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Branching, radiative and self-imaging elements for use in MxN couplers

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Abstract. *1xN, NxN and MxN couplers can be made by cascading 3-dB splitters or couplers or by using a radiative or a multi-mode-interference element for coupling the input to the output waveguides. A review of the three approaches is given in terms of performance.*

Introduction.

NxN and 1xN couplers are important components in optical communication networks. MxN couplers are used in wavelength (de)multiplexers based on optical phased arrays. The coupling function can be realized in (at least) three different ways:

- by cascading a number of 1x2 branching elements (Y-junctions or 3-dB couplers),
- by coupling the radiation field of the input guides to a series of output guides,
- by using the image multiplicating properties of multi-mode waveguides.

The performance of the couplers is usually expressed in terms of the following parameters: ***excess loss*** (loss in excess of the 1/N splitting loss), ***unbalance*** or ***non-uniformity*** (the maximum deviation from a uniform power distribution), and the ***fabrication tolerance*** for these parameters. Other relevant properties are polarization insensitivity, bandwidth and dimensions.

Branching elements.

The simplest branching element is a Y-junction. Y-junctions were the subject of many theoretical investigations and are most easily analyzed using a beam-propagation method [1]. Simulations indicate that if the branching angle is chosen sufficiently small for the coupler to be adiabatic transmission losses are negligible. Y-junctions have the advantage of a large bandwidth and a potentially good symmetry (low unbalance) if the photolithography is well controlled.

Two factors may degrade the performance of practical junctions. The presence of odd (guided or radiation) modes at the input of the junction will disturb the splitting uniformity. Such modes can be excited in the S-bends connecting cascaded Y-junctions which have, therefore, to be carefully designed [2]. Another problem rises from the fact that the gap between the two branches will be closed abruptly where it becomes smaller than the resolution of the lithographic process. At this discontinuity power of the fundamental mode will couple to (symmetric) higher order modes and be lost as radiation. The coupling loss is dependent on the filling ratio, i.e. the ratio between the minimal gap-width and the waveguide width. For single-mode Y-branches with a V-parameter value $V \approx 3$ the predicted loss for a filling ratio of 20% is in the order of 0.1 dB, with a quadratic dependence on the filling ratio. For low-contrast waveguides with waveguide widths in excess of 5 μm and a resolution better than 1 μm predicted losses are thus small.

Lowest excess loss was reported by Adar et al. [3] and Kobayashi et al. [4]: 0.4 dB excess loss per Y-junction for a junction length (including access waveguides) of 3 mm [3]. Reported non-uniformity for a 1x8 coupler with 3 junctions in series in each path is better than ± 0.3 dB over a wavelength range of 400 nm [4].

An alternative to the Y-junction is a 3-dB directional coupler. The main obstacles in applying such a coupler as a power splitter are the small bandwidth of synchronous couplers and the (related) problems involved in controlling the coupling ratio without active tuning circuit. Shani et al. [5] solved this problem by applying an adiabatically tapered directional coupler which is asymmetric at the input and symmetric at the output. The device showed 0.1-0.2 dB excess loss relative to a straight waveguide and a strongly flattened wavelength dependence (unbalance within 1 dB from 1.2 to 1.7 µm, 0.3 dB at 1.53 µm). The improved excess loss was paid for with a larger device length: 13 mm. Yanagawa et al. [6] demonstrated an 8x8 coupling matrix with a flattened wavelength response using alternating $\Delta\beta$ couplers; excess loss reported was not optimal, however.

Radiative elements

A direct MxN coupler can be realized by placing N output waveguides in the radiation field of M input waveguides, as depicted in figure 1. This principle was proposed by Dragone [7] and first applied in a star coupler by Dragone [8] and in a polarization splitter by Vellekoop and Smit [9]. Simulations indicate that coupling from the far-field into the array waveguides can be quite efficient (losses in the order of 0.1 dB) if the output waveguides are closely spaced, which requires a high lithographic resolution, however, and may be undesirable from a coupling point-of-view.

