Regular paper

Simple method for characterization of photonic crystal fibers

Mieczysław Szustakowski, Norbert Pałka, and Waldemar Grabiec

Abstract— We report on our experimental characterization of index-guiding photonic crystal fibers (PCF) from their far field intensity distribution. The algorithm presented below makes it possible to determine the geometrical parameters of the PCF (core diameter, air hole spacing and air hole diameter) from its far field pattern. We obtained good agreement with the manufacturer's data for all fibers tested.

Keywords—photonic crystal fibers, far field distribution, characterization.

1. Introduction

Over the past few years, a substantial progress has been made in fabricating photonic crystal fibers (PCF) – new dielectric structures with a refractive index that varies periodically in the transverse plane, with a period of the order of an optical wavelength [1]. Regular morphological microstructure incorporated into the material radically alters its optical properties. Two guiding mechanisms are possible in PCFs: index guiding (IG) or photonic band gap (PBG) [2]. As far as the IG case is concerned (Fig. 1a), a waveguide consists of a solid core and a cladding with an array of air holes. The guided modes may be trapped in a core with a higher refractive index than an averaged index of the cladding. On the other hand, the PBG fibers have a *hollow* core and also an array of air holes in a cladding. Now, the modes are trapped in a core of *lowered* index by a photonic band gap effect.

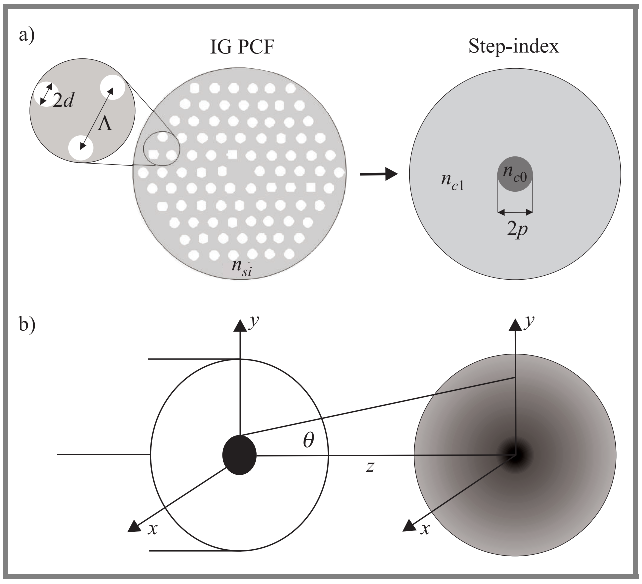

Fig. 1. The idea of effective index method (a) and far field intensity distribution scheme with angle θ and distance z (b).

This mechanism is based on Bragg reflection and prevents the light from propagating in a cladding material – so it has to propagate inside the hollow core. These two guiding mechanisms as well as a possibility of the tailoring fiber geometry determine the diverse nature and properties of PCFs [2, 3].

Because of their wide applications, PCFs require a simple method for characterization of their basic geometrical parameters: core diameter (ρ), air hole spacing (Λ) and air hole diameter (d) – see Fig. 1a. We report here on our experimental evaluation of characterization of index-guiding photonic crystal fibers from far field intensity distribution proposed by Varshney and Sinha [4].

2. Theory

An effective index method (EIM) is a simple tool that can provide a good description of the index guiding photonic crystal fibers [5]. The fundamental idea behind this method is to replace the periodic array of holes in silica structure by a properly chosen effective index (Fig. 1a) that can be described in terms of the propagation constant of the lowest-order mode that could propagate in the infinite cladding material [6]. As a result, a step-index fiber that consists of a cladding region with refractive index n_{c1} and a silica core with refractive index n_{c0} (equal to the refractive index of a pure silica n_{si}) is obtained.

The core radius (ρ) of the step-index fiber can be estimated from the formula $\rho = 0.64\Lambda$. Solving scalar wave equation one can obtain an effective refractive index (n_{eff}) and a modal field of the fundamental mode in the step-index fiber.

