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Regularities of Signal and Sensitivity Variation of a Reflection Fiber Optopair Sensor Dependent on the Angle between Axes of Fiber Tips*

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Abstract. Regularities of variation of output signal U of one reflection fiber optopair dependent on the distance h between active fiber tips and light reflecting body-mirror (U-h characteristics) and on the angle 2θ between the FAT axes, the distance between FAT being minimal ($b = b_{min}$), have been explored by modelling and experimentally. The parameters of U-h characteristics have been established: maximal sensitivity $S_{max}(h)$, localization and values of maxima and inflection points $(+, -)$ of a function $U(h)$, length of interval Δh in which the output signal $U(h)$ is linear (98 % of sensitivity maxima), as well as dependences of these parameters on the angle θ and distance h. It has been shown that the experimental results are well described by the formulas improved by the authors previously. It has been demonstrated that reflection fiber optopair sensitivity S_{max} to displacement considerably increases with an increase of the angle θ. It has been defined that, with an increase of the angle θ up to 20°, sensitivity increases up to 30 times when active fiber tips axes are almost parallel and the diameter of the fiber core is $100\ \mu$m, and $125\ \mu$m with cladding. Apart from that, S_{max} increases almost exponentially up to $\theta = 20^\circ$. A drawback of such an RFP is that with an increase of the angle θ, the size of the sensor head also increases. However, due to their considerably increased sensitivity, they can be and are wide used.

Keywords: fiber-optic sensor, nanometric displacement measurement, modelling, experiment.

1 Introduction

Reflection fiber optic sensors are widely used in measurements. They are usually comprised of a parallel fiber tip optopair [1–4]. Fiber optopairs are frequently used the active fiber tips (FAT) axes of which form an angle 2θ [4–10]. Unfortunately, no analysis has

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been made so far in order to decide when it is reasonable to use one or another reflection fiber optopair (RFP), in which FAT axes form an angle θ ($0 \le \theta < 90°$), $b = b_{min}$, and to determine the regularities of U-h characteristics (UHC) and sensitivity variation depending on the distance h to the light reflecting body and on the angle θ.

2 Experimental set-up

RFP U-h characteristics (UHC) were measured by using a circuit shown in Fig. 1b. Fibers **A**, **L** (WF 100/125 P 0.22) were installed in SMA 905 connectors. The angle between FAT axes is 2θ. The maximal output signal and minimal distance b_{min} were controlled by a special mounting desk (Fig. 2). SMA emitter (H22E4020IR), of 15 dBm power, $\lambda_{max} = 850$ nm and a stabilized current supply 80 mA were used. Output power of the sensor was measured by a precise fiber emission gauge LP-5025-8. Fibers **A**, **L** and the mirror (Au) were fastened on a precise xyz positioning device under a microscope. The positioning step was controlled by an electronic device and, in addition, by a micrometer (± 0.5 μm). The angle 2θ between FAT axes was defined by the microscope (Fig. 2) scale indices.

