Monitoring of Photonic-Crystal Fibers Positioning in the Connection Process

A. Filipenko, O. Sychova

Abstract – **In this report the monitoring method of PCF positioning at the connection process is offered. It is based on the matched filtration principle in the form of autoconvolution. Equations which connected PCF core axis coordinates with the maximum value of optical field intensity autoconvolution was obtained. It is shown that optical fiber displacement relatively base coordinates corresponds to half coordinates of autoconvolution maximum. Researches have shown that the offered method possesses high noiseproof factor and much higher accuracy in comparison with an integrated method.**

Index Terms – **Autoconvolution, connect, optical intensity distribution, photonic crystal fiber (PCF)**

I. INTRODUCTION

The scope of new type optical fibers, named photonic-crystal fibers (PCF), extends in the electronic techniques recently. There are air canals in PCF cladding unlike ordinary fibers. It is possible to change PCF optical properties over a wide diapason depending on geometry, channels sizes, interval between them and also their relative positioning (in the form of a hexagonal or a casual channels positioning). Therefore, even the slightest deformation of PCF geometry very strongly influences on a fiber optical characteristics, so and on a signal transmission.

In many cases, for example at installation of functional electronics elements based on PCF, there is a need of PCF connections among themselves or with ordinary fibers. It inevitably leads to occurrence of PCF geometry deformations and various displacements. As it is known, allowable displacement excess leads to considerable increase of insertion optical losses. One of the main problem at maintenance of insertion losses low level is the definition of a spatial location of positioning objects, in particular PCF, concerning base coordinates. As the last, can by cores axes of interfaced optical fibers or a base axis of the technology equipment.

The decision of the given problem is reach by working out of the special technique, which should provide the positioning errors not exceeding percentage units of controllable value and making the tenth part of a micrometer. The majority of existing methods is based on perception and the analysis of positioned fibers optical images and is intended for the parameters control of ordinary optical fibers [1-5].

The purpose of these researches is working out of the automated precision control method of PCF positioning at connections. The problems of a mathematical substantiation of technique principles, imitating modelling on the personal computer and experimental researches on the technology equipment were solve during researches.

II. THEORETICAL RESEARCHES

As is well known, in the fiber-optic connect process are decided tasks of PCF positioning, at which the current fiber position is determined.

To the characteristics, describing these connected PCF properties, concern:

- corner of a mutual inclination of connected PCF cores axes. In the majority of modern positioning devices this size should be eliminated by a premise of fibers in V-groove of positioning devices elements. However, as has shown operating experience and the researches, the given property is realised not always;
- value of longitudinal displacement of PCF cores;
- value of cross-section displacement of PCF cores.

Determine of the specified positioning parameters is rational for carrying out by means of an optical television control method with use of cross-section PCF sounding by a wide bunch uniform on light exposure of a light stream. The scheme of given method realisation is given on fig.1.

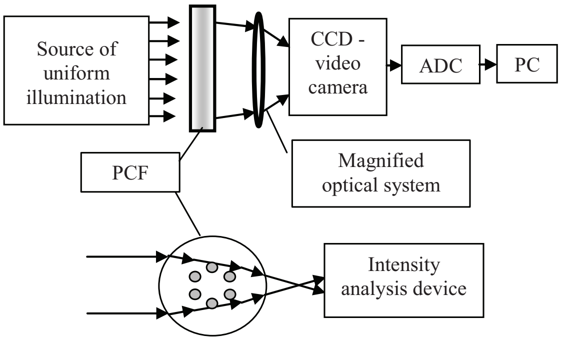

Fig.1. Scheme of the control system of PCF positioning

Here that property is use that at cross-section illumination the fiber represents focusing cylindrical lens, which make distribution of the optical field in a photodetector plane, allowing defining of a fiber optic-geometrical characteristics.

