Acousto-optical method for measuring the displacements of a laser beam in two directions orthogonal to its axis

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Abstract. The issues of improving the method for controlling the two-coordinate displacements $\Delta l_y$ and $\Delta l_z$ of a laser beam in the OY and OZ directions orthogonal to its OX axis are considered. It is proposed to use a fiber photodetector with a micro-optical lens at the input of the light guide to register the interference picture produced in the Fresnel zone by the first and zero diffraction orders formed by an acousto-optical (AO) modulator.

In the method, it is proposed to use a prismatic optical scheme placed in front of a single-axis AO modulator for a laser beam displaced $\Delta l_y$ and $\Delta l_z$ along two axes OY and OZ, forming two output beams. For the first beam, displacements along the OY axis are excluded: $\Delta l_y$-var, $\Delta l_z$=0, and the second beam is rotated relative to the first beam by 90° around the OX axis (i.e., $\Delta l_y$$\rightarrow$$\Delta l_z$) with the same exception of displacements along the OY axis with the achievement of the following: $\Delta l_y$=0, $\Delta l_z$-var. This technique allows you to use a single-axis (1D) AO modulator to control the two-coordinate (2D) displacements $\Delta l_y$, $\Delta l_z$ of the initial laser beam. We also discuss the implementation of a differential measurement method by using two phase measuring devices: an interpolator and a phase meter, and the effect of signal noise on the resolution.

1. Introduction
The production of high-precision products of rocket and space technology, aviation, ship, machine, instrument and machine tool construction and other industries can be provided by the use of high-precision control of object movements, in particular, acousto-optical (AO) laser measuring systems (LMS). The measurement of laser beam displacements in the directions orthogonal to its axis (for future - lateral displacements) is a local and very difficult problem, especially when striving for equal resolution of $l_{rx}$, $l_{ry}$, and $l_{rz}$ in three directions, along the OX, OY, and OZ axes [1,2]:

$$l_{rx}$$≈$$l_{ry}$$≈ $$l_{rz}$$.

The necessity for its solution arises for providing high-precision control of deviations from the straightness [3-14] of product surfaces, during the movement of working bodies of technological equipment, displacements of the scanning laser beam in the hybrid head [15] and other tasks.

To solve such problems, you can use two single-axis (1D) AO modulators located perpendicular to each other according to the sequential diffraction scheme (figure 1a) with the formation of a set of symmetric diffraction orders (figure 1b) [3].

We have already discussed the construction issues high-precision AO LMS for 3D measurements based on the use of a single-aperture two-axis (2D) L-shaped liquid AO modulator (figure 1c,d), which forms a two-coordinate region of the so-called "cell" with perpendicular moving ultrasonic waves [3]. The resolution of $l_{y}=l_{z}$$\approx$$\Lambda_{us}$/1214 was achieved, where $\Lambda_{us}$ is the length of the ultrasonic wave (for water, $\Lambda$$\approx$200 $\mu$m, and...
l_{y_1}≈l_{z_2}=0.16 \mu m), but this result does not allow us to fulfill condition (1): since l_{y_1}≈l_{z_2}=\Lambda_u/1214>>l_{rz}≈\lambda/1000 [16-19]... \chi/3000 [20], and the ratio \Lambda_u/\lambda can be from ≈10 to ≈350 for different AO modulators [1].

Now scientific works [1,2] are the basis for creating AO LMS three-coordinate (3D) measurement with condition (1) by using the phase-locked loop (PLL) system. For this purpose, it was supposed to use the above-described single-aperture two-axis (2D) L-shaped liquid AO modulators, but their production in solid-state or planar design is problematic. Therefore, the issue of developing the AO LMS lateral displacements of the laser beam along the two axes OY and OZ (2D) using single-axis (1D) AO modulators is still relevant.

