An optimal design strategy for MMI splitters

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Abstract: : *In this paper we design novel tapered 2x2 MMI splitters based on adiabatic tapered MMI sections which are both low loss and significantly more compact in length compared to their generic straight equivalents.*

Introduction

Multimode Interference (MMI) devices have gained in popularity due to their versatility for use in many optical circuits such as power splitters, power combiners, and Mach-Zehnder optical switches.

However, the large lengths associated with generic straight MMI structures leads to an undesirable demand on space in optical waveguide circuits. This has resulted in a variety of proposals and suggestions based on tapered designs for the MMI section which are aimed at reducing the length of MMI couplers [1-3]. In this paper we propose an entirely new tapered structure which is both compact and adiabatic, resulting in a minimum loss design. The adiabatic design of the device is achieved by ensuring there is minimal coupling between the modes in the tapered MMI section. This reduces the coupling losses incurred in the device and ensures near-perfect imaging. In addition we shall be comparing its performance to that of a parabolically tapered device.

Adiabatically Tapered 2x2 MMI Structures

In [4], we discussed the theory of an adiabatically tapered 1x2 MMI coupler. Here, we extend our results to the case of a 2x2 coupler.

In a straight multimode interference waveguide device, the formation of images is described by the self-imaging principle [4]. The straight waveguide section of the MMI can support a number of modes depending on its width. These modes propagate along the waveguide interfering destructively and constructively to form multiple images.

In a straight 2x2 3dB MMI coupler the double imaging length is given by [4]:

$$L = \frac{3}{8} L_\pi \qquad (1)$$

where L_π is half the beat length between the two lowest order modes,

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \simeq \frac{4 n_1 W_e^2}{3\lambda_0} \qquad (2)$$

Hence the double imaging length L is given by

$$L = \frac{n_1 W_e^2}{2\lambda_0} \qquad (3)$$

where n_1 is the refractive index of the MMI waveguide, λ_0 is the free space wavelength, $k_0 = 2\pi/\lambda_0$ and W_e is the effective width of the waveguide which takes into account the Goos-Hänchen shift at the waveguide boundaries.

In [1-4], it is shown that the length of an MMI can be significantly reduced by tapering the MMI section. However, for low loss the tapered section musy also be adiabatic.

It has been shown in [4] and [5] that the criterion which the sturcture must satisfy along its length to ensure adiabaticity and a more compact length is given by

$$\Omega << \rho(\beta_0 - \beta_1)/2\pi \qquad (4)$$

where $\Omega(z)$ is the angle between the tangent to the waveguide boundary and the central waveguide axis as shown in Fig. 1 below and β_0 and β_1 are the propagation constants of the two lowest order modes excited in the waveguide.

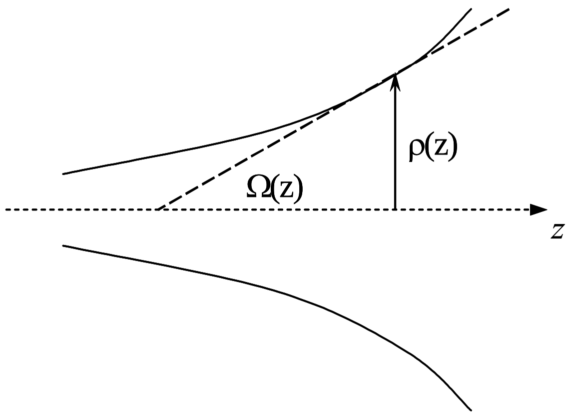

Fig. 1: Longitudinal section of tapered waveguide

Equation (4) defines the limit on the local taper angle as a function of *z* for an adiabatic taper. It has been shown that equation (4) provides a very good estimate for the adiabaticity of a tapered waveguide [5]. This means that the taper angle must be sufficiently small and also satisfy equation (4) at each position along the taper. The propagation constants, β_0 and β_1 depend on the local guide half-width $\rho(z)$, and thus the right hand side of equation (4) will vary with the degree of tapering.

