

A Fast Phasemeter for Interferometric Applications with an Accuracy in the Picometer Regime

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Abstract

The lock-in principle is a preferred method to determine the phase difference between electrical signals of heterodyne interferometer. A phase meter based on this method was developed at PTB allowing to detect fractions of an optical fringe in the range of a few picometers, which is verified by experimental results.

1. Introduction

Heterodyne laser interferometer systems have become instruments of choice for position measurements in precision machining and scientific institutes since the first commercial heterodyne system were launched in 1970 by the company HP. In order to meet the increasing demands in leading-edge applications resolution and speed of displacement measuring interferometers have been improved continuously. [1,2]

A common error source of displacement interferometers is attributed to the phase measuring electronics [3]. However, several techniques for phase measurements have evolved during the last decades. At first the measurement principle was based on metering the phase difference between measurement and reference arm by detecting zero-crossings allowing resolutions down to 0,31 nm [4,5]. By now phase measuring electronics based on digital lock-in methods are established, which are capable to perform fringe interpolations in the picometer regime. However, preceding work using digital lock-in amplifiers for this purpose was restricted due to the limited bandwidth of the ADC input stage and the data acquisition rates [6,7]. Furthermore the latest proprietary lock-in amplifiers are expensive and enable only tracking of at most two signals and prevent the adjustments of digital signal processing algorithms [8,9].

In this paper a phase measurement concept is proposed using the lock-in method on the basis of prior studies [10]. The PTB aims to achieve an uncertainty level of 10 pm and a simultaneous measuring operation of at least four axes allowing measurement speeds up to 10 mm/s. A state-of-the-art 100 MHz VME based digitizer board equipped with embedded

FPGA units is employed to develop an electronic measurement equipment for an interferometer system.

2. Implementation of the design

In heterodyne systems the displacement information is carried on AC waveforms, which exhibits compared to homodyne systems an improved signal-to-noise ratio due to a reduced spectral density of the noise in this frequency regime. In addition the influence of certain perturbations, caused for example by the use of optical fibres [11], can be prevented by using an appropriately chosen beat frequency. Therefore the phase measurement concept was designed for beat frequencies over 1 MHz.

A fast ADC board manufactured by Struck Innovative Systeme [12] is used to implement a phase measurement method capable to resolve fractions of optical fringes with picometer uncertainty. The VME board provides eight 16bit flash analogue-to-digital converters (ADC) with a signal-to-noise ratio of about 80 dB and a sampling rate up to 100 MHz. The input channels provided with a full scale range of 3 V are combined pairwise with a field programmable gate array (FPGA, Xilinx™ XC3S1000 series) enabling independent phase measurements of up to four differential interferometer axes. An onboard memory of 64 MByte is dedicated to each ADC. In addition digital inputs and outputs allow to synchronize the data acquisition to other systems via trigger signals.

The lock-in principle is a technique to filter signal components out at a determined reference frequency. In fact, digital lock-ins multiply the converted digital input data stream with a sinusoidal reference and apply a low pass filter on this stream. This obtains a high insensitivity to reference harmonics and inhibits erroneous zero drifts in comparison to analogue lock-ins. The limitations of this principle are mainly given by the analogue-to-digital converter performance. [13]

By means of VHDL¹ this phase-sensing method is implemented at each FPGA unit, which is shown in figure 1, and can be executed at full ADC sampling rate. The multiply-accumulate units (MAC) multiply the signals of the interferometer arms each with a sine and cosine reference wave and apply low-pass filtering by accumulating the data using a preassigned windowing function. The FPGA is suitable to implement user-defined reference waveforms with a wide range of frequencies tested between 10 kHz and 20 MHz. The arbitrary phase of the synthetic internal reference is used for both, the measurement and reference signal of the interferometer, and is removed by calculating the difference of both phases. The fraction of optical fringes is calculated using a CORDIC based arctangent function. Concurrently a

¹ VHDL: VHSIC (very-high-speed integrated circuits) hardware description language

fringe counter tracks the number of full interference orders. At last the evaluated data is stored in the onboard memory and can be read out in a circular buffer routine for continuous long-term capturing.

