PRIMARY TRACEABLE NANOMETROLOGY AT INMETRO BASED ON THE INTERFERENCE MICROSCOPE AND AFM CALIBRATION

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Abstract: Here we report development of the primary nanometrology capacity at INMETRO. The interference microscope (IM) of Linnik type has been developed and it is currently under optimization and characterization. Secondary calibration was made with commercial AFM. Our IM is traceable to the meter SI unit via stabilized He-Ne laser as a reference wavelength standard. The registration of the fringes is done by automated CCD system with 2 possible processing approaches: interferometric pattern processing and the phase stepping technique. We report some progress in development of the hardware and software adequate for sub-nanometer resolution of the instrument. The instrument permits both point ant topography kind of measurements. Thus, comparison of advantages and disadvantages of the both techniques can be performed. We also report development of the 3D topography comparator software for this specific task. Results of optical IM measurements are compared with those obtained with AFM. The detailed study of systematical errors of IM is being performed and some result are reported. The instrument is aimed for international key comparisons of step height standards.

Keywords: Nanometrology, Interference microscopy, AFM, gauge block, interferometry.

1. INTRODUCTION

Traceable Nanometrology of high accuracy is necessary to provide the quality control basis for nanotechnology. In its broad understanding nanometrology is the science and technology of measurements of the artifacts with nanometric accuracy. Since nanotechnology is playing more and more important role in the industry, it is the task of the metrology to provide better measurements to support this activity. In this respect, nanometrology at National Metrology Institute (NMI) of Brazil, INMETRO has started with development of high resolution Gauge block interferometry (GBI) about 10 years ago [1-2]. The GBI instrument was successfully characterized and used in several international comparisons. Now the next obvious step is to apply the knowledge in interferometry for measurements of smaller objects like step heights. Interference microscopy (IM) is commonly used for this and it is known to be quite accurate approach for this particular task [3]. Out of several known techniques of nanometrology IM is preferable since it provides direct traceability to wave length standards.

The IM can perform measurement directly relative to wave length standard such as frequency stabilized lasers. Thus, we can use IM for primary calibration of the secondary standards such as step heights. After secondary standard is calibrated it can be used to calibrate vertical axis of the AFM. The final result of this activity, therefore, is to provide AFM measurements traceable to the primary standards of length.

1. EXPERIMENTAL SET UP

We have constructed a new system that is Linnik type Interference Microscope based on frequency stabilized laser as a reference wave-length source. Construction was made on granite table with intermediate optical breadboard. Most of the opto-mechanical units used are relatively simple components originally manufactured by Newport and NewFocus. Optical beam-splitter of high quality was used to provide maximum accuracy of interferometer (due to minimum beam distortion).

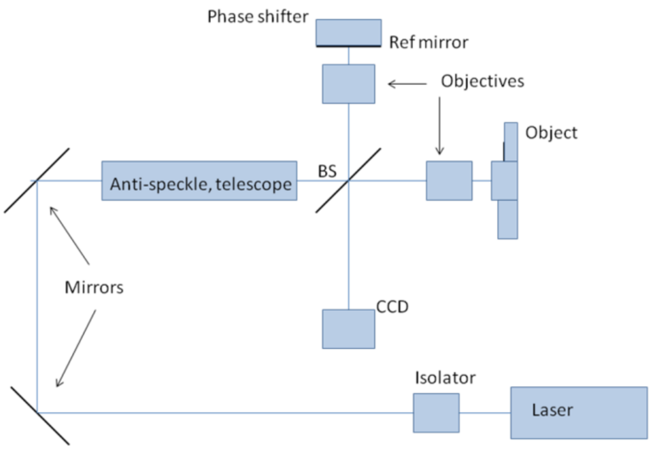

Fig. 1. Set up of Linnik type interferometer, where BS is the high quality 50/50 beam splitter, Object is the step height or master height standard, Objectives are the conformal pair of x10, x20 microscopic objectives. Ref mirror is the reference mirror optionally located on phase shifting PZT module.

Laser light used from He-Ne frequency stabilized laser (SpectraPhysics or Agilent) calibrated relative primary He-Ne Iodine stabilized laser standard. Fringe pattern is collected by high quality research grade digital CCD 1.5 megapixel camera of 12 bits resolution from PCO. The frames are taken by PC and processed with specially developed and tested dedicated fringe pattern processor software (SW). Reference mirror can be optionally located on phase shifting unit.

While we plan fringe processing to be the main method of measurement, we also would like to have step phase possibility for additional study of the systematical effects. From our previous experience with common GBI the phase stepping unit can be reliably calibrated "on-flight" within measurement if up to several fringes phase shift is available. Then shifting phase and recording output of the CCD with multiple frames (typically 100 or more) we can use corresponding sinusoidal fit to find exact phase difference for any point of interest. Simplest method of phase shifting is movement of the reference mirror, but in case of Linnik interferometer it is not really the best solution because by moving reference mirror the optimum optical path for fringe forming is disturbed. We are planning to use optical wedge for this purpose later on.