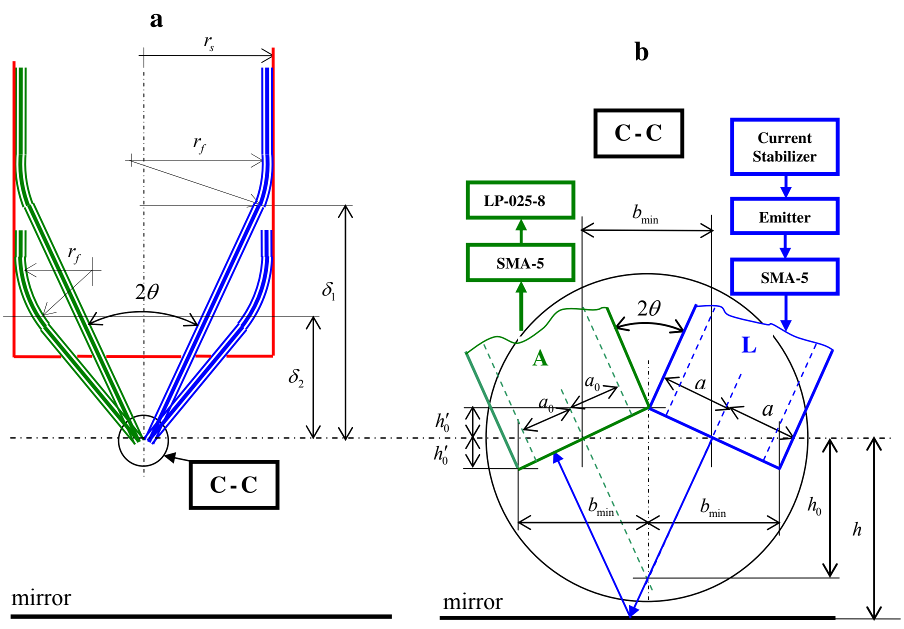

Fig. 1. **a** – Arrangement of fiber tips in a measuring head. **b** – Measuring scheme of an optopair output signal. LP-5025-8 is a fiber emitting light power meter. SMA-5 is a connector. Emitter – H22E4020IR. **L** is a light emitting fiber. A is a light receiving fiber. h is the distance to the mirror. h_0 denotes the peak position of U-h characteristics. h_0' is the distance when fiber tips touch the mirror.

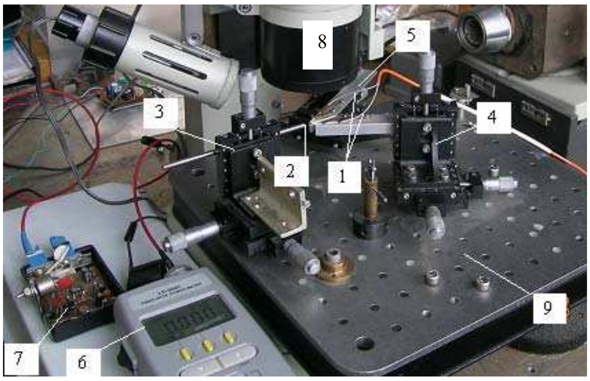

Fig. 2. The fiber optopair sensor set-up: 1 – fibers; 2 – mirror; 3 – translator of the mirror (± 1 μm): x, y, z; 4 – translator of fiber **L**: x, y, z, θ; 5 – translator of fiber **A**: x, y, z, θ; 6 – optical fiber light power meter; 7 – stabilized source of power supply; 8 – optical microscope for monitoring the fiber tips relatively to mirror; 9 – optical plate for fastening translators.

3 Modelling and experimental results

In order to determine UHC in theory, mathematical model was applied [6, 11]. If the distance between the centers of fiber tips **A** and **L** is minimal, i.e., $b_{min}(\theta) = 2a\cos\theta$ (Fig. 1b), then the UHC of a sensor (a signal emerging in fiber **A**) is expressed by the function $U(h\theta)$:

$$U(h,\theta) = \frac{C_0}{\pi R^2(z(h,\theta))} \exp\left\{\frac{-x^2(h,\theta)}{R^2(z(h,\theta))}\right\}, \tag{1}$$

here

$$x(h,\theta) = 2\bigl(h\sin\theta - a\cos^2\theta\bigr), \tag{2}$$
$$z(h,\theta) = 2h\cos\theta + a\sin\theta, \tag{3}$$
$$R(H) = a_0 + H^m k\tan\theta_c, \tag{4}$$

where a is the radius of fiber cladding, a_0 is the radius of fiber core, and C_0, k, m are constants defined in the experiment.

In a particular case, where $\theta = 0°$, formula (1), becomes (because $x(h) = -2a$ and $z(h) = 2h$)

$$U(h) = \frac{C_0}{\pi(a_0 + 2^m h^m k\tan\theta_c)^2} \exp\left\{\frac{-4a^2}{(a_0 + 2^m h^m k\tan\theta_c)^2}\right\}.$$

Experimental UHC are presented in Fig. 3. Measurements were taken at the angles θ between FAT axes $0°, 25°, 34.4°$ and $44°$.

