Fabrication and investigation of large-mode-area photonic crystal fibers

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This paper describes design, fabrication and testing of all-silica large-mode-area (LMA) photonic crystal fibers (PCFs) with three full hexagonal air capillaries rings in a cladding. The design is based on V (normalized frequency) and W (normalized transverse attenuation constant) parameters. Capillaries and rods for a PCF preform were fabricated using this preliminary design. The designed preform was stretched into LMA PCF fibers and then some values for fabricated PCFs, such as geometric dimensions, numerical aperture and attenuation have been measured. Measured values are compared with ones preliminary calculated by using V and W parameters. It is shown that the obtained experimental results are very near to calculated ones.

Keywords: Large mode area photonic crystal fibers; numerical aperture; attenuation; V and W parameters.

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1. Introduction

Fabrication and investigation of LMA PCFs began in the mid-90s of last century [1] and now a lot of theoretical and experimental results exist devoted to this type of fibers.

The LMA PCFs have a peculiarity that they have a big core, this helps to introduce in this core a light energy with a high power without any nonlinear effects [2]. This time the LMA PCFs have a lot of applications, such as in fiber lasers, in dispersion compensators, in different devices for sensing applications and so on [3]. Moreover, for a very high light power introduced into the LMA PCFs with fitted dispersion properties it is possible to obtain a high power supercontinuum generation [4]. Problem is that the cost of the existent LMA PCFs is very high until now and it is very difficult to buy fibers with needed geometric dimensions and dispersion properties. The main objective of this work is to design and manufacture the LMA PCFs with required properties. In our opinion this work is the first experimental one in Mexico describing in details fabrication and testing silica LMA PCFs, which are manufactured based on a preliminary design.

2. The method of PCF calculation based on V and W parameters

Recently, an analytical approach based on V (normalized frequency) parameter, which is usually used for design of conventional optical fibers, has been implemented for the design of micro-structured or photonic crystal fibers [5]. It has been shown in Ref. 5 that taking into account not only V parameter, but also the Wparameter (normalized transverse attenuation constant), which only depend on the wavelength and structural parameters, it is possible to design needed PCFs. This method provides a connection of parameters V and W for the PCFs. The only required parameters needed for calculations are an inner diameter of capillary tubes d and a distance between centers of these capillaries Λ [6]. The proposed formulas for the V and W parameters are:

$$V\left(\frac{\lambda}{\Lambda},\frac{d}{\Lambda}\right)=A_1+\frac{A_2}{1+A_3\exp(A_4\lambda/\Lambda)} \tag{1}$$

$$W\left(\frac{\lambda}{\Lambda},\frac{d}{\Lambda}\right)=B_1+\frac{B_2}{1+B_3\exp(B_4\lambda/\Lambda)} \tag{2}$$

Here λ is the operating wavelength, the fitting parameters Ai (i=1 to 4) and ***Bi*** (i=1 to 4) depend on d/Λ only. The parameters Ai and the parameters ***Bi*** we can obtain from the following formulas [7]:

$$A_i=a_{i0}+a_{i1}\left(\frac{d}{\Lambda}\right)^{b_{i1}}+a_{i2}\left(\frac{d}{\Lambda}\right)^{b_{i2}}+a_{i3}\left(\frac{d}{\Lambda}\right)^{b_{i3}} \tag{3}$$

$$B_i=c_{i0}+c_{i1}\left(\frac{d}{\Lambda}\right)^{d_{i1}}+c_{i2}\left(\frac{d}{\Lambda}\right)^{d_{i2}}+c_{i3}\left(\frac{d}{\Lambda}\right)^{d_{i3}} \tag{4}$$

Where the coefficients a_{i0} to a_{i3} and b_{i1} to b_{i3} are given in Table I of [5] and the coefficients c_{i0} to c_{i3} and d_{i1} to d_{i3} are given in Table II of [5]. Having the obtained parameters $V$and W, we can use the following formulas to find the effective refractive index of the cladding n_{FSM} and then the effective index of the fundamental mode n_{eff} :

$$V=\frac{2\pi}{\lambda}\cdot a_{\text{eff}}\cdot\sqrt{n_{\text{co}}^2-n_{FSM}^2} \tag{5}$$

$$W=\frac{2\pi}{\lambda}\cdot a_{\text{eff}}\cdot\sqrt{n_{\text{eff}}^2-n_{FSM}^2} \tag{6}$$

