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A fully-fibre coupled interferometer system for displacement and angle metrology

Paul Köchert[1*], Christoph Weichert[1], Sebastian Strube[1], Rainer Köning[1], Jens Flügge[1], Eberhard Manske[2]

[1] Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
[2] Ilmenau University of Technology, Institute of Process Measurement and Sensor Technology, Gustav-Kirchhoff-Str. 1, 98693 Ilmenau, Germany

*Corresponding author: paul.koechert@ptb.de

Abstract

We propose a compact heterodyne interferometer system for either angle, displacement or straightness measurements. It uses two offset-locked He-Ne lasers, fully-fibre coupled plane mirror interferometer optics and a self-developed phase meter. First measurement results show a standard deviation of 5 pm over 15 s at a filter bandwidth of 10 kHz while all interferometer beams were reflected by a common mirror.

Keywords: fully fibre-coupled interferometer system, offset-locked laser, heterodyne displacement interferometry, high resolution phase meter

1. Introduction

Heterodyne interferometers have been widely used for high-precision measurements at metrology institutes and in industrial applications since the first commercial heterodyne system was launched over 40 years ago [1]. Such systems can be integrated easily in machines following the Abbe principle [2], can have intrinsic traceability and provide a high signal-to-noise ratio.

An advanced displacement measuring interferometer system has been developed within a cooperation project between the PTB and the SIOS GmbH to conduct measurements with precision in the sub-nanometre range. In order to reduce costs as well as size and to increase the detectable motion speed, all components of the heterodyne interferometer system were reconsidered compared to previously realised setups [3, 4]. The performance evaluations show, that each system component was effectively adapted to achieve a resolving capability in the single picometre regime.

2. Laser interferometer system setup

The general configuration of the system setup, shown in Figure 1, contains a light source consisting of two offset-locked He-Ne resonators to generate a user-defined beat frequency, an interferometer optics reducing periodic nonlinearities and a high resolution phase evaluating electronics. In order to separate heat sources from the measurement setup the developed device was fully-fibre coupled.

2.1. Offset-locked light source

An alternative two-frequency laser source [5, 6] consisting of two offset-locked He-Ne resonators was used instead of an expensive Nd:YAG solid state laser in combination with two acousto-optical modulators, that had been operated previously in our laboratory setup to generate the beat frequency. Measurements using this uncalibrated laser system can be traced back to the SI-unit meter with a relative uncertainty of $1.5 \cdot 10^{-6}$ recommended by the CIPM [7]. Moreover, widely spread optical components for a wavelength of 633 nm can be used to design interferometer setups with spatially separated input beams. Both lasers provided an overall power of 2 mW.

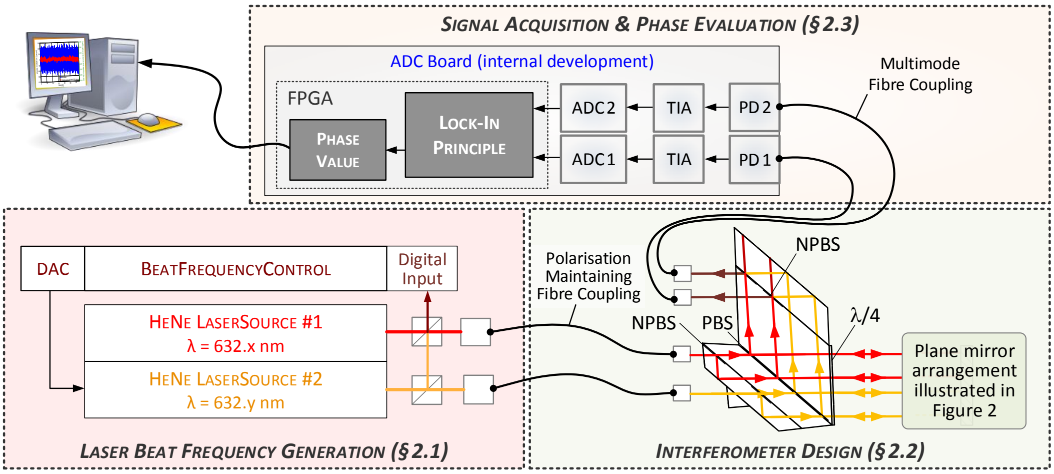

Figure 1. Structural diagram of the setup representing the three main parts of the proposed heterodyne laser interferometer to provide displacement, angular and straightness measurements. (ADC: analog-to-digital converter, DAC: digital-to-analog converter, FPGA: field programmable gate array, NPBS: non-polarising beam splitter, PBS: polarising beam splitter, PD: photo detector, TIA: transimpedance amplifier).