The delineating limit, i.e. the boundary between the taper being approximately adiabatic and nonadiabatic can therefore generated by equating the two sides of this equation:

$$\Omega = \rho(\beta_0 - \beta_1)/2\pi \qquad (5)$$

Device Design

The local delineating limit in the 2x2 splitter is derived from (2) and (5) as:

$$\Omega(z) = \frac{3\lambda_0}{16 n_1 w(z)} \approx \frac{\partial \rho}{\partial z} \qquad (6)$$

where w (z) is the local width of the MMI waveguide and $\frac{\partial \rho}{\partial z}$ is the local tangent and where we have ignored the Goos-Hänchen shift.

The shape profile of the adiabatic splitter can thus be derived by simply integrating equation (6). This will result in the width equation for one half of the 2x2 coupler, the other half is simply the mirror image.

$$w_{1/2} = \sqrt{\frac{3\lambda z}{4 n_1} + w_1^2} \quad \text{for } z > 0$$

and likewise for z<0

$$w_{-1/2} = \sqrt{-\frac{3\lambda z}{4 n_1} + w_1^2} \qquad (7)$$

where w_1 is the width of the middle section as shown in the Fig. 2 below.

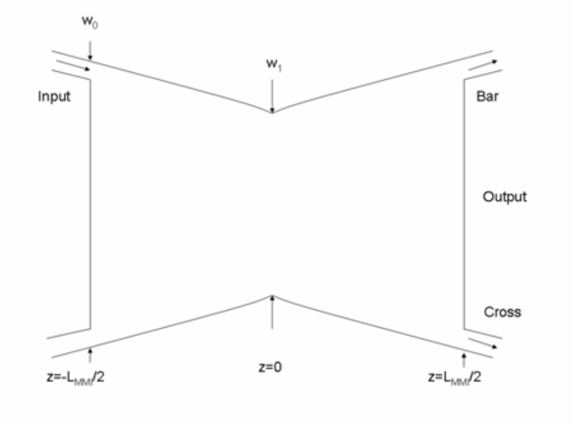

Fig. 2: 2x2 adiabatic MMI splitter showing the input and output waveguides

Simulation and Results

We have simulated the performance of the 2x2 adiabatic tapered MMI splitter using the BPM method. This was done using a BPM-CAD Waveguide Optics Modeling Software System by the Optiwave Corporation. Using waveguide parameters employed in [6], n_1 = 3.32517, n_2, the refractive index of the surronding cladding =3.17, λ_0 =1.507 µm, and w_1 = 2.46 µm. The evolution of the optical field through the MMI is shown in Figure 4 which was computed with a 4 µm long input waveguide of input width 1.1 µm and output waveguides of a similar 1.1 µm width. This simulation predicts a tapered MMI section length of 58 µm as shown in Figure 3. This is somewhat shorter than the length calculated for the straight waveguide, 82 µm.

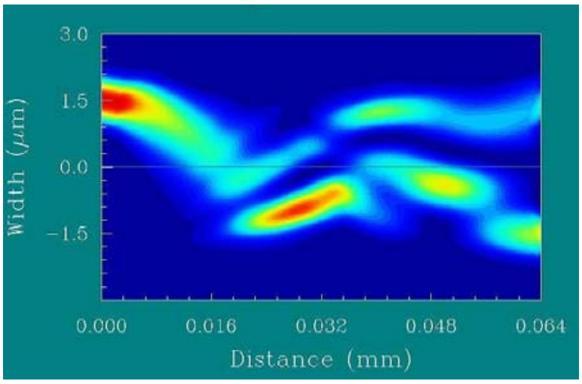

Fig. 3: BPM simulation of propagation through an adiabatically tapered 2x2 MMI splitter.

Simulations were also performed on quadratic tapered MMI splitters as shown in the Table 1 below.

Table 1: Comparison of output performance as measured in different couplers using BPM where n_1 = 3.32517, n_2 =3.17, λ_0 =1.507 µm.

	w_0	$d\Omega$	L_{MMI}	Loss(dB)	b%	c%
Straight	3.8	0	82	0.074	50	50
Adiabatic	4	0.4	58	1.27	40	60
Quadratic	4.1	0.4	50	0.52	46	54
Optquad	3.8	0.35	52	0.23	52	48

where w_0 is the initial and final width,

$d\Omega$ is the normalised width variation = $\frac{w_0 - w_1}{w_0}$,

L_{MMI} is the overall length of the MMI.

