Three-Core Weakly-Guiding Mode-Selective Fibre Couplers

Nicolas Riesen and John D. Love
Physics Education Centre
The Australian National University, Canberra ACT 0200, Australia

Abstract Summary

The coupling behaviour of two-core mode-selective couplers (MSC) depends on the spatial-orientation of the asymmetric higher-order modes. This restricts their use for mode de-multiplexing in few-mode fibre networks. The use of three-core MSC's is presented as a solution.

Keywords- few-mode fibres; mode-selective couplers; mode-splitting; spatial-mode-division-multiplexing.

I. Introduction

The ever-increasing demand for high-bandwidth optical fibre communications is destined to challenge the limits of single-mode fibre. This has led to a renewed interest in the use of few-mode fibre to exploit the extra degrees of freedom provided by several propagating modes. Few-mode fibre avoids the severe modal crosstalk experienced in highly-multimode fibre, thus allowing for each mode to be considered an independent data channel. The independent excitation and detection of the modes however presents major challenges. Currently there are no *simple techniques* available for multiplexing and de-multiplexing more than two orthogonal spatial modes. The multiplexing/de-multiplexing of two (and possibly more) modes could however in principle be achieved using *simple waveguide structures* such as mode-selective couplers (MSC) [1–3], asymmetric Y-junctions [4–6] or multimode interference devices (MMI) [7]. The use of asymmetric Y-junctions has recently been delineated [8]. Asymmetric Y-junctions allow for mode-division-multiplexing of elliptical and highly-birefringent fibre. As for multimode interference devices, they are typically limited to merely separating (or combining) the asymmetric from the symmetric planar modes [7].

This paper is concerned with the use of mode-selective couplers. More specifically, a novel multiplexing/de-multiplexing technique is presented that uses simple three-core mode-selective fibre couplers (MSC's). Mode-selective fibre couplers involve a higher-order mode in one fibre coupling to the fundamental modes of one or more other fibres, and vice versa. This situation differs from a traditional fibre coupler in which the mode-order remains unchanged. Mode-selective couplers rely on the matching of the modal propagation constants (e.g. using non-identical fibres). However if the higher-order mode is asymmetric (i.e. non-axisymmetric or having non-zero azimuthal number), the coupling behaviour also depends on the spatial-orientation of its electric field. This poses somewhat of an issue if MSC's are to be used in fibre mode de-multiplexers. This is because the spatial-orientations of the asymmetric modes are inherently unstable in any sizeable length of circularly-symmetric fibre. In the case of a two-core MSC the power transfer can range anywhere from *0* to *100%* depending on the spatial-orientation [2–3].

This paper however demonstrates that certain configurations of *three-core MSC's* can have 100% power transfer regardless of the spatial-orientation of the higher-order mode. This implies that three-core fibre MSC's can be used for mode-division-multiplexing of circularly-symmetric fibre. This is an obvious advantage over planar devices (i.e. asymmetric Y-junctions or multimode interference devices) which can only de-multiplex modes of fixed spatial-orientation (e.g. the modes of highly-birefringent or elliptical-core fibre). The main drawback of mode-selective couplers are their inherent wavelength dependence.

II. Coupled-Mode Theory

This section provides an analysis of three-core mode-selective fibre couplers, highlighting their ability to de-multiplex modes of arbitrary spatial-orientation. The general three-core mode-selective fibre coupler used in the analysis is shown in Fig. 1. The fibre cores are assumed to be both circularly-symmetric and weakly-guiding.

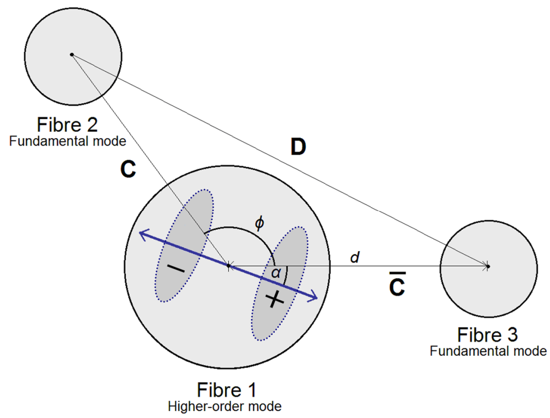

Figure 1. Three-core mode-selective fibre coupler (with LP_{11} shown in fibre 1)

N. Riesen is the recipient of both ANU, Canberra and CSIRO, Lindfield research scholarships.

A higher-order linearly-polarized mode (LP_{lm}) in core 1 is assumed to have the same propagation constant β, as the fundamental modes of two identical outer cores 2 and 3. Furthermore, the electric field of the higher-order mode in core 1 is assumed to have a cosine azimuthal dependence. This means that for the LP_{11} mode, for instance, the line defined by the angle α is perpendicular to the zero line of the anti-symmetric mode's field. So in other words if $\alpha = 0$ the lobes of the LP_{11} mode, for instance, are bisected by a horizontal line.

