Отримані результати показують, що при будь-якому з розглянутих видів дефектів модове поле буде мати 2 виражені максимуми. Також результати свідчать, що загальна потужність модового поля зростає зі зменшенням середнього діаметру повітряних капілярів. Іншим важливим результатом є те, що випадкове відхилення діаметру повітряних включень може призвести до збільшення потужності модового поля

Ключові слова: фотонно-кристалічне волокно, кварц, показник заломлення, гаусово розподілення

Полученные результаты показывают, что при любом из рассмотренных видов дефектов модовое поле будет иметь 2 выраженных максимума. Также результаты показывают, что общая мощность модового поля возрастает с уменьшением среднего диаметра воздушных капилляров. Другим важным результатом является то, что случайное отклонение диаметра воздушных включений может привести к увеличению мощности модового поля

Ключевые слова: фотонно-кристаллическое волокно, кварц, показатель преломления, гауссово распределение

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THE ANALYSIS OF PHOTONIC CRYSTAL FIBERS OPTICAL-GEOMETRICAL PROPERTIES AND THEIR IMPACT ON TRANSFER PARAMETERS

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1. Introduction

Microstructured optical fibers (MOFs) consist of dielectric materials (typically pure silica) with a regular array of air holes. There are two main categories of MOFs: fibers with a hollow core (HC) and with a solid core (SC). The SC MOFs are particularly interesting because have specific properties but without the fabrication and splicing difficulties encountered in the HC MOFs. Moreover, they also allow the photonic-bandgap (PBG) effect to be coupled with an actively doped SC and with the realization of wavelength-selective mirrors (Bragg gratings). These SC-MOFs are shown in Fig. 1.

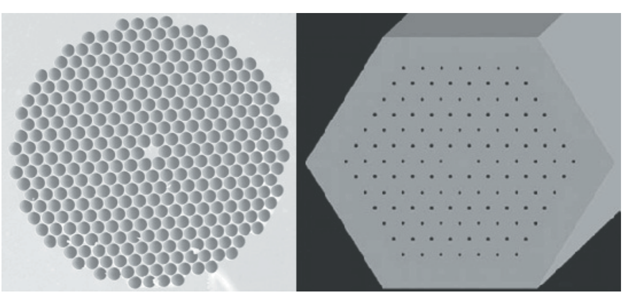

Fig. 1. Transverse profile of SC-MOFs

The optical properties of these SC-MOFs depend on several main parameters that are listed as follows:

1) the index contrast Δn between the high-index inclusions and the silica background;

2) the diameter d of the high-index inclusions;

3) the ratio d/Λ, where Λ is the distance between the inclusion centers (pitch);

4) the vacuum wavelength λ of the excitation radiation.

In this work we consider MOFs which consist of a silica core surrounded by a ring of air holes [1- 4].

Some defects are inherent to the fabrication process. One can mention, for example, the inhomogeneity of the initial germanium-doped preform: its diameter and refractive index evolve along its axis.

The variation of the preform diameter induces a variation of both the diameter and the position of the inclusions when the hexagonal stack is assembled before drawing. These defects (and others) will lead to transverse disorders in the final fiber, which have to be taken into account in the model [4].

2. Investigation of the impact of geometrical behaviors on operation and transfer parameters

To investigate the impact of geometrical behaviors on operation parameters we use finite-element method [4, 5]. The main research tasks are listed as follows:

1) extraction of the mode field form in an investigated optical fiber;

2) definition of the mode field form variations both at a random variation of air hole diameters and at a random variation of the centers position of air holes;

3) calculation of total mode field power variations depending on variation of inclusion diameter.

The air hole diameter of an investigated fiber d = 1.6 μm and the distance between inclusion centers (pitch) Λ = 2.3 μm. We used wavelength λ = 1.55 μm. Transverse profile of an investigated MOF is shown in Fig. 2, as well as its mode field distribution.