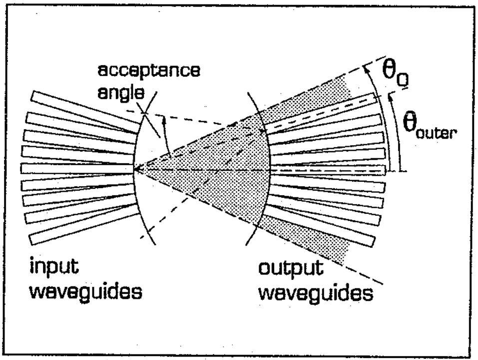

Figure 1 Star coupler and beam geometry

In its simplest form the design of such a coupler is straightforward. For waveguides with a V-parameter between 2 and 5 the fundamental mode profile $U_0(x)$ shows a good fit to a Gaussian distribution: $U_0(x) \approx exp\,(-x^2/w_0^2)$ in which w_0 is approximately 80% of the effective mode width: $w_0 = (2/\pi)^{1/2} w_e$ with $w_e = \int U_0^2(x)\,dx \,/\, U_0^2(0)$. The corresponding far field will be Gaussian too: $U(\theta) \approx exp\,[-sin^2(\theta)/sin^2(\theta_0)]$, with $sin\,(\theta_0) = \lambda_0\,/(N\pi w_0)$, and N being the effective index of the slab region. The modes of the output waveguides will be excited with amplitudes which are proportional to the local far field amplitude, so the relative intensities in the output channels follow directly from the far field intensity distribution.

From this simple consideration it follows that there will be a trade-off between the inter-channel uniformity and the excess loss of the coupler: the outer channels with relative intensity $I(\theta_{outer}) = exp\,[-2sin^2(\theta_{outer})/sin^2(\theta_0)]$ are limiting the splitting uniformity. For a good uniformity the ratio θ_{outer}/θ_0 should be chosen small, this will cause a large fraction of the radiation field to be missed by the output array. The corresponding loss can be estimated by integrating the spillover. A more detailed analysis is given by Smit [10].

Zirngibl et al. [11] combined a uniformity of ± 1.3 dB for TE and ± 2 dB for TM-polarization with an excess loss below 3 dB for a 1x16 splitter on InP by compensating the reduction of the intensity towards the outer sides of the array by an increase in the receiver waveguide width, as depicted in figure 2. A similar device on silicon was reported by Day et al. [12]. This approach is an elegant solution for 1xN splitters, it is less suited to MxN couplers, however, because the acceptance angle of the wide waveguides will be narrow, so that they will accept less radiation from input waveguides off their optical axis (see figure 1).

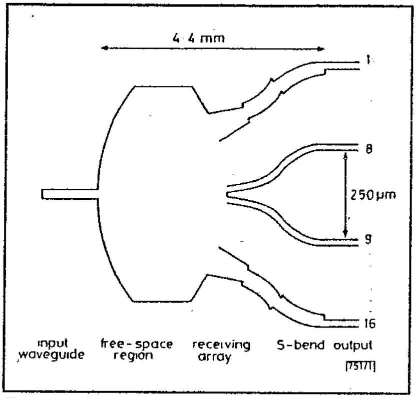

Figure 2 Radiation coupler with improved uniformity by adapting the receiver aperture (from Zirngibl et al. [11] © Electronics Letters)

Another approach to increase the uniformity is by modifying the input waveguides such that their far field approaches a rectangular intensity distribution. The far field being the Fourier transform of the near field, this requires a sinc-shaped field distribution at the input aperture. Such a distribution can be obtained by controlling the coupling to adjacent input waveguides such that the transferred power approaches the sidelobe intensity of a sinc function. If the same approach is applied to the output waveguides the angular acceptance distribution of the output waveguides (which equals their far field distribution) will become rectangular too, so that a (more) uniform transfer may be obtained for all channels of a MxN coupler. This approached was proposed by Dragone [13,14] and applied in a 7x7 demultiplexer on silicon containing two 7x15 star couplers (Dragone et al. [15], 1.2 dB non-uniformity, excess loss better than 1 dB per star coupler for the central channel). Okamoto et al. [16] realized an 8x8 star coupler on silicon with less than 1.7 dB excess loss and a standard deviation less than 0.44 dB for both 1.3 and 1.55 μm wavelength. The reported performance was obtained by tapering the waveguides in the coupling region and optimizing the taper ratio and the taper length with a BPM.

Radiative elements thus provide a compact alternative to Y-branch couplers, and seem to perform better for application with narrow waveguides (InGaAsP/InP). Advanced applications include integration in a 1x16 photonic switch [17] and with a DFB-laser array and optical amplifiers for distribution of 18 wavelengths over 19 output channels [18].

