Design principles of multifiber resonant directional couplers with hollow Bragg fibers: example of a 3×3 coupler

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When several hollow photonic crystal fibers (HPCFs) are placed in proximity to each other, radiation-induced interfiber coupling between their core guided modes is observed. Under certain conditions coupling between the core modes of two touching collinear fibers can have a resonant increase via excitation of a low-quality intermirror cavity resonant state. Such coupling, however, decreases dramatically within the first micrometer of intermirror separation. Moreover, when fibers are touching, in the frequency domain a large number of accidental degeneracies with fiber surface and mirror states complicate the design of a stable 2×2 coupler. To alleviate these problems we consider coupling among three hollow Bragg fibers. When placed in the vertices of an isosceles triangle, even for a finite separation between fibers, triangular interfiber cavity forms a high-quality resonator that can be tuned via additional structural elements to a particular frequency of interest. Interfiber surface states are suppressed by keeping the fiber separation finite, thus allowing stable coupling conditions in a 3×3 HPCF coupler configuration. © 2005 Optical Society of America

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Hollow photonic bandgap (HPBG) microstructured and Bragg fibers[1–3] are able to guide light through hollow (gaseous) cores, promising very low material loss and nonlinearity and achieving radiation confinement via reflection from the surrounding dielectric multilayer mirror. Examples of potential application of HPBG fibers are high-power guiding at a designable wavelength, ultralow nonlinearity fibers for telecommunication, and compact sensors where functional materials could be integrated directly in a hollow fiber core. Rapid progress in the development of Bragg fibers with an expanded choice of material combinations[1,4] has motivated research into Bragg fiber components[5–8] to provide a uniform guiding–switching fabric in which the same type of fiber is used to guide and manipulate light.

In my previous work with Saitoh and Koshiba,[7,8] we performed a feasibility study of 2×2 directional coupler design involving two HPBG Bragg fibers operating with lowest loss TE_{01} modes. It was found that, when the two fibers were touching, the beat length between two core guided modes became much smaller (strong coupling) than the radiation decay lengths of the supermodes, thus facilitating, in principle, directional energy transfer between two hollow waveguides. As an increase in mode coupling is mediated by resonant excitation of an open low-quality interfiber cavity, when intermirror separation was increased the coupling strength decreased dramatically in the first micrometer of separation. Further study also revealed that, when two fibers were touching, in the spectral domain many accidental degeneracies of TE_{01} modes with fiber surface modes were found, thus complicating the design of a stable coupler.

In this Letter the design of a novel 3×3 hollow Bragg fiber resonant directional coupler is investigated. This design offers coupling strength and stability superior to the 2×2 coupler design. The difference in performance is attributed to a simple observation that for any $N\times N$ coupler with $N>2$, where fibers are placed in the vertices of a polygon an interfiber cavity forms an almost closed high-quality resonator, the states of which could be used to promote energy flow between two otherwise weakly interacting fibers. Implemented with standard total internal reflection fibers, 3×3 couplers are already used in the application of gyroscopes and interferometers, as well as in power splitters and fiber lasers for splitting or combining several high-power beams, minimizing the use of free-space optics.

In this Letter a modified multipole method[8] is used to study the supermodes of a 3×3 coupler in a spec-

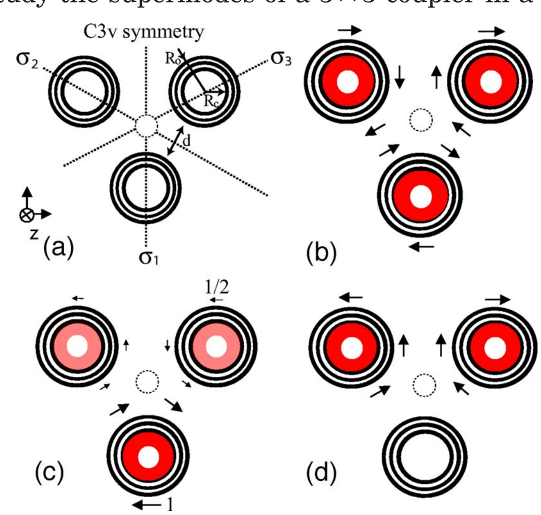

Fig. 1. (Online color) (a) Schematic of 3×3 coupler and vectors of the transverse electric fields of TE_{01}-like supermodes with (b) A_2, (c) E_1, (d) E_2 symmetries. Dotted circles, tuning dielectric rod that can be placed into the interfiber cavity.