Where n_{co} is the core index, a_{eff} is the effective core radius that for the PCFs is assumed to be $\Lambda/\sqrt{3}$. If we assume that the waveguide contribution to the dispersion parameter D is independent of material dispersion D_m, we have the following relation:

$$D=-\frac{\lambda}{c}\cdot\frac{d^2n_{\text{eff}}}{d\lambda^2}+D_m \tag{7}$$

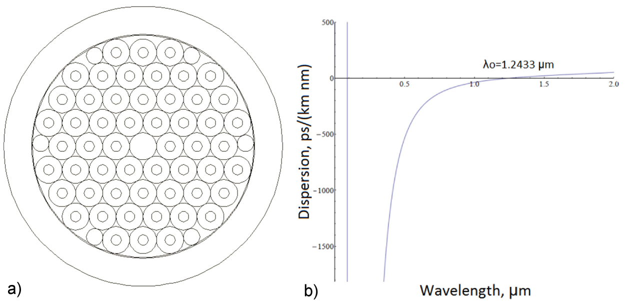

FIGURE 1. (a) Design of LMA PCF, (b) calculated fiber dispersion as a function of the wavelength.

Where c is the light velocity in vacuum and D_m is possible to find by using the Sellmeier relation. With the V parameter we can also find the angle of a light cone θ at the output of a PCF and also to find the value of the numerical aperture *NA* and a mode field radius W_{eff} as the following, obtained for conventional optical fibers, equations indicate:

$$\frac{w_{\text{eff}}}{a_{\text{eff}}} = 0.65 + \frac{1.619}{V_{\text{eff}}^{3/2}} + \frac{2.879}{V_{\text{eff}}^{6}} \tag{8}$$

$$\theta = \tan^{-1}\frac{\lambda}{\pi w_{\text{eff}}} \tag{9}$$

$$NA = n \cdot \sin\left(\frac{\theta}{2}\right) \tag{10}$$

3. Design and fabrication

The design of our LMA PCFs is based on a cladding tube with innner diameter of 16 mm and outside diameter of 20 mm. A preform for drawing of our LMA PCFs is stacked with four concentric hexagonal layers of capillaries around the solid core. The preform corner's capillaries are deleted, because this gives more preform stability, as seen in Fig. 1(a). Some filler rods are also placed in order to minimize a deformation during the manufacturing process and to avoid the appearance of undesired holes. Based on the designed pattern it is possible to calculate the diameter d of the capillaries, which will be obtained after stretching the fibers, and also the distance between centers of two adjacent capillaries or pitch Λ. Then, based on the parameters V and W, the LMA PCF dispersion is calculated. Figure 1 (b) shows calculated dispersion as a function of wavelength for the designed LMA PCF. During the fabrication process, first we fabricated capillaries and rods with needed diameters.

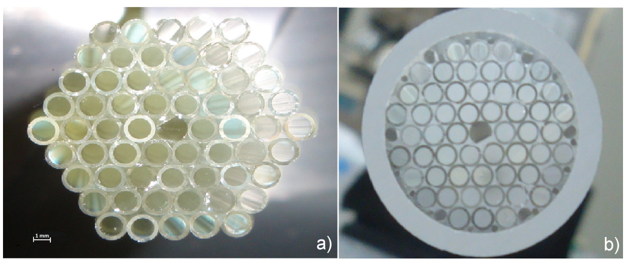

FIGURE 2. (a) Hexagonal arrangement of capillaries, b) preform ready to be stretched.