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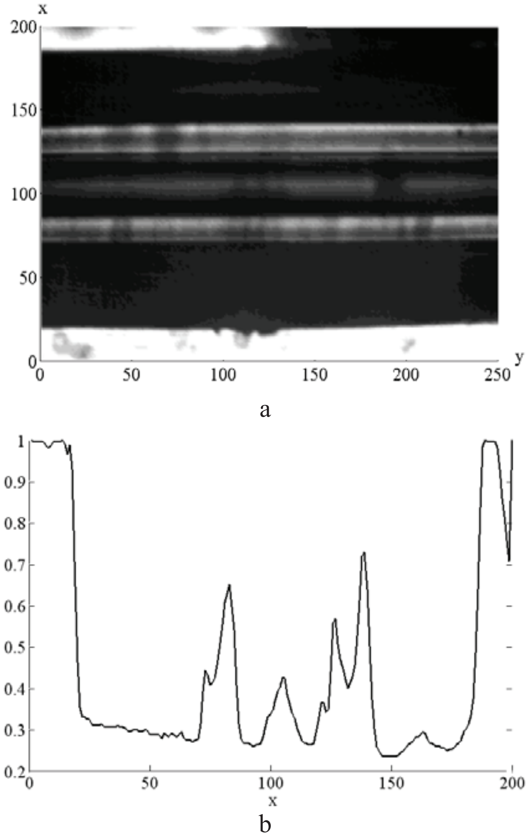
The initial information which is subject to the analysis, represents a matrix of the brightness codes corresponding to points of the image (fig.2,*a*). Resolution is caused by the matrix elements size and their quantity, and also objective magnification.



a

b

Fig.2. Image of an optical field obtained at PCF cross-section sounding (a) and corresponding to it 1D cross-section field intensity distribution (b)

Prominent features of the received image are:

- the greatest area on optical radiation intensity correspond to the free space surrounding of PCF. On level, these signals considerably exceed level of dark areas;
- the most dark areas correspond to areas of PCF cladding, free from air channels;
- at PCF displacement a zone occupied with background areas above and below a fiber (with reference to figure), change the sizes.

The main complexity of the given method realisation is the analysis of the measured information and conclusion about a condition of connection objects.

Let us consider decisions of the given problems offered in given work.

From features of an optical fibers structure known that in the absence of unacceptable defects the fields intensity distribution created by them has symmetric character concerning a core axis. The same feature is characteristic and for PCF. On fig.2,*b* the field intensity distribution in 1D variant, corresponding to the image of an optical field at the cross-section sounding PCF presented on fig.2, *a*.

From figures it is visible, that the signal is symmetric (though has the insignificant distortions caused by presence of defects and pollution of fibers surfaces and optical elements) and represents even function concerning an axis passing through the centre of symmetry and coinciding with a required core optical axis in the absence of displacement. Therefore, the problem of the radial displacement monitoring is reducing to definition of lateral shift of the signal symmetry centre. The decision of this problem is offer to be carrying out with use of a principle of the matched filtration in the form of autoconvolution [6–8].

The signal model in optical field intensity distribution section it is possible to present in a form

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

where $I(x) \approx E^2(x)$ – intensity distribution function; $n(x)$ – additive noise with zero average value.

The matched filter is the optimum filter minimising average square error at allocation useful making of $I(x)$ mix with noise $\xi(x)$.

The pulse response of the matched filter represents turned relatively y and shifted on function x_t and writing

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

Shift presence means, that for detection of a signal by duration x_t it is necessary to give it in during time x_t after beginning signal. The matched filtration consists in pass a signal $I(x)$ the filter with the pulse response $I(-x)$. The optimum filter does not depend on amplitude of a signal, i.e. instead $I(-x)$ it is possible to take $\alpha \cdot I(-x)$.