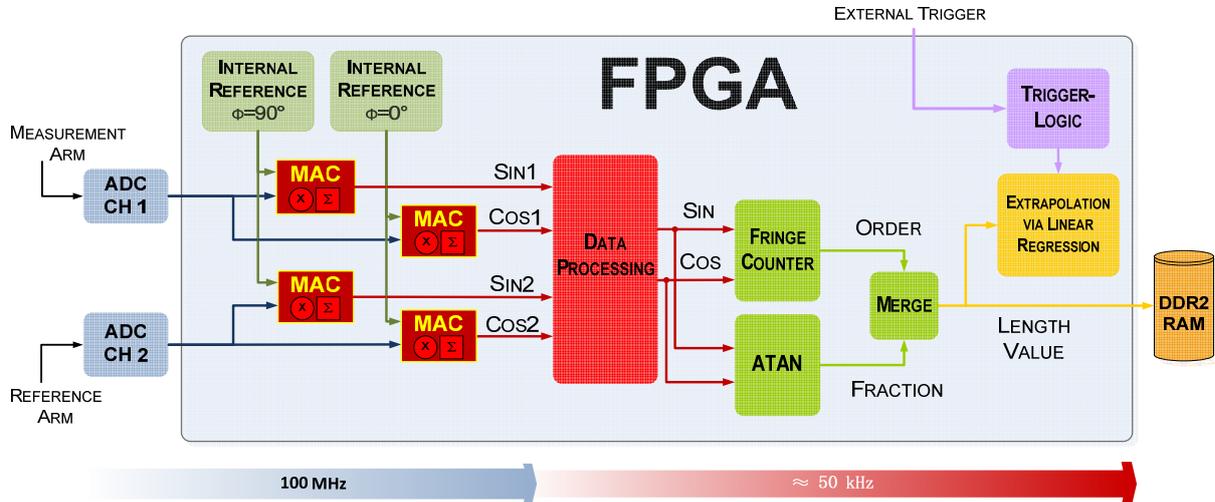


Fig. 1: Schema of lock-in based algorithm implemented into single FPGA for measuring one heterodyne interferometer axis

In order to compensate the time delay due to signal processing, which becomes relevant at high motion speed, a predictive position value can be generated at a point in time within the processing interval, which is e.g. stimulated by an external trigger signal. To provide position values with lowered data age in motion controller applications a best-fit line algorithm is calculated on the basis of previous length values at the FPGA.

3. Performance evaluation

The recently developed phase meter was verified by long-term measurements using two different experimental setups. Following phase information in picometer are equivalent to a double-pass interferometer operating with a He-Ne laser (633 nm wavelength).

At first the phase measuring system was tested using a signal synthesizer (Tektronix AFG3101) whose oscillator was synchronized to the ADC board frequency clock. Two channels were driven by a common sinusoidal signal with an amplitude of 1,25 V and an excitation frequency of 1,5625 MHz. The analogue-to-digital signals were mixed with an internal reference over a window length of 2048 resulting in a continuous data acquisition rate of 48,8 kHz. To avoid large mounds of data only one in 3000 points was saved.

The long-time phase measurement shown in figure 2 reveals a standard deviation of 31 μ rad (0,78 pm) and a peak-to-peak value of 293 μ rad (7,4 pm). An average determination over 500 values results in a standard deviation of 8,3 μ rad (0,21 pm).

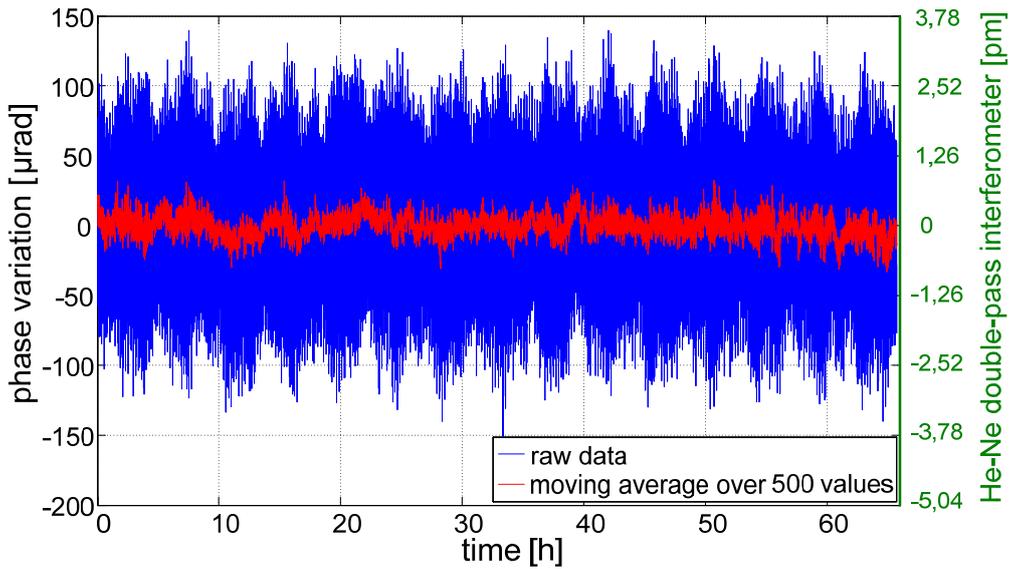


Fig. 2: Result of static test using a frequency generator (Tektronix AFG3101)

Secondly, the phase meter was investigated using a double-pass interferometer setup (fig. 3) and a Zeeman-stabilized He-Ne laser head (Agilent 5519A) operating at a heterodyne beat frequency of 2,671 MHz. Therefore the internal reference table consists of a window with 2671 values length leading to a data acquisition rate of 37,4 kHz. However, only every 500th value was saved. At this setup phase meter and laser head frequency clocks could not be synchronized to each other due to the limitations of the laser head.

