Transverse light guides in microstructured optical fibers

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Received July 19, 2005; revised September 17, 2005; accepted September 26, 2005

A novel class of microstructured optical fiber coupler is introduced that operates by resonant, rather than proximity, energy transfer by means of transverse light guides built into a fiber cross section. Such a design permits significant spatial separation between interacting fibers, which, in turn, eliminates intercore cross talk owing to proximity coupling. A controllable energy transfer between the cores is then achieved by localized and highly directional transmission through a transverse light guide. The main advantage of this coupling scheme is its inherent scalability, as one can integrate additional fiber cores into the existing fiber cross section simply by placing the cores far enough from the existing optical circuitry to prevent proximity cross talk and then making the necessary intercore connections with transverse light wires, in direct analogy with on-chip electronics integration.

OCIS codes: 060.2340, 060.1810, 230.5750.

One of the major trends in the development of all-fiber devices is the increasing integration of functionalities in a single fiber. The goal is being able to fabricate in a single draw a complete all-fiber component a preform level. Some of the advantages of all-fiber devices are simplified packaging, absence of subcomponent splicing losses, and environmental stability owing to the absence of free-space optics. The major roadblock to the achievement of complex all-fiber devices is the unavoidable complexity of a required transverse refractive-index profile. From an experimental point of view, complex preform geometries such as in microstructured optical fibers[1] (MOFs) and multicomponent material combinations such as in Bragg fibers[2] result in major challenges for preform fabrication and drawing. Assuming that these technological issues can be resolved, there is still a conceptual difficulty in going to increasingly complex fiber profiles. In particular, many of the interesting functions that fiber devices offer, such as modal dispersion profile design, directional power transfer among several fiber cores,[3–7] and intermode conversion, rely on proximity interaction between modes localized in different spatial regions. The requirement for finite overlap of interacting modes typically forces multicore systems to be designed to operate on a principle of proximity interaction, in which different cores are placed in the immediate proximity of one another. Such an arrangement forms an all-interacting system for which all the fibers have to be considered simultaneously with a complexity of system design that increases greatly with the number of fiber cores. Whereas it can be beneficial to have individual subcomponents designed on a proximity principle, scalable integration of several of them in the same fiber would require individual spatially separated noninteracting subcomponents and a transverse light wave circuitry that facilitates connectivity between them. In what follows, we demonstrate the principles of design of such transverse light guides that enable long-range energy transfer to be made between two greatly separated cores. We use a finite element method (FEM) mode solver to perform coupler modal analysis as well as a FEM beam-propagation method analysis[8] to confirm our findings.

In this Letter we revisit a work-horse of fiber components: a directional coupler. In its traditional design two fiber cores are placed in close proximity. In such a geometry, exponentially fast decaying evanescent fields of the core modes exhibit a finite overlap in the cladding region, enabling a complete energy transfer from one core into the other after a certain propagation length. When two cores are spaced farther apart, the coupling reduces exponentially fast. In what follows, we demonstrate a resonant, rather than proximity, directional coupler that allows energy transfer between two fiber cores to occur, regardless of the separation between them. To demonstrate the robustness of our design and investigate the importance of bandgap confinement for coupler radiation losses, we chose the most challenging case: the design of long-range coupling between two hollow core fibers guiding in the bandgap of a surrounding two-dimensional photonic crystal cladding. Structure and modal properties of individual hollow waveguides are detailed in Ref. 8. Briefly, we form a hollow core in a silica-based MOF with cladding refractive index $n=1.45$ by removing two rows of tubes and smoothing the resultant core edges. The pitch is $\Lambda=2$ μm, while $d/\Lambda=0.9$ in the cladding with a total of six hole layers in the reflector. The fundamental bandgap in which the core guided modes are found extends between 1.29 μm $<\lambda<$ 1.40 μm. To form a coupler we place two hollow cores N periods apart from each other, as in Fig. 1. We then introduce a transverse waveguide by reducing (high-index defect) or increasing (low-index defect) diameters of the