Using the effective index method and the Kirchoff-Huygens theory of diffraction, the normalized far field intensity distribution ($I(\alpha)$) of a step-index fiber (substitution of PCF) as a function of the normalized angle (α) can be written as [4]:

$$I(\alpha)=\left\{\frac{U^2W^2}{\left(U^2-\alpha^2\right)\left(W^2+\alpha^2\right)}\left[J_0(\alpha)-\alpha J_1(\alpha)\frac{J_0(U)}{UJ_1(U)}\right]\right\}^2, \tag{1}$$

where: $U=k_0\rho\sqrt{n_{c0}^2-n_{eff}^2}$, $W=k_0\rho\sqrt{n_{eff}^2-n_{c1}^2}$, J_0 and J_1 are the Bessel function of first kind of zero and first order, respectively, α is the normalized angle given by [4]:

$$\alpha=k_0\rho\sin\theta\,, \tag{2}$$

where θ is the angle (Fig. 1b), k_0 is the free space propagation constant and V_{eff} is the effective normalized frequency [7]:

$$V_{eff}=k_0\rho\sqrt{n_{c0}^2-n_{c1}^2}\,. \tag{3}$$

3. Algorithm of characterization of PCFs

The algorithm for characterization of PCFs makes use of the set of curves which can be analytically calculated for the required wavelength according to principles presented in Section 2. Far field intensity pattern of the step-index fiber that is a substitution of LMA-10 PCF is presented in Fig. 2a. Figure 2b shows curves depicting the variation of α_x/α_h ratio and α_h with effective normalized frequency (V_{eff}) for $\lambda=670$ nm. The α_x is the normalized angle of first minimum of the far field intensity distribution and α_h is the normalized angle where the intensity reaches half of its maximum. Figure 2c presents variation of effective normalized frequency (V_{eff}) with the air hole spacing (Λ) for the normalized air hole size (d/Λ) in the 0.2–0.6 range.

The algorithm of characterization is a follows. From the measured far field pattern one can determine the angle of first minimum (θ_x) and the angle of half intensity (θ_h). Next, taking into account that $\sin\theta_x/\sin\theta_h=\alpha_x/\alpha_h$ (Eq. (2)), two values: V_{eff} and α_h can be determined from the curves shown in Fig. 2b. Further, with knowledge of the normalized half intensity angle (α_h), the core radius (ρ) can be calculating from the Eq. (2). The air hole spacing (Λ) can be determined from the formula: $\rho=0.64\Lambda$. From Fig. 2c, the normalized air hole size (d/Λ) can be estimated using Λ and V_{eff}. Finally, knowing the ratio d/Λ and Λ, we can determine the air hole diameter (d). The procedure is presented schematically in Fig. 2b and 2c.

It is shown, that the algorithm presented above makes it possible to determine the geometrical parameters of the PCF: core diameter (ρ), air hole spacing (Λ) and air hole diameter (d) from analysis of the far field intensity distribution.

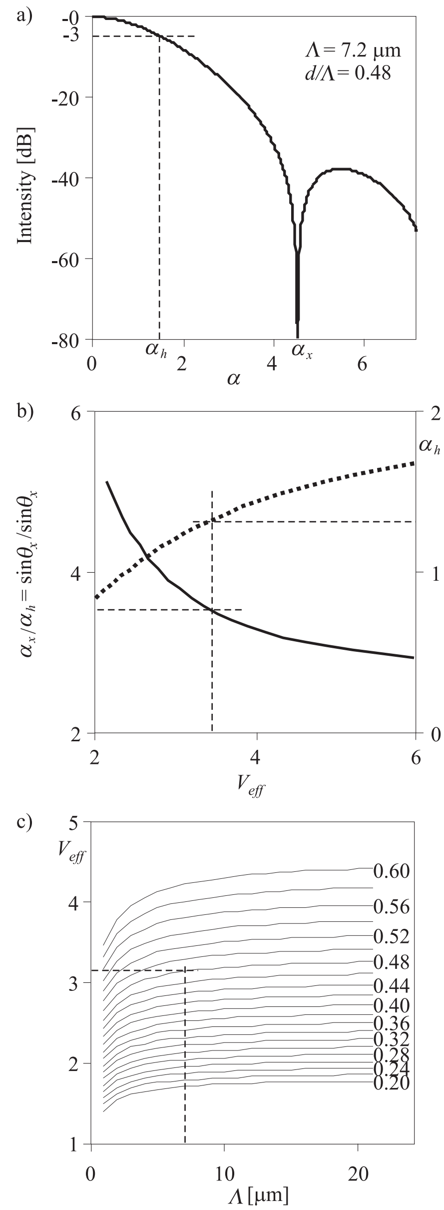

Fig. 2. Far field intensity pattern for the step-index fiber (a); variation of the ratio α_x/α_h (solid) and α_h (dotted) with the effective normalized frequency (V_{eff}) for $\lambda=670$ nm (b); variation of the effective normalized frequency (V_{eff}) with air hole spacing (Λ) for the normalized air hole size (d/Λ) in the 0.2–0.6 range (c). The dashed lines show results calculated for LMA-10 fiber.

