Directional coupling in hollow Bragg fiber bundles.

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Abstract: Coupling between TE01 modes of two collinear hollow-core Bragg fibers is characterized as a function of the inter-fiber separation and wavelength in a view of designing a directional coupler.

OCIS codes: 060.2340 Fiber optics components; 060.1810 Couplers, switches, and multiplexers

1 Introductrion

Hollow core Bragg fibers have been experimentally demonstrated to exhibit low loss guidance at $1.55\mu m$, $3.0\mu m$ and $10.6\mu m$ promising considerable impact in the long-haul and high power guidance applications almost anywhere in the IR. Hollow PBG fibers are able to guide light through a gaseous core featuring low material loss and nonlinearity, and achieving radiation confinement via reflection from surrounding dielectric multilayer mirror. Rapid progress in manufacturing of Bragg fibers motivated research in Bragg fiber components [1, 2, 3] to provide a uniform guiding/switching fabric, where the same type of fiber is used to guide and to manipulate light. In this letter we study coupling between "telecommunication" quality low loss TE_{01} modes of two closely spaced hollow Bragg fibers in a view of designing a directional coupler.

2 Coupling as a function of inter-fiber separation

We consider two hollow Bragg fibers of core radius R_c and outer mirror radius Ro separated by a distance d (Fig. 1(insert)). PBG mirror consists of two dielectrics with refractive indexes $n_h > n_l > n_c$, $n_c = 1$ is a core index and n_{clad} is a cladding index. To optimize the modal confinement in the hollow core, the mirror layer thicknesses d_h, d_l are chosen to form a quarter-wave stack for the grazing angles of incidence [4]. Thus, denoting λ to be a center wavelength of the primary Band Gap, $d_h\sqrt{n_h^2 - n_c^2} = d_l\sqrt{n_l^2 - n_c^2} = \lambda/4$. For a given λ, coupling between the modes of PBG Bragg fibers as a function of an inter-fiber separation d can be understood by inspecting dielectric profile along the fiber center line. Such a profile resembles 1D Bragg grating formed by the fiber reflector mirrors containing a central inter-mirror cavity defect of size d. When optical length of the central defect is $\lambda\nu/2$ for any integer ν, transmission through such a grating-defect-grating multilayer stack will exhibit a maximum at λ. 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 constitute a $\lambda/2$ defect. Introducing a free space wave number $k = 2\pi/\lambda$, modal propagation constant β, and a transverse modal wave number in the defect layer $k_t^2 = (kn_{clad})^2 - \beta^2$, the resonant condition for a half-wavelength defect becomes $dk_t = \pi\nu$. When inter-mirror separation d equals its resonant value we expect an increase in the inter-fiber coupling due to enhanced radiation leakage from one core to another mediated by the resonant inter-mirror cavity. Spectral width and the maximum of enhanced coupling peak will be a strong function of an inter-mirror cavity quality factor which is limited by the finite curvature of the reflector mirror. We now address the impact of cladding index n_{clad} on the Bragg fiber coupling. TE_{01} mode of a hollow Bragg fiber is situated close to the core material light line [4] so that $1 - \beta/(kn_c) \sim (\lambda/R_c)^2$, where typically $R_c \sim 10 - 15\lambda$ for a long-haul hollow Bragg fiber design. Hence, in the core material $k_{n_c}^t = \sqrt{(kn_c)^2 - \beta^2} \sim R_c^{-1}$, while in the material with $n > n_c$, $k_n^t \simeq k\sqrt{n^2 - n_c^2}$. Thus, if cladding index is the same as the core index $n_{clad} = n_c$, one expects a resonant increase in the coupling between Bragg fibers at $d = \pi\nu/(k_{n_c}) \sim \nu R_c$, while if $n_{clad} > n_c$, then $d \simeq \lambda\nu/(2\sqrt{n_{clad}^2 - n_c^2})$ for any integer ν. Moreover, as the distance $L = 2R_o + d$ between the fiber centers increase, the intensities of the radiated fields from the core of one fiber at the position of the second fiber will decrease as $E \sim \sqrt{Im(\beta)/L}$, where $Im(\beta)$ is proportional to the modal radiation loss. Classical consideration of inter-fiber coupling between similar modes suggests

