Multimode interference devices with input–output ports on the sides

David M. Mackie

Multimode interference ( MMI) devices are useful for power splitting and for the separation or combination of wavelengths or polarizations, usually in integrated optics. Input–output guides connect to the MMI region by ports. In all previously reported MMI devices, the input and output guides connect only to the ends of the MMI region; i.e., they are end ported. What is believed to be a novel arrangement of the input–output ports on MMI devices is described. By placing input–output ports either partially or entirely on the sides of the MMI region (i.e., side porting), a variety of benefits are achieved and a variety of new devices can be made. © 2006 Optical Society of America

**OCIS codes:** 130.0250, 130.1750, 130.3120, 250.0250, 250.3140, 250.5300.

1. Introduction

Multimode interference ( MMI) devices are used to separate and combine power, wavelengths, and polarizations, mostly in integrated optics ( IO).1–3 Power-splitting devices are required for many signal distribution and sensing applications.4–9 Wavelength separation–combination devices for 1.31 and 1.55 μm are required for fiber-optic communications.10–15 Wavelength separation–combination devices are also required for the optical pumping of a 1.55 μm signal with a 0.98 μm pump.16,17 Polarization separation–combination devices are required for various IO and fiber-optic sensing systems, such as optical gyroscopes and structural stress sensors.18–20

The standard MMI-based power splitting and separation or combination of wavelengths or polarizations ( SCWP) devices that have been previously described in the literature outperform competing non-MMI techniques. Like competing techniques, however, their input–output ports are initially close enough in the lateral direction to allow unwanted transfer of signal laterally from one guide to the other, as the signal is guided toward or away from the MMI region. Also, laterally separating the guides requires bends, which cause unwanted signal loss, both from mode mismatch at guide boundaries and from radiative effects of curvature. For 1 × N power splitters, the bends in the guides that are necessary to separate the intermediate outputs often cause unwanted nonuniformity in the powers at the final outputs. Thus performance of nearly all MMI devices can be improved by increasing the lateral separation of the ports and by separating the guides without using bends.

This paper describes a novel technique, which is referred to here as side porting, that accomplishes these two goals and has other advantages. Side porting has two components: (i) placing the input and output ports partially or entirely on the sides of the MMI region, rather than entirely on the ends, and (ii) setting the input and output guides at an angle to the long axis of the MMI region. This is shown schematically in Fig. 1(a). In all previous work, it has been tacitly assumed that MMI devices would not work unless the input and output ports were positioned somewhere on, and entirely confined to, the ends of the MMI region. This is referred to here as end porting. Side porting is, to the best of my knowledge, an entirely new concept for MMI devices, and has a number of advantages over the conventional method of end porting. First, in end porting, the input–output ports must either be made narrow relative to the width of the MMI region (which reduces throughput) or else be separated laterally by only a small distance (which increases cross talk or nonuniformity). In side porting, input–output ports can instead be separated by the entire width of the MMI region, without regard to the width of the port. Second, side-port input–output guides are straight, yet automatically separate laterally from one another, since they are...
naturally at opposite angles from the MMI long axis. There is no need for S bends. (In fact, I will show that curved guides can be eliminated entirely in many architectures.) Angling the input–output guides of MMI devices has been previously suggested by several research groups, but only in the context of end porting. For end porting, angled input–output guides degrade the performance unless the MMI region is nonrectangular (e.g., bow-tie shaped), which introduces additional difficulties in design and fabrication. Third, in side porting, the ports may be placed at different distances along the long axis of the MMI region. This can significantly shorten some devices while still providing good performance and can make possible entirely new types of devices. There are restrictions, of course, which will be discussed. This degree of freedom has never been reported for end porting and probably is not possible. Fourth, side porting is more compatible with some novel MMI designs than is end porting. For instance, some slotted MMI designs described in Sections 2 and 3 are limited or made more difficult to implement by end porting.

In Section 2 various types of standard end-ported MMI devices are briefly discussed. Then examples of the performance of various types of side-ported MMI devices are introduced.

2. Review of Standard Multimode Interference Devices

Figure 1(b) shows a schematic top–down view (not to scale) of a standard end-ported MMI-based device with off-center input. S-bend guides, which would be necessary to separate the output guides in (b), are not shown.
standard MZI, which consists of a $1 \times 2$ power splitter, S bends, two straight guides (the legs), a mechanism that changes the phase of the signal in one leg, and an identical $1 \times 2$ power splitter used in reverse as a power combiner. The output power from the power combiner varies sensitively as the phase of one port’s signal changes relative to the other port’s signal.

