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Transmission spectra and optical losses of infiltration-modified hollow photonic-crystal fibres

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Abstract. **Transmission spectra and optical losses of hollow photonic-crystal fibres (PCFs) filled with liquid-phase materials are studied. For hollow PCFs with a cladding period of about 5 μm and a core diameter of about 50 μm, infiltration with water increases optical losses by approximately two orders of magnitude relative to the optical losses of the same PCF before infiltration.**

Keywords: *photonic crystals, waveguide modes, periodic structures.*

1. Introduction

Photonic-crystal fibres (PCFs) [1 – 3] is a new type of optical waveguides offering new solutions in nonlinear [4, 5] and ultrafast [6] optics, nonlinear spectroscopy [7] and microscopy [8], optical metrology [9], and laser biomedicine [10]. With the air holes in the microstructure cladding infiltrated with materials possessing different dielectric properties, PCFs can perform new functions [11]. Recent experiments have demonstrated that PCF infiltration suggests the ways to create polyfunctional fibre-optic sensors [12 – 15] for a highly sensitive detection of biomolecules [16, 17], as well as for liquid- [18] and gas-phase [19, 20] analysis.

Infiltration can be used to engineer the properties of waveguide modes in PCFs and to develop a new class of fibre-optic switches. In particular, the infiltration of silica-core PCFs with liquid-crystal (LC) materials can substantially change the regime of radiation waveguiding in the fibre [21, 22]. Before the infiltration, guided modes in such fibres are supported by total internal reflection. By contrast, an LC-infiltrated periodic cladding can guide light in the silica core by its photonic band gaps (PBGs). The PBGs in such fibres can be tuned by applying an external voltage [21] or by using a control optical signal [22]. These findings suggest the ways toward the creation of highly efficient fibre-optic switches.

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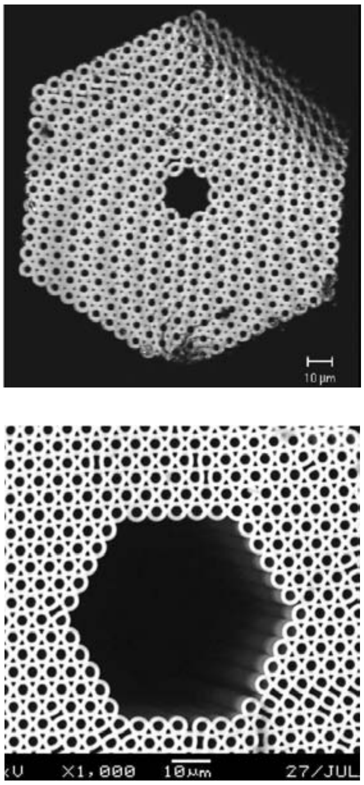
In this work, we investigate optical properties of hollow PCFs filled with liquid-phase materials. We will show that the infiltration of hollow PCFs with a liquid whose refractive index n_f meets the inequality $n_a < n_f < n_2$ (n_a is the refractive index of the air and n_2 is the refractive index of the solid-phase material of the fibre) increases the optical losses of guided modes confined to the core of the PCF. In particular, for a hollow PCF with period of about 5 μm and a core diameter of about 50 μm, infiltration with water increases optical losses by approximately two orders of magnitude. This result can be qualitatively understood in terms of the model of a hollow coaxial Bragg waveguide.

2. Structure and optical properties of hollow photonic-crystal fibres

2.1 Structure of experimental PCF samples

We experimentally studied the influence of infiltration on optical properties of hollow PCFs of two types. Hollow PCFs of the first type had a periodic cladding with a period $\Lambda \approx 4.6$ μm and a core diameter $D \approx 14$ μm. A typical scanning electron microscope image of the PCF cross section is shown in Fig. 1a. Such fibres can support isolated guided modes of laser radiation within the optical range of wavelengths [23, 24]. Their transmission spectra display well-pronounced peaks (Fig. 2a) related to the PBGs of the periodic cladding. A typical intensity attenuation length l for waveguide modes corresponding to maximum transmission is 10 – 15 cm.

