Stability analysis of VSL's twin heterodyne interferometer for measuring subnanometer drift displacement in opto-mechanical devices

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Abstract

The picodrift instrument presented in this abstract paper is performing well over the past years as is demonstrated by periodic recalibrations of a piezo stack, but recently an analysis of the stability is conducted to get a deeper understanding of the remaining intrinsic drift. This limits the sensitivity for long-term (minutes to tens of hours) drift measurements. Based on the outcome, the performance will be improved and that will enable new application such as calibrating low-noise displacement sensors for gravitational wave detectors and measuring the long-term dimensional stability of bolted and bonded joints in high-end precision instruments.

Introduction

Current advances in high-end manufacturing equipment result in realizing (sub)nanometer precision for production tools in e.g. semiconductor industry. This is enabled by control systems using displacement sensors and actuators to achieve precise motion with extremely high positioning accuracy. Understanding and taking into account small systematic deviations and non-linear errors of the sensors and actuator is essential for improving the performance of the systems. Additionally, irreversible (sub)nanometer drift phenomena in the construction and mounting of displacement sensors and actuator influences the accuracy and repeatability, such as creep, aging of bonding and glue, and micro-slip in bolted joints. To study these effects and to calibrate those sensors and actuators, instruments are needed with measurement uncertainties in the lower subnanometer range. In a review [1] of calibration methods for small-range displacement sensors, it shown that interferometric methods are available up to the subnanometer measurement uncertainty level.

At VSL's facilities a special balanced twin heterodyne interferometer, denoted the "picodrift instrument", is in operation. In short, the picodrift instrument [2][3][4][5] consists of two balanced interferometers with equal optical path length so that common dimensional perturbations such as thermal expansion in the interferometer bench are cancelled, and one interferometer is dedicated to compensating the refractive index changes in air. Additionally, each heterodyne interferometer consists of spatial separated beams to omit periodic measurement nonlinearity that is normally attributed to frequency mixing due to non-perfect polarization optical components.

Over the course of past years, the setup has been maintained and used for tests and calibrations, such as of a virtual height and lateral standards for AFM calibration [6][7]. Other tests have shown that the intrinsic stability of the setup has reached as low as ± 0.5 nm over 19 hours [4], however this intrinsic stability changes over years and also after maintenance of the system. Overall, the short-term stability of about 10 pm in tens of seconds is quite good, but there is still too high intrinsic drift at time scale of tens of hours limiting the sensitivity and application of drift measurements. The long-term dimensional stability of the setup needs to be improved.

Analysis of dimensional stability

Long-term measurements are limited by the intrinsic drift due to environmental induced instabilities. The aim is to get a deeper understanding of these instabilities, so that the knowledge can be used to improve the long-term stability. Not only are there variations in optical path due to changes in refractive index, but also the opto-mechanical stability is one of the contributors to the drift of the interferometer.

The objective of the stability analysis is to create an error budget based on the suspected instabilities, and to improve the stability of the overall system. These environmental instabilities are pressure and/or refractive index changes, thermal fluctuations and gradients, and vibrations.

One of the methods used to analyse these potential drift sources is a geometrical ray tracer combined with a Monte-Carlo simulation to estimate the linearized sensitivity of the optical components. These positional sensitivities can be used with the maximum thermal gradients to estimate the error motion, and thus the contribution of drift to the measurement.

Estimating system behaviour by means of modelling with ray tracing provided insight in component sensitivity. The obtained values for the linearized component sensitivity are shown in Table 1. Temperature measurements show that thermal gradients are lower than 2 mK. These thermal gradients directly impact the position stability of the optical components and therefore add intrinsic drift.

Table 1. Linearized sensitivity in six degrees of freedom for five components of the picodrift instrument: FC1 - Fiber Coupler 1, FC2 - Fiber Coupler 2, BS - Beam Splitter, PBS1 - Polarizing beam splitter 1, PBS2 - Polarizing beam splitter 2, VAC - vacuum tube, see layout in [4].

Linearized sensitivity (pm/um V pm/urad)						
	X	Y	Z	Rx	Ry	Rz
FC1	580	80	$3 \cdot 10^{-1}$	130	370	$2 \cdot 10^{-1}$
FC2	580	$3 \cdot 10^{-1}$	$3 \cdot 10^{-1}$	$4 \cdot 10^{-1}$	440	$2 \cdot 10^{-1}$
BS	80	$4 \cdot 10^{-2}$	$4 \cdot 10^{-2}$	$8 \cdot 10^{-1}$	600	20
PBS1	60	$3 \cdot 10^{-2}$	2	210	2	80
PBS2	60	$4 \cdot 10^{-2}$	2	330	1	80
VAC	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	2	1	$8 \cdot 10^{-4}$

With these simulations and measurements, the estimated total intrinsic drift due to thermal gradients is 100 pm which is smaller than the observed long-term drift amplitude of ± 0.5 nm. Additional effects caused by optical path length differences due to alignment errors cannot be the root cause for the long-term drift. Still to be investigated are (1) air path minimisation, which would limit the spatial refractive index variation, and (2) the pressure effects on single-mode polarisation-maintaining fibres, which would contribute to the long-term intrinsic drift of the interferometer. Currently, it seems that the opto-mechanical stability is not the mayor limiting factor for long-term measurements but can be improved upon.

