Fiber Optic Sensor of Linear Displacement

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ABSTRACT

The paper cover the description of an fiber optic sensor of linear displacement with a single multimode fiber and a movement mirror positioned near the output end of the fiber perpendicularly to its axis. The value of the signal of the considered sensor is determined by the rate of a beam reflected from mirror and introduced back into the fiber. New methods of increase in the band of measured shifts and enhancement of the sensor sensitivity are described in the paper. In particular, we propose to fill a space between the fiber face and the mirror by the light-absorbing liquid and to use polarization splitting of input and output beams. Mathematical descriptions of the sensitive element and the polarization beam splitting scheme are considered in the paper. We used a method of geometrical optics in Hamiltonian formulation for mathematical sensor modeling. Presented experimental results confirm the theoretical conclusion.

Key words:
Fiber optic sensor, linear displacement, polarization beam splitting

1.INTRODUCTION

Fiber optic sensors with a single multimode stepwise fiber and a movable mirror positioned near the output end of a fiber perpendicularly to its axis are the most easily producible and inexpensive ones. The value of the signal of the considered sensor is determined by the rate of a beam reflected from a mirror and introduced back into the fiber core. This sensor operates on the same principle as the scheme with co-axial radiating and received fiber in which the signal depends on the distance between the ends of these fibers. A considerable advantage of the sensor of linear displacement with a single fiber and a movable mirror is twofold increase in the sensitivity and the absence of the dependence of the signal level on decentring of fibers. Moreover, optical fiber with a half as many length is needed with the same optical elements being used for both introduction and extraction of a beam.

Principal sensor defects are limited band of measured shift and low sensitivity. New methods of increase in the band of measured shifts and enhancement of the sensor sensitivity are described in the paper. In particular, we propose to fill a space between the fiber face and the mirror by the light-absorbing liquid and to use a method of polarization splitting of input and output beams.

2.CONFIGURATION OF THE SENSOR

The proposed fiber optical sensor is shown in Figure 1. The device work in following manner. The linearly polarized beam from laser diode 1 passes after the polarizing beamsplitter 2 through microscope lens 3 and is launched into the multimode fiber 4. The opposite fiber end is connected with a sensor head 5. the sensor head consists of the capsule 6 with a movable mirror 7. The space between the fiber face and the mirror is filled by a light-absorbing liquid 8. The absorbing liquid particles should be of much smaller wavelength so that radiation scattering

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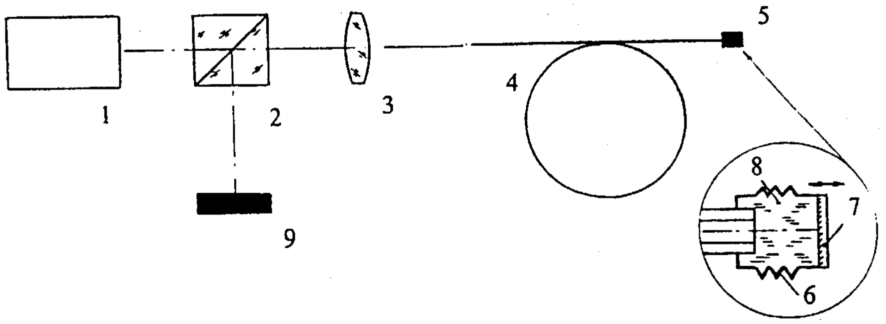

Fig.1. Configuration of a fiber optical sensor of linear displacement. Laser diode 1. polarizing beamsplitter 2, microscope lens 3, multimode fiber 4, sensor head 5, capsule 6, movable mirror 7, light-absorbing liquid 8, photodiode 9.

virtually does not exert an effect on device operation. The light reflected from mirror surface passes back through fiber 4 and microscope lens 3 and falls on the polarizing beamsplitter 2. The beamsplitter reflects the light to the photodiode 9.

A back-coupling efficiency of the sensor $k(z)$ is defined as:

$$k(z) = \frac{P(z)}{P(0)} \tag{1}$$

where z - a distance between the fiber face and the mirror,
$P(z)$ - a power of the radiation incident on the photodiode.

