Monitoring of physical parameters by fiber-optic recirculation sensor

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ABSTRACT

To use the new frequency-output fiber-optic recirculating sensor for voltage, electric current, dispersion properties of the optical fiber measurements has been proposed. Fiber-optic sensor was constructed as a closed optoelectronic contour formed by a source of radiation, an optical fiber delay line, photoreceiver and regeneration block. The sensitive element of this device was the optical fiber. Identification of measured parameters was carried out with high accuracy by the change of recirculation frequency in the contour. Sensitivity of these sensors was estimated.

Keywords:. fiber-optic sensor, recirculation frequency, voltage and electric current measurements, intermodal temporary dispersion, sensitivity.

1. INTRODUCTION

In connection with fast development of the automatic monitoring and management systems, introduction of new technological processes, transition to the flexible automated manufactures in such areas as energetic, industry, medicine, telecommunications the need for development of multifunctional information-measuring and diagnostic systems on the basis of fiber-optical sensors (FOS) grows promptly. In practice of FOS use the greatest importance have the following advantages of optical fibers: absence of induction, explosion safety, high dielectric durability, high corrosion resistance especial to the chemical solvents, oils, water. Such properties, as elasticity, small diameter and weight are rather useful also. Use of optical fiber as a sensor element is based on sensitivity of a fiber to an electromagnetic field (the Kerr effect), magnetic field (the Faraday effect), vibration, temperature, pressure, deformation etc.

There are several types of FOS distinguishing by the different optical schemes of light modulation by measured physical quantity: amplitude, phase, polarization, modulation of a spectrum or duration of optical radiation (time intervals or frequency of pulse sequence). Most perspective to our sight is the transition to frequency (temporary) representation of the information, based on dependencies of optical radiation delay in optical fiber on measured physical parameters. Since the time of a delay in fiber does not depend on amplitude of optical radiation, the frequency sensors in comparison with the widely used amplitude sensors appear practically protected from basic destabilizing factors at operation.

2. EXPERIMENTAL SETUP

In given paper it is offered frequency-output fiber-optic recirculating sensor (FORS) [1]. The optical fiber sensors with temporary representation of the information alongside with cheapness and high accuracy have also other advantages: allow to exclude or strongly reduce instability and drift of signals; there is no problem of an establishment and maintenance of a zero basic level; the data on a position and duration of pulses, and also frequency of their following are transferred practically without easing of a signal; the ambiguity of received results inherent to interferometrical measuring converters is excluded; the function of transformation is linear in wide range.

Since for frequency method of measurements the information about phase and polarization of an optical wave is not required, in the circuit of FORS the use of multimode injection lasers (IL) and optical fibers (OF) is possible, that considerably simplifies connection between optical elements. The application of multimode IL allows to reduce a level of noise inherent to a source of radiation. In paper [2] is shown, that the more modes present in a spectrum of radiation, the more effective there is an averaging of fluctuation on all longitudinal modes. Resulting amplitude noise of multimode IL is more than on the order of magnitude less than that for singlemode laser. By virtue of small coherence the multimode laser has the lowered sensitivity to noise, caused by the radiation reflected into the active layer of IL.

The function diagram of the sensor is shown in fig. 1. The device represents closed optoelectronic contour formed by a source of radiation, optical fiber delay line, photoreceiving device and block of regeneration. On each recirculation cycle the restoration of amplitude, shape and duration of a pulse is restored, that allows to obtain not fading oscillations. A sensitive element of the sensor is the optical fiber. The identification of measured physical quantity is carried out by frequency of recirculation, which is registered rather simple and with high accuracy. Basic optoelectronic components have the following parameters. Radiation source is multimode injection semiconductor AlGaAs/GaAs-laser, radiates on wavelength λ=0,825 μm, had a threshold current $I_{th} = 3{,}1 \cdot 10^{-2}$ A, output power $P = 2 \cdot 10^{-3}$ W at a current I=1,2I_{th}. Optical fiber delay line is standard telecom multimode gradient fiber with refraction index on an axis n=1,475 on wavelength of 0,82 μm and numerical aperture NA=0,2. Photoreceiver is a high speed germanium avalanche photodiode (APD).

