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JOURNAL OF NANOTECHNOLOGY RESEARCH

ISSN: 2688-8521

ReviewArticle

Transmittance of Tapered Photonic Crystal Fibers with Absorbing Coatings

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Abstract

The interaction effect of the fundamental mode of a Photonic Crystal Fiber (PCF) with a thin-film absorbing coating deposited on a surface of a fiber cladding on the optical transmission of the PCF is studied. It is shown that the transmission has a quasi-periodic spectrum that is determined either by a resonance coupling between the leaky fundamental PCF mode and leaky modes of the coating, or between the leaky fundamental PCF mode and cladding modes localized between PCF air channels and the coating. Examples are presented of using this effect for fiber-optic sensors of refractive index, pressure, and for sensing an adsorption layer of ammonia molecules deposited on a coating surface contacting with air.

Keywords: Optical fiber devices; Optical fiber sensors; Optical fiber taper; Photonic crystal fibers

Introduction

It is known that the fundamental mode of a Photonic-Crystal Fiber (PCF) can be resonance coupled with modes of a thin film PCF coating [1]. If the coating is absorbing, the coupling leads to a quasi-periodic spectral transmittance of the PCF that can be modified by interaction of coating modes with environment. This effect is explained by the coupling of leaky modes of the PCF core and the coating [1] and does not require close contact between the core and the coating, as it is in the case of fiber-optic sensors with lossy mode resonances [2, 3]. But when using untapered PCFs, the mentioned coupling of leaky modes can be rather weak. As a result, it can only be observed when sufficiently long stretches (tens of centimeters) of coated PCFs are used. Besides, to realize corresponding sensory effects it is necessary to keep the coating thickness d constant along the entire sensitive stretch of the PCF with a tolerance of $0.075\lambda/\sqrt{n_c^2-n_s^2}$, where λ is a light wavelength, n_c and n_s are refractive indexes of the coating and a fiber cladding, respectively [1]. For long PCF stretches this requirement is difficult to fulfil. It is hoped that the use of adiabatic PCF tapers with a length of a sensitive region (taper waist) of a centimeter order will overcome these difficulties. But due to a small transverse size of the taper waist, an interaction of the fundamental PCF mode with the absorbing coating of the taper waist has special features that are considered in this paper. Corresponding estimates are presented for transmission spectra of PCF tapers at sensing refractive index of a liquid, pressure in the liquid and an adsorption nanoscale layer. Numerical simulations of PCFs modal properties are performed with the use of the exact method of integral equations [1].

Operating mechanism

The structure under investigation is presented in Figure 1. Calculations are performed for a PCF consisted of a solid core surrounded by three rings of air holes arranged in a hexagonal pattern. The PCFs material is a quartz glass.

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Citation: Mauricio Salazar Sicacha, Vladimir P Minkovich, Alexander B Sotsky, Artur V Shilov, Luidmila I. Sotskaya. Transmittance of Tapered Photonic Crystal Fibers with Absorbing Coatings. Journal of Nanotechnology Research 4 (2022): 125-129.

Received: September 21, 2022
Accepted: October 10, 2022
Published: November 04, 2022

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DOI:10.26502/jnr.2688-85210035

The cladding diameter of PCF D_0=123.4μm, the diameter of air holes a_0=3μm, the photonic crystal pitch Λ_0=8.8μm [4]. At the adiabatic taper fabrication, the diameter of holes *a* and the pitch Λ within the taper waist modify by the rule [5] $a=(2A_w/D_0)a_0$, $\Lambda=(2A_w/D_0)\Lambda_0$. In taper calculations we used values $2A_w$ =44μm and L =3cm [3] (see Figure 1).