4. Evaluation experiment

In order to prove correctness of the presented characterization method, we build a setup shown schematically in Fig. 3a. Light from the laser ($\lambda=670$ nm) is coupled into the 10 meters long PCF: LMA-8 or LMA-10 made by photonic fibre A/S. Fiber data are shown in Table 1. The far field intensity distribution was observed using BCi4 CMOS C-Cam Technologies Camera (1280 × 1024 pixels, 7 μm pixel size, 12 bit resolution) and 3D beam laser software from MS Macrosystem. All necessary calculations were conducted by the Matlab-based software.

For every fiber we recorded two images for two fiber-camera distances (z). The first image (Fig. 3b) was obtained with normal exposure and used to find the angle of half intensity (θ_h), while the second image (Fig. 4a) was overexposed in order to find the angle of first minimum (θ_x). We show only a quarter of the intensity patterns because of symmetry properties of PCFs.

Figure 3c presents cross sections of intensity distribution for two angles: $\delta = \pi/6$ and $\delta = \pi/3$. The distance to the half intensity position (L_h) can be determined without ambiguity because the far field pattern is cylindrically symmetric for the half intensity values. Thus, knowing the fiber-camera distance (z) and pixel size, one can calculate the half intensity angle (θ_h) from simple geometrical considerations.

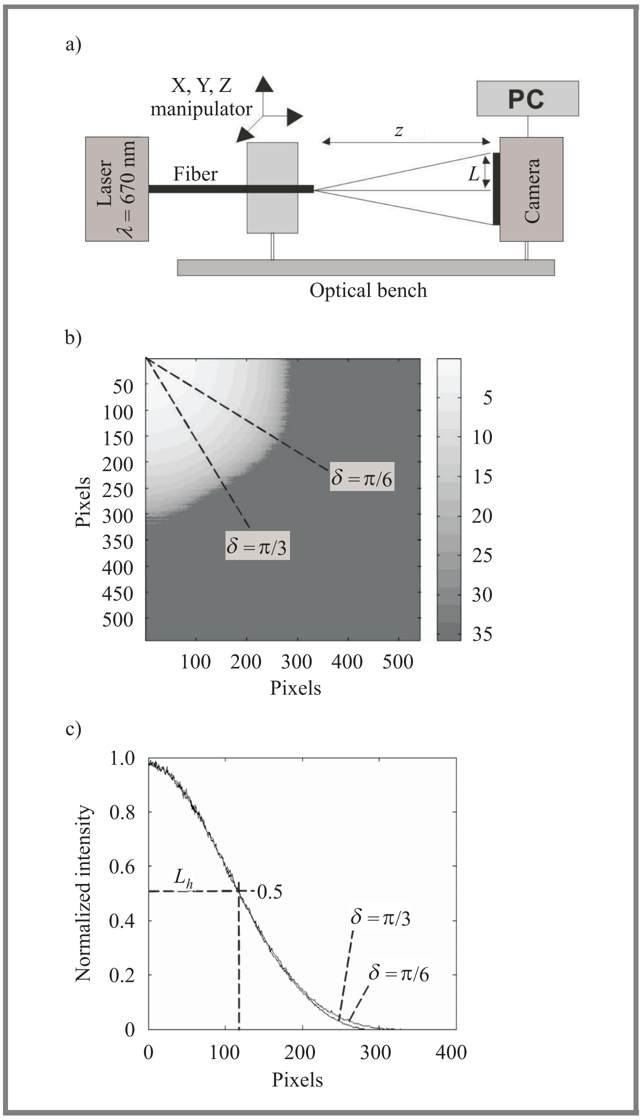

Fig. 3. Far field arrangement (a); normal far field intensity distribution – logarithmic scale (b); cross sections for two angles $\delta = \pi/6$ and $\delta = \pi/3$ (c). LMA-10 fiber, $z = 22$ mm, $\lambda = 670$ nm.