Referring to Fig. 1, the angle between cores 2 and 3 relative to core 1 is given by ϕ. The coupling coefficients between cores 1 and 2, and cores 1 and 3 are given by C and $\overline{C}$, respectively. The coupling coefficient between cores 2 and 3 is given by D. It is assumed that $D \ll C \cup \overline{C}$ and to a first order approximation D = 0. The assumption is accurate for sufficiently large values of ϕ. Note that even if $D \neq 0$, the coupled-mode equations could still be solved analytically. The assumption of D = 0 is however necessary to ensure a truly α-independent MSC (i.e. 100 % power decoupled irrespective of the spatial-orientation, α). In the case of finite values of D, coupling between the outer cores will occur at length scales of π/D. This length scale should be much larger than the coupler length scale π/C_R.

In this paper it is also assumed that the mode-selective coupler is weakly-coupled (i.e. coupling length per unit length is small) such that, $|C| \ll |\beta|$ and $|\overline{C}| \ll |\beta|$. This means that the distance d, between core 1 and either of the outer cores is assumed to be sufficiently large such that there is a small overlap of the modal fields. In this case the fields of the fibre modes can be considered in isolation [2], [9]. The fields of the modes are also assumed to be orthonormal.

Now, the z-dependences of each mode of the three fibre cores can be expressed as [9],

$$a_i(z) = b_i(z)e^{j\beta z} \quad i = 1,2,3. \tag{1}$$

where the amplitudes b_1, b_2 and b_3 satisfy the following coupled-mode equations,

$$\frac{db_1}{dz} = jCb_2 + j\overline{C}b_3; \quad \frac{db_2}{dz} = jCb_1; \quad \frac{db_3}{dz} = j\overline{C}b_1. \tag{2}$$

Note that only the forward-mode equations are considered, which are assumed to be decoupled from the backward-mode equations. This is a valid assumption for weakly-coupled MSC's that are also phase-matched (i.e. $\beta_1 = \beta_2 = \beta_3 = \beta$). Assuming core 1 initially contains all the power (i.e. $b_1(0) = 1$ and $b_2(0) = b_3(0) = 0$), the modal powers along the three cores are solved analytically,

$$P_1(z) = |b_1(z)|^2 = \cos^2(\Omega z) \tag{3}$$

$$P_2(z) = |b_2(z)|^2 = \frac{C^2}{\Omega^2}\sin^2(\Omega z) \tag{4}$$

$$P_3(z) = |b_3(z)|^2 = \frac{\overline{C}^2}{\Omega^2}\sin^2(\Omega z) \tag{5}$$

where $P_1(z)+P_2(z)+P_3(z) = 1$, and $\Omega^2 = C^2+\overline{C}^2$. If C_R denotes the radial dependence of the coupling coefficients then [2],

$$C = -C_R\cos(l(\alpha-\phi)) \qquad \overline{C} = -C_R\cos(l\alpha) \tag{6}$$

where l is the azimuthal number of the higher-order mode. Note that since the coupler is assumed to be phase-matched, the coupling behaviour is also reciprocal. From (6),

$$\Omega = C_R\sqrt{\cos^2(l(\alpha-\phi)) + \cos^2(l\alpha)}. \tag{7}$$

This implies that when the outer cores are at angle $\phi = \pi/2l + n\pi/l$, with $n = 0,1,2,3,...$, we have that $\Omega = C_R$. Therefore the power in each core is given by,

$$P_1(z) = \cos^2(C_R z) \tag{8}$$

$$P_2(z) = \sin^2(l\alpha)\sin^2(C_R z) \tag{9}$$

$$P_3(z) = \cos^2(l\alpha)\sin^2(C_R z). \tag{10}$$

The power decoupled from core 1 to the outer cores is therefore,

$$P_T = P_2(z) + P_3(z) = \sin^2(C_R z) \tag{11}$$

where the coupling length is given by $z_c = \pi/2C_R$. Therefore all the power of a higher-order mode can be decoupled regardless of the azimuthal orientation of its field α, when using a three-core MSC with outer cores at angle $\phi = \pi(n+1/2)/l$. In the special case where $l = 0$, $\Omega = \sqrt{2}C_R$ but C_R becomes $C_R/\sqrt{2}$ so $P_{2,3}(z) = \sin^2(C_R z)/2$. In the case of $l = 0$ only a two-core MSC is of course needed for total power transfer, although a three-core structure could be used to reduce the coupling length.

