High-resolution interferometric microscope for traceable dimensional nanometrology in Brazil.

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Abstract: The double color interferometric microscope is developed for step height standards nanometrology traceable to meter definition via primary wave-length laser standards. The setup is based on 2 stabilized lasers to provide traceable measurements of highest possible resolution down to the physical limits of the optical instruments in sub-nanometer to micrometer range of the heights. The wavelength reference is He-Ne 633 nm stabilized laser, the secondary source is Blue-Green 488 nm grating stabilized laser diode. Accurate fringe portion is measured by modulated phase-shift technique combined with imaging interferometry and Fourier processing. Self-calibrating methods are developed to correct systematic interferometer errors.

Keywords: Laser interferometry, phase-shift, optical nanometrology, dimensional metrology, step height standards.

1. INTRODUCTION

Nanometrology is the science of measurement at the nanoscale level. It is considered as the basis of the nanotechnology in quality control of the products [1]. As a part of large international investments in nanoscience various instruments has been developed to support specific nanotechnology measurement needs [2]. We consider common approach of Co-ordination of Nanometrology in Europe (Co-Nanomet) [1], to be a good model for implementation in the near future. According to the Co-Nanomet strategy, measurements in the nanometer range should be traceable back to internationally accepted units, meter in our case of dimensional nanometrology. This requires creation of national validated measurement methods, calibrated scientific instrumentation as well as qualified reference samples. The traceability chain up to the primary nationally realized units for the required measurements must be maintained for any nanometrology quantity under consideration. So far nanometrology has been established internationally in only a few special cases. Principal problem of nanoscience instruments such as SPM, AFM, TEM, etc. is that they are not directly traceable to SI meter unit, but via additional laser interferometers or via secondary calibrated reference standard artifacts. Co-Nanomet delegates traceability maintenance to NMI's, serving as centers of excellence (CoE). The concrete nanotechnology measurements and instrumentation is delegated to centers of dissemination (CoD): i.e. R&D groups at technical accredited laboratories, institutions and companies involved in nano-tech products implementation. With those recommendations we at Interferometry Laboratory, Optical Metrology Division of INMETRO (CoE, Brazil) are working toward creation of national CMCs for micro- and nano-meter scale with target uncertainty of < 0.5 nm.

Here we report interference microscope (IM) for traceable nanometrology within most interesting range from micro to sub-nanometer. The IM is supposed to provide continuous transfer of the meter unit from traditional length metrology to nanometrology. Relatively easy from technical point of view and historically most studied approach is a height Z one point 1D calibration of the material artifacts using wave-length calibrated light sources. Classical interferometry and IM for many decades has been proved a reliable solution for this calibration needs. Secondary standards used are step height standards (SHS).

Previously at INMETRO/DIOPT nanometrology facility prototype was created, based on single He-Ne 633 nm stabilized laser and phase-shift interference microscopy (PSIM) principle [3]. Serious disadvantage of the system was large averaging time required for achieving target sub-nanometer resolution [4]. This makes low power system very inconvenient, expensive to run and virtually non-suitable for routine nanometrology. Here we report further development of IM with extra light source: 40 mW blue-green grating stabilized laser diode that can be "on-flight" calibrated via direct wavelength comparison to red reference standard. High power laser IM application permits implementation of various modern detection techniques such as sinusoidal modulated PSI and time-gated imaging interferometry. Those improvements are implemented in the new prototype reported here. Performance is evaluated by computer simulation and compared with direct measurements using several different types of SHS.

2. SETUP AND SAMPLES

Optical setup consists of 3 main parts: (i) Light sources - stabilized lasers and beam conditioning anti-speckle unit with telescope (ii) IM itself with reference and measuring arms on automated movable stages for sample manipulation and phase-shifting; (iii) detector part based on CCD and variable zoom telescopic unit.