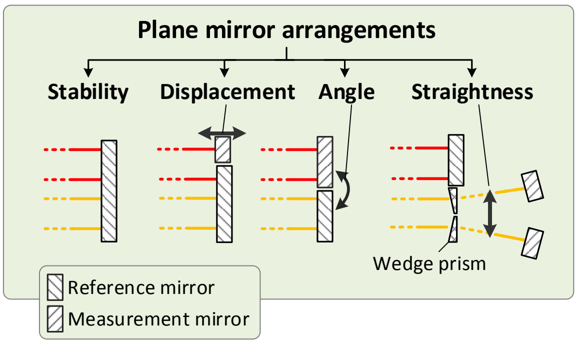

Figure 2. Schematic of possible configurations of the proposed heterodyne interferometer using various plane mirror arrangements.

The offset-lock procedure was operated by a high speed digital control [6] to adjust the beat frequency freely in the range between 100 kHz and 8 MHz. During this procedure, the frequency of the master laser was stabilized using a two-mode stabilization technique [8] providing a relative frequency stability of 10^{-8}. The digital control was capable of adjusting the frequency deviation between the master and slave resonator by thermal length adjustment of the latter. A stability of 8.6 Hz (Allan deviation) at an integration time of 1 s was achieved. This property had enabled us to select a suitable beat frequency for our interferometer setup, so that the resolution was not limited by laser intensity noise [9].

2.2. Interferometer optics design

Both laser beams were coupled into polarisation-maintaining fibres. The optical setup was conceptually designed on the basis of previous studies [3] and had been adapted to the new wavelength. It avoided periodic nonlinearities caused by frequency mixing by using spatially separated input beams [10] and provided a minimized dead path due to its differential arrangement as well as symmetrical beam paths through glass. The optics was mounted on a base made of aluminium using a three-point support to allow the compensation of thermal expansion. The dimensions of the interferometer head were 130x100x50 mm^3. This head can be incorporated to measure either displacement, angular variation or straightness by changing the mirror arrangement according to Figure 2. The superposed beams were coupled into multimode fibres and were then transferred to detector units consisting of fibre connectors, silicon photodiodes and transimpedance amplifiers, respectively.

2.3. Phase evaluation electronics

A phase evaluation electronics has been developed to sample the laser-interferometric signals with an acquisition rate of up to 125 MHz and to demodulate these signals with an approved lock-in method [4]. It contains an analogue front-end, a high speed dual channel analogue-to-digital converter with 16 bit and a field programmable gate array (FPGA) for high speed as well as low latency signal processing. Derived from the laser-interferometric signals the developed electronics generates position values with a data rate of 390 kSamples·s^{-1} and was capable to detect motion speeds up to 31 mm·s^{-1}. The user-defined demodulation principle can be easily adapted to track higher speeds up to 0.3 m·s^{-1}.

The resolving capability of the self-developed electronics was verified by using excitation signals generated by a function generator (Model: Tektronix AFG 3102), which was adjusted to a frequency of 4 MHz. It was exhibited a standard deviation of 47 µrad (2.35 pm) at full data rate.

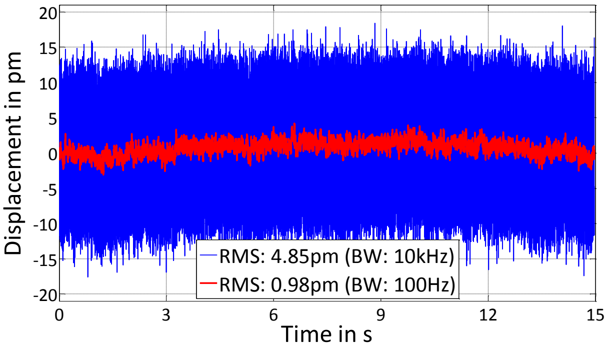

Figure 3. Measurement results of the interferometer setup with common mirror at a filter bandwidth (BW) of 10 kHz and 100 Hz.

3. Performance evaluation

The performance of the interferometer setup was investigated under laboratory ambient conditions at a measurement setup using a common mirror. During the measurements the offset-locked light source was configured to emit two laser beams with a beat frequency of 4 MHz. The measurement results, shown in Figure 3, demonstrated a resolving capability of our interferometer system better than 100 µrad at a filter bandwidth of 10 kHz, which is equivalent to 4.85 pm using a one-fold displacement interferometer configuration and a wavelength of 633 nm. The periodic nonlinearities have been determined by measuring the thermal contraction as well as expansion of an aluminium rod [11]. Their amplitude was about 70 pm and was mainly caused by multiple reflections.

4. Conclusion

We developed a heterodyne interferometer setup and were capable to measure displacements with sub-nanometre uncertainty. The setup can be extended to support multiple interferometer axes due to the high power light source. Additionally, the laser system can also be used together with commercial interferometer optics. Further developments focus on the angle and straightness measurement capabilities, which will be proved in a comparison with PTB's reference machine for calibration of length graduations, the so-called Nanometer Comparator (NMC). The NMC was recently upgraded to provide straightness calibrations [12].

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