Paper

Optimizing the Structure of Vector Bend and Strain Sensor on the Base of Three-Core Microstructured Fiber

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Abstract—In the paper the optical sensor allowing measuring a direction, values and localization of bends and stresses in building structures is described. The sensitive element of the sensor is the microstructured fiber with three cores. The use of three-core fiber makes it possible to define the direction of deformation. Distribution of mode fields in fiber cores depending on fiber structure and bend value and direction is analyzed. The optimization of the sensitive element parameters depending on the application is proposed.

Keywords—fiber bend, method of lines, microstructured fiber, mode field distribution, multicore fiber, optical sensor.

1. Introduction

Buildings, bridges, tunnels, dams, cranes and other constructions require effective maintenance to keep them working safely. For these purposes it is necessary to control continually their conditions, i.e., to measure their bend, stress, strain, temperature, vibration, formation of cracks and uniformity of constructional elements. The information about controlled variables makes it possible to calculate a settlement of footing and internal stresses, and strains in building structures, to obtain notion about structural elements displacement taking into account a rotation angle, and to draw a conclusion about degree of construction maintenance safety on the base of numerical modeling, and comparison of measured and master data. Optical fiber information-measuring systems are very promising and attractive instruments for monitoring building structures of different functions [1]–[3]. Sensors on the base of optical fibers have important technical advantages over traditional instruments, such as high mechanical strength, tolerance to high temperature, vibration and other environmental activities, immunity to electromagnetic interference, chemical neutrality, ability to carry out noncontact and remote sensing. Fiber-based sensors do not drift over time, so recalibration is unnecessary. By embedding optical fiber sensors into the structure of a building during construction, engineers can check the building's behavior throughout its lifetime and collecting at a central monitoring station a large number of continuous measurements.

By convention, optical fiber sensors can be divided into three types: point, distributed and quasi-distributed sensors [1], [3]–[5]. The point sensors measure and control parameters in particular points of the object. Usually, such devices are of a small size and high precision. The most frequently used point sensors are based on fiber Bragg gratings, long period gratings and interferometers. They can be utilized as local temperature indicators, strain gages, pressure sensors, accelerometers, etc.

The unquestionable advantage of the distributed sensors is the possibility to control parameters along the length (volume) of the object in any point where sensor fiber is introduced. The mode of operation of such sensor systems bases on the analysis of the parameter changes along the fiber length and on nonlinear optical effects. The disadvantage of the distributed measurement of the fiber parameter along the length is relatively small accuracy of definition of perturbation localization (several meters lengthwise), and relatively modest accuracy of value measurement. Distributed sensors can be used for control of wide areas, as the sensors of radiation and temperature, for analyzing, for example, temperature gradients.

Measuring systems on the base of quasi-distributed sensors are the attempt to combine the advantages of the both types described above. The quasi-distributed sensor comprises an array of point sensor elements connected by a single fiber. Each element has the unique characteristics and thus permits to analyze its state, independently from other sensor elements. The accuracy of such systems is determined by the accuracy of a separate sensor, and the array can include more than 100 elements. Sensor arrays allow monitoring the complex objects, engineering construction, bridges, tunnels, hull of ships and aircrafts, oil wells, etc., analyzing gradient of distribution of temperature, loadings, pressure, controlling a large number of point objects.

Nevertheless, the quasi-distributed sensors are not able to control the object state along the whole length of the fiber and hence unable to substitute the distributed sensors entirely. Moreover, the wavelength-division multiplexing (WDM) technique and set of photodetectors have to be used for transmitting the data from sensor array in a single fiber. Consequently, the number of available WDM channels limits the number of sensor elements.