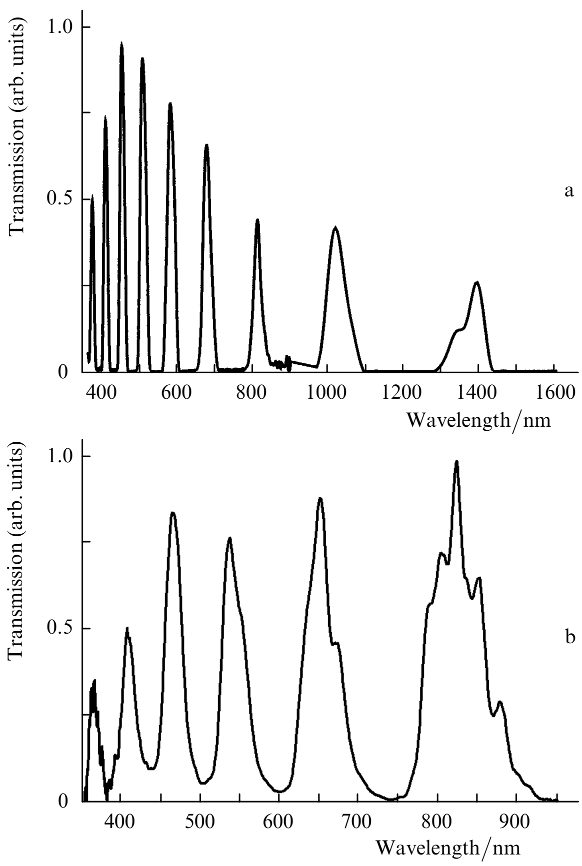
Hollow PCFs of the second type have a periodic cladding with a period $\Lambda \approx 5$ μm and a core diameter $D \approx 50$ μm (Fig. 1b). Fibres of this type offer much promise for the transportation and nonlinear-optical transformation of intense laser pulses [25]. Such fibres can be employed for the creation of gas analysers [26], novel fibre-optic sensors [18], as well as frequency converters [27] and compressors of high-power laser pulses [28]. Transmission spectra of the second-type hollow PCFs also feature characteristic peaks (Fig. 2b) related to the PBGs of the two-dimensionally periodic cladding. In view of the large ratio of the core diameter D to the radiation wavelength λ within the optical range, the fibres of this type are essentially multimode. As the PCFs of the second type are characterised by larger ratios D/λ relative to the first-type PCFs, diffraction phenomena in the second-type PCFs are much weaker and optical losses are lower. Typical intensity attenuation lengths for waveguide modes in the second-type PCFs range from 100 to 200 cm.



a

b

Figure 1. Scanning electron microscope images of hollow photonic-crystal fibres of the first (a) and second (b) types.



a

b

Figure 2. Typical transmission spectra measured for hollow photonic-crystal fibres of the first (a) and second (b) types. The fibre length is 10 cm.

2.2 Numerical analysis of guided modes in hollow PCFs

Two numerical methods were employed to understand the properties of the guided modes and transmission spectra of hollow PCFs. The first method involved a numerical solution of the wave equations for the transverse components of the electric field represented as expansions in orthogonal basis functions. The wave equation with the relevant boundary conditions is then reduced to an eigenvalue and eigenfunction problem for the corresponding matrix equation [29]. We consider a waveguide where a central cylindrical part with a radius R and a complicated refractive index profile is surrounded by a solid uniform cladding with the refractive index n_{cl}. The two-dimensional refractive index profile $n(r,\varphi)$ in the central part of the structure is represented in cylindrical coordinates r and φ as an expansion in polynomials and periodic functions in such a way as to provide the best fit for the hollow core and the photonic-crystal cladding of the PCF (examples of such expansions can be found in [30, 31]). The wave equations for the transverse components $\psi = \psi(r,\varphi)$ of the electromagnetic field are written as

$$\frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\psi}{\partial\varphi^2} + V^2(r,\varphi)\psi = W2\psi, \tag{1}$$

where $V^2(r,\varphi) = k^2R^2[n^2(r,\varphi) - n_{\text{cl}}^2]$; k is the wave number, $W^2 = k^2R^2(n_{\text{eff}}^2 - n_{\text{cl}}^2)$; $n_{\text{eff}} = \beta/k$ is the effective mode index; and β is the propagation constant for the waveguide mode, defined as an eigenvalue of Eqn (1).

