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# Waveguide Modes of Hollow Photonic-Crystal Fibers

**S. O. Konorov*, A. B. Fedotov*, **, O. A. Kolevatova*, V. I. Beloglazov***, N. B. Skibina***, A. V. Shcherbakov***, and A. M. Zheltikov*, ****

** Physics Faculty, M. V. Lomonosov Moscow State University, Vorob'evy gory, 119899 Moscow, Russia*
*e-mail: zheltikov@top.phys.msu.su*
*** International Laser Center, M. V. Lomonosov Moscow State University, Vorob'evy gory, 119899 Moscow, Russia*
**** Technology and Equipment for Glass Structures Institute, pr. Stroitelei 1, 410044 Saratov, Russia*
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Waveguide modes of microstructure fibers with a hollow core and a two-dimensionally periodic cladding are studied experimentally and theoretically. The spectrum of modes guided in the hollow core of these fibers displays isolated maxima, indicating that waveguiding is supported due to the high reflectivity of the fiber cladding within photonic band gaps. The main properties of the spectrum of modes guided in a hollow core of a photonic-crystal fiber and radiation intensity distribution in these modes are qualitatively explained in terms of the model of a periodic coaxial waveguide. *© 2002 MAIK "Nauka/Interperiodica".*

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Fibers with a two-dimensionally periodic microstructure (two-dimensional photonic crystal) and a hollow core is one of the most interesting and promising types of microstructure fibers [1–4]. Such fibers were demonstrated for the first time by Cregan *et al.* [5]. The photonic band gap in the transmission spectrum of a two-dimensional periodic cladding in these fibers provides high reflection coefficients for electromagnetic radiation propagating along the hollow core of the fiber, allowing a specific regime of waveguiding to be implemented. This mechanism of waveguiding is of special interest for telecommunication applications, opening, at the same time, the ways to enhance nonlinear-optical processes, including high-order harmonic generation, in a gas medium filling the fiber core [6]. The possibility of using such fibers for laser manipulation of small-size particles was recently demonstrated by Benabid @et al.@ [7].

In spite of many potential exciting applications of hollow-core photonic-crystal fibers in telecommunication technologies, high-power laser physics, and nonlinear optics, only a few experiments have been performed with such fibers. This is largely due to the difficulties one encounters when fabricating hollow photonic-crystal fibers. In this paper, we present the results of our experimental and theoretical investigations of glass fibers with a hollow core and a two-dimensionally periodic cladding. Such fibers may guide electromagnetic radiation due to the high reflectivity of the cladding within photonic band gaps, holding much promise for telecommunication applications, high-power laser radiation guiding, laser manipulation and laser guiding of atoms and charged particles, high-order harmonic generation, and transport of ultrashort laser pulses. We will demonstrate that the main properties of the spectrum of modes guided in the hollow core of photonic-crystal fibers can be qualitatively explained within the framework of the model of a periodic coaxial waveguide.

Microstructure fibers were fabricated with the use of a preform consisting of a set of identical glass capillaries. Seven capillaries were removed from the central part of the preform for the hollow core of photonic-crystal fibers. The cross-section image of a fiber fabricated by drawing such a preform is presented in Fig. 1. A typical period of the structure in the cladding of the fiber shown in Fig. 1 is about 5 μm. The diameter of the hollow core of the fiber is then approximately equal to 13 μm. The length of fiber samples employed in our experiments ranged from several centimeters up to 1 m.

The idea of lowering the magnitude of optical losses in a hollow fiber with a periodically microstructured cladding relative to the magnitude of optical losses in a hollow fiber with a solid cladding is based on the high reflectivity of a periodic structure within photonic band gaps [8]. In hollow fibers, the refractive index of the core is lower than the refractive index of the cladding. Therefore, the propagation constants of hollow-fiber modes have nonzero imaginary parts, and the propagation of light in such fibers is accompanied by radiation losses. The coefficient of optical losses in hollow fibers scales [9] as $\lambda^2/a^3$, where $\lambda$ is the radiation wavelength and $a$ is the inner radius of the fiber. Such a behavior of the magnitude of optical losses prevents one from using hollow fibers with very small inner diameters in nonlinear-optical experiments [10]. Our estimates show that the magnitude of radiation losses for the fundamental mode of a hollow fiber with a fused silica cladding and an inner radius of 6.5 μm may reach 20 $cm^{-1}$ for 0.8-μm

