The Autoconvolution Method Use for Positioning Photonic Crystal Fibers

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***Abstract* — In this paper, the autoconvolution method was investigated to determine the position of the longitudinal axis of the photonic crystal fiber and to determine the center of the mode field in the cross section. Knowing the center of the PCF mode field, one can determine the cross section in which the diameter of the mode field will be maximal. This allows a more precise positioning of two identical PCF during connection. The proposed method allows improving the quality of the positioning of the PCF by transverse, angular, longitudinal displacements, and also by the mutual angle of rotation of the connected PCFs.**

***Keywords* — photonic crystal fiber; mode field; optical fiber connection; optical fibers control; optical power loss; near-field technique; autoconvolution method.**

I. INTRODUCTION

There are several types of photonic crystal fibers (PCFs). In this work, PCFs, which consist of a quartz core and hollow capillaries located around it in a cladding along the entire fiber, were studied. Due to the air capillaries in the cladding, its effective refractive index decreases. Due to this, the light is refracted and moved along the quartz core, which has a higher refractive index (Fig. 1).

Due to the specific structure of the cross section, photonic crystal fibers have unique properties that are not inherent to standard single-mode or multimode optical fibers (OF). Therefore, the prospects for the use of PCF as various elements of functional electronics are already evident (dispersion compensators, efficient Raman lasers, optical amplifiers, switches, multiplexers, demultiplexers, supercontinuum generators, etc.).

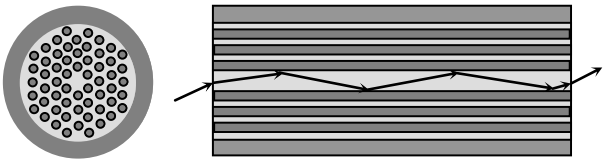

Fig. 1. Cross section and passing of light beams in PCF

Production technologies of PCF are constantly being improved, and the characteristics of the signal transfer in such fibers approach the parameters of standard OF. But for the introduction of functional electronics elements on the PCF in existing optical telecommunication systems, it is also necessary to solve the problem of ensuring their qualitative connections with standard OF or with other PCF.

Modern methods used to obtain standard OF connections have a number of disadvantages for their use in PCF connections. First of all, this is due to the complex geometric structure of the PCF, as well as their optical characteristics. As in the case of connecting standard optical fibers, the PCF connection can be performed either by detachable or non-detachable. But in both cases, this process is much more time-consuming and requires more precision.

When positioning PCF using classical methods can not determine the position of the core fiber directly in his image. Because the air holes in the cladding distort picture of the radiation intensity, which is obtained by transversal sounding of PCF by a light beam. In addition, in the case of the connection of two PCFs to each other, the quality of the connection affects the mutual arrangement of air holes in their cladding. To minimize losses, it is necessary to achieve the angular agreement of the PCF.

In this regard, an important and topical scientific task is the development of methods and means for ensuring high-quality connections of functional electronics elements on photonic crystal fibers.

The purpose of this work is to study the method of autoconvolution for determining the axis of the PCF in transverse and longitudinal light-beam sounding to improve the accuracy of positioning during the connection. This will reduce the loss of optical power of the signal caused by angular, transverse and longitudinal axis shifts and differences in the holes in the PCFs cladding (relative angles of rotation).

II. POSITIONING OF PCF AT TRANSVERSE ILLUMINATION

Positioning PCF in the process of connection is based on received images by profile alignment system. In this case, the optical fiber is illuminated perpendicular to its axis by a beam of light. A beam that passes through the fiber, refracted and out of it has a different angle. The distribution of the radiation stream at the output of the PCF is fixed by the video camera and subject to further processing.

The main stages of the study are:

- obtaining an image of the PCF field with transverse illumination;

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- formation of a one-dimensional signal of the intensity of the distribution of the field *I (x)*;

- signal offset;

- filtering and removing the background component of the signal;

- calculation of the signal autoconvolution and determination of the coordinate of its maximum value;

- determining the coordinate of the axis as half the coordinate of the autoconvolution maximum value.

The mode field in the PCF section as a sum of the useful signal and noise can be represented:

$$\xi(x) = I(x) + n(x)\,, \tag{1}$$

where $I(x) \approx E^2(x)$ is mode field distribution; $n(x)$ is noise.