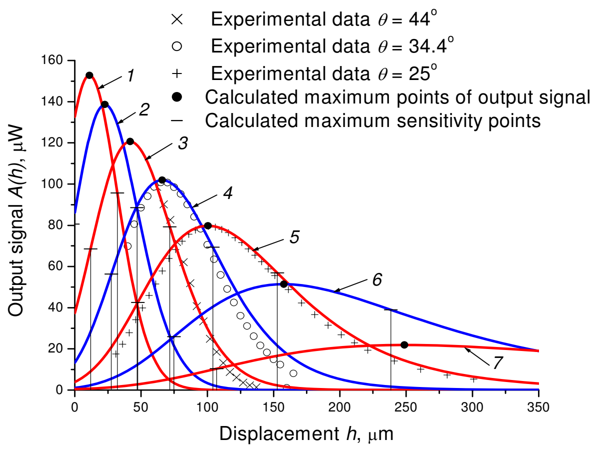

Fig. 3. Calculated and experimental values of the output signal in receiving fiber **A**. Calculated curves: $1 - \theta = 65°$, $2 - \theta = 55°$, $3 - \theta = 44°$, $4 - \theta = 34.4°$, $5 - \theta = 25°$, $6 - \theta = 15°$, $7 - \theta = 5°$.

UHC curves have a single maximum each the value of which is increasing and its position h_{max} is decreasing with an increase of the angle θ. The part of higher sensitivity of the curve is before reaching the maximum and of lower sensitivity after it. As shown by the experimental results, the part of higher sensitivity of the curve is decreasing with an increase of the angle between the FAT axes and it vanishes at the angle θ larger than $40°$, therefore we have the experimental points of decreasing values that depend on h.

As seen from Fig. 3, the modeling curves are well congruent with the experimental results. Therefore we can establish the regularities of dependence of the UHC on the angle θ by means of simulation.

In the modeling curves the part of higher sensitivity of a curve vanishes at shorter distances h. This is conditioned by the fact that in modelling the light out of emitting fiber is assumed to be propagated as out of a point source, the position of which is coincident with the intersection point of the fiber axis and the tip plane. This point (Fig. 1b) is as far from the mirror plane as the distance $h - 2a\sin\theta$. Only the first point of experimental curves can be measured via such a distance. Therefore the first point of experimental curves is a distant as $h'_0 = a\sin\theta$ that is a distance when the mirror touches the fiber tips (Fig. 1b). This fact is defined by observing via microscope. The main parameters of UHC are presented in Figs. 4, 6, 7 and 8.

The principal parameter of RFP U-h characteristics that determines metrological abilities of displacement sensors is sensitivity to displacement S_{max} (Fig. 6). In addition, (Fig. 8) illustrates variation of the dependence of the inflection point $(-)$ position h_- (curve 1), peak position h_p (curve 2), inflection point $(+)$ position h_+ (curve 3), peak signal value U_p (curve 4), values U_- of the inflection point $(-)$ (curve 5) and that of inflection point $(+)$ (curve 6) on θ. The length of interval Δh in which the output signals $U(h)$ are linear (98 % of sensitivity maxima), and their dependence on the angle θ are demonstrated in Fig. 7. RFP sensitivity S_{max} dependence on the distance h is shown in Fig. 4. As illustrated by calculation results, RFP U-h characteristics have higher positive sensitivity peak S_{max+} and a lower negative sensitivity peak S_{max-}. The positions of sensitivity peaks are congruent with the inflection points h_+ and h_- of UHC. At these points there is the highest measurement sensitivity and the percentage interval of linearity.

