Stability of a Fiber-Fed Heterodyne Interferometer

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Abstract

A heterodyne interferometer with spatially separated input beams is presented. The optical design realizes symmetric paths through glass and air, which results in a minimal dead path. An automatic correction of phase variations introduced by feeding the optics with fibers and by angle variations between the optics and the mirror is demonstrated. In addition to the resolution and linearity in the single digit picometer range, the long-term stability of the interferometer setup is investigated, involving the previous analysis of all different components of the setup. It is shown, that the long-term stability is still limited by the variations of the environmental conditions.

Introduction

Optical interferometers are frequently used in the contents of precision measurements, especially if these measurements need to be traceable to the unit of length. In order to realize minimal uncertainties the displacement interferometer has to perform linear and repeatable measurements. Realizing a high resolution alone is not sufficient. Therefore the PTB developed a heterodyne interferometer with minimal nonlinearities in the framework of the joint research project “Nanotrace” [1]. Those heterodyne interferometer nonlinearities, which are commonly associated with frequency mixing, are avoided by the presented design by two spatially separated input beams. In a comparison with an x-ray interferometer, periodic nonlinearities with amplitude of less than 5 pm were demonstrated [2]. The stability of an interferometer setup has a major effect on the uncertainty of time consuming measurements. It was analyzed by measuring the variations of the interferometer phase while all interferometer beams were reflected from a common mirror. The dead path of the interferometer optics, the stability of the mounting, the laser frequency and the stability of the phase evaluation will still, due to variations of the ambient parameters, affect the measured phase. Therefore the dead path was determined by a frequency variation of the laser. The stability of the phase evaluation as well as the influence of the heterodyne frequency generation, of the optical fibers and of the polarization state were qualified using a Mach-Zehnder setup, which contained every component of the presented interferometer setup except the interferometer optics. Instead of the optics a non-polarizing beam splitter was used to realize the beams interference. With the Mach-Zehnder setup a phase variation of less than ±5 pm over 50 hours was shown [3].

Setup

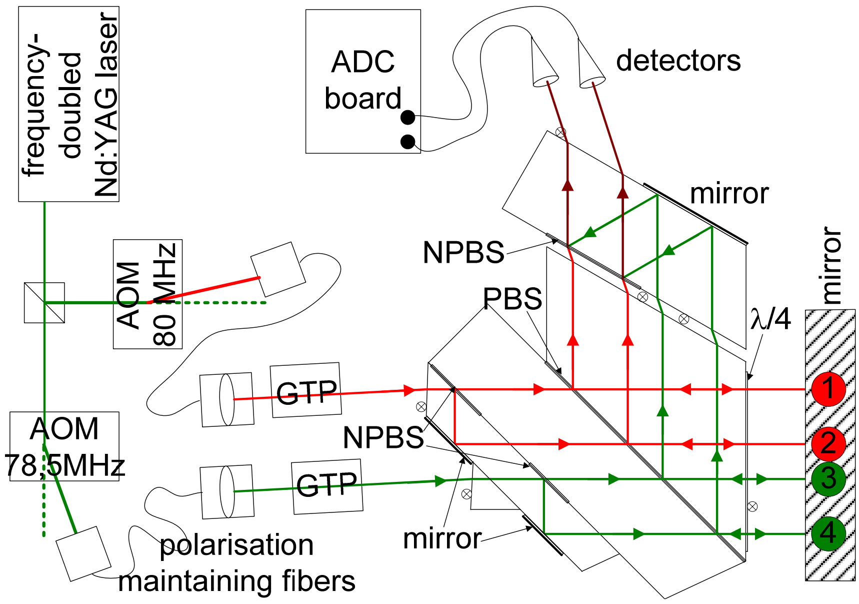

Fig. 1: Setup of the fiber fed heterodyne interferometer measuring against a common mirror

To increase the thermal stability of the interferometer setup the light source and the heterodyne frequency generation are spatially separated from the interferometer optics. A frequency doubled Nd:YAG laser emitting at a wavelength of 532 nm serves as the light source. The laser is working in single mode and the temperature of the pump diode, the YAG crystal and the PPKTP crystal are stabilized. These measures result in a laser frequency variation of less than 45 MHz over 3 hours. The light is split by a polarizing beam splitter (PBS) into two beams. Each beam is frequency shifted using acousto-optical modulators (AOM), one with a frequency of 80 MHz and the other one with 78,4375 MHz. The AOMs are driven by a two channel signal generator.

