NOISE RADAR TECHNIQUE IN OPTICS AND SEISMOLOGY

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NANO-DISTANCE MEASUREMENTS USING SPECTRAL INTERFEROMETRY BASED ON LIGHT-EMITTING DIODES

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The paper presents some results of the optical interferometry investigations based on the noise spectral interferometry method with use of low-coherent optical sources beyond their coherence zone. It is shown that when the path difference of arms in Michelson interferometer exceeds the coherence length of light-emitting diode radiation, the interference pattern in spectral domain enables to perform absolute measurements of micro- and nanodistances due to its dependence on both time delay and relative phase of the signals.

Keywords: spectral interferometry method, optical coherence tomography, Michelson interferometer, light-emitting diode, optical noise signal.

INTRODUCTION

Interferometry based on application of lasers with highly stabilized frequency provides precise measurements of linear shifts within the range of few millimeters up to tens of meters. Real application of existing laser interferometers for nano-scale measurements, i.e. for the scale much smaller of the laser wavelength, suffers of insufficient short-term stability of the laser frequency. The latter does not allow carrying out interferometric measurements of micro and nano distances. Which considerably limits applications of laser interferometers for nano distances measurements.

Therefore the search of alternative methods for optical interferometry methods has resulted at the end of the last century in development of optical coherence tomography (OCT) [1]. OCT performs cross-sectional imaging by measuring the magnitude and echo time delay of backscattered light [1]. OCT has found applications in such areas of medicine as ophthalmology, stomatology, dermatology, cardiology, etc. OCT is used in an industry for studying of material surface characteristics, surface roughness and other applications. In particular, in the paper production industry it is used for paper quality inspection.

The spectral interferometry method are researched and developed in radio-frequency region at Laboratory for Nonlinear Dynamics of Electronic Systems (LNDES) of Usikov Institute for Radiophysics & Electronics, NASU (Kharkov, Ukraine) long time [2-5]. Now, LNDS, Kharkov National University of Radio and Electronics (KHNURE, Kharkov, Ukraine) and Laser Laboratory of Synchrotron (Trieste, Italy) in common begin investigations of the spectral interferometry in an optical band for a nanometrology [6, 7].

In the papers, theoretical and experimental results on further elaborations of the noise spectral interferometry method for the micro-distances measurements are presented. In particular it has been found, which kind of optical sources can be used for such measurements, and which limit of measurement accuracy has been achieved.

1. THEORETICAL BASICS OF SPECTRAL INTERFEROMETRY METHOD

The method of noise spectral interferometry (or a method of double spectral processing) is based on a linear interference of spectral components of the noise probing and reflected signals [2-7] provided the distance to probing object exceeds the coherence length of the radiated signal:

$$l_c = \frac{c}{\Delta f}, \qquad (1)$$

where Δf is the width of the frequency spectrum of the noise probing signal, c is the speed of light in vacuum.

The method can be realized with the help of a classical Michelson interferometer.

In case of a single reflector, the power spectrum, $F_\Sigma(f)$, of the signal at the interferometer output (at the photodetector input) may be represented as follows:

$$F_\Sigma(f,\tau_0) = 2F(f)\{1+\cos(2\pi f\tau_0+\theta)\}, \qquad (2)$$

where θ is the phase difference between reference and reflected signals, t is current time, τ_0 is time of propagation of the signal up to the reflector and back, f – the frequency of harmonic spectral components of the broadband spectrum of optical radiation.

The analysis [3] of the power spectrum, $F_\Sigma(f)$, of the total (probing and reflected) signal allows to obtain the information about the distance to the reflector placed at the range L_0.

The power spectrum (2) is valid for infinite number of averaging, which is not achievable in practice. That is why we will suppose that in the measurements we are dealing with ergodic random signals, and averaging over ensemble of realizations may be substituted with averaging over time. The average interval is to be long enough to minimize scattering in the power spectrum estimation due to random nature of the probing signal. A large enough time-bandwidth product $\Delta f\, T_{mes} >> 1$ normally be used as criterion for choosing of an appropriate measurement/integration time T_{mes}.