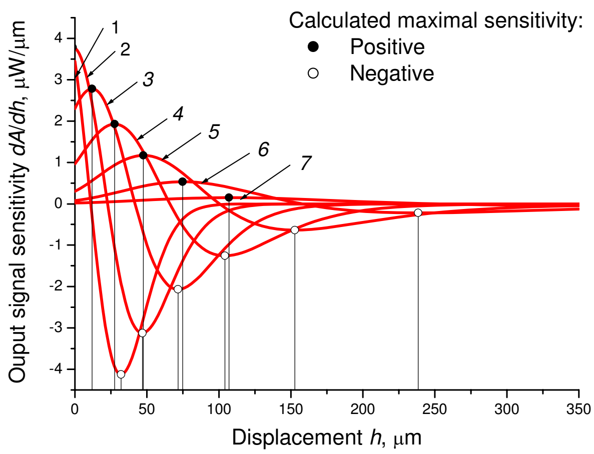

Fig. 4. Calculated sensitivity and maximal sensitivity values of the fiber optic sensor: 1 – $\theta = 65°$, 2 – $\theta = 55°$, 3 – $\theta = 44°$, 4 – $\theta = 34.4°$, 5 – $\theta = 25°$, 6 – $\theta = 15°$, 7 – $\theta = 5°$.

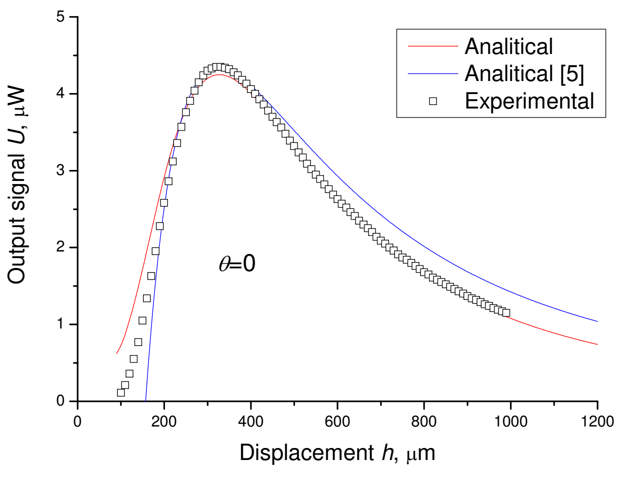

Fig. 5. Experimental values of the output signal ($\theta = 0°$) and that calculated by the authors, and by [9] in receiving fiber **A**.

Fig. 7 illustrates that the linearity interval is increasing with a decrease of the angle θ between the FAT axes, while the sensitivity S_{max} diminishing. It has been established that RFP sensitivity is increasing almost exponentially from $0°$ to $40°$ with an increase of the angle θ (Fig. 6). The negative RFP sensitivity is equal to $S = 0.149$ μW/μm as $\theta = 5°$, and to $S = 0.750$ μW/μm as $\theta = 25°$, i.e., the sensitivity increases 5 times. The positive RFP sensitivity increases from 0.046 μW/μm to 1.200 μW/μm, i.e., almost

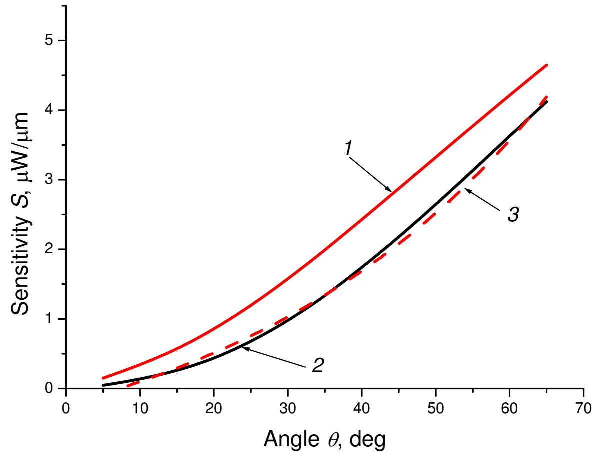

Fig. 6. Dependence of sensitivity on the angle θ. 1 – positive part of sensitivity curve; 2 – negative part of sensitivity curve; 3 – exponential approximation: $1.24\exp\{0.023\theta\} - 1.47$.