The frequency shifted beams are coupled into polarization maintaining fibers (PANDA type) with a length of 12 m to transfer the light to the optical setup. Each of the two incoming beams passes a Glan-Thompson polarizer (GTP) to eliminate the second guided mode of the fibers, which results from their imperfect extinction ratio. These two polarizers have to be well aligned relatively to each other and to the following polarizing beam splitter of the interferometer optics. The alignment can be achieved for example by using a third Glan-

Thompson polarizer. A misalignment of the polarizers will result in phase variations due to the imperfection of beam splitters and the different phase variations of the two guided modes of the optical fibers [3].

The design of the interferometer optics is based on plane parallel plates made of fused silica (Homosil). The first one is vacuum metalized to exhibit non-polarizing beam splitters (NPBS) and mirrors, such that each incoming beam is split into two parallel beams. All four beams pass through a polarization beam splitter vacuum metalized on the second plate and a quarter wave plate wrung on a glass prism. In general the interferometer optics can be used for different applications, depending on which beams are reflected by the moving mirror and by the reference mirror. An angle interferometer can be realized by reflecting the pair of the beams 1 and 2 by one mirror and the pair of the beams 3 and 4 by another one. The targeted application of the setup is a plane mirror interferometer, achievable by using any of the beams as measuring beam or with double resolution using beams 2 and 3 as measuring beams. In case of testing the stability of the interferometer setup all four beams are reflected by one common mirror. After the reflection the four interferometer beams pass again the quarter wave plate and are reflected at the polarizing beam splitter this time. Using a third plane parallel plate with a non-polarizing beam splitter and a mirror, the beam 1 interferes with beam 3 and beam 2 with beam 4, resulting in a beat frequency of 1,5625 MHz. The two detected signals can be considered as signals from two different sub-interferometers, one as measuring interferometer and the other one as compensation interferometer. The feeding of the interferometer optics with fibers results in phase variation in the micrometer range in each of the sub-interferometer, when the beat frequency generation is synchronized to the phase meter. This phase variation is perfectly compensated and the measured phase difference remains stable in the single digit picometer range (figure 2), due to the symmetry of the two sub-interferometers. Additionally the beat frequency is chosen in the MHz range to be far away from the eigenfrequencies of the optical fibers, which are in the single digit kHz range, to avoid the obligation of power stabilization at the fiber outputs [4]. The interferometer exhibits symmetric paths through glass and air. With a parallelism of 3 arcsec of the plane parallel plates the path difference in glass between the two sub-interferometer is smaller than 0,8 µm. The central glass prism in the interferometer optics is used to minimize the air path, at the price of higher sensitivity to temperature gradients in glass. For any applications an angular motion of the interferometer optics relatively to the mirrors is directly compensated, except for the influence of the topography or inhomogeneity of the glass.

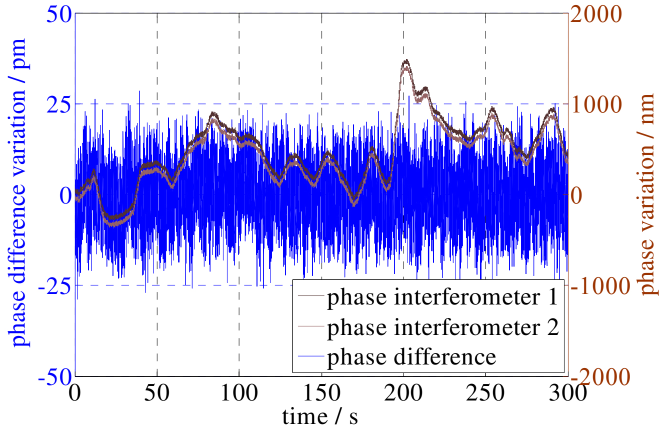

Fig. 2: Phase variation of the interferometer setup at an acquisition rate of 48,8 kHz (blue) and the corresponding phase variation of the single channels of the interferometer (red)

Before focusing on the silicon photodiodes, the beams pass Glan-Thompson polarizers and quarter wave plates to suppress multi reflections from the detector. The influence of potential reflections from other optical components is minimized by introducing a small tilt of all components, including the interferometer optics.

