Abstract—Analytical expressions are derived which relate the optical bandwidth and the fabrication tolerances of multimode interference (MMI) couplers to their most important design parameters. These expressions compare adequately with mode analysis simulations. For strong guided structures, the optical bandwidth is shown to be inversely proportional to the number of input and output ports \( N \) and to the length of the device. The fabrication tolerances are independent of \( N \) and proportional to the output channel separation \( D \). Measurements on MMI couplers in InP/InGaAsP corroborate the theoretical predictions.

**I. INTRODUCTION**

MULTIMODE interference (MMI) couplers, based on the self-imaging effect [1], [2], are rapidly gaining popularity. MMI couplers have already been applied as power splitters and combiners [3], [4], in polarization-independent switches [5], [6], in phase-diversity optical receivers [7], [8], and in ring semiconductor lasers [9]. The main advantages of such devices are low-loss, ultracompact size [10], and large fabrication tolerances. Furthermore, polarization-independent components can be realized by using strongly guided waveguide structures [5].

As future WDM communication networks use erbium-doped fiber amplifiers with bandwidths of the gain spectra of 20 nm and more, integrated components will need at least such large optical bandwidths. The aim of this paper is therefore to study the bandwidth capabilities of MMI couplers and to quantify their fabrication-related tolerances in performance.

First, the dependency of these properties on the geometrical design parameters, as well as on the number of input and output ports is discussed. We distinguish between different kinds of MMI couplers [11] as shown in Fig. 1. Depending on the design, \( N \times N, 1 \times N \), or \( 2 \times N \), self-imaging properties are obtained. For all these different cases, simple analytical expressions are derived using restricted interference, we find that the optical bandwidth is inversely proportional to the number of ports and to the length of the device. The fabrication tolerances remain independent of \( N \) and proportional to the output channel separation \( D \).

In the second part of the paper, we present optical bandwidth measurements we obtained on \( 2 \times 2 \) restricted interference MMI couplers used as 3 dB power splitters [12] and as cross couplers. In these restricted interference devices, the access waveguides are positioned in order not to excite the modes \( 2, 5, 8, \ldots \) of the multimode section; this permits the realization of short couplers [10]. The analytical approximations compare well with the experimental results, and also with the predictions of the more sophisticated mode analysis (MA) technique [12].

**II. THEORY**

We first consider the MMI coupler of Fig. 2. The behavior of the device can be described by using the paraxial approximation in strong guided structures [10]. The refractive index profile in the \( y \) direction is replaced by the effective index \( n_e \), so that only a two-dimensional problem has to be solved.

**A. Analytical Approximation**

Depending on the ratio of the MMI coupler length \( L \) to the square of the MMI coupler width \( W \), and on the lateral...
The term in parentheses is polarization dependent and, strictly speaking, we would have to define two optimal wavelengths \( \lambda_{\text{opt}}^{\text{TE}} \) and \( \lambda_{\text{opt}}^{\text{TM}} \) for TE and TM, respectively. For strong guided structures, the wavelength dependency almost disappears.

For well-separated output images, these variations lead first to an increase of the losses, the splitting ratio remaining more or less constant [12]. We therefore describe the optical bandwidth \( 2|\partial \lambda| \) and the fabrication tolerances \( \partial W \) in terms of excess losses. As shown in Fig. 4(a), the optical bandwidth \( 2|\partial \lambda| \) gives the whole wavelength range centered around \( \lambda_{\text{opt}} \) that leads to an excess loss lower than a value \( \alpha \). We choose to express the fabrication tolerances by the width variation since this geometrical parameter is the most critical one in strongly guided MMI couplers. The fabrication tolerances \( \partial W \) express only the half of the possible range of width variations to remain under the excess loss \( \alpha \) [Fig. 4(b)].

