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Waveguiding properties and the spectrum of modes of hollow-core photonic-crystal fibres

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***Abstract*. Glass fibres 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 fibres displays isolated maxima, indicating that waveguiding is supported due to the high reflectivity of the fibre cladding within photonic band gaps. The main properties of the spectrum of modes guided in a hollow core of a photonic-crystal fibre and radiation intensity distribution in these modes are qualitatively explained in terms of the model of a periodic coaxial waveguide.**

Keywords: *microstructure fibres, photonic crystals.*

Fibres with a cladding in the form of a two-dimensionally periodic microstructure (two-dimensional photonic crystal) and a hollow core are one of the most interesting and promising types of microstructure fibres [1 – 4]. Such fibres were demonstrated for the first time in paper [5]. The photonic band gap in the transmission spectrum of a two-dimensional periodic cladding in these fibres provides high reflection coefficients for electromagnetic radiation propagating along the hollow core of the fibre, 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 fibre core [6]. The possibility of using such fibres for laser manipulation of small-size particles was recently demonstrated in Ref. [7].

In spite of many potential exciting applications of hollow-core photonic-crystal fibres in telecommunication technologies, high-power laser physics, and nonlinear optics, only a few experiments have been performed with such fibres. This is largely due to the fact that such fibres are rather difficult to fabricate.

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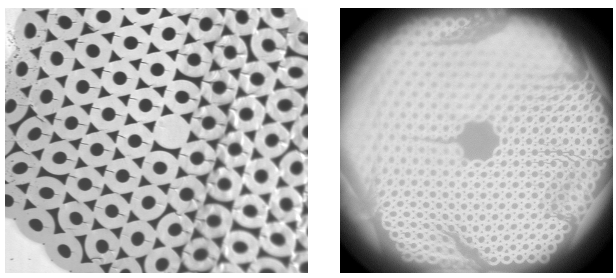
In this paper, we present the results of our experimental and theoretical investigations of glass fibres with a hollow core and a two-dimensionally periodic cladding. Such fibres may guide electromagnetic radiation due to the high reflectivity of the cladding within photonic band gaps, holding much promise 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 fibres can be qualitatively explained within the framework of the model of a periodic coaxial waveguide.

Microstructure fibres were fabricated with the use of a preform consisting of a set of identical glass capillaries. The image in Fig. 1a shows the cross section of a fibre fabricated by drawing such a preform with the central capillary replaced by a solid glass rod with no hole at the centre. A microstructure fibre produced as a result of this process had a solid core, guiding light through total internal reflection. Seven capillaries were removed from the central part of the preform for the hollow core of photonic-crystal fibres. The cross-section image of a fibre fabricated by drawing such a preform is presented in Fig. 1b. A typical period of the structure in the cladding of the fibre shown in this figure is about 5 μm. The diameter of the hollow core of the fibre is then approximately equal to 13 μm. The length



a b

Figure 1. Cross-section images of microstructure fibres with two-dimensionally periodic claddings consisting of arrays of identical capillaries (with a period of about 5 μm). In a fibre having a rod with no hole at the centre of the structure, waveguiding is achieved due to total internal reflection (a). In a fibre with a hollow core (having a diameter of about 13 μm), the core is formed by removing seven capillaries from the central part of the structure. Air-guided modes are supported in the hollow core of such a fibre due to the high reflectivity of a periodic structure of the cladding within photonic band gaps (b).

of fibre samples employed in our experiments ranged from several centimetres up to 1 m.

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

To qualitatively illustrate the idea of lowering the magnitude of optical losses in a hollow waveguide with a periodic microstructure cladding relative to the magnitude of optical losses in a hollow waveguide with a solid cladding, we will employ the result well known from the analysis of radiation propagation in a planar waveguide with a periodic cladding [8]. The decrease in the magnitude of optical losses in a hollow planar waveguide with a periodic cladding relative to the magnitude of optical losses in a hollow planar waveguide with a solid cladding can be quantified by determining the ratio of the logarithm of the coefficient of reflection from a periodic structure to the logarithm of the coefficient of reflection from the wall of a hollow waveguide [8, 10]. Around the centre of the photonic band gap in the reflection spectrum of the periodic structure in the waveguide cladding with a sufficiently large number of layers N, the coefficient of optical losses in a hollow planar waveguide with a periodic cladding α_{pbg} decreases exponentially [8] relative to the coefficient of losses in a hollow waveguide with a solid cladding α_{h} with the increase in the number of modulation periods of the refractive index in the waveguide cladding: $\alpha_{\text{pbg}}/\alpha_{\text{h}} \propto a\exp(-2|\kappa|Nd)$, where κ is the coupling coefficient of the forward and backward waves in the periodic structure of the waveguide cladding and d is the modulation period of the refractive index in the waveguide cladding. Thus, hollow waveguides with a periodic cladding allow optical losses characteristic of hollow-waveguide modes to be considerably reduced.