Figure 2 illustrates modal dispersion $\beta(\lambda)$, where β is a dimensionless mode propagation constant, for PCFs coated with a multifunctional butyl acrylate having the complex refractive index n_c=1.54-i0.00002 and surrounded with water ($\varepsilon_w = n_w^2$, $n_w = 1.33$, see Figure 1). In Figure 2 'phase index' means *Reβ*, 'loss' means $4\pi 10^7 |\mathrm{Im}\beta| / (\lambda \ln 10)$, where λ is taken in μm. Curves 3 - 6 in Figure 2 are results of a numerical solution by the contour integration method [6] of a dispersion equation for guide and leaky modes of a planar dielectric waveguide [7]

$$\left[\frac{\gamma_w}{\sigma}\left(\frac{\varepsilon_c}{\varepsilon_w}\right)^T - \frac{\sigma}{i\gamma_s}\left(\frac{\varepsilon_s}{\varepsilon_c}\right)^T\right]\sin(k_0\sigma d) + \left[1+\frac{\sigma}{i\gamma_s}\left(\frac{\varepsilon_s}{\varepsilon_c}\right)^T\right]\cos(\sigma k_0 d) = 0,$$

where $T=0$ for TE modes, $T=1$ for TM modes,

$$\gamma_w = \sqrt{\beta^2 - \varepsilon_w}, \quad \gamma_s = \sqrt{\varepsilon_s - \beta^2}, \quad \sigma = \sqrt{\varepsilon_c - \beta^2},$$

modeling the absorbing coating of thickness *d*.

Curves 3-6 in Figure 2 are computed basing on the reasons that from the point of view of geometric optics the fundamental mode of the PCF is mainly formed by meridional rays [1]. When considering a reflection of such rays from the coating, the latter can be approximately replaced by a plane-parallel layer of thickness *d*. In this approximation, the coating modes should be understood as the modes of a plane dielectric waveguide. In Figure 2 segments of curves 3 - 6 located above the curve 1 correspond to guide modes, and below curve 1 - to leaky modes. At the same time, curves 2' and 7' pass everywhere below curve 1. So, the PCF fundamental mode always is leaky. As a result, its propagation constant can be matched with only leaky modes of the coating at wavelengths indicated in Figure 2 by vertical dashed lines. In Figure 2*a* the loss of the fundamental mode for the untapered (regular) PCF with the 20μm polymer coating sharply grows in the close vicinity of these wavelengths. This means that observed in Figure 2*a* a quasi-periodic spectrum of the fundamental PCF mode loss qualitatively can be explained by resonance coupling this mode with leaky modes of the absorbing coating. This coupling leads to a resonance capture of energy for the fundamental PCF mode by the coating and the release of heat in it. With decreasing *d,* the interval between resonance wavelengths is increased [1]. As a result, in the spectral range of Figure 2*b*, there are only two resonance wavelengths (for the regular PCF they are located in the vicinity of λ=1.24μm).

It should be noted that the simple model of the coupled leaky modes cannot explain a complicated multipeak character of the exact loss spectrum observed in Figure 2

