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NANOMETROLOGY REGIME IN LENGTH MEASUREMENTS OF MATERIAL ARTEFACTS WITH NOMINAL LENGTHS UP TO 100 mm.

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Abstract – New calibrated double-sided method of interferometric length measurements with quartz reference plate is reported. The method is free from wringing errors, and can be used for the improvement of measurements of material artefacts. Limitations of the interferometric measurements are discussed. Some systematic errors are measured with a sub-nanometer resolution.

Keywords: gauge block, interferometry, nanometrology.

1. INTRODUCTION

In accordance with [1] nanometrology is defined as a dimensional measurement with an uncertainty of about 1 nanometer or less. Traditionally, atomic force microscopes (AFM) are used to realize this regime, as with commercially available instruments it is easy to achieve the necessary resolution when measuring the objects up to a few microns. Precise calibration of AFM is usually performed by optical interferometry, for example, by measuring a displacement of a material artefact with a precisely defined geometrical form [2]. As a result of nonlinearity and instability in time of displacement sensors of AFM, the nanometrology regime can be obtained for dimensions of about hundred of nanometers [2,3]. At the recent time, with the development of parallax-free methods in optical interferometry [4-7], it has become possible to achieve this regime when measuring end standards (gauge blocks) with nominal lengths up to several tens of millimeters, thus expanding the range of nanometrology by more than *four orders* of magnitude. Nowadays, we are working to achieve one nanometer uncertainty when measuring 100 mm gauge blocks in a fringe-pattern analyzing large Kösters interferometer (Carl Zeiss). In this case, the length of a material artefact is expressed in terms of wavelengths of a plane electromagnetic wave of known frequency, propagating in vacuum, when diffraction perturbation effects are reduced to a negligible amount. Thus we are able to realize conditions in exact agreement with the present Metre definition [8].

The key feature of the new methods [4-7] is a realization of measurements with extremely small wringing uncertainties. The main experiment in optical length metrology [9] has to be changed. In the classic method [9], only one interferometric measurement is performed, when wringing the block to the reference plate of approximately the same surface texture and determining the phase shift between the fringes visible on the surface of the gauge block and the fringes on the reference plate. The important limitation of the length of a gauge block L_D measured in accordance with [10] is a *model assumption:* i.e. a flat surface approximation made for the reference plate. As a consequence, there exists a problem in measurements of gauge blocks with nominal lengths above 15-20 mm. As a result of flatness deviations of the gauging surfaces, the lengths of these block measured in accordance with [9,10] are different for the wrings to different faces [5]. This effect of the surface topography is especially important in case of gauge blocks having one concave and one convex faces. In this case, wringing of the block to a convex face always results in a smaller length value L_{D}., than wringing to the concave face. The internationally accepted procedure of taking this effect into account is fixed in the Protocols of International comparisons (such as Key Comparisons of BIPM CL-K1 CL-K2, SIM.4.2 Inter-American Comparison). Their requirement is that the mean value of both measurements should be regarded as the length of L_D. Thus the effect of topography is included into the wringing uncertainty, and it inevitably results in the accuracy decrease of the interferometric length measurement, giving an additional uncertainty of ~ 10 nm in typical cases.

2. CALIBRATED DOUBLE-SIDED METHOD AND ITS EXPERIMENTAL TESTS

To overcome the problem of the surface topography, high-precision parallax-free methods have been developed [4-7], which are based on the interferometric measurements of differential type. The number of interferometric measurements is increased to four, and the parameter of interest (optical length, L_{OPT}, [6,7], mechanical length, L_M, [5,11], or the optical phase-change correction value $\Delta\delta$ [4,5]) is obtained as a difference of two differential measurements. The basic experiment in the new system is the measurement of optical length of the block by the double-sided method, performed on a quartz reference plate [6] (Fig.1). Here, two differential measurements (experiments 1,2 and 3,4) are performed against the same reference points on the plate. As we are using the difference between the results of these two measurements, the common reference simply cancels out from the final result. So, the new length specifying parameters L_{OPT} *has no model restrictions,* and can be measured with a sub-nanometer uncertainty level [11,12], if necessary. Meanwhile, for the measurements of L_D the uncertainty level is typically about 10-15 nm, even for thin gauge blocks [13].

