Resonant directional coupling of hollow Bragg fibers

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Coupling between the lowest-loss TE_{01} modes of two touching hollow-core Bragg fibers is considered with a view to designing a directional coupler. We have found that for fibers with core radii larger than 10 μm one can identify broad frequency ranges in which intermodal coupling strength exceeds supermode radiation losses by an order of magnitude, thus opening the possibility of building a directional coupler. We attribute such unusually strong intermode coupling both to the resonant effects in the intermirror cavity and a proximity interaction between the leaky modes localized in the mirror.

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Recently, hollow core photonic bandgap (PBG) microstructured and Bragg fibers were experimentally demonstrated to exhibit guidance and low transmission loss at 1.55,[1,2] 3.0, and 10.6 μm,[3] promising to have considerable influence on long-haul and high-power guidance applications almost anywhere in the IR. Hollow PBG fibers are able to guide light through their hollow (gaseous) cores with low material loss and nonlinearity and achieve radiation confinement by means of reflection from a surrounding dielectric multilayer mirror. Rapid progress in the development of Bragg fibers with an expanding choice of material combinations[4] has motivated research in Bragg fiber components[5,6] to provide a uniform guiding–switching fabric in which the same type of fiber is used to guide and to manipulate light.

Directional couplers made from PBG microstructured fibers are typically manufactured at the preform stage by arrangement of silica tubes to form two closely spaced silica or air cores separated by several air–silica layers, all surrounded by a hexagonal lattice of silica tubes. When the preform is drawn, the resultant microstructured fiber exhibits two closely spaced identical cores surrounded by a PBG reflector. Unlike for PBG microstructured fibers, the current state of Bragg fiber fabrication does not allow the cores of two Bragg fibers to be placed arbitrarily close while a common PBG reflector is created on the outside of both cores. In this Letter we demonstrate that enhanced resonant coupling is still possible even between stand-alone PBG Bragg fibers by their being allowed to touch, with the last two layers of their corresponding Bragg mirrors forming an open resonant cavity. However, in this setting an observed increase in the interfiber coupling is of a resonant nature rather than being solely the proximity effect encountered in standard directional total-internal-reflection fiber couplers.

Previously Skorobogatiy[7] characterized coupling strength between the collinear PBG Bragg fibers and the propagation losses of the lowest-loss telecommunication quality TE_{01}-like supermodes as a function of interfiber separation. In a stand-alone fiber, TE_{01} is a singlet with an electric field vector circling along the dielectric interfaces.[8] When a second, identical fiber is introduced, rotational symmetry of a single fiber is broken and interaction between the TE_{01} modes of Bragg fibers leads to the appearance of two supermodes with propagation constants β^- and β^+ closely spaced around β. We characterize interfiber coupling strength by the difference in the real parts of supermode propagation constants $\delta\beta = |(\mathrm{Re}\beta^+ - \beta^-)|$, whereas modal radiation losses are defined by the imaginary parts of the propagation constants. Unlike in silica fibers, in which the fundamental mode tail decays exponentially into the cladding, the radiation field from a hollow PBG Bragg fiber decays in the cladding only as an inverse square root of distance. As a consequence, we found that the beat length between supermodes in such fibers, $\pi/|\mathrm{Re}(\beta^+ - \beta^-)|$, remained of the order of supermode decay length $1/\mathrm{Im}(\beta^\pm)$ and exhibited periodic variations, even for very large interfiber separations of $\sim$100 μm. When two hollow Bragg fibers were spaced less than 1 μm from each other we observed a dramatic increase in the modal coupling without a substantial increase in the supermode losses. We suggest that one can understand coupling between hollow Bragg fibers by inspecting the dielectric profile along the fiber's center line (Fig. 1). Such a profile resembles a one-dimensional Bragg grating that is made from the fiber reflector mirrors and a central intermirror cavity defect that is formed by the two external layers of the fiber mirrors. The quarter-wave thickness of each mirror layer ensures the largest bandgap (stop band) of the reflector Bragg grating, so that radiation incoming from the hollow core onto the containing mirror will be maximally reflected. When the optical length of the central defect between the gratings is $\lambda\nu/2$, $\nu \in (0, 1, \ldots)$, the transmission through such a grating–defect–grating stack will exhibit a narrow maximum at λ, although the transmission everywhere else in the Bragg grating's stop band will remain suppressed. When there are two identical Bragg fibers, the first resonance occurs when the fibers are touching ($d = 0$) as the two outside high-index layers of the fiber mirrors create a $\lambda/2$ defect. A resonant increase in mode coupling at the