In order to get close expressions for \( 2|\partial \lambda| \) and \( \partial W \), we calculate the excess losses \( \alpha \) as a function of the MMI length variation \( |\partial L| \) and introduce the result in (4). The function \( \alpha(|\partial L|) \) can directly be expressed by overlapping the optical field amplitudes at the end of the MMI section with the fields of the output waveguides. Since we consider well-separated output images, this calculation has to be performed at only one output. The optical field amplitudes of the monomode symmetrical input and output waveguides can be approximated by Gaussian beams of waist \( d_0 \). By calculating the overlap \( T \) of such a Gaussian beam focused at \( L \) with the same Gaussian beam but focused at \( L + |\partial L| \), the length variation \( |\partial L| \) can be related to the excess losses \( \alpha \equiv -10 \cdot \log_{10} (T) \) as follows (Appendix):

\[
|\delta L| \leq Z \cdot d_0^2 \cdot \frac{\pi n}{2\lambda_{\text{opt}}} \quad \text{with} \quad Z = \left[ 4 - 5T^2 + \sqrt{(4 - 5T^2)^2 - 16T^2(T^2 - 1)} \right]^{1/2}.
\] (5)

Introducing this result in (4), we get for the optical bandwidth \( 2|\partial \lambda| \) and for the fabrication tolerances \( \partial W \),

\[
2|\partial \lambda| \equiv Z(\alpha) \cdot \frac{\pi}{4} \cdot \frac{aN}{M} \cdot \frac{d_0^2}{W^2} \cdot \lambda_{\text{opt}}
\] \quad and

\[
|\delta W| \leq Z(\alpha) \cdot \frac{\pi}{16} \cdot \frac{aN}{M} \cdot \frac{d_0^2}{W}.
\] (6)

These expressions apply for a general design of the MMI couplers. In most of the practical applications, the special design of MMI couplers with equidistant inputs (or outputs) is used. In this important case, the width \( W \) can be written as \( W \equiv N \cdot D \) with \( D \) the spacing of the channels measured between the axes of the waveguide. Equation (6) then leads to

\[
|\delta L| \leq Z(\alpha) \cdot \frac{\pi}{4} \cdot \frac{aN}{M} \cdot \left( \frac{d_0}{D} \right)^2 \cdot \lambda_{\text{opt}} \quad \text{and}
\]

\[
|\delta W| \leq Z(\alpha) \cdot \frac{\pi}{16} \cdot \frac{aN}{M} \cdot \left( \frac{d_0}{D} \right)^2 \cdot D.
\] (7)
B. Examples and Comparison

3. With this structure, polarization-independent switches have a large value of \( N \) and proportional to the channel spacing in practical applications. The optical bandwidth of MMI couplers is inversely proportional to the number of input and output channels. The curve \( \lambda \) is represented in Fig. 8.

Equations (6) and (7) have been written as a function of fixed design parameters, namely, of the “acceptable” excess losses \( \alpha \), of the kind of MMI coupler used \( (a, N, M) \), of the geometrical parameters at the inputs/outputs \( (d_0, W, D) \), and of the optimal wavelength \( (\lambda_{opt}) \) as given by system specifications. The curve \( Z(\alpha) \) is represented in Fig. 8.

2) \[ \alpha \] and \( W \) are proportional to the square of the normalized beam waist \( (d_0/D) \) \in [0, 1]. This term is related to the degree of overlapping of the self-images, and can therefore not be increased to values much higher than 1/2 in practical applications. The optical bandwidth of MMI couplers is inversely proportional to the number of input and output channels \( N \). This behavior can be a strong limitation for using a large value of \( N \). The fabrication tolerances are independent of \( N \) and proportional to the channel spacing \( D \).

B. Examples and Comparison with Mode Analysis (MA)

We consider the InP/InGaAsP waveguide structure of Fig. 3. With this structure, polarization-independent switches have been realized [5]. Optical bandwidth as well as fabrication tolerance measurements of MMI couplers using this waveguide structure will be presented.