Inside the central cylindrical domain with the radius R, the field is represented [29] as the expansion

$$\psi(r,\varphi) = \sum_{mn} A_{mn}\psi_{mn}(r,\varphi) \tag{2}$$

in the set of basis functions

$$\psi_{mn}(r,\varphi) = \mathrm{e}^{\mathrm{i}m\varphi}\left[\frac{\sin(n\pi r)}{\pi r} + \alpha_{mn}(W) + \beta_{mn}(W)r\right], \tag{3}$$

where

$$\alpha_{mn}(W) = n\delta_{m0}\left[1 + K_0(W)\frac{(-1)^n - 1}{WK_0'(W)}\right]; \tag{4}$$

$$\beta_{mn}(W) = n\left[-\delta_{m0} + (1-\delta_{m0})K_m(W) \times \frac{(-1)^n}{WK_m'(W) - K_m(W)}\right]; \tag{5}$$

and $K_m(x)$ is the modified Bessel function of the m order.

Outside the inner domain with the radius R, the solution to Eqn (1) is represented as

$$\psi(r,\varphi) = \sum_m B_m \mathrm{e}^{\mathrm{i}m\varphi} K_m(Wr). \tag{6}$$

Substitution of Eqns (2) and (6) into Eqn (1) yields an eigenfunction and eigenvalue problem for a matrix equation, with eigenfunctions and eigenvalues identified as field intensity profiles and propagation constants of waveguide modes, respectively. Figures 3a – 3d display the field intensity profiles in the guided modes of the second-type PCFs calculated with the use of the above-described technique.

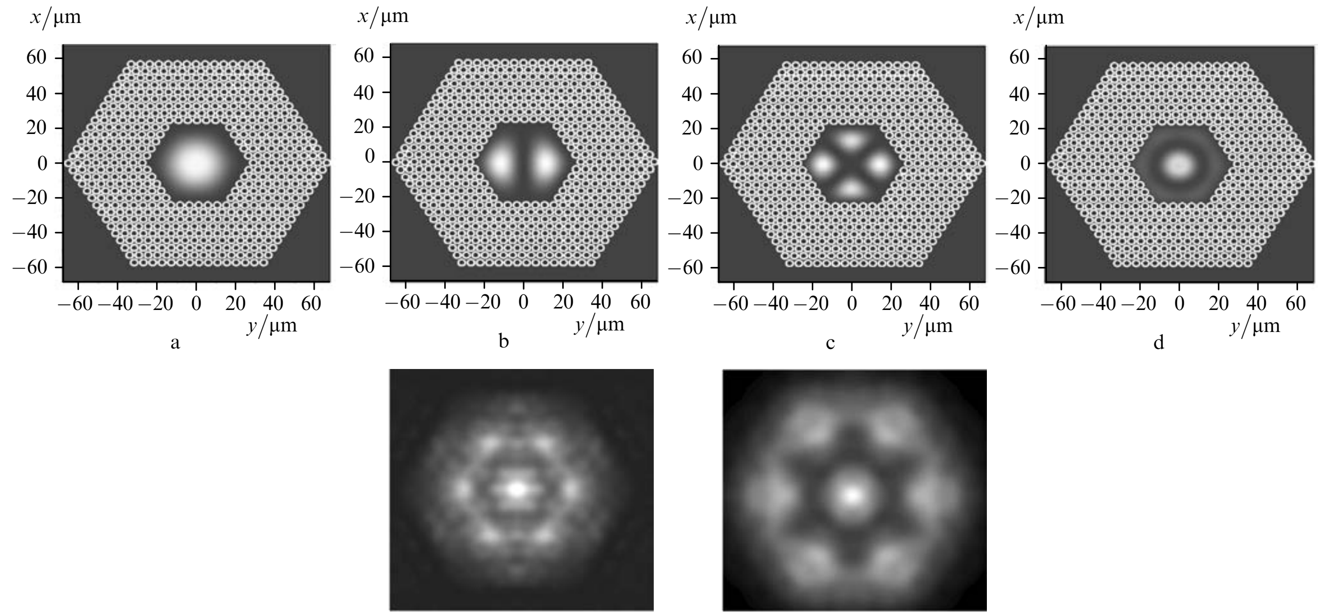


Figure 3. Field intensity profiles for the fundamental (a) and higher order (b – f) guided modes of hollow photonic-crystal fibres of the second type calculated by using the method of polynomial expansion (a – d) and the FDTD technique (e, f).

The second numerical method was based on the solution of the relevant set of Maxwell equations using the finite-difference time-domain (FDTD) technique [32]. In accordance with the generic FDTD approach, continuous electric and magnetic fields are approximated by discrete functions on a mesh within the area of space under study. Temporal and spatial derivatives in the wave equations are approximated by finite differences. Maxwell's equations are thus replaced by a set of ordinary algebraic equations, which is solved with appropriate boundary conditions and initial field distributions. As the solution reaches the stationary regime, the fast Fourier transform is applied, yielding the spectrum and the number of waveguide modes in the fibre.