With the help of the given system it is offered to carry out measurements of temperature, length of optical fiber, to control quality of connection of optical elements, to investigate dispersion characteristic of multimode optical fibers by registering the change of recirculation frequency of single pulses. The received values of recirculation frequency are processed by the computer, where according to the developed algorithms are transformed in appropriate measured physical quantity, that enables to supervise this quantity in a real time and to keep up the dynamics of process.

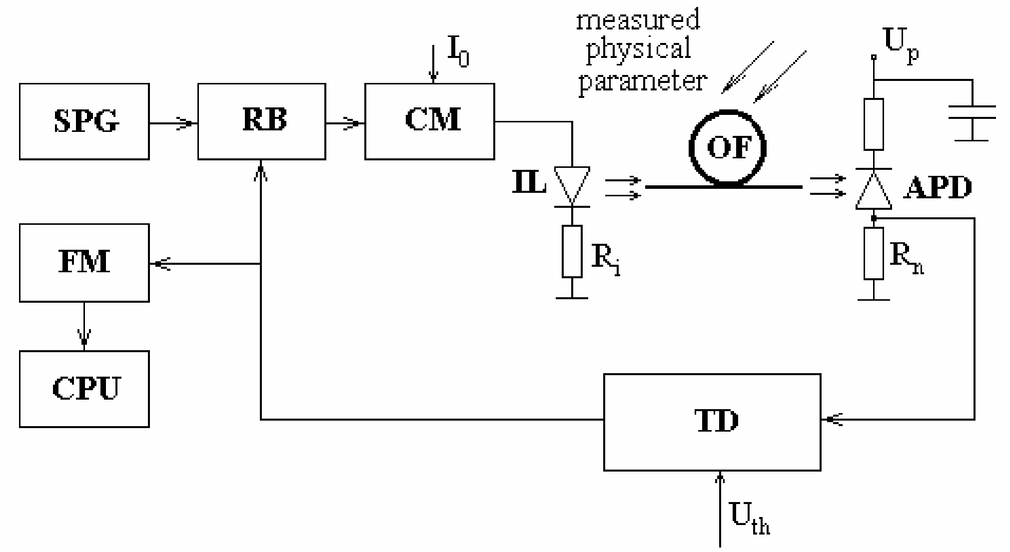

Fig. 1 Function diagram of the FORS

SPG–start pulses generator, RB– regeneration block, CM–current modulator, IL–injection laser, OF–optical fiber, TD–threshold device, FM–frequency meter, CPU–microprocessor.

As frequency-output FORS is at an initial stage of development, the important question is the metrological analysis of such measuring systems. We have carried out theoretical and experimental investigations of long-term instability and short-term fluctuations of recirculation frequency of a single pulse in closed optoelectronic contour. From experimental data we have received, that the relative long-time instability of recirculation frequency is $\chi = 4 \cdot 10^{-6}$ for fiber length L=50 m and $\chi = 2 \cdot 10^{-6}$ for L=300–500 m at bias direct current of IL I_0=0,9I_{th}. Short-term fluctuations are 70–80 ps for one cycle of circulation at the average period of 298 ns. Comparison of calculations and experimental data have shown, that at minimization of technical fluctuations the accuracy of such optical fiber systems can be increased in 4-5 times and approach to magnitude determined by the fundamental error components.

3. ELECTRICAL MEASUREMENTS

3.1 Sensor principle

In the past years, the electric power industry has been considering optical techniques as suitable alternatives to conventional instrument transformers for voltage and electric current measurements. Optical techniques present several advantages over conventional techniques such as easier isolation, wider bandwidth, higher dynamic ranges, and immunity to electromagnetic interference. Optical sensors do not contain any conductive element, are usually small, and can be produced at low cost. Furthermore, the sensor failure does not pose a threat to power station personnel or equipment in contrast to conventional oil-filled transformers that can explode or burn down. Several optical voltage sensors for high-voltage lines have been reported, most of them based on the electrooptic effect in bulk crystalline materials [3]-[5]. Optical fibers can be used for voltage measuring by using appropriate transducers. Electrostrictive [6] and piezoelectric materials [7], [8] have been successfully used as voltage transducing element. Usually, a length of single-mode fiber is bounded to the transducer and the deformation of the transducer induces a phase change in the light propagating in the fiber, which is detected by means of interferometric techniques [9].

