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Fiber-Optic Differential Pressure Sensor with a Cylindrical Lens

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Abstract: The study contains a proposal for a new attenuator Fiber-Optic Differential Pressure Sensor (FODPS). In its rod hole, the sensor has a cylindrical lens which provides an increase in transforming sensitivity and differential transformation of optical signals in the zone of measurement information perception. The sensor is intended for use in the areas of radiation, high temperatures and electromagnetic interferences.

Key words: Fiber-Optic Differential Pressure Sensor (FODPS), cylindrical lens, differential transformation, transforming sensitivity, high temperature, rod

INTRODUCTION

The disadvantages of “electric” measuring instruments is their poor reliability under radiation, influence of electromagnetic interference on measurement results when operating instruments are located in the area of facilities with a strong electromagnetic field, very large dimensions in the case of their intrinsically safe, explosion or fireproof design, impossibility to use them in high (up to 500°C) temperatures as their element base is not designed for such temperature ranges. The source of these drawbacks is that such instruments include “electric” measuring transducers located in the measurement area.

In the research, Badeeva *et al*. (2008) propose to use a Fiber-Optic Differential Pressure Sensor (FODPS) for the indicated applications. The researches (Murashkina and Pivkin, 2005) consider the variant of FODPS, the basic element of which is an attenuator-type Fiber-Optic Micro Displacement Transducer (FOMDT) with a circular hole. This FOMDT’s advantage is the possibility to implement optical signals differential transformation directly in the zone of measurement information perception thus reducing most of superfluous errors caused by destabilizing factors (Murashkina and Pivkin, 2005).

In the researches (Murashkina and Pivkin, 2005; Turbin, 2012; Rubtsov *et al*., 2015), it is proved that multiple reflections inside optic fiber result in beam symmetrization with regard to the optical axis of the optical fiber and illuminance averaging at the output (emitting) end of the fiber. The symmetrization leads to that the narrow conical bundle of rays meets the optic fiber’s straight-faced input end at a certain angle and fills the spatial zone bounded by two close coaxial surfaces at the outlet. Thus, in the section perpendicular to the optical axis, there is an annular zone (Fig. 1).

This fact allows transverse dividing the optical signal into two separate beams of two measurement channels (by its further transformations in a constructive manner) and implementing a differential transformation circuit.

The disadvantage of the FOMDT considered in the researches (Murashkina and Pivkin, 2005) is its low sensitivity of optical signal transformation because of non-informative light loss during its divergence at the optical fibers’ outlets within the aperture angle Θ_{NA} (Murashkina and Pivkin, 2005).

That is why it is proposed to place a cylindrical lens 4 in the hole of rod 1 (cutoff attenuator) connecting the membranes 2 and 3 of positive and negative sensor chambers (Fig. 2).

In this case, the light loss in the zone of measurement is minimized, since the lens 4 serves as not only a modulating but also a focusing element.

Here, the modulation of the optical signal is carried out by changing the curvature of the gas-glass interface when the cylindrical lens 4 moves under the influence of pressure differences in the rod 1.

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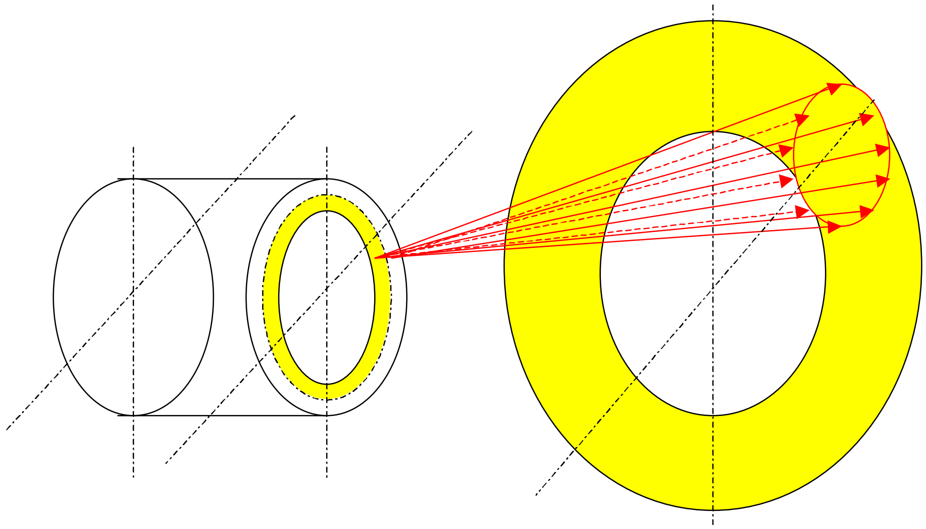