The interferometric signals are analyzed by an analog-to-digital converter (ADC) card manufactured by Struck Innovative Systems. The eight 16 bit input channels with a sampling rate up to 100 MHz are combined in pairs with a field programmable gate array (FPGA), which is used for the implementation of a lock-in algorithm for the phase determination. The lock-in algorithm implemented in VHDL is able to work at the full ADC input speed. Thereby the converted input signals are mixed down and a low-pass filter is applied on consecutive windows of 2048 values, which allows continuous data transfer rates of 48,8 kHz [5]. Feeding with sinusoidal waves from a signal generator, the stability of the phase meter was determined to be in the sub-picometer range [3, 5].

Dead path measurement

For highest uncertainty requirements of interferometric length measurements in air it is essential to correct the influence of the environment on the wavelength. This correction should not only take the measurement length into account, but also the initial optical path length difference between the measurement and the reference arm, the so-called dead path of the interferometer. We measured the dead path of the interferometer by detecting the phase variations caused by frequency variations of the light source in situ. It is not possible to differentiate a dead path through glass material from a dead path in environmental medium. In the case of one common mirror for all beams a path difference in air can only be caused by the topography of the mirror. Therefore here the dead path measurement identifies the quality of the design and manufacturing of the interferometer, as well as the homogeneity of the glass.

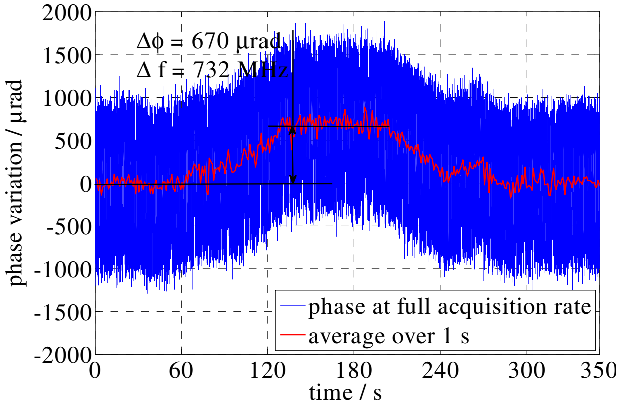

Fig. 3: Phase variation of the interferometer setup according to a laser frequency variation of 732 MHz

We used the frequency doubled Nd:YAG laser locked to the Doppler-free absorption line of iodine for the dead path measurement. The laser was locked at the first hyperfine structure of the line P54(32-0). Then by changing the current of the pump diode, the frequency of the laser was shifted by 732 MHz and locked again at the hyperfine structure P54(32-0)a14. Afterwards the frequency was shifted back. During the whole process the phase variation of the interferometer was recorded. The average phase shift according to eight frequency shifts is 670 µrad, corresponding to 14 pm for a double path interferometer.

The frequency variation by tuning the current of the pump diode, in addition also results in a power variation of the laser. To demonstrate experimentally that an amplitude variation of the interferometer signals does not affect the phase of the interferometer, the light coupled into the fibers was reduced by a modulation of the amplitude of the electric signals applied to the AOMs or using a half wave plate and a polarization beam splitter behind the laser. No influence has been observed on the phase except of a higher noise level due to the smaller contrast.

Long-term stability

In order to use interferometer for complex and time consuming measurement tasks, for example the measurement of a large number of structures on photomasks, its stability over a time frame of many hours is essential. Therefore a key point in the interferometer design is a low sensitivity to environmental influences. The nearly negligible dead path of the interferometer using a common mirror leads to an insensitivity of the setup to changes of the refractive index of air as well as to a small influence of a laser frequency variation. For the long-term measurements the laser was not frequency stabilized. But the output power of the laser was stabilized by controlling the current of the pump diode with the aid of a photodiode integrated inside the laser head. Even if we have shown that the phase of the interferometer is independent of the signal amplitude, this stabilization is needed to decrease the long-term phase variation over hours. Unpredictable phase effects like an increased noise of the phase, from 30 pm peak-to-peak to 60 pm, or a phase step of 5 pm over some minutes are eliminated with this stabilization of the pump diode. The mentioned phase effects are caused by the laser light source, probably by mode fluctuations of the pump diode [6].