Thus, the pulse characteristic of the matched filter within constant multiplier should represent the turned copy of a useful component, namely

$$h(x) = \alpha I(-x)\,. \tag{3}$$

It is known, that the linear filtration in spatial area is equivalent to mathematical operation of convolution

$$y(t) = \int_0^t x(\tau)h(t-\tau)d\tau\,. \tag{4}$$

As it is note, for the matched filter, $h(t) = x(-t)$ therefore

$$y(t) = \int_0^t x(\tau)x(\tau - t)d\tau\,. \tag{5}$$

Function of mutual correlation $x(t)$ and $x(-t)$ can be present in the form

$$C(\tau) = \frac{1}{T}\int_0^T x(t)x(t-\tau)dt\,. \tag{6}$$

Thus, the matched filtration reduced to convolution $x(t)$ and $x(-t)$ or to calculation of their autocorrelation function. Applying the given data, we will write output signal of the matched filter in the form of convolution integral

$$s(z) = \xi(x) * h(x) = \int_{-D/2}^{D/2} \xi(x)h(z-x)dx\,, \qquad (7)$$

where D –extent of a registration site.

At substitution (3) in (7) and $\alpha = 1$ a point $z = 0$ possible writing

$$s(0) = \int_{-D/2}^{D/2} I^2(x)dx + R_{ni}(0) \approx R_{ii}(0)\,, \qquad (8)$$

where the estimation mutual covariation function to noise and signal R_{ni} is close to zero owing to their statistical independence. Thus, the output signal of the matched filter corresponds to avtocovariation function of a useful component $I(x)$ and reaches a maximum at the moment of exact identification of this component.

The spent consideration allows to construct computer processing algorithm of the measured distribution of an optical field an autoconvolution method. These operations are registration of sequence of discrete values of a signal, formation of the second sequence with return renumbering of elements, paired multiplication of elements values sequences and summation of the received products at the varied parameter of shift z. Maximum resulting to value of the received sum there corresponds to such shift of the second sequence concerning to the first at which their coincidence by criterion of a minimum average square errors is observed.

III. MODELLING AND EXPERIMENTAL RESEARCHES OF PCF POSITIONING MONITORING

Possibilities of a positioning control method have been investigated by modelling on the computer. Following principles of the theory were investigated during experiments:

- calculate of autoconvolution for initial field intensity distribution at the set measurement error and a finding on its maximum value of PCF displaced centre coordinates;
- determining of values and their errors of core centre coordinates X_c, expressed through the gravity centre of image intensity function and an estimation of their parity with the coordinates defined by calculation of initial field autoconvolution.

Efficiency and potential possibilities of a technique were checked by modelling on the computer with use of pseudorandom numbers generator for imitation of measurement errors ε. Initial distribution of an electric field intensity $I(x)$ as realization of some statistical ensemble was set. The measurement error was set by size of 10% from field amplitude value in each point of distribution. After formation a signal with 10% error the coordinates of field distribution centre X_c calculates in according with equation defining the function gravity centre

$$Xc = \int_{-D/2}^{D/2} xI(x)dx \Big/ \int_{-D/2}^{D/2} I(x)dx\,. \qquad (9)$$

Further on this signal $\xi(x)$ was executed autoconvolution operation, determined index of formed array maximum element. For undertaking of researches were designed algorithm and program, realizing the examinee method. The algorithm scheme is present on fig. 3. Modelling was carried out in MATLAB.