Self-imaging elements

The self-imaging and image-multiplicating properties of multi-mode waveguide sections were predicted by Bryngdahl [19] and analysed in detail by Ulrich and Ankele [20]. They have been applied for the fabrication of 4x4 hybrids with phase quadrature outputs for application in coherent optical receivers [21,22]. Recent research of Soldano et al. [23-25], Pennings et al. [26,27] and Heaton and Jenkins et al. [28,29] demonstrated the superior performance and fabrication tolerance of couplers based on this principle and have led to a rapidly increasing interest in this component.

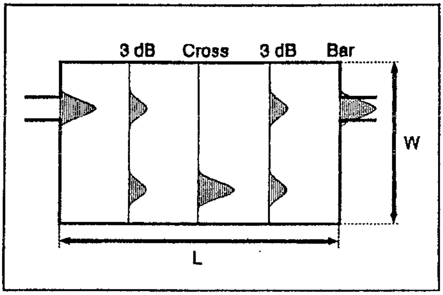

Figure 3 Bar, cross, and 3-dB states in a multi-mode waveguide section.

The self-imaging properties of rectangular multi-mode waveguide sections can be understood as follows. An arbitrary field applied at the input of the section, as shown in figure 3, will be decomposed into the modes of the waveguide. If these modes are well confined their mode profiles will be cosine shaped with $m+1$ half-periods within the multimode section (m being the mode order), so that their transverse propagation constants k_{xm} follow as $k_{xm} = (m+1)\pi/W$ in which W is the section width[1]. The propagation constants β_m of the modes follow from k_{xm} and the effective slab index N in the waveguide section as $\beta_m = (N^2 k_0^2 - k_{xm}^2)^{½}$, they can be approximated as $\beta_m \approx N k_0 [1 - (m+1)^2 \lambda_0^2 / 8NW^2]$ if $W \gg \lambda$. For the phase difference Ψ_m between the m-th mode and the fundamental mode after propagating through a section with length $L = 8NW^2/\lambda_0$ we find: $\Psi_m = (\beta_0 - \beta_m)L \approx F_m 2\pi$ with $F_m = m^2+2m$. From this relation it is seen that after a length L all modes have the same relative phases as at the input of the multi-mode section (except for an integer multiple of 2π), so that the input field distribution will be reconstructed: at $z=L$ the waveguide shows a bar state. The phase differences Ψ_m are not very sensitive to variations in the slab index N because the corresponding changes in the propagation constants of the different modes have approximately the same magnitude. MMI-couplers are, therefore, tolerant to variations in the film-thickness and the lateral index contrast (etch depth), and to changes in the polarization. The most critical parameter is the MMI-section width, which enters in the expression for β_m via k_{xm}, it should be controlled within a few tenths of a micron in order to obtain a good performance.

In addition to the ***self image*** (or ***bar state***) ***at*** $z=L$ there appear to exist single and multiple images at a manifold of locations, as can be seen from inspection of the factor F_m: $F_m = 0,3,8,15,24,35, ...$ for $m = 0,1,2,3,4,5, ...$ From this series it follows that at $z=½L$ the even modes have $\Psi_m = 0$ and the odd modes have $\Psi_m = \pi$ from which it follows that the original distribution will be mirrored around the waveguide axis: at $z=½L$ the waveguide thus shows a ***mirrored image*** or ***cross state***. From the symmetry properties of the excited modes it follows [20,10] that at $z=¼L$ (and $z=¾L$) a linear combination of the direct and the mirrored image with 90° phase difference exists, so at $z=¼L$ the waveguide section acts as a ***3-dB coupler*** when waveguides are connected symmetrically to it at both ends. More generally we find that at a length ***L/2n*** an ***n-fold image*** is found. Niemeier and Ulrich [21] showed that by properly connecting 2 input waveguides to a $L/8$-section a 2x4 coupler with quadrature outputs is obtained. The basic mechanism of these couplers being the interference of many modes they are called Multi-Mode Interference (MMI-) couplers, analogous to the Two-Mode Interference couplers.

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[1] For a more accurate analysis the effective width should be taken.

