

Luminous flux control in a fiber-optic measuring transducer

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Abstract. An open optical channel of a fiber-optic measuring transducer is studied as an object of control. Optical mechanical modulating elements, used in FOMT and OOC, mirror surfaces, limit and mirror attenuators, spherical and cylindrical lenses were determined. They are used for control of the luminous flux in the measurement information perception zone.

Introduction

Fiber-optic measuring transducers (FOMT), utilizing intensity change under influence of applied physical quantity can be divided into three classes [1]. Article [2] substantiates the use of the first class of FOMT in severe conditions of aerospace and aeronautic industry. Fluctuations of physical values cause changes in propagation of light in the measurement area - the fiber-optic channel gap. In this case, there is a change of the intensity of light radiation going from the feeding optical fiber (FOF) through the measurement zone to receiving optical fibers (ROF). Such transducers called fiber-optic measuring transducers with an open optic channel (OOC) [1]. In its turn, FOMT with OOC is divided into the following groups:

- open-end FOMT – intensity modulation of the optic signal is performed by the change of the relative position of FOF and ROF: transverse, lateral and angular micro displacements relative to each other
- mirror FOMT - intensity modulation of the optic signal is performed by the change of the position of the mirror put in a way of light beam in the transverse, lateral or angular direction
- attenuator FOMT - intensity modulation of the optic signal is performed by the change of the position and decreasing the optical power by a non-transparent attenuator or optical filter
- nephelometric FOMT - intensity modulation of the optic signal, passing through the object under research, is performed as a result of dispersion on nonhomogeneities and is proportional to the quantity of dissipative particles in a volumetric unit
- FOMT with violation of the total internal reflection, in which the intensity modulation of the optic signal decreases in case of violation of total internal function conditions. Or it can change unevenly when the refractive index of the environment changes. It also can vary depending on the gap between the optical fibers and a controlled object or depending on the value of the optical contact between the optical fiber and the controlled object.

Luminous flux control in the fiber-optic measuring transducer. The condition of the open optical channel in the process of being influenced by measured physical quantity X and non-measured parameters ξ_i of the environment determines reliability of measured results. Therefore let us select OOC as a controlled, which we will influence intentionally (figure 1).



Let A denote a multitude of optical signal parameters on the input of OOC. Let B denote a multitude of functional and technological input parameters. Disturbance vector E is a multitude of external influencing factors which affects the open optic channel. The state vector of OOC is a range of values of output parameters Y. Control actions and control devices represent a multitude of M. Measured physical value X can be designated as a control action if the information about the behavior of the physical process is given a priori.

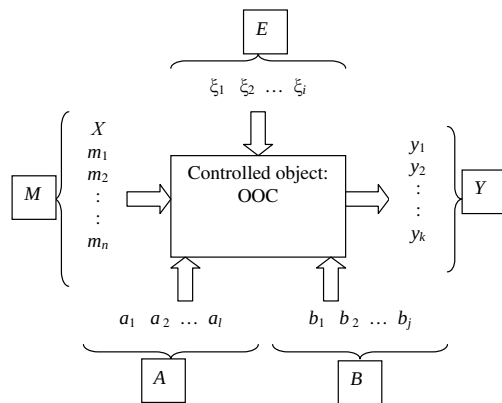


Figure 1. The open optic channel as a controlled object

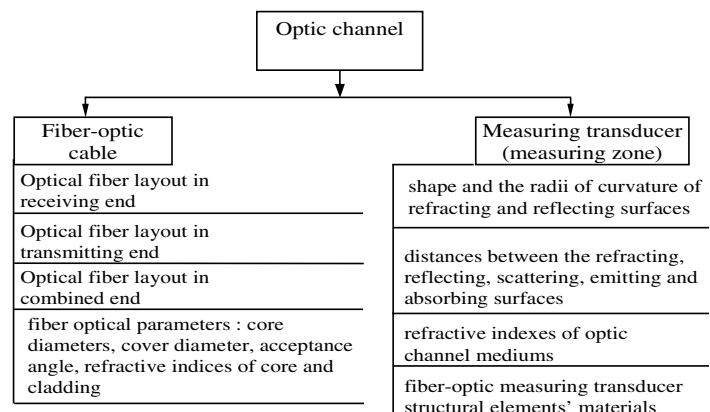


Figure 2. Structural and technological parameters of the open optic channel

Input parameters A include wavelength λ of probing signals, format of probing signals; the average power of P_{mes} in the impulse of probing signals, in dB/mW; susceptibility threshold Y_{thesh} , a dynamic range of input signals, in dB, frequency range f of measured physical value X, in Hz, measurement range $X_{min} \dots X_{max}$

