Bandwidth and Fabrication Tolerance Criterion for Multimode Interference Splitters

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Abstract: - The Optical bandwidth and fabrication tolerance of multimode interference (MMI) 3-dB couplers are investigated analytically. The optical bandwidth and fabrication tolerance are shown to be inversely proportional to the multimode section width. Among Symmetrical, paired, and general mechanism interference types, the symmetrical one has the highest bandwidth and fabrication tolerance.

Key-Words: - MMI coupler, Power splitter, Bandwidth, and Polarization

1 Introduction

Optical couplers and splitters play very important roles in an optical system, especially in emerging passive optical networks for broadband access. They currently represent the largest market for photonic integrated circuit and find use in broadcast types optical networks and for optical signal routing and processing. Many kinds of planar waveguide devices can be used as power splitter, such as Star couplers [1], Y (or X) splitters [2] directional couplers [3], and multimode interference (MMI) waveguides [4-6].

Devices based on MMI are potential choices, because MMI devices have advantage of low loss, polarization independence [4], compact size, and low fabrication cost [7]. However, MMI devices are wavelength-sensitive. Variation of signal wavelength may have a significant influence on the performance of the device. To have a wide band MMI device is then of great interest for study.

The aim of this paper is to study the bandwidth capabilities of 1×2 power splitter based on MMI and to quantify their fabrication tolerance. In section 2, we introduce the principal operation of MMI. Fabrication tolerance and bandwidth are investigated and discussed in Sections 3 and 4.

2 Principal operation of MMI

The principal operation of MMI coupler is based on the self-imaging effect in a multimode section [8]. Fig. 1 is a top view of symmetrical, paired, and general interference of 1×2 power splitter, which is showing the positions of the input and output waveguides.

Fig. 1 Schematic diagram of 1×2 power splitter in (a) Symmetrical, (b) Paired, and (c) General Interference.
The beat length and effective width of MMI section are given by [4]

\[ L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4n_2W^2_{\text{eff}}}{3\lambda} \quad (1) \]

\[ W_{\text{eff}} = W_{\text{MMI}} + \left( \frac{1}{\pi} \right) \left( \frac{n_2}{n_1} \right)^2 \left( n_2^2 - n_1^2 \right)^{-0.5} \quad (2) \]

Where \( L_\pi \) is beat (coupling) length (\( \mu m \)) between the two lowest order modes, \( n_2 \) is the effective index of the guiding film, \( n_1 \) is the refractive index of cladding layer, and \( \lambda \) is the operation wavelength.

### 3 Fabrication tolerance

Relaxed tolerances are important for fabrication as well as for operating conditions. Fabrication tolerances refer to the control of the geometrical dimensions during processing and its subsequent impact on device performance. Operation tolerances relate to the device behavior for changes in the wavelength, polarization, temperature, input field distribution, and refractive index.

A tolerance analysis can be performed [9] in which each image is considered as a Gaussian beam focused at a self-image distance \( z = L \). Then, the loss penalty produced by a (small) finite shift \( \delta L \) in the \( z \)-position of the output waveguides can be evaluated by overlapping the defocused beam with the output waveguide mode field. It is found that the length shift which produces a 0.5dB loss penalty is approximately equal to the so-called Rayleigh range [4]:

\[ \delta L(\mu m) \approx \frac{\pi n_2w_0^2}{\lambda} \quad (3) \]

Where \( w_0 \) is defined here as the Gaussian beam waist, and equals the full \( 1/e \) amplitude width of the input field \( f(x) \) [9]. Eq. (3) can be interpreted as an absolute length tolerance, which does not depend on the dimensions of the multimode waveguide. An important conclusion is that, for a given wavelength and technology, all tolerances can be relaxed by using wider access waveguides. The tolerances corresponding to other fabrication or operation parameters can now be related to \( \delta L \), using the definition of (1).

\[ \frac{\delta L}{L} = 2 \frac{\delta W_{\text{eff}}}{W_{\text{eff}}} \equiv \frac{[\delta \lambda]}{\lambda} \equiv \frac{\delta n_2}{n_2} \quad (4) \]

Where \( \delta L \), \( \delta W_{\text{eff}} \), and \( \delta n_2 \) factors are fabrications determines. The normalized power transmission of The Gaussian beam will be calculated at a deviation distance \( \delta L \) from the original image distance, say \( \alpha=0 \). It can be shown that the transmission \( (T) \) becomes the following [10]:

\[ T = \frac{1}{\sqrt{1 + \alpha^2}} \quad (5) \]

\[ \alpha = \frac{2\delta L}{\pi n_2w_0^2} \quad (6) \]

An excess loss value \( (EL) \) is required to analyze the transmission loss \( (\text{Loss} = 0 \text{ dB at } T=1) \) represented by a decibel value of \( T \).

In this section, the given information are \( n_2=1.48 \), \( n_1=1.378 \), \( \lambda = 1.55\mu m \), \( h \) (thickness of core) = 1\mu m, \( W = 8\mu m \). Fig. 2 shows excess loss with the fabrication tolerance of \( \delta L \) and its behavior is independent of the type of imaging. For a -0.5 dB loss tolerance (~90% transmission), \( \delta L \) can be as large as 10\mu m.

![Fig.2 Fabrication Tolerance \( \delta L \)](image)

For deviation in width (nominal=8\mu m) shown in Fig. 3, symmetrical imaging has greater width tolerance than paired or general imaging. For 1×2 images, -0.5 dB symmetrical imaging loss tolerance is nearly 1.4\mu m while paired and general imaging tolerance are 0.8\mu m and 0.4\mu m, respectively. Symmetrical images not only offer short image distances, they also offer higher fabrication tolerances.

For the change in guide index (nominal =1.48) shown in Fig. 4 , symmetrical 1×2 imaging at -0.5 dB loss has an index tolerance of 0.42 while at the same loss, the index tolerances are 0.3 and 0.1 for paired and general imaging, respectively. Thus, these large guide index changes in a practical system can be neglected since they should not occur under normal condition.
The approach adjusts the width and length of the multimode waveguide to achieve optimal device performance. It has shown that the length of the multimode waveguide can be varied in a well-defined range to find optimal device performance. This range is related to the propagation constant spacing of the fundamental and higher order modes of the multimode waveguide. In the numerical analysis, it was found that optimal performance could be achieved for various length/width combinations. Moreover, it was shown that not only the length but also the width of MMI coupler should be adjusted to achieve both low loss and good uniformity.

4 Optical bandwidth

Optical bandwidth represents a band of transmittable wavelength under a tolerance of EL and is simply 2 times the tolerance of $|\delta \lambda|$. This value can also be obtained with relationship in Eq. (4). Thus, a similar plot can be generated with the three types of imaging shown in Fig. 5. For a transmission tolerance of 90% or -0.5dB loss, symmetrical $1 \times 2$ produces a bandwidth of 380nm around the nominal value of 1.55$\mu$m while they are 300$\mu$m and 120$\mu$m for paired and general images.

Fig. 6 shows that optical bandwidth is inversely proportional to the width of MMI section for all types of mechanism interference.

Figure 6. Optical bandwidth vs. width of MMI section at all types of mechanism interference
5 Conclusion

The Optical bandwidth and fabrication tolerance of multimode interference (MMI) 3-dB couplers were investigated analytically. The optical bandwidth and fabrication tolerance have been shown to be inversely proportional to the multimode section width. Among Symmetrical, paired, and general mechanism interference types, the symmetrical one has the highest bandwidth and fabrication tolerance.

References