For signal distribution applications, $1 \times 2$ power splitters are often used in series to create $1 \times 2$ splitting, then $1 \times 4$ splitting, $1 \times 8$ splitting, $1 \times 16$ splitting, and so on. This is sometimes referred to as cascading $1 \times 2$ splitters. Such a structure is referred to as a $1 \times N$ power splitter. The structure of a standard cascaded $1 \times 16$ splitter is shown in Fig. 4. Note the need for many S bends.

3. Side-Ported Multimode Interference Devices

The calculations were based on the beam propagation method (BPM) in the effective index method (EIM). Both BPM and EIM are well known in the literature. That the approximations inherent in the BPM (such as the paraxial condition) were satisfied was ensured by comparing limiting test cases against finite-difference time domain (FDTD) calculations. The effective index of refraction of the waveguide (including the MMI region), $n$, was either 3 or 1.5, corresponding to GaAs or glass, respectively. The lateral index was 1, implying a pedestal etch. (A pedestal etch is not necessary for MMI functionality but was used in the calculations presented because it allows for small bend radii and thus is often used when one is trying to make small devices. Additional calculations for buried waveguides, which are not otherwise discussed here, yield comparable performance numbers.) Devices with a slot used a lowered effective index of refraction for the slot, $n_{\text{slot}}$. The wavelength, $\lambda$, varied from 0.98 to 1.55, depending on the device and the application. (All lengths in this paper are in micrometers.)

Figure 5 shows the top views of the calculated electromagnetic (EM) field evolution through side-ported MMI-based $1 \times 2$ power splitters. Figure 5(a) is for a device with $n = 3$, air boundaries, $\lambda = 1$, MMI width $= 8$, and input–output guide width $= 2$. Figure 5(b) is for a device with $n = 1.5$, air boundaries, $\lambda = 1.5$, MMI width $= 8$, and input–output guide width $= 2$. 

Fig. 2. Schematic top view (not to scale) of a standard MMI-based $1 \times 2$ power splitter with centered input, which requires curved guides. The outputs must be separated from one another with S-bend guides as shown, and their initial separation may be small, which in practice leads to nonuniformity. The complicated structure of S-bend guides is indicated.

Fig. 3. Schematic top view (not to scale) of a standard MMI-based Mach–Zehnder interferometer, which requires curved guides. It is composed of two end-ported MMI $1 \times 2$ power splitters–combiners, connected by two straight guides and four S-bend guides. (The individual parts of the S-bend guides are not shown.) There is also a phase-changing mechanism of some sort on one guide.

Fig. 4. Schematic top view (not to scale) of a standard MMI-based $1 \times 16$ power splitter, which requires curved intermediate guides. It is composed of 15 end-ported MMI $1 \times 2$ power splitters in four rows of 1, 2, 4, and 8, connected by 14 intermediate S-bend guides, and ending with 16 half-S-bend guides. (The individual parts of the S-bend guides are not shown.)
The relative intensities are shown, on a linear gray scale from white for zero to black for maximum. Both designs gave >98% throughput and <1% nonuniformity. These designs were produced in only 30 min each, which shows the simplicity of designing side-ported devices. The stated performance was achieved with no optimization except for the length. Note that the length scale is different for parts (a) and (b) and that the input–output angles are roughly 10° for both cases.

As a comparison, I did the same type of calculations, using the same parameters as for Figs. 5(a) and 5(b), for standard end-ported MMI-based 1 × 2 power splitters with nonslanted input–output guides. The input was centered, as is standard practice. With no S bends on either the input or the output, the best designs gave 99% throughput and 0.1% nonuniformity. (Since the device was symmetrical, the only source of nonuniformity was the finite precision of the calculation.) I next added S bends. This device looked like Fig. 2, except that the curvature and offsets of the S bends were optimized and the input was also an S bend, as would be the case for many applications. To compare this fairly with the side-ported device above, the total length of both devices was the same (including the output guides but not the input guides), and the lateral separation of the output guides was the same. The input guides were then added, with the same parameters as the output guide. Note that the S bends had the minimum amount of bend necessary (i.e., largest possible radius of curvature), so that the propagation remained paraxial (<13° off axis). The throughput decreased slightly to 97%, which is slightly worse than the value of 98% for the side-ported devices above. The nonuniformity also worsened slightly, increasing to 0.4%.