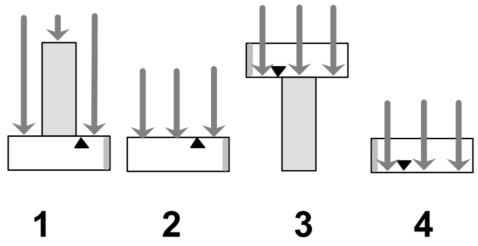

Fig.1. Set of experiments of the double–sided method on quartz plate. Experiments 1,2 give the front-side differential measurement M_{FS}, while experiments 3,4 give the back-side measurement result M_{BS}

The experiment 3 in Fig.1 is to be performed with a thick oil film (hundreds of nanometers). This reduces dramatically the effect of the refractive index perturbations in the quartz plate associated with the wringing procedure. Under these conditions, the experiment 4 gives the necessary correction for the combined effect of optical distortions in the interferometer and of the refractive index inhomogeneity of the plate. When the refractive index of oil n_o is somewhat different from the refractive index of quartz plate n_q, then as a result of the light reflection at the border between oil and quartz, there arises a Fizeau interferometer (plate – gauge block) that is coupled to the main Michelson interferometer [14].

The measurement result R for this type of the optical device, expressed in nanometers and obtained under the standard geometrical optics approximation [14] (when the beam diameters are so big that the diffraction effects can be neglected), can be presented in the form:

$$R= D_0 (\pi - \gamma) = \lambda_0 / (4\, n_0) - D_0 \gamma \qquad (1),$$

$$\gamma = \arctan \{(A \sin \Delta) /(B \cos \Delta - C)\} \qquad (2).$$

Here, $D_0=\lambda_0/(4\pi\, n_0)$;
λ_0 is a vacuum wavelength of the illuminating laser field in nanometers, and Δ is a round trip optical path of the Fizeau interferometer (in radian), which is equal to:

$$\Delta = (4\, \pi\, d\, n_0) / \lambda_0 = d / D_0 \qquad (3),$$

where d is an effective distance of the Fizeau interferometer, which is measured from the reference points on the plate to the mean effective surface of reflection, corresponding to a specified point on the block face. As it follows from [15], the effective plane of light reflection is located inside the gauge block material at the distance of the skin depth value δ_S relative to the mean plane of the roughness texture. So, the effective distance d includes the distance to the mean plane of the roughness texture $d*$ and the skin depth value δ_S.

The coefficients A, B and C in (2) are related to the amplitude reflection coefficients r_1 and r_2, corresponding to the oil/quartz and oil/steel interfaces, observed at normal incidence:

$$A = r_2\, (1 - r_1^2);\; B = r_2\, (1 + r_1^2);\; C = r_1\, (1 + r_2^2) \qquad (4);$$

$$r_2 =\{((1 - n_2^*)^2 + k_2^2) / ((1 + n_2^*)^2 + k_2^2)\}^{1/2} \qquad (5);$$

$$r_1 =(n_q^* -1) / (n_q^* +1) \qquad (6),$$

where $n_2^* = n_2 / n_0$ and $n_q^* = n_q / n_0$. The corresponding expression for the skin depth, valid for an arbitrary value of value of the refraction index n_0, is given by the equation:

$$\delta_S =\{\lambda_0/(4\pi\, n_0)\} \arctan \{(2 n_0 k_2)/(n_2^2 + k_2^2 - n_0^2)\} \qquad (7)$$

It is a generalization of the corresponding expressions presented in [15], and written for the case of n_0=1:

$$\delta_S^{air} =\{ \lambda_0 / (4\, \pi) \} \arctan \{(2\, k_2) / (n_2^2 + k_2^2 - 1)\} \qquad (8)$$

