Absolute distance sensing by dual laser interferometry

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Abstract

This article describes the interferometric measurement of the absolute distance to an object by means of combining a fixed and a tunable wavelength semiconductor laser. We developed a miniature fiber-optic interferometer that can measure the absolute distance in the sub-meter range with nanometer repeatability. This enables nanometer precise positioning even in case of an interferometer interruption.

1. Introduction

The repeatable alignment of objects with nanometer precision belongs to the key challenges in precision engineering. Laser interferometers are often used for position tracking because they provide position information with sub-nanometer resolution and high accuracy. However, incidents like a beam disruption, a power failure, a rapid change in the optical path, the removing of the target object from the beam path or simply the turn off of the interferometer lead to a loss of position information. This is especially undesired when working in extreme environments with reduced accessibility like, for instance, in particle accelerators or on board of satellites or probes. Overcoming this limitation requires the ability to measure the absolute position to an object. There are already a lot of successful approaches to this topic, but all of them suffer from low measurement bandwidth, extreme complexity and high costs, as some of them, for example, rely on the use of frequency combs.[1] We have implemented a new industry scalable method for the measurement of absolute distances with nanometer repeatability in the sub-meter range based on a previously reported incremental fiber-optic displacement interferometer.[2]

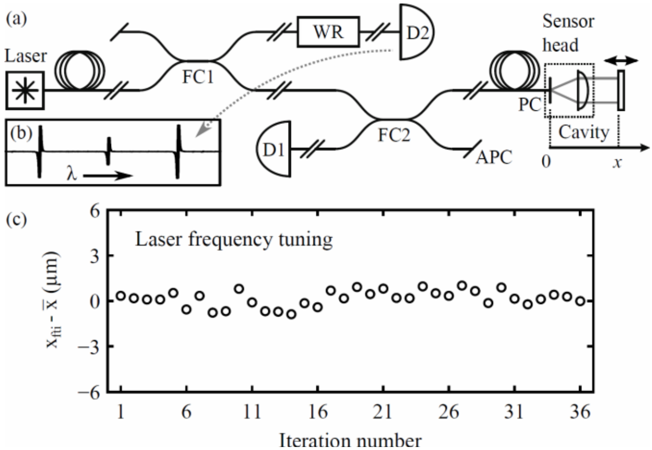

Figure 1: (a) Single laser fiber-optic setup for the measurement of incremental displacements of a target mirror. The laser light is routed through fiber couplers FC and detected at the detectors D. Fiber end and mirror form a low-finesse Fabry-Pérot cavity. (b) Gas cell demodulation signal as a function of the wavelength λ. (c) By tuning the laser wavelength, the absolute position x_{fti} can be measured with un uncertainty of about ±1 µm.

2. Measurement system

The basic fiber-optic setup of the displacement measuring interferometer is shown in Fig. 1a. The light from a wavelength modulated laser is routed to a low-finesse Fabry-Pérot cavity which is formed between the fiber end and a displacing target. For operation of the interferometer, the compact fiber-coupled sensor head is mounted facing to the target. It has a size of only few millimeters as it only consists of a collimating lens and a mounting for the optical fiber, which connects the sensor head with the interferometer and, in this way, enables remote sensing. The determination of the position change is performed using a quadrature detection method based on the filtered and the wavelength demodulated interference signal. Through wavelength stabilization to a NIST traceable molecular absorption gas (WR) the interferometer measures the displacement of a moving target reflector with sub-nanometer repeatability. The functionality can be expanded towards measuring absolute distances by tuning the wavelength of the laser between different absorption lines of a molecular absorption gas cell (Fig. 1b). However, the repeatability for a stable cavity is limited to several micrometers as shown in Fig. 1c. Moreover, target drifts during the frequency tuning would contribute disproportional to the total error.

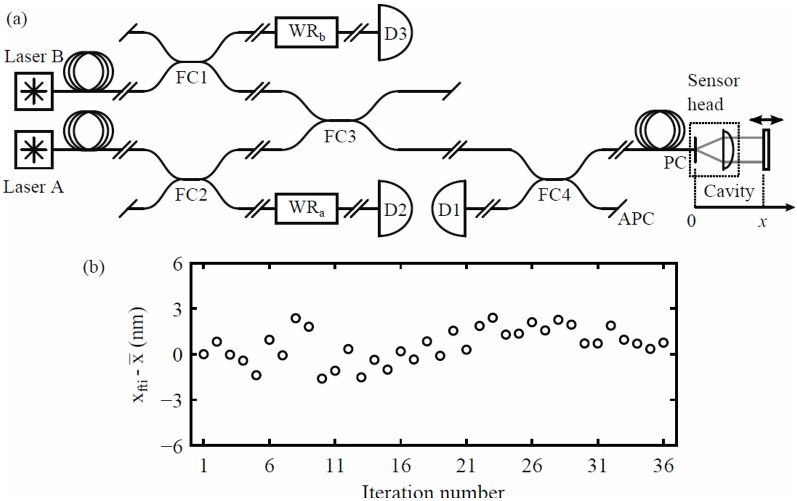

Figure 2: (a) Dual laser optical setup capable of measuring absolute distances with nanometer repeatability. Both lasers are wavelength stabilized to two reference gas cells WR. (b) Repeated measurement of the absolute position showing an uncertainty of ±3 nm.

To overcome these limitations, we are using a second setup (Fig. 2a) with two tunable lasers which are wavelength modulated with different frequencies. The superimposed light generates a beating pattern with a larger effective wavelength, thus increasing the range in which the absolute position is unambiguously related to interference phase. Additionally, the wavelength of one laser is tuned in order to obtain a coarse value of the absolute distance, while the second laser tracks changes of the target position. In this way, the interference order of the beating wavelength is determined, which allows to determine the absolute distance unambiguously. In order to achieve nanometer repeatability, the beating wavelength phase is related to the real interference phase of one laser. By continuously tracking the target position, the absolute distance can be determined even during target displacement. The separation of both interference signals is achieved by different modulation frequencies of both laser wavelengths. A quadrature detection technique based solely on the demodulation of the superimposed detector signal at the respective first and second harmonic frequency allows recovering the interference phase of both lasers and this without the use of optical filters or beam splitters [3], thus making the system robust against external influences. The computation of the absolute position information is performed using the phase information of both laser wavelengths gained during the wavelength sweep. The process of measuring the absolute distance is performed during operation as an incremental displacement sensor. Once the absolute distance is measured, the incremental distance change can be measured at Megahertz bandwidth. Due to its outstanding robustness and compactness, our interferometer is ready to meet positioning requirements even in the harshest environments like cryogenic temperatures or ultrahigh vacuum.

3. Conclusion

Combining the simultaneous measurement of the interference phase of two fixed wavelengths with the measurement obtained from sweeping the wavelength of one laser allows unambiguous measurement of the absolute distance to a movable object with nanometer repeatability and this without the need for initialization at a preset position origin. The measurement is independent from cavity drifts and does not affect the high bandwidth differential position measurement. In essence, the wavelength sweep of one laser simply adds a reference mark to the displacement measurement, thus allowing to keep track of the target movement even in presence of a disruption.

References:

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