![Figure 1. AO modulators for measuring lateral displacements of the laser beam: sequential diffraction scheme with two orthogonally positioned AO modulators (a) and its diffraction spectrum (b), L-shaped liquid AO modulator forming orthogonally moving ultrasonic waves: sketch (c) and its photo (d).](image)

**2. Formulation of the problem**
In accord with above, the objectives of this work are to develop and study a high-precision AO LMS lateral displacements of the laser beam along the two axes OY and OZ (2D) using a single-axis (1D) AO modulator.

**3. Theory**
This part discusses the design, operating principle, and relationships of parameters developed by AO LMS for high-precision measurements of lateral displacements of a laser beam using a single-axis (1D) two-aperture AO modulator.

**3.1. Design and principle of operation of AO LMS lateral displacement**
The developed AO LMS of transverse displacements (figure 2) consist of three main ideas:
1) convert the two-axis displacement (2D) \Delta l_y and \Delta l_z in the plane YOZ of the input laser beam in single-axis displacement along the axes OY and OZ forming two output laser beams by introducing a prismatic optical system (in future - the optical system) before the AO modulator and measuring the displacements of the two beams single-axis (1D) AO modulator with two apertures;
2) using the first \text{E}_1 and zero \text{E}_0 diffraction orders in the near diffraction zone (Fresnel zone) after AO modulation and registering the resulting interference pattern by a sequentially located raster and a fiber photodetector (FPD) with a micro-optical lens at the input of the light guide;
3) implementation of a differential measurement method by using two phase measuring devices that work together: an interpolator and a phase meter for "fast inaccurate" and "slow accurate" measurements.

The optical system 1 (figure 2a) forms from one input beam 2, which has two-coordinate displacements \Delta l_y and \Delta l_z in the YOZ plane, two output optical streams 3 and 4, displaced only along the OY axis:
\[ \Delta l_y = \Delta l'_y, \Delta l'_y = \Delta l''_y. \] The optical stream 3 is used to measure the displacements \( \Delta l_y \) along the OY axis of the input optical flow (displacements \( \Delta l_z \) along the OZ axis are excluded):

\[
\begin{align*}
\Delta l_y &= \Delta l'_y, \\
\Delta l'_y &= \Delta l''_y.
\end{align*}
\] (2)

and for the second, a 90° rotation is performed - to measure the offsets \( \Delta l_z \) along the OZ axis of the input optical flow (displacements \( \Delta l_y \) along the OY axis are excluded):

\[
\begin{align*}
\Delta l_z &= 0, \\
\Delta l'_z &= \Delta l''_z.
\end{align*}
\] (3)

The first and second laser beams 3 and 4 pass through the AO modulator 5 excited by the generator 6 with the appearance of two pairs of optical streams at its output in the Bragg diffraction mode, each of which consists of the first \( E_1 \) and zero \( E_0 \) diffraction orders. In future the description is compiled for the first channel with using of numbering for the second channel in parentheses. The first \( E_1 \) diffraction order is deflected along the OY axis by a double Bragg angle \( \alpha_{br} \) [21] and until it goes beyond the zero \( E_0 \) diffraction order, i.e. in the near diffraction zone (Fresnel zone), it interferes with it to form a running interference pattern with an interval \( \Lambda_{ip} \). The running interference pattern illuminates the raster 7 (8) with the interval \( \Lambda_{r} \) with the formation of running combination lines with the step \( \Lambda_{cl} \) and is recorded in the FPD 9 (13), consisting of a series of connected input microlens 10 (14), a light guide 11 (15) and a photodetector 12 (16). The optical fiber allows remove the photodetector 12 (16) from the measuring circuit, due to its small diameter (200-500 μm), its end acts as a diaphragm when registering an interference pattern in the near Fresnel zone. And the input microlens 10 (14) facilitates the introduction of optical beams into the light guide, reducing the requirements for angular adjustments. So, this makes it possible to simplify the optical scheme of AO LMS lateral displacement.

The photodetector 12 (16) converts interfering optical fluxes into an output electrical signal at a difference frequency (taking into account the Doppler frequency shift \( f_{dop} \) from beam displacements). It is fed to the input of the measuring circuit 17 (18), namely the input of the series-connected system PLL (figure 2b) allows to weaken the noise in the signal and then to the entrance phase measurement unit 22, consisting of phase interpolator (in future - the interpolator) 23 and high-precision phase meter (in future – phase meter) 24.