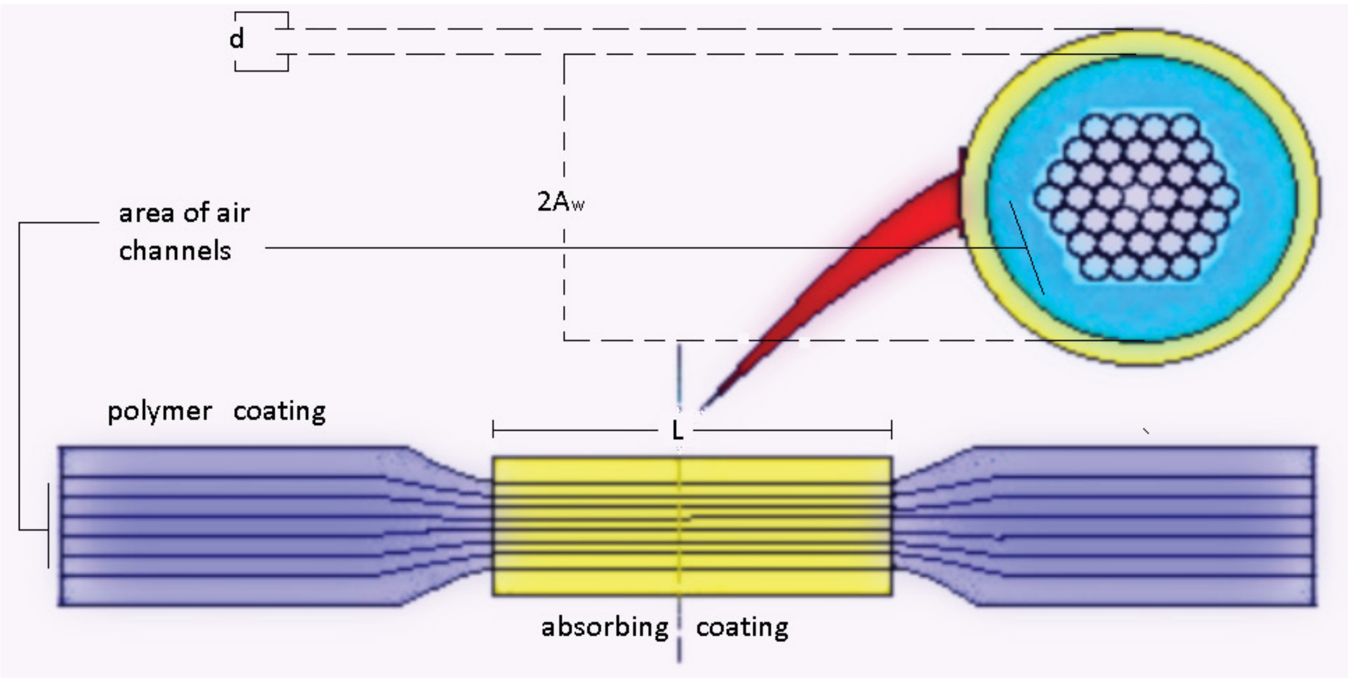

Figure 1: An adiabatic taper of a PCF with three hexagonal rings of air channels and an absorbing coating with length *L* and thickness *d* around the taper waist of diameter $2A_w$.

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DOI:10.26502/jnr.2688-85210035

in the vicinity of resonance wavelengths. Note also that according to Figure 2, the attenuation of the fundamental mode for the regular PCFs is rather weak. To observe it, tens of centimeter lengths of the coated PCFs are required, which is not acceptable for a number of sensor applications. This drawback can be corrected by fabrication of an adiabatic PCF taper. In accordance with Figure 2*b*, such a device allows a more pronounced influence of the absorbing coating on PCF transmission. But in this case, the above mentioned simple coupled mode model cannot completely explain transmission properties of the taper waist. Indeed, in the case of a tapered fiber in Figure 2*b*, together with two sharp attenuation peaks located in the vicinity of the resonant wavelengths λ=1.285 μm and λ=1.299 μm, a number of other broader attenuation peaks are observed. These additional peaks can be attributed to a resonance coupling of the fundamental PCF mode concentrated in the fiber core with leaky modes of the fiber cladding that concentrated in the area between air channels and the absorbing coating [5] and therefore effective interact with the coating. This mechanism is confirmed by considering Figure 3, which compares the intensity distributions of the tapered PCF fundamental mode, related to the loss peaks at the wavelength λ=1.244 μm that is far from right pair of dashed lines refer to the PCF under investigation and at the wavelength λ=1.279 μm that can be attributed to the above straight coupling between the PCF fundamental mode and modes of the absorbing coating (see Figure 2*b*).

