



Low-loss waveguide crossing using a multimode interference structure

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Abstract

A novel design technique for low-loss waveguide crossing using the self-imaging properties of multimode interference (MMI) structures is presented. The technique exploits the observation that optical fields with a small $1/e$ width relative to that of the MMI structure in the image reformed region experience negligible propagation loss even in the absence of lateral guiding mechanism around the region. This allows the introduction of a slab in the MMI region. The technique could also be used to design planar light-wave circuits with small wavelength-dependent loss which is important for DWDM devices. Using two-dimensional wide-angle BPM simulations, taper width technology and MMI structure technology is compared for low-loss slab propagation in orthogonal intersection. We also demonstrate that low-loss crossing waveguides with intersection angle as small as 23° can be achieved with the aid of MMI structures.

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1. Introduction

The self-imaging properties of multimode interference (MMI) are commonly employed in planar lightwave circuits [1] to make compact power splitters [2,3], combiners, and Mach Zehnder

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interferometers [4] with good tolerance to fabrication errors. Although the self-imaging properties of MMI are well known, however, the application of MMI structures to attain low-loss waveguide crossing has only recently been studied. Stuart [5] introduced MMI lenses to achieve low-loss slab propagation and synthesizes a nearly ideal two-dimensional focusing Gaussian beam using an MMI waveguide lens for a given feed waveguide width and slab width. The beam is fed to a slab region and then transformed to the initial mode using a second identical MMI lens. In Stuart's technique, a strong relationship exists between the index delta, MMI waveguide width and the slab width for low-loss slab propagation and it presents a restriction to the slab width for a given index delta.

In this paper, we report an alternative design technique of using MMI structures to attain low-loss slab propagation to relax the aforementioned restriction. In MMI waveguides, the $1/e$ width of an optical field changes periodically, which increases and then decreases to almost the same width of the input optical field at the single image reformed position. At that position, the waveguide width (i.e the MMI structure width) is larger than the $1/e$ width of the optical field and little optical power exists around the sides of the waveguide. Therefore, any perturbations immediately outside the waveguide around this region would have little effect to the propagation of the optical field and low-loss slab propagation could be achieved when a slab is introduced to this region. Results obtained using two-dimensional beam propagation method (BPM) simulations [6] show that the slab width can be varied over a fairly large range without introducing significant insertion loss. Also, in this case, a nearly ideal Gaussian beam is not required, thus permitting larger tolerance in the length of the MMI structure.

2. MMI simulation results and discussions

Two-dimensional BPM simulation was used to analyze the proposed technique. Consider the MMI region shown in Fig. 1(a), with a cladding refractive index, n_{cl} , of 1.5 and index delta ($n_{core} - n_{cl}$)/ n_{cl} of 2%, where n_{core} is the core refractive

index, at a wavelength of 1.55 μm . The initial waveguide has a width of 5 μm , which connects abruptly to the MMI region and excites the higher order modes. The width of the MMI region is 7.5 μm and supports the three lowest TE modes. However, a fundamental mode propagates from the initial waveguide to the MMI region only excite the even modes, i.e. TE_0 and TE_2 , due to the structure symmetry. Using overlap integral for the modes of the initial waveguide and MMI region, the coupling efficiency from the TE_0 of the initial waveguide to the TE_0 and TE_2 modes of the MMI region were found to be 95% and 4.8%, respectively. The total coupling efficiency from the initial waveguide to the MMI region is therefore 99.8%, indicating a loss of only 0.009 dB to the unguided modes. The beat length, L_B , between the two even modes of the MMI waveguide is given by $2\pi/(\beta_0 - \beta_2)$. The refractive index of the TE_0 and TE_2 modes in the MMI waveguide is 1.5277 and 1.5100, respectively. Therefore, for 1.55 μm wavelength light, the beat length between the two modes is 87.6 μm . As a consequence of the self-imaging properties of multimode waveguides, the two modes would reform the image of the excitation mode periodically at mL_B , where m is an integer, behaving similar to that of a self-focusing graded index waveguide. Fig. 1(b) shows the $1/e$ width of the optical field propagating in the single-mode waveguide and the MMI region, obtained using two-dimensional BPM simulations. The length of the initial waveguide is 50 μm and the length of the MMI waveguide is 175.2 μm (two times of L_B). The $1/e$ width of the optical field is the smallest in the middle of the MMI waveguide and has a value of 5.19 μm . This is slightly larger than the 5.08 μm $1/e$ width of the optical field in the initial 5 μm -width waveguide but is more than 44% smaller than the width of the MMI waveguide. If we assume optical field with $1/e$ width of less than the MMI structure width could propagate through the middle region of MMI waveguide with negligible loss, even though there is no lateral guiding mechanism, then a slab region introduced into this region could have widths of up to about 50 μm , as observed from Fig. 1(b). Fig. 1(c) shows the two-dimensional BPM simulation results which indicate that low-loss slab cross-