To extract the useful signal $I(x)$ from the mix with noise $\xi(x)$, it is proposed to use a matched filter.

In this case, the pulsed response of the matched filter to the constant multiplier must be a reference copy of the useful component, namely

$$h(x) = \alpha I(-x)\,. \tag{2}$$

The result of the matched filtering is described by the convolution integral

$$s(z) = \xi(x) * h(x) = \int_{-D/2}^{D/2} \xi(x) h(z-x)dx\,, \tag{3}$$

where *D* is extent of a registration site.

If substituting (2) in (3) and $\alpha = 1$ in a point $z = 0$ we have

$$s(0) = \int_{-D/2}^{D/2} I^2(x)dx + R_{ni}(0) \approx R_{ii}(0)\,, \tag{4}$$

where the valuation mutual covariation R_{ni} to noise and signal function is close to zero owing to their statistical independence.

The generated test signal was filtered and removed the background component. After that, the autoconvolution of this signal was calculated. In fig. 2 presents the results of calculations.

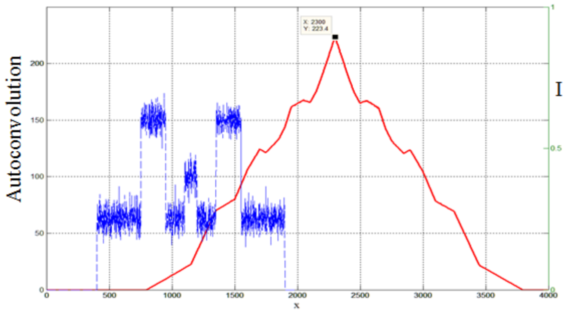

Fig. 2. Test signal with removed background after filtration (dashed line) and its autoconvolution (solid line)

The coordinate of the maximum autoconvolution K = 2300 corresponds to the double coordinate of the PCF axis. Determining the coordinates of the PCF axis in each cross section, we obtain an axis image in the XY area. Knowing the position of the axes of the PCF, which must be connected, it is possible to perform positioning for transverse, angular and longitudinal shifts.

Measurement of the radiation intensity in transverse illumination of the PCF was carried out using an experimental setup. It includes welding device optical fibers Coringer AFS-48. During the experiment, a PCF with a quartz core and one circle with six holes in the cladding were researched. The measurement result is shown in Fig. 3.

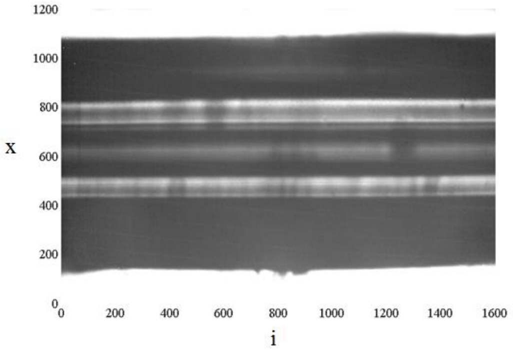

Fig. 3. The resulting image of the PCF under transverse radiation

The field intensity distribution in the cross section i=200 after the filtering and exclude background and its autoconvolution are shown in Fig. 4.

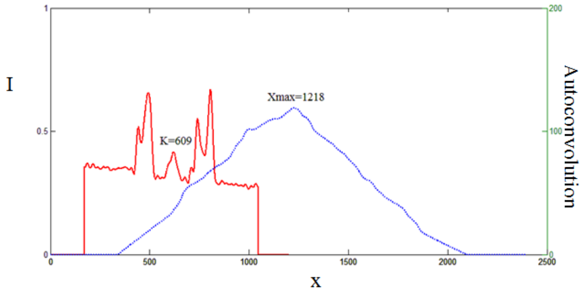

Fig. 4. Measured of the field intensity with the excluded background (solid line) and its autoconvolution (dashed line) in the cross section i=200

III. POSITIONING PCF AT LONGITUDINAL ILLUMINATION

The mode field PCF has a complicated form in the cross section. In Fig. 5 can be seen flowing of mode field in the cladding between the holes of inner (first) ring. An important parameter is the overlap area of mode fields when connecting two photonic-crystal fibers. The more overlapping mode fields, the less signal loss we will get. Therefore, it is necessary to ensure that the holes in the PCF cladding coincide, i.e. should take into account the angle of their mutual rotation.

