Traceable calibration of non-linearities in laser interferometers

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ABSTRACT

Laser interferometer systems are known for their high resolution, and especially for their high range /resolution ratio. In dimensional metrology laboratories, laser interferometers are popular workhorses for the calibration of measurement equipment. The uncertainty is usually limited to about 10 nm due to polarization- and frequency mixing. For demanding applications however nanometer uncertainty is desired. We present the measurements of interferometer components, which will be used to calculate an integral non-linearity by a virtual interferometer, of which the results will be verified with a traceable Fabry-Perot interferometer with sub-nm uncertainty.

Keywords: Laser interferometry, heterodyne, sub-nm, non-linearity

1. INTRODUCTION

The fundamental limitations of laser interferometer systems for achieving (sub-)nm uncertainties in small displacement measurements are in the photonic noise and in residual non-linearities which are inherent of periodic interferometer signals and which repeat each fraction of a wavelength. These deviations result from both the laser and from the phase measurement system of the interferometer itself,[1] but they can also result from polarization states of the laser and the optics used: beam splitters, retardation plates used with plane mirrors and corner cubes can influence the polarization state in interferometers using polarizing optics, or influence the contrast in interferometers with non-polarizing optics. We work with heterodyne laser interferometers, which use a polarizing beam splitter.

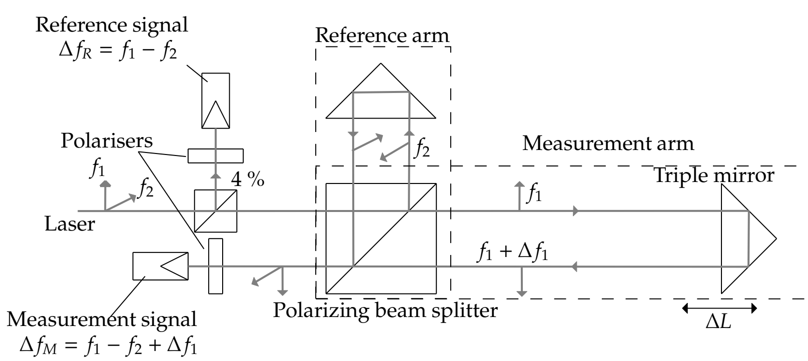

Figure 1. Schematical representation of the principle of a heterodyne laser interferometer.

In figure 1 the schematical principle of a heterodyne interferometer is presented. As a result of non-ideal optics and laseroperation the two beams emerging from the laser source will not be orthogonally linear polarized. Instead, they will be elliptically polarized[2] and non-orthogonal. Further the optics used, inherit polarizing properties themselves resulting in non-ideally split polarizations. Finally the effect of misalignment in optics must be mentioned. All these effects result in polarization mixing in the measurement and reference beams. As a result non-linearities exist in the interferometer measurements. Non-linearities with a perdiodicity of one wavelength of optical displacement are called first order non-linearities.

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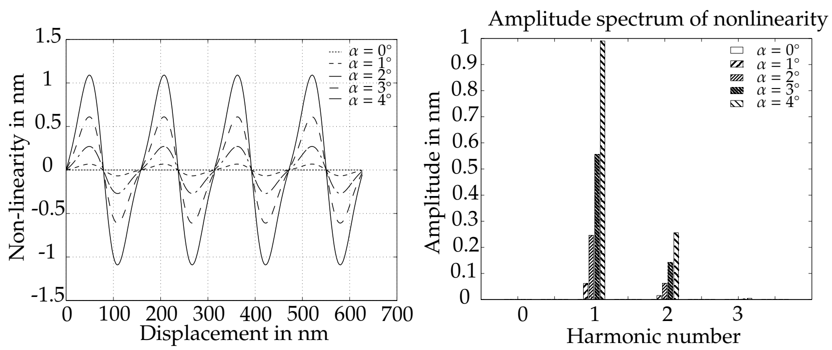
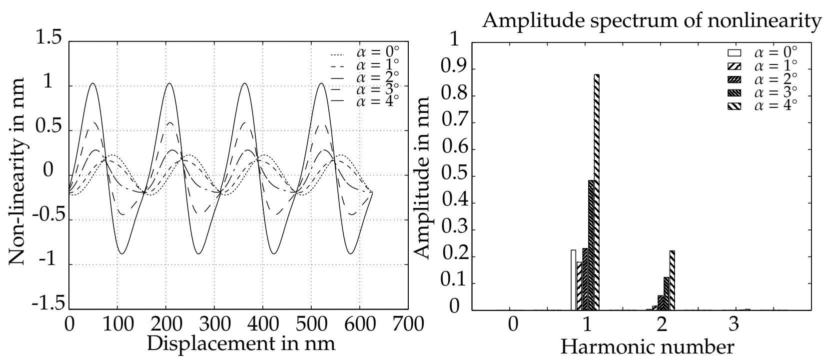
2. SIMULATED NON-LINEARITY OF A COMMERCIAL LASERINTERFEROMETER