We first consider restricted interference MMI couplers described by (6). The inputs and outputs of width \( w = 3 \mu m \) are positioned at \( W/3 \) and \( 2W/3 \), in order not to excite the modes 2, 5, 8, … For a geometrical width of \( W = 18 \mu m \), the equivalent width is \( W_{eq} = 19.2 \mu m \) and 19.0 \( \mu m \) for TE and TM, respectively; this is due to the lateral penetration of the evanescent fields at the side of the MMI section. The parameters \( a, n, \) and \( d_0 \) have the values \( a = 3, n = 3.3, d_0 = 3.4 \mu m \). The length is \( L = L_c/2 = 530 \mu m \) for the 3 dB MMI coupler (two images of equal intensity at the outputs) and \( L = L_c/2 = 530 \mu m \) for the cross-MMI coupler (one image at the cross-channel output). In Fig. 4, the optical bandwidth and the fabrication tolerances described by (6) are compared with the results obtained by the more sophisticated mode Analysis (MA) method [12] for the TE polarization. With the MA, no strong guiding and paraxial approximations are used, and effects like image broadening can be described. This leads to a nonzero excess loss at the optimum. Except for these losses, the bandwidth and fabrication tolerances calculated with both methods are very similar.

Then we analyze the case of a general \( N \times N \) MMI coupler with equidistant inputs/outputs corresponding to (7). The structure of Fig. 3 is used with a constant channel spacing \( D \). In Fig. 5(a) the inversely proportional dependency of the optical bandwidth on \( N \) is illustrated. The optical bandwidth of MMI couplers becomes a limiting parameter for values of \( N \) greater than 8. The dependency of the fabrication tolerances on \( D \) is shown in Fig. 5(b). The value of \( D \) should remain somewhat greater than \( d_0 \) in order to assure well-separated output images. From (7), we infer that scaling down both \( D \) and \( d_0 \), keeping the ratio \( d_0/D \) constant, will linearly tighten the fabrication tolerances, but the MMI coupler length \( L \) will quadratically decrease (2).

III. EXPERIMENT

MMI couplers with the same waveguide structure (Fig. 3) as for the theoretical calculations of Fig. 4 have been produced on InP/InGaAsP material. These devices are fully compatible with an electrooptic phase shifter and can be integrated in polarization-independent four-port Mach–Zehnder optical switches [5].

A number of 3 dB MMI couplers, as well as cross-MMI couplers with restricted interference have been integrated, with \( W \) ranging from 17.5 to 18.5 \( \mu m \) in steps of 0.25 \( \mu m \). The 3 dB MMI couplers have a length \( L = L_c/2 = 530 \mu m \) and divide the intensity of each input port equally into both output channels. The cross-MMI couplers have a length \( L = L_c/2 = 530 \mu m \) and connect each input to the corresponding cross output. The input and output waveguides were placed at 1/3 and 2/3 of the equivalent MMI coupler width in order to obtain a restricted interference mechanism by not exciting the modes 2, 5, 8, … [12]. Curved access waveguides with offsets were applied with a radius of 2 mm and a width of 3 \( \mu m \).

A thick InP top and weakly doped layers adjacent to the quaternary InGaAsP guiding layer keep the absorption losses...
The layers were grown by metal–organic vapor phase epitaxy (MOVPE) on an n⁺InP substrate. The waveguides were patterned by magnetron-enhanced CH₄/H₂ reactive ion etching.

For the measurements, the devices were placed between 40× IR anti-reflection-coated microscope objectives. The light of a wavelength-tunable external grating semiconductor laser was launched into each MMI coupler input and recorded from both outputs by a Ge photodiode. Measurements with TE and TM polarized light were successively performed.

We define the excess losses $\alpha$ and the unbalance (UB) due to wavelength and width variations by

$$\alpha \equiv -10 \cdot \log_{10} \left( \frac{(P_{\text{bar}} + P_{\text{cross}})}{(P_{\text{bar}} + P_{\text{cross}})_{\text{opt}}} \right) \quad \text{and}$$

$$\text{UB} \equiv 10 \cdot \log_{10} \left( \frac{P_{\text{bar}}}{P_{\text{cross}}} \right).$$

The value $(P_{\text{bar}} + P_{\text{cross}})_{\text{opt}}$ corresponds to the sum of the two output intensities at the optimal wavelength and MMI coupler width. We first measured MMI couplers with a geometrical width $W = 18 \mu m$ at various wavelengths. Then MMI couplers with different widths $W$ were measured at fixed wavelength $\lambda = 1.52 \mu m$. The measurements are compared with the analytic approximations of (6) and Fig. 4.