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

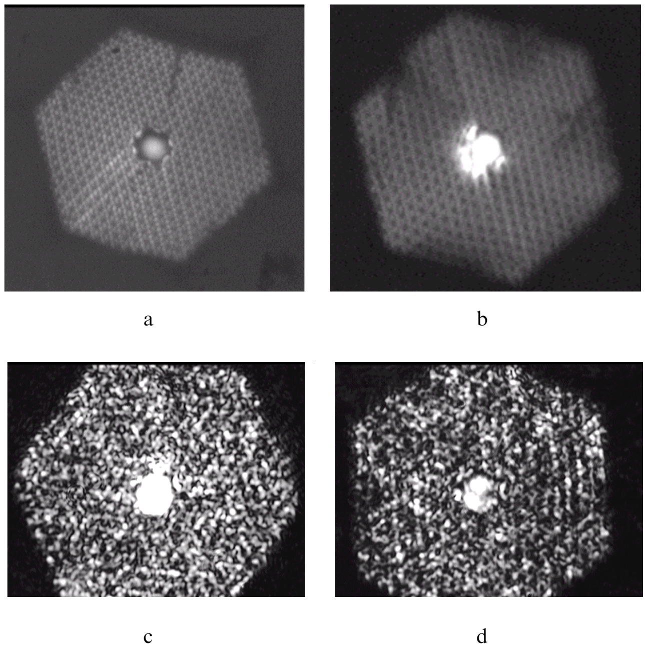


Figure 2. Radiation intensity distribution in the cross section of a hollow photonic-crystal fibre with a period of the structure in the cladding of about 5 μm and the core diameter of approximately 13 μm. A waveguide mode is excited in the hollow core with (a) a broad beam of incoherent light, which also excites cladding modes, (b) a narrow beam of incoherent light, resulting in virtually no excitation of cladding modes (camera is saturated to visualise radiation propagating along the cladding), (c) diode-laser radiation with a wavelength of 633 nm, leading to the excitation of the fundamental mode, and (d) 633-nm diode-laser radiation, resulting in the excitation of higher order waveguide modes in the hollow core of a photonic-crystal fibre.

To investigate the spectrum of modes guided in the hollow core of photonic-crystal fibres, 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 fibres were measured within the range of wavelengths from 450 up to 1000 nm. These spectra displayed characteristic well-pronounced isolated peaks (Fig. 3a). Transmission of a 10-cm segment of a hollow-core photonic-crystal fibre at 633 nm was about 10%. Similar peaks in transmission spectra of hollow photonic-crystal fibres have been observed earlier in paper [5]. The origin of these peaks is associated with the high reflectivity of a periodically structured fibre 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 characterised by high losses, giving virtually no contribution to the signal at the output of the fibre.

To understand the properties of the spectrum of guided modes and the spatial distribution of radiation intensity in a hollow photonic-crystal fibre, we employed the model of a periodic coaxial waveguide. A two-dimensional periodic structure of the fibre cladding is replaced within the framework of this model by a system of coaxial glass cylinders with a thickness $b \approx 4.3$ μm and the inner radius of the ith 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 fibre) and c is the thickness of the air gap between the cylinders. The latter

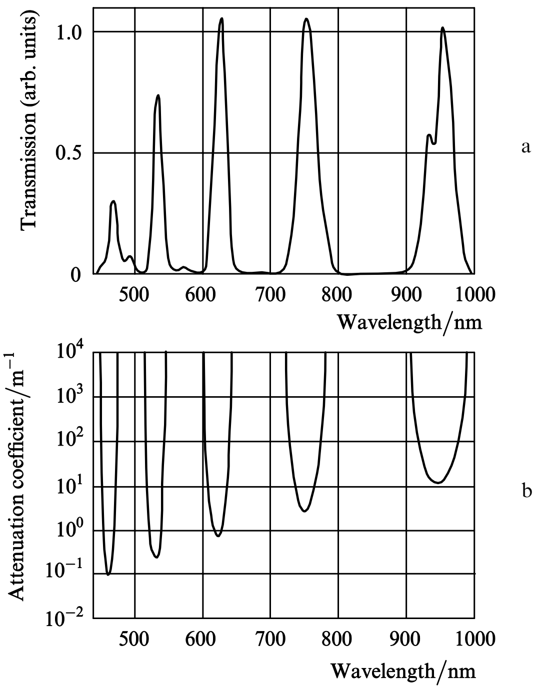


Figure 3. (a) The spectrum of modes measured for a hollow photonic-crystal fibre with a period of the structure in the cladding of about 5 μm and the core diameter of approximately 13 μm. (b) The attenuation coefficient of the TE_{01} waveguide mode calculated as a function of the wavelength for a periodic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

parameter was chosen in such a way as to comply with the air-filling fraction of the fibre 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], devoted to the properties of modes in coaxial waveguides.