The radial dependence of the coupling coefficient (i.e. for coupling between core 1 and core 2, 3) depends on the fibre and source parameters and was previously derived [2],

$$C_R = (-1)^l \frac{2\sqrt{2}k\rho_2\Delta_2 u_1 u_2 n_{co,2}^{3/2}}{\rho_1 v_1 v_2^3 n_{co,1}^{1/2}} \frac{K_l(w_1 d/\rho_1)}{K_1(w_1)\sqrt{K_{l-1}(w_2)K_{l+1}(w_2)}} \tag{12}$$

where, k is the wave-number, ρ_i is the core radius, Δ_i is the relative index difference, u_i and w_i are the core and cladding modal indices, $n_{co,i}$ is the core index, K is the modified Bessel function of the second kind, d is the spacing between the axes of cores 1 and 2 (or 1 and 3), and v_i is the normalized frequency. As before, subscripts denote the higher-order mode fibre (i = 1) or one of the two outer cores (i = 2). The coupling coefficient (12) assumes weak-coupling and weak-guidance. Note that in the case where $l = 0$, C_R becomes $C_R/\sqrt{2}$.

III. Numerical Simulations

The following numerical Beam Propagation Method (BPM) simulations confirm the predicted α-independent behaviour of the three-core fibre MSC's. The parameters common to both simulations are: $n_{co,1,2} = 1.4446$, $\Delta_{1,2} = 6.85\times10^{-3}$ and $\lambda = 2\pi/k$ = 1550 nm. The simulations shown in Fig. 2, demonstrate the α-independent decoupling of an LP_{11} mode when using a three-core MSC with two outer cores that have an angular offset ϕ = $\pi/2$ with l = 1 and n = 0. Here, ρ_1 = 4.338 μm, ρ_2 = 2 μm and the coupler length is $z_c \approx 3.0$ mm. Note also that the power in the two outer cores could be combined in practice in order to avoid a power penalty.

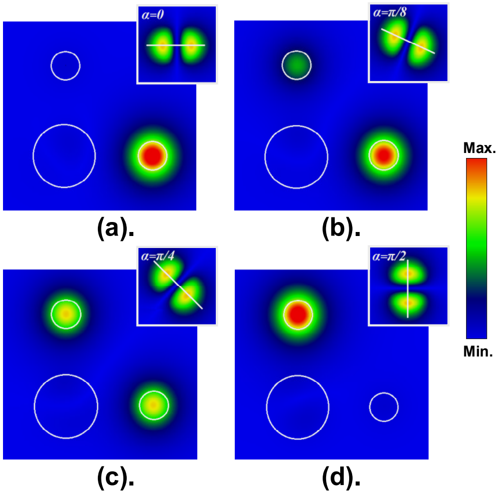

Figure 2. The decoupling of an LP_{11} mode (i.e. see insets) from a two-mode core to two outer cores which have an angular offset $\phi = \pi/2$. The total decoupled power is independent of the mode's spatial-orientation α, as demonstrated for (a) $\alpha = 0$, (b) $\alpha = \pi/8$, (c) $\alpha = \pi/4$ and (d) $\alpha = \pi/2$.

The simulations of Fig. 3 also demonstrate the α-independent behaviour of three-core MSC's for the case of the LP_{21} mode. In this example $\phi = 3\pi/4$ with $l = 2$ and $n = 1$. The parameters for this simulation are $\rho_1 = 6.48$ μm, $\rho_2 = 1.992$ μm and the coupler length is $z_c \approx 4.1$ mm.