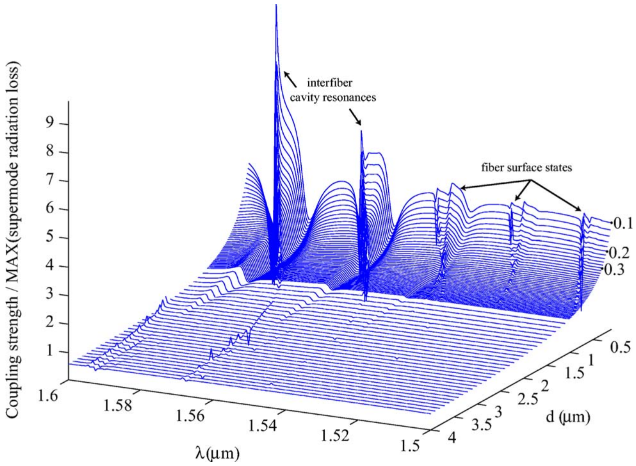

Fig. 2. (Online color) 3×3 coupler design regimes. The ratio of coupling strength to the highest supermode loss is shown as functions of λ and d. In the narrowband coupling regime, $0.15\ \mu\text{m} \lesssim d \lesssim 0.3\ \mu\text{m}$, coupling is strong only around pronounced cavity resonances. In the broadband coupling regime, $d \lesssim 0.15\ \mu\text{m}$, coupling is strong for almost all λ.

tral region $1.5\ \mu\text{m} < \lambda < 1.6\ \mu\text{m}$. Each Bragg fiber is made from five alternating dielectric layers with refractive indices $n_h = 2.8$, $n_l = 1.5$, starting and ending with a high-index layer [Fig. 1(a)]. The core and cladding layers are assumed to be air $n_{\text{clad}} = n_c = 1$. High- and low-index mirror layer thicknesses $d_h = 0.157\ \mu\text{m}$, $d_l = 0.367\ \mu\text{m}$ are chosen so that the radiation loss of the TE_{01} mode reaches its minimum value at $\lambda_c = 1.55\ \mu\text{m}$. The fiber core radii are $R_c = 10\ \mu\text{m}$. With these parameters the radiation loss of the TE_{01} mode in a free-standing fiber is almost constant in the whole region $1.5\ \mu\text{m} < \lambda < 1.6\ \mu\text{m}$ and is in the range 3.87–4.0 dB/m. As TE_{01} is air-core guided, it is typically located just above the air light line $\beta_{TE_{01}} \lesssim \omega$. In the following we assume that the centers of three identical Bragg fibers are placed in the vertices of an isosceles triangle with intermirror separation d, forming a coupler with $C3v$ symmetry. If there were no coupling between fibers, the combination of three TE_{01} modes of individual fibers would form a threefold degenerate state. When coupling between fibers is taken into account such a state will split into a nondegenerate state A_2 [Fig. 1(b)] and a twofold degenerate state E_1, E_2 [Figs. 1(c) and 1(d)]. We characterize interfiber coupling strength by the difference in real parts of supermode propagation constants $\Delta\beta = |\text{Re}(\beta^+ - \beta^-)|$, while modal radiation losses are defined by the imaginary parts of their propagation constants. The beat length between supermodes after which power launched into a single fiber will split equally into three fibers of a coupler is $4\pi/3/\Delta\beta$ (assuming comparable losses of supermodes), while the power decay length is proportional to $1/\max[\text{Im}(\beta^\pm)]$. Thus, for a coupler to function properly, the minimum ratio of coupling strength to the highest supermode loss has to be at least $\Delta\beta/\max[\text{Im}(\beta^\pm)] \gtrsim 4$ (corresponding to a 10 dB loss per coupling length). If at a certain λ this condition is satisfied, we may call coupling at that wavelength strong.