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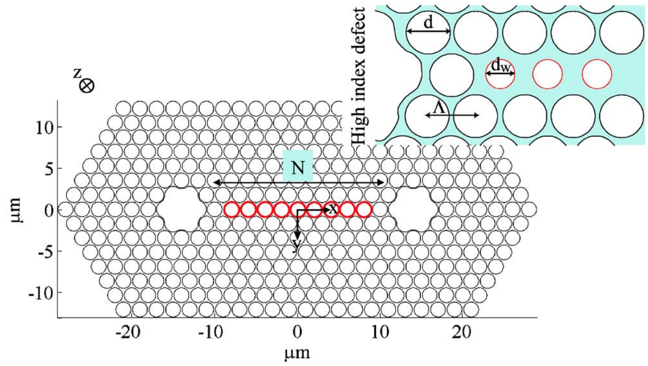

Fig. 1. (Color online) Schematic of a two-hollow-core MOF coupler.

holes along the line joining the cores. As the hollow core size is small, to keep from disturbing the guided mode of a single fiber we keep the sizes of the holes closest to the cores unchanged.

In a stand-alone fiber, the lowest-loss mode is a doublet with an electric field vector that has either x or y as the dominant component. We call such fields x or y polarized, respectively. In what follows, we consider a y-polarized mode only. When a second, identical core is introduced (no line defect yet), the proximity interaction between the core modes of the same polarization leads to the appearance of even and odd (with respect to reflection in the OY axis) supermodes with effective refractive indices denoted n_{eff}^{y+} and n_{eff}^{y-} closely spaced about $n0_{\mathrm{eff}}^{y}$ of a single-core fiber mode. Interfiber coupling strength is then defined as $\Delta n_{\mathrm{eff}}^{y} = |\mathrm{Re}(n_{\mathrm{eff}}^{y+} - n_{\mathrm{eff}}^{y-})|$, and modal radiation losses are defined by the imaginary parts of their effective indices. The coupling length after which power launched in one core will be completely transferred into the other core is $L_c = \lambda/(2\Delta n_{\mathrm{eff}}^{y})$. To find an upper bound on the radiation losses of a coupler we define the power decay length: $L_d = \lambda/\{4\pi \max[\mathrm{Im}(n_{\mathrm{eff}}^{y\pm})]\}$; then the maximum power loss over a single coupling length is $1 - P(L_c)/P(0) = 1 - \exp(-L_c/L_d)$. As fields of the core modes guided by photonic-bandgap decay exponentially fast into the cladding, proximity coupling between the cores also decreases exponentially fast when the separation between the cores is increased. Detailed analysis shows that for interfiber separation $N=4$ the coupling length is ~ 10 cm, for $N=7$ it is ~ 1 m, and for $N=11$ it is ~ 20 m. In what follows we demonstrate that introduction of a transverse waveguide permits reduction of a coupling length to a subcentimeter scale, even for large intercore separations, thus making such resonant coupling practically independent of interfiber separation.

We now consider a high-index line defect (transverse waveguide) in the $N=11$ coupler of Fig. 1 that we have created by reducing the sizes of the holes along the intercore line to $d_w/\Lambda = 0.85$. At the top of Fig. 2 the dispersion relation of the supermodes relative to the dispersion relation of a fundamental mode of an isolated core is presented. At $\lambda \sim 1.294$, 1.306, 1.320, 1.331 μm, the y-even supermode exhibits avoidance of crossing with transversely guided modes of a line defect (which can also be viewed as a planar waveguide). Excitation of transversely guided modes of a line defect is possible, as a hollow core guided mode has a considerable transverse wave vector component in photonic bandgap cladding. Consider $\lambda \sim 1.306$ μm. In its vicinity there are three interacting modes, a y-odd mode (point 2 in Fig. 2) and two y-even modes (points 1 and 3) that are mixed with a line defect mode. The field distribution in a y-odd mode is similar to that of two noninteracting core modes, whereas the field distribution in the y-even modes exhibits strong mixing with a line defect mode (Fig. 2, inset).