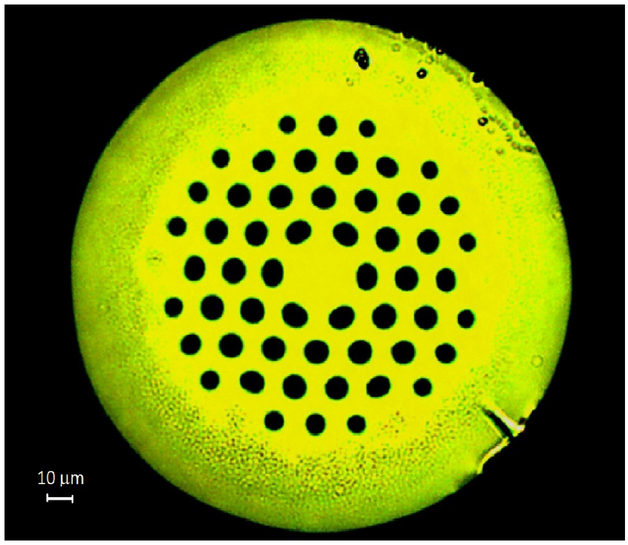

FIGURE 3. Transversal cut image of LMA PCF N7 obtained at using of a DC-163 digital optical microscope.

Then we put them into a special hexagonal form, as can be seen in Fig. 2(a). After that we removed the corner's capillaries and put some additional rods to support the circular form, like in our design. The last step is to put this arrangement into the cladding tube to create the preform, see Fig. 2(b).

4. Results

We manufactured 4 different types of fibers from the same preform: the first one, which was called N6, was manufactured at temperature of 1950°C, the second fiber (N10) - at temperature of 1940°C, the third fiber (N7) was manufactured at temperature of 1930°C and finally the fourth fiber (N9)- at temperature of 1920°C. In Fig. 2 we can see a transversal cut image of the fiber N7, obtained at using of an optical microscope with 40x objective.

In this work we made the following measurements of manufactured LMA PCFs:

- Geometrical dimensions with an atomic force microscopy (AFM),
- Numerical aperture (NA) and Gaussian mode field diameter (MFD),
- Attenuation in the fibers.

4.1. LMA PCF geometric dimension measurements with atomic force microscopy (AFM)

Preliminary experiments showed that the use of optical microscopes for geometrical dimension measurements of our LMA PCFs leads to measurement errors, mainly for inner diameters of capillaries. That is why we used for our measurement an atomic force microscope (AFM), namely a com-

TABLE I. Averaged values obtained with AFM.

I	$d(\mu$m)	$\Lambda(\mu$m)	$D_{ext}(\mu$m)	$D_{core}(\mu$m)	d/Λ
N6	3.516	10.664	122.2	21.79	0.33
N10	3.515	10.313	123.2	20.39	0.34
N7	4.1403	10.312	122.8	20.15	0.40
N9	4.453	10.429	120.2	19.45	0.43
Calculated	4.594	12.080	125	19.58	0.38

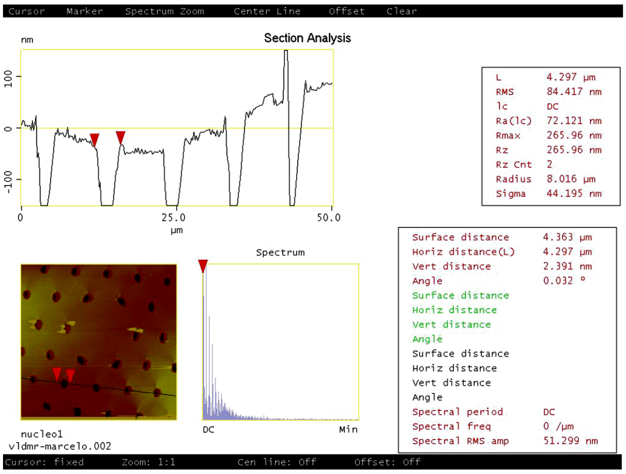

FIGURE 4. AFM measurement example of a capillary diameter d.

mercial scanning atomic force microscope (Digital Instruments) with a resolution of 50 nm for 30×30 μm images. Using this microscope we measured the following geometric dimensions of our fibers: distances between the centers of two adjacent capillaries or pitch Λ, inner diameters d of each capillaries, diameter of the core D_{core}, and a fiber external diameter D_{ext}. In Fig. 4 we can see one example of our measurement with AFM. The measurements of diameters d and distances Λ for our fibers did not give identical results, so we calculated averages of these values and these values are shown in Table I.