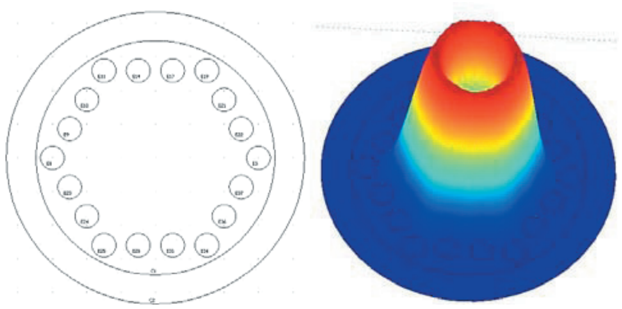

Fig. 2. Transverse profile of the investigated fiber and its mode field distribution

To define the mode field form variations both at a random variation of air hole diameter and at a random variation of the centers position of air holes we implement the effect of disorder first on one of two selected parameters, and then on two simultaneously: the air hole diameters and the positioning of air holes (for both transversal directions x and y). For each type of disorder we consider deviation in a range from –10% up to +10% of the Gaussian distribution that we use in order to generate the structures. Note that all the 18 air holes are subject to random perturbation.

These three photographs show that at any of the considered defect types mode field will have two pronounced maximums even at insignificant variations of geometrical parameters. Results also have shown that position of maximums in relation to the center of symmetry of a fiber changes. It is evident that at practical use an investigated type of the MOF special angular positioning end faces of fibers is necessary.

To calculate total mode field power variations depending on variation of inclusion diameter first we implement the effect of disorder on air hole diameters (we consider deviation in a range from –10% up to +10% of the Gaussian distribution), and then we consider fixed deviation of ±5% and ±10% of all air hole diameters. In the first case we will consider total mode field power versus the mean diameter of air holes. Note that we will represent normalized values of total mode field power.

Results presented on fig. 3 show, that total mode field power increases with decreases of mean diameter of air holes. Another important result is that random variations of diameter of inclusions (air holes) can lead to an increase of total mode field power (when mean diameter of air holes is less than 1.6 μm).

Fig. 3 also shows, as expected, that computed total mode field power (normalized value) decreases when air hole diameter increases. This evolution can be interpreted as a consequence of the increase of the core diameter (effective area). Moreover, results of calculation of mean-square variation of inclusions diameter versus diameter of air holes show that at reduction of air hole diameter mean-square variation of total mode field power increases. Consequently, at reduction of air hole diameter spreading of the mode field in an investigated fiber is observed.

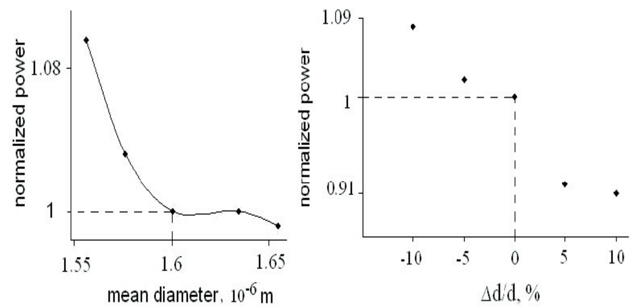

Fig. 3. Normalized power versus the mean diameter of air holes and normalized power versus the fixed diameter of air holes

3. Analysis of the mode field diameter influence in connected PCF on signal transmission

In many events appears need of photonic-crystal fibers connection between itself or with other function electronics elements. In consequence of the complex structure of cladding such fibers, as well as their dispersion and polarisation by particularities a process of PCF connection and following analysis of contribute signal attenuation is difficult. Mainly this is connected with the complex form of mode field distribution intensity. On the Fig. 4 are shown radiating intensity distributions for standard singlemode fiber (above) and PCF (down).

Take aim given study is determination of dependency of transmission signal loss from effective mode fields areas connect microstructure fibers.

