Mode-selective couplers for few-mode optical fiber networks

John D. Love and Nicolas Riesen*

Research School of Physics and Engineering, The Australian National University, Canberra, ACT 0200, Australia
**Corresponding author: nicolas.riesen@anu.edu.au*

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The excitation and separation of individual modes in a few-mode optical fiber network can be realized using mode-selective couplers. For excitation at the beginning of the fiber, two-core mode-selective couplers can be used, while at the end of the fiber, either two- or three-core mode-selective couplers are required for demultiplexing of the field symmetric or field asymmetric modes, respectively. Both analytical and numerical solutions are presented to quantify the mode-selective functionality. © 2012 Optical Society of America

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Currently there is rapidly growing interest in the potential use of few-mode, weakly guiding fibers as a solution for meeting the ever-increasing demand for bandwidth in long-distance optical networks. Each mode of a few-mode fiber can be used as an independent data channel, so that an N-mode fiber would have approximately N times the bandwidth of a single-mode fiber. Unlike multimode optical fiber networks where all bound modes are excited and detected *simultaneously* and indiscriminately at the beginning and end of the system, a technological challenge for few-mode fiber networks is the excitation and detection of *individual* modes at either end. There are at least two potential approaches toward the solution of this problem using simple light-processing fiber or planar waveguide devices. One approach is based on asymmetric, mode-transforming, multipronged Y-junctions that can be used to multiplex highly birefringent or elliptical-core few-mode fibers [1]. A second approach is based on mode-selective couplers (MSCs), which can be used to demultiplex circular-core fiber. The basic theory and analysis of evanescent coupling between phase matched, nonidentical modes in two-core MSCs has already been delineated [2].

Two-core MSCs can in principle be used to excite any mode at the beginning of a few-mode fiber, simply by matching the propagation constant of an excited fundamental mode in one core of the coupler with the propagation constant of the fundamental or higher-order mode in the second core. Thus a linear/inline sequence of N two-core MSCs, as shown schematically in Fig. 1, enables independent excitation of N modes from N fundamental mode sources. The length of the coupling region in each coupler matches the coupling length for 100% power transfer between the two cores [2].

As each of the excited modes in the few-mode fiber propagates, the orientation of its field will be randomly rotated by the inevitable slight nonuniformities that are frozen into the fiber during fabrication. For axisymmetric LP_{0m} modes ($m = 1, 2, \ldots$), the fields are invariant under such rotations and a linear concatenation of the same two-core MSCs used to excite these modes can be used to separate the modes into discrete fundamental modes at the end of the fiber.

Accessing the power in the remaining asymmetric modes at the end of the few-mode fiber is a more challenging problem, due to the random orientation of the asymmetric modal fields [2]. Figure 2 shows the cross section of a fundamental mode LP_{01} to higher-order mode LP_{lm} two-core MSC. The field orientation of the higher-order mode makes angle α with the horizontal line linking the core axes [2]. The coupling coefficient between these two modes is proportional to the overlap integral of the two modal fields over one of the cores. This has been demonstrated to depend on $\cos(l\alpha)$ for the configuration shown, where l is the azimuthal number of the higher-order mode [2].

If $\alpha = \pi/2l$, the antisymmetry of the product of the fields about the horizontal axis gives a *zero coupling coefficient* that is independent of the separation d of the two core axes; i.e., none of the power in the higher-order mode can be coupled to the fundamental mode, generating errors in the output data stream.

To eliminate this null situation and to avoid the dependence of the coupling on angle α, a three-core MSC could be used with the cross section shown in Fig. 3. Core 1 supports a higher-order mode, while cores 2 and 3 support fundamental modes, such that all three modes have the same propagation constant. The coupling coefficients between cores 1 and 2, cores 1 and 3, and cores 2 and 3 are C, $\bar{C}$, and D, respectively. The orientation of the higher-order mode in core 1 makes angle α with the horizontal axis, and ϕ is the angle between the lines joining cores 1–2 and cores 1–3.

The interaction between the modes of each core due to coupling can be described by a set of three coupled-mode equations [3]. These are first-order linear differential equations and can be readily solved analytically or numerically. For present purposes, the coupling coefficient D between cores 2 and 3 can be assumed to be significantly smaller than either C or $\bar{C}$ and to a first-order approximation $D = 0$. For finite values of D, coupling between the outer cores 2 and 3 will occur over a length scale of π/D. Assuming a large ϕ, this length scale will be much larger than either coupling length scale π/C or

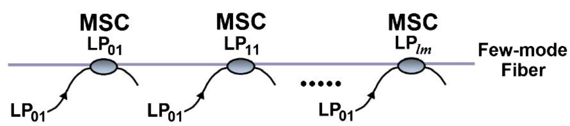

Fig. 1. (Color online) Linear sequence of MSCs.

