Nanotrace: the investigation of non-linearity in optical interferometers using X-ray interferometry

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Abstract

Seven European National Measurement Institutes (NMIs) have recently joined forces within the European Metrology Research Programme funded NANOTRACE project to develop the next generation of optical interferometers having a target uncertainty of 10 pm. These will be needed for NMIs to provide improved traceable dimensional metrology that can be disseminated to the wider nanotechnology community thereby supporting the growth in nanotechnology. A comparison of performance of the best potential candidate interferometers will be made using X-ray interferometry.

Keywords: Optical interferometry, X-ray interferometry, non-linearity, nanometrology

1. Introduction

The growth in nanotechnology had led to an increased requirement for dimensional measurements with sub nanometre accuracy. The main instrument used for traceable dimensional metrology is the optical interferometer. At the nanometre level it is prone to non-linearities that affect measurement validity. This is particularly problematic when measuring displacements that correspond to a non-integer number of optical fringes. Although the non-linearity can be corrected using software or reduced by careful interferometer design, a residual component remains [1]. Traceable measurements of the residual component can be made using X-ray interferometry. Owing to the variety of optical interferometry applications and potential techniques available for reducing interferometer non-linearity it was felt that the most effective approach was to develop several different interferometer systems and to make a systematic comparison of their performance. These include multipass techniques, high harmonic detection, high frequency lock-in techniques, multiwavelength interferometry, combined optical-capacitive sensors, high accuracy phase meters, and locked Fabry-Perot cavities. The technique chosen for verification of the optical interferometers performance is X-ray interferometry and is discussed in the next section. However, owing to the specialized nature of the technique the development of a portable optical transfer standard is also planned.

2. X-ray interferometry

X-ray interferometry was first demonstrated by Bonse and Hart [2, 3] and a few years later Hart [4] showed that an X-ray interferometer could be used for metrology. Unlike most optical interferometers, the fringe spacing in an X-ray interferometer is independent of the wavelength of the incident radiation; it is determined by the spacing of diffraction planes in the crystal from which X-rays are diffracted. Silicon is the material normally used for an X-ray interferometer (XRI) since it is readily available in a pure, defect free form with a known crystallographic orientation and lattice parameter [5-7]. The fringe spacing in an X-ray interferometer is therefore not only several orders of magnitude smaller than that in an optical interferometer thereby obviating the need for fringe division as with optical interferometry, but it is also traceable.

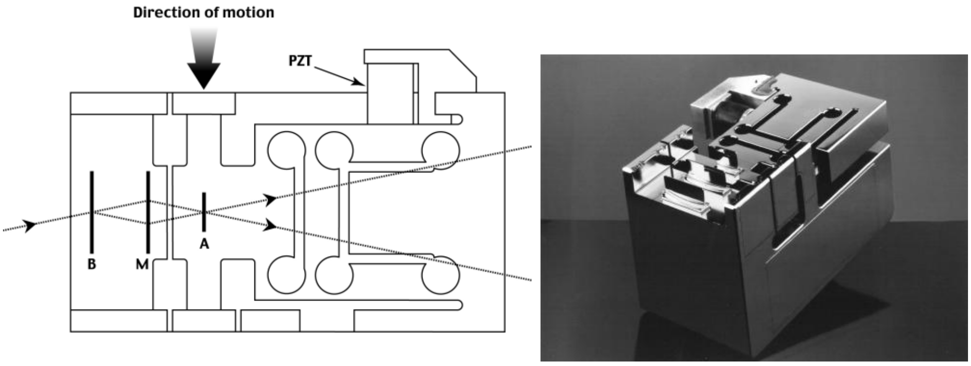

Fig. 1a and b. Schematic diagram and photograph of the monolithic X-ray interferometer.

Figures 1a and b shows a schematic diagram and photograph of the monolithic XRI developed for the combined optical and X-ray interferometer project (COXI) [8]. It is made from a single crystal of silicon in which three thin, vertical, equally spaced lamellae were machined. A flexure stage that has a range of 10 micrometres and is driven by a piezoelectric transducer (pzt) has been machined around the third lamella. X-rays are incident on the first lamella, (B) and are Bragg diffracted. Two diffracted beams are produced; the first lamella can be thought of being analogous to the beamsplitter in an optical interferometer. The two beams diffracted from the first lamella are incident on the second lamella (M), analogous to the two mirrors in a Michelson interferometer. Two more pairs of diffracted beams are produced and one beam from each pair converges on the third lamella (A). These two beams give rise to a fringe pattern whose period is equal to that of the lattice planes from which the X-rays were diffracted. For the (220) planes in silicon this is 0.192 nm. The pattern would be too small to resolve individual fringes, however when the third lamella is translated (by the pzt) parallel to the other two lamellae, a Moiré fringe pattern between the coincident beams and the third lamella is produced with a period of 0.192 nm. Consequently, the intensity of the beams transmitted through the third lamella varies sinusoidally as the third lamella is translated. By measuring the intensity of one of these transmitted beams it is possible to measure the displacement of the third lamella. Since the displacements are traceable, the X-ray interferometer can be regarded as a ruler with subnanometre divisions. At the sides of the interferometer, there are three optical mirrors allowing the XRI to be interfaced to an optical interferometer

By servo controlling the pzt used to move the third lamella it is possible to either hold the third lamella in a fixed position or move it in discrete steps equal to one X-ray fringe period [9]. A comparison of the results obtained by the optical interferometer with the displacement of the X-ray interferometer yields the non-linearity in the optical interferometer. The non-linearity of an NPL designed Jamin interferometer and a Heidenhain encoder have both been measured using X-ray interferometry [10, 11]. In both cases cyclic errors with amplitudes of much less than 100 pm were observed once the Heydemann correction [12, 13] had been applied.