Loss is the output power loss measured in decibels and *b* and *c* are the proportion of power in both the bar and cross outputs respectively relative to the total power output. This defines coupler's the splitting ratio.

Looking at the results under the Adiabatic and Parabolic profiles in Table 1, with a similar $d\Omega$ of 0.4, one can see that the splitting is much more symmetric in the quadratic profile i.e. much more even. The total output power loss is also smaller. This can be attributed to the phase changes which occur at the midplane of the adiabatic device as $\frac{dW}{dz} \neq 0$ at z = $L_{MMI}/2$ as can be seen in Figure 2 above. This leads a discontinuous change in the propagating wavefront and hence in poor imaging i.e. poor splitting ratio and lower power output level.

In order to correct the discontinuity problem incurred in the adiabatic tapered coupler, we introduce a design refinement to the middle portion of the MMI waveguide.

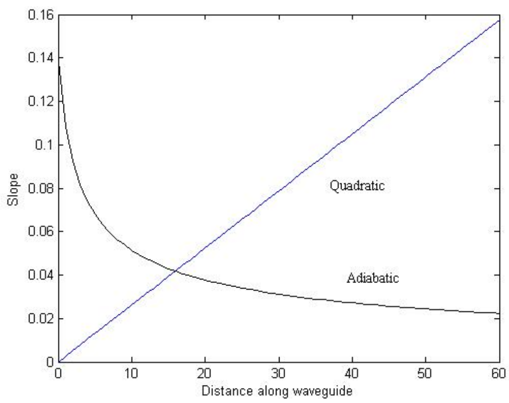

Fig. 4: Comparison of slopes of quadratic and adiabatic half-profiles where n_1 = 3.32517, n_2 =3.17, λ_0 =1.507 µm. Looking at Fig. 4, one can see that the half-quadratic profile obeys the angle criterion up until a length of about 12 µm when the slope exceeds the minimum allowable by the adiabatic criterion. However, one can create hybrid structure which includes a quadratic profile as proposed in [6] of full quadratic length 24 µm and thereafter a profile which follows the adiabatic criterion as shown in Fig. 5. Such a waveguide will combine the beneficial properties of both structures; the continuous change of width $\frac{dW}{dz} = 0$ in the quadratic section and the negligible coupling in the adiabatic tapered section.

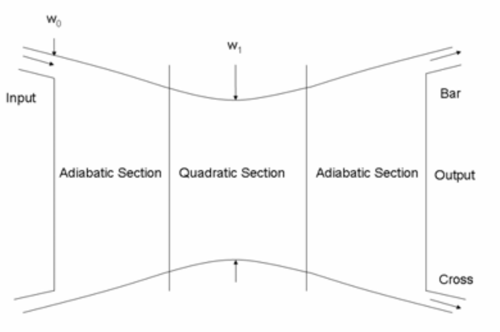

Fig. 5: 2x2 hybrid splitter showing the adiabatic and quadratic sections.

The hybrid structure was simulated using the parameters given above with the BPM-CAD program resulting in the results under the OptQuad profile in Table 1. One can see that the total output power loss is much less and the splitting ratio improved accompanied with an additional reduction in MMI length which is only 52 microns. The figure below shows the evolution of the optical field through the hybrid OptQuad MMI splitter.

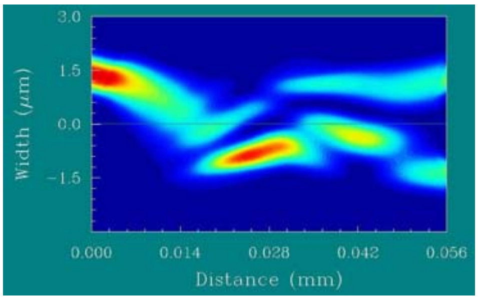

Fig. 3: BPM simulation of propagation through a hybrid tapered 2x2 MMI splitter.

Conclusions

In this paper we have presented the theory and design for adiabatic tapered 2x2 MMI splitters which are more compact than straight MMIs yet have comparable low loss. We have also considered the problem of discontinuity incurred in purely adiabatic splitters and proposed a hybrid structure which has a simulated loss which is much lower than that for quadratically tapered devices based on similar parameters. Although we have discussed the design of 2x2 3dB splitters in this paper, the theory presented here is easily extended to more general NxM devices.

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