When three modes interact, complete power transfer between the cores is still possible with the same definition of coupling length as before, given that the distance between points 1 and 2 is the same as that between points 2 and 3; we call this a resonant condition. At the bottom of Fig. 2 the coupling length across the bandgap is presented, with a coupling strength $\Delta n_{\mathrm{eff}}^{y} = \min[|\mathrm{Re}(n_{\mathrm{eff}}^{y1+} - n_{\mathrm{eff}}^{y-})|, |\mathrm{Re}(n_{\mathrm{eff}}^{y2+} - n_{\mathrm{eff}}^{y-})|]$, which gives the correct coupling length at resonance. At $\lambda = 1.306$ μm the coupling length becomes as small as $L_c = 3$ mm. If there were no transverse waveguide connecting the cores, proximity coupling would be extremely small, resulting in a coupling length of $L_c \sim 20$ m.

Another important characteristic of a resonant coupler is radiation loss over a single coupling length. Previously we estimated an upper bound for such a loss to be $1 - P(L_c)/P(0)$. In Fig. 2 the radiation loss over one coupling length across the bandgap is shown. At resonance, the coupling loss exhibits a large increase, whereas far from resonance in the region dominated by proximity coupling the radiation

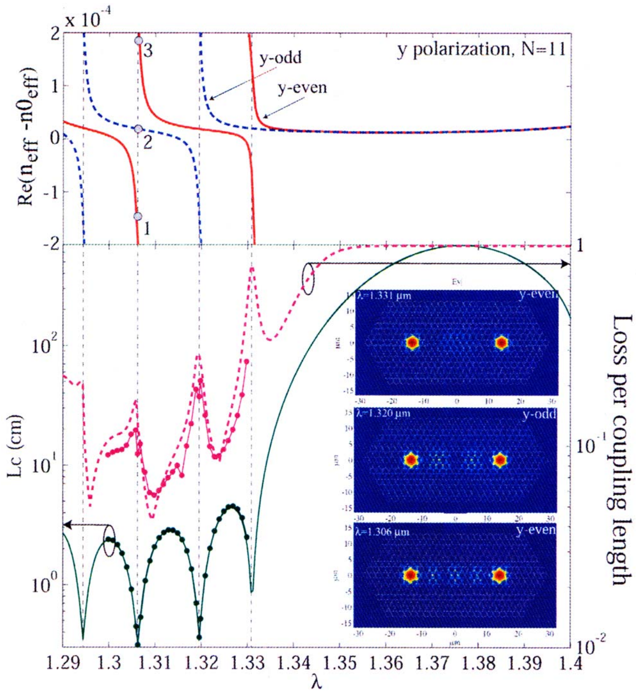

Fig. 2. (Color online) Resonant coupling between two cores separated by 11 periods and connected by a line defect. Top, dispersion relations of supermodes. Bottom, inset, field distribution of mixed modes at consecutive resonances.

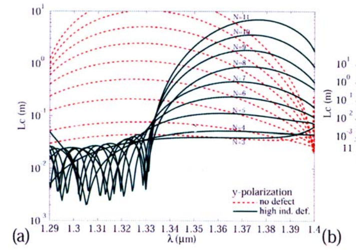

Fig. 3. (Color online) Coupling length across a bandgap as a function of intercore separation N. (a) Solid curves, resonant coupler; dashed curves, proximity coupler. (b) Fabry–Perot resonances.