Although fiber-optic interferometric sensors can provide very high sensitivity, several factors make this type of sensor unsuitable for most practical applications. In first, this is differential drift in the interferometer arms by random fluctuations of temperature or pressure. Accurate polarization control and polarization induced fading are other practical difficulties for the implementation of fiber-optic interferometric sensors. Thirdly, used single-mode optical fibers demand of more difficult connection devices and also are less strong which in comparison with multi-mode. In fourth, the interferometric picture is sensitive to vibrations and other mechanical influences.

To avoid the mentioned imperfections, in given paper it is offered to measure voltage and electric current by FORS. A sensitive element of the sensor are the standard telecom multi-mode optical fibers which have L=50 m and L=375 m length and were wound onto the piezoelectric tube (PET). PET was made of PZT-5H ceramic. The tubes have 0,2 m and 1,4 m long, d=50 mm in diameter with thickness of h=4 mm. When voltage is applied to the piezoelectric, geometric dimensions of piezoelectric tube are changed, optical fiber parameters are changed too and recirculating frequency depends on the applied voltage. The identification of measured voltage is carried out by recirculating frequency.

3.2 Results

Change the piezoelectric tube size result in change a OF length and photoelasticity effect. Photoelasticity effect is conditioned by OF longitudal deformation and is expressed in change the fiber refraction index. Sensitivity of sensor is defined the stability of recirculation frequency. Minimum value of the voltage change ΔU_{min}, which can register the sensor, must exceed relative long-time instability of recirculation frequency $\chi=\Delta f/f$. Value of χ depends on nonmeasured destabilizing factors. According to carry out investigations [10], $\chi = 4\cdot 10^{-6}$ for fiber length L=50 m and $\chi = 2\cdot 10^{-6}$ for L=375 m. Increase of OF length leads to reduction χ, however this enlarges sizes of sensitive element. Sensitivity FORS possible to estimate according to expression:

$$\Delta U_{\min} = \frac{\pi d \chi h}{\xi K L}\sqrt{\frac{E}{\varepsilon\varepsilon_0}}\,, \tag{1}$$

where K–electromechanical coupling index, E–Jung module for piezoelectric material.

Parameter ξ determine photoelasticity properties of optical fibers and is given by:

$$\xi = 1 - \frac{n^2}{2}\left[p_{12} - \nu\left(p_{11} + p_{12}\right)\right], \tag{2}$$

where ν–is the Poisson ratio of the core (ν=0,164), p_{11} and p_{12}–are strain-optic tensors (p_{11}=0,121, p_{12}=0,27).

Magnitude of physical parameters, used at calculations, following: K=0,49, E=10^{11} N/m^2, ε=1350, $\varepsilon_0 = 8{,}85\cdot 10^{-12}$ F/m.

From the carried out researches follows, that the sensitivity of recirculating voltage sensor is 0,8 V at fiber length 50 m and 0,03 V at 375 m. Comparison with interferometric sensors has shown that the sensitivity of recirculating sensor does not concede to the fiber-optic interferometric voltage sensor, thus they are more reliable and there are no many of destabilising factors.

Efficiency of the sensor can be calculated on formula:

$$\Delta f / U = f\,\xi\frac{K}{h}\sqrt{\frac{\varepsilon\varepsilon_0}{E}}\,\frac{L}{\pi d}\,. \tag{3}$$

At L=50 m f=3351772 Hz (I_0=0,9I_{th}, U_{th}=8 mV) and according to (3) $\Delta f/U$=34 Hz/V.