3.THEORY OF SENSITIVE ELEMENT

We used a method of geometrical optics in Hamiltonian formulation for mathematical sensor modeling [1]. A next system of equations is obtained as a result:

$$k(z) = \{1 - \frac{1}{2\pi\bar{z}^2}[\bar{z}(1 + 2\bar{z}^2\sqrt{1-\bar{z}^2} - (1-4\bar{z}^2)\arcsin\bar{z} +$$

$$\gamma a\frac{NA}{n}(\pi\bar{z}^3 - \frac{1}{12}(16\bar{z}^4 + 2\bar{z}^2 + 3)\sqrt{1-\bar{z}^2} + \frac{1-8\bar{z}^4}{4\bar{z}}\arcsin\bar{z})]\}\exp(-2\gamma z)$$

$$\text{when } 0 \le z \le \frac{an}{NA};$$

$$k(z) = \frac{1}{4\tilde{z}^2}[1 - \frac{\gamma a^2}{4z}]\exp(-2\gamma z) \qquad (2)$$

$$\text{when } z > \frac{an}{NA},$$

where a - a radius of a core, NA - a numerical aperture of fiber, n - a index of liquid refraction, γ - a coefficient of liquid absorption, $\tilde{z} \equiv \frac{zNA}{an}$.

If $\tilde{z} \le 05$, then the first equation of systems (2) with an accuracy to 2% may be written

$$k(z) = \{1 - [1.75 + \gamma \frac{NA}{n}(a - z\frac{NA}{n})]z\frac{NA}{2an}\}\exp(-2\gamma z). \qquad (3)$$

With the coefficient of liquid absorption $\gamma < 1/2a$, the contribution of terms in braces in the equations of system (2) which contain the quantity γ, becomes negligible. In this case the formulae

$$k(z) = \{1 - \frac{1}{2\pi\tilde{z}^2}[\tilde{z}(1 + 2\tilde{z}^2\sqrt{1 - \tilde{z}^2} - (1 - 4\tilde{z}^2)\arcsin\tilde{z}]\}\exp(-2\gamma z)$$

$$\text{when } 0 \le z \le \frac{an}{NA};$$

$$k(z) = \frac{1}{4\tilde{z}^2}\exp(-2\gamma z) \qquad (4)$$

$$\text{when } z > \frac{an}{NA},$$

should be used.

Similar to equation (3), when $z \le an/2NA$, the first equatio of systems (4) is simplified

$$k(z) = \{1 - 0.85z\frac{NA}{an}\}\exp(-2\gamma z). \qquad (5)$$

Sensitivity of the sensor signal μ to the mirror displacement is determined by the derivative of the function $k(z)$ at the point z=0:

$$\mu = \frac{dk(0)}{dz} = -[0.85\frac{NA}{an} + 05\gamma\left(\frac{NA}{n}\right)^2 + 2\gamma]. \qquad (6)$$

As is shown, the required value of the parameter μ may be provided by the corresponding choice of the coefficient of absorption and the refraction index of liquid, numerical aperture and the radius of the fiber core.

4.THEORY OF POLARIZATION BEAM SPLITTING SCHEME

The polarization method of the separation of input and output beams allows one to additionally increase sensitivity of the sensor. In this case the fact that, on the hand, radiation of semiconductor lasers is linearly polarized [2] and, on the other hand, multimode fibers depolarize the beam passing through them is used. The scheme of polarization separation will be described in the Cartesian system of coordinates the X axis of which is parallel to the polarization plane of the initial laser beam. The coefficients of reflection and transmission by a beamsplitter of the corresponding components of polarization are denote as R_x, T_x and R_y, T_y with $R_x + T_x = R_y + T_y = 1$. The power losses on radiation transmission through a fiber are taken into account by the factor χ. Respectively, the total value of the back flow Φ returning to the beamsplitter is equal to

$$\Phi = \chi T_x \Phi_0, \qquad (7)$$

where Φ_0 is the value of radiation flow of the initial laser beam.