Determining the position of the intersection of the PCF, in which the diameter of the modal field will be maximal, will enable the connection of two PCFs with less losses of optical power at the junction, which are associated with inconsistencies of modular.

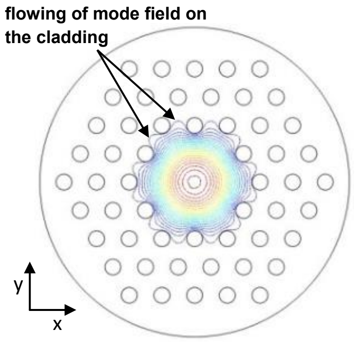

Fig. 5. Cross section of PCF and received principal mode field distribution at a wavelength λ = 1.55 µm

The following sequence of actions is proposed:

- obtaining an image of the mode field in the cross section of the PCF;

- filtering the image to reduce the noise effect on the calculations accuracy;

- determination of the mode field distribution center by the autoconvolution method;

- determination of the mode field diameter for each of the sections passing through the distribution center;

- definition of the cross section, in which the diameter of the mode field will be maximal.

For research purposes, a software PCF model was constructed with a core radius of 19.7 µm, a holes diameter in the cladding of 6.4 µm and a distance between holes of 13.2 µm (Fig. 6). Further the distribution of the principal mode field at the wavelength λ = 1.55 µm is obtained.

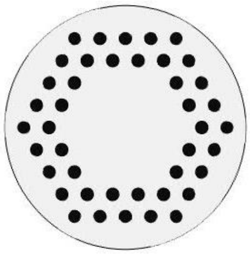

Fig. 6. PCF model

The reduction of the calculation error is realized by filtering the received distribution of the mode field. This was done using the Butterworth filter of lower frequencies of the fourth order and the normalized cutoff frequency w=0.5π rad/s. After filtering, the mode field intensity distribution is normalized to unity (Fig. 7) and subject to further processing.

To determine the center of the mode field intensity distribution, we use the function of a two-dimensional autoconvolution of this distribution:

$$s(\tau,\upsilon)=I(x,y)**I(x,y)=\int\limits_{x1}^{x2}\int\limits_{y1}^{y2}I(x,y)I(\tau-x;\upsilon-y)dxdy$$

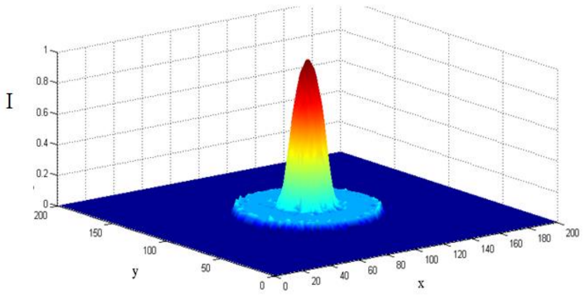

Fig. 7. The mode field intensity distribution is normalized to unity

In Fig. 8 shows the autoconvolution of the mode field intensity distribution.

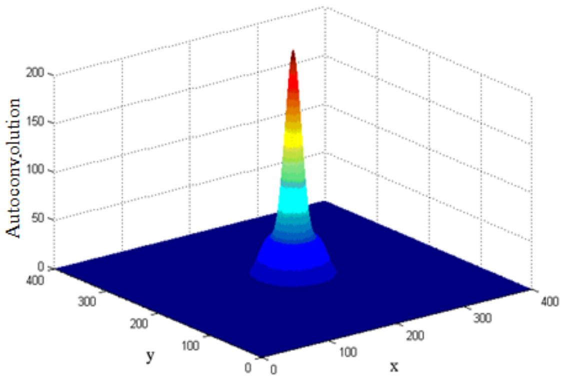

Fig. 8. Autoconvolution of the mode field intensity distribution (calculated coordinates of the maximum autoconvolution value x=200, y=200)

Coordinates of autoconvolution maximum exactly twice greater than center coordinates of mode field distribution.