Applications of the picodrift instrument

Over the course of the past years, recalibration of the piezo stacks (virtual standards) for AFM calibration [6] is used as a benchmark for the performance of the picodrift instrument. Recent recalibration is compared to the calibration of the past and is shown in table 2. A minor decay in sensitivity is observed that can be attributed to aging of the piezo stack. These piezo stacks are powerful standards to calibrate nanometrology instruments, such a AFMs or White-Light Interferometers (WLIs) in the subnanometer scanning range where physical standards have limitations.

Table 2. piezo stack (virtual height standard) sensitivity in pm/V of the set voltage of the power supply (for the 1 mV to 10 V range) and the measured peak-to-peak amplitude for sinusoidal and square wave with 10 Hz frequency measured in the past years (see fig. 9 in [6]).

[pm/V]	2016	2019	2024
Sinus	1 967	1 942	1 935
Square	1 967	1 931	1 938

Gauge blocks are the most accurate physical realization of length standards and gauge block interferometers are the instruments to calibrate the length with the lowest measurement uncertainties. The coefficient of thermal expansion (CTE) of a gauge block needs to be known with a low measurement uncertainty in order to achieve best calibration result for the length of a gauge block. CTE calibrations in a static way can be quite elaborate in time because the full instrument has to be stabilized to several temperature points in order to estimate the CTE value. Using the picodrift instrument having a very high sensitivity for length changes and being equipped with high accuracy temperature sensors could be used to dynamically measuring the CTE of gauge blocks. Either a cooled or heated gauge block is inserted into the sample path of the interferometer and have its temperature relaxed to the ambient temperature while measuring the change in length and simultaneously recording the material temperature. In figure 1, a measurement result is shown for a 40-mm gauge block cooling down from 29 °C to room temperature. Typically, such a measurement lasts between one and two hours. This measurement method is currently being tested and the calibration method will soon be validated including the measurement uncertainty value.

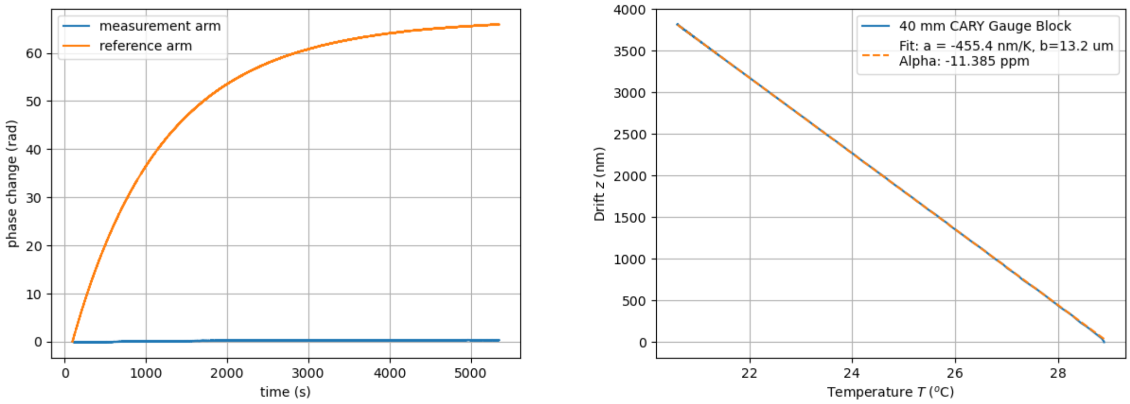

Figure 1. left - Measured phase change in sample (measurement arm) and refractometer (reference arm). Right - Measured drift of the gauge block versus material temperature during cooling down to room temperature and the estimated CTE value of 11.39×10^{-6} K^{-1}.

Conclusions and outlook

Based on results shown about recalibration of piezo stacks, it can be concluded that the performance of the picodrift instrument over the course of many years is very stable. For these short-term measurements of the piezo stack (at 10 Hz driving frequency) the estimated relative measurement uncertainty is 0.1 % [6]. The outcome of the opto-mechanical stability analysis will soon be implemented to improve of the long-term stability and sensitivity of the picodrift instrument. Currently, new application fields for the picodrift instrument are being investigated.

In the field of gravitation wave detectors studies are being conducted to design the third-generation detector [8][9] having a few orders of magnitude higher sensitivity at lower frequencies (0.1 Hz – 10 Hz). Therefore, seismic sensors in isolation stages, and sensors and actuator in vibration damping chains needs to be improved to have a very low noise at lower frequencies (0.01 Hz – 10 Hz). The picodrift instrument will be prepared to characterize and validate prototype sensors for the gravitation wave detectors.

Structural and dimensional stability on the long-term is an issue that has been studied a lot for space optics in satellites [10], but has gained also more recent attention in the high-end precision equipment where subnanometer stability of opto-mechatronic systems is getting more demanding. For instance, alignment of sequential process steps it is important that reference positions remain stable over time (0.001 Hz – 1 Hz). To study these effects the picodrift instrument will be prepared to characterize instabilities, such as microslip in bolted joints and drift in bonded joints over minutes to tens of hours.

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