Carried out investigations have showed that for signals with frequency 50 Hz and voltage U_{eff}=220 V observed the good correlation between the theoretical and experimental data. Differential nonlinearity not exceed 2%, additional temperature error is 0,01%/(10 K), dynamic range is 50-60 dB. FORS is moisture-resistant, inconvertible to the vibrations and impact mechanical loads, long-lived, reliable, consume not much energy, has low cost, because cheap and well-known in telecommunication optoelectronic components are used.

The given scheme of fiber–optic recirculating sensor as is shown on fig. 1 only without piezoelectric tube can be used for electric current measurements. Multimode optical fiber becomes covered by a thin layer of aluminium with resistance some Ohm on meter of fiber length. The electric current is passed through an aluminium environment. Change of optical fiber temperature is caused by Joule losses of electric energy in an aluminium covering, it results in change of length and a refraction index of optical fiber. Recirculation frequency accordingly changes. The accuracy of sensor depends on it temperature sensitivity. In [11] was shown that the temperature sensitivity FORS makes up $0{,}1^0$C for OF length more then 100 m. Therefore such sensor can measure effective value of a current up to 5 A with accuracy 70 mA and up to 14 A with accuracy 0,2 A.

4. MEASUREMENTS OF DISPERSION PROPERTIES OF MULTIMODE OPTICAL FIBERS

4.1 Measurement method

In practice for a choice of multimode optical fibers with necessary parameters frequently there is a task of express-analysis of them dispersion characteristics with accuracy up to several percents used simple techniques, and also reliable and cheap devices. At measurements temporary dispersion on working wavelengths as a rule pulse modulation of radiation source output power is used and in this case common dispersion is estimated on dependence of an optical pulse expansion along length of a fiber [12]. However, for OF in length of hundred meters and the less given method is not absolutely suitable, as in this case to arrive necessary accuracy of measurements it is needed significant complication of the receiving and processing equipment.

As is known, in multimode OF any short optical pulse entered into a fiber, consists of a number of beams (spatial modes), propagating along an optical axis and on trajectories inclined to it under various angles, beginning from zero and up to some critical φ_{cr}, when complete internal reflection on border of core-cladding still is possible. Thus, the beams will overcome OF of length L for various time and entered in a fiber simultaneously, on an exit will appear divided in time. This expansion of a light pulse at its distribution on a fiber is known as intermodal (multibeam) temporary dispersion. The value of its expansion is defined by a superposition of beams leaving from OF under various angles and getting on a reception area of the photodetector.

For definition root-mean-square value of intermodal dispersion σ_m (being dominant in multimode fibers) in OF length (10-500) m recirculation method is offered to be used by us [13], based on change of single pulse recirculation frequency at displacement of end faces of researched and short (length 1-2 m) OF rather each other. The technique of measurement consists in the following. The air interval between end OF faces is the selector of spatial modes. At coincidence of OF optical axes the recirculation frequency is maximal, as the "fast" beams propagating along an optical axis get on the reception block. As a result of relative displacement of fibers there is a spatial selection of modes and the reduction of recirculation frequency is observed, since the period of circulation is defined by more "slow" modes propagating under an angle to an optical axis (fig. 2). The value of relative displacement is defined by a critical angle φ_{cr}, under which the beams leave from OF, caused, in turn, meaning of the OF numerical aperture according to the following expression:

$$NA = \sin\varphi_{cr} = (n_0^2 - n_1^2)^{1/2}\,, \tag{4}$$

where n_0 and n_1– refraction index on an axis and a cladding of OF accordingly.

Thus, registering change of recirculation frequency and knowing OF length, it is possible to estimate value σ_m.

4.2 Experimental results

For an estimation of definition accuracy of intermodal dispersion by the recirculation method the following experiment has been carried out. The piece of researched multimode gradient OF by length L=51 m, having refraction index on an axis n_0=1,475, numerical aperture NA=0,2 and diameter of core D_1=50 μm, was excited by an optical pulse by duration 3 ns generated by the multimode semiconductor injection laser with wavelength λ=0,825 μm. The second piece of length 2,5 m had NA=0,2 and D_2=30 μm and was connected by the APD, having diameter of photoreception area 200 μm. The first piece was hard fixed, the end of another was displaced in a radial direction relatively of the optical axis with the help of micrometric alignment device. Distance between OF end faces was $S\approx150$ μm.