Based on a Jones-matrix formalism a model was build enabling the calculation of non-linearities out of different sources of non-linearities as mentioned before. The advantages of a Jones matrix formalism above an analytical formalism[3] is the possibility to include the polarization properties of optics and the simplicity to change the optical setup of the model. Further, by implementing a Fourier analysis to the model a clear representation of first and second order non-linearities is gained. As an example the non-linearity was calculated resulting from an ideal lasersource with rotated ideal flat-mirror optics, the results are shown in figure 2(a).



(a) Ideal optics



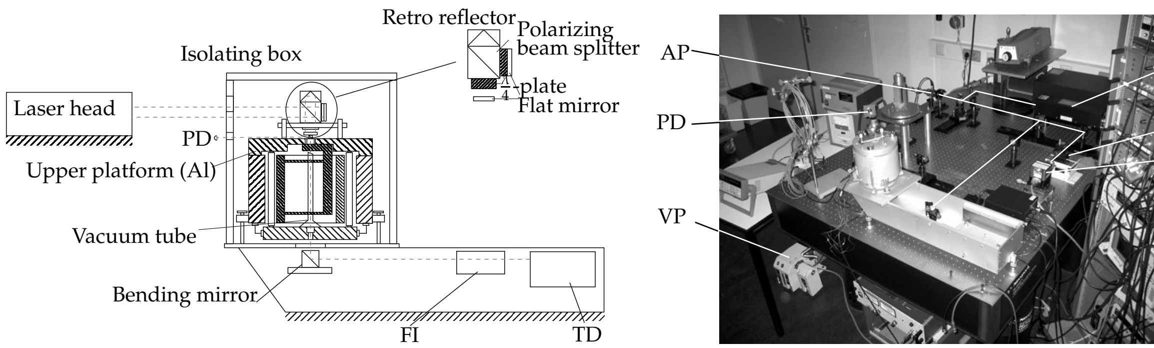
(b) Real optics

Figure 2. Influence from polarization properties of interferometer optics on calculated non linearity for rotated optics with angles (α) varying from 0° to 4°.

With use of an ellipsometer the polarizing properties of those flat mirror optics were investigated. The setup consisted on a null-measurement and a four-zone method.[3] The latter to exclude effects of the ellipsometer optics. The results were: A leakage of 3.2% for the polarizing beamsplitter and a surprising quarter waveplate phase error between fast and slow axis of 7.85°. Further a leakage of less than 0.2% was measured between the waveplate transmission axes. The ellipticity of the laserhead was measured using a circular polarized laser source, a polarizer and a spectrum analyser, as described by Lorier.[2] The ellipticity was 1 : 148 in E-field for the first frequency and 1 : 164 in E-field for the second frequency. Substituting these numbers into the model results in a calculated non-linearity as shown in figure 2(b).
As can be seen in the right side of figure 2(a) the result of an ideal interferometer with rotated optics is a first order non-linearity with a nearly linear dependence of the rotation angle in combination with a second order non-linearity. By implementing the polarization properties of the interferometer optics in the model this linear dependency is disturbed as shown in the right side of figure 2(b). Thereby also disturbing the symmetry in the non-linearity, due to a relative larger second order non-linearity as can be seen in the left side of figure 2(b).

3. TRACEABLE CALIBRATION SETUP

In the section Precision Engineering of the Eindhoven University of Technology a calibration facility was developed with a range of 300 μm and an uncertainty of 1.2 nm.[4] Since then the HeNe slave laser was replaced by a narrow linewidth diode laser, see figure 3(b). The measurement principle is based on a Fabry-Perot cavity to which a diodelaser is frequency locked. When one of the mirrors of the Fabry-Perot interferometer is displaced, the slave laser tracks the change in resonance frequency of the cavity. At the same time the displacement of the upper mirror is measured by a commercial displacement laser interferometer system, an Agilent 5528 system (see figure 3(a)). The frequency counter measures the frequency difference between the slave laser and an iodine stabilized HeNe-laser. A comparison of the laser readout with the displacement derived from the frequency measurement gives the calibration data.