In addition, the generator 6 creates two reference antiphase signals following to the phase measurement unit 22, the first of which is also used to excite the AO modulator 5. The PLL system circuit is classical, consisting of a phase detector 19, a low-pass filter 20, and a voltage-controlled generator 21.

Displacements of the two laser beams lead to corresponding displacements of the traveling interference patterns past the fiber, leading to registration and measurements by both channels of two phase shifts and displacements \( \Delta l'_y \) and \( \Delta l''_y \), by which the corresponding two-coordinate displacements \( \Delta l_y \) and \( \Delta l_z \) in the YOZ plane are judged.

The differential measurement method for both channels of the AO LMS is described in detail in [22]. It consists in the implementation by the interpolator 23 and the phase meter 24 “fast inaccurate” and “slow accurate” measurements of lateral displacements in large and small ranges, respectively. And the part of the digital code \( \Delta N_{int} \) the interpolator 23 measured for “fast inaccurate” measurements corresponding to the fractional part of the movements, i.e. a small range, is fed to the input of the phase meter 24 for “slow accurate” measurements.

Now the schemes of the interpolator 23 have been sufficiently developed [23,24] and the phase meter 24 can be implemented on the basis of digital signal processing [25-27] too.
3.2. The definition of the interval raster

In accordance with the above description of the design, the AO LMS lateral displacements uses a raster 7 (8) with an interval $\Lambda_r$. And it makes it possible to switch from registering an interference pattern with a small interval $\Lambda_{ip}$ to registering combination lines with a big interval $\Lambda_{cl}$ formed by their spatial combination. The $\Lambda_{cl}$ value increases according to the expression:

$$\Lambda_{cl} = \Lambda_{ip} \cdot \frac{\Lambda_r}{\Lambda_{ip} - \Lambda_r}$$

(4)

For a stable photodetection the condition is met usually: $d_{ml} \leq \Lambda_{cl}/6$... , taking into account which the raster interval $\Lambda_r$ is determined by the formula (for the worst case, when $d_{ml} \leq \Lambda_{cl}/6$):

$$\Lambda_r = \frac{6d_{ml} \cdot \Lambda_{ip}}{d_{ml} - \Lambda_{ip}}$$

(5)

When $d_{ml} = 0.3$ mm and $\Lambda_{ip} = 15.4$ μm, the raster interval $\Lambda_r$ should be $\Lambda_r \approx 15.5$ μm, being a well-executed value.

3.3. The parameters of the diffraction orders in AO modulation

In accordance with the ratio of the diameters $d_0$ and $d_1$ of the zero $E_0$ and first $E_1$ diffraction orders (figure 3a), we can write $d_0 = d_1 + 2\Delta d_{tp}$, respectively. Also, taking into account the deviation of the first $E_1$ diffraction order, we can write and, accordingly, get $d_0 = d_1 + L_{aom} \cdot \tan \alpha_{br}$. And then the expression for the ratio of the intensities of diffraction orders can be written as the formula:

$$\eta = \frac{I_1}{I_1 + I_0} = \frac{S_1}{S_1 + S_0} = \frac{d_1^2}{d_1^2 + d_0^2} = \frac{d_1^2}{d_1^2 + (d_1 + L_{aom} \cdot \tan \alpha_{br})^2},$$

(6)

where $I_0$, $I_1$, $S_0$, $S_1$ are the intensity, area, and diameter of the zero $E_0$ and first $E_1$ diffraction orders.