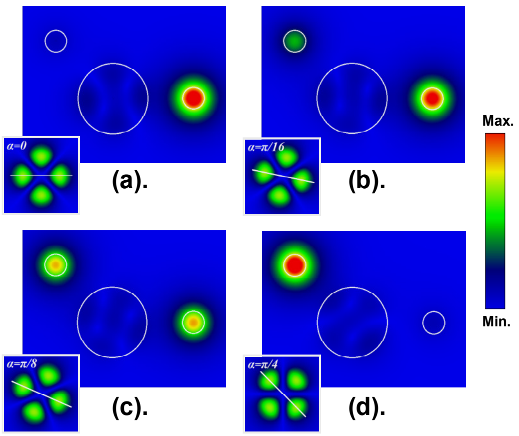

Figure 3. The decoupling of an LP_{21} mode (i.e. see insets) from a four-mode core to two outer cores which have an angular offset $\phi = 3\pi/4$. The total decoupled power is again independent of the mode's spatial-orientation α, as demonstrated for (a) $\alpha = 0$, (b) $\alpha = \pi/16$, (c) $\alpha = \pi/8$ and (d) $\alpha = \pi/4$.

IV. MSC Multiplexers/De-multiplexers for Few-Mode Fibre Networks

This paper has shown that three-core mode-selective fibre couplers allow for the de-multiplexing of any given asymmetric spatial-mode (i.e. $l > 0$) regardless of its spatial-orientation. As suggested, two-core mode-selective couplers are nonetheless sufficient for de-multiplexing the symmetric spatial-modes (i.e. $l = 0$). Therefore a linear sequence of two- and three-core couplers constituting the *de-multiplexer*, could allow for the separation of all modes at the end of a few-mode fibre. A linear sequence of two-core mode-selective couplers would be sufficient for the *multiplexer*, since the spatial-orientation of the modes excited at the start of the fibre is irrelevant.

V. Conclusion

In summary this paper has presented and numerically verified, theory describing the behaviour of three-core mode-selective fibre couplers. The paper has shown that these simple devices could be used for de-multiplexing all the power of any given fibre mode, regardless of its spatial-orientation. A series of inline two- and three-core MSC's could therefore be used as the mode demultiplexer of a few-mode fibre network, whereas a series of inline two-core MSC's could be used as the multiplexer. Difficulties are expected to arise when multiplexing/de-multiplexing modes with closely-spaced propagation constants. This problem can be avoided by limiting the number of modes guided by the fibre, so as to avoid a 'continuum' of propagation constants. The wavelength dependence also limits the level of wavelength division multiplexing (WDM) possible when using mode-selective couplers.

Major practical challenges concerning MSC's include their fabrication as well as minimizing their dependences on external variables [1], [10]. The principles presented in this paper also apply to other waveguide structures, such as buried-channel waveguides and possibly also microstructured optical fibres.

Acknowledgment

The authors would like to thank John W. Arkwright and Jong H. Chow for useful suggestions and discussion.

References

[1] K. Y. Song, I. K. Hwang, S. H. Yun, and B. Y. Kim, “High performance fused-type mode-selective coupler using elliptical core two-mode fiber at 1550 nm,” IEEE Photonic. Tech. L., vol. 14, pp. 501–503, April 2002.

[2] N. Riesen and J. D. Love, “Weakly-guiding mode-selective fiber couplers,” IEEE J. Quant. Electron., vol. 48, pp. 941-945, July 2012.

[3] J. D. Love and N. Riesen, “Mode-selective couplers for few-mode optical fiber networks,” unpublished.

[4] J. D. Love and N. Riesen, “Single-, few-, and multimode Y-junctions,” J. Lightw. Technol., vol. 30, pp. 304–309, February 2012.

[5] N. Riesen and J. D. Love, “Design of mode-sorting asymmetric Y-junctions,” Appl. Optics, vol. 51, pp. 2778–2783, May 2012.

[6] J. D. Love, R. W. C. Vance, and A. Joblin, “Asymmetric, adiabatic multipronged planar splitters,” Opt. Quant. Electron., vol. 28, pp. 353–369, July 1996.

[7] J. Leuthold, R. Hess, J. Eckner, P. A. Besse, and H. Melchior, “Spatial mode filters realized with multimode interference couplers,” Opt. Lett., vol. 21, pp. 836-838, June 1996.

[8] N. Riesen, J. D. Love, and J. W. Arkwright, “Few-mode elliptical-core fiber data transmission,” IEEE Photon. Technol. Lett., vol. 24, pp. 344-346, March 2012.

[9] A. W. Snyder and J. D. Love, Optical Waveguide Theory, London, U.K.: Chapman & Hall, 1983, pp. 542–546.

[10] K. Y. Song and B. Y. Kim, “Broad-band LP02 mode excitation using a fused-type mode-selective coupler,” IEEE Photon. Technol. Lett., vol. 15, pp. 1734–1736, December 2003.