It is seen that power spectrum (2) contains periodic alternations of maxima and minima along the frequency (wavelength) axis, which are (as it is shown in [3]) the results of constructive, distractive and intermediate interferences of harmonic spectral components of the stationary signals being summed in the output arm of the interferometer. The period of these alternations is inversely proportional to the time-delay τ_0 of the reflected signal with respect to the reference one which enables estimating the reflector distance. For this purpose the difference Δf_m of frequencies f_1 and f_2 is to be measured, corresponding to positions of two neighboring extrema (maximum or minimum) in the power spectrum (2) and the distance are tied via the following formula [2-7]:

$$L_0 = \frac{c}{2\Delta f_m} = \frac{c}{2(f_1 - f_2)}. \quad (3)$$

2. EXPERIMENTAL SETUP

For realization of the noise spectral interferometry method for nanodistance measurement an experimental setup of the optical Michelson interferometer (hereinafter - the interferometer) was assembled. The block diagram of the setup is showed in fig. 1.

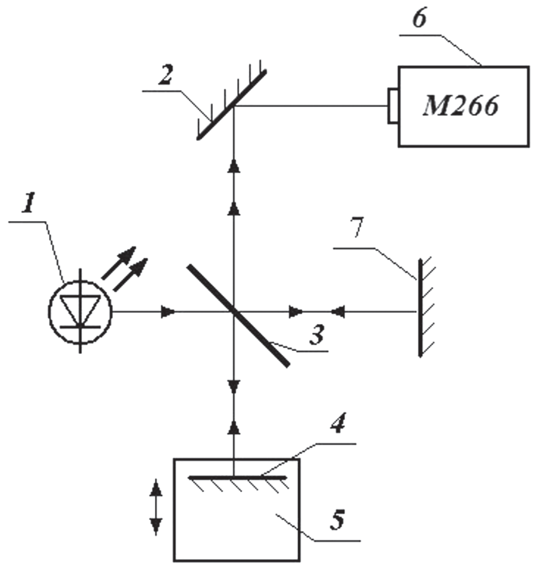


Fig. 1. Block diagram of the experimental setup. The Michelson interferometer. 1 – the source of random optical radiation (Toshiba TLRH190P LED); 2 – mirror, 4, 7 – Ag mirrors (Metal Mirror Ag: Er2, Newport); 3 – beam-splitting plate 50/50 (10RQ00UB.2, Newport); 5 – translation stage (F1-055/721299 Magini and C firms with micrometric screw TESA with 2 μm grating period); 6 – spectrum analyzer (on the basis of "M266 Solar Laser Systems" monochromator/spectrograph, made in Byelorussia)

The period of alternation of the spectrum extrema increases, when reducing the measured distance, therefore it is required to use not only wideband sources of radiation, but also wideband optical spectrum analyzers. "M266 Solar Laser Systems" monochromator/spectrograph (Byelorussia) has been used as the spectrum analyzer. It has a diffraction grating of 1200 lines/mm and a photodiode array with 2048 channels. Average value of a spectrum resolution of the M266 is less than 0.22 nm.

Investigation of the spatial interference has been carried out with the aim of estimation of the coherence length. Interference fringes in cross-section of a beam are visible within the limits of the coherence length of the radiation source. Hence, we can find the coherence length of the source if we determine visibility of the interference fringes.

3. OPTICAL NOISE SIGNALS SOURCES

Several methods may be applied to obtain band limited noise optical signals with various size of a spectrum width [6, 7]. One of them is noise modulation of the optical signal generated in a single-frequency and a single mode He-Ne laser using an acousto-optic modulator. At all advantages of this method it is very expensive. Other method is to use a single-mode radiation of semiconductor lasers. Semiconductor lasers being based on usual technology, work with a Lorentz radiation line-width up to 200 MHz. This width depends on a working current of the semiconductor laser, therefore it is possible to provide its increase or small reduction depending on the selected operating mode of the semiconductor laser.

Another perspective source of random optical radiation which can be used in optical noise radar or OCT is a femtosecond laser (PL) which works in a mode of generation of white light (supercontinuum) [8, 9]. PL have an extremely wide range of light (hundreds of nanometers) in the infrared region with central wavelengths of 800 nm, 1000 nm, 1300 nm. These wavelengths semiconductor PL emit, for example, Ti:Al2O3, Nd:Glass or Yb fiber, and Cr:Forsterite lasers. Axial image resolution in OCT systems based on these lasers reaches 4.1 microns. The main disadvantage of the PL is their relatively high cost, which imposes a limit on the scope of their application.