loss follows a general trend to be smallest inside a bandgap and increasing toward the bandgap edges. For a system with a line defect, while it is in resonance there is a substantial power transfer to a localized (in the direction perpendicular to the waveguide) defect state. As the dispersion relation of a supermode is close to that of an air line, confinement in a defect state is due solely to the bandgap of the cladding, and because of the defect strong localization associated radiation loss is large. In this example an upper-bound estimate gives a 17% loss per coupling length. In principle, one can reduce these losses by increasing the number of layers in photonic bandgap cladding. Long-range coupling and a complete power transfer at resonance were confirmed with beam-propagation method simulations. In the bottom part of Fig. 2, results of beam propagation method simulations of coupling length, as well as loss over a single coupling length, are presented as solid curves with circles and exhibit excellent agreement with mode analysis predictions. At resonance, complete power transfer between the cores is observed over the coupling length, whereas out of resonance, only a partial power transfer is observed.

In the inset of Fig. 2 we present amplitude distributions at three consecutive resonances of the y components of electric fields in the supermodes strongly mixed with the transverse guided modes of a line defect. The standing-wave pattern in the intercore region arises from excitation of both forward and backward propagation modes in a transverse waveguide. Also, toward shorter wavelengths the number of spatial oscillations in the defect region increases. In this respect, modes of a line defect are analogous to the Fabry–Perot resonances excited in a short transverse waveguide terminated by the hollow cores. The origin of localized Fabry–Perot states in the intercore region can be understood from a simplified interaction model. In particular, we consider coupling in our system to be analogous to coupling between the core guided modes of two collinear fibers via an in-plane guided mode of a slab waveguide; fiber center lines are assumed to be in the plane of the slab. Modes of a slab waveguide are degenerate with respect to the traveling direction along the waveguide plane. At a given frequency ω we define a propagation constant of a guided slab mode as $k(\omega)$, with the direction of propagation anywhere in the plane of a slab. The guided fiber mode is now characterized by in-plane propagation vector $(\beta,0)$, where the OX axis is along the center line of a fiber and the OY axis is perpendicular to the fiber and in the plane of a slab waveguide. For a given frequency ω the guided fiber mode will be phase matched with two modes of a slab waveguide with propagation vectors $(\beta, \pm k_t)$, where the transverse propagation constant is defined as $k_t = [k(\omega)^2 - \beta^2]^{1/2}$. If k_t is real, guided slab modes will form a standing wave (Fabry–Perot resonance) whenever the constructive interference condition is satisfied ($k_t L \sim \pi p$), where L is the distance between fibers and p is an integer. As the interfiber distance is increased, more resonances will appear in the intercore region, with the spectral separation between resonances inversely proportional to the spatial intercore separation. In a hollow core MOF coupler $\beta \sim \omega$ and $k(\omega) \sim n_{\text{clad}}\omega$; thus for an interfiber separation of $N\Lambda$ the spectral separation between resonances will be $\Delta\lambda \sim \lambda^2/(2N\Lambda\sqrt{n_{\text{clad}}^2 - 1})$. In Fig. 3(b) the coupling length as a function of interfiber separation is presented across the bandgap for a line defect $d_w/\Lambda = 0.85$. One can observe the appearance of Fabry–Perot resonances with reduced spectral separation between them as the interfiber distance is increased. At resonance the coupling length is of the order of several millimeters regardless of the interfiber separation [Fig. 3(a)]. Note that all the resonances are concentrated in the region $\lambda \lesssim 1.34\ \mu$m, suggesting that transverse guided modes of a high-index line defect are pulled down from the upper edge of a bandgap. Toward longer wavelengths, coupling becomes dominated by proximity effects, as there are no line defect states available at lower frequencies.

Finally, we note that the introduced coupler is polarization dependent. We found that high-index line defects $d_w/\Lambda < 0.9$ can support only y polarization, whereas low-index line defects $d_w/\Lambda > 0.9$ can support both kinds of polarization. We believe that it is possible to design a polarization-independent resonant coupler by proper choice of a low-index line defect geometry; research toward this end is under way.

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