The following article is the final version submitted to euspen after peer review; hosted by CERN.
DOI: 10.7795/EMPIR.18SIB01.CA.20200818

Modulation-based long-range interferometry as basis for an optical two-color temperature sensor

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Acknowledgment: The authors would like to thank T. Meyer for technical support.
This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

Full citation of the original article published by euspen:

Proceedings of the 20th international conference of the European society for precision engineering and nanotechnology
June 8th – 12th June 2020
Virtual Conference
ISBN: 978-0-9957751-7-6

Modulation-based long-range interferometry as basis for an optical two-color temperature sensor

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One critical issue when surveying large structures like telescopes outdoors is the compensation of the refractivity-induced beam bending in levelling. For this, the temperature gradients in the plane along the line of sight need to be determined. We are currently developing a dispersive optical thermometer. It will be realized by an absolute interferometer with two different colours (532 nm, 1064 nm). We target a compact optical interferometer design. Therefore, we implement a 2f/3f detection scheme for phase detection: the laser frequency of the light source is sinusoidally modulated, and the interferometric phase derived from the harmonic signals. In our contribution, we discuss the measurement scheme, approach-included challenges and present first verification experiments over a range of 20 m.

2f/3f detection, laser modulation

1. Introduction

A key problem in large-scale dimensional metrology is to deal with the local inhomogeneity of the index of refraction. Temperature gradients, e.g., are a substantial source of error when determining the position of the reference points of large telescopes as used for Very Long Baseline Interferometry (VLBI) – a key quantity to improve the accuracy of the Global Geodetic Observation System (GGOS) [1]. Capturing these inhomogeneities with classical sensors requires dense and impractical sensor networks. Alternative integrating sensor designs based on spectroscopy [2], sound wave propagation [3] or electromagnetic dispersion [4] seem promising. In the last years, our group successfully demonstrated dispersion-based absolute interferometer schemes based on heterodyne interferometry [5,6]. But these suffer from a high degree of complexity. Since for the use at space observatories such a thermometer must operate on open fields. Therefore, a simple construction is important in terms of handling, robustness and sensitivity.

Modulation-based signal detection – often referred to as 1f/2f or 2f/3f interferometry- is an alternative to enable multiwavelength interferometry [7]. Its basic optical design is a simple Michelson Interferometer set up (Figure 1). By frequency modulation of the laser source a phase modulation of the interference signal is created. The amplitude of the consecutive harmonics (1f, 2f, 3f) are proportional to the sine or cosine of the phase values, to the amplitude of the respective order Bessel functions and the arm length difference. To increase the attainable precision and accuracy of the quadrature detector system the amplitude of two consecutive harmonics are adjusted to be equal [8]. The quality of modulation-based detection interferometry data depends on an optimization of the modulation depth to the path length difference. For an application on large structures, this can only be achieved to a certain degree, in particular, if their position is not fixed. In this study, we realize a simple modulation-based single colour interferometer and perform measurements over macroscopic distances to explore the applicability of this scheme to large-scale metrology.

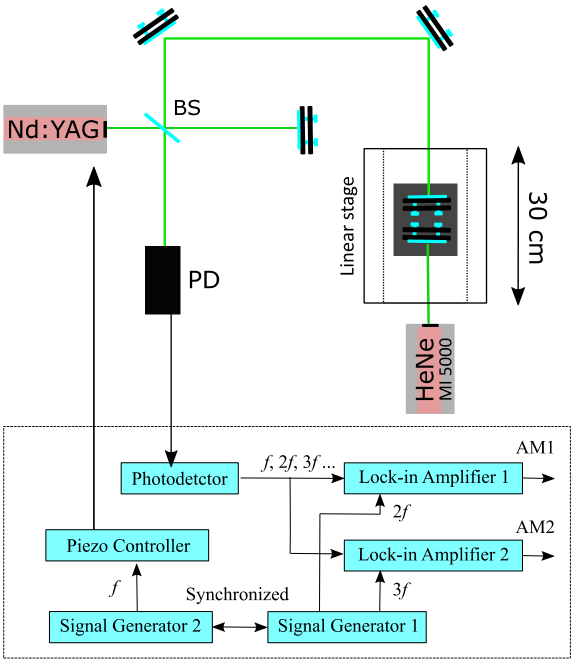

Figure 1. Experimental setup including a Beamsplitter (BS), Photodetector (PD).

2. Experimental Setup

Our 1f/2f or 2f/3f signal detection is based on a Michelson Interferometer fed by a Nd:YAG laser (Coherent Prometheus,

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see Figure 1). Here, we realize a counting interferometer with a moveable mirror on a linear stage (PI LS-180) and a Nd:YAG laser source (λ= 532.27 nm). The difference between the measurement arm and the reference arm can be varied for short range (1 m) and long range (20 m) experiments. A sinusoidal modulation of the laser frequency of 47.1 MHz is induced by a sinusoidal variation of the laser cavity length via a piezo controller with frequency of 9kHz and a peak-to-peak amplitude of 23.55 V. The resulting interference signal of the photodetector is split to one of the two lock-in detectors (Stanford SR850 DSP). The sine (1f or 3f) and cosine (2f) signal are detected individually. The reference signal needed by the lock-ins is provided by an external signal generator which also modulates the laser source. An encoder converts the sine and cosine signal into TTL format. This limits the measurement accuracy to $\lambda/4$. A HeNe based commercial interferometer (SIOS MI5000) is placed opposite to our set up. The lock-in signals are recorded by an encoder (PCIe-6361). Synchronization of reference and measurement signal are ensured by an external created trigger.