In the literature on measurements of nano-distances researches in which were used low-coherence radiation sources with a wide spectrum width were already described [10, 11]. Due to this feature of the used optical radiation sources, the given area of measurements refers to as a low-coherence interferometry or a white-light spectral interferometry.

In industrially released measuring devices (microscopes, profilometers, etc.) and in researches described in a scientific literature, as the sources of optical radiation so-called superluminescent diodes, various kinds of lamps (tungsten- and quartz lamps) are usually used [12, 13]. But the lamps have low power spectral density.

The most frequently used radiation sources for the spectral interferometry, for example, for the OCT, are superluminescent diodes due to their high spectral power and relatively low cost. Superluminescent diode (SLD) is a light-emitting diode operating in a superluminescence mode. The SLD has characteristics which is necessary to implement OCT inherent in LEDs and lasers. The SLD is similar to semiconductor lasers which amplifies spontaneous emission pn-junction. But, unlike a laser, SLD has no reflecting mirror surfaces, ie, there is no cavity. So, resulting radiation output of SLD is not monochromatic like a laser radiation and contains all wavelengths in the band of gain. Thus, it has a wide band, like LEDs, which is necessary for the implementation of OCT.

Positive qualities of the SLD are high power radiation (tens of milliwatts), like lasers and broad spectral band, like LEDs, tens of nanometers. For greater tissue penetration now SLD with a wavelength of 1300 nm are used, which can reach an axial resolution of 10 microns. For OCT applications SLD with greater spectral width are required. Therefore the rapid development of technology has led to the emergence of a composite SLD. Spectral width of the source exceeds the 150 nm and, therefore, it has a better axial resolution (5.3 microns).

The most cost-effective source of noise optical radiation, which could provide distances measurements from one micron and less, is an ordinary light-emitting diode (LED), the spectrum width of which exceeds that of a semiconductor laser. It allows expanding the range of measured distances towards its reduction.

In the present paper we suggest to use the LEDs which are released serially for indication and illumination needs, namely Toshiba TLRH190P InGaAlP LED and OSHR5111P LED from OptoSupply.

The researched Toshiba TLRH190P LED has the following characteristics: a central wavelength of the LED radiation is 645 nm with spectrum width at half is about 15 nm; Radiation level from the LED output diverges within the 40 angle only. Due to these properties, radiation of the LED has been used in interferometer without additional collimation and beam focusing.

The manufacturer positions the given type of LEDs as «LED Lamp» by virtue of high brightness of radiation which is 19 cd. The example of spectral characteristic of TLRH190P LED radiation is shown in fig. 2.

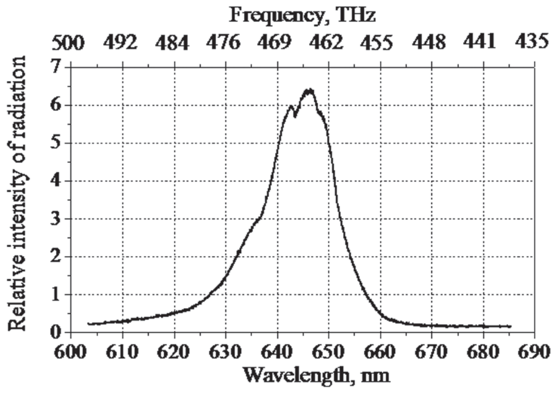


Fig. 2. Radiation Spectrum
of the Toshiba TLRH190P LED

Also second type of LED named OSHR5111P from OptoSupply Company was investigated. Light intensity of the OSHR5111P LED is 50 cd, a radiation wavelength under LED manual is 625 nm (at an experimental sample it is about 637 nm), a divergence angle at 3dB level of the maximal radiation intensity is 15 degrees; a width of a spectrum is about 20 nm. The example of spectral characteristic of the OSHR5111P LED radiation is shown in fig. 3.