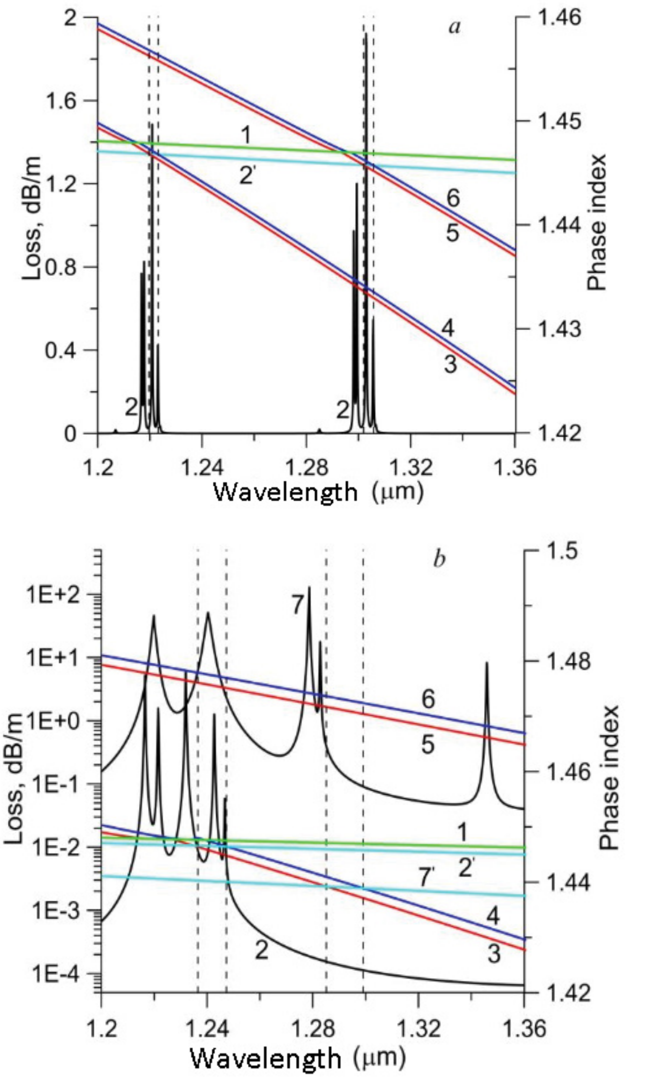

Figure 2: Spectral dependencies of mode propagation constants for straight and tapered PCFs with a polymer coating of thickness *d*=20μm (*a*) and *d*=5μm (*b*). Curves 2, 2' and 7, 7' are loss and a phase index of the PCF fundamental mode with $2A_w=D_0$ and $2A_w$=44μm, respectively; curves 1 (right axes) refer to the silica refractive index; curves 3 - 6 are phase indexes of modes for absorbing coatings; curves 3, 5 refer to TM modes, 4, 6 - to TE modes. Dashed lines indicate intersection points of curves corresponding to index matching of PCF modes and the absorbing coatings.

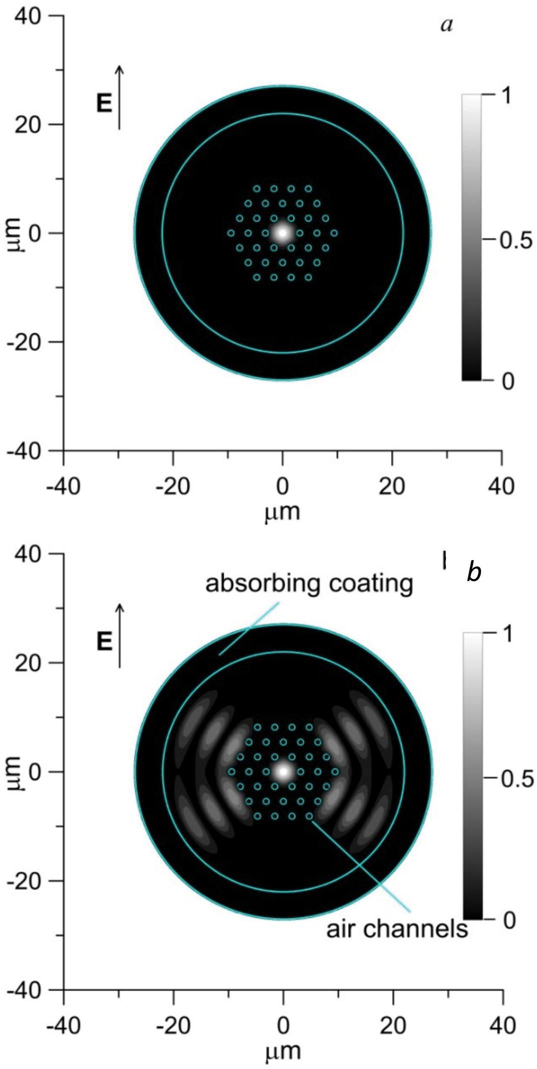

Figure 3: Optical densities of the adiabatic taper waist working mode related to the maxima of the loss at λ=1.279 μm (*a*) and λ=1.244μm (*b*) (see curve 7 in Figure 2*b*). Arrows **E** indicate the main orientation of the mode electric field vector.