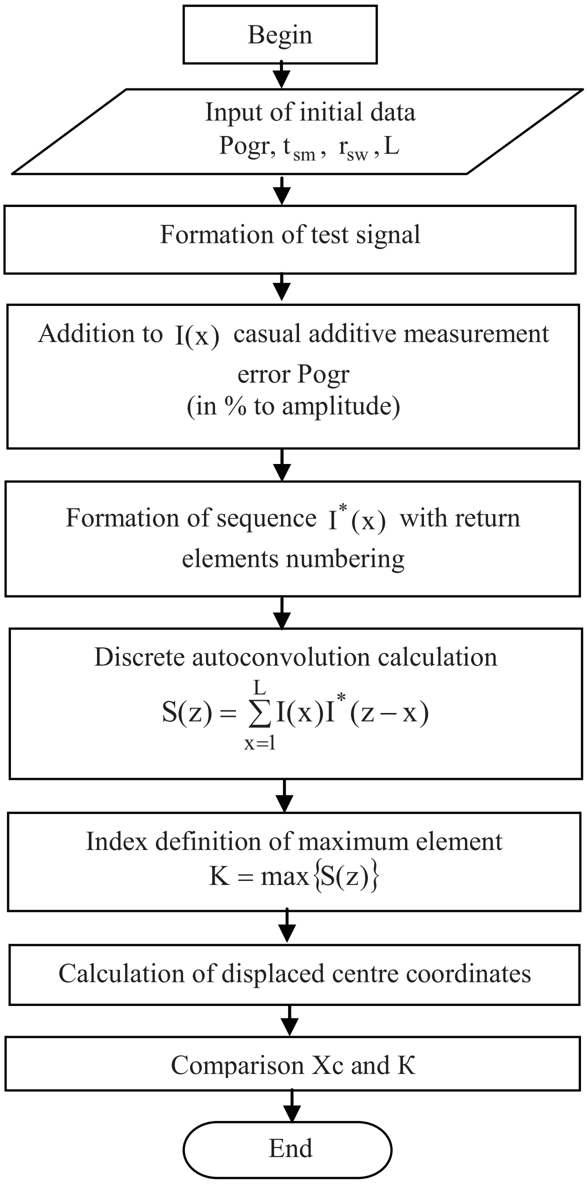


Fig. 3. The algorithm scheme of modelling researches

The offered control method of PCF positioning has been experimentally investigated on research technology equipment. Researches were executed on the strategy, which is similar to modeling on PC, with use of the measuring set-up realizing a near field technique. Sensitivity and accuracy of method under experimental researches was check by means of standards displacing the images on the given value ρ, controlled by the qualify meter of small displacement "Micron-02".

Experimental researches on the automated equipment of Fujikura optical fibers splicing have been spent for research of autoconvolution method application in the set-up realizing transversal fiber sounding (fig.4).

Making PCF initial distribution of optical field at transversal illumination to the fiber axes (see fig.2) and its autoconvolution are represented on fig. 5. It is necessary to notice, that autoconvolution maximum locate on distance of the doubled coordinates in comparison with a starting axes position.

As it was already noted, PCF have concerning the axis a symmetric structure. However, generated by them optical fields at influence of various factors can be characterized by essential asymmetry of distribution. To these factors the light sources nonuniformity, defects of the form and surfaces, presence of pollution on control objects and optical elements, nonuniformity of CCD-matrix sensitivity and charge carrying concern.

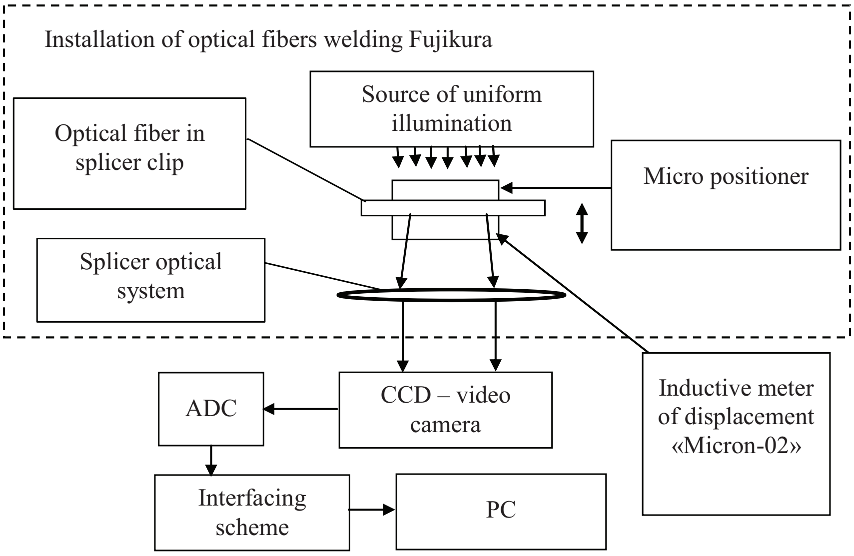


Fig. 4. The experimental set-up scheme on the basis of the Fujikura optical fibers splicing for research of a autoconvolution method at cross-section PCF sounding