The situation is more complicated for the first minimum angle (θ_x), where the position of the minimum intensity depends on the angle δ. Figure 4b presents cross sections of intensity distribution for two angles: $\delta = \pi/6$ and $\delta = \pi/3$.

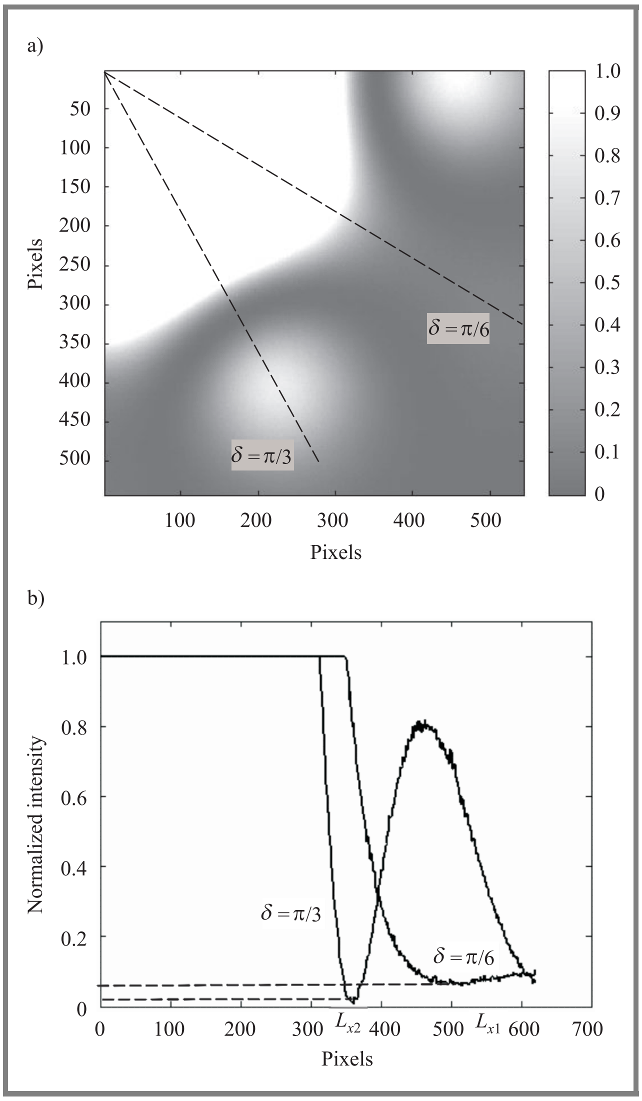

Fig. 4. Overexposed far field intensity distribution (a); cross sections for two angles $\delta = \pi/6$ and $\delta = \pi/3$ (b). LMA-10 fiber, $z = 22$ mm, $\lambda = 670$ nm.

To solve this problem, we assumed that the distance to the first minimum (L_x) equals the mean value of L_{x1} and L_{x2}. Value L_{x1} corresponds to the biggest L_x ($\delta = \pi/6$), while L_{x2} to the smallest one ($\delta = \pi/3$). Now, the first intensity angle (θ_x) can be easily calculated.

Taking advantage of the Fig. 2b and 2c as well as procedure presented in Section 3 one can estimate the parameters

Table 1
Experimental results

Fiber	Manufacturer's data			Measurement data							
	Λ [μm]	d [μm]	V_{eff}	z [μm]	α_x/α_h	α_h	V_{eff}	Λ [μm]	d [μm]	δ_Λ [%]	δ_d [%]
LMA-8	5.6	2.58	2.922	15	3.878	1.141	2.967	5.43	2.55	3.0	1.2
				26	3.866	1.146	2.980	5.56	2.67	0.7	3.5
LMA-10	7.2	3.46	3.112	22	3.762	1.184	3.104	7.13	3.42	1.0	1.2
				28	3.752	1.188	3.118	6.95	3.34	3.5	3.5

of the PCF. The dashed lines in Fig. 2b, 2c, 3b, 3c, 4a, and 4b show results of measurements and calculations for LMA-10 PCF, and $z = 22$ mm, $\lambda = 670$ nm. Table 1 presents the measured parameters for two PCFs: LMA-8 and LMA-10.