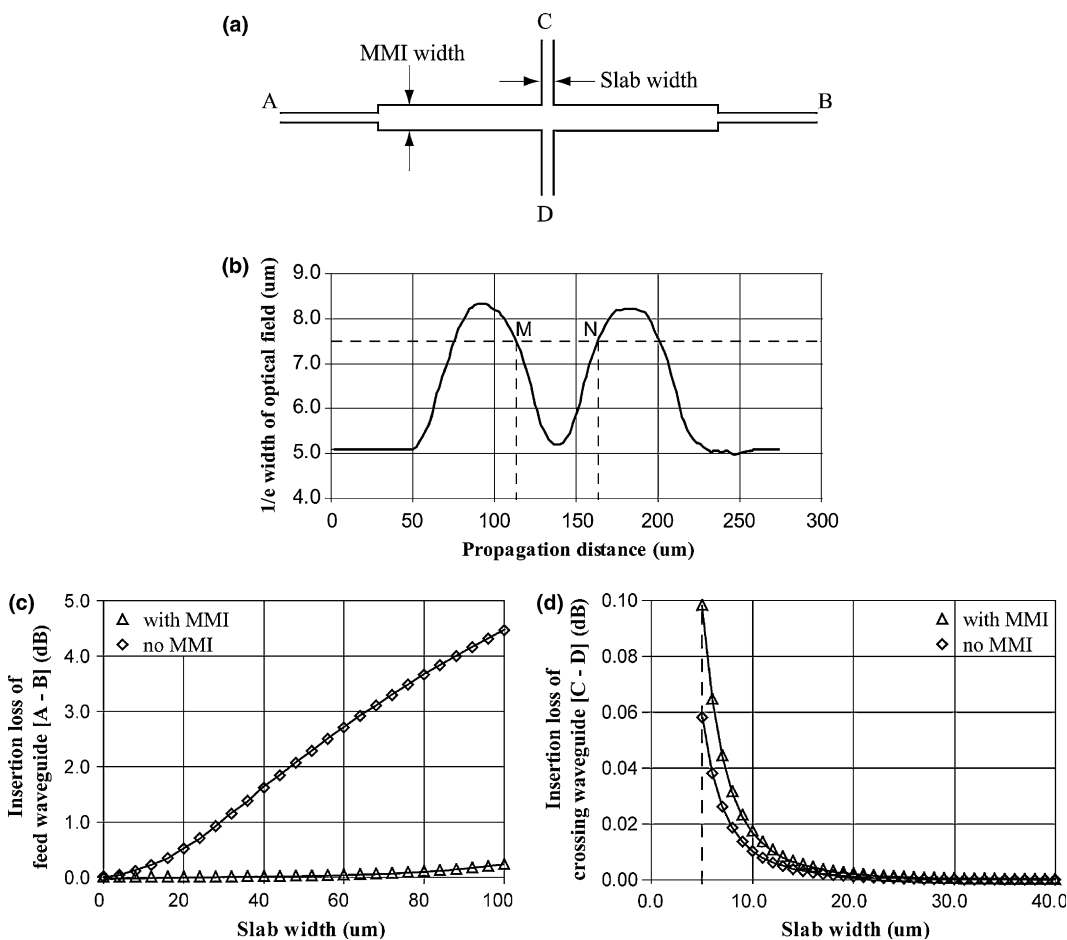


Fig. 1. (a) A 5 μm -wide feed waveguide couple to a 175.2 μm -long, 7.5 μm -wide MMI waveguide and then back to a 5 μm -wide waveguide [A–B]. In the middle of the MMI waveguide, a crossing waveguide [C–D] is inserted. (b) Evolution of the 1/e width of the optical field propagating [from A to B] in the complete waveguide structure. (c) Insertion loss of the feed waveguide [A–B] versus slab waveguide widths with (triangle dots) and without (diamond dots) the MMI structure. (d) Insertion loss of the crossing waveguide versus slab waveguide widths with (triangle dots) and without (square dots) MMI structure.

ing of less than 0.1 dB can be achieved even with slab width as wide as 80 μm . However, for slab crossing without the MMI structure, loss of more than 0.1 dB would occur even with slab width of 8 μm .