Instead of the staff technical vision system was used CCD-camera, analog-digital converter, interfacing scheme and personal computer. Experimental equipment also contains in the structure a microscope with fiber fastening and moving module, a light source – semiconductor infrared laser. As moving devices were used staff micrometric positioners in a hand control mode. Movement of fibers V-groove clamper were check by the qualify displacement inductive meter "Micron-02" with a moving measurement error of 0.02 microns. The photonic-crystal fiber with a quartz core was used as control object.

The researches technique consisted in formation of PCF image shift in a CCD-camera plane, registration of optical field intensity, its transformation to the digital form and processing on the algorithm described above. Real displacement varied from 0 to 5 microns.

The measurement error of core centre coordinates by autoconvolution technique does not exceed one element of image. Last, as it was noted, defined by coordinate grid of system of microscope – CCD-matrix (for used experimental set-up at microscope magnification $300^{\times}$ corresponds to 0.1 microns).

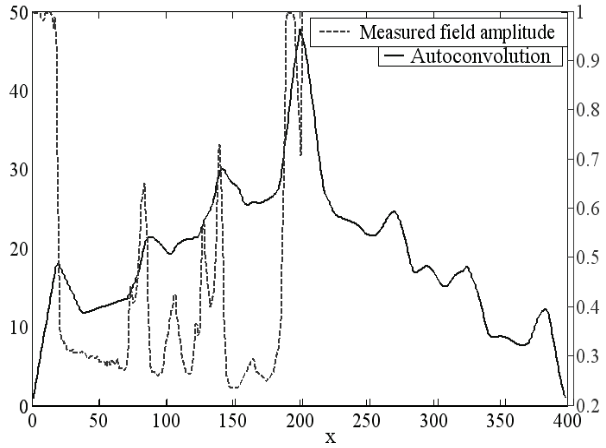


Fig. 5. 1D PCF optical intensity distribution and its autoconvolution

Researches have shown, that in spite of enumerate influences, proposed technique has high noiseproof factor and much higher accuracy in contrast with the integral method. Last it will be obvious to displace coordinates of a fiber axis in area of values with greater intensity that inevitably leads to the roughest errors reaching of several tens of image elements.

Researches results of offered method accuracy are shown in the table. The parameter «Displacement of initial field» is presented by results of measurement by standard device "Micron-02". From the table analysis it is visible, that an error for the real fields generated by control objects, does not exceed two elements of the image that correspond to size less than 0.2 microns. Taking into account the given size and positioning accuracy at designing of measuring system should get out quantity of discretization elements within duration of a useful signal and possible diapasons of its displacement.

On fig.6 3D pattern of image intensity distribution and its autoconvolution are resulted. Apparently from image to determine the maximum corresponding to fibers axes does not represent complexity.