It is seen from Table 1 that there is a good agreement between parameters of photonic crystal fibers measured using our method and data provider by fiber manufacturer. Generally, the measured parameters (Λ and d) are lower than the real values. Relative errors of the air hole spacing (δ_Λ) and air hole diameter (δ_d) estimation are below 4%.

5. Conclusions

We present an experimental evaluation of the simple method of characterization of index guiding photonic crystal fibers by means of their far field pattern. In this method, the PCF in question is approximated by a step-index-fiber. The set of calibration curves can be calculated analytically for required wavelength using the far field intensity distribution of the step-index fiber. These curves are used to determine the geometrical parameters of PCF.

We have proposed a measurement procedure that makes use of normally exposed and overexposed images to find the characteristic points of the far field pattern. We also overcame the problem of determination of the first minimum of intensity distribution for photonic crystal fibers with six fold symmetry.

We have obtained a good agreement with manufacturer's data for all fibers tested – the relative errors of measurement for geometrical parameters of PCFs are less than 4%.

The method presented in this paper can be used for easy and quick determination of geometrical parameters of the index-guided PCFs.

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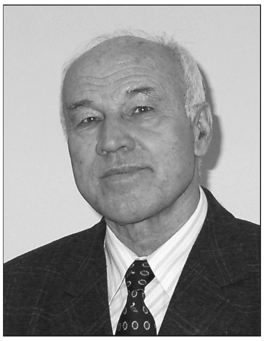

Mieczysław Szustakowski was born in Perespa, Poland, in 1933. He received the M.Sc. degree in quantum and solid body electronics, the Ph.D. degree in technical physics and Assistant Professor degree in optoelectronics, all from the Military University of Technology (MUT), Warsaw, Poland, in 1968, 1973 and 1976, respectively. Since 1983 he has been Professor of optoelectronics. In 1968 he joined the Military University of Technology and worked there as a chief of Coupled Field Laboratory, dean of Chemical and Technical Physics Faculty. From 1987 to 1991 he had been working as a Director of Institute of Plasma Physics and Laser Microfusion. Since 1991 he has returned to the Institute of Applied Physics, Military University of Technology. Now he works as Professor. Since 1995 his scientific interests have been in acoustooptics, fiber optics in local area network, fibre optics sensor and integrated optics. At present his main field of interests is acoustooptics signal processing, photonic crystal fibres and fibre optic security systems.

Professor M. Szustakowski is a Member of Polish Chapter of the International Society for Optical Engineering, Polish Committee of Optoelectronics, International Fundation for Research of Optoelectronics and Member of Committee of Electronics and Telecommunication of Polish Science Academy. He is a co-author of more than 60 publication of fiber optic and acoustooptic physics and application, 2 books and 5 patents.

e-mail: mszustakowski@wat.edu.pl
Institute of Optoelectronics
Military University of Technology
Kaliski st 2
00-908 Warsaw, Poland

Norbert Pałka was born in Gniezno, Poland, in 1975. He received the M.Sc. degree in physics – fiber optics technology, the Ph.D. degree in optoelectronics, all from the Military University of Technology (MUT), Warsaw, Poland, in 1999 and 2004, respectively. In 1999 he joined the Military University of Technology as an research worker in Institute of Optoelectronics. Since 1999 his scientific interests have been in fiber optics sensors, especially interferometric and fiber Bragg gratings. At present his main field of interests are photonic crystal fibres and fibre optic security systems.

e-mail: npalka@wat.edu.pl
Institute of Optoelectronics
Military University of Technology
Kaliski st 2
00-908 Warsaw, Poland

Waldemar Grabiec was born in Dębica, Poland, in 1962. He received the M.Sc. degree in telecommunications from the Military University of Technology (MUT), Warsaw, Poland. Since 1998 he has been working as an Assistant and Lecturer at Military University of Technology. His current research areas: optical telecommunications, all optical networks (AON), photonic crystal fibers.

e-mail: waldemar.grabiec@wel.wat.edu.pl
Institute of Telecommunications
Military University of Technology
Kaliski st 2
00-908 Warsaw, Poland