The initial condition for the incident light field was defined in the form of a Gaussian beam with a characteristic width close to the fibre core diameter. Simulation artefacts originating from reflections from the boundary of the integration domain were prevented by introducing a narrow totally absorbing layer along this boundary. Field intensity profiles in the modes of the second-type hollow PCFs calculated with the use of the FDTD technique are presented in Figs 3e and 3f.

2.3 A coaxial waveguide model and fibre losses

In this section, we present simple, but physically instructive relations qualitatively demonstrating the main tendencies in the behaviour of the optical loss of hollow PCFs as a function of the refractive indices of constituent materials. To this end, we will analyse a model of a hollow coaxial Bragg waveguide [33 – 36]. Consider a waveguide with a hollow core filled with a material with a refractive index n_1 and a cladding consisting of N pairs (periods) of coaxial, periodically alternating cylindrical layers with refractive indices n_1 and n_2 ($n_1 < n_2$) and thicknesses d_1 and d_2. A certain angle of incidence of an electromagnetic wave on such a periodic cladding would satisfy the Bragg resonance condition for the given radiation wavelength and parameters of the periodic structure. On this resonance, the waves reflected from the interfaces between the layers inside the cladding constructively interfere, providing a high reflectivity of the periodic structure.

From these qualitative arguments, we conclude that a periodic cladding is characterised by a high reflectivity only within finite spectral ranges — photonic band gaps. Transmission spectrum of such a waveguide features peaks, which correspond to the guided modes meeting the conditions of Bragg resonances with the structure of the cladding. A photonic-crystal cladding of a Bragg waveguide with a finite number of periods N is characterised by nonzero transmission, allowing the modes to leak out of the hollow core even at the centre of the PBG. For TE modes in such a waveguide, the magnitude of optical losses can be estimated with the use of the following asymptotic relation [37]:

$$\alpha(\mathrm{dB/km}) \approx 0.522 \frac{k_1^3}{\beta_1 n_2} |\mu_{\mathrm{TE}}|^{2N}, \tag{7}$$

where k_1 is the wave number in the bulk of the material with the refractive index n_1 and β_1 is the propagation constant of the mode confined to the hollow core of the waveguide. In a particular case when the cladding of a Bragg waveguide consists of quarter-wave coaxial layers ($k_1 d_1 = k_2 d_2 = \pi/2$), the parameter $|\mu_{\mathrm{TE}}|$ is given by [37]

$$|\mu_{\mathrm{TE}}| = \frac{n_1}{n_2}. \tag{8}$$

Taking $\beta_1 \approx \gamma\omega n_1/c$, where γ is a constant and ω is the radiation frequency, we arrive at the following order-of-magnitude estimate for the magnitude of optical losses α_{f} in a hollow Bragg waveguide filled with a material with the refractive index n_{f}:

$$\alpha_{\mathrm{f}} \approx \left(\frac{n_{\mathrm{f}}}{n_{\mathrm{a}}}\right)^{2N+2} \alpha_{\mathrm{a}}, \tag{9}$$

where n_a is the refractive index of the material in the holes of the waveguides before its infiltration and α_a is the loss of the waveguide before its infiltration.

Obviously, this expression can provide only a rough estimate of the change in the optical losses caused by the infiltration of a hollow PCF. The model used to derive this relation does not include, in particular, the realistic structure of photonic bands of a two-dimensional periodic cladding in hollow PCFs used in experiments described below. A lower index contrast of constituent materials in infiltrated hollow PCFs narrows the PBG, thus reducing the sector of wave vectors corresponding to a closed PBG in the first Brillouin zone of the two-dimensional photonic-crystal cladding. On the other hand, Eqn (9) is physically instructive, as it gives a qualitative understanding of the main tendencies in the behaviour of the optical loss in infiltrated PCFs as a function of the dielectric properties of the materials forming the waveguide. We will demonstrate below that the relations derived in this section can be employed for a rough estimate of the range of refractive indices of materials for the infiltration that would provide an acceptable level of optical losses in fluid-infiltrated PCFs.