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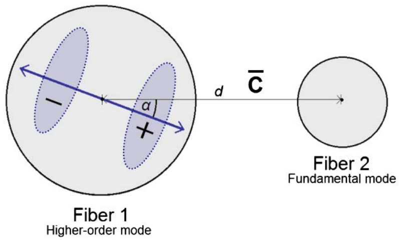

Fig. 2. (Color online) Two-core fiber MSC with LP_{11} field shown schematically in fiber 1.

$\pi/\bar{C}$, regardless of the value of α. The assumption of $D \ll \bar{C} \cup C$ is also necessary to ensure a truly α-independent MSC (i.e., 100% power transfer irrespective of α).

In this approximation, the axial z-dependences, $f_i(z)$, of each of the three modes (assumed to be orthonormal) can be expressed as [3]

$$f_i(z) = b_i(z)e^{j\beta z} \qquad i = 1, 2, 3, \tag{1}$$

where the z-dependent amplitudes b_1, b_2, and b_3 satisfy the forward coupled-mode equations,

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

These forward-mode equations are decoupled from the backwardmode equations because of the phase matching and the assumption of weak coupling (i.e., $|C|$, $|\bar{C}| \ll |\beta|$). Assuming that only core 1 is initially excited at $z = 0$, then $b_1(0) = 1$ and $b_2(0) = b_3(0) = 0$. Accordingly the modal powers propagating along the three cores are readily solved analytically to give

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

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

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

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

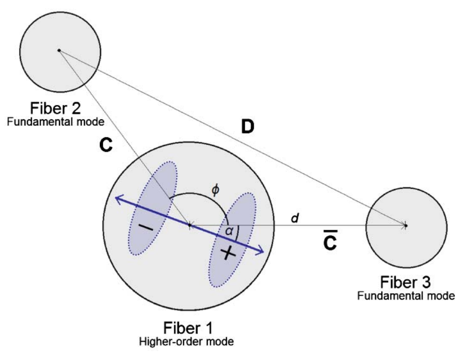

Fig. 3. (Color online) Three-core fiber MSC with LP_{11} field shown schematically in fiber 1.

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

where l is the azimuthal number of the linearly polarized LP_{lm} mode. Since the coupler is assumed to be phase matched, the coupling behavior is reciprocal. From Eq. (6),

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

This implies that when the centers of cores 2 and 3 are separated by angle $\phi = \pi/2l + n\pi/l$ for $n = 0, 1, 2, 3, \ldots$, then $\Omega = C_R$. For these angles, 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 2 and 3 is, therefore,

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

and 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 $\phi = \pi(n + 1/2)/l$. With careful choice of integer n, minimal coupling between the outer cores can be ensured. 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.

The radial dependence of the coupling coefficient (i.e., for coupling between core 1 and core 2 or 3) depends on the fiber and source parameters and is given by [2],

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

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, $n_{\mathrm{co},i}$ is the core index, K is the modified Bessel function of the second kind, d is the spacing between the centers of cores 1 and 2 (or 1 and 3), and v_i is the normalized frequency. Subscripts denote the higher-order mode fiber ($i = 1$) or one of the two outer cores ($i = 2$). The coupling coefficient Eq. (12) assumes weak guidance and weak coupling. Since weak coupling is assumed, the modal field of each core can be modeled in isolation.

The following numerical beam propagation method (BPM) simulations confirm the predicted α-independent behavior of the three-core fiber MSC. The parameters common to both simulations are $\rho_1 = 6.48$ μm,

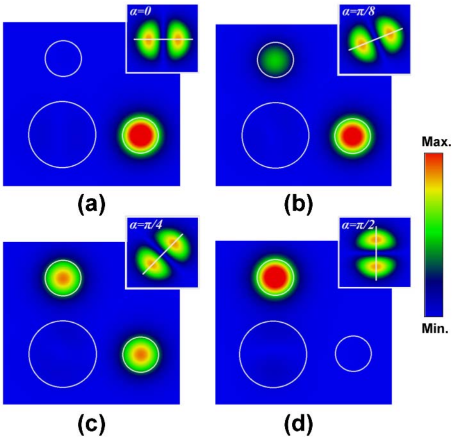

Fig. 4. (Color online) Decoupling of an LP_{11} mode (shown in insets) from a four-mode core, to two outer cores with angular offset $\phi = \pi/2l + n\pi/l$, where $l = 0$ and $n = 0$. The total decoupled power is independent of the mode's spatial orientation α, as demonstrated for (a) $\alpha = 0$, (b) $\alpha = \pi/8$, (c) $\alpha = \pi/4$, and (d) $\alpha = \pi/2$.