Fig. 1: Formation of an annular zone at the optical fiber outlet

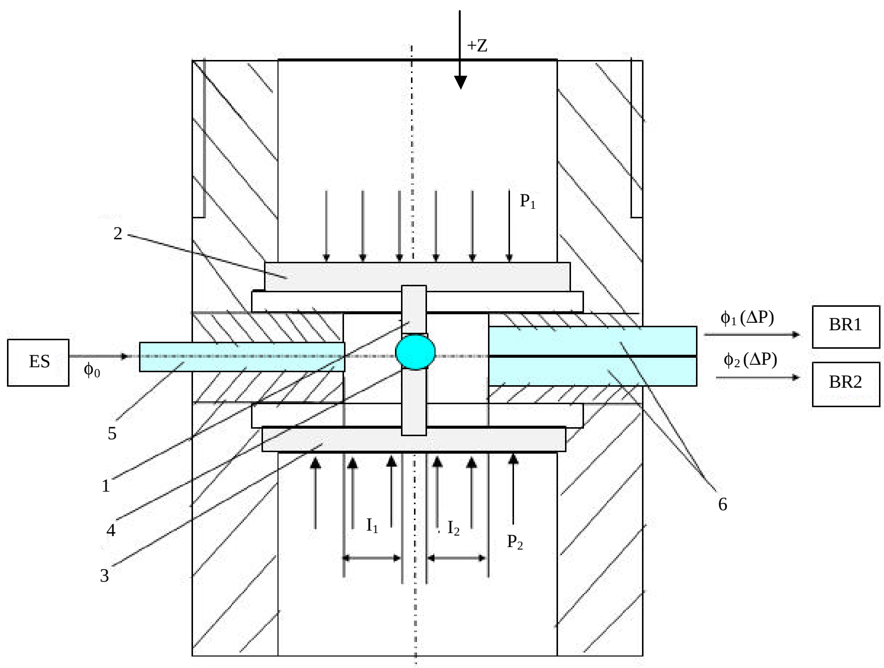

Fig. 2: Simplified design diagram of the FODPS with a cylindrical lens; ES: emitting source; BR1, BR2: beam receivers of the first and second measurement channels; l_1: spacing between the emitting end of IOF (Input Optical Fiber) and the receiving side surface of the lens; l_2: spacing between receiving ends of OOF (Output Optical Fiber) and the emitting side surface of the lens

Figure 3 shows the light spot located in the area of the Output Optic Fibers (OOF) ends which are placed vertically above each other. The initial position of the cylindrical lens $z_l = 0$. Let us study the area of intersection of the light spot with the core of one OOF (Fig. 4). The area of the segment is determined by the equation of the curvilinear trapezoid bounded by the ellipse:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$$

and the circle $x^2+(y-d)^2=R^2$:

$$S_{BR}=2\int_0^x a^2\sqrt{1-\frac{x^2}{b^2}}-\left(\sqrt{r_?^2-x^2}\pm d\right)\Big\rangle dx \qquad (1)$$