The measurements obtained with 3 dB MMI couplers of length $L = 530 \mu m$ are shown in Fig. 6. The results for both polarizations overlap almost completely. The couplers are, to a good approximation, polarization independent. The unbalance remains close to 0 dB and is, on the entire measurement region, never greater than 1 dB. The unbalance measurements compare well with the predictions of the MA (dashed line).

Fig. 5. (a) Optical bandwidth of general $N \times N$ MMI couplers with equidistant inputs and outputs. The curves are calculated with (7). $D = 5 \mu m$. (b) Fabrication tolerances of general $N \times N$ MMI couplers with equidistant inputs/outputs. The curves are calculated with (7). $N = 4$, $\lambda = 1.52 \mu m$, $M = 1$, $a = 1$, $d_0 = 3.4 \mu m$, $n = 3.3$, TE polarization.

IV. CONCLUSIONS

The optical bandwidth and the fabrication tolerances of MMI couplers have been analytically studied. We derived...
simple expressions that relate these two basic properties of MMI couplers to the main design parameters. The optical bandwidth is shown to be inversely proportional to the number of input and output waveguides \( N \), while the tolerances are independent of \( N \) but are proportional to the waveguide separation \( D \). Both \( 2d^4 \) and \( dW \) are proportional to the square of the normalized beam waist \( d_0 \), itself directly related to the degree of overlapping of the self-images.

We successfully compare these analytic expressions with more sophisticated mode analysis simulations and to measurement results obtained using an InP/InGaAsP waveguide structure compatible for switch integration. We realized and measured 3 dB MMI couplers as well as cross-MMI couplers based on restricted mode interference. For 1 dB excess losses, optical bandwidths of more than 100 nm and of about 80 nm have been found for 3 dB and cross couplers, respectively, while the fabrication tolerances are \( \pm 0.5 \) and \( \pm 0.25 \) \( \mu \text{m} \), respectively.

V. APPENDIX

In this Appendix, we derive the relation between the length variation \( \delta L \) and the excess losses \( \alpha \). We consider a Gaussian-beam propagating in the \( z \), diverging in the \( x \), and maintaining its profile in the \( y \) direction. Its focus is at \( z = 0 \) and its Gaussian waist is \( d_0 \). The amplitude can be written as

\[
u(x, z) = \left( \frac{8}{\pi d^2} \right)^{1/4} e^{-\frac{(2x)^2}{\delta^2}} \cdot e^{i(\pi n x^2/\lambda R)} \cdot e^{i\varphi(x)} \quad (A1)
\]

with \( \varphi(x) \) a phase term independent of \( x \). The parameters \( R \) and \( d \) are defined as

\[
R(z) = z \cdot \left( 1 + \left( \frac{1}{2z^2} \right)^2 \right)
\]

and

\[
d^2(z) = d_0^2 + (2\Sigma)^2 \quad (A2)
\]

The losses can be calculated by overlapping this Gaussian beam focused at \( z = 0 \), with the same Gaussian beam but focused at \( z = \delta L \). We get, after complex integration,

\[
\int_{-\infty}^{\infty} u(0, x)u^*(\delta L, x) \, dx = -\sqrt{2} \cdot \sqrt{1 + \delta L^2} \cdot e^{-i\varphi(x)} \quad (A3)
\]

with the definition \( Z = (2\delta L)/(\pi n d_0^2) \).

The excess losses \( \alpha \) are related to the transmission \( T \) by

\[
\alpha \equiv -10 \cdot \log_{10} (T)
\]

Solving this equation in \( Z \) leads to (5) for \( T \in [0, 1] \). The relationship among \( \alpha, Z, \) and \( T \) can be found in Fig. 8. References


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