(a) (b)

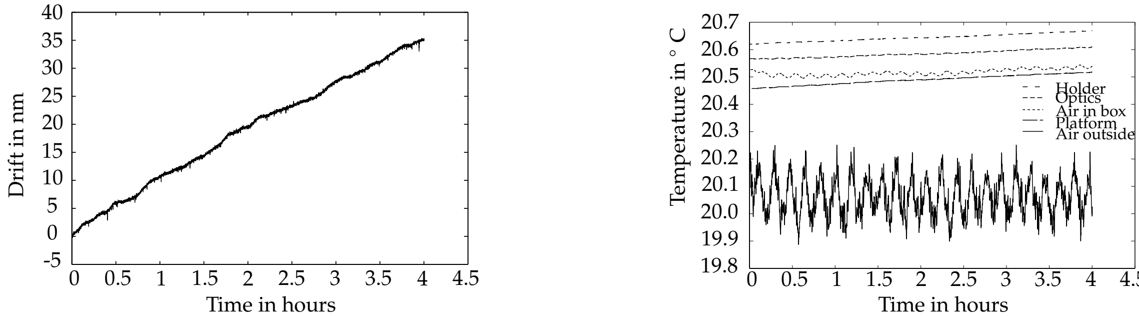
Figure 3. The used Fabry Perot calibration setup with SL: Stabilized HeNe-laser, TD: tunable diode laser, FI: Faraday Isolator, PD: Photo diode, VP: Vacuum pump, AP: Avalanche photo diode.

3.1. Measurement results

First the drift of the setup was determined. This drift is shown in figure 4(a). The drift was 35 nm in 4 hours during a linear temperature change of 0.045° of the holder and optics. After careful analysis it seems most likely that this is the effect of thermal expansion of the optics itself in combination with a change in refractive index. A calibration was carried out with an Agilent 5528 laser system combined with the flat mirror optics, of which the polarization properties were measured earlier with ellipsometry. The schematics of the setup, together with a photograph are shown in figure 3(b). In this photo the isolating box was removed together with the thermistors. Since this Agilent laser cannot be triggered extensive averaging must be caried out. With the shown drift a compromise must be made between the measurement range and accuracy. The first calibration was carried out over a range of 650 nm back and forth with a rotated laser head (3.3°), due to a non-horizontal platform the rotation seems exagerated in the photo. The non-linearity was modelled also and the results are shown in figure 5(a). The asymmetry mentioned in section 2 can be seen also in this measurement. As can alse be seen the measurement noise is quite large as a result of fast measurement. The standard deviation of the model compared to the measurement was 0.3 nm. In order to test the non-linearity with a well-aligned laser head, a range of 180 nm was scanned back and forth with large averaging. This measurement is shown in figure 5(b) together with the simulation. In this case the standard deviation of the model compared to the measurement was 0.14 nm.

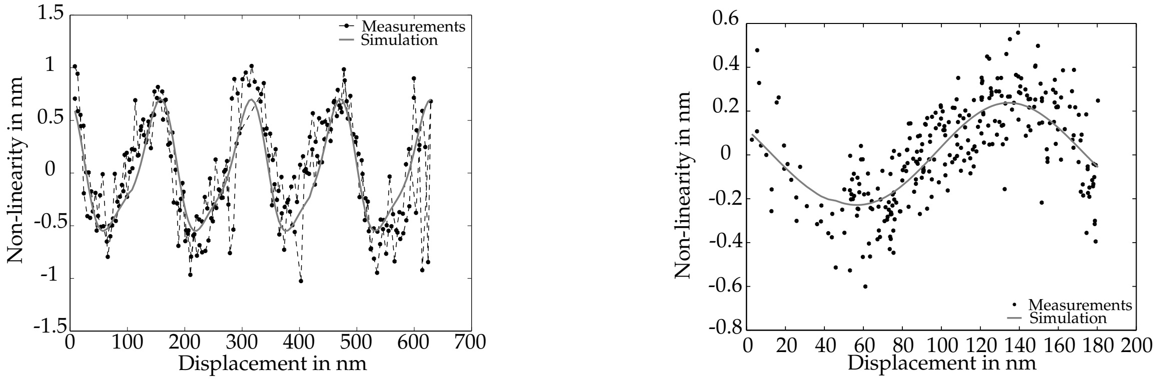
4. CONCLUSIONS

Presented are the results of the modelling of non-linearity in a commercial heterodyne interferometer with use of the measured polarization effects of laser source and optics. The model was verified with a traceable calibration on a Fabry-Perot cavity. From this it can be concluded that the effect of polarization properties on the non-linearity of the laser interferometer is significant, and should be considered when making measurements with nm accuracy.



(a) Drift of setup (b) Temperature

Figure 4. Measurements with the Fabry-Perot setup



(a) Optics rotated 3.3° (b) Well aligned

Figure 5. Measurements with the Fabry-Perot setup

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