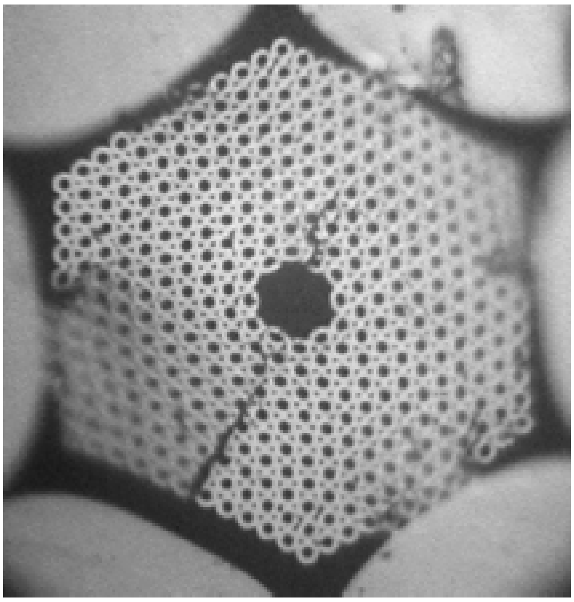

**Fig. 1.** Cross-sectional image of a microstructure fiber with a two-dimensionally periodic cladding consisting of an array of identical capillaries. This periodic cladding supports guided modes in the hollow core of the fiber due to the high reflectivity of a periodic structure within photonic band gaps. The hollow core of the fiber is formed by removing seven capillaries from the central part of the structure. The period of the structure in the cladding is about 5 μm and the core diameter is about 13 μm.

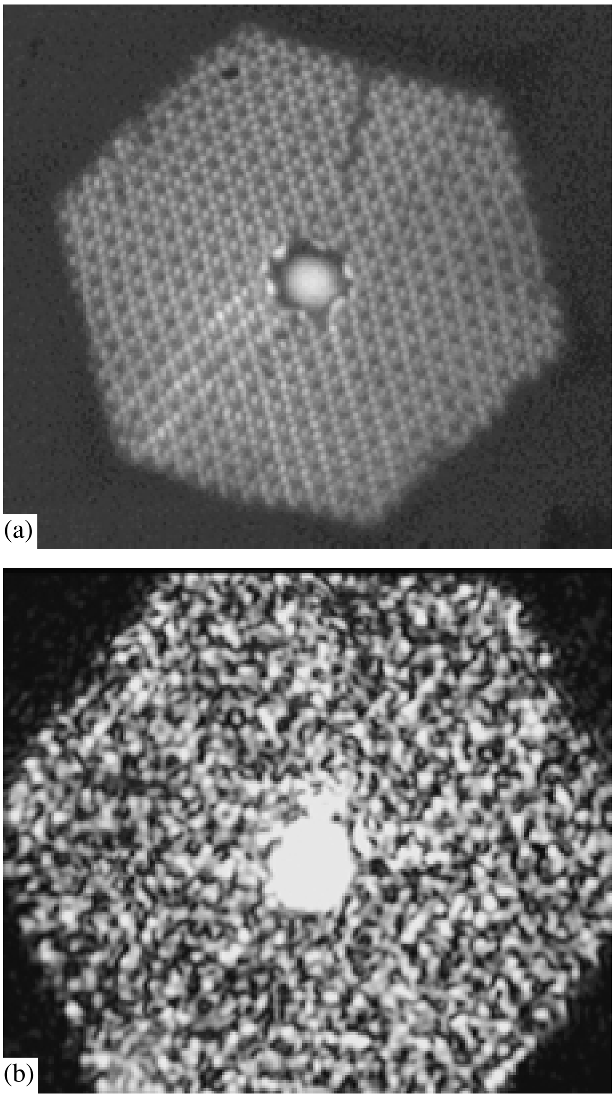

**Fig. 2.** Radiation intensity distribution in the cross section of a hollow photonic-crystal fiber with a period of the structure in the cladding of about 5 μm and the core diameter of approximately 13 μm. (a) A waveguide mode is excited in the hollow core with a broad beam of incoherent light. (b) The fundamental waveguide mode of the hollow core is excited with 633-nm diode-laser radiation.

radiation, which, of course, imposes serious limitations on applications of such fibers. Radiation losses can be radically reduced in the case of hollow fibers with a periodic cladding.

