Position sensing with suppression of the drift of the refractive index of air for high resolution interferometry

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Abstract

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 1*E-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. The optical setup consists of three interferometers sharing the same beam path where two measure differentially the displacement while the third evaluates the changes in the measuring range acting as a tracking refractometer. The principle is demonstrated on an experimental setup and a set of measurements describing the performance is presented.

1.Introduction

Commercial interferometric systems rely on compensation of index of refraction of air done by measuring of the fundamental atmospheric parameters – temperature, pressure and humidity of air, accompanied sometimes by the measurements of concentration of carbon dioxide. The value of refractive index is extracted by evaluation of empirical Edlen formula. The limits of the Edlen formula together with problems with measuring close to the interferometer laser beam result in relative uncertainty achievable this way on the level of approx. 10^{-6}, maybe more but depending on the air flow within the setup. This is quite a poor value compared to the relative stabilities of modern laser etalons being about 10^{-13} (Nd:YAG iodine stabilized laser) or even better. Together with low noise level of laser sources, high resolution of digital signal processing the interferometric measurement without the influence of the air could offer much better precision.

2. Experimental configuration

We proposed a concept with an over-determined counter-measuring interferometric displacement measuring setup [17-19] where the length in one axis was measured by two interferometers with their position fixed to a highly stable mechanical reference. In this case the reference relied on a material with thermal stability low enough to overcome the uncertainty caused by fluctuations of the refractive index of air. We used “0”–grade Zerodur ceramics from Schott, with stability at 10^{-8}/K level for a wide range of temperatures from 0°C to 50°C. In a smaller range the coefficient of thermal expansion should have a plateau with even smaller thermal expansion. 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 the overall length is not a sum value of two but an independently measured value (fig. 1).

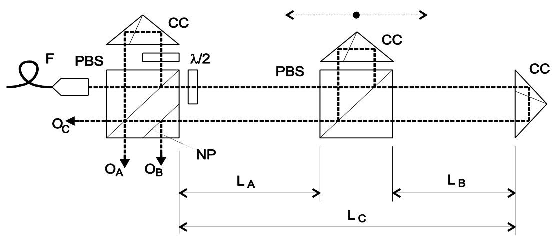

Figure 1. Configuration with corner-cube reflectors measuring directly the overall length and two particluar displacements. CC: corner-cube reflector, PBS: polarizing beamsplitter, NP: non-polarizing plane, $\lambda/2$: half-wave plate, F: fiber-optic light delivery, O_A, O_B, O_C outputs, L_c. L_a, L_b: particular lengths determining the position of the moving carriage.

The system consists of three independent interferometers where each measures the specified part of the overall length (A, B, C, see fig. 1). The left polarizing beamsplitter with a corner-cube reflector serves as a reference arm for the interferometer measuring the distance between the left reference point and the moving carriage (A) as well as for the interferometer measuring the overall length (C). The moving carriage carries another beamsplitter with corner-cube reflector generating a reference arm for the interferometer measuring the distance between the moving carriage (B) and the right reference point. The beam of the interferometer C only passes through the beamsplitter on the moving carriage. Beam paths on air of the interferometers A and B are identical with proportional parts of the beam path of the interferometer C.

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. 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. Considering the physical length of the interferometer C constant, or constant with precision overwhelming the precision of the refractive index evaluation the output of the interferometer C serves a reference for the atmospheric wavelength stabilization. Average value of wavelength in the range given by interferometer C is kept constant and the carriage moves within.

The carriage position can be seen in our arrangement as overdetermined, it is measured from both sides, referred here as A and B. The carriage displacement may be referenced either to the left or right end of the measuring range. Still the identity of the displacement measuring beam path (on air) and the beam path of the tracking refractometer is limited by the ratio given by the carriage position. 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. System performace

The key aim of this design has been a reduction of sensitivity of the overall measuring interferometer to the moving central optical element at the carriage, especially to its angle deviations. For the interferometer C the central beamsplitter cube is a transmissive element acting as plan-parallel plate. Its angle misalignment of 1 arc minute produces lengthening of the optical length measured by the interferometer C over 0.2 nm when the cube is 15 x 15 x 15 mm in size. It is a product of lengthening of the geometrical length due to lateral shift and lengthening of the beam path in glass. One arc minute is the maximum guidance error of our linear positioning stage. A recording showing the stability of the interferometric system under the carriage motion is in Figures 2 and 3.

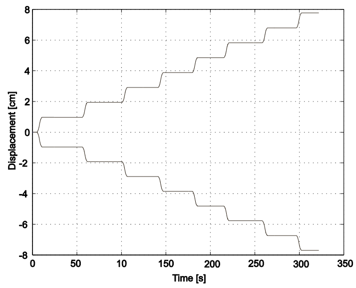

Figure 2. Recording of the outputs of the interferometers A and B in counter-measuring setup during step motion over approx. 8 cm of travel.