For ray dilution (double Bragg angle) $\alpha_{br} = 2.17^\circ$ [17-19] and $L_{aom}=20$ mm we have $L_{aom} \cdot \tan \alpha_{br}=0.76 \cdot 10^{-3}$ m, allowing you to plot the dependence of (6) on $d_1$. As can be seen, it asymptotically tends to 0.5 when $d_1$ changes from 0.5 to 3 mm (figure 3b).
3.4. The range of measurement

The measurement range $L_{\text{meas}}$ depends on the diameters of the microlens $d_{\text{ml}}$ and interference pattern $d_{\text{ip}}=d_1$ depending on the size of the first diffraction order $E_1$ (figure 4):

$$L_{\text{meas}} = d_{\text{ip}} - d_{\text{ml}}.$$  \hspace{1cm} (7)

The maximum value of $L_{\text{meas}}$ has no fundamental design limitations and when $d_{\text{ml}}=0.3 \text{ mm}$ and $d_{\text{ip}}=2 \text{ mm}$, it is equal to 1.7 mm. And for this data we can get almost $\approx 110$ spatial periods can be met (for $L_{\text{aom}}=15.4 \mu\text{m}$), i.e. the total phase shift reaches $\approx 220\pi$ rad, which significantly exceeds the technical characteristics of AO LMS lateral displacements described in [3].

When we use a round interference pattern for illuminate the round input microlens of the FPD light guide, only its central working part, which is close to the elliptical shape, is used (in figure 4 highlighted with broken lines). And the efficiency of using the interference pattern $G$ in this case can be estimated as the ratio of the area of such an ellipse $S_{\text{el}}$ associated with the radius of the microlens $r_{\text{ml}}$ to the area of the round interference pattern $S_{\text{ip}}$:

$$G = \frac{S_{\text{el}}}{S_{\text{ip}}} = \frac{\pi r_{\text{ml}}^2}{\pi r_1^2} = \frac{r_{\text{ml}}^2}{r_1^2}. \hspace{1cm} (8)$$

And for $d_{\text{ml}}=0.3 \text{ mm}$ and $d_1=2 \text{ mm}$, we have $G=0.15$ or just 15%. So the improvement of AO LMS should be aimed at a significant increase in the value of $G$.

**Figure 3.** Geometric model of diffracted beam propagation $E_1$ (a), intensity ratio $\eta$ of the diffraction order $E_1$.

**Figure 4.** Displacement of the interference pattern within the measurement range $L_{\text{meas}}$ formed by the optical fluxes $E_0$ and $E_1$ relative to the microlens of the light guide (the part of the interference pattern used is highlighted with a gray background with a dotted contour).
3.5. Analysis of the measurement error of AO LMS lateral displacements

The accuracy of measurements in the LMS lateral displacements is determined by four blocks: FPD, PLL system, interpolator and phase meter and its different combinations affect the measurement error when implementing two modes of operation "fast inaccurate" and "slow accurate" measurements.

The measurement error for "fast inaccurate" measurements is determined by the noise of the measurement signal $\Delta \phi_n$ from the FPD and attenuated by the PLL system, the intrinsic noise of the PLL system $\Delta \phi_{pll}$ and the quantization error of the interpolator $\Delta \phi_{int}$.

The measurement error for the "slow accurate" measurement also consists of three components: noise measurement signal $\Delta \phi_n$ made by FPD and attenuated by the PLL, the intrinsic noise of the PLL system of $\Delta \phi_{pll}$ and error phase meter $\Delta \phi_{phas}$. So, the noise’s error $\Delta \phi_n$ can be determinate by the expression [16]:

$$\Delta \phi_n = \frac{1}{\pi \sqrt{Q}}$$

(9)

where Q is the signal-to-noise ratio. In the late 80's last century, the level of Q≤600 was achievable [16], and now for modern photodetectors it can be than Q≈1000. Therefore the phase measurement error calculated by the formula (9) will be $\Delta \phi_n=0.01$ rad and the absolute error of displacement measurements determined by the next relation

$$\Delta l_n = \frac{\lambda_{632}}{8\pi} \Delta \phi_n$$

(10)

will be equal to $\Delta l_n = \frac{\lambda_{632}}{8\pi} \approx 25$ nm. The signal-to-noise ratio Q depends on the bandwidth $\Delta f_{bw}$ of the measuring circuit $Q = \frac{k_{pld}}{\Delta f_{bw}}$, which for different studies [16-19], taking into account the photodetecting coefficient of the photodetector $k_{pld}$, allows us to write

$$\Delta \phi_n = \frac{1}{\pi \sqrt{\frac{\Delta f_{bw}}{k_{pld}}}}$$

(11)

