Hybrid multicore photonic-crystal fiber for in-phase supermode selection

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We examine a hybrid multicore photonic-crystal fiber, where the cores are separated by high-index solid rods and the microstructure cladding is built on a hexagonal lattice of air holes in silica. Antiresonant reflection from high-index solid rods is shown to assist the field confinement in the cores of such a fiber. When the cores are doped with a laser-active material, the maximum gain is achieved for the in-phase supermode, which translates into a high-quality Gaussian-like beam profile in the far field. © 2010 Optical Society of America

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Novel types of fibers push the frontiers of optical science and technologies. Specifically designed photonic-crystal fibers (PCFs) have been shown to support single-mode guiding of light beams with large-mode areas, allowing a substantial increase in the output power of fiber-laser systems [1]. An alternative approach to the design of high-power fiber-laser systems involves the development of fibers with multiple cores allowing a coherent combination of laser radiation from individual cores [2–4]. The work in this direction has resulted in the creation of interesting multicore fiber structures for high-power fiber lasers with reduced optical nonlinearities and favorable thermomechanical properties [5]. A broad use of multicore fibers in fiber lasers is, however, impeded by the difficulties in suppressing high-order supermodes, which dramatically lower the beam quality of the fiber-laser output [2–4]. Several promising PCF-design strategies for supermode selection in multicore fiber lasers have been proposed. In particular, Michaille *et al.* [2] demonstrated stable phase locking in six- and seven-core fibers through evanescent mode coupling. Li *et al.* [3] examined an in-phase mode selection in multicore-PCF-based lasers using the Talbot effect. Chuncan *et al.* [4] showed that a microstructure fiber can serve as a mode-selecting component in a multicore fiber laser. Here, we demonstrate a principle of in-phase supermode selection in a multicore fiber laser based on a hybrid PCF structure where the cores are separated by high-index solid rods and the microstructure cladding is built on a hexagonal lattice of air holes in silica.

The generic structure of a hybrid M-core PCF considered in this work is illustrated in Figs. 1(a) and 1(b) for $M=2$ and 7, respectively. The fiber cladding includes a hexagonal lattice of air holes [black circles in Figs. 1(a) and 1(b)] in silica (shown in gray). The fiber cores are separated by high-refractive-index rods (white circles). Requirements to the fabrication of such fibers are fully compatible with the standard stack-and-draw PCF-production technology [6]. For the specific PCF design considered in this work, we assume that the fiber is made of silica (the refractive index is $n_1=1.444$), with the material of high-index inclusion rods being a Ge-doped silica with a refractive index of $n_2=1.6$. The material dispersion of silica and high-index inclusions are neglected. The pitch of the fiber-cladding lattice is set equal to $\Lambda=5\ \mu$m, while the diameters of the air holes and the Ge-doped rods are both taken equal to $d=2\ \mu$m.

High-index rods can significantly modify the properties of modes supported by the fiber. When the eigenmodes of the high-index rods can be resonantly excited, radiation tends to leak out of the PCF cores into the rods, inducing a strong loss. Off these resonances, however, the rods can serve as antiresonant reflectors [7–9], modifying the PCF modes. The transmission spectrum of an isolated silica core with $n_1=1.444$ surrounded by three rings of high-index rods (white circles) with $n_2=1.6$ [Fig. 1(c)] is presented in Fig. 1(d). The dips in transmission observed at Λ/λ

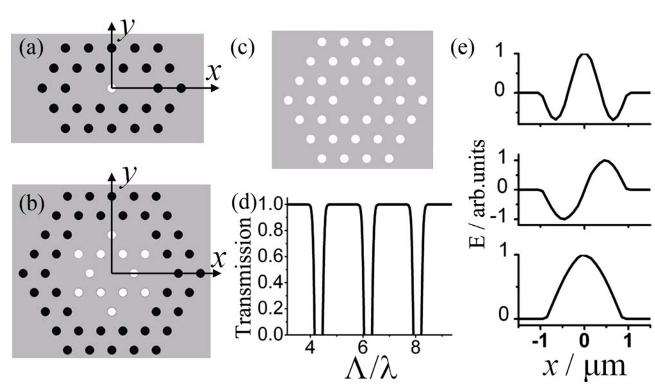

Fig. 1. (Color online) (a)–(c) Cross-section views of (a) a hybrid dual-core PCF, (b) a hybrid seven-core PCF, and (c) an all-solid bandgap PCF. White, gray, and black represent Ge-doped rods, undoped silica, and air holes, respectively. (d) The transmission spectrum of the all-solid bandgap PCF. (e) Electric field profiles in the first- (lower panel), second- (middle panel), and third- (upper panel) order modes of a high-index rod.

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≈ 4.53, 6.35, and 8.16 result from a resonant excitation of the first-, second-, and third-order eigenmodes of the high-index rods. The respective frequency bands where these modes of high-index rods are resonantly excited will be referred to as the first-, second-, and third-order resonant bands. For the first- and third-order modes of the rods, the spatial field profiles are symmetric with respect to $x=0$ [upper and lower panels in Fig. 1(e)]. For the second-order mode, the field profile in the rod is antisymmetric [middle panel in Fig. 1(e)].