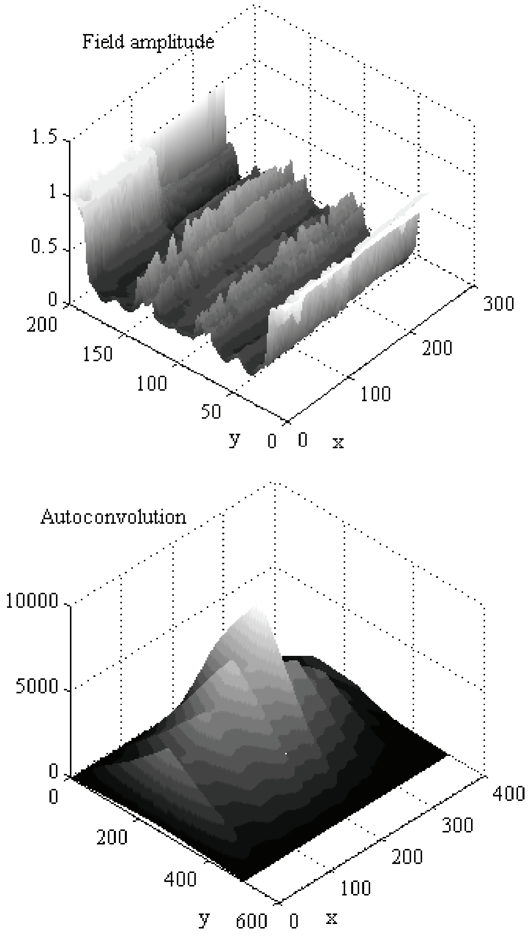


Fig. 6. 3D pattern of the measured field distribution and its autoconvolution

Result of the given method application is two arrays – a matrix of the axis centre X_c (a matrix in which the elements corresponding to core axis, are equal «1», the others – «0») the dimension $[i \times j]$ coinciding with dimension by an initial matrix of image intensity codes,

$$\begin{cases} x_c(i,j) = 1 & \text{при} \quad \text{conv}(i,j) = \max \\ x_c(i,j) = 0 & \text{при} \quad \text{conv}(i,j) \neq \max \end{cases},$$

$$X = \left[x_{c\,i,j}\right] = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \qquad (10)$$

TABLE

Parameter	PCF	PCF position at splising
Displacement of initial field, μm	12.6	10.25
Displacement of autoconvolution (in elements of image)	251	202
Displacement of autoconvolution, μm	25.1	20.2
Calculation PCF displacement, μm	12.55	10.1
Absolute error, μm	-0.05	-0.15
Relative error, %	-0.4	-1.5

and a vector dimension of sections quantity $C[j]$, which elements have the values equal to numbers of lines i, in which are observed maximum autoconvolution

$$C = [m(i,j)] = [5 \quad 5 \quad 5 \quad 0 \quad 4 \quad 4 \quad 4 \quad 4]. \qquad (11)$$

On fig.7 present the result of autoconvolution technique application to the measured image.

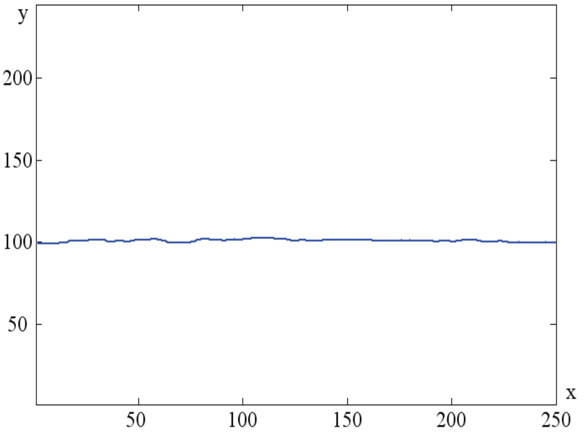


Fig.7. PCF core line restored by an autoconvolution technique

IV. CONCLUSION

In the report, the control method of photonic-crystal fibers positioning was developed based on the analysis of the measured distribution of optical field intensity and calculation of autoconvolution its discrete values. Method possibilities been investigated by modelling on the PC. Shown, that there is obviously expressed and unequivocally defined autoconvolution maximum even in the presence of considerable measurement errors of field amplitude. Therefore, the given method possesses high noiseproof factor and much higher accuracy in comparison, for example, with an integrated method at which coordinates of fiber axis strongly depend on the amplitude distribution form that leads to the roughest errors reaching the several tens elements of the image.

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