OOC is determined by structural and technological parameters of multitude B (figure 2). Change of these parameters provides a required process of transduction in the fiber-optic measuring transducer. It is evident that optical fiber positioning schemes in the fiber-optic cable and materials of structural elements remain unchanged. Other parameters can change under the direct influence of value X or by intermediate conversion. The study has defined that to reduce the temperature error caused by S_{B1} , S_{B2} , nonproportional changes under ambient temperature shift, it is necessary to use single-type radiation detectors with the same point of sensitivity deviation, which leads to partial compensation of the temperature error.

Output parameters Y of the fiber-optic measuring transducer include a dynamic range of introduced optical losses in FOMT, in dB; nominal transfer function, $F(X)$, the depth of FOMT signal response modulation, average power P_{ir} in the signal response impulse of FOMT, in dB/mW; output signal variation, the limit of scaled intrinsic error γ_0 , in %, the limit of the assumed value of the reduced additional error γ_0 , %.

Optic channel control function M provides maximum informational performance of the fiber-optic measuring transducer – achieving required parameters of the output optical signal in the measurement range. Function M is realized in the local area of existence of the preset vector of effects by means of control elements. They convert the received measuring information according to the determined algorithm.

Control influence on the open optic channel provides demanded energy relations, forming rational spatial structures of the light flux in the fiber-optic measuring transducer.

Figure 3 shows a control scheme of the optical channel (mirror FOMT).

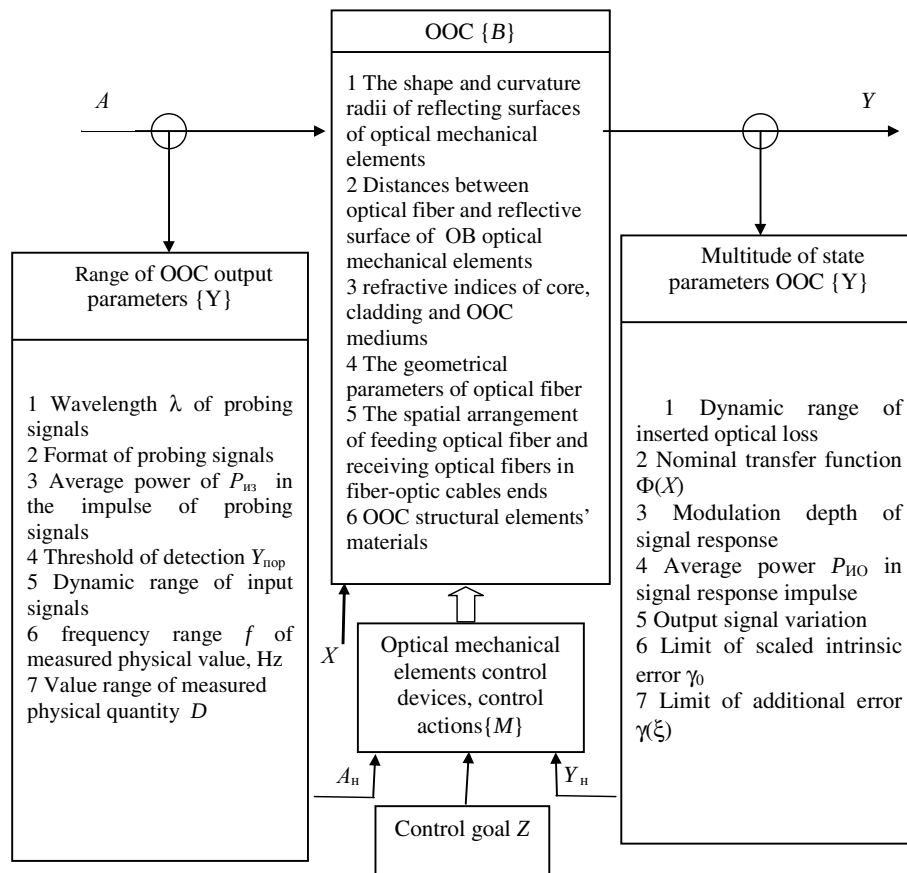


Figure 3. The control circuit of the optical channel fiber-optical transformer of a reflective type

The control of the luminous flux of the optical channel of the fiber optic measuring transducer is realized by means of control elements, devices (optical mechanical elements) and control parameters of the open optical channel. In each case, there are control devices, specifically introduced into the structure of OOC, or design and technological parameters of the optical signal propagation medium, changed during the measurement process (Figure 4).

