Features of an acousto-optical two-channel laser displacement interferometer with multi-frequency photodetectors with subpycometer resolution

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Abstract. The article discusses the issues of improving acousto-optical (AO) heterodyne laser displacement interferometers (LDI) by using two independent multi-frequency photodetectors: high-frequency (HF) and low-frequency (LF) low-noise, working with "fast inaccurate" and "slow accurate" measuring channels, respectively. The "fast inaccurate" channel allows you to measure displacements with high velocity movements. The scheme of the "slow accurate" channel is based on the joint operation of a phase-locked frequency system and a small-range phase meter, providing high resolution for low velocity. Such a scheme of AO LDI most fully implements its capabilities in the control of start-stop cyclic movements of objects, providing high resolution at the initial and final stages of movements with low velocity. A metrological analysis of the "slow accurate" channel is carried out, the possibilities and conditions for achieving AO LDI at low velocity of subpicometer resolution are shown.

1. Introduction

Currently, laser displacement interferometers (LDI) are actively used for high-precision control of product displacements [1-10]. The current trend of their improvement is to increase the resolution to the level of subpicometric values, less than 1 pm [7-9]. LDI with acousto-optic (AO) modulation of the optical flow can be considered one of the most promising [11-20]. To increase the resolution of AO LDI, it was proposed to use two measuring channels (in future - channel) with the same stages for measuring cyclic start-stop movements: "fast inaccurate" and "slow accurate". The "fast inaccurate" channel can be based on the use of a phase interpolator, and the "slow accurate" one can be based on a phase-locked loop (PLL) with a small-range phase meter (in future - a phase meter). The "slow precise" channel allows for low velocity of movement to narrow the spectrum of input noise, most of which is formed, as a rule, by a photodetector, thereby increasing the resolution of AO LDI.

When using one common photodetector for both channels, they strive to increase its maximum frequency of the optical signal, which allows to increase the associated maximum of movement velocity. However, this leads to a significant and disproportionate increase in the noise level of the photodetector, which limits the resolution of the AO LDI. Therefore, an attempt to increase the resolution of AO LDI forces us to switch from one to two independent photodetectors used: high-frequency (HF) and low-noise low-frequency (LF) to work with "fast inaccurate" and "slow precise" channels, respectively.

For AO LDI with a similar structure, no metrological analysis has been carried out to understand the possibilities of achieving a subpicometric resolution of less than 1 pm. Existing publications in the open press do not disclose these issues and this article is aimed at filling this shortcoming.
2. Formulation of the problem
The main objective of this work is to study the developed AO LDI, which contains two channels for "fast inaccurate" and "slow accurate" measurements with two different multi-frequency photodetectors. The criterion for the successful operation of these developed AO LDI and the optimal ratio of the parameters of its component blocks is the achievement of a subpicometric resolution, i.e. less than 1 pm.

3. Theory
To study the features of AO LDI with two independent multi-frequency photodetectors in order to achieve subpicometric resolution, the issues of composition, features of the principle of operation and metrological analysis are further sequentially considered. Due to the fact that the metrological parameters of AO LDI are determined by the parameters of the "slow accurate" channel, its analysis will be given the main attention.

3.1. Structure and principle of operation of linden trees with two different frequency photodetectors.
One of the variants of the AO LDI according to the scheme with the AO modulator "at the input" with the mode of light diffraction in the Bragg mode is shown in figure 1. It shows: laser 1, AO modulator 2, optical circuit 3, movable trippel prism 4, two micro lenses 5 and 6 for two Y-shaped fiber-optic (FO) splitters 7 and 8, HF photodetector 9, LF photodetector 10, phase interpolator (in future – interpolator) 11, PLL 12, adder 13, phase meter 14.

The PLL 12 is described in [18-20] and has a standard circuit in the form of a ring from a serial circuit of a phase detector (with an additional digital output N_{pd}), a low-pass filter, a voltage-controlled generator (VCG) based on a highly stable quartz oscillator, the frequency output signal of which is fed to the AO modulator 2. The cutoff frequency of the low-pass filter is controlled by a frequency detector depending on the Doppler frequency rise, the effect of which is discussed further (not shown in figure 1).

The photodetector 9, the interpolator 11 and the adder 13 form a "fast inaccurate" channel of AO LDI, and the photodetector 10, the PLL system 12 and the phase meter 14 are "slow accurate".