Fig. 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 fibre can guide radiation with minimal losses. The model of a periodic coaxial waveguide, as can be seen from Fig. 4, also gives a satisfactory qualitative description of radiation intensity distribution in waveguide modes of a photonic-crystal fibre. Our theoretical results are consistent on the qualitative level with the predictions of simulations [12] performed with the use of a more accurate and more sophisticated model of a hollow-core photonic-crystal fibre.

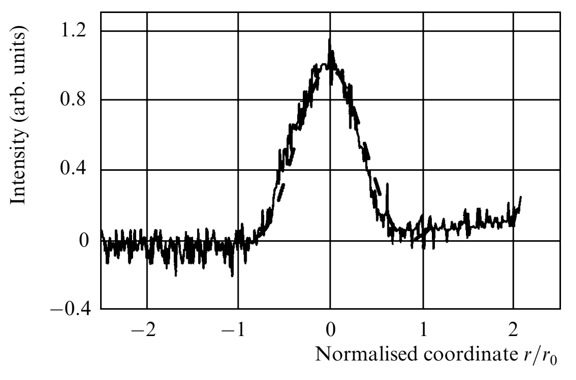


Figure 4. Transverse intensity distribution of electromagnetic radiation (solid line) measured at the output of a hollow-core photonic-crystal fibre and (dashed line) calculated with the use of the model of a periodic coaxial waveguide.

The spatial distribution of 633-nm diode-laser radiation (this wavelength falls within one of the passbands, corresponding to the guided modes of our fibre) at the output of an 8-cm hollow photonic-crystal fibre shown in Fig. 2d indicates the existence of multimode regimes of waveguiding around this wavelength. Such regimes of waveguiding can be employed to enhance high-order harmonic generation in nonlinear gases filling the hollow core of photonic-crystal fibres. Phase-matching conditions should be satisfied for higher efficiencies of optical harmonic generation, requiring in the case of an optical fibre the equality of the propagation constant of the harmonic waveguide mode and the propagation constant of the nonlinear polarisation induced in the gas [13]. 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 core diameter of a hollow fibre [10]. Our photonic-crystal fibre with a small core diameter is, therefore, characterised 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 fibres, as the leaky modes guided in hollow fibres 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. As shown in [6], optical harmonic generation can be phase-matched in high-order waveguide modes of hollow-core photonic-crystal fibres with an appropriate choice of fibre parameters, as well as the content and the pressure of the gas filling the fibre core. These fibres also suggest new solutions for guiding high-power laser pulses of the existing lasers and laser systems that are currently under construction.

Experimental investigations performed with the use of the created fibres show that such glass structures can be employed to transport and, if necessary, to focus soft X rays [14, 15]. Experiments and theoretical studies also suggest that polycapillary glass structures and photonic-crystal fibres can guide and focus ultrashort X-ray pulses, including ultrashort field waveforms synthesised from high-order harmonics. Strong waveguide dispersion, inherent in hollow fibres with a small core radius, can be employed to compensate for the initial chirp and, eventually, to compress short X-ray pulses.

The fibres 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 fibres 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 fibres (see, e.g., [14, 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 a fast growth in optical losses). The fibres 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 fibres seem optimal for laser frequency conversion through stimulated Raman scattering.

Thus, we have created and investigated fibres 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. We have measured transmission spectra and radiation intensity distributions for the modes guided in the hollow core of such fibres. The main properties of the spectra of air-guided modes in hollow photonic-crystal fibres and radiation intensity distributions in these modes can be qualitatively explained in terms of the model of a periodic coaxial waveguide. Electromagnetic radiation is guided in the hollow core of such fibres 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 fibres with a solid cladding. Due to their remarkable properties, hollow photonic-crystal fibres created and investigated in this work hold much promise for telecommunication applications and can be used to guide high-power laser pulses. Calculations carried out for a hollow coaxial waveguide with a periodic cladding [16] show that optical losses in such waveguides can be made less than 1 dB km^{-1}. Serious technical difficulties have to be overcome to achieve a comparable level of losses for hollow fibres with a cladding in the form of a two-dimensional photonic crystal.

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