Hollow Bragg fiber bundles: when coupling helps and when it hurts

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Received January 20, 2004

Coupling between leaky modes of collinear hollow-core Bragg fibers is considered. It is found that coupling is unusually strong because of resonant effects in the interfiber cavity when the fibers are touching each other and decreases dramatically with the first tens of nanometers of fiber separation. However, residual coupling with a strength proportional to the fiber radiation loss is long range, decreasing as an inverse square root of the interfiber separation and exhibiting periodic variation. The possibility of building a directional coupler from touching Bragg fibers is discussed in view of the findings. © 2004 Optical Society of America

OCIS codes: 060.2310, 060.2340, 060.2280, 230.0230.

Recently, hollow-core photonic bandgap (PBG) microstructured and Bragg fibers have been experimentally demonstrated to exhibit guidance and low transmission loss at 1.55,[1] 3.0, and 10.6 μm,[2] promising considerable benefits for long-haul transmission and high-power guidance applications almost anywhere in the IR. Hollow PBG fibers guide light through a hollow (gaseous) core featuring low material loss and nonlinearity, by achieving radiation confinement by reflection from the surrounding dielectric multilayer mirror. Development of hollow PBG fibers motivated research on the design of directional couplers based on similar fibers to provide a uniform guiding–switching fabric, where the same type of fiber is used to guide and to manipulate light, thus addressing compatibility issues and reducing link losses.

Because of the wider availability of microstructured PBG fibers, most recent experimental and theoretical work has concentrated on the design of directional couplers based on such fibers.[3–7] In particular, at the preform stage, silica rods are arranged to form two closely spaced silica or air cores separated by several air–silica layers, all surrounded by a hexagonal lattice of silica rods. When the preform is drawn, the resultant microstructured fiber exhibits two closely spaced identical cores surrounded by a PBG reflector. Theoretically, coupling between two cores has been studied by finite-element–difference methods with absorbing boundary conditions.[8,9]

In this work, for what is believed to be the first time, coupling between PBG fibers of another type, hollow Bragg fibers,[2] is considered. The main interest is to characterize the coupling strength between collinear PBG Bragg fibers, and propagation losses of the lowest loss telecommunication quality[10] TE_{01}-like supermodes. The issue of interfiber modal coupling can be important when several hollow photonic crystal fibers are placed in proximity with one another, because of the long interaction range between such fibers driven by radiation leakage. The possibility of building Bragg-fiber-based directional couplers for TE_{01} modes is also addressed. Unlike for PBG microstructured fibers, the current process of Bragg fiber fabrication does not allow one to place the cores of two Bragg fibers arbitrarily close while creating a common PBG reflector on the outside of both cores. It is shown that enhanced resonant coupling is still possible even with standard Bragg fibers by tuning the separation between them to specific values with Bragg fiber mirrors of adjacent fibers, creating an open resonant cavity.

Two collinear hollow PBG Bragg fibers of core radius R_c, outer mirror radius R_o, and intermirror separation d are considered. Figure 1 shows a schematic of the system together with a dielectric profile along the line passing through the fiber centers. It is assumed that the PBG mirror is made of two dielectrics with refractive indices $n_h > n_l > n_c$, where n_c is a core index (for hollow fibers $n_c = 1$), while the corresponding mirror layer thicknesses d_h and d_l are chosen to form a quarter-wave stack for grazing angles of incidence.[10] Thus, denoting λ to be the center wavelength of the primary bandgap, $d_h(n_h{}^2 - n_c{}^2)^{1/2} = d_l(n_l{}^2 - n_c{}^2)^{1/2} = \lambda/4$. The cladding index n_{clad} may be chosen at will. From inspection of Fig. 1, the dielectric profile along the fiber center line resembles a one-dimensional