In the process of operation, laser radiation 1, following through the AO modulator 2, forms the first E(+1) and zero E(0) diffraction orders of different frequencies that pass through the optical system 3, are spatially separated in it and then follow the routes, respectively:
- movable trippel-prism 4 → microlens 5 (point A) → FO Y-shaped splitter 7 → RF photodetector 9 (point C) and LF photodetector 10 (point D);
- micro lens 6 (point B) → FO Y-shaped splitter 8 → RF photodetector 9 (point C) and LF photodetector 10 (point D).

At the optical inputs C and D of the HF photodetector 9 and the LF photodetector 10, the zero E(0) and first E(+1) diffraction optical fluxes interfere satisfactorily, and the electrical signals generated by them act on
the sequentially connected interpolator 11 with the synthesizer 13 and the PLL 12 with the phase meter 14. The detailed operation of the channel wallpaper is described in [18-20]. The possibility and conditions of using optical fibers in the lip, make it possible to make the scheme of AO LDI more compact.

With the training of two different frequency response photodetectors (figure 2a) the cycle of the cycle of movement of the controlled object [0; t_{meas}] (figure 2a) consists of low-velocity movements that do not exceed the specified level v_{1}: v \leq v_{1} at the stages of acceleration [0; t_{1}] and braking [t_{2}; t_{2}] and high-velocity movement [t_{2}; t_{2}] at v_{2} < v \leq v_{max}, where v_{max} is the maximum of movement velocity. The "slow accurate" channel is applied to the stage of low-velocity movements, and the dynamic capabilities of the "fast inaccurate" channel allow the use of the entire cyclamen in the liquid. The two-stage operation mode can be recorded conditionally using the Heaviside function \( I(t) \):

- for a "slow accurate" channel without learning the transient process (figure 2c):
  \[
P_{pll}(t) = I(t) - I(t-t_{1}) + I(t-t_{2}) - I(t-t_{meas})
  \]  

- for the "fast inaccurate" channel (figure 2d):
  \[
P_{inf}(t) = I(t)
  \]

3.2 Analysis of the operating modes of the LDI channels.

In accordance with the above description, the operation of the LDI with two multi-frequency photodetectors is based on the functioning of two channels: "fast inaccurate" and "slow accurate". The features of their work are discussed below. However, the main focus is on the metrological analysis of "slow accurate", in particular, considering the possibility of achieving its subpicometer resolution, i.e. less than 1 pm.

3.2.1 Analysis of the operation of the "fast inaccurate" channel.

The operation of the "fast inaccurate" channel is based on the operation of a phase interpolator and is carried out by calculating the fractions of the orders of interference with the resolution \( \Delta l_{fi} \) which is determined by the expression [18]:

\[
\Delta l_{fi} = \frac{\lambda}{2k_{int}} = \frac{\lambda}{2^{n+1}},
\]
where $k_{\text{int}} = 2^N_{\text{int}}$, $k_{\text{int}}$ and $N_{\text{int}}$ are the interpolation coefficient and the bit depth of the interpolator, where $\lambda$ is the laser wavelength. Thus, at $\Delta l_{\text{rel}} = \lambda/64 \approx 0.01 \, \mu m$, 16 measurement channels are used [21].

### 3.2.2. Analysis of the operation of the "slow accurate" channel.

The "slow accurate" channel is intended for measuring the phase shift with a high-precision phase meter 14 inside the interval $\Delta l_{\text{int}}$, "under-measured" by the "fast inaccurate" channel. The first input signal for the phase meter 14 is a digital code in the form of the lowest digits of the adder 13, and the second is an analog signal following from the output of the PLL system 12.

The use of the PLL system reduces the bandwidth of the passing signal generated by the photodetector, $\Delta f_{\text{ph}}$ to the value of the cutoff frequency of the low-pass filter of the PLL $\Delta f_{\text{pll}}$, determined by the Doppler run of the frequency $f_{\text{dop}}$, depending on the maximum of movement velocity $v_1$ of the object for "slow accurate" measurements. The use of the previously mentioned frequency detector in the PLL system to control the cutoff frequency of the low-pass filter can be considered the most promising, which makes it possible to form a proportional relationship between the $\Delta f_{\text{pll}}$ and $v_1$:

$$\Delta f_{\text{ph}} \approx \Delta f_{\text{pll}} = f_0 + k_{\text{pll}} f_{\text{dop}} = f_0 + k_{\text{pll}} \frac{2 \cdot v_1}{\lambda} ,$$  \hspace{1cm} (4)

where $k_{\text{pll}}$ is "frequency" coefficient, $f_0$ is initial frequency.