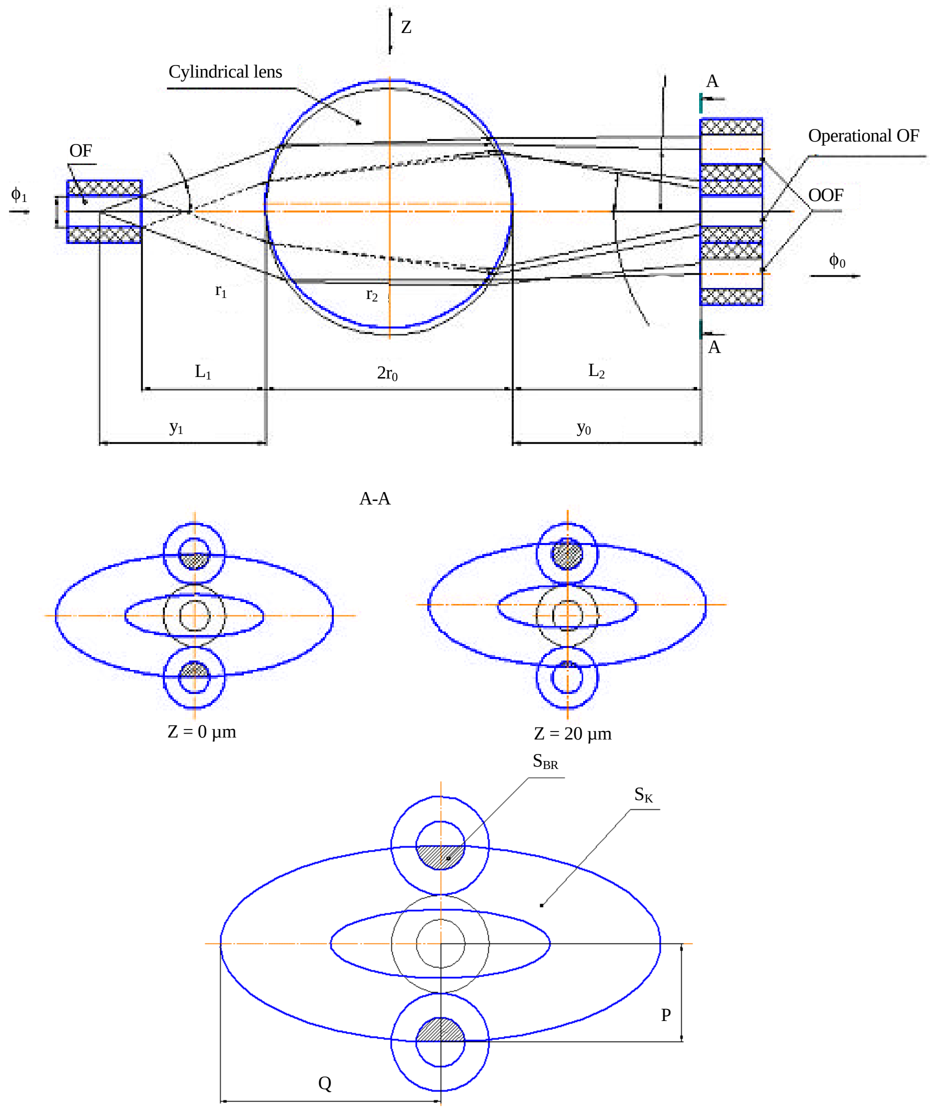

Fig. 3: Calculation and design diagram of the FODPS differential micro displacement transducer with a cylindrical lens

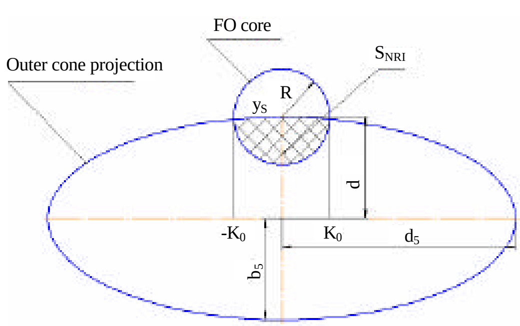

Fig. 4: Geometric constructions for the determination of the area

To find the coordinates of intersection points of the light spot (ellipse) and the FO core (circle), it is necessary to solve a system of equations for each figure:

$$\begin{cases} x^2 + (y-d)^2 = R^2 \\ \dfrac{x^2}{a^2} + \dfrac{y^2}{b^2} = 1 \end{cases} \quad (2)$$

where, d: spacing between the centers of the ellipse and the circle. From whence:

$$y^2(a^2 - b^2) + 2db^2y + (R^2b^2 - d^2b^2 - a^2b^2) = 0 \quad (3)$$

After dividing this expression by b^2, we obtain a quadratic equation:

$$y^2\left(\frac{a^2}{b^2}-1\right)+2dy+(R^2-d^2-a^2)=0 \quad (4)$$

the solution of which is possible in the following form:

$$y_0=\frac{-2d+2\frac{1}{b}\sqrt{(d^2-b^2)(R^2-d^2-a^2)}}{2\left(\frac{a^2}{b^2}-1\right)}, \quad (5)$$
$$x_0=\sqrt{R^2-(y_0-d)^2}$$