The additional loss incurred by the introduction of the MMI structure to the crossing waveguide was also evaluated using two-dimensional BPM simulations. Fig. 1(d) shows the insertion loss of the crossing waveguide of different widths with (triangle dots) and without (diamond dots) the MMI structure. The extra loss to the crossing

waveguide is less than 0.01 dB when its width is greater than 9 μm . However, for slab width less than 9 μm , the extra insertion loss increases rapidly. This problem can be overcome by introducing MMI structure to the crossing waveguide as well. Coupling loss is induced by radiation mode coupling at the MMI-waveguide junctions and it increases when the MMI width increases. In this study, the slab width is chosen to be equal to the MMI width as shown in Fig. 2(a) and varied between 7 and 9 μm . The results presented here are also true for waveguides with different refractive

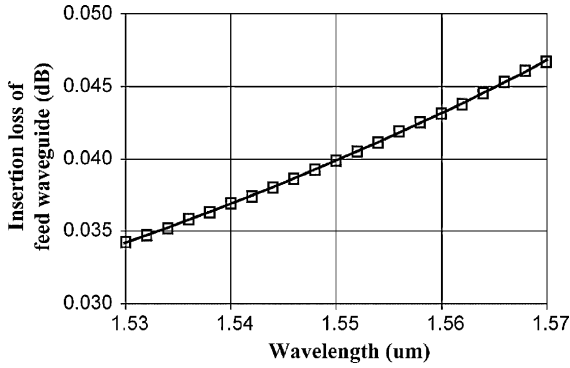


Fig. 2. Insertion loss of the MMI structure shown in Fig. 1(a) versus transmission wavelength.

Table 1

Insertion loss of MMI structures for low-loss slab crossing (the slab length is two times the beat length)

MMI width (μm)	Beat length	Coupling loss	Slab loss (slab width = MMI width)
7	79.5	0.016	0.018
7.5	87.6	0.018	0.019
8	96.2	0.018	0.019
8.5	105.6	0.020	0.024
9	115.4	0.024	0.031

index delta, except that low index delta waveguide has longer focus length.

Table 1 lists the beat length, coupling loss and slab loss of MMI structures with width between 7 and 9 μm. In all cases, the length of the MMI structure is kept at twice of that of the beat length and the width of the feed waveguide and index delta are 5 μm and 2%, respectively.

The wavelength-dependent loss of the complete structure was also simulated and the result is shown in Fig. 2. Increase of the insertion loss with wavelength is expected because the $1/e$ width of the optical field is larger for longer wavelength. The loss increases from 1530 to 1570 nm is less than 0.015 dB, indicating that this structure is fairly wavelength independent.

As stated earlier, one of the main contributions to the coupling loss is due to the radiation mode coupling at the MMI-waveguide junctions. In the following section, we compare the performance of the MMI cross-slab structure as shown in Fig. 3(a) with one that employed the taper width tech-

nology [7] which is commonly used to minimize intersection loss.

3. Comparison of the MMI cross-structure with the tapered cross-structure

Taper width technology is used to minimize the intersection loss in waveguides. It uses two tapers to taper up to a wide waveguide and then down again to the narrow waveguide. The schematic of a cross-waveguide using taper width technology to reduce loss is shown in Fig. 3(b).