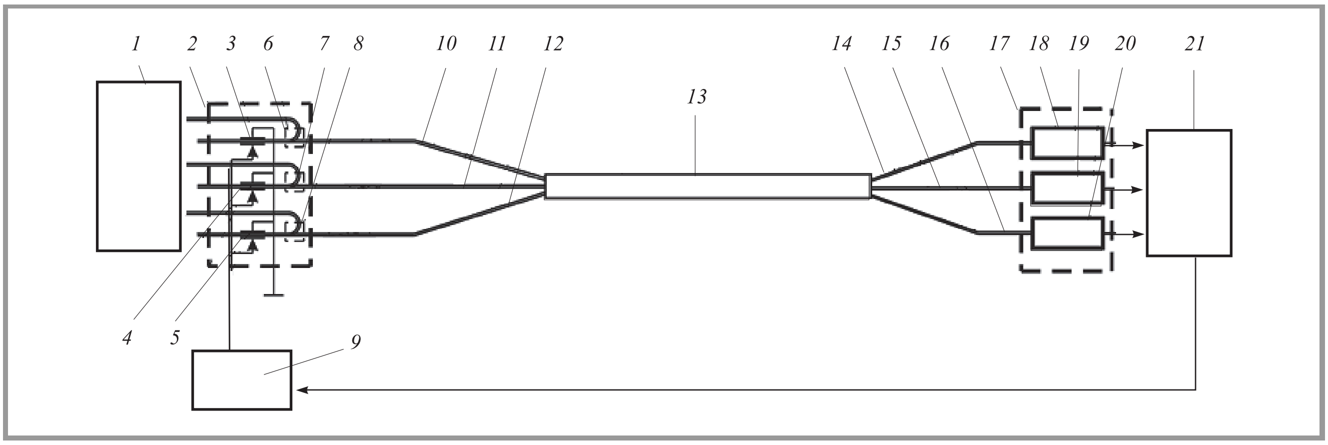

Fig. 1. Structural diagram of the optical fiber vector bend and strain sensor device. Explanations: *1* – broadband radiation source, *2* – controlled spectral filter, *3–5* – fiber Bragg gratings, *6–8* – *Y*-shaped couplers, *9* – control voltage block, *10–12* – input optical fibers, *13* – microstructure fiber (sensitive element), *14–16* – output optical fibers, *17* – photodetector array, *18–20* – photodetectors, *21* – measuring device.

Therefore there is still a practical interest to develop and optimize the structure of distributed sensors for continuous measurement of the parameters of the objects under control. One way to increase the distributed sensor accuracy is to measure the parameters on multiple wavelengths and then to average the logged data. The fibers have to operate in a single mode regime for all used spectral regions. From that point of view, the use of microstructured fibers as a sensing elements seems to be very promising. Microstructured fibers have enormous potential in achieving exotic microstructures with relative ease of manufacturing, and they can also be made as single-mode over a wider range of wavelengths in contrast to conventional fibers [6]–[9]. For sensor applications, two or more guiding cores are required, rather than just a single one [10]–[17]. By manipulating air hole diameter d, holes pitch Λ, number of holes N, and the distance between guiding cores, it is possible to vary the properties of microstructured fiber such as dispersion, leakage loss, single-mode regime, numerical aperture and effective-mode area, and control the mode field distribution, and therefore modifying the characteristics of the sensor.

Existing sensors are not able to define the bend direction. On the other hand, the ability to determine direction of the deformation can be very important for sensors used, for instance, for monitoring the condition of bridges, cranes, blades of wind turbines, etc. Therefore there is a need to develop sensors enabling to measure both value and direction of the deformation along the whole length of the controlled object, with sufficient accuracy for practical purposes.

In this paper we describe the vector bend and stress sensor based on a three-core microstructured fiber. In Section 1, we consider the structural diagram and operation principles of the sensor. Such a device can be used for precise measurements of the value and direction, both of the bends and displacements of building units, and determining their internal stresses and strains. Therefore the optimization of sensor element parameters depending on the purpose of use has to be carried out. For that, in Section 2, we have calculated the distribution of the mode fields in fiber cores and analyze it depending on the fiber structure and bend.

2. Structural Diagram and Principle of Operation of the Sensor

Figure 1 shows the structural diagram of the proposed sensor device. The device consists of a broadband radiation source in the form of the array from three light-emitting diodes, controlled spectral filter based on controlled fiber Bragg gratings (FBG), sensing cell, control voltage block, photodetector array and measuring device. As the sensing element, we propose to use a three-core microstructured fiber. Three cores correspond to hexagonal symmetry of the microsructured fiber structure and enable to calculate the bend direction by the simplest algorithm [16], [17].

Light from the broadband radiation source simultaneously enters into the corresponding cores of the microstructure fiber through the input fibers. Bending the microstructure fiber leads to redistribution of mode power between cores [14], [15]. The difference between mode amplitudes in different cores increases with bend radius decrease. For this reason, by comparing the measured power in microstructure fiber cores it is possible to define the bend radius of the fiber. The bend direction is determined on the base of the ratio of amplitudes of radiation of separate wavelength bands in different cores of the microstructured fiber.

