Interferometry in a passive Fabry-Perot cavity with the detection of a standing wave

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Abstract

We present a measuring technique for displacement and position sensing over a limited range with detection of standing-wave pattern inside of a passive Fabry-Perot cavity. The concept considers locking of the laser optical frequency and the length of the Fabry-Perot cavity in resonance. Fixing the length of the cavity to e.g. a highly stable mechanical reference allows to stabilize wavelength of the laser in air and thus to eliminate especially the faster fluctuations of refractive index of air due to air flow and inhomogeneities. Sensing of the interference maxima and minima within the cavity along the beam axis has been tested and proven with a low loss photoresistive photodetector based on a thin polycrystalline silicon layer. Reduction of losses was achieved thanks to a design as an optimized set of interference layers acting as an antireflection coating. The principle is demonstrated on an experimental setup.

1. Introduction

The most precise techniques for measurement or macroscopic objects are based on interference of light of a highly coherent laser source. Incremental interferometry techniques derived from a Michelson interferometer become a cornerstone for measurement of geometrical quantities in primary metrology, calibration of mechanical length standards and also in industrial applications where ultimate precision is needed. Improvement of resolution compared to simple counting of a length element – the wavelength – has been achieved by a combination of optical techniques and advanced electronic digital signal processing of the interference signal.

Measurement of the refractive index became a part of any interferometric setup that cannot be avoided. The limiting factor seems to be the stability of the atmosphere around the beam path. The practical limit for determining the refractive index of air is determined by the thermal gradients and air fluctuations that can be avoided depending on the application. In case of all commercial interferometric systems the compensation of index of refraction of air is done by measuring of the fundamental atmospheric parameters – temperature, pressure and humidity of air, accompanied in some cases by the measurements of concentration of carbon dioxide. The value of refractive index is extracted by evaluation of empirical Edlen formula [1, 2, 3, 4]. Thus, the limits of this indirect determination of the refractive index are primarily given by the configuration of the measuring setup, by the air flow and stability of atmospheric conditions close to the laser beam rather than by the precision of sensors measuring temperature, etc. or the formula itself.

All measurements of the refractive index of air performed by refractometers or by evaluation of the Edlen formula suffer one principal limit which is the fluctuations of air along and around the laser beam axis together with thermal gradients present in the air – mainly in the vertical direction. To reduce this effect we proposed an interferometric measuring system designed to operate within a defined measuring range combining refractometry and displacement interferometry with a single beam path. This concept links the value of refractive index of air to the mechanical reference – a highly stable frame made of a material with a low thermal expansion coefficient. This concept has been demonstrated in a regime of stabilization of wavelength [5, 6, 7].

The idea of stabilized wavelength within a certain defined measuring range leads quite directly to a cavity – based design. A passive Fabry-Perot cavity has been traditionally used as an etalon for laser frequency stabilization in a large number of configurations and applications. Linking a laser optical frequency to a resonance of the cavity means in fact a stabilization of wavelength within a cavity where the standing wave has been generated. We tried to use this "grid" of the standing wave as a reference for direct position sensing. The concept of measuring within a standing wave generated by a reflector has been reported previously [8], but we propose here the measurement within a cavity together with the effect of stabilization of wavelength.

2. Cavity – based position sensing interferometer

The arrangement with stabilization of the laser wavelength can be also considered a standing-wave interferometer. This leads directly to an attractive option, where instead of couterpropagating beams or a complex of interferometers a cavity-like setup may serve as a reference for stabilization of wavelength. This approach needs a component able to track the interference maxima and minima along the beam axis inside of the cavity. In [8, 9, 10] a transparent photodetector has been reported even in a design with two active domains separated by a distinct spacing suitable for generation of quadrature signals usual in displacement interferometry. Suitable balance between the losses caused by the detector to the beam passing through and its sensitivity has to be found when it should be placed into a passive resonant cavity (Figure 1).

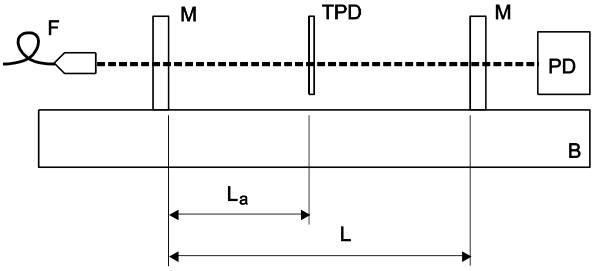

Fig. 1. Configuration with a passive Fabry-Perot cavity. M: cavity mirror, PD: photodetector, TPD: transparent photodetector, F: fiber-optic light delivery, B: baseplate, La, L: displacement and overall length.