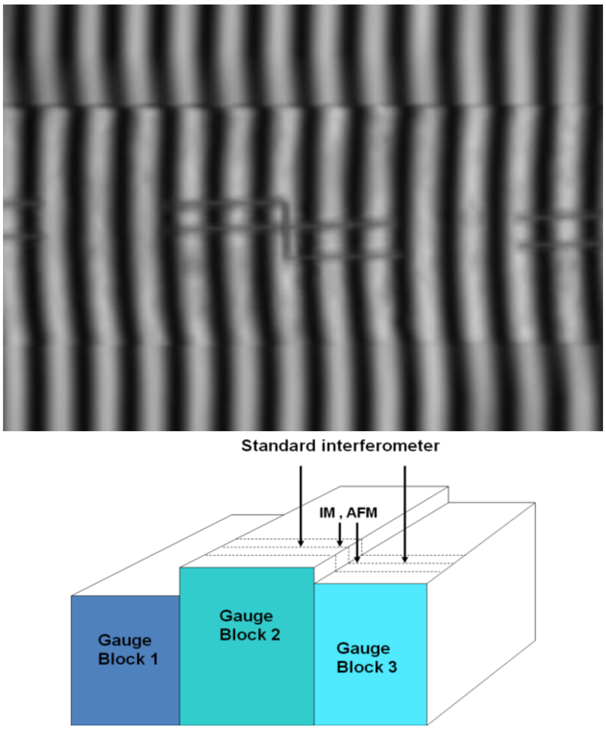

Fig. 2. Interferogram of triple GB standard. On the buttom is the layout of the triple GB step Master Standard.

We used as the secondary Z height standard the Mitutoyo triple step gauge block, Step Master. The Step Master is a master secondary standard used for the z-axis (vertical direction) calibration of optical and stylus instruments. The standard is made of interconnected 3 gauge blocks of different heights as shown in Fig.2. The choice of this particular standard was carefully considered from the point of view that it is the only artifact that can be measured by both classical Michelson type GB interferometry and microscopic methods such as AFM and IM.

Preliminary study of the reference secondary standard made with Zeiss interferometer has shown that the artifact exhibits quite flat surfaces of all 3 Gauge blocks. Among the other advantages of this type of standard we should mention high long time stability and negligible roughness difference (known as the phase change correction) between the blocks produced from same material and polished to the same texture finish. The nominal difference of one stepwas 10 um while in the other was 2 um.

2. DATA PROCESSING

We have developed set of software tools suitable for fringe image processing, phase shifting interferometry and post processing data visualization. The main software (SW) module of fringe pattern processing is based on multi-parameter iterative fit of the digitized pattern along the vertical line. Prior to fit it is possible to perform direct / reverse FFT with Gaussian filter in between. This filter is known not to perturb the phase and it is used to remove pixel noise from the interferometric pattern. Additionally pixel noise was removed by averaging several frames to produce the final interferogram used for processing.

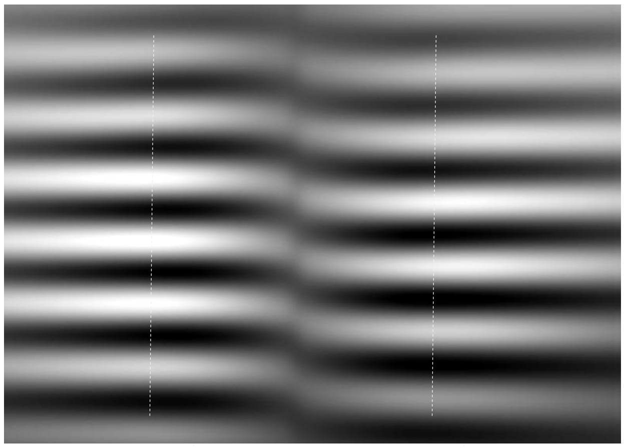

Fig. 3. Fringe pattern for 10 um GB step taken with Linnik interferometer. Vertical dashed lines are the eye guide used to select digitized area of the pattern.