Controlled fiber Bragg gratings are used for measuring the frequency components of the optical signals coming to the photodetectors. In order to increase the accuracy of the measurement of the bend value and direction, the set of signals on separate wavelengths is injected into each core

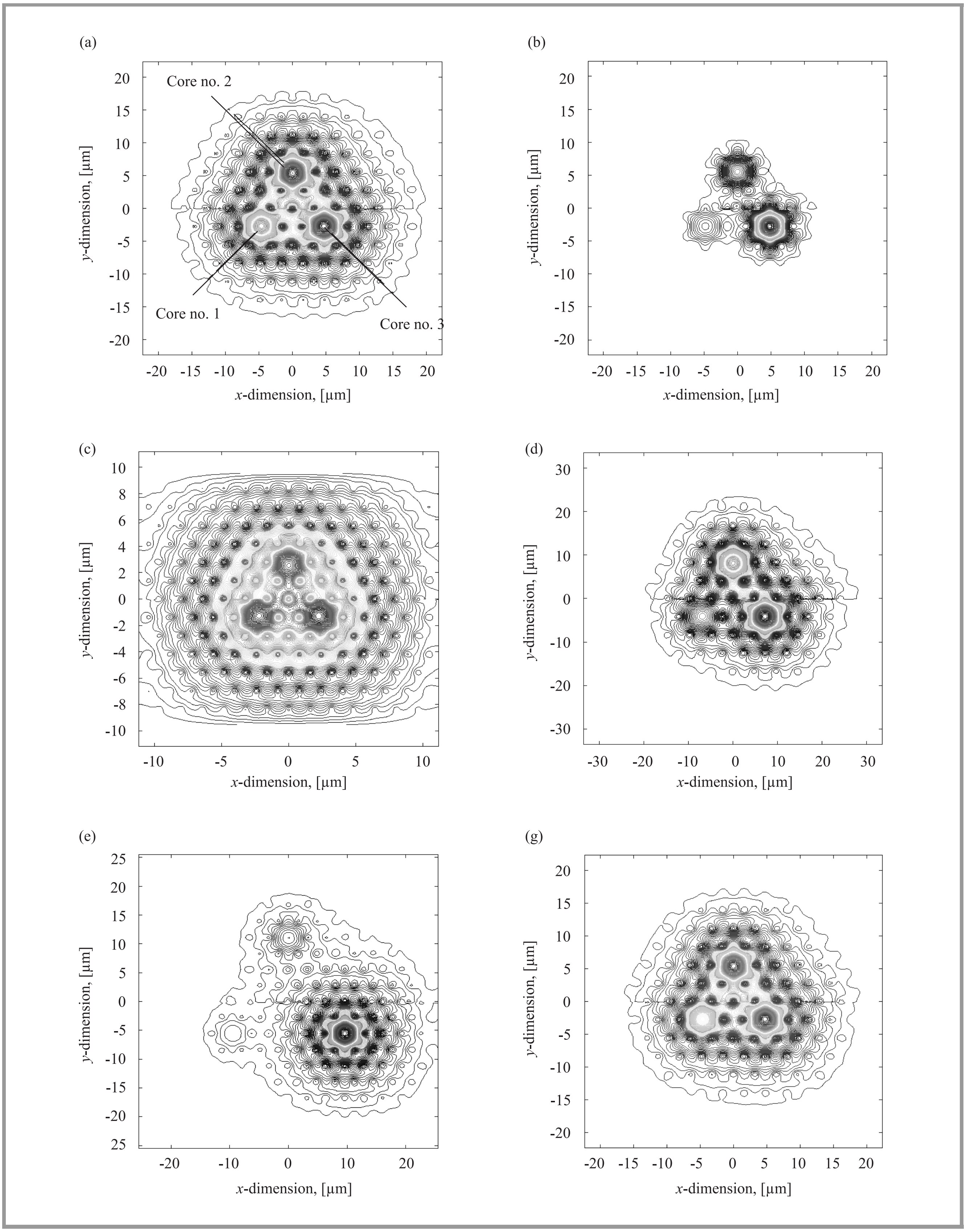

Fig. 2. Transverse distribution of the optical radiation intensity in cores of microstructure fibers bent with $R = 10$ cm and core separation in two holes, $d/\Lambda = 0.2$, $\Lambda = 3.2$ μm (a); $d/\Lambda = 0.4$, $\Lambda = 3.2$ μm (b); $d/\Lambda = 0.2$, $\Lambda = 1.6$ μm (c); $d/\Lambda = 0.2$, $\Lambda = 4.8$ μm (d); core separation in five holes, $d/\Lambda = 0.2$, $\Lambda = 3.2$ μm (e) for optical wavelength $\lambda = 1.5$ μm and core separation in two holes, $d/\Lambda = 0.2$, $\Lambda = 3.2$ μm, $\lambda = 1.3$ μm (g).