Presence of a clearance between OF, and also the displacement of their end faces rather each other results not only in change of mode structure of accepted radiation, but also to reduction of optical power getting on a reception area of the photoreceiver. The reduction of a signal level arriving from the photodetector on the threshold device of the regeneration block can result in change of an operation delay time. This is also entails change of recurculation frequency, which under certain conditions can exceed changes of recurculation frequency, caused by dispersion properties of optical fiber. To eliminate the given phenomenon the displacement current of APD was supported constant within the limits of 56-57 μA at each measurement, i.e. with accuracy approximately 20%. Thus, the reduction of optical power arriving on the photoreceiver, was compensated by increase of APD avalanche multiplication coefficient.

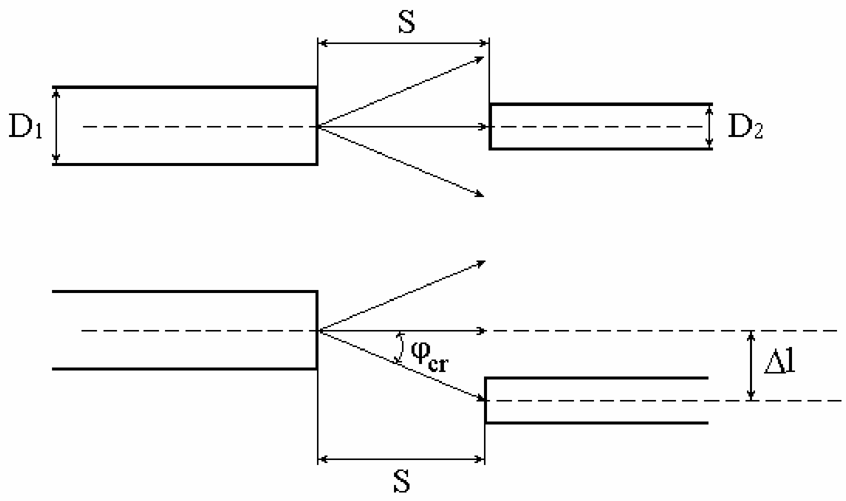

Fig 2. Method of intermode dispersion definition for multimode optical fibers, based on change of recirculation frequency at selection of spatial modes.

From (4) and fig. 2 expression for account of displacement size for a researched fiber is received:

$$\Delta l = \frac{S}{\sqrt{\left(\frac{1}{NA}\right)^2 - 1}} . \tag{5}$$

Hence, at an air clearance between end faces of fibers 150 μm, that the spatial modes leaving from researched OF under a critical angle, get on an optical axis of a OF short piece, it is necessary to displace it on 30 μm of a rather optical axis. It was received, that at coincidence of fibers optical axes the average recirculation frequency at time of measurement 1 s and removal of seven experimental results for each point, was equaled f_0=3350516 Hz. The relative long-term instability of recirculation frequency had value $4\cdot10^{-6}$. At relative displacement of OF optical axes on Δl=30 μm the recirculation frequency already was f_1=3348416 Hz, and the change of recirculation frequency was equaled $\Delta f\approx2100$ Hz (fig. 3). It is connected both to change of mode structure of radiation, and with change of a operation delay time of the regeneration block at the expense of reduction of a signal power at constant value of the comparator threshold. As it was noticed above, the contribution of the last phenomena approximately equals 20%. Hence, the difference of delay time between modes propagating along an axis of a fiber and on trajectories, inclined to it, in Gauss approximation of the pulse form is calculated according the formula:

$$\sigma_m = \frac{0,425}{L}\left(h_m\left[\frac{1}{f_1}-\frac{1}{f_0}\right]\right), \tag{6}$$

where OF length is measured in kilometers, and h_m defines that part of change of recirculation frequency, which is caused by intermodal dispersion.