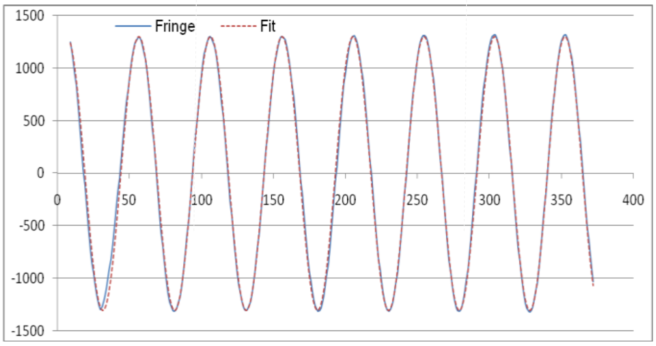

Fig. 4. Quality of the fringe (solid) and the fit (dash). Typical difference in most of the pattern is less than 1% almost invisible. Pixel number on X axis, the relative intensity of the CCD image on Y axis.

The fit function is sinusoidal with following parameters: Amplitude, phase, frequency, phase modulation and amplitude modulation. A minimization criterion is least square difference between measured data and a model function. Analyzing fringe pattern along several lines instead of just 2 we can figure out topography of the master step GB object.

It has been previously shown that using our fringe processing algorithm the resolution of the interferometer can be as high as 0.1 nm (about λ/6000) or better. While the accuracy of the measurement is determined by the quality of the GB and it might be as good as 1 nm [1, 2]. In Fig. 3 we demonstrate the quality of the fringe pick-up and fitting with our algorithm (see Fig.4). In here we note that both pixel and intensity (bits) resolution as well as stability/uniformity of CCD is quite essential for obtaining good results.

In order to compare measurement with Atomic Force Microscopy (AFM) we have measured the same secondary master standard using commercial Witec Alpha 300 AFM. Measurements with AFM cannot be done using large area of the step. Also since blocks are slightly curved, typically it is desirable to compare several measurements done in different places of the standard moving along the step direction.

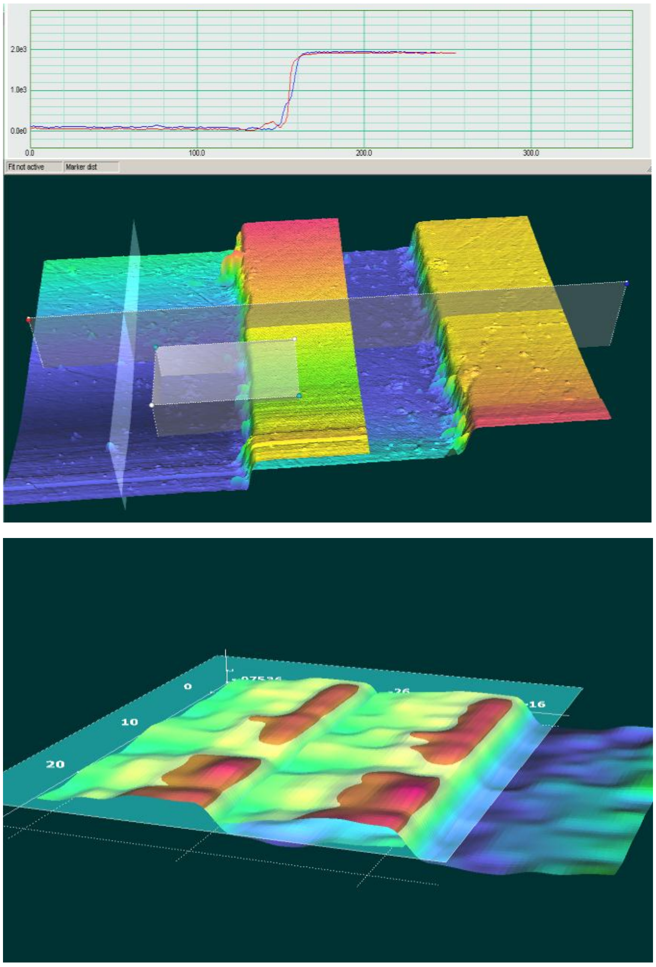

Fig. 5. Comparison of the data with AFM comparator 3D mode. Interactive Cube is used to mark the area of interest for parameter calculation. Planes are set to read intersection with corresponding 2D plots (upper part). At lower image Z intersection plane is used for detailed map comparison between 2 measurements.

In Fig.5 we show typical comparison for data from 2 different locations. For detailed comparison of the different measurements we have developed dedicated 3D Software that permits visualization of several surfaces in one screen with interactive virtual reality style rotation, pan, zoom. Several mouse driven measurement tools are instrumental for analysis of the intersection areas and volumes. All together this approach mekes it easy data drill down and detailed comparison of the features of interest. Some screen shots are presented in Fig.5.

3. STUDY OF THE SYSTEMATICAL ERRORS

One of the most important and difficult tasks of the primary comparators is detailed characterization of the instrument and uncertainty evaluation. This task implies measurement of the systematical errors of the instrument. While Carl Zeiss interferometer was studied in this respect [4,5] the new Linnik interferometer investigation and characterization is ongoing work of our laboratory.