3. Transparent photodetector

The key component for position sensing inside of a passive Fabry-Perot cavity is a low-loss transparent photodetector with very low reflectivity. Our design is a detector in a form of a thin photoresisitive silicon coating with conductive electrodes on both sides. This reduces the losses while only the silicon layer is in the beam path. When deposited in a form of a thin film on a glass substrate contribute to the measuring length in a negligible way, the glass substrate on the other hand follows the need of small thermal expansion coefficient. This setup consists of a fused silica substrate, active silicon layer and a set of antireflection coatings. The set of layers including the active one was proposed and optimized for minimum reflectivity as a whole system (Figure 2).

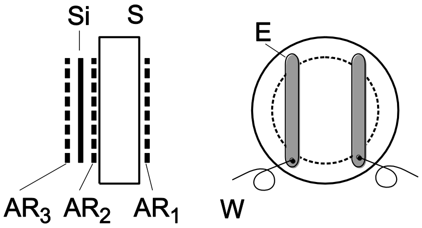

Fig. 2. Transparent photodetector design. AR: antireflection coatings, Si: silicon layer, S: fused silica substrate, E: Titanium electrodes, W: wiring.

The thickness of the active layer reflected the intention to have its optical thickness smaller than $\lambda/4$ to be able to resolve the discrete maxima of the standing wave. The real thickness is also a result of the optimization of the reflectivity. All the TiO_2 and SiO_2 layers were deposited by electron-gun evaporation in a vacuum chamber and the

Silicon active layer by PECVD technology at 13.56 MHz in the mixture of Silan and Hydrogen. The calculated transmissivity at 532 nm wavelength was 88%, real measured value was 66%, while the losses were due to absorption in Silicon layer only, reflectivity thanks to AR coatings was at the 0.1% level.

4. Intra-cavity position sensing

The concept of intra-cavity position sensing was demonstrated in a setup with a hemispherical resonator. A stable configuration with 200 mm mirror spacing and a concave mirror with 800 mm diameter of curvature were chosen. The cavity was fed by a low-noise, frequency doubled Nd:YAG laser designed for metrology applications equipped with double PZT tuning. Faraday isolator protecting the laser from retroreflections and a telescope for beam shaping were placed between the laser and cavity. The beam coupling was adjusted to achieve a fundamental TEM00 mode in the cavity.

The experiment described here was a proof of concept so the cavity body was assembled as a four-rod assembly with unspecified thermal expansion. Locking of the laser optical frequency to the resonance of the cavity was done via modulation of the laser frequency and phase-sensitive detection with 1-f derivative spectroscopy technique. The level of frequency modulation was set small compared to the cavity linewidth to reduce its influence to the level of signal detected by the transparent photodetector. To proof the ability of the system to measure position within the cavity the transparent photodetctor was moved on a PZT driven nanopositioning stage along the beam axis. Recording of the detector output is in Figure 3.

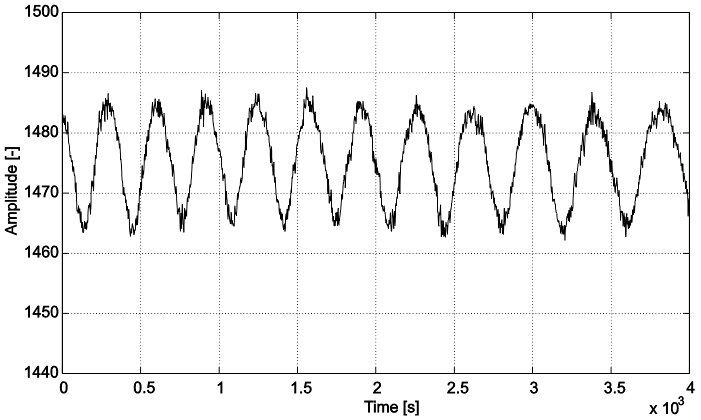

Fig. 3. Recording of the output of the transparent photodetector during motion along the beam axis within the passive Fabry-Perot cavity.

5. Conclusion

Technique based on a concept combining a stabilization of wavelength to a stable mechanical cavity together with position sensing in the same beam axis represents a significant step towards raising precision of practical dimensional metrology especially in the nanoscale region. In configurations where the laser interferometer(s) measure a displacement of a defined object (such as movable table of a microscope) over specified range there might be the right chance to implement the compensation of refractive air fluctuations. The increase of complexity and cost of two-directional measurement can be considered relatively small compared to the sophisticated positioning stages with angle and motion control. The application of such systems seems to be directed into primary nanometrology in combination with tools such as local probe microscopy and related techniques.

The arrangement presented here describes a design of a transparent photodetector with losses low enough to be operated inside of a cavity and reflectivity also low enough to avoid reflections and coupled cavities effect. Its ability to detect displacement within a grid of interference maxima and minima inside of a cavity with stabilized wavelength was proven. Its coincidence with resonance maximum results in higher losses compared to coincidence with resonant minimum. This results in variations in the cavity Q-factor and optical power in the cavity but does not result in optical frequency shift. The stability of the wavelength within the measuring range given by the cavity length is preserved. This arrangement when equipped with quadrature, direction resolving detection can operate as a fully length measuring interferometer with suppression of fluctuations of the refractive index of air.

6. Acknowledgments

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7. References

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