Equation (1) is similar to (8) in [14], and turns into it in a particular case of n_0 equal to 1. It is valid for the d values smaller than half of a fringe, that is for $d < \lambda_0 /(4n_0)$. The expressions (1-6) give, in explicit form, the relation between the phase shifts following from the amplitude reflection coefficients and the corresponding fringe fraction values observed in the optical interferometer. As pointed out in [9], for the case of viewing the block through the plate, there arises a half fringe displacement of the interference pattern, that is described by the first term in (1). It is convenient to introduce a new variable R^* given by expression:

$$R^*= \lambda_0 / (4\, n_0) – R = D_0\, \gamma \qquad (9),$$

that corresponds to the readings of the coupled interferometer when measurements are performed relative to the π-shifted fringe on the reference plate. In the particular case, when the refractive index of the oil n_0 is equal to the refractive index of the reference plate n_q , and there is no reflection at the border between quartz and oil, the quantity R^* is acquiring a simple physical meaning. For $n_0=n_q$, the reflection coefficient r_1 and C become equal to zero, $A=B$**,** and the quantity γ in (1) is simply substituted by Δ (3). Under these conditions, we are coming to the conclusion that for the variable R^*, holds the relation:

$$R^* = d = d^* + \delta_S \qquad (10).$$

It means that the interferometer in the experiment 3 of Fig.1 measures the distance to the effective plane of light reflection d. If the gauge block is made of non-absorbing dielectric material, then k_2 =0 and δ_S =0, and the reading of the comparator R^* is exactly equal to the distance to the mean plain of the roughness texture [15]. It also follows from [15] (see p.55) that for typical steel gauge block surfaces, with very high precision (of about $2x10^{-5}$ of a fringe fraction), the effective plain of light reflection coincides with the mean plain of the roughness texture, shifted inside the block by the skin depth value. So, the parameter $d*$ in (10) shows the distance to the mean plain of the roughness texture, that is measured relative to two fixed points on the reference plate.

When $n_0<n_q$, a corresponding correction $\rho = d - R^*$ is to be added to the result of the measurement by the

coupled interferometer R^* to obtain the distance to plain of reflection *d*. Typical dependences of ρ on the results of the measurement by the coupled interferometer R^* are presented by plots of Fig.7 in [16] for steel blocks with n_2=2.4; k_2=3.4 and two different oils with refractive indexes 1.41 and 1.507.

For the experiment 1 in Fig.1 holds the same relation (10), where the skin depth value δ_S is calculated using (8). For steel blocks the difference between the δ_S values measured in oil and in air is quite small: for example, for n_0=1.4 at the wavelength of 633 nm this difference is 0.09 nm, only. For TC blocks at the same wavelength the difference is even smaller and is equal to 0.04 nm for n_0=1.5. Thus the measurement result of the double-sided method shows the perpendicular distance between the plains of the light reflection from the opposite gauging surfaces of the block, that corresponds to the centers of the gauging faces. The key feature of the method is that the result of the measurement is not practically affected by the inevitable distortions of the optical system of the interferometer and by the optical inhomogeneity of the reference plate. This is a result of the performance of the compensating measurements of experiments 2 and 4 of Fig.1.

It is worth emphasizing here that the signs of the quantities R and R^* in (9) are different. It means that the reading of the coupled interferometer R^* (back-side measurement) corresponds to the length measurements in the opposite direction relative to the measurements of *R*, or relative to the length measurements of experiments 1,2,4 in Fig.1. Taking this into account, it is natural that, while for the front-side differential measurement result M_{FS}, the measured correction for the optical distortions and plate curvature, obtained as a result of execution of experiment 2, is subtracted from the result of experiment 1, the results of the measurements of experiments 3 and 4 are summed to obtain a distortion-free back-side measurement result M_{BS}. The experimental confirmation of this consequence of the relation (9) is presented in Fig.2.