3. Experimental results and discussion

Transmission spectra measured for hollow PCFs before and after infiltration with a fluid are presented in Figs 4 and 5. When the PCFs of the first type were filled with water, we were not able to excite any of the guided modes confined to the fibre core. Overall, this result agrees well with our expectations based on the estimate of losses with the use of Eqn (9). Before infiltration, the loss of the fundamental mode in the first-type PCF, shown in Fig. 1a, was $\alpha_a \approx 0.09$ cm^{-1}. The number of periods N in the cladding of this fibre is $N = 10$. When this fibre is filled with water ($n_f \approx 1.3$), the loss estimated with Eqn (9) is $\alpha_f \approx 30$ cm^{-1}.

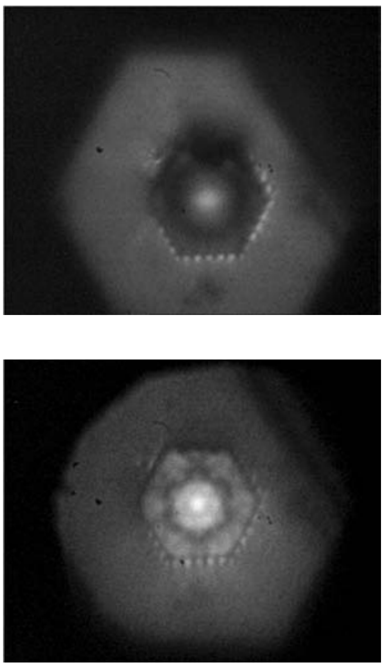


Figure 4. Field intensity profiles measured for the guided modes of the second-type photonic-crystal fibre filled with water

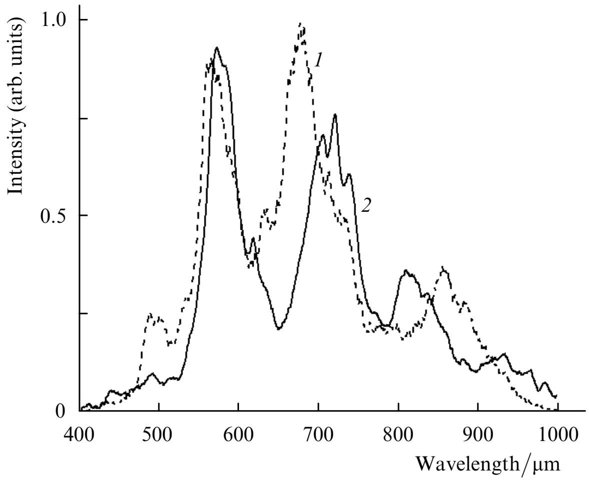


Figure 5. Transmission spectra for the second-type photonic-crystal fibre measured before (*1*) and after (*2*) infiltration with water. The length of the sample is 1 cm.

The characteristic length within which the fundamental mode leaks from the core of such a fibre is 0.3 mm. The high loss does not allow the observation of waveguiding in the fundamental and higher order modes of this PCF in experiments.

When the PCFs of the second type were filled with water, we could observe the fundamental and higher order guided modes confined to the fibre core (Figs 4a, 4b). We have also detected transmission peaks corresponding to these modes (Fig. 5). The typical attenuation length for the fundamental mode in the second-type PCFs filled with water was estimated as 1 cm. Qualitatively, this result agrees well with the predictions of Eqn (9). Before infiltration, the fundamental mode of the hollow PCF of the second type is characterised by the optical loss coefficient $\alpha_a \approx 0.005$ cm^{-1}. The number of periods N in the cladding of this fibre (Fig. 1b) is 9. With the air holes in this fibre filled with water, Eqn (9) yields $\alpha_f \approx 1$ cm^{-1}, which fits well the results of measurements. Radiation intensity profiles in the modes of the PCF filled with water agree well with the results of simulations performed with the use of the orthogonal polynomial expansion method and the FDTD technique (cf. Fig. 3d versus Fig. 4a, as well as Figs 3e, 3f versus Fig. 4b).

4. Conclusions

Results of experimental and theoretical studies presented in this paper show that the infiltration of hollow PCFs with a liquid whose refractive index n_f meets the inequality $n_a < n_f < n_2$ (n_a is the refractive index of the air and n_2 is the refractive index of the solid-phase material of the fibre) increases the optical losses of guided modes confined to the core of the PCF. For a hollow PCF with period of about 5 μm and a core diameter of about 50 μm, infiltration with water increases optical losses by a factor of approximately 200. This result can be qualitatively understood in terms of the model of a hollow coaxial Bragg waveguide. Investigations presented here demonstrate that the infiltration of hollow PCFs with liquid-phase materials can be used to engineer the properties of waveguide modes in PCFs and to develop new types of fibre-optic sensors and switches.

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