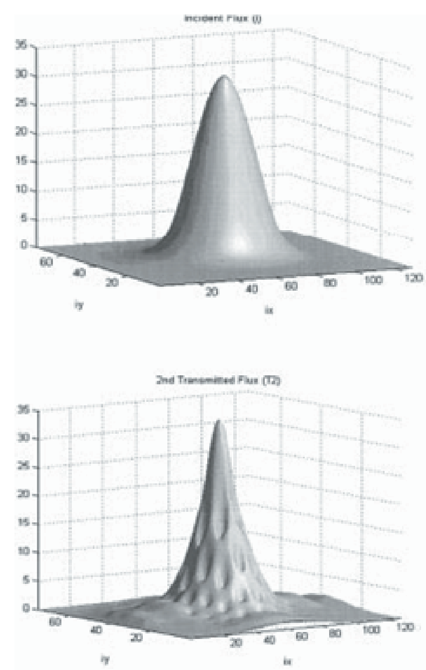

Fig. 4. Intensity distributions of radiating for standard singlemode fiber and PCF

Distribution of radiating intensity for the fundamental mode in the transverse section photonic-crystal fiber is shown on Fig. 4. Electrical field toward axis can be calculated using the equation Maxwell [6, 7].

So primary task is determination of transverse field distribution, which decompositions of two component on axises x and y

$$\vec{e}_t(x,y) = e_x(x,y)\hat{x} + e_y(x,y)\hat{y} . \quad (1)$$

Transverse distribution an electrical field in fiber section possible to write as decompositions on system of functions Hermite-Gaussian

$$e_x(x,y) = \sum_{a,b=0}^{F} \varepsilon_{ab}^{x} \psi_a(x)\psi_b(y),$$
$$e_y(x,y) = \sum_{a,b=0}^{F} \varepsilon_{ab}^{y} \psi_a(x)\psi_b(y), \quad (2)$$

where $\psi_i(s)$ $(i = a, b,\ s = x, y)$ - function Hermite-Gaussian elements:

$$\psi_i(s) = \frac{2^{-i}\pi^{-1/4}}{\sqrt{(2i)!\omega}} \exp\left(-\frac{s^2}{2\omega^2}\right) H_{2i}(s/\omega), \quad (3)$$

where $H_{2i}(s/\omega)$ - $2i$ -th order Hermite-Gaussian polynomial.

$$A_{eff} = \frac{\left(\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} |E(x,y)|^2 dxdy\right)^2}{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} |E(x,y)|^4 dxdy} . \quad (4)$$

Having substitute expression for intensity of radiating (1) in expression (4), we find that

$$A_{eff} = \frac{2\left(\pi\omega \sum_{a_1,a_2=0}^{F-1} \varepsilon_{a_1,a_2}^2\right)}{\sum_{a_1,a_2,\ldots a_8=0}^{F-1} A_{a_1,a_2,\ldots a_8}}, \quad (5)$$

where

$$A_{a_1,a_2,\ldots a_8} = \varepsilon_{a_1,a_2}\varepsilon_{a_3,a_4}\varepsilon_{a5,a_6}\varepsilon_{a_7,a_8}\delta_1\delta_2 \times$$
$$\times\sqrt{(2a_1)!(2a_2)!(2a_3)!(2a_4)!(2a_5)!(2a_6)!(2a_7)!(2a_8)!} \quad (6)$$

$$\delta_1 = \sum_{t_1=0}^{\min(2a_1,2a_3)} \sum_{t_2=0}^{\min(2a_5,2a_7)} \frac{(2\gamma_1)!}{(-4)^{\gamma_1}\gamma_1!t_1!(2a_1-t_1)!}$$
$$\overline{(2a_3-t_1)!t_2!(2a_5-t_2)!(2a_7-t_2)!} \quad (7)$$

$$\delta_2 = \sum_{t_1=0}^{\min(2a_2,2a_4)} \sum_{t_2=0}^{\min(2a_6,2a_8)} \frac{(2\gamma_2)!}{(-4)^{\gamma_2}\gamma_2!t_1!(2a_2-t_1)!}$$
$$\overline{(2a_4-t_1)!t_2!(2a_6-t_2)!(2a_8-t_2)!} \quad (8)$$

$$\gamma_1 = a_1 + a_3 + a_5 + a_7 - t_1 - t_2,$$

$$\gamma_2 = a_2 + a_4 + a_6 + a_8 - t_1 - t_2 \quad (9)$$

Calculated value A_{eff1}, A_{eff2} of effective mode field areas for two connected fibers, possible define the losses, caused by their difference. In this case signal power transmission coefficient ($T < 1$) approximate can be present in the form

$$T \approx \frac{4A_{eff1} \cdot A_{eff2}}{(A_{eff1} + A_{eff2})^2} . \quad (10)$$