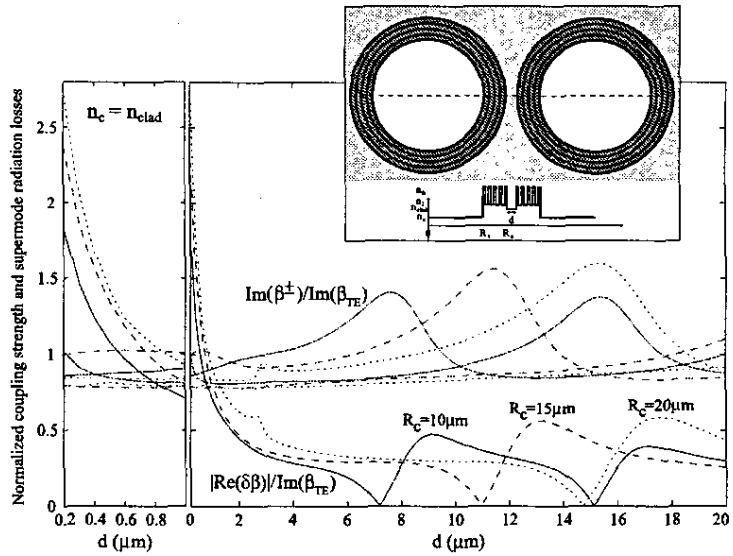

Fig. 1. Normalized coupling strength and supermode radiation losses as a function of inter-mirror separation d. Different lines correspond to different fiber core radii, solids - $R_c = 10\mu m$, dashed - $R_c = 15\mu m$, and dotted - $R_c = 20\mu m$. Left plot is a zoom-in of a nearly touching fiber region $0.2\mu m < d < 1\mu m$ exhibiting dramatic increase in the fiber coupling compared to modest supermode radiation losses; (Insert) Pair of collinear hollow Bragg fibers. Dielectric profile along the inter-fiber center line resembles a 1D Bragg grating with a central defect formed by the two external layers of the fiber mirrors.

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 $Im(\beta)/\sqrt{L}$ dependence of the coupling strength with modal radiation losses and inter-fiber separation.

We quantify coupling strength between the modes of a hollow Bragg fiber pair employing both multipole and finite element methods [5, 6]. In a stand alone fiber, TE_{01} is a singlet with electric field vector circling along the dielectric interfaces. When second identical fiber is introduced, rotational symmetry of a single fiber is broken and interaction between TE_{01} modes of Bragg fibers leads to appearance of two supermodes with propagation constants β^- and β^+ close to β. We characterize inter-fiber coupling strength as a difference in the real parts of supermode propagation constants $\delta\beta = |\beta^+ - \beta^-|$, while modal radiation losses are defined by the imaginary parts of their propagation constants. Bragg fiber under study has 7 mirror layers (starting and ending with a high index layer), $n_c = 1$, $n_h = 2.8$, $n_l = 1.5$, $n_{clad} = n_c$, operating wavelength is $1.55\mu m$. In Fig. 1 normalized coupling strength and radiation losses of supermodes as a function of inter-fiber separation are presented for several core radii $R_c = 10, 15, 20\mu m$. Normalization factor for each curve is a corresponding radiation loss of TE_{01} mode - $0.66dB/m$, $0.13dB/m$, $0.04dB/m$. Periodic variation in the coupling strength for increasing inter-fiber separation is clearly observable. As argued in the previous section, when $n_c = n_{clad}$ position of the maxima of modal coupling scales proportionally to the core radius R_c, which is also seen in Fig. 1. Locations of the maxima in the coupling strength match well with the predicted resonant condition for the optical defect size. From Fig. 1 one also observes a very slow decrease in coupling with inter-fiber separation. By analyzing the values of the coupling maxima as a function of distance up to $d = 100\mu m$ we observe a clear $|\delta\beta| \sim (L)^{-0.5}$ dependence. In the region of small inter-mirror separations $0.2\mu m < d < 1\mu m$ (left subplot of Fig. 1) one observes a substantial increase in the coupling strength that considerably surpasses supermode losses.