When using a PLL system, the above – defined value of $\Delta l_n=25$ nm corresponds to the bandwidth $\Delta f_{bw}$ determined by the cutoff frequency of the low-pass filter and associated with the maximum Doppler frequency range - $\Delta f_{dop}=30$ MHz. A decrease in $\Delta f_{bw}$ leads to a corresponding decrease $\Delta \phi_n$. Assuming that, provided that the PLL is stable, the $\Delta f_{bw}$ decreases up to 100 times - from 30 MHz to 300 kHz, then we get $\Delta \phi_n=0.001$ rad. Substituting expression (9) into formula (10):

$$\Delta l_n = \frac{\lambda_{632}}{2\pi^2} \sqrt{\frac{\Delta f_{bw}}{k_{pld}}}$$

(12)

The graph of the $\Delta \phi_n$ dependence on the change in the bandwidth $\Delta f_{bw}$ in the range from 100 kHz to 1 MHz is shown in figure 5 and is almost linear.
The intrinsic noise of a PLL system consists of the noise of its main elements: a voltage-controlled generator and a phase detector. Now, for modern electronics we can to ignore the noise of modern phase detectors. The noise of a voltage-controlled generator is manifested in jitter, i.e. in the uncertainty of the signal front $\Delta t_{jit}$ in the time scale (in fractions of seconds), which is associated with the spectral power density of the noise $S_{\phi}(f) = \sum \Delta_f f^{1}$.

$$\Delta t_{jit} = \frac{1}{2\pi} \sqrt{\int S_{\phi}(f) df}.$$  \hfill (13)

determining the corresponding component of the measurement error from the phase shift

$$\Delta \phi_{jit} = 2\pi f \cdot \Delta t_{jit}.$$  \hfill (14)

and by movement

$$\Delta \phi_{jit} = \frac{\Lambda_{jit} \cdot \Delta \phi_{jit}}{2\pi},$$  \hfill (15)

For different voltage-controlled generators, the we can have $\Delta t_{jit} \approx 1$ ps [28] and then when using a solid-state AO modulator based on paratellurite with $f_{\text{com}}=40$ MHz [19] and assuming that the Doppler frequency range $f_{\text{dop}}<<f_{\text{com}}$, we get $\Delta \phi_{jit}=0.25\cdot10^{-3}$ rad and $\Delta \phi_{jit}=\frac{\Lambda_{jit}}{25\cdot10^{-3}}$ respectively.

The measurement error caused by quantization introduced by the interpolator $\Delta \phi_{int}$ is determined by the expression:

$$\Delta \phi_{int} = \frac{2\pi}{k_{int}} = \frac{2\pi}{2^n},$$  \hfill (16)

where $k_{int} = 2^n$, and $k_{int}$ and $N_{int}$ are the number of quanta (discrete) and the bit depth of the interpolator. For $k_{int}=5$, as in [23,24], we get $\Delta \phi_{int}=2\pi/32=0.2$ rad and $\Delta \phi_{int}=0.48$ mm, respectively.

Assuming that the error $\Delta \phi_n$, $\Delta \phi_{jit}$ и $\Delta \phi_{int}$ independent from each other and have normal distribution, it is possible with their geometric addition to error AO LMS lateral displacement $\Delta \phi_n$ for "fast inaccurate" measurements $\Delta \phi_n = \sqrt{\Delta \phi^2 + \Delta \phi_{jit}^2 + \Delta \phi_{int}^2} = \sqrt{(10^{-3})^2 + (0.25\cdot10^{-3})^2 + 0.2^2} \approx 0.2$ rad. Using this value to determine the absolute measurement error according to the formula (15), we finally get $\Delta 1_n = 0.5 \mu$m.