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DOI:10.26502/jnr.2688-85210035

Sensor applications

Since the electrodynamics properties of the PCF absorbing coating can be influenced by the environment, a change in parameters of the environment will lead to a modulation of the leaky modes propagation constants for the absorbing coating and, as a consequence, to the modulation of the fiber transmission in the vicinity of the resonance wavelengths. Figure 4 refers to the PCF taper with the polymer coating of thickness d=5μm, surrounded with water, studied in the previous section.

At calculation of a pressure sensor, we took into account, that a change in pressure results in changing the coating thickness Δd and also in the photo elastic shift Δn_c of its refractive index. Both these factors influence the propagation constants of the coating leaky modes. According to the theory of elasticity [8], the relationship between the increment in a coating thickness and the increment in pressure ΔP in the environment is given by the formula

$$\Delta d = -\frac{\Delta P\, B(B^2 - A_w^2)(1+\sigma)(1-2\sigma)}{E[B^2 + A_w^2(1-2\sigma)]},$$

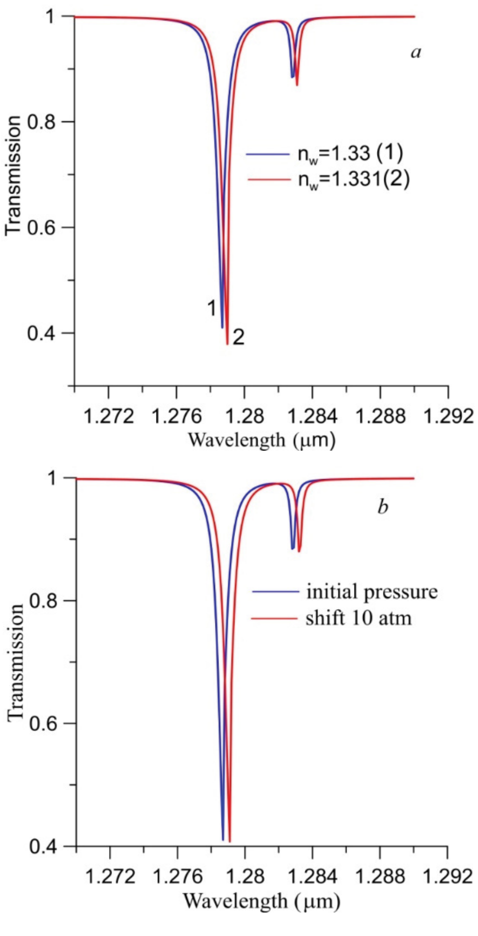

Figure 4: Shift of the adiabatic PCF taper transmission minima in dependence on change of refractive index (a) or pressure (b) in a surrounding liquid.

where $B = A_w + d$, E is the Young's modulus, σ is the Poisson's ratio for the coating. Photo elastic shift Δn_c was estimated by the formula $\Delta n_c = K\Delta P$, where K is the Brewster's coefficient. For butyl acrylate we used $E = 7\cdot 10^8\,Pa$, $\sigma = 0.3$, $K=10^{-10}\,1/Pa$. According to Figure 4, sensors of described before type with the absorbing polymer coating are well suited for testing parameters of liquids. Many different absorbing coatings for silica fibers are known this time [2, 3]. Our calculations have shown that the most of these coatings can be used in sensors of the considered type. However, the described effect of the leaky mode resonance coupling manifests itself in different ways, when low-refractive and high-refractive absorbing coatings are used. This confirmed by data presented in Figures 5 and 6. They refer to the coating of tin dioxide doped with antimony (7 weight percent), selectively adsorbing ammonia molecules from air. Calculations are performed for the adiabatic taper with the above parameters, but surrounded by air instead of water. The SnO_2 coating thickness is 0.6 μm, its complex refractive index $n_c = \sqrt{\varepsilon_c} = 1.90819 - i0.00042$.