We can calculate the resolution of the "slow accurate" channel $\Delta l_{\text{sa}}$ by using the best values of the parameters of individual blocks, to understand the conditions for achieving subpicometric resolution.

So, the total phase error of the AO LDI $\Delta \phi_{\Sigma}$ is limited by three main components: the jitter - instability of the front of the signal $\Delta \phi_{\text{jit}}$, the error of the phase meter $\Delta \phi_{\text{phas}}$ and the introduced noise of the photodetector $\Delta \phi_{\text{ph}}$. It is also necessary to mention the noise of laser 1 and AO modulator 2, but we will consider their level negligible. Assuming their independent nature and the normal distribution law, the total phase error of the AO LDI $\Delta \phi_{\Sigma}$ can be calculated using the geometric addition formula:

$$\Delta \phi_{\Sigma} = \sqrt{\Delta \phi_{\text{jit}}^2 + \Delta \phi_{\text{phas}}^2 + \Delta \phi_{\text{ph}}^2} .$$  \hspace{1cm} (5)

Then the resolution of $\Delta l_{\text{sa}}$ is determined by the expression:

$$\Delta l_{\text{sa}} = \frac{\lambda \cdot \Delta \phi_{\Sigma}}{4\pi} ,$$  \hspace{1cm} (6)

which, taking into account the expression (5), is transformed to the following form:

$$\Delta l_{\text{sa}} = \frac{\lambda \cdot \Delta \phi_{\Sigma}}{4\pi} = \frac{\lambda \cdot \sqrt{\Delta \phi_{\text{jit}}^2 + \Delta \phi_{\text{phas}}^2 + \Delta \phi_{\text{ph}}^2}}{4\pi} .$$  \hspace{1cm} (7)

### 3.2.2.1 Phase error from the jitter of the PLL’s VCG.

The calculation of the phase error of the $\Delta \phi_{\text{jit}}$ caused by the VCG's jitter can be carried out using the formula [18]:

$$\Delta \phi_{\text{jit}} = 2\pi f \Delta t_{\text{jit}} .$$  \hspace{1cm} (8)

Now, the minimum value of the jitter in the best variants of the VCG [22-23] can be brought up to $0.1 \cdot 10^{-12}$ s. With such a jitter value for the frequency range from 10 MHz to 60 MHz, the phase error values from the jitter $\Delta \phi_{\text{jit}}$ are in the range from $6.28 \cdot 10^{-6}$ rad to $37.7 \cdot 10^{-6}$ rad.

### 3.2.2.2 Phase meter error.

To measure the phase difference in a small range, a precision high-frequency phase meter developed for measuring nanovibrations can be used as part of AO LDI. Its phase measurement error is mainly limited by its own noise and is $\Delta \phi_{\text{phas}} = 6.28 \cdot 10^{-7}$ rad [24-26].
3.2.3 Phase error due to photodetector noise.

Until relatively recently, 10-30 years ago, the noise of the photodetector was the most important limitation determining the resolution of AO LDI [15,16]. Progress in the construction of the schemes of AO LDI led to the understanding that the reduction of the influence of these noises can be implemented in two ways:

1) selection of photodetectors with an optimal ratio between the frequency of AO modulation $f_{\text{mod}}$ and the level of the photodetector's own noise, taking into account their significantly nonlinear increase from frequency;

2) noise suppression of the measuring signal due to the use of a PLL.

The possibilities of minimizing the phase error from the noise level of the AO LIP photodetector are discussed further.

3.2.3.1 Analysis of the photodetector's own noise of the "slow accurate" channel of AO LDI.

An expression is known for the phase error caused by the photodetector's own noise $\Delta \phi_{ph}$, based on the signal-to-noise ratio $Q$ and written by the formula [18-20]:

$$ \Delta \phi_{ph} = \frac{1}{\pi \sqrt{Q}}. \quad (9) $$

The components affecting the signal-to-noise ratio $Q$ were considered in [15,16] and it was shown that the equation for the signal-to-noise ratio can be written as a formula:

$$ Q = \frac{SP^2 \gamma^2 \gamma_{\text{coup}} \gamma_{\text{opt}} \gamma_{\text{meas}}}{4\Delta f \left[ qI_o \left( \gamma_{\text{op}} + \gamma_{\text{meas}} \right) + 2SP_{\text{NEP}} \right]}, \quad (10) $$