Using the same index delta as described in the previous section, we first determine the insertion loss at the intersection of crossing waveguides without MMI structure or tapering. The insertion loss was calculated to be 0.058 dB for 5 μm-width waveguides and is indicated in Fig. 3(c). We used the same slab width, W_S , for the waveguides at the intersection region for both cases (refers Fig. 3(a) and (b)) to minimize the insertion loss. In the taper case, a taper length, L_T , of more than 140 μm was employed so as to achieve adiabatic coupling and the slab length, L_S , was chosen to give the least loss (for example, $L_S = 52$ μm for $W_S = 7.5$ μm). The insertion loss of waveguide intersections that employ a MMI structure or taper width structure with difference slab widths are shown in Fig. 3(c). The simulation results show that the insertion loss is smaller for taper width structure if the slab width is greater than about 8.5 μm. With narrower slab width, however, the MMI structure offers a lower insertion loss and could be 100% better than the taper width case when the slab width is about 7 μm. The mechanism of the propagation for the optical field crossing the waveguide for the MMI structure and taper width structure are quite different. The optical field in the MMI structure refocused in the centre of the intersection of the waveguides and has a narrow optical field, whereas in the taper width structure, the mode field expanded and some optical power is lost to the crossing waveguide. Therefore, losses mainly occurred in the waveguide-MMI junction for the MMI structure case but in the taper width case, it occurred in the intersection region. The taper length is also fairly long (>140 μm in our case),

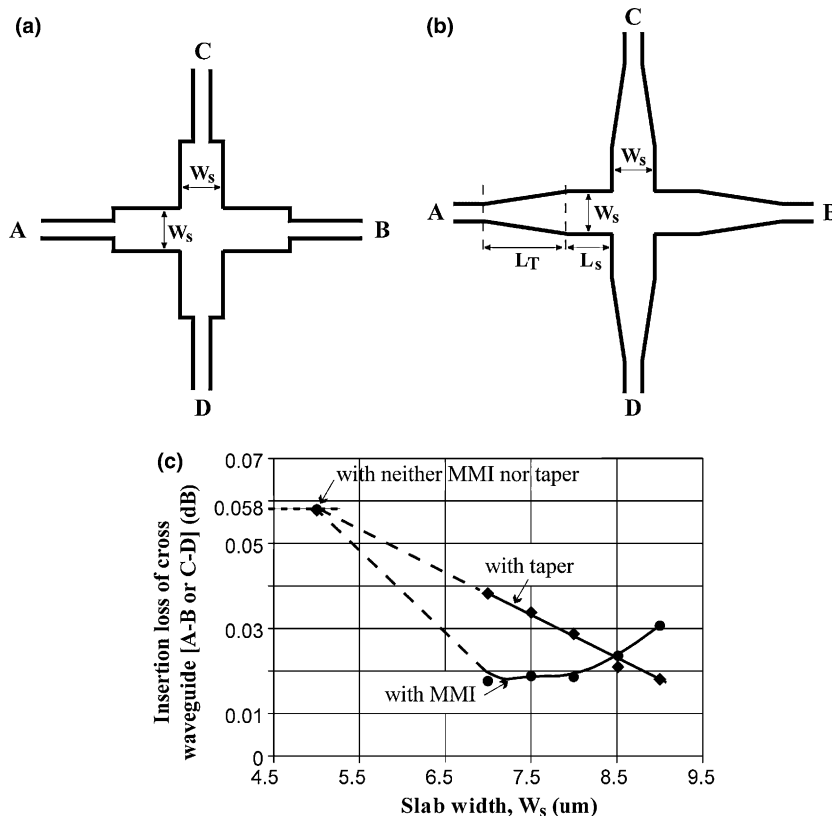


Fig. 3. (a) The structure of a cross waveguide with MMI structure to improve insertion loss. (b) The structure of a cross waveguide using taper width technology. (c) Insertion loss of the cross waveguide [A–B or C–D] versus slab waveguide widths with MMI (circle dots) and with taper (diamond dots) structure.

so the taper width structure shown in Fig. 3(b) is about four times that of the MMI structure shown in Fig. 3(a). In practice, narrower slab width and smaller structure size are preferred as they provide a saving in the premium substrate estate. In our analysis, we did not consider any material absorption loss; however, because of the much longer taper length, the taper width structure will suffer even more loss in comparison to the MMI structure case.