We now examine the properties of modes supported by a dual-core fiber shown in Fig. 1(a) inside the transmission bands, where high-index rods provide antiresonant reflection [Fig. 1(d)]. Figures 2(a) and 2(b) present the spatial field profiles for the even and odd supermodes of such a dual-core fiber at $y=0$. The fields of these supermodes are localized in the cores. Inside the rods (dashed area), the field distribution is symmetric for the even supermodes and antisymmetric for the odd supermodes. Within the frequency bands where the modes of the high-index rods can be resonantly excited, the even and odd supermodes can display a distinctly different behavior [Figs. 2(c) and 2(d)]. In particular, within the band where the first-order mode of the high-index rod is excited, the field is mainly localized in the cores in the case of the odd supermode [lower panel in Fig. 2(d)], whose symmetry is different from the symmetry of the rod mode. By contrast, the even supermode in this frequency band tends to confine the field to the high-index rod [lower panel in Fig. 2(c)], because the even supermode and the rod mode have the same symmetry, with their dispersion curves approaching each other within the band of resonant excitation of rod modes. The field profile in the supermodes of a multicore fiber is thus controlled by the symmetry properties of the supermode and the modes of the high-index rod.

The above analysis of a dual-core hybrid fiber gives the key to understand the properties of a seven-core hybrid PCF with 12 high-index rods shown in Fig. 1(b). Within the transmission band centered at $\Lambda/\lambda=5$, the fiber supports an in-phase supermode [Fig. 3(a)] and six supermodes [one of them is shown in Fig. 3(b)] where the field distribution is neither purely symmetric nor purely antisymmetric. Within the first- and third-order resonant bands, the field of the in-phase supermode becomes localized inside the rods. However, within the second-order resonant band, the field of this supermode remains localized in the cores [Fig. 3(c) and the solid line in Fig. 3(d)], although the field profile in this regime is drastically different from the in-phase supermode field profile within the $\Lambda/\lambda=5$ transmission band [dashed curve in Fig. 3(d)]. The far-field beam profiles provided by the in-phase supermode of the seven-core hybrid PCF within the $\Lambda/\lambda=5$ transmission band and within the second-order resonant band are compared in Fig. 3(e). The far-field beam profile generated by the in-phase supermode within the second-order resonant band features much weaker sidebands [solid curve in Fig. 3(e) and the map in Fig. 3(f)] and is much closer to the far-field beam profile provided by a total-internal reflection (TIR) silica–air seven-core PCF where all the high-index rods are replaced with air holes [dashed-dotted curve in Fig. 3(e)].

We now consider a multicore PCF where the cores

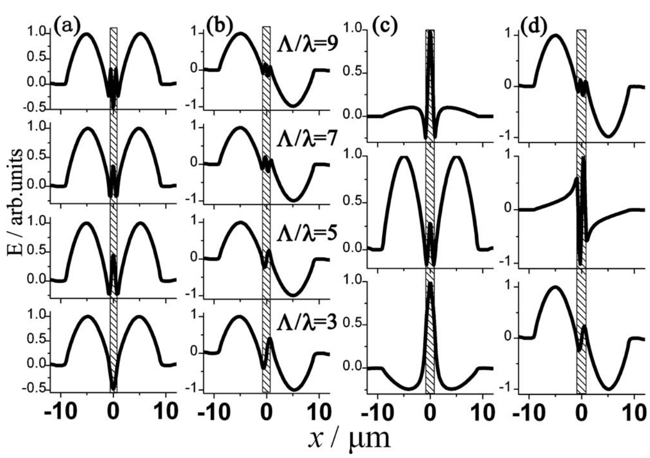

Fig. 2. Electric field profiles for the supermodes of the dual-core fiber shown in Fig. 1(a) at $y=0$: (a) even and (b) odd supermodes within transmission windows centered at (from bottom to top) $\Lambda/\lambda=3$, 5, 7, and 9; (c) even and (d) odd supermodes within the frequency bands of resonant excitation of the first- (lower panel), second- (middle panel), and third- (upper panel) order modes of the high-index rods (shown by the dashed areas).