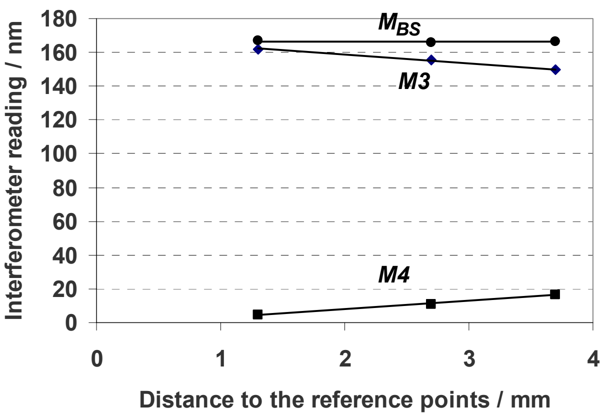

Fig.2. Dependences of the measured values of the experiment 3 in Fig.1 (*M3*), of the experiment 4 (*M4*) and of the back-side differential measurement M_{BS} on the distance to the reference areas on the quartz plate relative to the gauge block edges.

Here, we present the results of the experiments *M3, M4* and of the differential measurement M_{BS} (marked with rhombs, squares and dots, respectively) as a function of the distance of the reference areas on the plate from the gauge block edge. The quantity *M3* corresponds to the measured distance from the reference areas on the plate to the plain of optical reflection in the gauge block material. *M4* shows the correction on the interferometer optics and the inhomogeneity of the quartz plate. The result of the differential measurement M_{BS} can be considered to be free from optical distortions: the standard deviation for the corresponding experimental points in the plot of Fig.2 is 0.33 nm, that is well within a sub-nanometer range. So, this is a true parallax-free measurement, as it is defined in [4].

The uncertainty of the back-side measurement can be further improved by an additional averaging procedure over several interferograms. For example, the mean value of M_{BS}, obtained for all the points of Fig.2, for the "Sad" type interferograms gives the value of 166.48 nm. Meanwhile, the corresponding value for the "Smile" type interferograms is 166.37 nm. So, the resulting spread of data relative to the mean value of 166.42 nm is ±0.055 nm for this averaging procedure.

The experiments of Fig.2 give the indication that the wringing perturbations of the quartz plate are quite small. In detail this subject has been studied in [7,16]. Here, we present a plot (Fig.3) showing the results of the measurements of the optical length of a 5-mm steel block on the z-cut crystalline quartz plate.

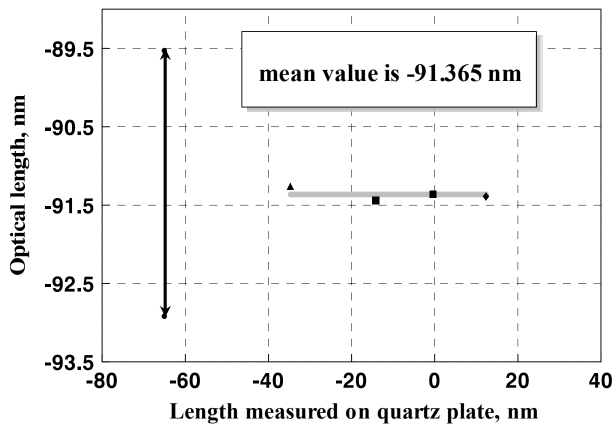

Fig.3. Optical length measurements of a 5-mm steel gauge block as a function of the front-side differential measurements M_{FS}, characterizing the increasing oil film thickness between the block and the reference plate. (See text for other details).

