euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Development of a miniature, multichannel, extended Fabry-Perot fiber-optics laser interferometer system for low frequency SI-traceable displacement measurement

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Abstract
The goal of this work was to build a directly SI-traceable laser interferometer displacement sensor with a sensor head no bigger than a single optical fiber diameter (0.125 mm). The sensor was designed and built specifically to serve as the primary displacement and force gauge sensor in an SI-traceable precision nanoindentation platform. The sensor is based on a fiber-optic, homodyne, low finesse, single detector Fabry-Perot cavity that is set up between a reflective surface and the cleaved end of an optical fiber whose laser wavelength is modulated sinusoidally. By modulating wavelength while cavity length is being changed, the signal measured by the detector has a spectrum consisting of responses at the modulation frequency and its harmonics. Those signals can be used to extract target displacement. This approach extends the working distance to well beyond 25 mm, while still maintaining sub-nanometer performance.

Keywords: Interferometry, laser, Fabry-Perot, modulation, displacement, sensor

1. Introduction

Laser interferometry has become a foundation of SI-traceable displacement measurement techniques. With ever decreasing cost per channel, miniaturization, and a multitude of commercially available off-the-shelf systems, these systems create attractive applications unheard-of a few years ago. Even though significant efforts have been made to shrink the size of the optical components necessary for a fully functioning laser interferometer sensor, most currently available commercial sensors still have a sensing element on the order of millimeters or more [1].

The goal of the work presented in this paper, which builds on our previous experience with fiber-based laser interferometer systems [2], was to build a directly SI-traceable laser interferometer displacement sensor with a sensor head no bigger than a single optical fiber diameter (0.125 mm). The sensor was designed and built specifically to serve as the primary displacement and force gauge sensor in an SI-traceable precision nanoindentation platform (PNP) [3].

2. Sensor design

The sensor is based on a fiber-optic, homodyne, low finesse, single detector Fabry-Perot (FP) cavity that is set up between a polished surface and the cleaved end of an optical fiber (Figure 1). When the cavity length changes, a Fabry-Perot laser interferometer system has an output best described by a low finesse cavity reflectivity, and is typically used only near a quadrature point, *i.e.*, the mid-point between an interference maximum and minimum. At or near that point, the intensity-displacement relation is assumed to be linear to within a 1 % error for displacements on the order of 100 nm for wavelengths near 1550 nm, but displacements larger than this cannot be tracked.

To overcome this limitation and extend the working range of our sensor, the laser wavelength (nominally 1550 nm) is continuously modulated sinusoidally at a frequency of f = 1.2 kHz, which was chosen based on the upper modulation frequency limit of our rapidly tunable laser (RTL). By sinusoidally modulating the wavelength while cavity length, *h,* is being changed, the signal measured by the detector has a spectrum consisting of responses at the modulation frequency f and its harmonics. The optimal modulation depth depends on the cavity length, and typically is 0.5 nm (peak-to-peak) for cavities on the order of few mm. Taking a closer look at the f and $2f$ signal intensities, I_f and I_{2f} respectively (Figure 2), it can be seen that when the cavity is changing they resemble sine and cosine. Those signals can be combined into a rotating vector created between point (0,0) and point (I_f,I_{2f}). Changes in cavity length caused by motion of the polished surface are then calculated from:

$$\Delta h = \frac{\lambda}{2}\left(\frac{\alpha}{360} + n\right),\ \ \alpha = \arctan\left(\frac{I_{2f}}{I_f}\right),$$

where λ is the wavelength, n is the number of times the

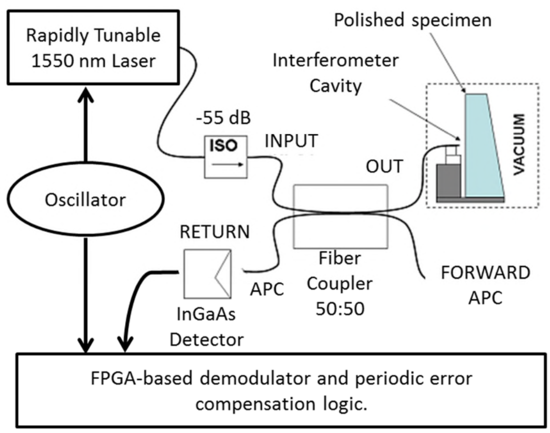

Figure 1. Main system components.