After double transmission in a reverse beam, along with the component Φ_x polarized parallelly to the plane of initial laser beam oscillations, the component with orthogonal polarization Φ_y arises. A beamsplitter reflects the radiation flow Φ' to the photodiode:

$$\Phi' = R_x\Phi_x + R_y\Phi_y. \qquad (8)$$

The ratio $\Phi' / \chi\Phi_0$ is the efficiency of operation of the scheme of beam splitting. Denote it by the quantity η. Consequently

$$\eta = \frac{1}{2}(1 - R_x)[(R_x + R_y) + Q(R_x - R_y)] \qquad (9)$$

where $Q = \frac{\Phi_x - \Phi_y}{\Phi_x + \Phi_y}$.

A maximum value of the efficiency of splitting $\eta_{\max}$ is attained at the following parameters of a beamsplitter:

$$\begin{cases} R_x = \dfrac{Q}{1+Q}, \\ R_y = 1 \end{cases} \qquad \begin{cases} T_x = \dfrac{1}{1+Q}. \\ T_y = 0 \end{cases} \tag{10}$$

In this case

$$\eta_{\max} = \frac{1}{2(1+Q)} \tag{11}$$

As seen from (10) in the case of complete depolarization of radiation by a fiber (Q=0) the use of polarization beamsplitter with $R_x=0$, $T_x=1$, $R_y=1$, $T_y=0$ is optimal. Here the efficiency of beams splitting is 0.5. The use of semitransparent beamsplitter with $R_x=0.5$, $T_x=0.5$, $R_y=0.5$, $T_y=0\ .5$ gives a half as many efficiency 0.25 (see equation (9)).

5.EXPERIMENTAL RESULTS

Verification of mathematical model the sensitive element has been carried out on the experimental installation with a multimode stepwise optical fiber, a core diameter 50 μm, numerical aperture 0.10. There was the air space ($n=1, \gamma=0$) between the fiber face and the mirror. In Fig.2 a back-coupling efficiency which is typical for sensor is plotted versus the distance between the fiber face and the mirror. The theoretical dependence is seen to describe the experimental data well enough that confirms correctness of the mathematical model.

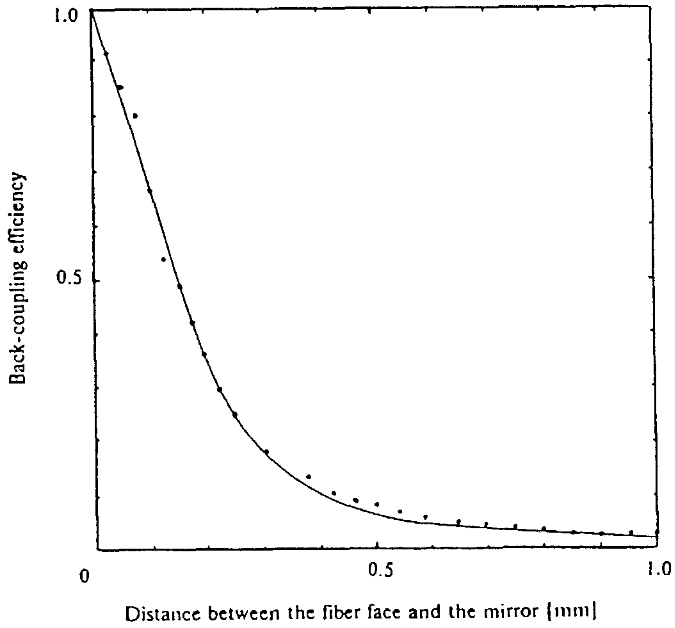

Fig.2. Measured (...) and calculated (—) back-coupling efficiencies of the sensor head with $2a=50\mu\text{m}$, $NA=0.10, n=1, \gamma=0$

6.CONCLUSIONS

Two methods allowing to increase sensitivity of linear displacement fiber optic sensors with a single multimode fiber and a movable mirror are proposed. In particular, it is suggested to fill a space between the fiber end and the mirror by the light-absorbing liquid and to use the polarization beam splitting scheme. Theoretical bases of these methods are given. In arrangement of the movable mirror onto the corresponding transformer described sensor may be used for measurement of temperature, pressure, humidity, acceleration, vibration, flow velocity, various electric and magnetic parameters etc.

7.REFERENCES

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