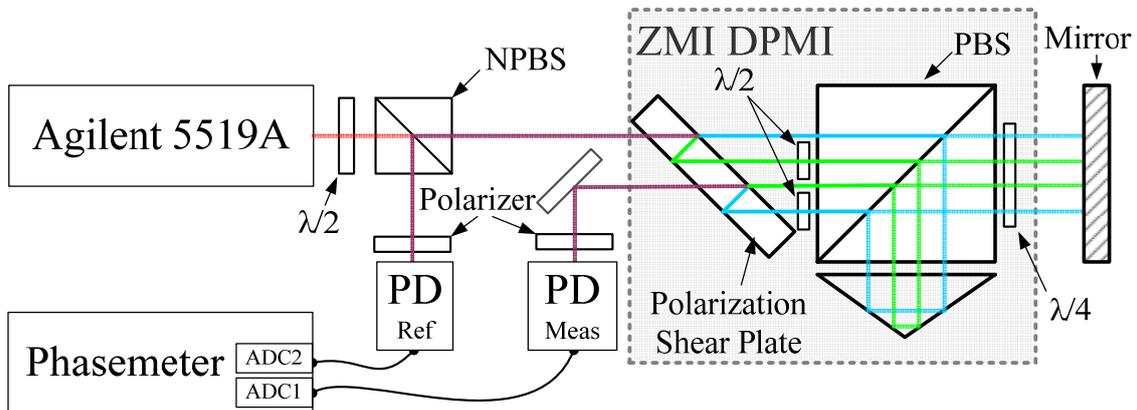


Fig. 3: Experimental setup of a double-pass interferometer [15] with common mirror for phase meter measuring (PD – Photo detector; PBS – Polarizing Beamsplitter; NPBS – Non-Polarizing Beamsplitter)

During a measurement of 65 hours a standard deviation of 282 μrad (7,1 pm) and a peak-to-peak value of 2,36 mrad (59,8 pm) has been achieved. The scatter of the results in-

creases compared to the above measurement with frequency generator by a factor of eight to nine, which is likely to be introduced by additional noise e.g. of the photo detectors and their amplifiers, a smaller amplitude of 0,65 V at the measurement arm and the missing synchronization of frequency clocks. The observed phase drift might have occurred due to unstable environmental conditions as well as a tilting of the common mirror. Anyhow a phase stability less than 0,06 nm was achieved over a measuring time of 65 hours as shown in figure 4.

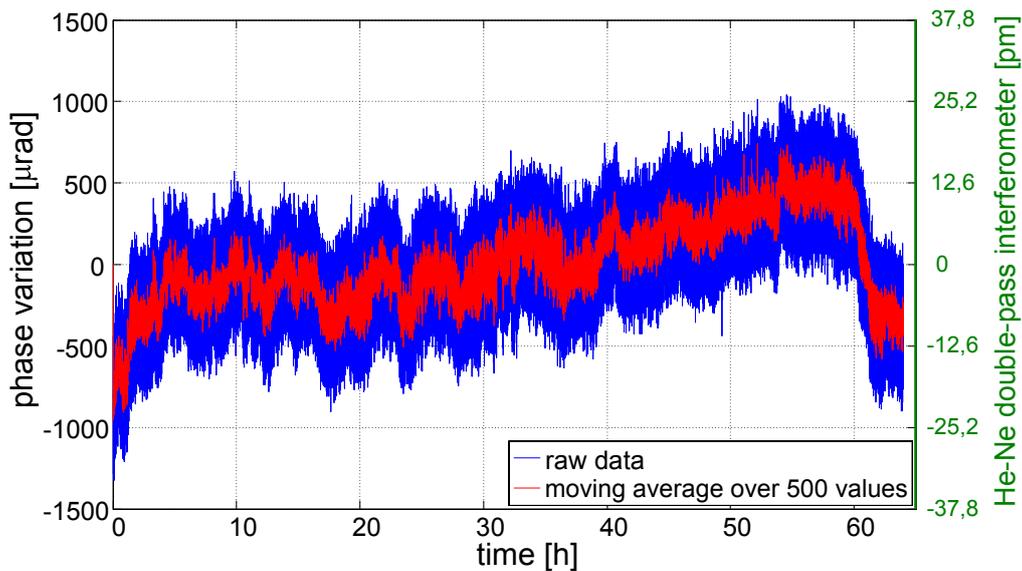


Fig. 4: Result of static test using a double-pass interferometer setup and Agilent 5519A laser head

4. Conclusions

A phase evaluation electronics for heterodyne measuring interferometer systems with uncertainty requirements in the 0,1 nm range has been described. To verify the phase measuring characteristics of the evaluation unit, static tests with electrically generated signals as well as with signals at a differential interferometer have been accomplished, which demonstrated a standard deviation less than one pm for the electrical test and a long-time interferometer stability of about 60 pm. The indicated performance was achieved using a low-cost state-of-the-art FPGA based electronic board, which offers synchronous measurements of up to four differential interferometer axes and provides flexible adaptations for various fields of application.

Further development will synchronize at least two phase measuring cards, which will permit a multi-axis tracing of up to eight interferometer axes or systems. For high-precision servo

control systems an extrapolation of length values can be applied to compensate signal delays of e.g. the VME bus to provide real-time motion signals with lowered data age.

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