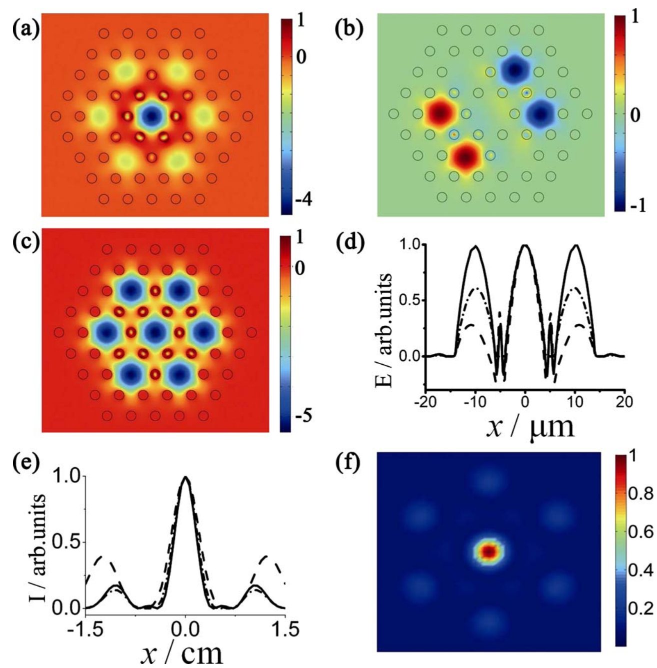

Fig. 3. (Color online) (a)–(c) Electric field profiles for the supermodes of the hybrid seven-core PCF: (a) the in-phase supermode and (b) a mixed-symmetry supermode within the transmission band centered at $\Lambda/\lambda=5$ and (c) the in-phase supermode in the second-order resonant band. (d),(e) Field profiles for the in-phase supermode at $y=0$ (d) inside the fiber and (e) in the far field within the second-order resonant band (solid curves) and the $\Lambda/\lambda=5$ transmission band (dashed curves). The field profiles for a seven-core TIR PCF are shown by the dashed-dotted lines. (f) Far-field beam profile from the in-phase supermode within the second-order resonant band.

are doped with a laser-active material providing a small-signal gain $g_0 = 0.2\ \mathrm{cm}^{-1}$ with a saturation intensity of $I_s = 64.4\ \mathrm{kW/cm}^2$. In the seven-core TIR PCF, the in-phase supermode has the lowest gain ($0.169\ \mathrm{cm}^{-1}$) among all the guided modes, while the maximum gain ($0.176\ \mathrm{cm}^{-1}$) is achieved for one of the out-of-phase supermodes. For the hybrid seven-core PCF, on the other hand, the maximum gain ($0.173\ \mathrm{cm}^{-1}$) is provided by the in-phase supermode. Since only the cores are doped with a gain material, the second largest gain ($0.136\ \mathrm{cm}^{-1}$), achieved for one of the out-of-phase supermodes, is much lower, enabling an efficient discrimination of in- and out-of-phase supermodes.

To quantify the advantages of a hybrid multicore PCF for in-phase supermode selection, we introduce the gain rank R_g for the in-phase supermode, which takes discrete values of $1, 2, \ldots, N_s$, where N_s is the number of supermodes supported by the fiber, with $R_g = 1$ if the in-phase supermode has the highest gain and $R_g = N_s$ if its gain is lowest among all the supermodes. In Fig. 4, we present this gain rank of the in-phase supermode calculated as a function of the P/I_{sat} ratio (with P being the laser power) for the hybrid and TIR seven-core PCFs. As can be seen from these calculations, the hybrid seven-core PCF provides a much broader dynamic range of in-phase supermode selection compared to a TIR PCF with a similar design. The confinement loss of the hybrid seven-core PCF (1.5 dB/m), calculated by applying the perfectly matched absorption layer boundary condition, is well below the gains attainable for in-phase supermodes and is therefore tolerable for fiber-laser systems.

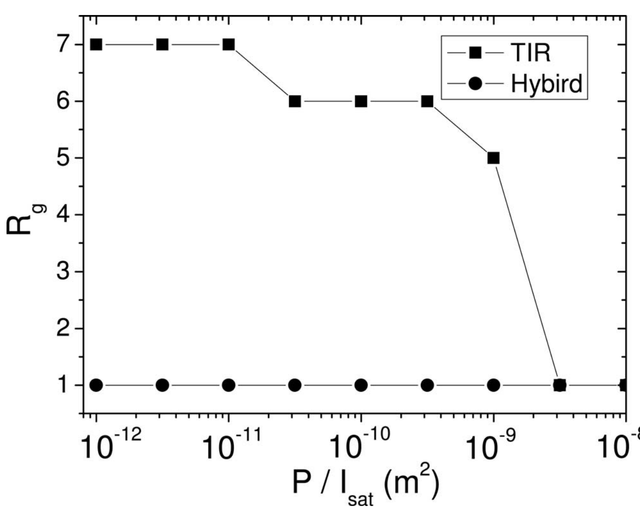

Fig. 4. Gain rank R_g of the in-phase supermode calculated as a function of the P/I_{sat} ratio for the hybrid (circles) and TIR (rectangles) seven-core PCFs.

It should be noted that, with the chosen fiber-cladding lattice pitch and diameters of air holes and Ge-doped rods, each core of the fiber is not endlessly single-mode. Our simulations performed for different Λ and d values confirm that the in-phase supermode selection capability of the considered fiber design is robust with respect to variations in Λ and d, remaining effective also within the range of wavelengths where the fiber cores support more than one guided mode.

We have shown here that antiresonant reflection from high-index solid rods enhances the field confinement in the cores of a hybrid multicore PCF. When the cores of such a fiber are doped with a laser-active material, the maximum gain is achieved for the in-phase supermode, which translates into a high-quality Gaussian-like beam profile in the far field.

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