The measurement error analysis for "slow accurate" measurements is as follows. This mode of operation is characterized by a significant decrease in the speed of controlled object movements, as well as a
corresponding decrease in the Doppler frequency range. For calculations taking into account such a narrow "frequency" approach, we can use the above example, in which, provided that the PLL is stable, the $\Delta f_{bw}$ decreases by a factor of 100 from 30 MHz to 300 kHz, the phase measurement error will be $\Delta \phi_n = 0.001$ rad.

The measurement error of the PLL $\Delta \phi_{pll}$ due to the intrinsic noise of its elements has already been determined above and is $\Delta \phi_{pll} = 0.25 \cdot 10^{-3}$ rad, and this value does not change for this operating mode. For a phase meter, the measurement error due to intrinsic noise is at the level of $\Delta \phi_{phas} = 2 \pi \cdot 10^{-7}$ rad [25].

Also, as before, assuming that the errors of $\Delta \phi_n$, $\Delta \phi_{pll}$ and $\Delta \phi_{phas}$ are independent with a normal distribution law, it is possible to obtain the error of AO LMS of lateral displacements for "slow accurate" measurements when adding them geometrically:

$$\Delta \phi_{sa} = \sqrt{\Delta \phi_n^2 + \Delta \phi_{pll}^2 + \Delta \phi_{phas}^2} = \sqrt{(10^{-5})^2 + (0.25 \cdot 10^{-3})^2 + (6.28 \cdot 10^{-7})^2} \approx 0.001 \text{ rad}.$$ Then the absolute measurement error $\Delta l_{sa}$ by the formula (15) is obtained:

$$\Delta l_{sa} = \frac{\Lambda_{aim} \cdot 0.001}{6.283} = \frac{\Lambda_{aim}}{6283} \approx 2.4 \text{ nm}.$$ Thus, the measurement errors for the stages of "fast inaccurate" and "slow accurate" measurements are $\Delta l_{fi}=0.5 \mu m$ and $\Delta l_{sa}=2.4 \text{ nm}$, respectively, differing by almost 200 times.

4. Experimental result

To clarify the optical parameters, we used the results of experimental studies in various areas related to individual blocks or issues of the work of the developed AO LMS lateral displacement.

4.1. Using the interference pattern of diffraction orders in the Fresnel zone, registering it using the FPD.

In [29], the possibility of using the Fresnel zone of the first $E_1$ and zero $E_0$ diffraction orders after AO modulation and photodetecting the interference pattern was experimentally confirmed. The equality of the period of ultrasonic waves in the AO modulator $\Lambda_{aim}$ and the period of the interference pattern $\Lambda_{ip}$ is shown:

$$\Lambda_{aim} = \Lambda_{ip}.$$ In [30], the use of two diffraction orders in the Fresnel zone after the AO modulation for recording the shifted interference pattern is considered using the example of the AO LMS for controlling the position of the product boundary.

4.2. Optical matching of optical flows after AO modulation and FPD

The study of the efficiency $W$ of introducing a divergent optical flow into an optical fiber with a core diameter of 62.5 μm with a flat end $W_e$ and an input hemispherical microlens $W_{ml}$ (figure 6a) is considered in [31,32] on the example of using a radiation source of a semiconductor laser diode LED LASER HLDP-650-A-5-02 ($\lambda=0.65 \mu m$) with a rectangle radiating area with dimensions of 1×6 μm (figure 6b). It is shown that the dependence of $W_e$ on the gap is close to a linearly decreasing dependence, and the dependence of $W_{ml}$ is nonlinear, exceeding the values of $W_e$ in the section [0; l_1] and reaching level 1, i.e. 100% at the $l_1$ coordinate (figure 6c). Thus, the use of microlens increases the efficiency of the process of introducing a divergent optical flow into the optical fiber up to 25-35% with the optimal selection of all parameters of the optical connection.

