellent comparison to be made between the relative accuracies of these models by comparing the optimised value of L_{MMI} across a large design space. For simplicity, we considered the design of 1×2 MMIs in our analysis. However, this can be extended to the design of higher order $M \times N$ MMI structures as required.

An MMI based on the waveguide structure described above was designed and optimised for $W_{Input} = 2.5\ \mu\text{m}$ and $W_{MMI} = 8.5\ \mu\text{m}$. Using the analytical expressions for L_{MMI} and MMI_{Sep} from [14] as an initial guess, the structure was optimised by varying both L_{MMI} and MMI_{Sep} until a peak in the MMI coupling efficiency was found. The *coupling efficiency* of an MMI determines how much light couples through the structure, and ranges between 0 and 1.0. For a lossless 1×2 MMI coupler, 50% of the input light is coupled out of each output arm. In this case, the full MMI would have a *coupling efficiency* of 100%, or 1.0. For the MMI considered here, the

Table 1
Waveguide parameters.

Width (μm)	Height (μm)	Thickness (μm)	n_1	n_2
2.5	2.5	2.5	3.38	3.17