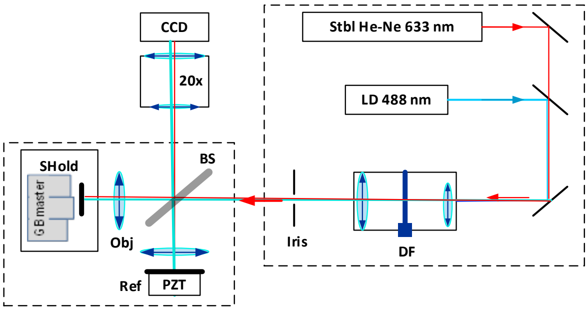

Fig.1. Optical setup of IM includes: **BS** - beam splitter, **SHold** - sample artifact on holder XYZ stage, **Ref** - reference mirror on PZT, **Obj -** two microscopic objectives, **DF** - rotating diffuser with beam collimator, **Iris -** variable diaphragm, **CCD -** imaging part with 20x zoom eye-piece.

PZT in Fig.1 is the phase-shifter used both for PSI and for calibrations of the blue laser relative to the red reference laser in procedure similar to wave-meter operation. We move reference mirror certain distance measuring (digitizing) shape of the interferometer fringes. The phase difference between the lasers gives the wavelength difference.

To cover target range of measurements we used 2 types of reference standards, macroscopic and microscopic artifacts: i) steel gauge block master set (GBS) from Mitutoyo, with two steps of 2 and 10 μm; ii) Al or SiO_2 coated steps on mono-crystal Si, so called step height standards (SHS).

3. SUB-NANOMETER RESOLUTION

To reach highest possible resolution required by modern nanometrology we improved several key techniques of data acquisition and processing. Detection part of hardware is based on HQ scientific grade 1.5 Mpixel CCD, effective 14 bits intensity resolution with averaging. This imaging output is further improved by pixel binning and 2D FFT Gaussian filtering processor. Final output is fit by multi-parameter sinusoidal function to extract phase values at point of the interest. With our HW we can use either fringes along the CCD image in frame (imaging interferometry) or PSI method. The above procedure is used for fringe fraction extraction in both imaging and phase-shifting methods at resolution of about < 100 pm. Such high resolution can be fully benefited from correspondingly high accuracy of the PSI unit. PSI hardware is tilt-moved 3 degrees of freedom unit that is fed with 24 bit DAC output amplified by low noise HV unit. The most complete and informative technique we developed is multiple step phase shifting with 4D (XY-Z-A) imaging voxel cube hyper-data acquisition, where XY directions are pixels (SHS points), Z - phase scan and A - fringe intensity for phase extraction. Result of the single scan is 100-200 series of fringe images sampled at variable stepped Z length of the interferometer reference arm, so called *image stack* or voxel cube. In Z direction we have multiple point sinusoidal signal lines each corresponding to certain point on the sample (pixel). FFT procedure is applied and topography phase map is calculated. Processing of the 4D data sets requires substantial computational power so that parallel methods with either multicore or multi node architecture is desirable.

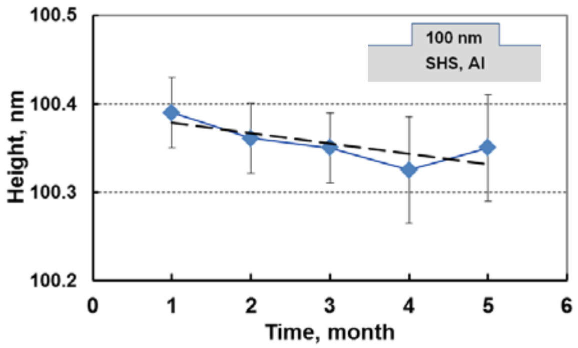

Fig.2 Drift of the measurement during several months. 100 nm SHS made of Aluminum.

Hardware and algorithm improvement resulted in accurate phase (length) determination down to sub-nanometer or sub-Ångström level. The resolution test is repeatability of real output (Fig.2) that is good enough to detect drift of about 50 pm of the whole set-up or/and sample.