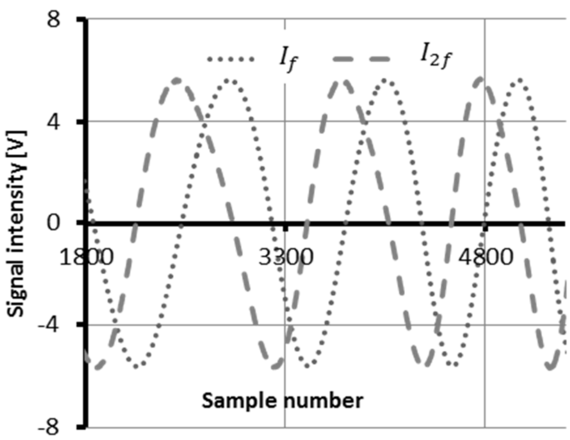

Figure 2. Demodulated signals at f and 2f during mirror displacement.

vector completes a full revolution, and α is the angle (in degrees) formed between the vector and the horizontal axis. This approach extends the working distance of a laser interferometer to well beyond 25 mm, while still maintaining sub-nanometer resolution.

2.1. Error compensation strategies

One inherent problem related to using a FP cavity in this extended mode is the inclusion of periodic errors described by Wilkinson *and Pratt* [4]. We have developed two methods for reducing the magnitude of these errors: one based on a look-up table created during system operation, and another based on post-processing the data using the model developed in Ref. [4].

2.2. Experimental approach to error compensation

In this method, a cavity is continuously swept by an open-loop piezoelectric-based nano-positioner capable of a maximum displacement of approximately 35 µm. It is generally known that piezoelectric actuators, if operated in voltage-controlled mode, exhibit nonlinear voltage-displacement characteristics. During a 35 µm cavity sweep with 1550 nm laser wavelength, the rotating vector completes a maximum of 45 full revolutions. Because all these data can be stored and overlapped, they can be averaged in post-processing to reveal cyclic nonlinearities. In this method the idealized angle is reconstructed; that is, the angle that the vector should have if no nonlinearities existed, is plotted against the actual measured angle. Multiple overlapped cycles are used to extract angular errors. A bicubic spline function is then used to fit the data to average all overlapping cycles into one monotonic data set. These data form a base for creating a 7200 point lookup table with linear interpolation used in between points.

By using this method alone, it was possible to reduce the amplitude of the periodic errors from approximately 50 nm down to the single-nanometer level.

2.3. Amplitude normalization technique and offset removal

Other sources of periodic errors include differences in f and $2f$ amplitudes, as well as minute DC voltage offsets present in signals. Since basic trigonometry is used to compute the angle from f and $2f$ intensities, it is assumed that their corresponding amplitudes are equal, and the rotating vector forms a perfect circle centered at the point (0,0). Any deviation from that creates periodic errors.

Amplitudes of both f and $2f$ depend strongly on laser wavelength modulation depth, the optimal amplitude of which is dependent on laser cavity length: the longer the cavity, the smaller the modulation depth required.

To maintain a constant ratio of f and $2f$ amplitudes, a closed-loop proportional-integral-derivative (PID) system has been incorporated. The signal from a detector is separated into f and $2f$ components using a lock-in amplifier implemented with field-programmable-gate-array (FPGA) methods. Amplitudes and residual offsets of the f and $2f$ signals are then measured individually for every interference cycle. Offsets are then removed by subtracting the measured values from corresponding f and $2f$ signals. The amplitude ratio of f and $2f$ is sent to the PID controller, which changes wavelength modulation depth to keep the ratio at unity.

3. Conclusion

This paper presents the development of a miniature, multichannel, extended Fabry-Perot fiber-optic laser interferometer system designed for a precision SI-traceable nanoindentation application. The system meets all requirements, achieving sub-nanometer noise levels, high stability, immunity to minute fiber-target misalignments and a surprising level of immunity to surface roughness. Ongoing research focuses on reducing periodic errors further with both theoretical and experimental approaches. A future paper will describe in detail an analytical approach to modelling and error compensation of similar systems, technique for absolute cavity length measurement and detailed sensor performance, including: sensor stability and noise, maximum measurement range for a mirror-polished target, maximum fiber-target angular misalignment and permissible target roughness.

Disclaimer

Commercial equipment and materials may be identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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