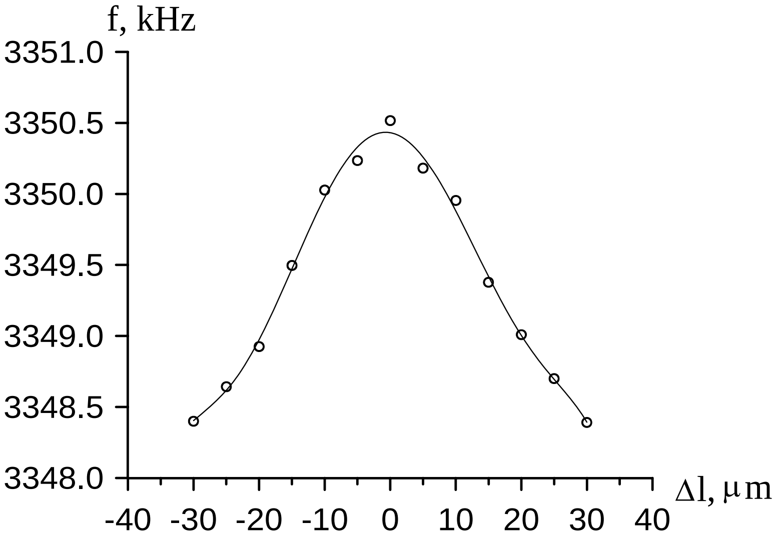

Fig. 3 Dependence of FORS recirculation frequency from value of displacement of a fiber end face relatively of an optical axis.

Thus, intermodal dispersion in our experiment makes value σ_m=1,247±0,014 ns/km. An optical bandwidth of the fiber Δf_{OF} is defined from a condition [12], that the maximal speed of the information transfer B should not exceed value $1/4\sigma$, thus the influence of intersymbolical interference does not exceed 1 dB. Common dispersion σ of multimode OF represents resulting action of intermodal σ_m and chromatic σ_{ch} dispersion. Since chromatic dispersion as a rule is less then intermodal on two order, the expression for definition Δf_{OF} can be written down as follows [12]:

$$1,34\Delta f_{OF} = B = 1/4\sigma_m . \tag{7}$$

From (7) we find, that Δf_{OF}=149,6±1,5 $\mathrm{MHz}\cdot\mathrm{km}$. The experimentally received value of the OF bandwidth well coincides with passport data of a researched fiber 150 $\mathrm{MHz}\cdot\mathrm{km}$ for given wavelength. The measurements error of intermode dispersion is defined by value of relative long-term instability of recirculation frequency and does not exceed 1%. The given technique allows to define intermodal temporary dispersion of multimode OF both with gradient and with a step profile of a refraction index.

4.3 Determination of other characteristics of gradient optical fiber

Dispersion property of multimode gradient OF strongly depend on parameter of refraction index profile α and can differ on some orders [12]. For minimization intermode dispersion at manufacturing fibers usually aspire to make value α close to 2, however during manufacture OF for various samples magnitude α, as a rule, deviate from optimum. It is known [12], that σ_m for given wavelength is connected to parameter α by the following ratio:

$$\sigma_m = \frac{LN_0\Delta}{c}\left[\frac{C_1^2\alpha^2}{(\alpha+2)(3\alpha+2)}+\frac{C_1C_2\alpha^2\Delta}{(\alpha+2)(2\alpha+1)}+\frac{C_2^2\alpha^2\Delta^2}{(\alpha+2)(5\alpha+2)}\right]^{1/2}, \tag{8}$$

where

$$C_1=(\alpha-2-4\delta)/2(\alpha+1);\quad C_2=(3\alpha-2-8\delta)/(3\alpha+2)\qquad \Delta=\left(n_0^2-n_1^2\right)/2n_0^2;N_0=n_0-\lambda\frac{dn_0}{d\lambda};\quad \delta=-\frac{n_0}{2N_0}\frac{\lambda}{\Delta}\frac{d\Delta}{d\lambda}\quad .$$

The spectral dependence of refraction index n_0 with high accuracy is described by the known trinomial Salmeir dispersion formula:

$$n_0^2-1=\sum_k\frac{G_k\lambda^2}{\lambda^2-\lambda_{1k}^2}\,, \tag{9}$$

where the coefficients G_k and λ_{1k} are defined experimentally.