where $\gamma_{\text{coup}}$ is the coupling coefficient that takes into account the incomplete alignment of the fronts and the degree of overlap of the optical beams, $\gamma_{\text{op}}$ and $\gamma_{\text{meas}}$ are coefficients that take into account the effects of inconsistency in the size of the sensitive area of the photodetector and the beam diameter, possible vignetting and diffraction divergence of the beams, $P_0$ is the laser radiation power, $S$ is the photosensitivity of the photodetector, $P_{\text{NEP}}$ is the equivalent optical radiation power per unit frequency of the bandwidth, the dimension of $W/Hz^{1/2}$ (in future - noise level), $\Delta f$ is bandwidth, $q$ – electron charge, $1.6 \cdot 10^{-19}$ Coul.

The left polynomial of the denominator of expression (10), containing the coefficients of $\gamma_{\text{op}}$ and $\gamma_{\text{meas}}$, is associated with shot noise from the signal illumination of the photodetector. The right denominator polynomial in formula (10), containing the parameter, determines noise components such as shot noise from dark current, thermal noise, amplifier and filter noise, etc.

The $P_{\text{NEP}}$ parameter is a reference and, as a rule, is available for almost all photodetectors. The values of the $\gamma_{\text{op}}$ and $\gamma_{\text{meas}}$ coefficients, taking into account the effects of inconsistency between the size of the sensitive area of the photodetector and the beam diameter, possible vignetting and diffraction divergence of the beams, are individual for each optical scheme of the laser interferometer. It is difficult to estimate them in advance and for calculations it is more convenient to focus on the average values of $\gamma_{\text{op}}$ and $\gamma_{\text{meas}}$, assuming the following condition:

$$ qI_o \left( \gamma_{\text{op}} + \gamma_{\text{meas}} \right) = k_{\text{opt}} \cdot P_{\text{NEP}}^2, \quad (11) $$

Then from expression (10) we get

$$ Q = \frac{SP^2 \gamma^2 \gamma_{\text{coup}} \gamma_{\text{opt}} \gamma_{\text{meas}}}{4\Delta f \cdot P_{\text{NEP}}^2 \left( k_{\text{opt}} + 2S \right)} = \frac{k_{\text{adj}}}{4\Delta f \cdot P_{\text{NEP}}^2}, \quad (12) $$
where \( k_{ad} = \frac{SP^2 \gamma^2_{\text{opt}} \gamma_{\text{meas}}}{k_{\text{opt}} + 2S} \) is the adjustment coefficient of AO LDI.

As can be seen, the main parameters affecting the signal-to-noise ratio \( Q \) are the bandwidth of the photodetector \( \Delta f \) and its noise level \( P_{\text{NEP}} \).

\[
\Delta l_{sa} = \frac{\lambda \cdot \Delta \varphi}{4\pi} = \frac{\lambda}{4\pi \sqrt{Q}} = \frac{\lambda \cdot P_{\text{NEP}}}{2\pi} \sqrt{\frac{\Delta f}{k_{ad}}}.
\]  

(13)

3.2.3.2 Noise suppression of the photodetector by using the PLL.

The output noisy signal of the photodetector \( 10 \) in the "slow accurate" channel passing through the PLL \( 12 \) is cleared, filtered from most of the noise and follows the input of the phase meter \( 14 \).

For the research of AO LDI, we need to know the efficiency of using the PLL for filtering the noise of the photodetector. This can be estimated by the so-called coefficient of resolution increase from noise reduction \( k_n \) (in future - the noise reduction coefficient), which we will write in the following form:

\[
k_n = \frac{\Delta l_{sa1}}{\Delta l_{sa2}} = \frac{Q_1}{Q_2} \approx \frac{f_{\text{aom}}}{f_{\text{dop}}},
\]  

(14)

where \( \Delta l_{sa1} \) and \( \Delta l_{sa2} \) are the displacement error "slow accurate" channels determined by different signal-to-noise ratios after the photodetector and after the PLL.

On the basis of this formula, the values of \( k_n \) are calculated and depicted in figure 3 five dependences of the noise reduction coefficient of \( k_n \) on the Doppler raid of the frequency \( lgf_{\text{dop}} \) are constructed (for values of 10 Hz, 100 Hz, 1 kHz, 10 kHz, 100 kHz, 1 MHz, 10 MHz) for five frequencies of AO modulation \( f_{\text{aom}} \): 10 MHz, 14 MHz, 25 MHz, 45 MHz, 60 MHz.