4. NOISE AND SYSTEMATIC EFFECTS

Detailed characterization and some comparisons of the IM were performed. Main systematic errors were evaluated, minimized and suitable corrections found.

<u>Repeatability and statistics</u> was measured using long series of automatic data acquisition with IM realignments between series. This involves significant amount of data processing and time. Experimental decrease of random noise is shown in Fig.2 for He-Ne laser standard.

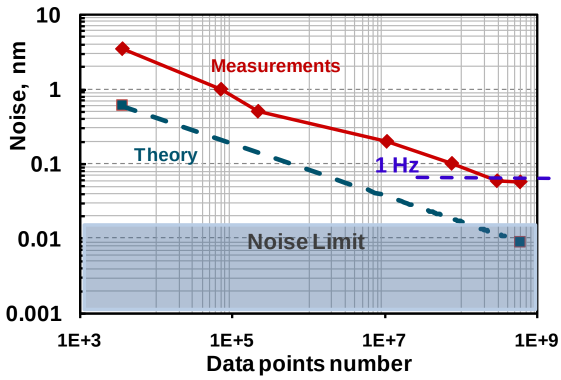

Fig.3. Stability of the measurement SHS 100 nm height deposited Aluminum (INMETRO).

The noise trend was not improving after certain periods of averaging, indicating that some residual noise is present, mostly related to vibrations as was confirmed with measurements of INMETRO Vibration Lab (LAVIB). Basically we have reached the low frequency flicker-noise floor close to 1 Hz and the optical table resonant frequencies characteristic time. The solution is to move detection away from resonances and flicker-noise. Blue laser of larger power, modulation PSI and time-gated imaging, all those techniques were implemented to move data of interest detection to higher frequency with corresponding fast acquisition and noise reduction. Expected noise at same conditions is shown as blue line in Fig.2.

<u>Aperture correction</u> *(obliquity error)* typically has largest contribution to uncertainty of IM

instruments. Theoretical analysis and PC-simulation was made, resulting in numerically generated function: the value of correction vs. variable numerical aperture (NA). The function was compared with data measured at the same conditions to evaluate real influence of the effect. Variable iris diaphragm at the IM input was utilized. Similar effective NA decrease is produced by eye-piece, that is telescopic variable zoom unit (20x, Fg.1). The minimized correction in our geometry is relatively small: >1.002 due to possibility NA variation down to >0.1 or less values. For nominal 100 nm for SHS the correction was measured to be about 100 pm.

Phase-shifter nonlinearity effect results in phase differences at beginning and end of phase scan that can be detected analyzing full phase record wave-form. This effect found to be significant for fringe displacements 4 integer numbers or more. The effect was measured and adequate mathematical model function of modulation additional term is used to compensate this error within target 0.1 nm operation.

Wavefront distortions errors follow from unequal optics and alignment in IM sample and reference arms. The SHS height as defined by ISO 5436-1-2000 and measured by interferometry incorporates defects of optics associated with as on-off-axis path difference (*considered as Abbe offset)*. Related wavefront correction is determined by height $\boldsymbol{Z_{corr}=0}$ measurement on flat area of the same SHS. The correction is acquired during each measurement cycle. This procedure corrects associated error down to 100 pm target accuracy.

5. CONCLUSIONS

New step height nanometrology CoE facility was developed and characterized. By principle of operation the facility is a hybrid type IM with combined PSI and fringe pattern processing algorithms. Equipped with different color wave-length stabilized lasers the IM provides full automated traceable self-calibrated operation.

As compared to previous IM prototype with red He-Ne only [3], high resolution is achieved at shorter measuring time. Signal-to-noise ratio is improved of about x10 times. Improvements pushed system to physical limits of optical interferometry. This next step in optical nanometrology was possible due to implementation at INMETRO / DIOPT optical frequency comb generator based on femtosecond laser facility that provides novel light source for precision dimensional metrology [5-6].

6. ACKNOWLEDGMENTS

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7. REFERENCES

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