3. Optical interferometer techniques

For traceable length measurements at the nanometre level the main challenge for optical interferometry is accurate interpolation of the laser wavelength. This is affected by the periodic non-linearities caused primarily by optical imperfections and the influence of noise on phase detection. There are different ways to minimize these effects and the project aims to develop three of these; (1) improvements to the optical configuration to minimize the signal periodicity or to generate electronic signals of higher quality, (2) optimizing the phase measurement electronics and mathematical methods to reduce periodic nonlinearities (3) implementation of a measurement system with two different periodicities to determine and correct nonlinearity.

3.1 Development of new optical configurations

Using a multipass interferometer where multiple reflections increase the number of fringes in a given length, the resolution of an individual fringe can be greatly increased. Although the causes of nonlinearities are not eliminated, their effects are scaled by the reduction in length of the optical fringe. The design is based on an arrangement of the interferometer mirrors which allows a multiplication of the optical path by a factor of more than 30 thus allowing a fine subdivision of the optical fringe and an expected proportional reduction of errors associated with periodical nonlinearities [14]. Furthermore the envisaged optical set-up will have tilt detection capability at the nanoradian level, thus allowing an accurate control of the mirror displacement [15]. The configuration will be used with HeNe and Nd:YAG and is expected to have a resolution close to 10 pm for a displacement range of up to 100 μm.

Another configuration being developed is a fibre fed plane mirror heterodyne optical interferometer using spatially separated beams of different frequencies to avoid the frequency mixing in classical polarisation divided beams. Preliminary measurements using a similar approach with retro-reflectors showed that non-linearity levels of less than 100 pm were achievable [16].

The third approach is based on a tunable laser ‘locked’ to the resonance curve of a Fabry-Perot (FP) interferometer with the length of the cavity being modulated by the displacement to be measured. Changes of the laser frequency are proportional to the displacement so by tuning the laser, the interferometer works at fixed phase and consequently is virtually free from nonlinearities. Furthermore, since the distance measurement is obtained through a frequency measurement, the method is also extremely sensitive with the predicted measurement uncertainty being better than 50 pm.

3.2 Optimizing the phase measuring electronics and development mathematical methods to reduce periodic nonlinearities

Again several approaches have been adopted for improving phase measurement.

Improvements in phase measurement and non-linearity reduction have been achieved in heterodyne interferometers using an electro-optic-modulator (EOM), to generate a non-linear fringe modulation, combined with high-harmonic detection [17]. The method is based on fast phase-shifting of the optical path to null the phase difference of the heterodyne beat signals at each sub-wavelength displacement to be measured and has achieved non-linearity of less than 100 pm. This is currently being extended to modulate the fringe and use high-harmonic detection and fast lock-in detection techniques to thicken optical fringes, which together with a high speed (100 MHz) FPGA based data acquisition system will allow dynamic measurements with continuous compensation of the optical non linearity.

Another method utilising high accuracy frequency counters for phase measurement of heterodyne interferometer signals is being investigated. The detected beat signals are first mixed down to a suitable frequency range and then converted to sharp rectangular waveform with high quality comparators. The time difference and periodicity of the signals are measured with frequency counters and phase difference is analysed. The selected phase measurement scheme removes most of the periodic nonlinearity of the laser interferometer, since only the time difference of zero crossings of the signals is used for phase determination. Preliminary test has shown that phase resolving power target is achievable.

3.3 Implementation of two independent measurement systems with different periodicity to determine and correct nonlinearity

Multiwavelength interferometry using a frequency stabilized He-Ne laser 633 nm and a frequency doubled Nd:YAG laser 532 nm allow separation of periodical phase errors associated with the respective wavelengths. A common path design is utilized with the combination of the two laser beams using a dichroic mirror prior to the interferometer and a calcite beam displacer is used to separate the beams in the interferometer. The common path design reduces the interferometer's sensitivity to turbulence and other extraneous path changes. The phase shift due to displacement of the mirror is detected using two homodyne quadrature detectors and analog signals are processed in real time using a Heydemann type correction to compensate for the non-orthogonal and elliptical nature of the beams. Preliminary results show that residual non-linearity could be below 100 pm after elliptic correction.

In some instances the phase dependent non-linearity can be modelled so that phase meter values can be corrected to within 100 pm using a correction table. This has been realised using a capacitive sensor to provide a reference signal against which the sub-periodic non-linearity was determined. Although displacements measuring capacitive sensors are inherently linear devices, their linearity is not ideal due to edge effects, plate tilt, flatness and stray capacitances. These effects cause slowly changing and non-periodical non-linearity, which is different in nature from the non-linearity of the laser interferometer. The smooth non-linearity of the capacitive sensor can be first measured by the laser interferometer using a step length that is an integer multiple optical fringes (i.e. $\lambda/4 \approx 158$ nm). The periodical non-linearity of the laser interferometer is then measured using the linearized capacitive sensor as a reference and using sub-period stepping. An average of the measurements, after removal of first degree polynomial dependence between capacitive and interferometric position, gives a phase dependent non-linearity correction vector which is then used to give a linearized interferometric position.

4. Conclusion

The results of this project should produce a detailed comparison of the state of the art developments in optical interferometry and enable NMIs to provide traceable measurements at the sub nanometre level.

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