In accordance with the common terminology, control devices for distribution of the light flux parameters in space and variance in the spatial-temporal spectrum of radiation called modulators.

Devices that control the direction of flux propagation are called deflectors. Devices intended for fixed or stepped change of the power of luminous flux are called attenuators.

In the fiber-optic measuring transducer, control devices are used for entering information about the measured value in a light wave. This operation is called modulation. Therefore, attenuators and deflectors with sufficient accuracy can be attributed to modulators. But historically, in electronics, the term modulators often implies the devices that control the luminous flux under the influence of the electric field. In fiber-optic measuring, the term “modulators” is excluded due to the absence of current-carrying circuits. Therefore, the division of the control devices into three groups, above, is more justified. The main group of control devices comprises optical mechanical elements, in which, as a result of mechanical movement (rotating, reciprocating or angular displacement) of the control element, the modulation of intensity of the luminous flux is carried out in accordance with the law of variation of the measured parameter.

The group of optical mechanical modulators is sparse and is represented mainly by various types of lenses and lens sets moving in accordance with the law of variation of the measured physical quantity. Also, they can move between the radiating end of the feeding optical fiber and the receiving end of the receiving optical fiber or the joint end of the optical fiber with one or another deflector.

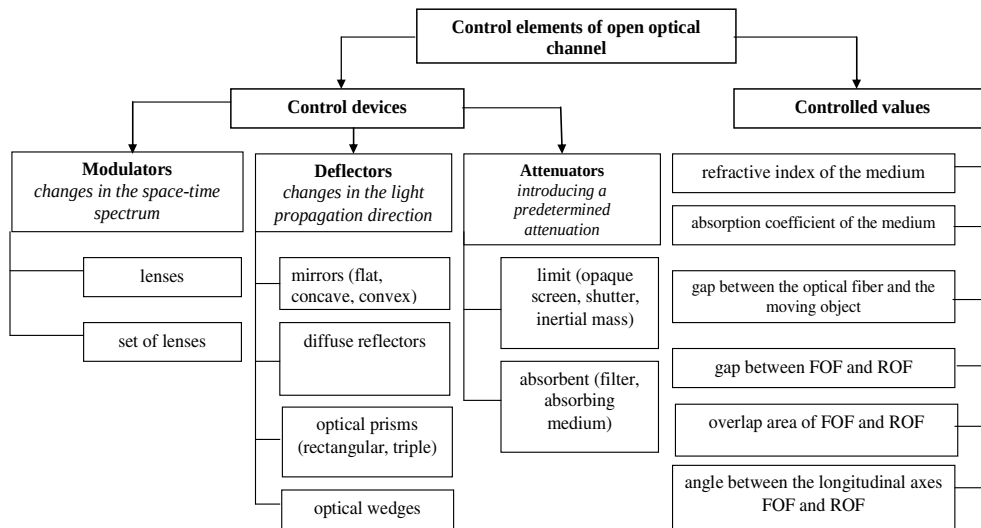


Figure 4. Classification of the control elements of the open optic channel

Optical mechanical deflectors provide a deflection flux using moving or rotating mirrors, optical prisms, pyramids, wedges. Flux deviation is carried in two mutually perpendicular planes or so that the beam moves along a circle whose center coincides with the axis of rotation (figure 5).