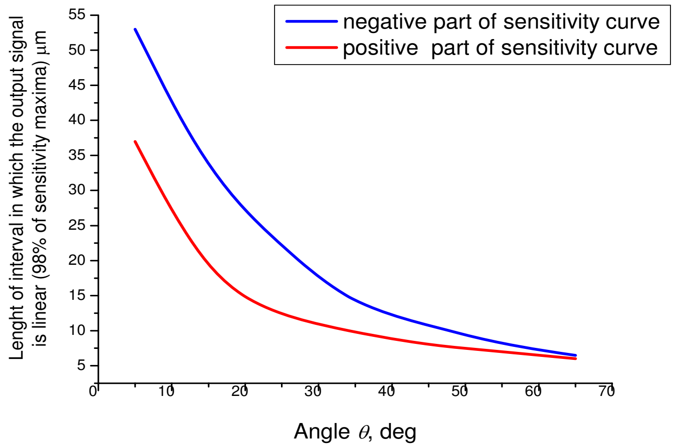

Fig. 7. Length of the interval in which the output signal $U(h)$ is linear (98 % of sensitivity maxima).

30 times. These results show evidently why those RFP, the FAT axes of which form an angle up to $25°$, are used for measurements though in this case, the size of the measuring head increases. There is no sense to increase angle θ any more, because light losses grow considerably due to a diminishing fiber inflection radius [12] r_f (Fig. 1)

$$r_f = \left(\frac{r_s - \delta \tan\theta}{\sin\theta}\right) \cot\left(\frac{\theta}{2}\right), \tag{5}$$

where δ is the height of the straight part of fiber that is determined by the way of mounting (Fig. 1a, quantities δ_1 and δ_2), and r_s is the measuring head radius of a sensor.

The work [9] presents the calculation of the RFP output signal when the angle between FAT axes is equal to zero. The exponential part of formula (1) is approximated by parabola in this work. In order to corroborate the adequacy of model (1) used, comparisons of the experimental and calculation results are presented in Fig. 5.

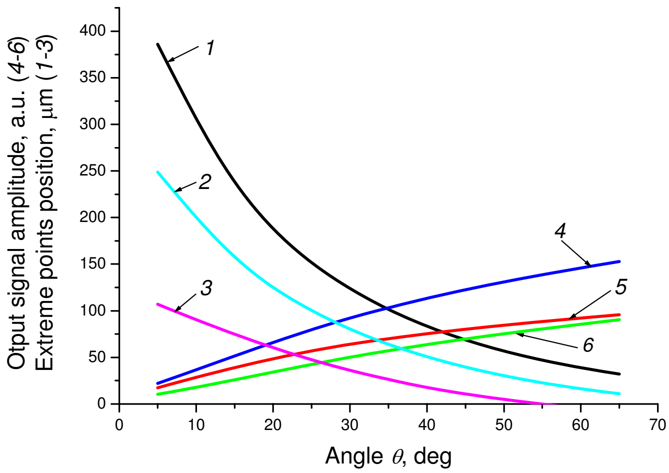

Fig. 8. Dependences of the main parameters of U-h characteristics on the angle θ: 1 – inflection point $(-)$ position h_-; 2 – peak position h_p; 3 – inflection point $(+)$ position h_+; 4 – values of the signal peak U_p; 5 – values of the inflection point $(-)$ signal U_-; 6 – values of the inflection point $(+)$ signal U_+.

4 Conclusions

Regularities of the signal $U(h)$ of the one reflection fiber optopair on the distance h to the light reflecting body-mirror (U-h characteristics) an on the angle θ between fiber tip axes were investigated by means of modeling and experiments. We have established that the parameters of U-h characteristics such as positions of inflection points and that of peak on h are varying exponentially.

Experimental and modeling results are well congruent. It has been shown that the experimental research results are well expressed by the above formulas improved by us [3].

We have proved that sensitivity of a fiber pair to displacement S_{max} increases with increase of the angle θ. The sensitivity S_{max} is lowest when fiber active tips axes are parallel ($\theta = 0°$). The sensitivity S_{max} of a fiber optopair, the diameter of the fiber core of which is 100 μm (with cladding 125 μm), increases about 30 times after an increase of the angle θ up to $30°$, moreover, is increasing almost exponentially. The position h_p of the U-h characteristics peak and that of inflection points h_+, h_-, as well as the linearity interval are exponentially decreasing with an increase of the angle θ.

The drawback of such a fiber optopair is the fact that with an increase of the angle θ, the size of the sensor head also increases. However, due to their higher sensitivity, they can be and are wide used.

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