Using the received value σ_m and solving a return task with use of the expression (8-9), we find, that for a researched fiber with n_0=1,475 and n_1=1,4614 (agrees (4) from a condition, that the numerical aperture NA=0,2) value α is equal 2,54±0,025. The knowledge of α-profile magnitude enables to calculate distribution of the refraction index on spatial coordinate in miltumode gradient OF:

$$n(r_f)=\begin{cases} n_0\left[1-2\Delta\left(\dfrac{r_f}{a}\right)^{\alpha}\right]^{1/2} & r_f\le a,\\ n_0\left(1-2\Delta\right)^{1/2}=n(a) & r_f>a,\end{cases} \tag{10}$$

where r_f– distance of a beam from an optical axis, a– radius of a fiber core,
and also trajectory of a beam distribution on a fiber, which for paraxial beam approach has a view:

$$d^2r_f/dz^2=(1/n_0)(dn/dr_f)\,, \tag{11}$$

where z– distance, measuring along an optical axis.

Using the received value α, we appreciate number of modes, propagating in the given OF piece under the following formula [12]:

$$M_g=\frac{\alpha}{\alpha+2}a^2\beta_v^2\Delta\,, \tag{12}$$

where $\beta_v=2\pi n_0/\lambda$– constant, which characterizes periodicity of flat TEM-waves.

The common number of modes propagating in multimode gradient fiber and determined by the formula (12), in our case was equaled $M_g\approx400$, while the number of modes, propagating in multimode step OF with similar parameters is calculated under the formula [12]:

$$M_s=\frac{1}{2}(2\pi a/\lambda)^2\left(n_0^2-n_1^2\right) \tag{13}$$

and compiled $M_s\approx720$. It means, that at illumination of such fibers by a source equally stimulating all modes, the gradient fiber will pass about 56 % of power transmitted by a step fiber.

For realization of measurements and accounts are necessary to know following a priori data of a researched OF piece: refraction index on an axis of a fiber n_0, numerical aperture NA, diameter of a core. OF length can be defined on recirculation frequency from expression:

$$f=\left[T_z+\frac{Ln_0}{c}\right]^{-1}\,, \tag{14}$$

where T_z– time determined by a delay in electronics and optoelectronics elements. The value T_z is determined for known length of a fiber at the definition regimes of FORS elements operations.

5. CONCLUSION

Thus, as a result of the carried out investigations the opportunity of use of the optoelectronic recirculation system as a multifunctional optical fiber sensor with simple, reliable and unified design was shown. The sensitive element of this device was the optical fiber. Identification of measured parameters was carried out with high accuracy by the change of recirculation frequency in the contour. FORS is moisture-resistant, inconvertible to the vibrations and impact mechanical loads, long-lived, reliable, consume not much energy, has low cost, because cheap and well-known in telecommunication optoelectronic components are used.

The voltage sensor is based on the liner piezoelectric effect of a PZT ceramic tube. Sensitive element of this device was the optical fiber, which was wound onto the piezoelectric tube. From the carried out researches follows, that the sensitivity of recirculating voltage sensor is 0,8 V at fiber length 50 m and 0,03 V at 375 m. Sensitive element of electric current sensor was optical fiber covered by a thin layer of aluminium. The electric current is passed through an aluminium environment. Such sensor can measure effective value of a current up to 5 A with sensitivity 70 mA and up to 14 A with sensitivity 0,2 A.

The technique of dispersion characteristics definition of multimode optical fibers for length since tens meters and more by the recirculation method was advanced. Accuracy of the given method and the minimal lengths of researched OF are limited by stability of recirculation frequency. The carried out experimental researches have shown, that the value σ_m OF in length 51 m can be defined with an error 1%. It is quite enough for many practical applications. Knowing σ_m, it is possible to calculate an α-profile for the given piece of gradient OF. The knowledge of exact magnitude of an α-profile allows to receive distribution of a refraction index on spatial coordinate, trajectory of an optical beam distribution on OF, number of propagating in OF spatial modes.

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