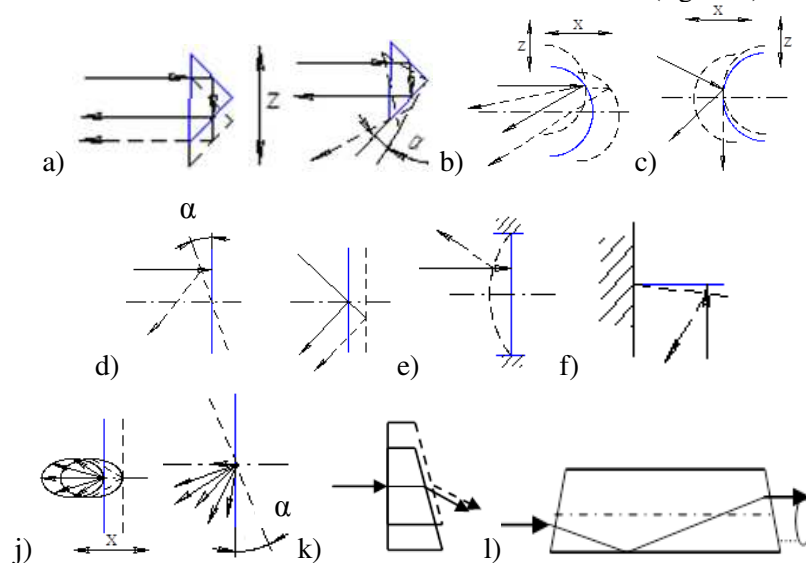


Figure 5. Control devices for radiation deflection: *a* – prism; *b* – concave mirror; *c* – convex mirror; *d* – flat mirror; *e* – membrane; *f* – spring beam; *j* – diffuse reflector; *k* – optical wedge; *l* – Dove prism

The efficiency of optical mechanical elements control of the light flux in the open optical channel is evaluated according to the following criteria: the depth of modulation of the optical signal, the value of the introduced losses, sensitivity to control exposure, the conversion efficiency of the optical signal, inertia and manufacturability of optical mechanical elements, operation in harsh operating conditions throughout the lifetime of a given accuracy conversion.

Maximum modulation depth of intensity $m_{\max}$ by means of optical mechanical elements is defined by equation

$$\begin{cases} m_{\max} = \frac{|I_m - I_0|}{I_0} & \text{when } I_m \leq I_0, \\ m_{\max} = \frac{|I_m - I_0|}{I_m} & \text{when } I_m \geq I_0, \end{cases} \quad (1)$$

where I_0, I_m – light intensity at the output of OOC without the applied effects and after application of the maximum impact.

The maximum depth of modulation is an important quality criterion, since it affects the signal/noise ratio on the radiation receiver, also called a contrast ratio. When processing optical signals, the contrast should be 20...100, i.e. at least 10 dB.

The modulation depth is directly related to loss implemented by optical mechanical elements. If the light intensity at the entrance of the optical mechanical element equals I_i , implemented loss L is defined as follows:

$$\begin{cases} L = 1 - \frac{I_m}{I_i} & \text{when } I_m \geq I_0, \\ L = 1 - \frac{I_0}{I_i} & \text{when } I_m \leq I_0. \end{cases} \quad (2)$$

First of all, mirror surfaces, intended for introduction of predetermined optical attenuation of the fiber-optic pressure transducer into OOC in the function of the measured physical value, comply with listed requirements (1) – (2).

Compared to other control devices, mirrors provide substantially less uninformative loss caused by loss of the luminous flux at interfaces.

The limit attenuators, which action in the fiber-optic displacement transducers with OOC is based on the change of optical losses as a result of the mechanical movement of the elements – attenuators, also meet requirements (1) - (2). Optical losses in attenuators are created as a result of the introduction of additional design elements with variable profile, variable absorption coefficient or variable reflectivity between the emitting ends of the feeding optical fiber and receiving ends of the receiving optical fiber. They are characterized by the initial optical losses, dynamic range settings resistance to external influencing factors, and mechanical stress on the optical fiber is excluded.