The dependency of the center-to-center spacing d and the displacement of the cylindrical lens z_i is defined by the linear function $d(z) = p_1z_i+p_2$. The factors p_1 and p_2 are approximation function coefficients. For example, if pressure makes the membranes bend within the range ±20 μm, the function d(z) takes the form $d(z) = 4.2z+0.5$. The minor semi-axis a and the major semi-axis b of the ellipse are defined by the equation:

$$a=tg\Theta_{BX2}\left[\frac{r_C\sin\gamma_2}{\sin T_{BX2}}-\frac{r_C\sin\gamma_1}{\sin T_{BX1}}\right] \quad (6)$$

$$b=\Theta_{NA}\left[\frac{\cos T_{NA}(2d_c+r_C tgT_{NA}\pm Z)}{\sin\Theta_{BX1}}-r_C\right] \quad (7)$$

Where:

r_C = The radius of the cylindrical lens

$\Theta_{BX1}, \Theta_{BX2}$ = The angles of incidence of the ray on the external and internal borders of the light flux at the input to OOF; they are defined by the Eq. 9 and 10 correspondingly:

$$\Theta_{BX1}=2\left[\begin{array}{l}\arcsin\left(\frac{\cos\Theta_{NA}(2d_? + r_C tg\Theta_{NA}\pm Z)}{r_?}\right)-\\ \arcsin\left(\frac{\cos\Theta_{NA}(2d_? + r_C tg\Theta_{NA}\pm Z)}{r_?}\cdot\frac{n_B}{n_C}\right)\end{array}\right]-\Theta_{NA} \quad (8)$$

$$\Theta_{BX2}=2\left[\begin{array}{l}\arcsin\left(\frac{\cos\Theta_{NA}(d_C + r_C tg\Theta_{NA}\pm z_i)}{r_C}\right)-\\ -\arcsin\left(\frac{\cos\Theta_{NA}(d_C + r_C tg\Theta_{NA}\pm z_i)}{r_C}\cdot\frac{n_B}{n_C}\right)\end{array}\right] \quad (9)$$

where, γ_1, γ_2 are the ray's angles of inclination to the normal on the external and internal borders after the light flux comes out of the cylindrical lens; they are defined by the Eq. 11 and 12 correspondingly:

$$\gamma_1=\arcsin\left(\frac{\cos\Theta_{NA}(2d_C+r_C tg\Theta_{NA}\pm z_i)}{r_C}\right) \quad (10)$$

$$\gamma_2=\arcsin\left(\frac{\cos\Theta_{NA}(d_C+r_C tg\Theta_{NA}\pm z_i)}{r_C}\right) \quad (11)$$

The lighted area of the OOF receiving ends is determined by the following equations:

- For the first channel (OOF1):

$$S_{BR1}=2\int_0^{x_0}a_b^2\sqrt{1-\frac{x_0^2}{b_b^2}}-\left(\sqrt{r_C^2-x_0^2}\mp p_1z_i+p_2\right)\Big)dz_i \quad (12)$$

- For the second channel (OOF2):

$$S_{BR2}=2\int_0^{x_0}a_b^2\sqrt{1-\frac{x_0^2}{b_b^2}}-\left(\sqrt{r_C^2-x_0^2}\mp p_1z_i-p_2\right)\Big)dz_i \quad (13)$$

The 'up' sign means the movement of the cylindrical lens upwards and the 'down' sign downwards regarding its initial position $z_i = 0$.

The area of the lighted zone on the plane of the OOF receiving ends is an elliptical ring, the borders of which are IOF extreme rays:

$$S_K=\pi a_b b_b-\pi a_M b_M \quad (14)$$

Thus, the function of transformation for the FOMDT with a cylindrical lens takes the form:

$$\Phi(z_i)=\Phi_0\frac{2\int_0^{x_0}a_b^2\sqrt{1-\frac{x_0^2}{b_b^2}}-\left(\sqrt{r_C^2-x_0^2}\mp p_1z_i\pm p_2\right)\Big)dz_i}{\pi a_b b_b-\pi a_M b_M} \quad (15)$$

The calculation result should give the following parameters: the spacing between the IOF end and the surface of the cylindrical lens l_1, the spacing between the lens surface and the OOF ends l_2, the cylindrical lens radius r_c.