To find the required diameter of the microlens $d_{mle}$ optical fiber, the relationship between the ratio of the microlens diameter $d_{ml}$ to the diameter of the fiber $d_f$ for a spherical microlens (figure 6d) $d_{ml} / d_f$ with the numerical aperture NA (figure 6e) [31] transmitting a divergent optical flow for a quartz-polymer fiber with a core diameter of 400 μm is determined. As can be seen, for next condition $d_{ml} / d_f \leq 1.05$ [32] we get $\text{NA} \leq 0.35$ with the angle of entry of rays into the light guide in the range of $\alpha_t \leq 20^\circ$, reducing the requirements for angular alignment of the light guide relative to optical flows.
5. The discussion of the results
1. When we use an AO modulator based on para tellurite (TeO₂) the interval of the interference pattern can be just \( \Lambda_{ip} = 15.4 \mu m \). And introduction a raster with an interval of \( \approx 15.5 \mu m \) allows you to increase the step of the combination lines \( \Lambda_{cl} \) to \( \approx 2.3 mm \), providing reliable photo detection for the input microlens of the VFU with a diameter of \( d_{ml} = 0.3 mm \).

2. The measurement range is \( L_{meas} = 1.7 mm \) for diameters of the VFU’s input microlens and the first diffraction order \( E_1 \), respectively, \( d_{ml} = 0.3 mm \) and \( d_1 = 2 mm \). So we can get the total phase run of \( \Delta \Psi_c = 220\pi \) rad for the interference pattern \( \Lambda_{ip} = 15.4 \mu m \), but the efficiency of using optical streams of circular cross-section does not exceed \( G = 0.15 \) or just 15%.

3. Due to the use in the Fresnel zone of the first and zero diffraction orders with the use of solid-state AO modulator based on para tellurite (TeO₂) with \( v_{sys} = 616 m/s \) and \( f_{sys} = 40 MHz \) with dual Bragg angle=2,17° the ratio of intensities of the first diffraction order to the input optical flow \( \frac{I_1}{I_0} \) tends to \( \approx 0.5 \).

4. Measurement errors for the steps of "fast inaccurate" and "slow accurate" measurement is \( \Delta l_{fi} = 0.5 \mu m \) and \( \Delta l_{sa} = 2.4 nm \), respectively, differing by almost 200 times.

5. The using of the input microlens can increase the efficiency of the introducing a divergent optical flow into the optical fiber by 25-35% with the optimal selection of all parameters of the optical connection. And the ratio of the microlens diameter \( d_{ml} \) to the fiber diameter \( d_f \) should be \( d_{ml}/d_f \leq 1.05 \), providing \( NA \leq 0.35 \) with the angle of entry of rays into the fiber in the range of \( \leq 20^\circ \) and reducing the requirements for angular alignment of the fiber relative to optical flows.
6. Conclusion

1. The converting two-coordinate displacements (2D) Δl_y and Δl_z in the YOZ plane of the laser beam into single-coordinate (1D) displacements of two laser beams along the axe OY allows you to use a single-axis (1D) AO modulator with two apertures to measure these displacements by introducing a prismatic optical system in front of the AO modulator.

2. The construction of the AO LMS lateral displacements by using the first and zero diffraction orders in the Fresnel zone and registering the resulting interference pattern with a fiber photodetector with a micro-optical lens at the input of the light guide makes it possible to simplify its optical scheme, reducing the requirements for angular adjustments.

3. The implementation of the differential measurement method by using two phase measuring devices: an interpolator and a phase meter for “fast inaccurate” and “slow accurate” measurements allows to increase the resolution of the AO LMS the lateral displacements of the laser beam.

4. An increase in the resolution is possible by reducing the bandwidth Δf_{bw} of the PLL system used.

5. The improvement of the AO LMS lateral displacements also involves further research in the following areas:
   – the features to create AO LMS lateral displacements of the laser beam along the two axes (2D) OY and OZ based on a single-aperture single-axis (1D) AO modulator, including in the Raman-Nat diffraction;
   – the ability to create a AO LMS for controlling three-coordinate (3D) displacements using a single-axis (1D) single-aperture AO modulator;
   – the increasing the efficiency of using the optical flow due to the formation of an elliptical interference pattern.

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