In Fig. 2 the ratio of coupling strength to the highest supermode loss is plotted as a function of wavelength and interfiber separation $d \geq 0.1\ \mu\text{m}$. Note the rapid decrease in coupling strength with increasing interfiber separation. To satisfy minimum coupling strength requirement at least for some λ, interfiber separation has to be smaller than $0.3\ \mu\text{m}$. When $0.15\ \mu\text{m} \lesssim d \lesssim 0.3\ \mu\text{m}$, coupling is strong only around few pronounced interfiber cavity resonances, and narrowband intermode coupling is possible in the vicinity of such resonances. When $d \lesssim 0.15\ \mu\text{m}$, coupling strength increases considerably for almost all λ, thus allowing, in principle, design of a broadband coupler for $d \lesssim 0.15\ \mu\text{m}$. However, for such small separations many fiber surface states also become excited (as in Ref. 7), making coupling stability difficult to maintain.

In Fig. 3, an example of narrowband coupling for $d = 0.3\ \mu\text{m}$ is presented. The frequency range of strong coupling is $\lambda = 1588.9 \pm 0.3$ nm. In the inset of Fig. 3, the $\log_{10}$ of normalized field amplitude $|\bar{E}|/\max(|\bar{E}|)$ of the A_2 supermode is presented. Although some field penetration into the fiber mirrors is visible, most of the field is confined either in the fiber cores or inside the interfiber cavity. For this particular 1×3 design at $\lambda = 1589$ nm the coupling length is 3.4 m, with an 8 dB total loss to radiation.

To avoid coupling to the fiber surface states we have to keep the separation between the fibers finite, $d \gtrsim 0.15\ \mu\text{m}$. As the coupling strength decreases rapidly within the first micrometer of interfiber separation, designing a broadband coupler becomes challenging. To compensate for the reduction in the coupling strength due to finite interfiber separation, we have to modify the cavity resonator to "pool into" the resonance at a desired wavelength, thus increasing interfiber coupling. To tune the interfiber cavity we place a dielectric rod of radius $R_r = R_o(2/\sqrt{3} - 1)$ [dotted circle in Fig. 1(a)] in the symmetry center of a coupler. To gain a physical understanding of what

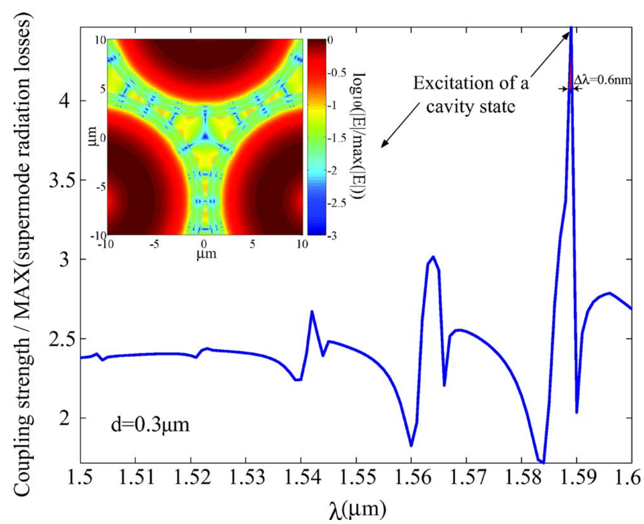

Fig. 3. (Online color) Narrowband coupling, $d = 0.3\ \mu\text{m}$. The ratio of coupling strength to the highest supermode loss is shown as a function of λ. Inset, $\log_{10}$ of the normalized field amplitude of cavity resonance $\lambda = 1589$ nm.

happens when the cavity is changed continuously from empty to one with a rod, the refractive index of a tuning rod is varied continuously within $1.0 \leqslant n_r \leqslant 1.4$.

In Fig. 4 the ratio of a coupling strength to the highest supermode loss as a function of wavelength and resonator rod index n_r is presented for a coupler with interfiber separation of $d=0.3$ μm. The regions of increased coupling correspond to the near degeneracies of TE_{01}-like supermodes and leaky resonator states. As the cavity states are excited above the light line of air they are more similar to Fabry–Perot cavity resonances than to the guided modes of a tuning rod. For a given λ, when the rod index increases, at some n_r the optical length of a cavity becomes large enough to support a resonance. When n_r is increased further, more resonant states become excited.