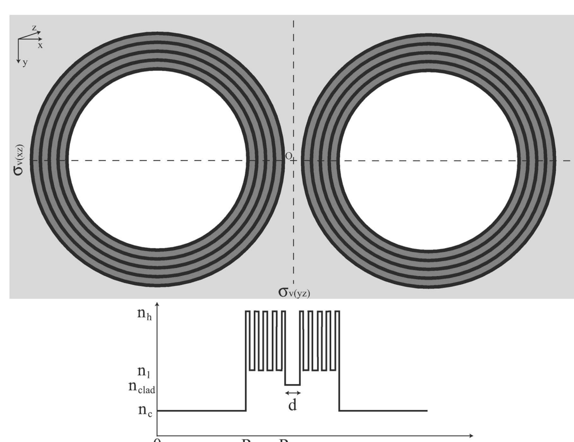

Fig. 1. Pair of identical hollow Bragg fibers separated by intermirror distance d. The dielectric profile along the interfiber center line resembles a one-dimensional Bragg grating with a central defect formed by the intermirror cavity.

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Bragg grating made of fiber reflector mirrors and a central defect of size d corresponding to the intermirror cavity. The quarter-wave thickness of each mirror layer ensures the largest bandgap (stop band) of the reflector Bragg grating so that radiation coming in from the hollow core onto the confining mirror will be maximally reflected. However, when the optical length of the central defect inserted between two Bragg gratings is $\lambda\nu/2$, $\nu \in (0, 1, \ldots)$, it is known that the transmission through such a grating–defect–grating multilayer stack will exhibit a narrow maximum at λ, although the transmission everywhere else in the Bragg grating stop band will remain strongly suppressed. In the case of 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 (see Fig. 1). Introducing a free-space wave number $k = 2\pi/\lambda$, modal propagation constant β, and transverse modal wave number in the defect layer of refractive index n and thickness d as $k_n{}^t = [(kn)^2 - \beta^2]^{1/2}$, we rewrite the resonant condition for a half-wavelength defect as $dk_n{}^t = \pi\nu$. Thus, anytime the intermirror separation d approaches its resonant value we expect an increase in the interfiber coupling because of enhanced radiation leakage from one core to another mediated by the resonant intermirror cavity. The spectral width and the maximum of an enhanced coupling peak will be a strong function of the intermirror cavity Q factor. Because of the cylindrical shape of the fiber Bragg reflectors, the intermirror cavity Q factor is ultimately limited by the finite curvature of the fiber, $\sim R_o{}^{-1}$. Finally, to increase the spectral width of a coupling peak one can adopt a standard solution from thin-film filters where the structure of the Bragg reflector is modified to present a sequence of several low-quality quarter-wave stacks coupled together by half-wave defects, exhibiting a steplike transmission response with a designable spectral width.

Next, the effect of cladding index n_{clad} on PBG Bragg fiber coupling is addressed. It was demonstrated[10] that low-loss modes in the PBG Bragg fibers have their propagation constants situated close to the core material light line, $1 - \beta/(kn_c) \sim (\lambda/R_c)^2$. Typical values of the core radii for a long-haul PBG Bragg fiber[10] are $R_c \sim 10–15\lambda$. Thus, in the core material $k_{n_c}{}^t = [(kn_c)^2 - \beta^2]^{1/2} \sim R_c{}^{-1}$, and in the material with $n > n_c$, $k_n{}^t \simeq k(n^2 - n_c{}^2)^{1/2}$. If the cladding index is the same as the core index, $n_{\text{clad}} = n_c$, one would expect a resonant increase in the coupling between PBG Bragg fibers at $d = \pi\nu/(k_{n_c}) \sim \nu R_c$, whereas if $n_{\text{clad}} > n_c$, then $d \simeq \lambda\nu/[2(n_{\text{clad}}{}^2 - n_c{}^2)]^{1/2}$, where $\nu \in (0, 1, \ldots)$ in both cases.

As the distance $L = 2R_o + d$ between the fiber centers increases, the intensities of the radiated fields from the core of one fiber at the position of the second fiber will decrease with distance as $E \sim [\text{Im}(\beta)/L]^{1/2}$, where $\text{Im}(\beta)$ is proportional to the modal radiation loss. Classical consideration of interfiber coupling between similar modes suggests that the coupling strength is proportional to the overlap of the fields of one fiber in the mirror region of the other fiber, leading to the $\text{Im}(\beta)/\sqrt{L}$ dependence of the PBG Bragg fiber coupling strength on modal loss and interfiber separation.