Although the performance of the new side-ported device is therefore seen to be better than the standard end-ported device with S bends, the advantage shown so far is only slight. However, it is well established in the literature that in practice (i.e., for actual fabricated devices) S bends are quite detrimental to both throughput and nonuniformity. The discrepancy between experience and the above results was due to the use of very fine meshes in the calculations, which corresponded to unrealistically small lithographic resolution. The designs were forced to conform to a lithographic resolution of 0.1 μm and recalculated (with the same calculational mesh as before). The results were dramatic. The performance of the side-ported design decreased only slightly, giving 97% throughput and 2% nonuniformity. In contrast, the performance of the end-ported S-bend design was greatly affected, giving 88% average throughput and 14% nonuniformity. Decreasing the lithographic resolution to 50 nm restored nearly all of the performance of the side-ported design but still only gave 96% throughput and 4% nonuniformity for the end-ported S-bend design. Decreasing the lithographic resolution to 25 nm restored both designs to their ideal performance. I also tested the effect of a lithographic (and/or etch) roughness of 10 nm (i.e., tiny random design perturbations). Again, the end-ported S-bend design fared badly under real-world conditions. In fact, the side-ported design’s throughput of 98% was unaffected and its nonuniformity was actually reduced from 1% to 0.1%. The end-ported S-bend design’s throughput and nonuniformity both worsened significantly from 97% and 0.4% to 96% and 2%, respectively. Thus the advantage of side porting over end porting with S bends is significant once fabrication constraints are taken into account. I believe there are two physical reasons for this advantage. First, MMI regions generally have less scattering loss than corresponding lengths of single-mode waveguides, probably due to reduced sidewall interactions. End porting with S bends requires longer single-mode waveguides than side porting. Second, the offsets between curves of the S bends are critical parameters, so S bends are even more sensitive to nonideal fabrication than straight waveguides.

An alternative comparison was made by designing standard end-ported MMI-based 1 × 2 power splitters with slanted input–output guides. Such devices would not need S bends. They only differed from the devices of Figs. 5(a) and 5(b) by being end ported rather than side ported (and also the length was reoptimized). Their sensitivity to fabrication constraints was similar to side-ported devices. However, the best designs gave only about 95% throughput and 1% nonuniformity. Thus the (easily accomplished) design change from end porting to side porting significantly decreased the loss from 5% to less than 2% and also slightly decreased the nonuniformity.

To see the importance of the improvement in throughput of a MMI-based 1 × 2 splitter for side

![Fig. 5. Top views of the calculated electro-magnetic field evolution through side-ported MMI-based 1 × 2 power splitters for a device with (a) n = 3 and λ = 1 and (b) n = 1.5 and λ = 1.5.](image-url)
porting compared to slanted end porting, consider the $1 \times 16$ power splitter shown in Fig. 6. This device has slanted inputs and outputs to the MMI regions. First, note that there are no intermediate S bends, which will greatly decrease the design and fabrication complexity and improve the performance, compared to the standard $1 \times 16$ power splitter of Fig. 4. Second, note that the light must proceed through four layers of splitting from the single input to the 16 outputs. If the $1 \times 2$ splitters are end ported, then the throughput will be $(95\%)^4 = 81\%$. But if they are side ported, then the throughput will be $(98\%)^4 = 92\%$. Moreover, some signal distribution architectures require much more splitting: $1 \times 64$ or even $1 \times 256$. The throughput improvement of side porting over end porting becomes overwhelming for such devices: 87\% instead of 70\% for $1 \times 64$, 83\% instead of 63\% for $1 \times 256$.

One can also make a side-ported MMI-based turner, which allows the waveguide direction to be changed without the need for any curved waveguide sections. The length is set to twice the self-image length, and the output is in the opposite lateral direction from the input. Figure 7 shows how the turner can be combined with side-ported $1 \times 2$ splitters and a phase-changing device to make a MZI that requires no S-bend sections. This should be compared to Fig. 3, which shows a standard MZI that requires four S-bend structures.

Figure 8(a) shows the top view of the calculated EM field evolution through a side-ported MMI-based turner for a device with $n = 3$, air boundaries, $\lambda = 1$, MMI width = 8, and input–output guide width = 2. The intensity is shown, on a linear gray scale from white for zero to black for maximum. Figure 8(b) shows the same thing, but for $n = 1.5$ and $\lambda = 1.5$. These designs were produced in only 30 min each. Both designs gave >95\% throughput, with no optimization except length. The first self-image and two $1 \times 2$ splitting positions are clearly visible within the MMI region. Note that these turners have other uses besides MZI devices. For example, a large-angle turn can be accomplished with no curved waveguides by concatenating several small-angle side-ported MMI turners.