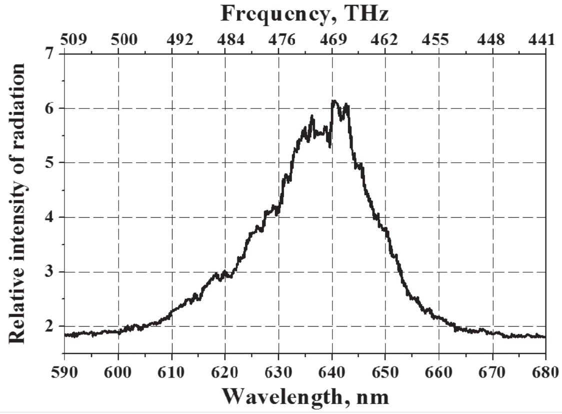


Fig. 3. Radiation Spectrum of the OptoSupply
OSHR5111P LED

4. THE MEASUREMENT METHOD AND MEASUREMENTS RESULTS

After the interferometer has been checked up in conditions of the spatial interference in the coherence zone of radiation, its tuning has been done. Then the difference of the interferometer arms has been increased more than the coherence length. After that the spatial fringes vanished and a periodical structure appeared in the spectral area, i.e. in the noise radiation spectrum which has been registered at the interferometer output, the spectral interference was observed which is well described by the equation (2). If the mounted difference of the interferometer arms is more than the coherence length of the LED noise radiation the periodic structure has been observed in the registered radiation spectrum. The radiation spectrum at the interferometer output for the case of the arms difference exceeds the LED coherence length is shown in fig. 4a. Fig. 4b shows result of Fourier analysis of the Toshiba TLRH190P LED spectrum that is shown in fig. 4a [7].

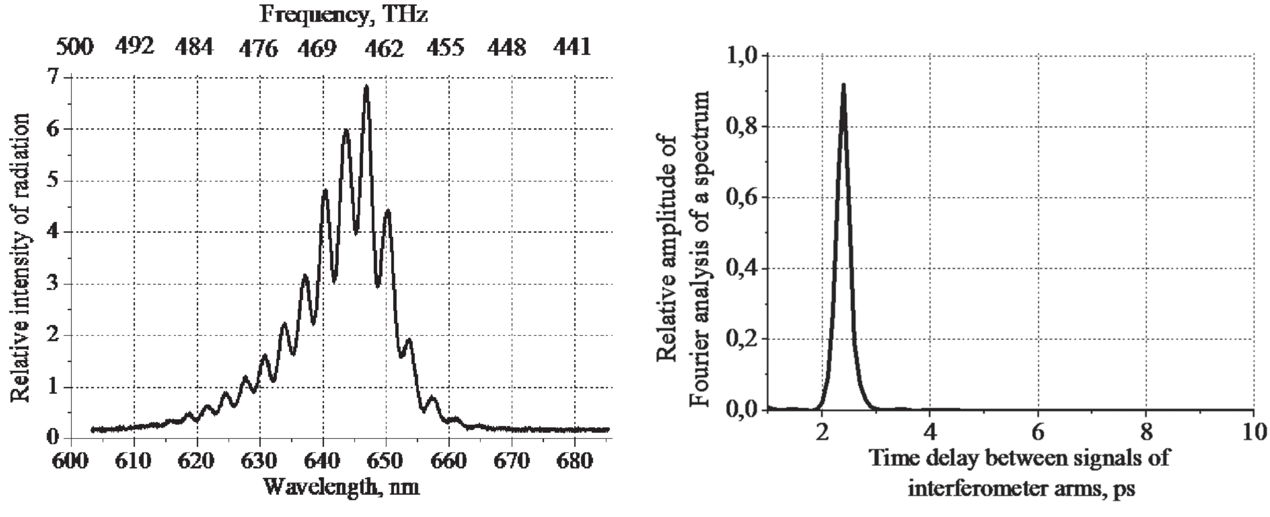
Fig. 5 shows the radiation spectrograms and the result of Fourier analysis of the OptoSupply OSHR5111P LED.

Estimated value of a spectral fringes contrast is 0.27 for the Toshiba TLRH190P LED and 0.45 for the OptoSupply OSHR5111P LED. For example, the spectral fringes contrast of the superluminescent diode used in the work [11] and shown in Fig. 6 equal 0.6. So it has similar value with the researched LEDs.