of microstructure fiber. Spectral ranges of the signals for each core are different. When the fiber is bent, the optical power on different wavelengths redistributes over all cores. A control voltage supplied into the FBG's electrodes changes the refractive index of the electrooptical material. That results in variation of optical wavelength, at which the FBG reflection is maximal (Bragg wavelength). Therefore by supplying the variable control voltage into the FBG's electrodes, it is possible to scan sequentially the spectrum of the signals coming into the photodetectors. By averaging the signals coming from the sensing element on different wavelengths, it is possible to determine the bend value and direction with high accuracy.

3. Calculating the Mode Fields and Optimizing the Sensor Design

We use the algorithm based on the Method of Lines [14], [15], [18]–[21] modified for the structure under investigation, for calculation of the mode field distribution and dispersion parameters of multicore microstructure fibers.

By using the developed algorithm we have calculated transverse field distribution of the propagating fiber modes for different bend values and different fiber parameters, like an air hole diameter d, hole pitch Λ, core separation, etc.

The results of calculations are shown in Figs. 2–4. Figure 2 presents contour pictures of intensity distribution of optical radiation at $\lambda = 1.5$ μm wavelength in cores of bent microstructure fibers with core separation in two holes, $d/\Lambda = 0.2$, $\Lambda = 3.2$ μ m (a), $d/\Lambda = 0.4$, $\Lambda = 3.2$ μm (b), $d/\Lambda = 0.2$, $\Lambda = 1.6$ μm (c), $d/\Lambda = 0.2$, $\Lambda = 4.8$ μm (d), core separation in five holes, $d/\Lambda = 0.2$, $\Lambda = 3.2$ μm (e) and core separation in two holes, $d/\Lambda = 0.2$, $\Lambda = 3.2$ μm, $\lambda = 1.3$ μm (g). Bend radius of all fibers is $R = 10$ cm.

It follows from the figures that bending the fiber causes a redistribution of the mode power between fiber cores. The ratio of optical power transmitting in two cores located along the bend direction defines the bend value, while the relative shares of optical power in each of the three cores depend on bend direction. Thus by measuring the ratio of optical radiation intensity in three fiber cores, it is possible to determine both direction and value of the fiber bend. For instance, in Fig. 2 the bend direction corresponds to the line connecting cores 1 and 3, and optical power redistribution caused by the bend occurs mainly between these cores. When the bend direction changes by 60°, the power redistribution takes place mainly between cores 1 and 2 and so forth.

Figure 3 shows the maximal values of mode field amplitudes in fiber cores no. 1 and 3 located on bend axes as a function of bend radius. Amplitude values are normalized to the mode amplitude in core 2. Numbers of cores are indicated in Fig. 2(a). Figure 3(a) shows the mode amplitudes of radiation at $\lambda = 1.5$ μm wavelength for different core separation and ratio d/Λ values. Curves *1* and *2* represent respectively the mode amplitudes in cores 1 and 3 of the fiber with $d/\Lambda = 0.2$ and core separation in two holes, curves *3* and *4* show the same in cores of the fiber with $d/\Lambda = 0.4$, core separation in two holes, curves *5* and *6* are related to a fiber with $d/\Lambda = 0.2$ and core separation in five holes. For all curves the hole pitch is

