Self-calibration of the secondary laser source in two-color Linnik interferometer

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Abstract. The imaging Linnik interferometer equipped with two lasers of different colors is under development and metrological study at National Metrology Institute of Brazil (INMETRO). This work reports the self-referenced method for practical calibration of the secondary laser wavelength. The method is based on accurate digitalization and comparison of the waveforms for both reference He-Ne stabilized laser at 633 nm and secondary laser diode at 488 nm. The process makes use of multiple step phase-shifting technique for waveform measurement and multi-parameter fit for wavelength extraction. The advantage of the method is that no extra hardware of realignment of interferometer is required to perform the calibration.

Keywords. dimensional surface metrology, laser interferometry, interference microscope, phase-shift, optical nanometry

1. Introduction
The interference microscopy (IM) is a valuable dimensional metrology tool that provides absolute measurements traceable to the wavelength standards. Because of highly flexible nature of the IM, specific solutions have been developed for both metrology laboratory needs and for industrial quantitative inspection [1]. In recent years there was several important improvements in this classical field such as extension to 3D areal surface topography, combination with phase-shifting interferometry (PSI), height scanning technique, etc. [2,3] One of such extra enhancements of IM is use of multiple color light sources including white [4-6]. This addition permits resolution of integer fringe ambiguity on sharp features of measured object.

In the case of our IM we currently use two-color version of Linnik interferometer with one main He-Ne stabilized laser and secondary blue-green grating stabilized diode laser (DL) model DL-100 PRO from TOPTICA Photonics AG (Germany) at about 488 nm [7]. While the main laser is calibrated by frequency beat relative to the primary He-Ne iodine stabilized standard, calibration of the diode laser is not an easy task. Thanks to robust cavity design, temperature control and superior electronics, the DL is very stable laser, but still there are always possible frequency changes due to mode hopping and
unexpected drifts. This problem requires “on flight” wavelength calibration of the secondary source. The obvious approach is to use high stability He-Ne laser to verify frequency of the DL.

The traditional wave-meters perform the calibration of the wavelength by comparison of fringe numbers as counted by the interferometer with long distance traveling retroreflector in one arm. If the fringe number is measured for both reference and unknown lasers, then the ratio gives the wavelength relative to reference. This can be easily achieved with a specific setup out of interferometer, but is very inconvenient within IM. On the other hand, long distance travel is only necessary for simplifying electronics/computation of the wave-meter. Indeed, if one can measure the whole waveform accurately enough to extract wavelength with acceptable accuracy then shorter travel is sufficient to perform the calibration.

2. Experimental setup and procedures

Our Linnik interferometer is a PSI type instrument, meaning that the phase-shifter (PS) is already built-in for phase measuring operation [7,8]. We use the same PS unit and similar smooth phase-shifting method as for main phase measuring operation (figure 1). In this PS method the reference mirror is moved by PZT with multiple small steps while the system takes images of output CCD at each position.

![Experimental setup of the Linnik interferometer. BS is the beam-splitter, Ref.Mirror is the reference mirror movable by PZT motorized holder. OL1 and OL2 are the objective lenses in both reference and measurement arms of the interferometer respectively. Filters are the cut-off glass filters that geometrically separate beams of different lasers.](image)

Typically, we use 100 to 200 steps of 10-30 nm each. The software acquires the data from the CCD as series of frames (image stack) usually one for each PZT position. The data from single pixel or average from the group of neighboring pixels gives change of intensity of the interferogram during phase shifting. This data has the shape of digitized sinusoidal waveform with several interference fringes (figure 2). The sophisticated multi-parameter fit is applied to extract wavelength/frequency from the
waveform. The waveform is distorted by nonlinearity of the PZT, so a simple sinusoidal fitting model is not adequate for accurate frequency extraction. We use a model function of the following form

\[ F(x) = A \sin(\omega x + \Omega_m x^2 + \Phi), \]  

where \( x \) is the value proportional to PZT voltage, \( A \) is the amplitude, \( \omega \) is the frequency, \( \Omega_m \) is the frequency modulation coefficient, and \( \Phi \) is the phase that carries height information.