In comparison with the curve 7 in Figure 2b, the analogous dependency 2 in Figure 5 is less complicated. In the considered spectral range, it has only one loss peak refers to the direct coupling of the PCF fundamental mode with leaky coating modes. It was confirmed by the calculation of the fundamental PCF mode intensity distribution at the wavelength λ =1.297μm, corresponding to the maximum of the mode loss in Figure 5. This distribution is qualitatively the same as one in Figure 3a. Figure 6 illustrates the shift of the PCF transmission spectrum upon a deposition on the coating of an adsorption layer of ammonia molecules with a thickness of 1nm and the refractive index $n_a = 1.355$.

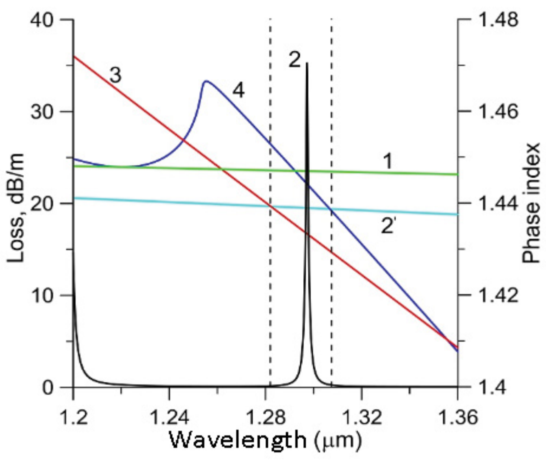

Figure 5: Spectral dependencies of mode propagation constants for the adiabatically tapered PCF with $2A_w$=44μm and SnO_2 coating surrounded with air. Curve designations are the same as in Figure 2a.

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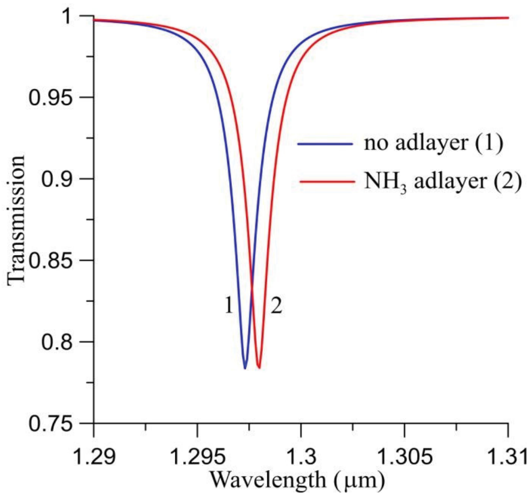

Figure 6: Shift of the adiabatic PCF taper transmission at formation of an adsorption layer of ammonia molecules on a surface of the SnO_2 coating.

Conclusions

We report on a quasi-periodic spectral transmission of a single-mode photonic crystal fiber with absorbing thin-film coatings. Two mechanisms for implementation of such the transmission have been established. In the first one the leaky fundamental mode of the PCF is resonance coupled with leaky modes of the coating. This coupling leads to a resonance capture of energy of the fundamental PCF mode by the coating and the release of heat in it. The second mechanism is more complicated and can be observed in PCFs with sufficiently small cladding diameters that can be realized in a taper waist. It consists of a resonance coupling of the leaky fundamental PCF mode with cladding modes localized between air channels and the absorbing coating. In comparison with the last mechanism, the first one allows narrower spectral absorption bands to be realized. For this reason, it is more attractive for sensor applications. In our sensor examples of refractive index, pressure and ammonia molecules it is shown that a small modulation in refractive index and (or) the PCF absorbing coating thickness leads to a detectable modulation of the fiber transmission in the vicinity of resonance wavelengths.

Declarations

Acknowledgements

Sotsky A.B., Shilov A.V. and Sotskaya L. I. would like to thank a Byelorussian State Scientific Program ¨Photonics 1.3.03¨ for partially support of this work. The authors also would like to thank their colleagues Monzón-Hernandez, D., Kir´yanov, A.V., and Calixto S. for productive scientific cooperation.

Funding

Declared at acknowledgements.

Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated.

Authors´ contributions

All authors contributed to the preparation, writing and reviewing of the manuscript. All authors have read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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