The double-sided arrow shows the spread of data of a few nanometers when the block was wrung without oil to the reference plate. This spread is associated with the temperature induced variations of stresses in the quartz plate induced by the wringing forces. Then ringing perturbations were gradually reduced by the oil film slowly penetrating into the wringing contact, and the point marked by triangle corresponds to a air gap between the block and the reference plate at the center of the gauging surface, when there was no any direct contact between the block and the plate in the measured area. The measured value of the optical length, corresponding to the difference from the nominal value of 5.00 mm, was –91.33 nm (when reduced to the oil measurement conditions). This value should be compared with the measurement result obtained at the end of the experiment when the block was slowly moving across the surface of the plate. The mean value obtained in the range M_{FS} values from -3 to 28 nm was –91.39 nm, and it is shown as rhomb in Fig.3. These data points were complemented by the stationary points, corresponding to new the wrings of the block with the oil films, but without any additional cleaning of the gauging surfaces. The corresponding values (marked with squares) were –91.44 nm (M_{FS} = -14 nm), and –91.36 nm for M_{FS} = -0.3 nm, respectively. The time interval between these two points was more than a month. The mean value of these four points is –91.37 nm with the standard deviation σ of 0.046 nm. Using Table G.3 in [17], we find that for the degrees of freedom ν=3, the coefficient t_p is equal to 3.16, and the corresponding uncertainty interval at 95% confidence level, which is obtained by the multiplication of the t_p coefficient and the experimentally measured σ-value, is ~0.13 nm. This uncertainty interval, which corresponds to the measurements performed in a wide range of the oil film thickness and corresponds to the normal distribution containing infinite number of measurements [17], we shall use to characterize the possible optic perturbations in the quartz plate associated with a wringing procedure. From this experiment we conclude that the remaining wringing deformations in the quartz plate, that are dramatically reduced by the oil film of about 100 nm thickness, are well within a sub-nanometer range, and the plate can be regarded in a free, unperturbed condition. Thus, the experiment 4 in Fig.1 gives the necessary correction for the quartz optical inhomogeneity.

A typical uncertainty budget of a double-sided measurements is presented in the other paper of some of these authors in the same issue.

To find by the calibrated double-sided method (CDSM) [4] the mechanical length of an arbitrary block L_M, which is related to L_{OPT} by relation:

$$L_M = L_{OPT} + 2\delta_S + \delta_{R,1}* + \delta_{R,2}* \qquad (11),$$

we are to measure the optical length of the block using the double-sided method, described in detail above, and to determine also the sum of the optical phase change values for both faces of the block, given by expression:

$$2\delta_S + \delta_{R,1}* + \delta_{R,2}* = 2\,\delta^m \qquad (12).$$

To find the latter, we are to use two reference gauge blocks [4], for which reproducible wringing is possible [5]. For one of these blocks we measure the optical phase change value δ^m as it is demonstrated in [4,7]. Then using another reference block, we measure the difference of the δ^m-values between the first reference block and the unknown block [5]. In this way we find the value of $2\delta^m$ of the unknown block. As it is demonstrated in [5] on the example of 50-mm and 100-mm gauge blocks (see Figs. 10 and 11 in [5]), high-precision determination of the roughness correction (with the uncertainty level of ~0.1 nm) is possible for relatively long gauge blocks, having complex shapes of the gauging surfaces. As it follows from Fig.12 in [5], one face of the 50-mm block (shown in Fig.12b) is *convex*, and the other (Fig.12a) is *concave* at the centres of the gauging faces. Nevertheless, the difference in δ_R^* -values measured for the wrings to these faces is within ±0.06 nm, while the difference in the length values L_D, obtained by the standard method of optical interferometry [9,10], is 12.1 nm for this block (Fig.11 in [5]). The determined value of the roughness correction, measured for both faces of the 50-mm and 100-mm blocks, is within 0.1 nm. As demonstrated experimentally in [6], the result of the double-sided measurement is, practically, the same for the wrings to both surfaces of a gauge block. As the effect of topography is also not present in the measurements of reference gauge blocks permitting reproducible wringing [5,6], so we are coming to the conclusion that the effect of topography of a block surface, which is easily detected in the standard method of optical interferometry [5], does not practically exist in the modern parallax-free methods of optical length measurements [4-7].

3. ADDITIONAL REQUIREMENTS FOR REALIZATION OF NANOMETROLOGY REGIME

To reach the regime of nanometrology, except new methods of measurements, it is necessary to reconsider procedures of applying different corrections to the measurement result. In the first place, we are to analyze attentively the inclination error correction – one of the largest in optical interferometry for long gauge blocks [9].