Figure 2. Digitized waveforms obtained from He-Ne reference laser (upper curve) and Blue LD under measurement (lower curve). Axes units are the relative intensity vs. PZT step number. Dots are the measured data points and lines are the results of the fitting procedure. Noise in data points is reduced by optimizations.

The frequency is not constant due to nonlinear movement of the PZT. Meaningful wavelength in this condition can be attributed to the frequency at the certain point of the whole movement range. We have tried both initial point and the point corresponding to the middle step. Both were giving the same repeatability.

Beams of two lasers can be separated either by geometrical filtering of the fields or by measuring lasers one by one in separate PZT scans. In Figure 1 we show geometrical separation with cutoff filters, i.e. upper part of the field of view is illuminated by LD, while lower by reference He-Ne. We have tried both methods of beam separation. Each method has advantages and disadvantages discussed below.

3. Optimization and uncertainty estimation

The repeatability of this type of measurements typically is restricted by the noise of the IM system. We have identified several important sources of the noise: (a) CCD pixel noise, (b) laser output, (c) electrical voltage noise of PZT driver, (d) mechanical vibrations. Some noise can be effectively reduced by suitable equipment and optimized measuring procedures.

The pixel noise is reduced by binning pixels. We use 4x4 or 8x8 pixel square binning. The noise in laser output is reduced increasing exposure time of CCD. Also we use 2 frames at one PZT position
averaging frames, which further decreases both pixel and laser noises. The noise in voltage of PZT is decreased using adequate digital to analogue converter (DAC) to generate phase-shift signal and low-noise high-voltage amplifier. In our case we use 24-bit DAC built-in model SR850 lock-in amplifier from Stanford Research Systems, USA and analogue amplifier model NV40 from Piezosystem Jena GmbH, Germany. The analogue amplifier was tested to operate at less than 0.3 mV RMS noise level. The combination of these two instruments makes it possible to perform sub-nanometer positioning tasks with suitable repeatability.

We have studied some systematic errors of the IM system. It was observed that due to distortions of the optical path by objective lenses the frequency of the waveforms is not equal for all the aperture. Further similar inhomogeneity of the field of view is produced by the fact that phase shifter does not move the reference mirror exactly perpendicular to the optical axis. In this conditions measuring waves at different points of the field will produce systematic error. Thus, geometrical separation of the laser beams as shown in figure 1 is possible but not the best solution. We use the shutter that closes one beam and opens the other instead measuring laser one at a time. An obvious advantage of this approach is that the same pixel area is used for both lasers eliminating above error. The disadvantage is that different PZT movement events are used that potentially have not the same positioning. The study of multiple measurements demonstrated that repeatability of the PZT is good enough for our target wavelength accuracy.

To estimate A type uncertainty of the wavelength measurement we have performed multiple repeatability tests. We measure reference and sample laser one after another several times calculating the results and statistics in series of 20 to 50 measurement cycles. The final result was about 5x10-5 in relative wavelength, that we consider to be close to noise limited minimum.

The systematic errors are mostly compensated by the fact that this is relative type of measurement, where systematic errors are similar or the same in both reference and test scans. Possible sources of the systematic error might be: (1) misalignment between two lasers, (2) frequency drifts or jumps of LD, (3) dispersion within objectives that result in different path of two lasers. We have checked possible misalignment error by realignment of lasers several times and by deliberate slight misalignments introduced for test purpose. The resulting difference was about 10-4 relative. Tests of possible frequency changes in LD were performed by continuous measurement of the laser during several hours of operation. Repeating the test several days we come to the conclusion that possible mode hopping or drifts do not affect the final result within the noise limit of 5x10-5. Calculation of possible wavelength change in 2-3 consequent mode hops has confirmed this conclusion. To estimate dispersion error, we removed both objective and performed measurement in Michelson interferometer configuration. The result was that dispersion is not affecting significantly the measurement. Perhaps this is because we use apochromatic objectives known to be dispersion compensated.

All those experiments indicate that the final uncertainty is about 2x10-4 at k=2 (95% confidence level). This uncertainty meets our target requirements. Thus, the method and procedures were proved convenient and reliable for coincidence method application.

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