In Fig. 5 the ratio of coupling strength to the highest supermode loss as a function of wavelength is presented for a coupler with interfiber separation of $d=0.3$ μm and a resonator rod of $n_r=1.14$. There are several regions of strong resonant coupling. For $\lambda=1563-1569$ nm, for example, the maximum coupling strength between the modes in a coupler with a cavity rod is a factor of 7 larger than the coupling in a coupler with an empty cavity. In the inset, the $\log_{10}$ of a normalized field amplitude $|\bar{E}|/\max(|\bar{E}|)$ of the A_2 supermode is presented. Most of the field is confined either in the fiber cores or in the cavity tuning rod. For this improved 1×3 design the coupling length at $\lambda=1568$ nm is 32 cm, with 3.2 dB total loss to radiation. Note the considerable improvement in bandwidth and reduction of coupling length compared with those of the empty cavity coupler.

Finally, I comment on the computational limitations of a multipole method and potential experimental realization of HPCF couplers. Because of the large fiber core radii, I considered fibers suspended in the air to improve numerical convergence of a multipole method. When the cladding index is considerably greater than air, the finite element method (FEM) becomes more appropriate. In experimental implementation, the cladding and the interfiber cavity will have to be made from a solid material to provide mechanical support to closely separated fibers. Preliminary calculations using the FEM[9] suggest that a coupler with a solid cladding behaves qualitatively in the same way as an air-filled coupler, the largest difference between the two being the number of resonance states in the interfiber cavity.

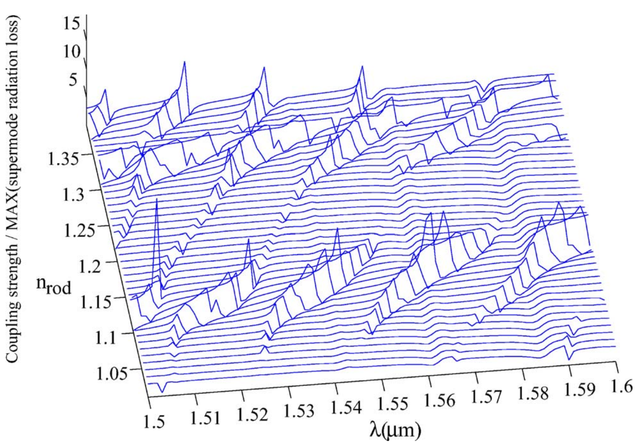

Fig. 4. (Online color) 3×3 coupler with fiber separation $d=0.3$ μm and a resonator rod. The ratio of coupling strength to the highest supermode loss is shown as a function of λ and resonator rod index n_r. Near degeneracies of the supermodes and resonator states correspond to the regions of coupling increase.

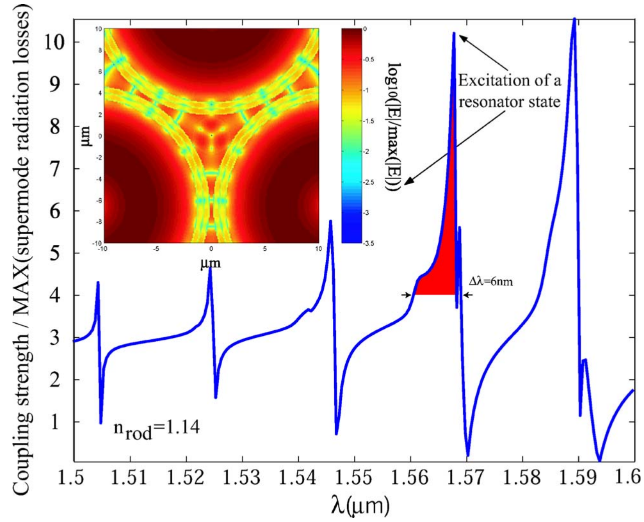

Fig. 5. (Online color) 3×3 coupler with fiber separation $d=0.3$ μm and resonator rod of $n_r=1.14$. The ratio of coupling strength to the highest supermode loss is shown as a function of λ. Inset, $\log_{10}$ of the normalized field amplitude of a cavity resonance $\lambda=1568$ nm.

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