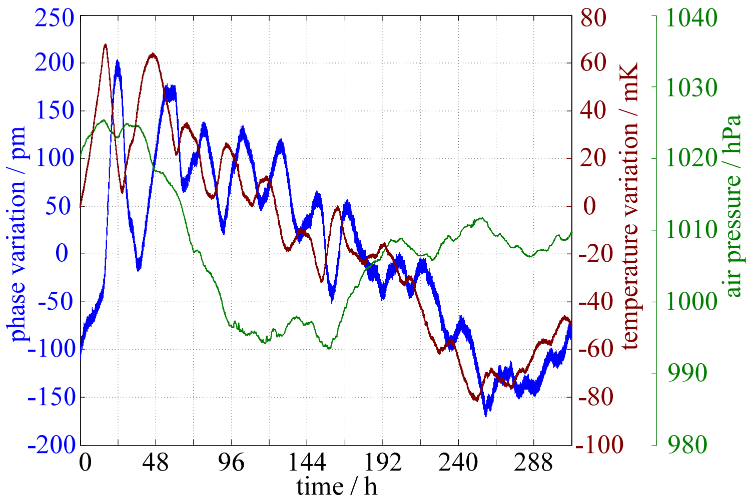

Fig. 4: Phase variation of the interferometer setup over 13 days and the corresponding ambient parameters

At a data acquisition rate of 48,8 kHz the phase varies in the range of ±1750 µrad with an standard deviation of 351 µrad over 300 seconds, which corresponds to a standard deviation of 7,4 pm for a double path interferometer.

To analyze the long-term stability of the heterodyne interferometer it was placed in a temperature stabilized environment. The average over one second of the phase varies in the range of ±187 pm (standard deviation of 91 pm) over 13 days. The largest phase drift over one hour is 53 pm and typical one is in the order of 6 pm. According to the measured ambient parameters the variation of the refractive index of air is dominated by the variation of the air pressure. But the phase variation correlates with the temperature variation of ±75 mK, indeed with a delay of round about 8 hours. Assuming a linear relation a temperature drift of 1 K would cause a phase drift of 2,5 nm. Therefore an influence of the refractive index of air can be negated.

Discussion

For the presented heterodyne interferometer the influence of the dead path is nearly negligible due to the symmetric optical design. The long-term stability of the phase meter and the other interferometer components, except of the interferometer optics, were shown using a Mach-Zehnder setup. With this setup, if the polarization state is well aligned, the variation of the average of the phase difference is smaller than ±5 pm over 50 hours despite the phase variations introduced by the optical fibers. Moreover these experiments have demonstrated that the heterodyne frequency generation, the detectors and their amplifiers do not have major effects on the long-term stability of the phase. The presented interferometer setup offers the same standard deviation and stability as the Mach-Zehnder setup over minutes. To achieve a stability of the phase in the single digit picometer range anytime, the output power of the laser needs to be stabilized. A frequency variation of the laser causes only minor changes of the phase as long as all interferometer beams are reflected by one common mirror. Any motion of this mirror will not change the phase due to the direct compensation of angle variations between the interferometer optics and the mirror, even if the interferometer is slightly misaligned. But taking the topography of the mirror and interferometer optics into account a motion of the interferometer beams will probably result in a phase variation.

A position variation of the fiber outputs relatively to each other or relatively to the interferometer optics can cause a motion of the beams. A geometrical estimation shows, that a variation of the angle between the two incoming beams of only 220 nrad (0,05 arcsec) will bring up a phase variation of 400 pm. This is a consequence of the 15 degree angle between the second and the third plate of the interferometer optics and may explain the measured long-term phase variation correlated to the temperature variations, as shown in figure 4. A deformation of the holders or the base plate made of aluminum can probably result in a relative position variation of the two fiber outputs with a time delay to the measured temperature of air and consequently in a phase variation. The design of the interferometer optics avoids the influence of phase variations introduced by the optical fibers, minimize the dead path as well as periodic nonlinearities, but puts a challenge to the stability of the relative position of the two fiber outputs. Anyway a synchronous motion of both fiber outputs relatively to the interferometer optics is compensated, except for topography influences.

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