The considered spectra have a similar periodic channels structure with a good contrast of spectral fringes (lines). Due to this Fourier-processing of the spectra in these cases enables to determine unequivocally a time delay of signals between interferometer arms and hence the difference of interferometer arms lengths, i.e. allows to determine distances.

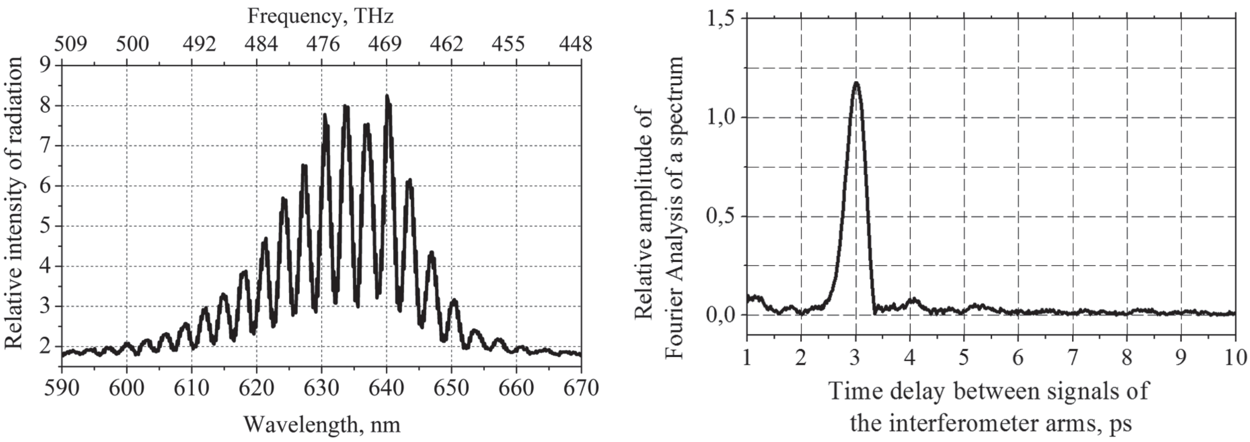
Fig. 7 shows the dependencies of the time delay between the signals, which are distributed in the arms of the interferometer (signals of the interferometer arms) based Toshiba TLRH190P LED (that is proportional to the measured distance), on the position of the measure arm mirror of the interferometer near the coherence zone [7].

Scanning began outside of the coherence zone, passed through the coherence zone (the interferometer arms are equal), and came to an end behind the