Our experimental studies confirm the possibility of using hollow photonic-crystal fibers with a core diameter of about 13 μm to guide coherent and incoherent radiation. Figure 2 displays the spatial distributions of intensity of incoherent (Fig. 2a) and coherent (Fig. 2b) radiation obtained by imaging the output end of a hollow photonic-crystal fiber with the above-specified parameters. Optimizing the geometry of coupling of laser radiation into the fiber, we were able to achieve a high degree of light-field confinement in the hollow core of the fiber without losing too much energy through mode excitation in the photonic-crystal cladding (Fig. 2a). The spatial distribution of radiation intensity at the output end of the fiber under these conditions corresponded to the fundamental waveguide mode.

To investigate the spectrum of modes guided in the hollow core of photonic-crystal fibers, we used a diaphragm to separate radiation transmitted through the hollow core from radiation guided by the cladding. The spectra of modes supported by the hollow core of photonic-crystal fibers were measured within the range of wavelengths from 450 up to 1000 nm. These spectra displayed characteristic well-pronounced isolated peaks (Fig. 3a). Similar peaks in transmission spectra of hollow photonic-crystal fibers have been observed earlier by Cregan *et al.* [5]. The origin of these peaks is associated with the high reflectivity of a periodically structured fiber cladding within photonic band gaps, which substantially reduces radiation losses in guided modes within narrow spectral ranges. Radiation with wavelengths lying away from photonic band gaps of the cladding leaks from the hollow core. Such leaky radiation modes are characterized by high losses, giving virtually no contribution to the signal at the output of the fiber.

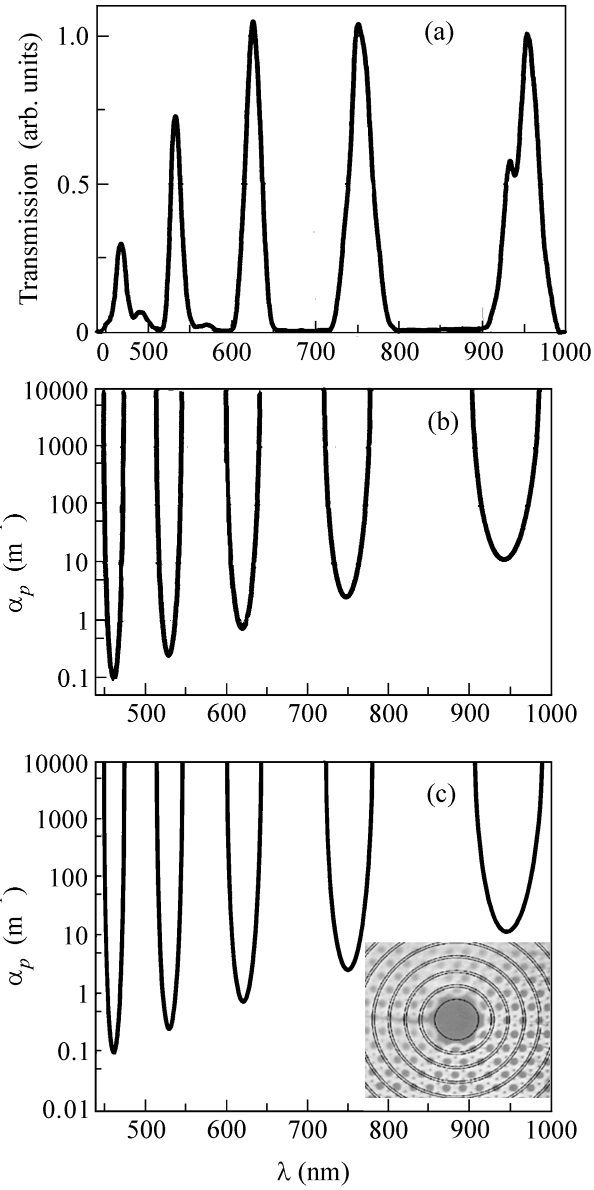


**Fig. 3.** (a) The spectrum of modes measured for a hollow photonic-crystal fiber with a period of the structure in the cladding of about 5 μm and the core diameter of approximately 13 μm. (b) The attenuation coefficient of the $TE_{01}$ waveguide mode calculated as a function of the wavelength for a periodic coaxial waveguide (see the inset) with $r_0$ = 6.5 μm, $b$ = 4.3 μm, and $c$ = 0.7 μm.