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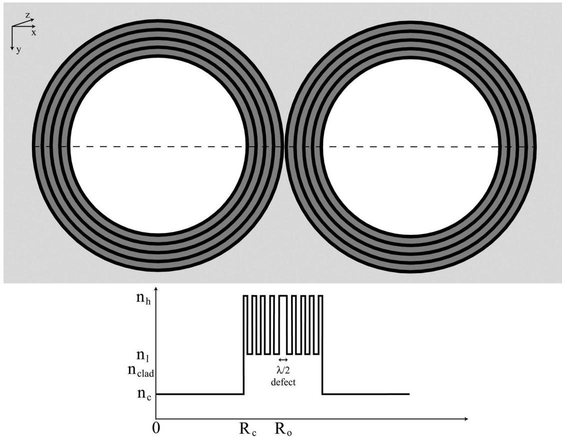

Fig. 1. Pair of identical touching hollow Bragg fibers. The dielectric profile along the interfiber center line resembles a one-dimensional Bragg grating with a central defect formed by the two external layers of the fiber mirrors.

interfiber separations that correspond to the $\lambda\nu/2$ optical lengths was demonstrated in Ref. 7; the multipole method and interfiber separations $d > 0.2$ μm were used.

In this Letter we report a study with a finite-element mode solver[9] of the feasibility of designing a directional coupler based on two touching hollow Bragg fibers. We assume that the PBG mirror is made from two dielectrics with refractive indices $n_h > n_l > n_c$, where n_c is an index of the core. Mirror layer thicknesses d_h and d_l are chosen to form a quarter-wave stack for the grazing angles of incidence.[8] Thus, when λ is the center wavelength of the primary bandgap, $d_h\sqrt{n_h{}^2 - n_c{}^2} = d_l\sqrt{n_l{}^2 - n_c{}^2} = \lambda/4$. The Bragg fibers under study have seven mirror layers (starting and ending with a high-index layer), $n_c = 1$, $n_h = 2.8$, $n_l = 1.5$, and $n_{\mathrm{clad}} = n_c = 1$. We first characterize the coupling strength between fibers and the radiation losses of the supermodes as a function of fiber core radii R_c at a fixed frequency $\lambda = 1.45$ μm. Because of the cylindrical shape of the fiber Bragg reflectors, the intermirror cavity Q factor is limited by the mirror's finite curvature, with Q and thus interfiber coupling increasing for larger core radii. In Fig. 2, normalized coupling strength and radiation losses of supermodes are presented. The normalization factor for each curve is a corresponding radiation loss of the TE_{01} mode of a stand-alone fiber. One observes that with increasing core radius the coupling strength exhibits a tendency to increase gradually relative to the radiation losses of the supermodes. For core radii larger than 10 μm the ratio of the coupling strength to the supermode radiation loss approaches a factor of 10, which, in principle, would allow a directional coupler to be built. Resonant features correspond to the points of accidental degeneracy of TE_{01} with higher-order modes.

In Fig. 3 we plot normalized coupling strength and supermode radiation losses as a function of wavelength λ for $R_c = 15$ μm and three interfiber separations: $d = 0, 0.2, 0.5$ μm. For $d = 0.5$ μm the coupling strength is weak, of the order of the supermode radiation losses, changing smoothly as a function of frequency. As interfiber separation decreases, the coupling strength exhibits a rapid increase across a broad frequency range together with the appearance of many sharp resonances ($d = 0.2$ μm in Fig. 3). When fibers are touching, $d = 0$ μm, the coupling strength strongly dominates supermode radiation losses in a broad frequency range. For 1.4 μm $< \lambda <$ 1.55 μm, for example, the ratio of coupling strength to the supermode radiation losses reaches a factor of 10. For a corresponding planar system of grating–defect–grating with the dielectric profile of Fig. 1 the resonance peak is, however, only several nanometers wide in contradiction to Fig. 3's very broad resonant features. Thus a simple picture of enhanced interfiber coupling has to be modified. As the spectral width of the enhanced coupling peak depends strongly on the intermirror cavity Q factor, we believe that the broad resonant features in Fig. 3 can be explained by the low Q factor of the resonant intermirror cavity that is due to the finite curvature of the fiber. As our mode solver was limited to core radii less than 20 μm, we were not able to investigate further the narrowing of the resonance for larger radii. Another prominent feature of Fig. 3 is the presence of sharp and broad regions of increase in the supermode losses. Because of the multimode nature of hollow Bragg fibers, the lowest-loss TE_{01} mode exhibits multiple points of accidental degeneracy with higher loss modes. At such degenerate points the TE_{01}-like supermode exhibits a sharp loss increase by picking up some of the higher-order mode loss. In general, we have found that broad frequency regions of increase in the supermode losses are due to interaction with low-angular-momentum modes. For example, by inspecting the band diagram of a stand-alone fiber we found that in the region 1.55 μm $< \lambda <$ 1.65 μm an $m = 2$ mode crosses the TE_{01} mode twice, staying almost degenerate with it in the whole interval. In