The side-ported device shown schematically in Fig. 1(a) is not the most generalized version. In principle, the input and output guides may be offset along
the long axis from the ends of the MMI region and/or from each other. An example is shown in Figs. 9 and 10. Figure 9 shows the schematic top view (not to scale) of a side-ported MMI-based SCWP device that has one output guide offset by a distance \( d \), relative to the end of the MMI region. Both polarizations (wavelengths) enter the MMI region from the input. One polarization (wavelength) is self-imaged onto one output, and the other polarization (wavelength) is self-imaged onto the other output. The process also works in reverse. The ability to offset one output relative to the other enables the device to be shorter and to perform better than the standard end-ported SCWP device shown in Fig. 1(b). Even if an end-ported SCWP device was designed with slanted input–output guides to eliminate the need for S bends [not shown in Fig. 1(b)], this extra design freedom of offsetting an output guide would still not be available. (Recall that slanted end porting performs less well than side porting.)

Figure 10 presents results for an example side-ported SCWP device, a wavelength splitter that separates pump light \((\lambda = 0.98)\) from signal light \((\lambda = 1.55)\). Shown is a top view of the calculated EM field evolution with \( n = 1.5, \) air boundaries, MMI width \( = 8, \) \( d = 14, \) input–output guide width \( = 2 \). Figure 10(a) shows the pump and Fig. 10(b) shows the signal. (The offset \( d \) was applied to the left-hand output guide, rather than the right-hand guide as indicated in Fig. 9.) The intensity is shown, on a linear gray scale from white for zero to black for maximum. This design was produced in 4 h. The throughput of the signal was 95\%, with 1\% cross talk of pump light into signal output. MMI length and signal output guide offset were optimized. Several MMI widths and input–output guide angles were tried.

Note that a more generalized side-ported MMI-based SCWP device could be used to optically amplify a signal. Mutually incoherent pump light could be introduced (and removed) via multiple narrow side ports, positioned near the top and bottom, and at intermediate self-images of the signal (on the side laterally opposite the self-image, where the signal intensity is nearly zero). Distributing the pump sources along the length of the MMI region allows greater signal amplification for a given pump power.

A wide range of MMI variations have been proposed, such as modifying the shape of the MMI region,\(^{23–25}\) layering the MMI region to make it anisotropic,\(^{33}\) and putting slots in the MMI region.\(^{26–30}\) Side porting is, in general, compatible with other MMI variations. Figures 11 and 12 illustrate an example of this compatibility. Figure 11(a) shows a schematic top view (not to scale) of an end-ported slotted MMI-based switch. In the slot-off condition, the light exits the MMI region on the opposite lateral side from the input (i.e., the upper left output in the figure). In the slot-on condition, the self-image length is halved, so the light exits the MMI region on the same lateral side as the input (i.e., the upper right output in the figure). There are three weaknesses to this design. First (as previously pointed out), the outputs must be subsequently separated by S bends (which are not shown). Second, the slot width is constrained by the presence of the input–output guides along the ends of the MMI region. Making the slot too wide, so that it overlaps with the input–output ports,
lessens the throughput and increases the cross talk, both of which are undesirable. Third, the ideal device length is slightly different for the slot-on and slot-off conditions. The length must be set to a compromise, which compromises the performance. Figure 11(b) shows a schematic top view (not to scale) of a side-ported version of a slotted MMI-based switch, which corrects all three of these weaknesses. The inputs and outputs are angled, so signal separation can be achieved without S bends. The ports are out of the way of the slot, eliminating one design constraint. One output port can be offset in the longitudinal direction relative to the other, eliminating another design constraint.

Figure 12 shows top views of the calculated EM field evolution through a side-ported slotted MMI-based switch with $n = 1.5$ (including the slot), air boundaries, $\lambda = 1.5$, MMI width = 16.1, slot width = 0.3, $d = 8.7$, and input–output guide width = 2. The slot-off condition is shown in Fig. 12(a) and the slot-on condition is shown in Fig. 12(b). The intensity is shown, on a linear gray scale from white for zero to black for maximum. This design was produced in 4 h. The off case gave 95.5% throughput, and the on case gave 95.0% throughput, with $<0.1\%$ cross talk. Length, slot index, and output guide offset were optimized.

4. Conclusion

Side-ported MMI devices outperform conventional end-ported MMI devices, yet are actually easier to design since they require no (or fewer) S bends. MMI devices are already easier to fabricate than some competing IO devices (e.g., Y-branch splitters), because they are more tolerant of the rounding off of sharp corners. Side porting increases this advantage by increasing the initial separation of outputs. Side porting is not restrictive; it can be combined with the many types of novel MMI devices that have been proposed. Last, by introducing additional design freedoms, side porting increases the effectiveness of MMI devices and allows novel MMI devices.

References

7. L. J. Harrison, T. J. Tayag, G. J. Simons, M. Stead, G. W. Euliss, and R. P. Leavitt, “Monolithic integration of 1.3-mm Stark-ladder electroabsorption waveguide modulators with...