In the Table I we have also presented calculated values for the fiber according to the preliminary design. It can be concluded from the Table I that the PCF N9 have almost similar geometric dimensions as the calculated fiber, the capillary diameter d coincides almost with one experimentaly obtained. However, the distance Λ between capillaries centers for the fiber N 9 is a little different than the calculated one.

4.2. Output angle, numerical aperture, and Gaussian mode field diameter of the fibers

Figure 5 illustrates the measurement procedure of an output angle and a numerical aperture (NA) for our LMA PCFs.

In the arrangement of Fig. 5 we have a 5 mW He-Ne laser, whose radiation was carefully launched into a core of PCFs under study using a microscopic objective. At the output of the fiber a photodetector with a power meter was arranged

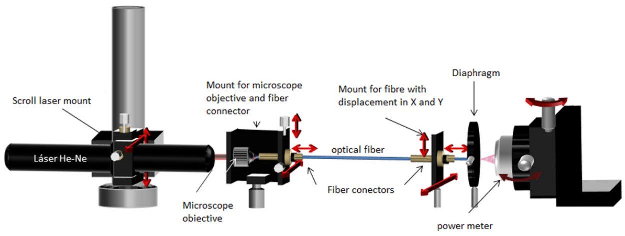

FIGURE 5. Set-up for measurement of output angle and numerical aperture of our LMA PCFs.

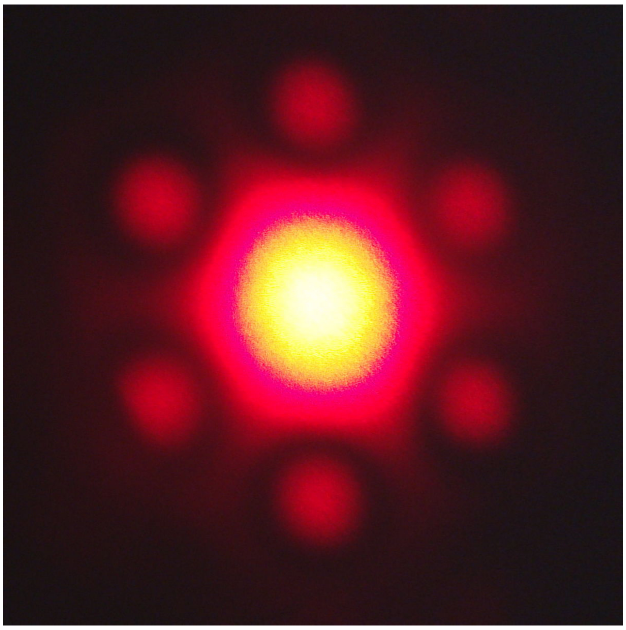

FIGURE 6. Photograph of a far-field image for PCF N9.

at a given distance. In front of the detector a 0.5 mm diaphragm was placed. To obtain the PCFs far-field intensity profiles we moved the fiber output end in X and Y axes (directions of X and Y axes were perpendicular to the fiber axis and orthogonal to each other). Figure 6 shows a photograph of a far-field image for a PCF N9.

The results of measurements for our PCFs far-field intensity profiles are shown in Figs. 7 to 8. Figure 7(a) shows a measured far-field intensity profile of the fiber N6 with length L_{fib} =1.15 m, Fig. 7(b) shows the profile of the fiber N10 with L_{fib} =1.40 m, Fig. 8(b) shows the profile of the fiber N7 with L_{fib} =1.25 m and Fig. 8(a) shows the profile of the fiber N9

TABLE II. Results of angle θ_1 measurements, *NA* and MFD obtained.