3. Measurement Results

Figure (2a) shows the exemplary cosine (2f) and sine (3f) signal by the lock-in detectors when moving the stage 350 µm with a velocity of 0.05 mm/s and an arm length difference of 2.30 m. Nevertheless, the signal is clear and stable over the entire movement range of 300 mm also for extended arm length differences. The amplitude of the sine and cosine signal changes individually depending on the arm length difference. Therefore, we performed two different experiments. Firstly, we changed the arm length difference and analysed the modulation amplitude. In the short-range experimental data shown in Figure (2b) the modulation amplitude is adjusted every 15 mm (arm length difference from 1.30 m to 1.60 m) so that both amplitudes of the 1f/2f (2f/3f) signal are equal. In theory, this modulation amplitude can be calculated by $\Delta\nu = \frac{\Delta\theta c}{4\pi s}$. $\Delta\theta$ is here defined as the phase for which the consecutive Bessel functions first coincide ($\Delta\theta_{1f/2f} = 2.63, \Delta\theta_{2f/3f} = 3.76$), and s represents the arm length difference and c the speed of light. As can be seen in Figure (2b), the slope of theoretical and experimental curves is nearly the same. A possible explanation for the offset of about 10 MHz is an imperfectly balanced amplification scheme of the cosine and sine amplitudes in the detection scheme. Our experiments hence show that a dynamic change of the modulation amplitude in a movement range of 300 mm is unnecessary. By increasing the difference in arm length over a larger range, however, the signal decreases more substantially. Then, the modulation amplitude must be adjusted. For an arm length difference from 2 m to 20 m, e.g., the optimum modulation amplitude decreases by 29.1 MHz for our experimental configuration (Figure (2c)).

Secondly, the short-range experiment is also instructive to study a sensible choice of the modulation signal for the sine information. For this, we measure a 300 mm (arm length difference 2.80 m to 2.83) distance consecutively with the 1f/2f and 2f/3f interferometer under very similar environmental conditions. As reference, the HeNe Interferometer is used. The deviation of the length measurements is shown in Figure (2d). The observed magnitude of the observation can be explained by a misalignment of the two opposing beams. For a travel length

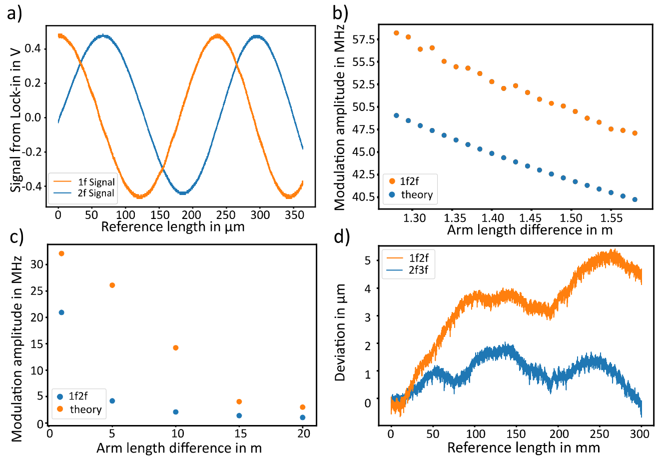

Figure 2. a) Sine and cosine signal detected by the Lock-ins and deviation of length measurement. b) and c) Modulation amplitude changes depending on the arm length difference d) Deviation of length measurement to reference

of 300 mm the cosine error for the given configuration can be estimated to be in the order of up to 3 µm. This is in good agreement with the observed deviation magnitude. In details, a similar trend of the deviation of the 1f/2f and 2f/3f can be recognized. Nevertheless, the deviation significantly decreases for the 2f/3f signal. In principle, the 1f/2f signal provides a higher signal power. But the signal is superposed by the fundamental intensity modulation. This explains the higher deviation of the corresponding measurement data. Based on these results we will focus on 2f/3f signals for future setups.

4. Conclusions

We have realized a basic interferometer based on modulation interferometry and performed measurements over macroscopic distances of 300 mm up to 20 m with a special emphasis on the modulation amplitude. The optimum modulation amplitude Δν changes insignificantly for the shorter moving range. A dynamic adaption of the modulation amplitude seems less critical for a millimetric distance variation. We confirm that the 2f/3f signal shows a significantly smaller deviation than the 1f/2f signal from the reference. If the signal power is sufficient, the 2f/3f signal seems preferable. In principle, robust modulation-based phase signals for arm length differences up to 20 m have been demonstrated. This shows the applicability of this demodulation scheme for long-range applications.

Acknowledgements

The authors would like to thank T. Meyer for technical support.
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