To model the spectrum of guided modes and the spatial distribution of radiation intensity in a hollow photonic-crystal fiber, we employed the model of a periodic coaxial waveguide. A two-dimensional periodic structure of the fiber cladding is replaced within the framework of this model by a system of coaxial glass cylinders (see the inset in Fig. 3b) with a thickness $b \approx$ 4.3 μm and the inner radius of the $i$th cylinder equal to $r_i = r_0 + i(b + c)$, where $r_0$ is the radius of the hollow core (about 6.5 μm for our fiber) and $c$ is the thickness of the air gap between the cylinders. The latter parameter was chosen in such a way as to include the air-filling fraction of the fiber cladding (about 14% in our experiments) and was set equal to approximately 0.7 μm for our calculations. In our theoretical analysis, we employed the results of earlier work [11, 12] devoted to the properties of modes in coaxial waveguides.

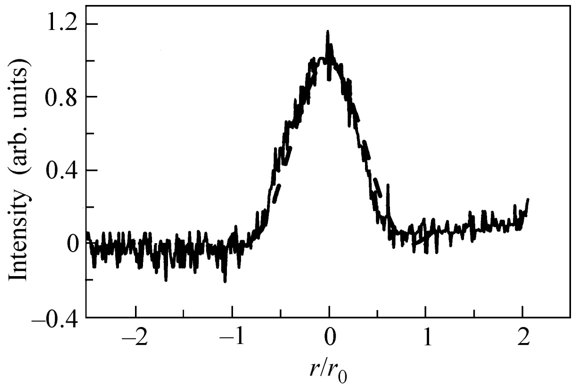


**Fig. 4.** Transverse intensity distribution of electromagnetic radiation (solid line) measured at the output of a hollow-core photonic-crystal fiber and (dashed line) calculated with the use of the model of a periodic coaxial waveguide.

Figure 3b presents the attenuation coefficient for the $TE_{01}$ mode calculated as a function of the wavelength for a periodic coaxial waveguide with the above-specified parameters. Comparing these results with the experimental data shown in Fig. 3a, we find that the model of a periodic coaxial waveguide provides qualitatively adequate predictions for the positions and the widths of spectral bands where the hollow core of a photonic-crystal fiber can guide radiation with virtually no losses. The model of a periodic coaxial waveguide, as can be seen from Figs. 4 and 5, also gives a satisfactory qualitative description for radiation intensity distributions in the fundamental (Fig. 4) and higher order (Fig. 5) waveguide modes of a photonic-crystal fiber. Our theoretical results are consistent on the qualitative level with the predictions of simulations [13] performed with the use of a more accurate and more sophisticated model of a hollow-core photonic-crystal fiber.

The spatial distribution of 633-nm diode-laser radiation (this wavelength falls within one of the passbands in Fig. 3, corresponding to the guided modes of our fiber) at the output of an 8-cm hollow photonic-crystal fiber shown in Fig. 5b indicates the existence of multimode regimes of waveguiding around this wavelength. As shown in [6], multimode waveguiding regimes in hollow photonic-crystal fibers can be employed to enhance high-order harmonic generation in nonlinear gases filling the hollow core of photonic-crystal fibers. The waveguide contribution to the mismatch of propagation constants related to guided modes of the pump and harmonic radiation increases with a decrease in the