![Figure 3](image)

**Figure 3.** The dependences of the noise reduction coefficient \( k_n \) on the Doppler frequency \( f_{\text{dop}} \) and the cutoff frequency of the low-pass filter of the PLL.

As can be seen from this figure, a noticeable increase in \( k_n \) begins at values of the Doppler frequency \( f_{\text{dop}} \leq 10 \) kHz, corresponding to the of movement velocity \( \approx 3 \) mm/s.
4. Experimental result

Reference data on the $P_{\text{NEP}}$ noise level are collected for the following photodetectors (at $\lambda=0.65$ microns): ACUBE-3000-10 (with the sign *) according to 2019 data from [27], Si-PIN photodiode OE-300-SI-30 according to 2019 data from [28] (with the sign **), PIN photodiode, according to 2011 data from [15,16] (with the sign ***). As can be seen, progress has been made in minimizing the noise level of $P_{\text{NEP}}$ photodetectors approaching the values of $3.8 \times 10^{-15}$ W/Hz$^{1/2}$ (for 10 MHz) and $1.5 \times 10^{-15}$ W/Hz$^{1/2}$ (for 25 MHz). However, all the collected data obtained at different times from different photodetectors and from different manufacturers contain unreliable incorrect data that could be missing when using photodetectors created at the same time in the same series from the same manufacturer. Therefore, for a more accurate metrological analysis, it is legitimate to slightly adjust the values of the $P_{\text{NEP}}$ noise level due to approximate linear interpolation in the frequency range between 10 MHz and 25 MHz for the value of 14 MHz, as well as 25 MHz and 60 MHz for the value of 45 MHz. As a result of simple calculations, we obtain two desired values of the $P_{\text{NEP}}$ noise level: $\approx 100 \times 10^{-15}$ W/Hz$^{1/2}$ (for $f_{\text{sam}}=14$ MHz) and $\approx 8.2 \times 10^{-12}$ W/Hz (for $f_{\text{sam}}=45$ MHz), forming adjusted $P_{\text{NEP}}$ noise level data (Table 1, line 2).

Taking into account the above, the values of the total phase error $\Delta \varphi_{2}$ and the resolution of the "slow accurate" $A\Delta\varphi$ channel are calculated. The calculation results are presented in the form of dependency graphs (figure 4) for four values of the Doppler frequency range $\Delta f_{\text{dop}}$: 10 Hz, 100 Hz, 1 kHz, 10 kHz and corresponding to the following velocities $v_{\text{mov}}$: $3.16 \times 10^{-6}$ m/s, $3.16 \times 10^{-5}$ m/s, $3.16 \times 10^{-4}$ m/s, $3.16 \times 10^{-3}$ m/s.

| $N_{\varphi}$ | Parameters | $A\Delta\varphi$ of AO LDI (MHz) |
|-----------|-------------|-----------------|
| 1 | Noise level (from guide) $P_{\text{NEP}}$, W/Hz$^{1/2}$ | 3.8 $\times 10^{-15}$ | 2.4 $\times 10^{-12}$ | $1.5 \times 10^{-15}$ | $3 \times 10^{-12}$ | $11 \times 10^{-12}$ |
| 2 | Noise level (corrected) $P_{\text{NEP}}$, W/Hz$^{1/2}$ | $\approx 100 \times 10^{-15}$ | $15 \times 10^{-15}$ | $8.2 \times 10^{-12}$ | $11 \times 10^{-12}$ |

Table 1. Noise and accuracy parameters of the "slow accurate" channel of AO LDI.

In figure 4, the horizontal line corresponding for the value of $A\Delta\varphi=1$ pm is highlighted. As can be seen, the achievement of the resolution of AO LDI of subpicometric values of $A\Delta\varphi<1$ pm (highlighted horizontal line) for the proposed scheme is possible at frequencies less than 25 MHz.

The following assumptions were made for the calculations. At $\Delta f=4 \times 10^{7}$ Hz and $P_{\text{NEP}}=30 \times 10^{-12}$ W/Hz$^{1/2}$ by using equation (12), the value $Q=1000$ was calculated by calculation [15,16]. However, similar some articles [15,16,18,19], to increase the reliability of the results obtained, a lower value, namely, $Q=600$, will be taken as the basis for further calculations.