Since, the transducer uses differential circuit of the light flux control, it is important to illuminate the lens surface uniformly. To uniform the illumination and to

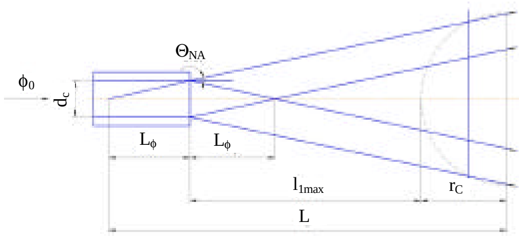

Fig. 5: Geometric constructions to determine the distance from IOF 5 to the surface of the cylindrical lens 4

increase the brightness, the lens should be located at the minimal distance from the IOF emitting end equal to two distances of forming L_Φ of the light flux $L\Phi = 0.5d_C/tg\Theta_{NA}$. As the increase of the spacing between the IOF emitting end and the cylindrical lens can lead to the withdrawal of the lens from the lighted zone (Fig. 5), it is required to place it at a distance not bigger than $l_{1max} = L\text{-}L_\Phi\text{-}r_C$, where $L = r_C/tg\Theta_{NA}$. Then:

$$l_{1max} = \frac{r_?}{tg\Theta_{NA}} - \frac{0.5d_?}{tg\Theta_{NA}} - r_? \quad (16)$$

It has been found that the minimal distance from IOF 5 to the surface of the cylindrical lens 4 (Fig. 2) is efined by the following expression:

$$\frac{1.5d_?}{tg\Theta_{NA}} \le l_1 \le \frac{r_?}{tg\Theta_{NA}} - \frac{0.5d_?}{tg\Theta_{NA}} - r_? \quad (17)$$

The receiving ends of the OOF 6 regarding the side surface of the lens 4 (Fig. 2) are located at the distance:

$$l_2 = \frac{\cos\Theta_{NA}(2d_C + r_? tg\Theta_{NA})}{\sin\Theta_{BX}} - r_? \quad (18)$$

where, Θ_{BX} is the angle of emission entry to the output optic fiber, which is defined by the expressions 9 and 10.

In mathematical modeling, the authors measured the spacing l_1 between the end of the IOF 5 and the surface of the cylindrical lens 4, the spacing l_2 between the surface of the lens 4 and the ends of the OOF 6, the radius of the cylindrical lens r_c. They also simulated lens displacement along the axis Z (Rubtsov *et al*., 2015). It was determined that the spacing l_2 is related to the diameter of the fiber optic core d_C by the ratio $l_2 = 7.5d_C$.

Figure 6 illustrates the result of calculation of refracted light cones with the displacement of the cylindrical lens axis upwards by 0.01 and 0.02 mm (z_i).

The modeling results, given as $K(z) = \Phi/\Phi_0$ according to the calculation Eq. 15, at the outlets of the OOF 6 for different l_1, l_2 and r_C values (Fig. 3), are provided in Fig. 7.

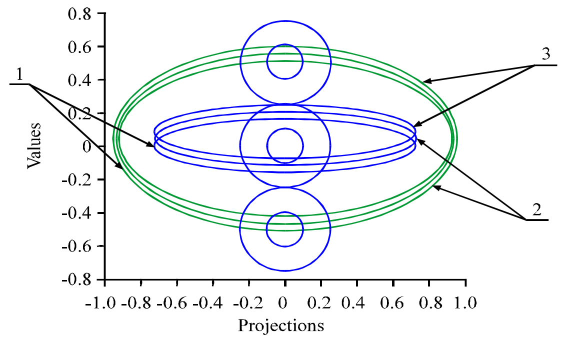

Fig. 6: The projection of the light cones on a screen; 1: without displacement; 2: with cylindrical lens displacement (0.01mm); 3: with cylindrical lens displacement (0.02 mm)