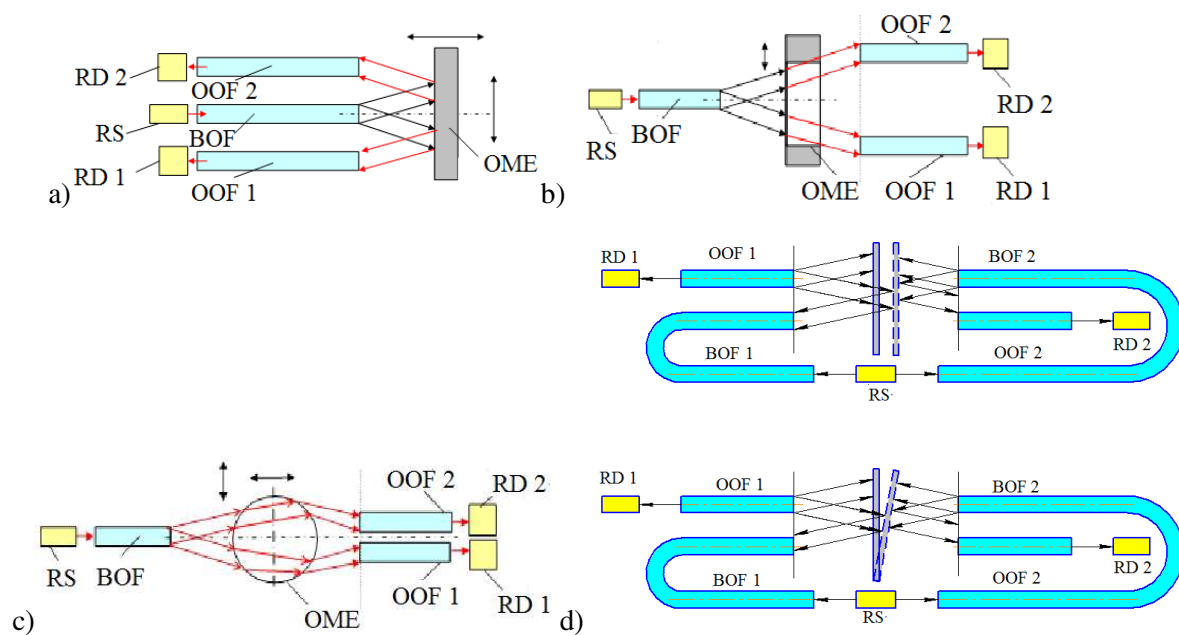
This type of optical attenuators includes absorption filters and media with a varying absorption coefficient, limiting attenuators, curtains, opaque screens, inertial masses having a variable structure profile, reflective attenuators with variable surface reflectance.

The main problem of creating fiber-optic with modulation of the luminous flux intensity is a low sensitivity of conversion of the optical signal, conditioned by high losses in the luminous flux when introducing optical radiation in the feeding optical fibers. Therefore, it is inexpedient to use absorbing filters and media in fiber-optic pressure sensors, which dramatically reduce the conversion sensitivity.

Limit attenuators with a variable profile of the construction most often represent shutters, opaque screens, inertial masses with openings of various shapes (circular, square, rectangular, ellipsoidal, etc.). Their operating principle is based on the overlap of the light flux coming from the feeding optical fiber to the receiving optical fiber. In this case, the uninformative light flux losses are low, since it is possible to arrange the feeding optical fiber, receiving optical fiber and attenuator so they got maximum luminous flux going through the attenuator. This condition requires precise alignment of the fiber-optic pressure sensors' elements relative to each other, thereby reducing manufacturability of the design, and this can be attributed to the drawback of limit attenuators.

Reflective attenuators with variable surface reflectance represent blinds, opaque screens, the surface of which is turned to the common face of the optical fiber and has an absorbing and reflecting part. Their operating principle is based on the absorption of the light-flux by the absorbing surface of attenuator and reflection of the light flux by reflecting the surface of the attenuator in a direction of the receiving optical fiber. In this case, the feeding optical fiber and the receiving optical fiber are arranged on one side relatively the attenuator, which reduces the alignment requirements and simplifies the

assembly process of the fiber-optic pressure transducer. For fiber-optic sensors with an open optic channel, it is advisable to use mirror reflective surfaces, limit reflective attenuators, lens attenuators. It is known that fiber-optic measuring transducers with open optic channel have significant additional errors, caused by changes in the parameters of sources and detectors, optical fiber bends, under the influence of external destabilizing factors. Paper [1] substantiates the possibility of improving the metrological characteristics of fiber-optic sensors in case of differential control of the luminous flux directly in the zone of measurement information perception. Optical mechanical elements in the open optical channel gap are used for implementing the differential luminous flux control algorithm. The differential group of optical mechanical elements is more numerous. Their action consists in the following: the radiation flux, depending on transmission of optical mechanical elements relatively the optical axis of the receiving optical fibers, falls into two or more FOF, the optical signals at the output of which are compared with each other (figure 6) [1].



RS- radiation sources, BOF- bringing optic fiber, OME- optical modulating element, OOF- outlet optic fiber, RD- radiation detector

Figure 6. Implementation of the differential conversion scheme in the differential fiber-optic measuring transducer: a – of a reflector type; b – with limit attenuators with a circular bore; c – with a cylindrical (or ball) lens; d – with two reflecting surfaces.

Acknowledgments

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