To strengthen this simple analysis the coupling between the lowest-loss telecommunication quality TE_{01} modes of the two identical collinear PBG Bragg fibers is quantified by use of a multipole method[11] to solve for the leaky modes of a fiber pair. In a stand-alone fiber, TE_{01} is a singlet state with the electric field vector circling along the dielectric interfaces.[10] When a second identical fiber is introduced, the 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^+ close to β. The remaining symmetry of a system is described by a C_{2v} group that includes reflections in the (xz) and (yz) planes and inversion with respect to the system symmetry center O (see Fig. 1). Symmetry considerations show that at O one of the supermodes will have a local maximum of the electric field, and the other will have a node. The coupling strength between fibers and radiation losses of the supermodes as a function of the intermirror separation d for $n_c = n_{\text{clad}}$ is demonstrated. The interfiber coupling strength is characterized as the difference in the real parts of the supermode propagation constants $\delta\beta = |\beta^+ - \beta^-|$, and the modal radiation losses are defined by the imaginary parts of their propagation constants. The Bragg fiber under study has seven mirror layers (starting and ending with a high index layer), $n_c = 1$, $n_h = 2.8$, $n_l = 1.5$, $n_{\text{clad}} = n_c = 1$, and three different core radii $R_c = [10, 15, 20]$ μm; the operating wavelength is 1.55 μm. In Fig. 2 the normalized coupling strength and the radiation losses of the supermodes are presented. The normalization factors for the curves are the corresponding radiation losses of TE_{01} mode, 0.66, 0.13, and 0.04 dB/m, for different core radii. One may observe that the coupling strength exhibits periodic variation as separation between the fibers increase. As was argued above, when $n_c = n_{\text{clad}}$ the position of the maxima of modal coupling scales proportionally to the core radius R_c,

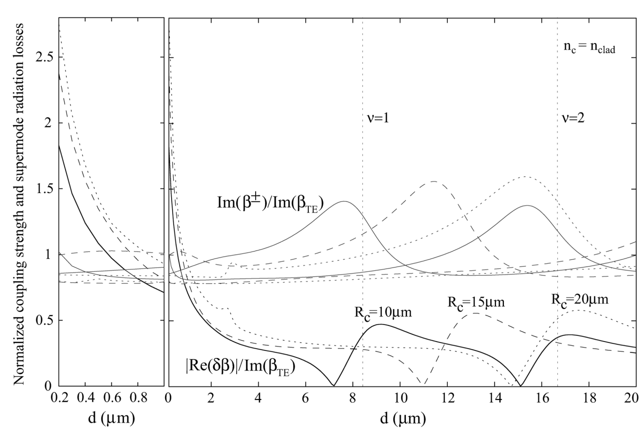

Fig. 2. Normalized coupling strength and supermode radiation losses as a function of intermirror separation d. The different fiber core radii R_c are labeled in the figure. The left-hand plot is an enlargement of the nearly touching fiber region 0.2 μm $< d <$ 1 μm exhibiting a dramatic increase in fiber coupling compared with almost constant supermode radiation losses.

which is clearly observable from Fig. 2. The locations of the maxima in the coupling strength match well with the predicted half-wave condition for the optical defect length $d = \pi\nu/(k_{n_c}) \sim \nu R_c$ (resonants ds for $R_c = 10\ \mu$m are marked in Fig. 2 by vertical dotted lines for $\nu = 1, 2$). The locations of the maxima in the supermode losses are also close to the half-wave separation between fiber mirrors, suggesting that loss increase is due to field leakage out of the open intermirror cavity, where at resonance the field intensity is enhanced. From Fig. 2 one also observes a very slow decrease in coupling with interfiber separation. By analyzing the values of the coupling maxima as a function of distance up to $d = 100\ \mu$m, one can observe a clear $|\delta\beta| \sim (2R_o + d)^{-0.5}$ dependence. When looking in the region of small intermirror separations $0.2\ \mu\text{m} < d < 1\ \mu$m (left-hand plot of Fig. 2), one observes a substantial increase in the coupling strength that considerably surpasses the supermode radiation losses when the distance between mirrors is decreased. Moreover, for the same intermirror separation d, the coupling strength increases with an increase in the fiber core radius, signifying that the quality of the intermirror cavity resonator increases as R_c increases. Overall, from Fig. 2 we observe that, for $n_c = n_{\text{clad}}$, coupling between Bragg fibers stays comparable to the supermode radiation losses even at very large separations, whereas in the region of almost-touching fibers, $d < 1\ \mu$m, the coupling strength considerably exceeds the supermode radiation losses.