3 Spectral characteristics of coupling

In Fig. 2 we plot normalized coupling strength and supermode radiation losses as a function of λ for $R_c = 15\mu m$ and inter-fiber separations $d = 0, 0.2, 0.5\mu m$. For $d = 0.5\mu m$ the coupling strength is weak and on the order of the supermode radiation losses. As inter-fiber separation decreases $d = 0.2\mu m$, the coupling strength

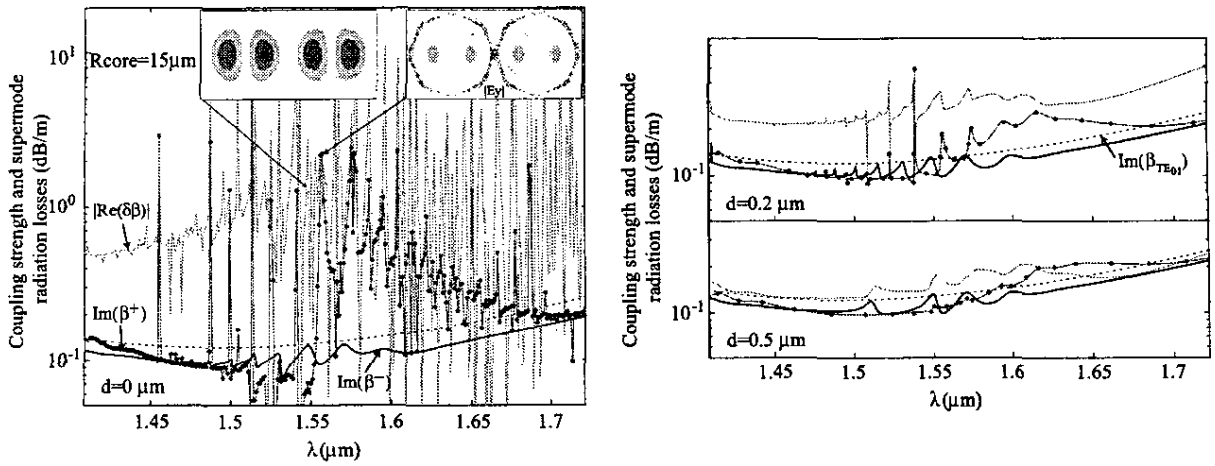

Fig. 2. Normalized coupling strength and supermode radiation losses as a function of λ for $R_c = 15\mu m$ and inter-fiber separations $d = 0, 0.2, 0.5\mu m$. For $1.4\mu m < \lambda < 1.55\mu m$, $d = 0$ coupling strength surpasses supermode radiation losses by a factor of 10. Sharp resonances in the coupling strength correspond to the accidental mode crossing of TE_{01} with high angular momenta modes of the reflector. In the insert $|Ey|$ fields are presented in the vicinity and directly at one of the sharp resonances.

exhibits a rapid increase across a broad frequency range together with appearance of many sharp resonances. When fibers are touching $d = 0$, coupling strength strongly dominates supermode radiation losses in a broad frequency interval around $1.55\mu m$. For a planar grating-defect-grating system with a dielectric profile of Fig. 1(insert) the resonance peak is, however, only several nanometers wide which is in contradiction with Fig. 2 broad resonant features. We believe that such broad resonances can be explained by a low quality factor of the resonant inter-mirror cavity due to a finite curvature of the mirror. Another prominent feature of Fig. 2 is a presence of sharp and broad regions of increase in the supermode losses. Because of a multimoded nature of hollow Bragg fibers, lowest loss TE_{01} mode exhibits multiple points of accidental degeneracies with higher loss modes. At such degeneracy points TE_{01}-like supermode demonstrates sharp loss increase by "picking-up" some of the higher order mode loss. In general, we find that broad frequency regions of supermode loss increase are due to interaction with low angular momenta modes. Thus, by inspecting a band diagram of a stand alone fiber we find that in a region $1.55\mu m < \lambda < 1.65\mu m$ an $m = 2$ mode crosses TE_{01} mode twice staying almost degenerate with it in the whole interval. In Fig. 2 this broad modal interaction region is characterized by an increase in supermode losses. On the other hand, by inspecting modal fields around sharp resonances (inserts in Fig. 2, $d = 0$) we conclude that such resonances correspond to the points of TE_{01} degeneracy with high angular momentum mirror modes having fields tightly confined to the Bragg reflectors. At resonance, such hybrid modes have intensity maxima in the inter-mirror cavity defect. Sharp resonances tend to disappear quickly with increase in the inter-fiber separation.

We have demonstrated that for a pair of touching hollow Bragg fibers frequency regions can be identified where inter-fiber modal coupling dominates strongly over supermode radiation losses, thus opening an opportunity for a design of a directional Bragg fiber coupler. Special care should be taken to avoid accidental modal degeneracies between the mode of operation and higher order modes.

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