Interferometry with Stabilization of Wavelength within a Fixed Measuring Range

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1 Introduction

We present an interferometric technique based on differential interferometry setup for measurement in the subnanometer scale in atmospheric conditions. One of the important limiting factors in any optical measurement are fluctuations of the refractive index of air representing a source of uncertainty traditionally compensated when the index is evaluated indirectly from the physical parameters of the atmosphere. Our proposal is based on the concept of overdetermined interferometric setup where a reference length is derived from a mechanical frame made from a material with very low thermal coefficient on the 10^{-8} level. The technique allows to track the variations of the refractive index of air on-line directly in the line of the measuring beam and to compensate for the fluctuations.

2 Stabilization of Wavelength

Proposed concept relies on direct stabilization of wavelength to a mechanical reference. The principal optical arrangement [1] consists of a set of two counter-measuring interferometers. The moving element, representing the displacement to be measured, moves within stable grid of fringes/wavelengths insensitive to the varying refractive index of air. The key improvement here is the ability to measure, or compensate, for the refractive index variations in the beam path identical with the position sensing. Concepts proposing referencing wavelength to external mechanical reference have been proposed before [2] but thermal gradients and inhomogeneity of the atmosphere results in a large uncertainty caused by measurement of the refractive index of air at a place different to the measuring beam.

In this contribution we present a new version of this concept focused on a design applicable in real displacement measurements. The setup consists of three interferometers where each measures the specified part of the overall length (A, B, C, see Fig. 1).

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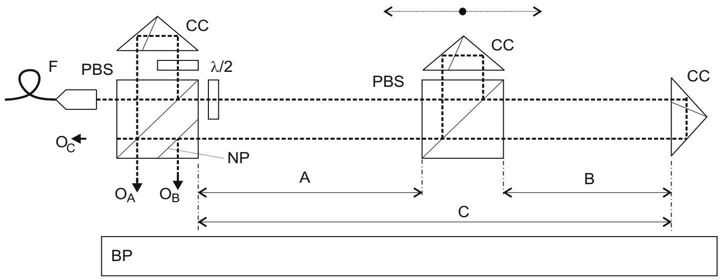

Fig. 1 Configuration with corner-cube reflectors measuring directly the overall length and two particular displacements. CC: corner-cube reflector, PBS: polarizing beamsplitter, NP: non-polarizing plane, λ/2: half-wave plate, F: fiber-optic light delivery, OA, OB, OC: outputs, A, B: measured displacements, C: overall length, BP: baseplate.

The principle combines one-axis interferometric measurement with Michelson type interferometer and tracking refractometer that is able to follow the variations of the refractive index just in the beam path of the measuring interferometer. This is the key improvement over other concepts of stabilization of wavelength in air [3, 4]. Our arrangement includes two interferometers measuring the displacement in a counter-measuring setup and a third one that gives the information of the overall optical length changes. The interferometer C serves a reference for the atmospheric wavelength stabilization.

The carriage position can be seen in our arrangement as overdetermined, it is measured from both sides, referred here as A and B. The value of the refractive index may differ in the left and right part (A, resp. B) of the setup. The best approximation of the resulting carriage position should be thus a value calculated from both A and B positions.

3 Fluctuations of the Refractive Index of Air

Performance of this system can be judged on the basis of understanding of the behavior of the fluctuations of the refractive index of air. The concept presented here offers fast response to any change of the optical length in the refractometer beam path, as fast as the response of the interferometer output in case of calculated compensation [5] or as fast as it is offered by the control loop of a stabilized laser in a regime of stabilization of wavelength [6].

The spectral interpretation of the length noise associated with the fluctuating refractive index shows similar characteristics with the laser induced noise [7, 8]. As expected the dominating bandwidth here lies in the low-frequency part, where the fluctuations gradually grow into drifts, thermal and pressure induced. Corner frequency for both recordings differs, for the closed enclosure it is 40 Hz, for the open environment 200 Hz (Fig. 2).

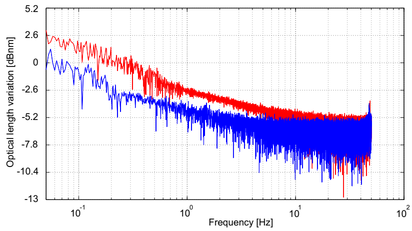

Fig. 2 Power spectral density of the position noise caused by the refractive index fluctuations monitored by the interferometer C in a closed thermal box (blue) and open laboratory environment (red)

The interferometric setup was subject to a slow drift of the refractive index of air induced through heating of the air within the thermal control box. The aim was to compare the recording of the varying refractive index evaluated through Edlen formula with tracking of these variations through the laser optical frequency in the regime of stabilization of wavelength. The laser was locked through a servo control loop to the constant output of the interferometer C, at the beginning of the experiment reset to zero value. In Fig. 3 we show the refractive index drift and the corresponding drift of the laser optical frequency. The proof of the concept was based on comparison of these two recordings.

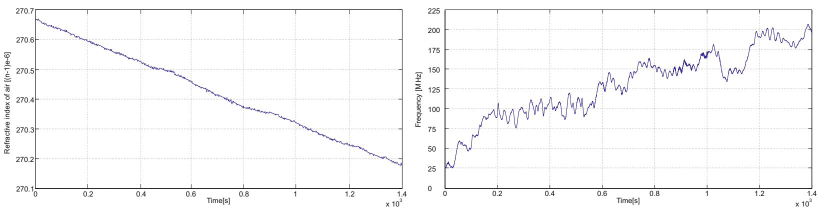

Fig. 3 Recording of a slow refractive index drift evaluated through Edlen formula (left) and the optical frequency tuning of the laser with stabilized wavelength over the measuring range (right)

The gradual drop of the refractive index recorded over approx. 20 min recorded in Fig. 3 performs a smooth decrease due to slow response of the sensors for measuring of the parameters of the atmosphere. The recording of the optical frequency shows the sensitivity of the system following the small-scale variations and thus the ability of this system to compensate for them.

4 Conclusion

Performance of this system can be judged on the basis how the laser locked to the constant wavelength is able to follow the fluctuations of the refractive index of air and how relevant the displacements measured by the interferometers A and B are within the measuring range set by the interferometer C with the stable wavelength. The agreement between the recordings of indirectly measured refractive index and laser frequency tuning can be expressed as on the level 2 x 10^{-8} difference between the relative change of refractive index and relative change of laser optical frequency (Fig. 3).

In the regime of laser frequency control and wavelength stabilization the response time of the servo loop controlling the laser optical frequency should be also above the limiting corner frequencies visible in the Fig. 3 to achieve the best performance. The continuous tuning range of the laser must also correspond to the relative change of the refractive index. Considering the parameters of atmosphere, for example the drift of temperature over 1 K needs tuning of the laser over approx. 1 GHz. The concept presented here is well able to follow the fluctuations of the refractive index of air and effectively compensate for them. It is not able to measure the absolute value of the refractive index.

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