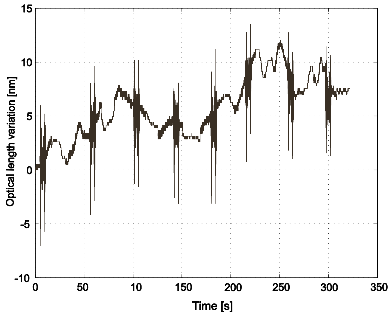

Figure 3. Recording of the output of the interferometer C measuring of the overall length of the measuring range recorded simultaneously with the recordings in Fig. 5.

Motion of the carriage together with the level of variation optical length caused by the fluctuations of the refractive index is in Figure 4. The slow motion of the carriage over a short range here is a result of a thermal drift of the positioning stage and any vibrations seen in the previous figure are eliminated. The recording shows outputs from the three interferometers (A, B, and C) in an enclosed environment reducing the air flow (only to convection air currents inside). Outputs from the interferometers were recorded with their counters reset at the start of the measurement. The carriage was approximately in the middle of the measuring range. The air path of the whole measuring range (monitored by the interferometer C) was 195 mm. The recording shows absolute changes of the measured optical lengths over the time interval 50 min. We added also the sum of A and B. This value shows a good agreement with the result of the interferometer C showing that the output C can monitor the varying refractive index in both A and B very well.

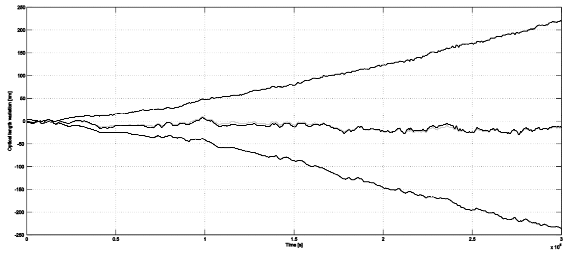

Figure. 4. Recording of the variations of the interferometers A (bottom line), B (top line), and overall length measuring C (middle line) together with the sum of A and B (middle grey line) over time in an enclosure.

This level of agreement should be interpreted in comparison with the sole variations of A, resp. B, representing here the displacement of the carriage. This may be seen as a limiting factor of the resolution and of the possibilities of the method to compensate for the drift. The agreement also shows that the best approximation of the measured carriage displacement should be derived from both A and B values, most likely an average of both. This limit is a limit of homogeneity of the environment and will be worse in case of increased air flow. On the other hand the level of variations will increase as well, so the mean value of agreement should be considered in comparison with the mean value of the overall fluctuations. According to our estimation the level of uncertainty associated with the refractive index fluctuations will improve at least one order, not to mention the speed of response.

The recording in Figure 7 shows the nature, especially the speed of the fluctuations of the refractive index of air. The key benefit of the proposed technique, next to the identical beam paths for displacement measuring and refractive index monitoring, is the ability to respond fast to all the variations. A comparison with indirect measurement and evaluation of refractive index through modified Edlen formula has been shown in [1] and a comparison of the tracking, controlled laser optical frequency with the Edlen formula in [2]. In both cases a commercial weather sensor unit especially designed for interferometry has been used. The response time of all the sensors limits significantly the ability of this indirect method to follow the fast changes seen in Figure 7 and only the long-term drift in the order of minutes corresponds with the output of the tracking refractometer.

4. Conclusion

This concept actually links one source of uncertainty to another. Namely the fluctuating optical density of the environment – the refractive index of air to mechanics of the interferometric setup. The sense of doing so lies in the level of uncertainty, where the refractive index dominates one or two orders, also due to the speed of these variations, where the material properties of a frame or a baseplate result in very small drift due to thermal dilatation and finally the mechanical reference simply cannot be eliminated while always there has to be something measured with respect to something. The information about varying optical length within the defined measuring range can be used either for calculating a correction for the measured displacement [1] or for direct stabilization of wavelength [2]. In the second case tunability of the laser may be the limiting factor from the point view of speed as well as range [3,4].

In our case the reference relied on a material with thermal stability low enough to overcome the uncertainty caused by fluctuations of the refractive index of air. We used "0"–grade Zerodur ceramics from Schott, with stability at 10^{-8}/K level for a wide range of temperatures from 0°C to 50°C. In a smaller range the coefficient of thermal expansion should have a plateau with even smaller thermal expansion. To follow the principle of referencing to high-stability mechanical frame, it should include the central beamsplitter on the moving carriage to be made out such material as well, at least quartz glass. In our case in this design assembled for a "proof of principle" experiment we used SF-14 glass for technology reasons. This may be also seen from the point of view that the system cannot completely bypass the indirect evaluation of the refractive index. It is able to follow only the fluctuations. Relying on high stability material such as Zerodur and the need to compensate even the smallest material thermal drift may make it too expensive and complicated. But when we would seek improvement at the scale where the differences are (seconds and tens of seconds) the slow thermal expansion of the material may not be the crucial problem. The measurement can still rely on Edlen formula [5, 6] for slow monitoring of the refractive index and on the scale below approx. 1 minute limit this method can be included into the measurement scheme. Thus even with no expensive low-expansion materials it can bring an improvement. This improvement may be seen as a sort of noise-eater for noise introduced by fast-varying fluctuations of the atmosphere.

6. Acknowledgments

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