To summarize, it has been found that, unlike in silica fibers, where the modal tail decays exponentially into the cladding, the radiation field from a hollow PBG Bragg fiber decays in the cladding very slowly as an inverse of the square root of the interfiber separation. Moreover, the beat length between supermodes, $\pi/\text{Re}(\beta^+ - \beta^-)$, stays of the order of the supermode decay length $1/\text{Im}(\beta^\pm)$ even for very large interfiber separations, $\sim 100\ \mu$m. When two straight pieces of PBG Bragg fiber are spaced less than $1\ \mu$m from each other, a dramatic increase in the modal coupling without a substantial increase in the supermode losses is observed. It seems that such a dramatic increase in coupling is due to a resonant effect in the intermirror cavity, which becomes a half-wave defect in the quarter-wave stack of the mirror layers. In this regime the supermode beat length becomes much smaller than the supermode decay length, opening a possibility of building a directional coupler exhibiting only a fraction of the modal losses along the coupler length. Finally, it was also observed that, although the multipole method[11] performs efficiently at intermirror separations $d/R_o > 0.1$, it exhibits slow convergence at smaller separations and at $d/R_o < 0.01$ convergence becomes problematic. To study touching fibers one will have to resort to alternative methods, among which the finite-difference–element mode solvers with absorbing boundary conditions are good candidates.

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References

1. C. M. Smith, N. Venkataraman, M. T. Gallagher, D. Muller, J. A. West, N. F. Borrelli, D. C. Allan, and K. W. Koch, Nature **424,** 657 (2003).
2. B. Temelkuran, S. D. Hart, G. Benoit, J. D. Joannopoulos, and Y. Fink, Nature **420,** 650 (2002).
3. M. A. van Eijkelenborg, A. Argyros, G. Barton, I. M. Bassett, M. Fellew, G. Henry, N. A. Issa, M. C. J. Large, S. Manos, W. Padden, L. Poladian, and J. Zagari, Opt. Fiber Technol. **9,** 199 (2003).
4. B. H. Lee, J. B. Eom, J. Kim, D. S. Moon, U.-C. Paek, and G.-H. Yang, Opt. Lett. **27,** 812 (2002).
5. G. Kakarantzas, B. J. Mangan, T. A. Birks, J. C. Knight, and P. St. J. Russell, in *Conference on Lasers and Electro-Optics*, Vol. 56 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2001), pp. 599–600.
6. M. Kristensen, in *Digest of Conference on Lasers and Electro-Optics Europe* (Optical Society of America, Washington, D.C., 2000), p. 1.
7. B. J. Mangan, J. C. Knight, T. A. Birks, P. St. J. Russell, and A. H. Greenaway, Electron. Lett. **36,** 1358 (2000).
8. K. Saitoh, Y. Sato, and M. Koshiba, Opt. Express **11,** 3188 (2003), http://www.opticsexpress.org.
9. F. Fogli, L. Saccomandi, P. Bassi, G. Bellanca, and S. Trillo, Opt. Express **10,** 54 (2002), http://www.opticsexpress.org.
10. S. G. Johnson, M. Ibanescu, M. Skorobogatiy, O. Weisberg, T. D. Engeness, M. Soljačić, S. A. Jacobs, J. D. Joannopoulos, and Y. Fink, Opt. Express **9,** 748 (2001), http://www.opticsexpress.org.
11. T. P. White, B. T. Kuhlmey, R. C. McPhedran, D. Maystre, G. C. M. de Sterke, and L. C. Botten, J. Opt. Soc. Am. B **19,** 2322 (2002).