After determining the position of the maximum value of the autoconvolution, it is necessary to determine the diameter of the mode field in each of the sections passing through the distribution center. The equation of the section is as follows:

$$y(x)=y_0+tg(\alpha)\cdot(x-x_0),$$

where $x_0;y_0$ is coordinates of mode field distribution center; $\alpha=0...180^\circ$ is angle of the section rotation.

To measure the mode field, the method of the near field was used, based on the measurement with the help of focused optics. The distribution of radiation power to the matrix photodetector is transmitted. The installation for implementing the method of the near field contains an optical system, multielement CCD-photodetector, ADC and computer (Fig. 7). The obtained image of the mode field (Fig. 8) is filtered from the influence of noise and subject to further processing.

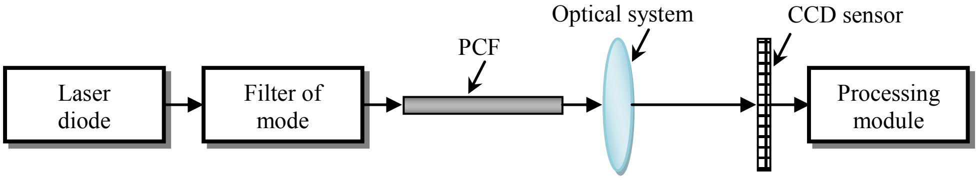

Fig. 7. The measuring scheme the fibers parameters by the near field method

The result of determining the diameter of the mode field in each section is presented in Fig. 9. Knowing the positions of the maximum diameter of the mode field for each connected PCF, one can reduce the loss of the optical signal by increasing the overlap of the mode fields.

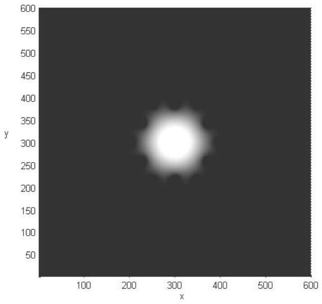

Fig. 8. Measured the image of PCF mode field

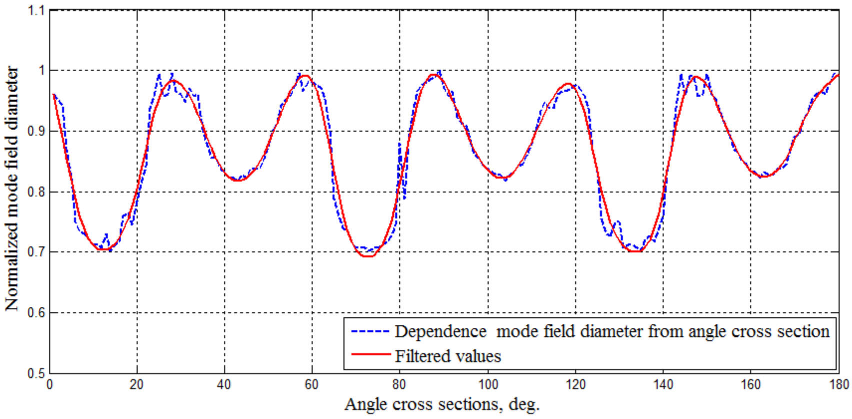

Fig. 9. Change of mode field diameter depending on the rotation angle of crossing *D(α)*

It is known that the points of the extremum of a function are determined by the derivative. Therefore, to determine the maximum diameter of the mode field, it is sufficient to find the points in which the derivative of the function *D(α)* will be zero and will change its sign from plus to minus.

Thus, it was found five values of the angle of inclination of the sections, in which the mode field diameter is maximum (Table 1). The normalized values for maximum diameters range from 0.989 to 0.996. The difference between the values is not significant, so you can position the PCF on any of the angles found.

TABLE I
RESULTS OF CALCULATIONS

The sections position, deg.	31	60	89	120	148
Normalized mode field diameter	0,989	0,996	0,996	0,992	0,992

IV. CONCLUSIONS

In this paper, the autoconvolution method was investigated to determine the position of the longitudinal axis of the photonic crystal fiber and to determine the center of the mode field in the cross section. The main limitation of the proposed method is the presence of axial symmetry of the distribution of the mode field in the cross section. That is, in the first round of the PCF cladding there should be an even number of air holes. The proposed method allows improving the quality of the positioning of the PCF for transverse, angular, longitudinal misalignments, and also by the mutual angle of rotation of the connected PCFs.

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