In Fig.1 in [5] we showed the results of high precision measurements of the inclination error of the gauge block in our interferometer [4,6], when using a 100 mm gauge block wrung to a steel plate and changing slightly the angle of the illuminating laser beam [5] in the vertical direction. The presented data correspond to the results of the differential measurements (gauge block over plate and free plate), so that these data are corrected on the combined effect of interferometer optics distortions and base-plate flatness deviations. The position of the maximum of the curve, corresponding to the case of the minimum value of the inclination error, is associated with the divergence of the beams in the interferometer. But what's about the inclination error, which is always present in the pattern-analyzing interferometers and is related to a small tilt of the gauge block surface relative to the reference mirror of the Michelson interferometer? For example, 20 fringes of red light observed on the gauging face of a 100-mm block correspond to some additional inclination error of 1.6 nm, which, for sure, our interferometer can resolve. The solution gives Fig.4, where the data for the "Sad" and "Smile" type of interferograms are presented, that have opposite directions of measurements of the fraction of the interference order [9]. The data corresponds to 22-23 fringes observed on the free gauging surface of the block. As it follows from Fig.4 the procedure of tuning the interferometer to the maximum of the curve by variation of the position of the laser spot inside the input diaphragm of the interferometer [5] automatically includes the effect of the tilt of the reference mirror. But the price for this is that the interferometer can be tuned only to one type of the fringes ("Sad" type in our case), and the maximum of the other curve (for “Smile” type interferograms) corresponds to large intensity losses due to diffraction losses of the beam spot on the edge of the diaphragm. We note here also that switching to the “Smile” type of interferograms for the interferometer tuned to the “Sad” type fringes results in the inclination error of about 9 nm! The calculated additional shift of ~2 nm for 24 fringe interferogram is observed for tuning interferometer to the zero-th fringe, corresponding approximately to the symmetric position between the two curves in Fig.4.

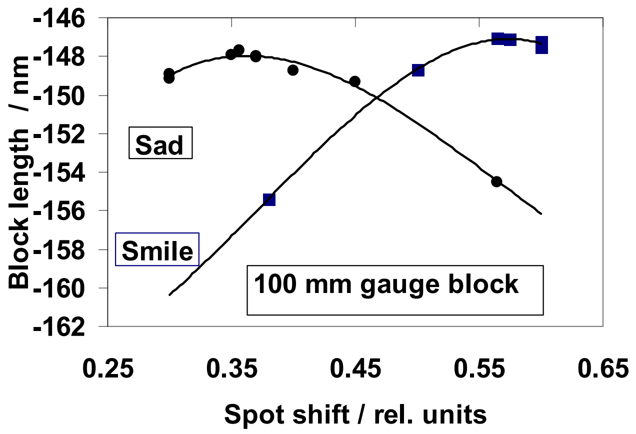

Fig.4. Measured block lengths (variations from the nominal 100 mm value), obtained for “Sad” and “Smile” types of interferograms, as functions of the laser beam spot displacement at the input diaphragm of the interferometer (in arbitrary units).

The second problem deals with the correction for the combined effect of optics distortions of the interferometer and the curvature of the reference plate in the front-side differential measurement of Fig.1. The question is whether the propagation of the slightly distorted beams in the interferometer along the length of the block does affect the value of the correction of the experiment 2 in Fig.1, or not? The answer to this problem is given by the results of the study shown in Fig.5.