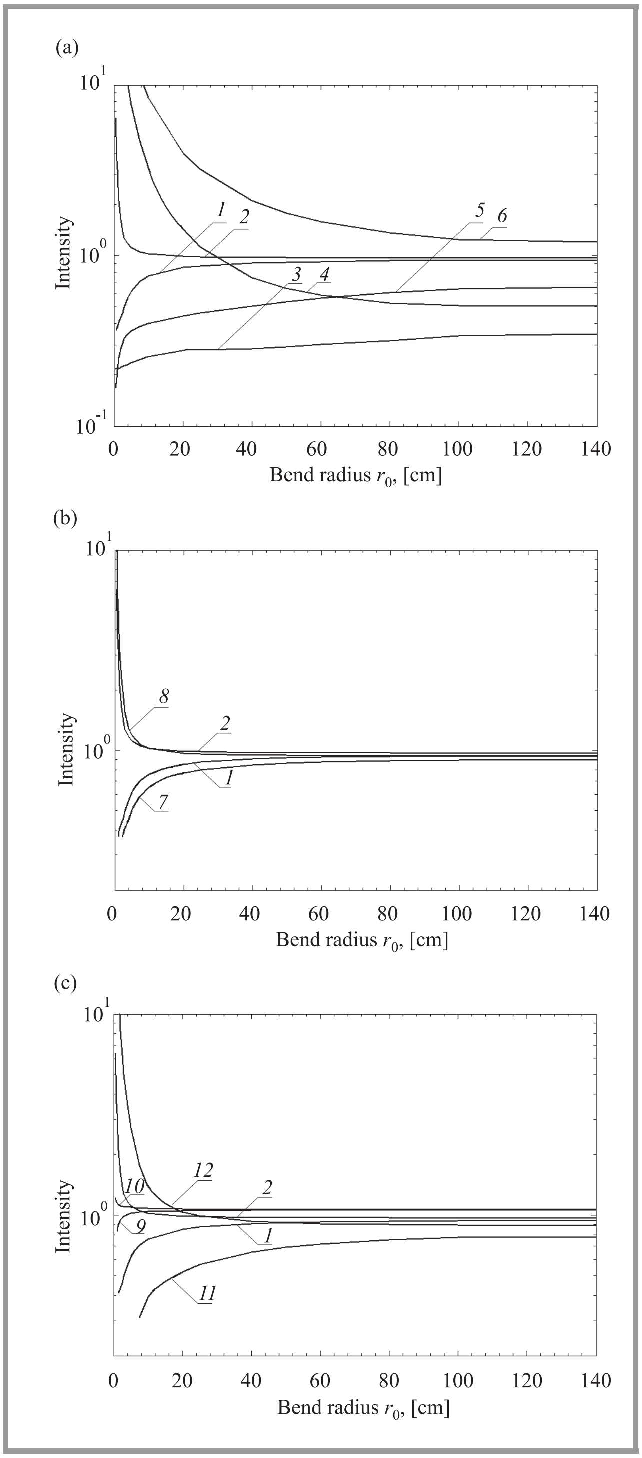

Fig. 3. Maximal values of mode field amplitudes in fiber cores located on bend axes versus bend radius for different values of core separation and ratio d/Λ (a), different radiation wavelengths (b), and different values of hole pitch (c).

$\Lambda = 3.2$ μm. Curves *7* and *8* (Fig. 3(b)) relate to the fiber with parameters the same as curves *1* and *2*, but for $\lambda = 1.3$ μm. The comparison of the dependencies of mode amplitudes on bend radius for different values of hole-to-hole separation is presented in Fig. 3(c). Curves *9* and *10* respectively represent the mode amplitudes in cores 1 and 3 of the fiber with core separation in two holes, $\Lambda = 1.6$ μm, curves *11*, *12* relate to the fiber with $\Lambda = 4.8$ μm. Optical wavelength is $\lambda = 1.5$ μm and parameter $d/\Lambda = 0.2$. Figure 4 shows the ratio of the mode field amplitudes in right and left accordingly to the bend cores in dependence on bend radius for fibers, with core separation in two holes, $\Lambda = 1.6$ μm and $d/\Lambda = 0.2$ (curve *1*), $\Lambda = 3.2$ μm, $d/\Lambda = 0.2$ (curve *2*), $\Lambda = 4.8$ μm, $d/\Lambda = 0.2$ (curve *3*), $\Lambda = 3.2$ μm, $d/\Lambda = 0.4$ (curve *4*), core separation in five holes, $\Lambda = 3.2$ μm and $d/\Lambda = 0.2$ (curve *5*) for $\lambda = 1.5$ μm wavelength. Curve *6* is plotted for the fiber having the same parameters as *2*, but for $\lambda = 1.3$ μm.