The important information concerning possible drifts of the interferometer read out can be obtained by automatic continuous measurement of the length during changes of environment conditions such as temperature. Our interferometer is fully automated and permits this tipe of measurements. The systematic drift is shown in Fig .6.

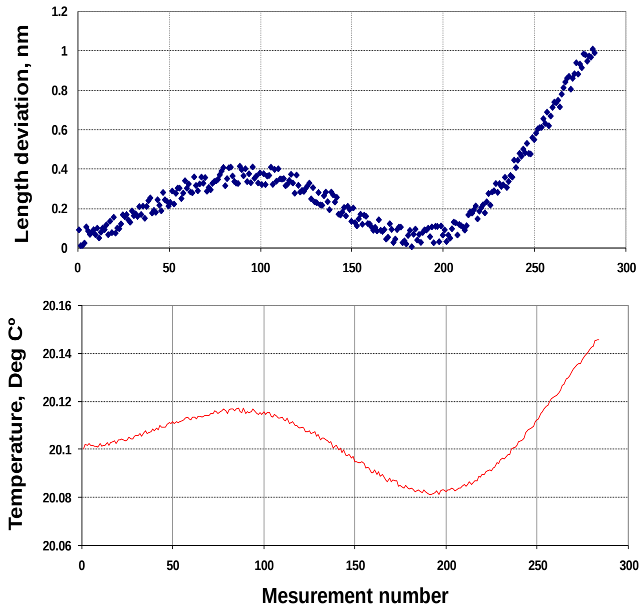

Fig. 6. Correlation of the temperature drift with measured length. About 300 measurement performed during several hours of continuous read out.

The correlation was expected and observed. We attribute temperature related drift with possible changes in optical path of the measured or reference part of the interferometer.

The most serious errors of Linnik type of the interferometers is known to be misalignment of the reference and measuring shoulders. While our interferometer software permits to control misalignments we have developed simple but very efficient self calibration procedure. In this procedure we measure step and immediately after that calibrate the fringe pattern on reference flat surface of the gauge block. We can optionally use flat surfaces of both gauge blocks in the master standard to perform such self calibration. It the surface of the gauge block is flat this in ideal case will remove misalignment error.

We have performed several measurements deliberately misaligning interferometer. Some of the results are presented in Fig.7.

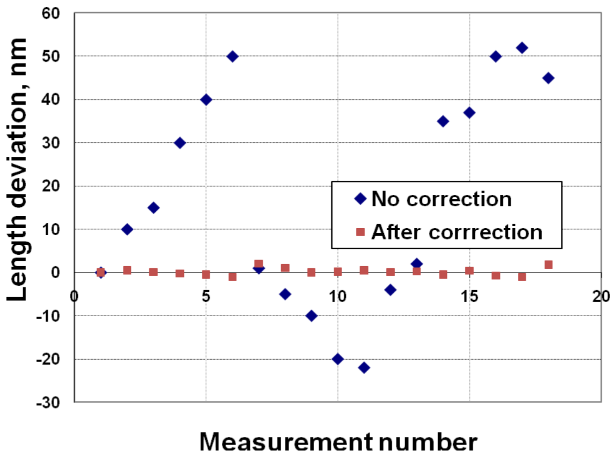

Fig. 7. Misalignment error of interferometer. Several measurements non-corrected and after correction. Standard deviation of the corrected values is about 0.8 nm.

The typical spread of misaligned data was about 100 nm. While after applying the correction from self calibration procedure above the data spread is within 1 nm.

4. RESULTS AND DISCUSSION

In general, it is not easy to compare the results of different type of the instruments because each has its own advantages and restrictions. In case of the step GB main restriction is on area measured. While step GB is quite flat in the areas recommended by Mitutoyo for measurement, it is not that flat close to edges of the block. And those are exactly the only areas where microscopic instrumentation can be used. Using Carl Zeiss interferometer closest approximation to the edge is about 0.3 mm restricted by pixel size of the camera and diffraction at the edge. Reliable results from AFM we achieved with XY range of about 40 um. And as usual repeatability of all instruments was better than 1 nm, which indicates that all can be calibrated or studied for systematic errors up to better accuracy.

The results were in agreement within 2-3 nm with data obtained by Mitutoyo GBI, Linnik interferometer and Zeiss interferometer. But the difference between interferometric and AFM measurements was a bit higher up to 20 nm in worst case.

In here one should recall that this type of measurements of relatively big step is the difficult case of errors accumulation in simple AFM instruments without additional interferometers for on-flight recalibration. Because nonlinear PZTs always increase errors with increase of range (Z range in this case). So, in general we were satisfied with these preliminary results. Obviously, commercial AFM of this kind is itself not easy instrument and should be studied for systematic errors, especially in large ranges for all 3 axes.

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