4. Angled intersection with the MMI structure

Low-loss waveguide crossing with angle of intersection of less than 45° is crucial for increasing the density of planar light-wave circuits. In this section, we demonstrate that MMI structures

could be employed in small angle crossing to improve the loss performance. Fig. 4(a) and (b) show the cross-waveguides with an intersection angle of θ° without and with the $7.5 \mu\text{m}$ -wide MMI structure, respectively. Results obtained from wide-angle two-dimensional BPM simulations [8] for the two cases are shown in Fig. 4(c). As expected, the loss increases with decreasing θ° , because more power is coupled to the adjacent waveguide. Without the MMI structure, the insertion loss is about 0.12 dB when θ° is decreased to 40° . However, with the aid of the MMI structure, the performance improved significantly and for the same loss the angle can be decreased to as small as 23° . Another concern in crossing waveguide is the crosstalk. Simulation results in Fig. 4(c) show that crosstalk of better than 30 dB is achievable when the intersection angle is greater than 17° and this

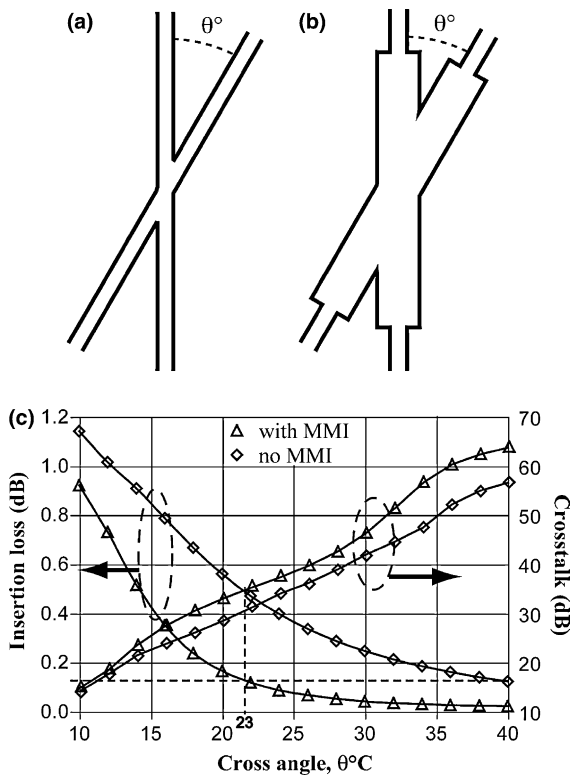


Fig. 4. (a) Crossing waveguides intersect at an angle of θ° . (b) Crossing waveguides with MMI structure intersect at an angle of θ° . (c) Slab propagation loss and crosstalk versus cross angle for the cases shown in Fig. 3(a), indicates by diamond dots and in Fig. 3(b), indicates by triangle dots.

is increased to about 37 dB when the angle is 23° . These results show that MMI structures provide a practical solution for waveguides with an angle of intersection as small as 20° .

5. Conclusion

In conclusion, we reported a novel design technique that exploits the self-imaging properties of MMI structures and the negligible effects of the

absence of lateral guiding mechanism around the region where the $1/e$ width of an optical field in the image reformed region is smaller than that of the MMI region to achieve low-loss waveguide crossing. Using two-dimensional BPM simulations, the MMI structure technology and taper structure technology were compared in orthogonal waveguide intersections. A small angle of intersection is crucial for increasing the density of planar light-wave circuits and we have also demonstrated that MMI structure technology could be employed to decrease the angle of intersection while at the same time providing low insertion loss.

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References

- [1] L.B. Soldano, E.C.M. Pennings, *J. Lightwave Technol.* 13 (1995) 615.
- [2] T.J. Tayag, D.M. Mackie, G.W. Bryant, *IEEE Photon. Technol. Lett.* 10 (1998) 1262.
- [3] L.B. Soldano, F.B. Veerman, M.K. Smit, B.H. Verbeek, A.H. Dubost, E.C.M. Pennings, *J. Lightwave Technol.* 10 (1992) 1843.
- [4] R.M. Jenkins, R.W.J. Devereux, J.M. Heaton, *Opt. Commun.* 109 (1994) 410.
- [5] H.R. Stuart, *Opt. Lett.* 28 (2003) 2141.
- [6] K. Okamoto, *Fundamentals of Optical Waveguides*, Academic Press, London, 2000.
- [7] H.G. Bukkems, C.G.P. Herben, M.K. Smit, F.H. Groen, I. Moerman, *IEEE Photon. Technol. Lett.* 11 (1999) 1420.
- [8] G.R. Hadley, *Opt. Lett.* 17 (1992) 1426.