i	R_x(mm)	R_y (mm)	L (mm)	$L_{\text{fib}}(m)$	θ_1°	*NA*	Gaussian MFD (μm)
N6	10.50	11.00	180	1.15	3.418	0.030	20.09
N10	12.00	12.50	195	1.40	3.595	0.031	18.50
N7	12.50	13.50	202	1.25	3.682	0.032	18.43
N9	11.00	12.50	183	2.00	3.674	0.032	16.07
Design					3.071	0.026	14.47

TABLE III. Comparison between theoretical and experimental results.

i	Angle θ_1°		Error (%)	Numerical aperture(NA)	
	Theoretical	Experimental		Theoretical	Experimental
N6	3.067	3.418	11.410	0.0267	0.02982
N10	3.244	3.595	10.805	0.0283	0.03136
N7	3.681	3.682	0.0426	0.0321	0.03213
N9	3.826	3.674	3.976	0.0334	0.0321

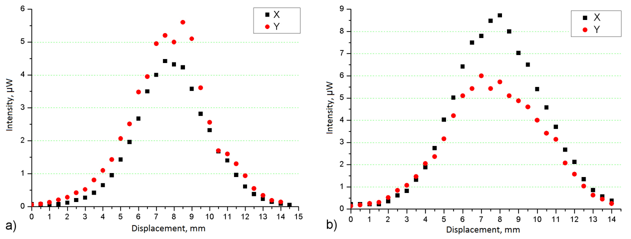

FIGURE 7. Far-field intensity profiles: a) for fiber N6, b) for fiber N10.

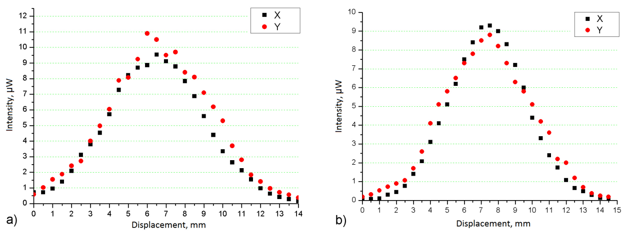

FIGURE 8. Far-field intensity profiles: a) for fiber N7, b) for fiber N9.

with L_{fib} =2.00 m. After collecting the far-field intensity profiles for these four fibers, an angle $\theta_1 = \theta/2$ between the fiber axis and 5% intensity point (average of R_x and R_y) was calculated using the distance L between the outside end of the fiber and the photodetector. Then numerical apertures were obtained for the four fibers using the following formula:

$$NA = \sin\theta_1 \tag{11}$$

At calculation of Gaussian MFD for designed fiber we used formula (8), at calculation of MFD for our fabricated PCFs we used experimental far-field intensity profiles. All obtained data are shown in Table II.

For comparison, calculations of θ_1 and *NA* were made for each of the four PCFs fabricated. At the calculations we used capillary diameters d and the distances Λ, measured for the fibers with the AFM. Based on these data and using above-mentined formulas for V and W parameters we calculated the theoretical angle θ_1 and the theoretical numerical aperture (NA) for the fibers. The experimental and theoretical results are presented in Table III.

4.3. Attenuation in the fabricated PCFs

We also measured attenuation in our fibers. The measurements were made using the cutback technique. Figure 9(a) shows attenuation of the fiber N6. At measurements we used pieces of the fiber with lengths of 30, 10, and 2 m. We can see in Fig. 9 (a) that attenuation of the fiber is about 110÷700 dB/km in the wavelength range of 1100-1700 nm and minimal attenuation is about 110 ÷ 120 dB/km in the wavelength range of 1500-1700 nm. The water peak reaches its maximum attenuation level of about 700 dB/km at a wavelength of approximately 1390 nm. Figure 9 (b) shows attenuation of the fiber N10. At measurements we used the same pieces of the fiber. The fiber has the highest attenuation from all fabricated fibers, with a lower attenuation of 250-270 dB/km within the wavelength range from 1500 nm to approximately 1650 nm. The water peak is about 850 dB/km at a wavelength of approximately 1390 nm. In Fig. 10 (a) we can see the attenuation of the fiber N7. At mesurements we used the same pieces of the fiber as before. This fiber has much less attenuation than the fiber N 10. It reaches its minimum value of 40-60 dB/km at wavelengths ranging from 1500 nm up to 1650 nm. The water peak reaches his maximum level of 500 dB/km at approximately 1390 nm. Fiber N 9, whose attenuation is shown in Fig. 10 (b), is without doubt the best one from all fabricated fibers. At measurements we used