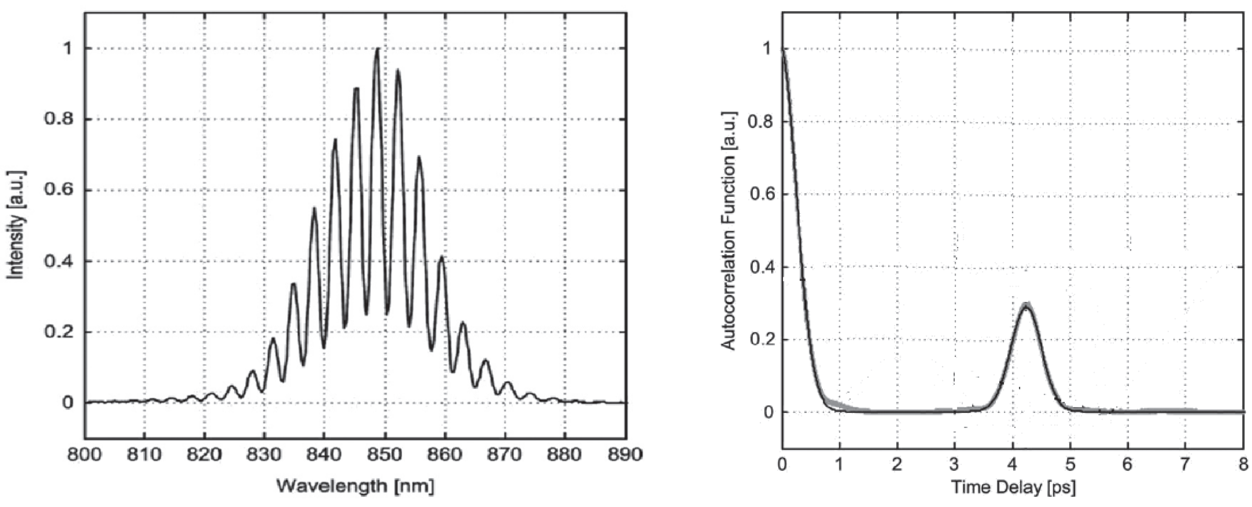
a *b*

Fig. 4. *a* — Power spectrum of noise optical radiation of the Toshiba TLRH190P LED at the output of the Michelson interferometer: the arms difference exceeds the coherence length of the LED noise radiation; *b* — the result of the second Fourier transform being applied to the spectrogram of fig. 4a



a *b*

Fig. 5. *a* — Power spectrum of noise optical radiation of the OptoSupply OSHR5111P LED at the output of the Michelson interferometer: the arms difference exceeds the coherence length of the LED noise radiation; *b* — the result of the second Fourier transform being applied to the spectrogram of fig.5a.



a *b*

Fig. 6. SLD characteristics: *a* — the output channelled spectrum from the SLD based optical-fiber Fabry-Perot interferometer [11]; b — the autocorrelation function of the spectrum in Fig. 6a.

coherence zone. As a result it is possible to observe behavior of the radiation spectrum from the output of the interferometer on borders of the coherence zone.

The interferometer arms difference was changed with a step 1 μm. On the abscissa axis of the diagrams of fig. 7 and 8, position of the mirror of the measuring interferometer arms at begin of scanning was accepted as zero value for simplicity of perception.

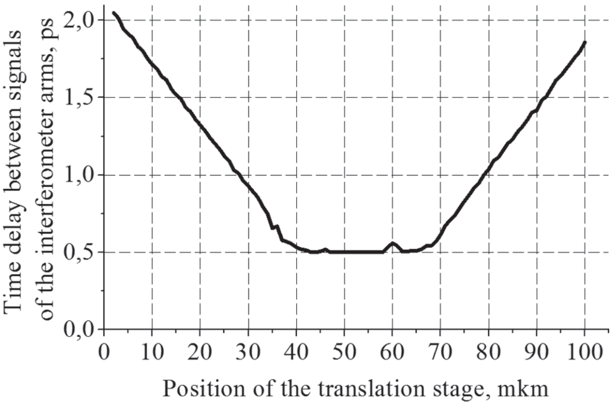


Fig. 7. The experimental dependencies the time delay between the signals of the Toshiba TLRH190P LED based interferometer arms on the position of the measure arm mirror of the interferometer near the coherence zone.

At position of the measuring interferometer arm mirror 4 (fig. 2) in a range ~35-69 μm (fig. 7) the periodicity of the structure of the LED spectrum is practically not observed, i.e. the spectral interference in the given area is absent. The given range is ~34 μm, i.e. about ±17 μm from a point of interferometer arms equality. Meanwhile, as it has been told earlier, the experimental researches of the spatial interference have shown that the radiation coherence length from the output of the interferometer is ~16-18 μm. Thus, it is possible to draw a conclusion that the spectral interference effect begins to be shown abroad the coherence zones i.e. on the distance exceeding the coherence length.

The relative error of the measurement presented in fig. 7, corresponding to the maximal absolute error at confidence probability 0.95 is 1.5-3 %.

The result of the measurements for the interferometer arms difference within the range more than 1 mm is shown in fig. 8. The interferometer arms difference was changed with step 10 μm. The top border of a distance range was limited to resolution of the measuring equipment, i.e. the Solar M266 monochromator/spectrograph. Fig. 8 presents the experimental dependence of inversely of the period of the radiation spectrum non-uniformity of the Toshiba TLRH190P LED on the interferometer arms difference in ranges more than 1 mm [7].

The diagram in fig. 8 shows linear dependence of the period in the radiation spectrum pattern on the interferometer arms difference. Thus, knowing the period of the spectrum pattern of the LED, we can determine the interferometer arms difference, i.e. in case of use of the given circuit in a distancemeter, we can determine the distance up to the object the above accuracy.

The relative error of the measurement presented in fig. 8 is about 0.5% for the maximal absolute error at the 0.95 confidence probability.