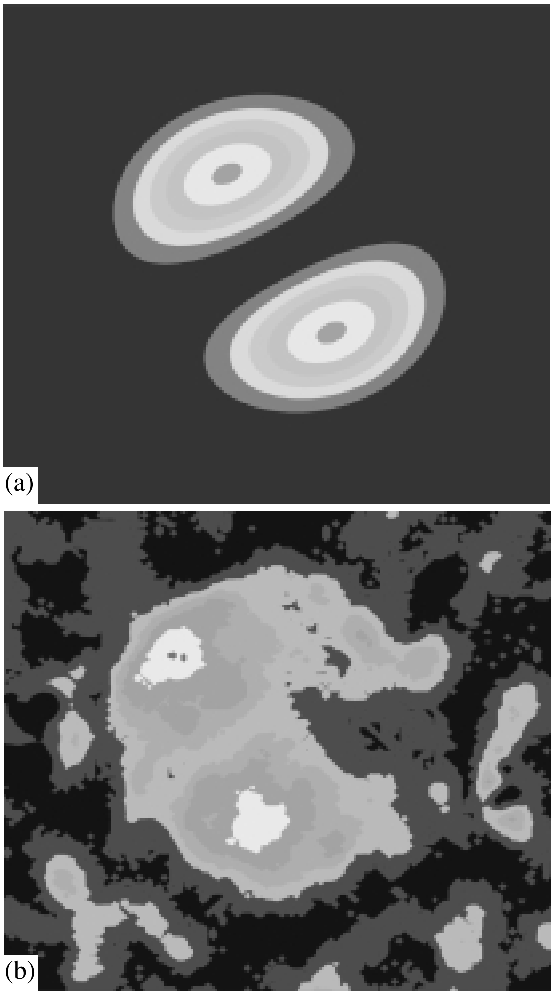


**Fig. 5.** (a) Transverse distribution of the electric field squared in a higher order mode of a hollow-core photonic-crystal fiber calculated with the use of the model of a periodic coaxial waveguide. (b) Transverse intensity distributions of electromagnetic radiation measured at the output of a hollow-core photonic-crystal fiber with a higher order waveguide mode of the fiber excited with 633-nm radiation of a diode laser.

core diameter of a hollow fiber [10]. Our photonic-crystal fiber with a small core diameter is, therefore, characterized by a strong dispersion of guided modes, allowing considerable phase mismatches related to the material dispersion of nonlinear gases to be compensated. This efficient phase-mismatch compensation becomes possible due to the unique properties of hollow photonic-crystal fibers, as the leaky modes guided in hollow fibers with a solid cladding and a diameter of the hollow core of about 13 μm would have, as mentioned above, unacceptably high losses.

Since hollow waveguides with a periodic cladding permit radiation losses characteristic of hollow-waveguide modes to be radically reduced, waveguides of this type seem to offer new solutions in guiding high-power laser radiation and enhancing nonlinear-optical processes, including self- and cross-phase modulation, as well as optical harmonic generation and wave mixing. The results of preliminary experiments and theoretical studies [14] suggest that polycapillary glass structures and photonic-crystal fibers can guide and focus ultrashort x-ray pulses, including ultrashort field waveforms synthesized from high-order harmonics. Strong waveguide dispersion, inherent in hollow fibers with a small core radius, can be employed to compensate for the initial chirp and, eventually, to compress short x-ray pulses.

The fibers created and studied in this work can be used for the creation of high-sensitivity gas sensors based on linear and nonlinear spectroscopic techniques. Waveguiding regimes attainable with hollow photonic-crystal fibers with a small core diameter allow the amount of gas necessary for spectral analysis to be considerably reduced and permit nonlinear-spectroscopic studies to be performed with low-power laser pulses. In particular, experiments on four-wave mixing in hollow fibers (see, e.g., [15]) are usually carried out with capillaries with a typical inner diameter on the order of 100 μm (the use of capillaries with smaller inner diameters leads to the fast growth of optical losses). The fibers considered in this paper would allow comparable levels of nonlinear signal to be achieved with 60 times less powerful laser pulses. The spectra of modes guided by these fibers seem optimal for laser frequency conversion through stimulated Raman scattering.

Thus, we have created and investigated fibers with a hollow core and a photonic-crystal cladding with a period of the structure in the cladding of about 5 μm and the core diameter of approximately 13 μm. Electromagnetic radiation is guided in the hollow core of such fibers due to the high reflectivity of the cladding within photonic band gaps. This regime of waveguiding allows optical losses of guided modes to be radically reduced as compared with waveguide modes in hollow fibers with a solid cladding. Due to their remarkable properties, hollow photonic-crystal fibers created and investigated in this work hold much promise for telecommunication applications and can be used to guide high-power laser pulses. These fibers offer a unique opportunity of implementing nonlinear-optical interactions of waveguide modes with transverse sizes of several microns in a gas medium, opening the ways to improve the efficiency of optical frequency conversion for ultrashort pulses and enhance high-order harmonic generation. The fibers studied in this paper can be employed to produce and guide ultrashort pulses, to manipulate atoms and charged particles, and to develop highly sensitive gas sensors. We have shown that the main properties of the spectrum of modes guided in the hollow core of photonic-crystal fibers, as well as the radiation intensity distribution in the fiber core can be qualitatively explained within the framework of the model of a periodic coaxial waveguide.

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