$n_{\mathrm{co},1,2} = 1.4546$, $\Delta_{1,2} = 6.85 \times 10^{-3}$, $d = 15$ μm, and $\lambda = 2\pi/k = 1550$ nm. The simulation of Fig. 4 demonstrates the α-independent decoupling of an LP_{11} mode ($n_{\mathrm{eff}} = 1.44987$, $\mathrm{MFD}_{\mathrm{eff}} = 13.5$ μm, and $A_{\mathrm{eff}} \approx 144$ μm^2 $= 1.47 A_{\mathrm{LP01}}$) when $\phi = \pi/2$. Here, $\rho_2 = 3.457$ μm and the coupler length is $z_c \approx 8.2$ mm. Note also that the power in the two outer cores could be combined in practice in order to avoid any power penalty (e.g., using single-mode fibers spliced to the outer cores, or using fabrication techniques that permit arbitrary routing of the outer cores). In addition, the simulation of Fig. 5 demonstrates the α-independent decoupling of an LP_{21} mode ($n_{\mathrm{eff}} = 1.44638$, $\mathrm{MFD}_{\mathrm{eff}} = 15.0$ μm, and $A_{\mathrm{eff}} \approx 176$ μm^2 $= 1.80 A_{\mathrm{LP01}}$) when $\phi = 3\pi/4$. The two MSCs simulated share the same few-mode core, as is the case in the proposed architecture of Fig. 1. The parameters used for the second simulation are $\rho_2 = 1.992$ μm and $z_c \approx 4.1$ mm.

The results presented here outline the potential role of MSCs for multiplexing/demultiplexing individual modes of few-mode fiber given a fixed source wavelength. If dense wavelength-division multiplexing (DWDM) is introduced into each of these modes, then the coupling to the outer core(s) should ideally be wavelength-independent. This facet could, for instance, be achieved through the design of special fiber-core profiles [4] that provide propagation constant matching across the DWDM wavelength range.

In terms of losses, conventional polished single-mode couplers can have losses well below 1%, and it is likely that similar performance could be achieved with two- or three-core MSCs. In fact early experimental demonstrations of two-core MSCs have achieved coupling ratios as high as 97% and losses as low as 5%, despite imperfect phase matching [5]. The mode extinction ratios achievable will depend on the spread in modal propagation constants and with judicious choice of coupling lengths, very high levels of mode isolation could be expected (i.e., in theory as low as ~ -60 dB with even better performance if $\phi \sim \pi$) [5]. In terms of fabrication, potential approaches include the *femtosecond direct write* technique [6], the *grinding and polishing* technique [5], and the *fused-taper* approach (involving the fused tapering of an appropriate bundle of carefully positioned cores) [7]. There is also potential for the fabrication of photonic-crystal three-core MSCs.

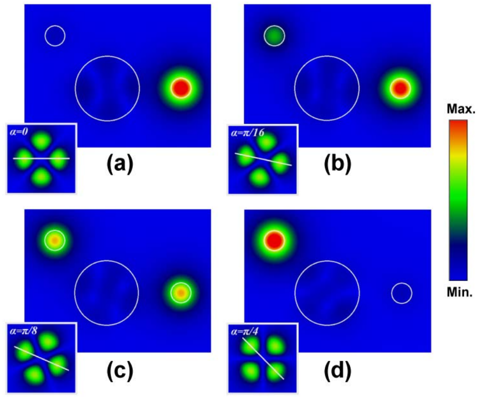

Fig. 5. (Color online) Decoupling of an LP_{21} mode (shown in insets) from a four-mode core, to two outer cores with angular offset $\phi = \pi/2l + n\pi/l$, where $l = 2$ and $n = 1$. The total decoupled power is again independent of the mode's spatial orientation α, as demonstrated for (a) $\alpha = 0$, (b) $\alpha = \pi/16$, (c) $\alpha = \pi/8$, and (d) $\alpha = \pi/4$.

The MSCs presented in this Letter are simple waveguide-based devices that are expected to have low insertion losses and minimal modal crosstalk. More complicated mode multiplexing approaches that are gaining interest include the use of *bulky* free-space optics where the mode selectivity is achieved using fixed phase plates or programmable liquid crystal on silicon (LCOS) panels [8]. Despite having lower wavelength dependence than that predicted for MSCs, these techniques often have very high insertion losses, modal crosstalk, and inherent complexity [8].

In summary, this Letter has proposed the use of two- and three-core MSCs for multiplexing/demultiplexing the modes of a few-mode fiber. Three-core MSCs are necessary for demultiplexing all the power from an asymmetric fiber mode with random spatial orientation of its transverse field. The principles presented in this Letter are also expected to apply to other waveguide structures, such as buried-channel waveguides and microstructured fiber.

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