The calculations given in [15,16] showed that the level of shot noise was $\approx 30\%$ of the total noise level. Over the past almost 10 years after the completion of work [15,16], modern low-noise photodetectors have appeared with a significantly lower level of internal noise of photodetectors, so that the level of shot noise caused by the signal illumination of the photodetector begins to prevail in formula (10). Therefore, we can assume a corresponding increase in the signal-to-noise ratio of modern photodetectors by 3.3 times, i.e. up to $Q=2000$. 

...
Figure 4. The dependence of the AO LDI resolution $\Delta l_{sa}$ on the frequency of the optical signal $f_{\text{com}}$.

Figure 5 shows diagrams of the ratio of phase errors of AO LDI for three values of AO modulation frequencies $f_{\text{com}}$: 10 MHz (a), 25 MHz (b) and 60 MHz (c). As can be seen, at $f_{\text{com}}=10$ MHz (figure 5a), the phase errors of the phase meter $\Delta \phi_{\text{phas}}$ and the noise of the photodetector $\Delta \phi_{\text{ps}}$ are significantly less than the phase error of the jitter of the VCG of the PLL $\phi_{\text{jit}}$, determined by the minimum allowable jitter $\Delta t_{\text{jit}} = 0.1$ ps. The diagram in figure 5b shows similar ratio of phase errors for AO modulation frequencies $f_{\text{com}}$: 25 MHz, which allows to ensure the subpicometric resolution of AO LDI.

With an increase in the frequency of AO modulation $f_{\text{com}}$ up to 60 MHz, the phase error from the noise of the photodetector $\Delta \phi_{\text{ps}}$ increases significantly, exceeding the phase error from the jitter $\phi_{\text{jit}}$ (figure 5c). This ratio leads to an increase in the total phase error $\Delta \phi_{\Sigma}$, at which the resolution of $\Delta l_{sa}$ exceeds 1 pm.

Figure 5. Diagrams of the phase error ratios of $\Delta \phi_{\text{jit}}, \Delta \phi_{\text{ph}}$ and $\Delta \phi_{\text{phas}}$ for three values of AO modulation frequencies $f_{\text{com}}$: 10 MHz (a), 25 MHz (b) and 60 MHz (c).

Thus, when the frequency of AO modulation $f_{\text{com}}$ reaches $\approx 25$ MHz, the permissible ratio of phase errors $\Delta \phi_{\text{jit}}, \Delta \phi_{\text{ph}}$ and $\Delta \phi_{\text{phas}}$ is formed, which allows achieving subpicometric resolution. A further increase in frequency of AO modulation $f_{\text{com}}$ leads to an increase in the phase error from the photodetector noise and an appropriate increase in the total phase error $\Delta \phi_{\Sigma}$ and resolution $\Delta l_{sa}$, exceeding the level of 1 pm.

5. The discussion of the results

1. The use of two independent HF and LF photodetectors for working with "fast inaccurate" and "slow precise" channels allows you to form two ranges of product movement velocities. The use of a low-frequency photodetector with a "slow accurate" channel in the low-velocity range allows you to achieve maximum resolution.
2. The main components of the phase error of AO LDI are due to the jitter of the PLL’s VCG, the error of the phase meter and the noise of the photodetector. Using the PLL allows you to narrow the proportion of photodetector noise, reducing the total phase error.

3. An increase in the frequency of AO modulation of AO LDI leads to a significant disproportionate increase in the noise level of the photodetector, the phase error from which reaches the level of phase error from the jitter of the VCG of the PLL system.

4. The use of modern photodetectors makes it possible to achieve a subpicometric resolution of less than 1 pm at frequency of AO modulation $f_{\text{mod}} \leq 25$ MHz at maximum velocities of less than 3 mm/s.

6. Conclusion

1. One of the most effective ways to increase the resolution of AO LDI without reducing the of movement velocity can be implemented on the basis of two channels "fast inaccurate" and "slow accurate" with independent multi-frequency photodetectors.

2. The relationship between the resolution of the AO LDI $\Delta l_{\text{res}}$, the noise level $P_{\text{NEP}}$ and the velocity of movement $v$, which forms the Doppler frequency raid $f_{\text{Dop}}$ allows you to select photodetectors with the desired frequency-noise characteristics for two-channel AO LDI.

3. One of the areas of improvement of AO LDI at the stage of "slow accurate" measurements may be related to the search for opportunities to increase the frequency of AO modulation of more than 25 MHz and the maximum velocity in the range of more than 3 mm/s.

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