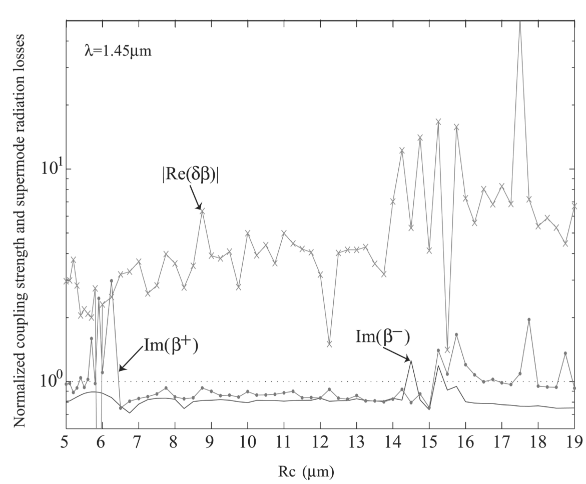

Fig. 2. Normalized coupling strength and supermode radiation losses as a function of fiber core radii R_c at $\lambda = 1.45$ μm. With increasing core radius one observes the tendency for a gradual increase of the coupling strength relative to the highest radiation loss of the supermodes.

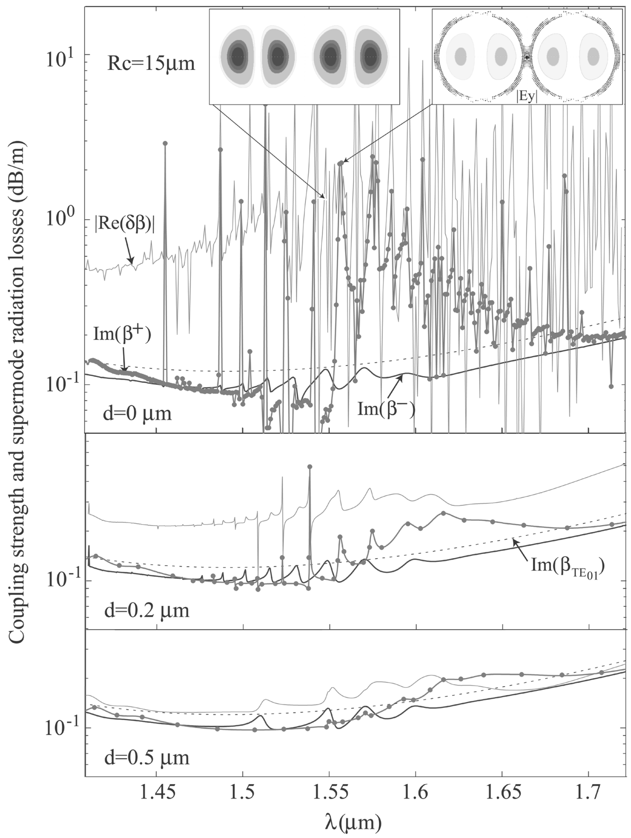

Fig. 3. Normalized coupling strength and supermode radiation losses as a function of wavelength λ for $R_c = 15\ \mu$m and interfiber separations $d = 0, 0.2, 0.5\ \mu$m. For $1.4\ \mu\text{m} < \lambda < 1.55\ \mu$m one observes a factor-of-10 ratio of coupling strength to the highest radiation loss of the supermodes. Sharp resonances in the coupling strength correspond to the accidental mode crossing of TE_{01} with high-angular-momentum modes of the reflector. For $d = 0\ \mu$m the $|Ey|$ fields are presented at the frequencies close to and directly at one of the sharp resonances. The region $1.55\ \mu\text{m} < \lambda < 1.65\ \mu$m is dominated by prolonged coupling between TE_{01} and an $m = 2$ mode, leading to a broad resonance and to an increase in the supermode losses.

Fig. 3, for $d = 0\ \mu$m this broad modal interaction region is characterized by an increase in supermode loss. We further verified our assumption by modifying the location of the modal degeneracy region by adding more layers to the reflector and observing a consistent shift of a broad resonance. On inspecting the modal fields about the sharp resonances (Fig. 3, $d = 0\ \mu$m, insets), we concluded that such resonances correspond to the points of degeneracy of a TE_{01} mode with high-angular-momentum mirror modes. At a sharp resonance, a hybrid mode has an intensity maximum in the intermirror cavity defect, while the fields in the hollow fiber cores are reduced. We have verified that in a stand-alone fiber there are a large number of high-angular-momentum, $m > 6$, leaky modes with propagation constants close to the air line and fields concentrated mostly in the fiber reflector. In a region just outside the fiber, such modes exhibit fast decay in the cladding. Thus, sharp resonances caused by interaction with such modes disappear quickly with increasing interfiber separation, as is clearly observable from Fig. 3.

In conclusion, we have demonstrated that, for two touching PBG Bragg fibers of substantially large core radii, the frequency regions in which a large increase in modal coupling is observed without a substantial increase in the supermode losses can be identified, thus presenting the opportunity for design of a directional coupler. Because of the multimode nature of hollow PBG Bragg fibers, special care should be taken to prevent accidental mode degeneracy between the mode of operation and higher-order modes at the frequency of interest.

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