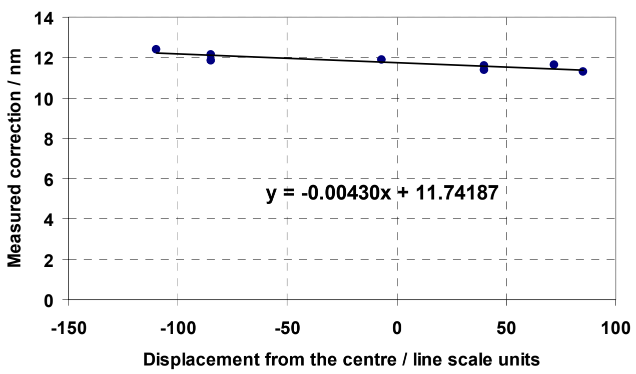

Fig.5. Experimental dependence of the combined correction for the optical distortions of the interferometer and the curvature of the reference plate on the displacement of the reference plate relative to the central, equal-arms position of the Michelson interferometer.

Here, we demonstrate the variation of the combined effect of the curvature of the plate and of the optical distortions of the interferometer [5] as a function of the displacement of the reference plate along the optical axis of the interferometer. In this experiment the reference plate was moved in both directions relative to the position of the equal arms condition of the Michelson interferometer. A slight variation of the correction value (of about ±0.4 nm) is observed for the plate displacement of ±100 divisions of the special scale in the interferometer, which measures the position of a gauge block inside the instrument. Now we shall demonstrate how this dependence can be used for the uncertainty evaluation of the effect of the optical distortions.

First, we are to note that the software of the interferometer measures the phase shift of the fringe observed on the block surface relative to the fringes observed on the two reference areas of the plate, which are located strictly symmetrically relative to the measured point. So, if we consider the dependence of the function, describing the effect of optical distortions in the interferometer, on the distance to the reference areas X, it will be a purely even function of the variable X: the interferometer measures the phase of the fringe on the block relative to the half of the sum of the phases of fringes on the reference areas. We can put the zero reference point of this transverse coordinate X to the center of the gauging surface of the block.

Second, the dependence of the function describing the optical distortions in the interferometer on the other transverse coordinate Y has been measured experimentally in [4] (Fig.7). It has a typical scale of about a couple of millimeters in the Y-direction, that results in the variation of the optical correction of about 1 nm. So, for the displacement of the reference plate in the Z-direction, along the optical axis of the measuring arm of the interferometer (Fig.5), the position of the zero point can be regarded the same for all the Z-values: the displacement of the reference plate along the lapped surface in the interferometer is performed with the possible shift in the Y direction of less than 0.1 mm, while the sensitivity of the corresponding function describing the effect of optical distortions is about 0.5 nm/mm. So, we are coming to the conclusion that the correction on the optical distortions of Fig.5 should be measured for the Z-position of a free reference plate, coinciding with the position of the plate, when it is wrung to the block. The error of the plate positions in the wrung and in the free states of about 5 scale divisions (2.5 mm) is quite possible, as it results in a very small correction (~0.02 nm), as it follows from the equation shown in Fig.5. So, we are coming to the conclusion that the propagation of the slightly distorted optical beams along the length of the block (in the cross section of the reference plate) does not spoil the parallax-free regime of the measurement, realized by the double-sided method.

Besides realization of new methods of measurements of optical interferometry, we continue updating optical interferometers in order to expand the range of nanometrology to longer gauge blocks. Now we are modifying the large Carl Zeiss, Kösters interferometer [9]. The key features of this new fringe pattern-analyzing instrument are as follows:

1. an automatic way of measurements;
2. the use of an internal refractometer, which permits to perform measurements directly in terms of vacuum wavelength of the laser radiation;
3. a wide range of nominal lengths of measured gauge blocks;
4. high-precision measurements of the temperature of gauge blocks relative to the INMETRO ITS-90 temperature scale (with the uncertainty of a small fraction of the mK).

5. CONCLUSIONS

As a result of the development of new parallax-free methods of length measurements by optical interferometry, development of high-precision optical interferometers and through application of the precisely measured corrections on the main influence factors, the range of the regime of the length measurements of material artifacts with ~ 1 nanometer uncertainty level have been dramatically increased relative to the one, obtained with atomic force microscopes. With the new Kösters interferometer we hope to reach nanometrology regime in measurements of gauge blocks up to 100 mm, including.

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