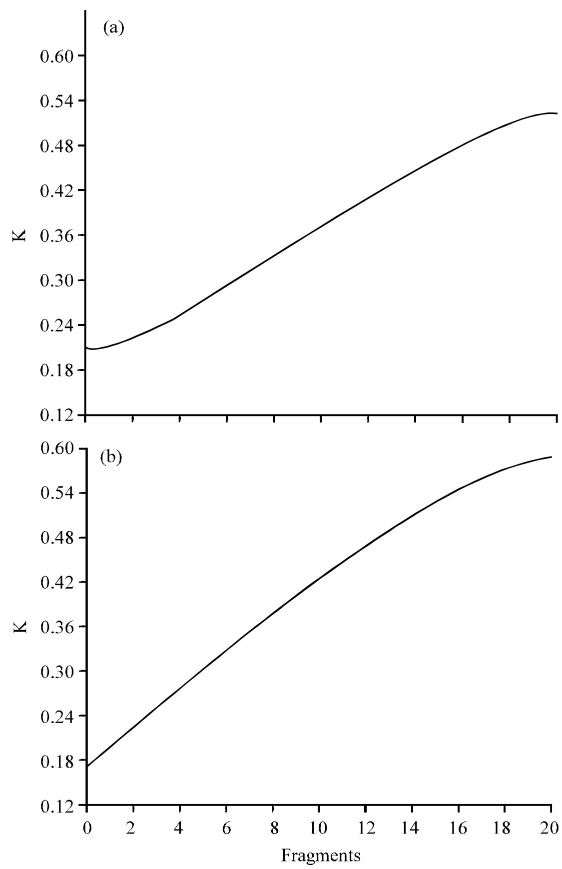

Fig. 7: The results of mathematical modeling in Matlab (fragment); a) $r_c = 1.5$; $l_1 = 0.5$; $l_2 = 1.1$; b) $r_C = 1.5$; $l_1 = 0.5$; $l_2 = 1.5$

Figure 7b shows a preferred transformation function, proceeding from the condition of maximum sensitivity. To attain minimal linearity error, it is necessary to limit the range of lens displacement from 0-16 μm.

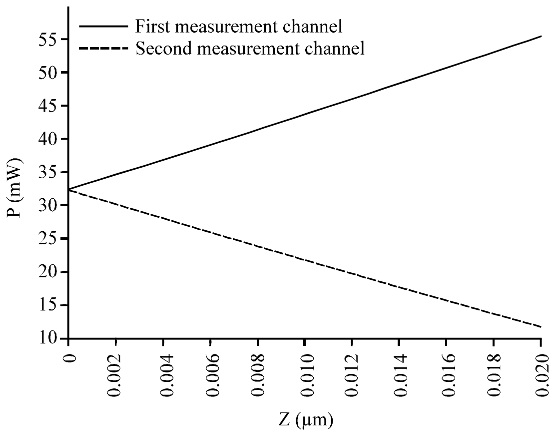

Fig. 8: An example of experimental dependences of the optical power for the FOMDT with a cutoff attenuator and with a cylindrical lens

The analysis of the obtained dependencies revealed that transferring maximal possible power of the light flux emission to the zone of transforming an optic signal of the FOMDT with a cylindrical lens is achieved at the following optical system's parameters (Fig. 7b): the radius of the cylindrical lens 4 r_C = 1.5 mm; the spacing between the end of IOF 5 and the surface of the cylindrical lens 4 l_1= 0.5 mm; the spacing between the back surface of the lens 4 and the ends of OOF 6 l_2 = 1.5 mm. With other parameters, there are critical losses of light flux or non-uniform distribution of the light power.

The analysis of the experimental dependence of the optical power P_{exp} = f(z) for the FOMDT first and second measurement channels as a part of FODPS showed that the maximal linearity error value $|\gamma|_{max}$ is 0.07%, the transformation sensitivity of the FOMDT with a cylindrical lens dU/dZ = 1.11 mW/µm which is 1.5...2 times bigger than the sensitivity of an attenuator-type FOMDT with a circular hole (Fig. 8). The technical result of this technological solution is the following.

CONCLUSION

The proposed FODPS implements the differential transformation of the light flux in the measurement zone, which helps to achieve a more linear transformation function and higher accuracy of measuring differential pressure under the impact of external factors. The influence of external environment non-informative parameters and the impact of fiber-optic cable bends on measurement accuracy are also greatly reduced; there is a decrease of the errors caused by changes in emitting source power, imprecise alignment of the optical fibers and the shutter relatively to each other because these factors cause proportional changes in the signals of the two measurement channels which do not result in changing their relations.

The proposed FODPS technological solution provides high reliability under radiation, in intrinsically-, explosion- or fire- unstable conditions, under influence of electromagnetic interference in the area of facilities with a strong electromagnetic field as well as small dimensions and the possibility of utilizing it in high (up to 500°C) temperatures.

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