Having substitute in given expression of formula for calculation of effective modes areas connected fibers (5) and having convert its, we find that

$$T \approx \frac{2\sum_{a_1,a_2,\ldots a_8}^{F-1} A_{a_1,a_2,\ldots a_8}\left(\omega_b \sum_{b_1,b_2=0}^{F-1} \varepsilon_{b_1,b_2}^2\right)^2 \times}{\left[\sum_{a_1,a_2,\ldots a_8}^{F-1} A_{a_1,a_2,\ldots a_8}\left(\omega_b \sum_{b_1,b_2=0}^{F-1} \varepsilon_{b_1,b_2}^2\right)^2 +\right.}$$
$$\frac{\times \sum_{b_1,b_2,\ldots b_8}^{F-1} A_{b_1,b_2,\ldots b_8}\left(\omega_a \sum_{a_1,a_2=0}^{F-1} \varepsilon_{a_1,a_2}^2\right)^2}{\left.+\sum_{b_1,b_2,\ldots b_8}^{F-1} A_{b_1,b_2,\ldots b_8}\left(\omega_a \sum_{a_1,a_2=0}^{F-1} \varepsilon_{a_1,a_2}^2\right)^2\right]^2} \quad (11)$$

If we know transfer coefficient it's possible to calculate the optical losses value

$$\alpha_T = -10\lg(T). \quad (12)$$

If two identical types of fiber with the same mode field distribution are connected, transfer coefficient is equal to one and, respectively, losses are zero. But in practice, these values can't be achieved due to various factors that influence the quality of the connection.

4. Conclusion

The found results show that at any of considered defect types mode field will have two pronounced maximums. Results presented in this work show, that total mode field power increases with decreases of mean diameter of air holes.

Another important result is that random variations of diameter of inclusions (air holes) can lead to an increase of total mode field power. At practical use an investigated type of the MOF special angular positioning end faces of fibers is necessary. We also have shown that random variations of inclusions diameter can increase total mode field power.

Conduct analysis of prospects PCF using in electronic technique components. The signal losses caused by the difference of mode fields effective areas connected fibers are determined. Further researches in this sphere are direct on the study of influence other optical-geometric parameters PCF, and well as their connection on the signal transmission. Conduct work on the choice of geometric unbalances determination methods between fibers and control design-technological parameters of connected PCF.

We believe that all presented results will be helpful for tolerance of fabrication processes and for better understanding of the role of random variation of geometrical behaviors (arising at fabrication processes) on operation parameters of microstructured optical fibers.

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Abstract

In microstructured optical fibers some defects are inherent to the fabrication process. One can mention, for example, the inhomogeneity of the initial preform: diameter, position of the inclusions (when the hexagonal stack is assembled before drawing) and refractive index that evolves along its axis. These defects will lead to transverse disorders in the final fiber. Therefore, the analysis of photonic crystal fibers optical-geometric properties and their impact on transfer parameters is very important. We note that in our investigation we use finite-element method.

The obtained results show that at any of considered defect types the mode field will have two pronounced maximums. The results presented in this work show that total mode field power increases with decreasing the mean diameter of air holes. Another important result is that random variations of diameter of inclusions (air holes) can lead to an increase of total mode field power. We also have shown that random variations of inclusions diameter can increase the total mode field power. In the part 2 the signal losses caused by the difference of mode fields effective areas of connected fibers are determined. Further research in this sphere is directed to the study of influence of other optical-geometric PCF parameters, as well as their connection to the signal transmission.

All presented results will be helpful for tolerance of fabrication processes and for better understanding the role of random variation of geometrical behaviors (arising at fabrication processes) on operation parameters of microstructured optical fibers

Keywords: *photonic crystal fiber, quartz, photonic-bandgap, index contrast, Gaussian distribution*