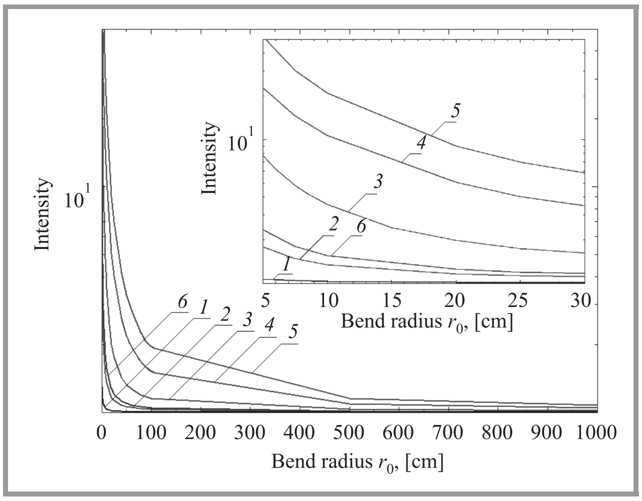

Fig. 4. Dependence of relative mode field amplitudes in fiber cores located on bend axes on bend radius..

As it follows from the figures, fibers with a larger ratio of the air hole diameter d to hole separation Λ, i.e., with larger air filling, as well as fibers with larger hole pitch and/or core separation are more sensitive to the bend. In such fibers, the mode fields are stronger concentrated in separate cores, and any break of the steady state conditions leads to substantial transmitting optical power from one core to another. In fibers with smaller ratio d/Λ, Λ and/or core separation the mode fields in different cores interact stronger with each other, and such an arrangement is likely to be more stable to an external influence. For instance, for fibers with $d/\Lambda = 0.2$ and core separation in two holes the appreciable optical power coupling between cores takes place for bend radii of 500 cm. When the core separation is increased up to five holes, the same effect occurs for R smaller than 900 cm. The sharp rise of the mode concentration in one core that is unusable for measuring and associated large radiation losses occur if such fibers are bent with radiuses around 3 and 10 cm, respectively. For fibers with Λ equal to 1.6 and 4.8 μm a noticeable increase of power exchange between cores takes place for bend radiuses 300 and 600 cm, respectively. The sharp rise of power concentration in one core occurs for R equal to 1 and 15 cm.

The reduction of the optical wavelength λ increases the sensor sensitivity as well. However the wavelength variation is possible only within a limited range. Thus only slight enhancement of the mode power transmitting from one core to another with the fiber bend can be achieved in that way.

4. Conclusions

In the paper we have proposed the concept and operation principles of distributed optical vector sensor of bend and deformation based on three-core microstructured fiber. The sensor accuracy is higher than the one of conventional distributed sensors, due to measurement at several wavelengths and following average of the registered signal. This is achieved by using a microstructured fiber as the sensitive element which has a wide spectral range of single mode operation. The use of three-core fiber makes it possible to define the direction of deformation.

The optimization of the sensing element is carried out on the base of the numerical calculations of the mode parameters, and field distribution over the fiber cores, depending on fiber structure and bend value. The numerical simulation shows that the sensor devices based on the fibers with small core separation, small hole pitch and small air filling (small d/Λ) are preferable for measuring the flexible building construction liable to large bend. Such sensors possess wider measurement range of the bend value. For instance, the fiber with $d/\Lambda = 0.2$, $\Lambda = 3.2$ μm and core separation in two holes allows bend measuring up to $R = 3$ cm. The fibers with larger d/Λ, Λ and/or core separation are more sensitive to the bend. Therefore, it is practically useful to apply them for measuring the small bends and deflections of the rigid building constructions, i.e., those effects that produce the internal stresses and strains in such units, and can cause their failure. For instance, fibers with $d/\Lambda = 0.4$ allows measuring the bends starting from $R = 800$ cm. Sensors based on such fibers en-sure high accuracy of the measurement of small bends and deflections of the constructive parts. It is necessary to notice that if the core separation or air filling of the fiber photonic crystal cladding is increased substantially, then the cores become completely isolated from each other. The modes of such structure correspond to the modes of separate fibers, and mode power transfer between cores wouldn't take place.

The small correction of the sensor sensitivity can be obtained by changing the wavelength of the used optical radiation.

Special attention has to be paid to regular laying the fiber when installing the sensor on the surface of controlled object. That is necessary in order to avoid the fiber twist that can cause incorrect determination of the bend direction.

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