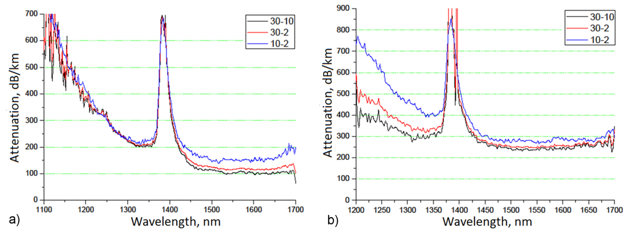

FIGURE 9. Attenuation spectra: (a) of fiber N 6, (b) of fiber N 10.

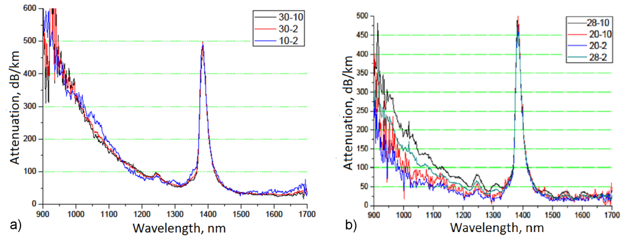

FIGURE 10. Attenuation spectra: (a) of fiber N7, (b) of fiber N9.

pieces of the fiber with the lengths of 28, 10, and 2 m. The fiber has the lowest attenuation, reaching 15-30 dB/km between 1500 nm and 1700 nm. The water peak reaches about 500 dB/km. This fiber has also a little attenuation between 1200 and 1300 nm ranging from 20 to 50 dB/km.

5. Conclusions

We have reported about design, fabrication and testing of geometric dimensions and optical properties for all-silica LMA PCFs with a solid core surrounded by cladding with a three full number of hexagonal air capillaries rings. Preliminary we used an analytical approach based on V and W parameters to calculate LMA PCF properties and to design a fiber preform. At stretching at temperatures of 1920°C, 1930°C, 1940°C, and 1950°C we fabricated four LMA PCFs: N 9, N 7, N 10, and N6, respectively. The LMA PCFs with external diameters D_{ext} of about 125 μm, with core diameters D_{core} = 19.45, 20.15, 20.39, and 21.79 μm, with averaged inner capillary diameters d = 4.453, 4.1403, 3.515, and 3.516 μm, and with averaged distances between the centers of two adjacent capillaries (pitch) Λ = 10.429, 10.312, 10.313, 10.664 μm have been fabricated. These geometric dimensions were very close to calculated ones (D_{ext}=125 μm, D_{core} =19.58 μm, d = 4.594 μm, and Λ = 12.080 μm). Measurements of LMA PCF geometric dimensions also show that the most accurate and reliable measurements are possible to make only at using of a scanning atomic force microscope. Experimental measurements of output angles θ_1 and numerical apertures *NA* for fabricated fibers showed that experimental values are very close to calculated. In the worst case (for fiber N 6) the error was about 11% from the calculated value, whereas in the best case (for fiber N 7) the error was less than 1%. We also measured attenuation in fabricated fibers. The highest attenuation of about 250 to 270 dB/km (in a better case) has been obtained for a fiber N 10 (stretching temperature of 1940°C) in the wavelength range from 1500 nm to 1650 nm, the lowest one of about 15 to 30 dB/km between 1500 nm and 1700 nm has been obtained for a fiber N 9 (streaching temperature of 1920°C). This means that some optimal temperatures exist (in our case of about 1920°C) at fabrication of our LMA PCFs. At these temperatures a silica glass viscosity, a draw stress and deformations of PCFs cross-section have some best values. At such optimal parameters it is possible to fabricate LMA PCFs with low attenuation and with geometric dimensions, which correspond to characteristics of calculated LMA PCFs. However, detailed research on this issue was out of the scope of our work and it is underway.

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