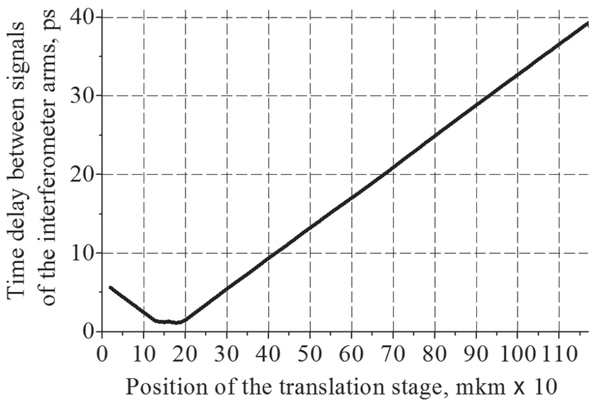


Fig. 8. The experimental dependencies the time delay between the signals of the Toshiba TLRH190P LED based interferometer arms on the position of the measure arm mirror of the interferometer.

At change of the interferometer arms difference by 1 μm (minimally possible step for the used mechanics) the period of the spectrum structure changes on the average by 2.5 nm. The spectrum analyzer has its 0.22 nm wavelength resolution, which gives a distance resolution of the measuring setup under consideration to be not less than 100 nm.

CONCLUSIONS

The paper describes the theoretical model of the noise spectral interferometry in an optical band. As the result of experimental test of the method of optical spectral interferometry the possibility of periodic modulation of the radiation spectrum of the Toshiba TLRH190P LED and OptoSupply OSHR5111P LED have been shown. This is shown possibility of use of the low-cost industrial-produced low-coherent optical radiation sources for measure the micro- and nanodistances using the method of spectral interferometry. The authors suggest and see the perspectives of using such LEDs in OCT devices, as they are much cheaper superluminescent diodes commonly used in the OCT. This will reduce the cost of devices based on them.

It was investigated the capability of the application of the noise spectral interferometry for the micro- and nanodistances measurements. Minimum measuring distance is the coherence length of the radiation source. This is due to the fact that the periodicity of structure spectrum is appeared at the distance exceeding the coherence length [7]. So, the minimum measured distance can be down to tens of micrometers or less. For Toshiba TLRH190P LED minimum measured distance determined by its coherence length and is equal ~18 μm [7]. The value of the maximal measured distance is mainly determined by the resolution of measurement equipment.

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Konstantin A. Lukin, for photograph and biography, see this issue, p. 24.

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Измерение нано-расстояний с использованием спектральной интерферометрии на основе светодиодов / К.А. Лукин, М.Б. Данаилов, Ю.П. Мачехин, Д.Н. Татьянко // Прикладная радиоэлектроника. – 2013. – Том 12. – № 1. – С. 166–171.

В работе представлены результаты исследований оптической интерферометрии на основе низкокогерентных источников излучения вне зоны когерентности. Показано, что когда разность плеч интерферометра Майкельсона превышает длину когерентности излучения светодиода, явление спектральной интерференции обеспечивает абсолютные измерения микро- и нано-расстояний в соответствии со временем задержки и относительной фазой между опорным и зондирующим сигналами.

Ключевые слова: метод спектральной интерферометрии, томография оптической когерентности, интерферометр Майкельсона, светодиод, шумовой оптический сигнал.

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Вимірювання нано-відстаней з використанням спектральної інтерферометрії на основі світлодіодів / К.О. Лукін, М.Б. Данаїлов, Ю.П. Мачехін, Д.М. Татьянко // Прикладна радіоелектроніка. – 2013. – Том 12. – № 1. – С. 166–171.

У роботі наведено результати досліджень оптичної інтерферометрії на основі низько-когерентних джерел випромінювання поза межами зони когерентності. Показано, що коли різниця пліч інтерферометра Майкельсона перевищує довжину когерентності випромінювання світлодіода, явище спектральної інтерференції забезпечує абсолютні вимірювання мікро- та нано-відстаней згідно з часом затримки та відносною фазою між опорним та зондуючим сигналами.

Ключові слова: метод спектральної інтерферометрії, томографія оптичної когерентності, інтерферометр Майкельсона, світлодіод, шумовий оптичний сигнал.

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