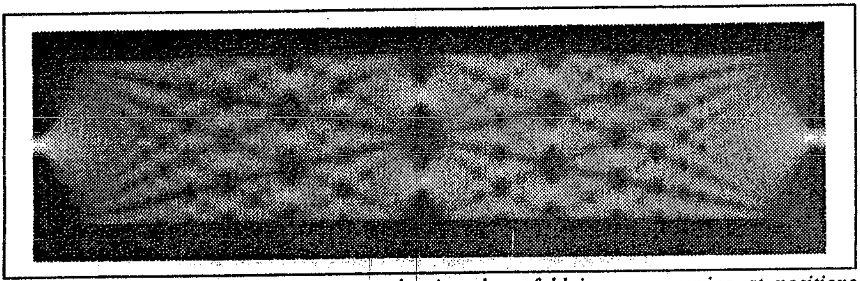

Figure 4 Simulated intensity pattern showing the n-fold images occuring at positions L/8n. (Heaton et al. [29] © British Crown Copyright DRA 1992).

A special case of great interest is symmetrical excitation at the center of the the MMI-section, so that only even modes are excited. It is seen that for the even modes the F_m are multiples of 8, so that self images occur periodically at distances *L/8*. Heaton at al. [29] demonstrated ***n-fold images*** occuring at distances ***L/8n***. They realised 1xN-power splitters in AlGaAs with N varying from 2 to 20 with a length of Nx30 μm, a splitting uniformity better than ± 4% and insertion loss lower than that of the (narrow) straight reference waveguides which were included in the experimental design. Figure 4 shows a picture of the (simulated) intensity distribution which clearly demonstrates the mechanism of this type of coupler.

The above consideration suggests that the shorter we make the waveguide section, the more images it produces. This is not true: for an *n*-fold image to fit in the MMI-section its width has to be at least *n* times the width of the input waveguide. Because *L* is proportional to W^2 the coupler length $\frac{1}{2}L/n$ will be proportional to *n*.

An important advantage of MMI-couplers is that they are polarization-insensitive; the phase-differences Ψ_m are determined by the difference in propagation constant between the modes, this difference turns out to be rather polarization insensitive for many waveguide structures. Pennings [26] realized a 750 μm long (including S-bends) polarization insensitive 3-dB coupler on InP with insertion loss and unbalance better than 0.5 and 0.1 dB respectively, and an extremely compact (300x1750 μm^2) polarization insensitive 4x4 phase quadrature hybrid [27] with less than 1 dB insertion loss, 0.3 dB unbalance and a maximal phase deviation of 3^o, which demonstrates the potential of this type of element.

Even shorter couplers can be made if a special arrangement of the input waveguides is chosen. Inspection of the factor F_m reveals that it is a multiple of 3 except for the modes with *m=2,5,8, ...* For the other modes it is seen that, after division by 3, F_m remains even for the even modes and odd for the odd modes. If modes 2,5,8, .. are not excited cross and 3-dB-states will thus occur at L/6 and L/12, respectively, in the same way as they occur at L/2 and L/4. For a 3-dB coupler such an excitation is easily obtained by positioning the input channels at (approximately) 1/3 and 2/3 of the waveguide width: around these positions modes 2,5,8, ... show odd symmetry so that they will not be excited by an input field which has even symmetry around this point. Advantages of this type of coupler are its (3x) shorter length and the corresponding three-fold reduction of phase errors due to fabrication errors in the MMI-section width or wavelength deviations, which substantially increases the fabrication tolerance and the bandwidth of the component. Disadvantageous is the increased sensitivity for the positioning of the input channels, which is not very critical, however. Soldano et al. [23] realized polarization insensitive 3-dB couplers on silicon with 155 μm MMI-section length which showed less than 0.5 dB insertion loss and 0.1 dB unbalance. The 1-dB optical bandwidth of this type of coupler was shown to be in the order of 100 nm [31], which is sufficient for many applications.

Recent application of MMI-couplers in polarization insensitive switches [32,33] and a monolithically integrated optical receiver [34] illustrate the potential of this promising component.

Conclusions

Best MxN couplers reported based on Y-junction trees and radiative couplers have comparable performance. Radiative couplers are more compact, however, and are better suited for use in wavelength demultiplexers and wavelength switches. Both have a potentially large bandwidth. Multi-Mode Interference couplers perform better than radiative couplers with respect to splitting uniformity and insertion loss, and have the advantage of simple design and reduced requirements on photolithographic resolution.

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