A HIGH-ACCURACY, MULTI-CHANNEL, FIBER-BASED DISPLACEMENT/ DISTANCE MEASURING INTERFEROMETER SYSTEM

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INTRODUCTION

This paper describes a high-accuracy, high-stability multi-channel fiber-based interferometer system with compact sensors that combines high-accuracy displacement and absolute distance measuring capability [1,2,3]. This technology distinguishes itself from other fiber sensors in that it addresses applications requiring a relatively large number (up to 64 in a single system, more through synchronized systems) of thermally passive, electro-magnetic interference (EMI) immune, compact sensors with exceptional long-term drift performance and high reliability. Further, this device also provides a large standoff (~mm) and a large measurement range (~mm) with a dynamic range characteristic of interferometric sensors, i.e., this technology is not limited by the range-resolution trade-off characteristic of other sensor types [4].

PRINCIPLE OF OPERATION

This section describes the two operating modes of the sensor: an absolute distance measurement mode that establishes the position of the target relative to the sensor in an absolute sense and a displacement measurement mode that tracks the motion of the target from an initial position.

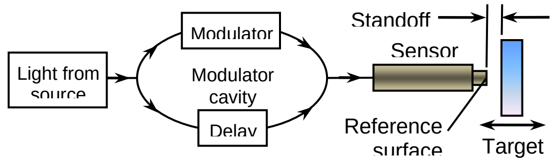
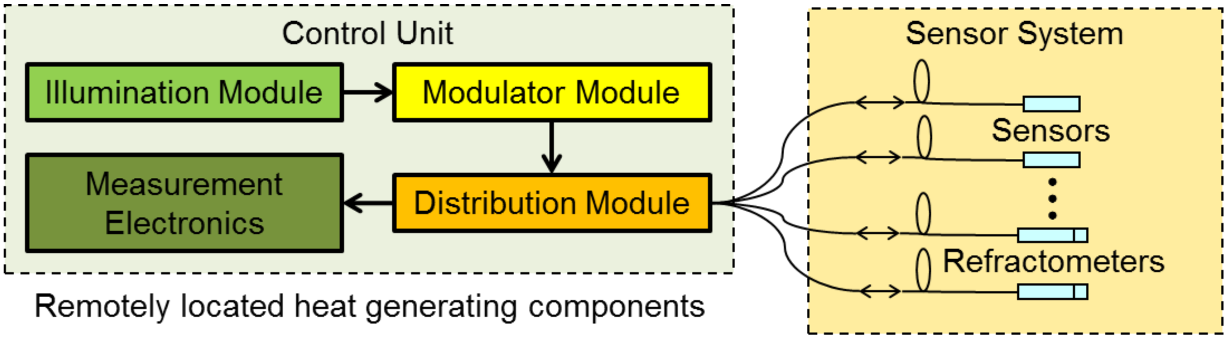


FIGURE 1. Principle of operation

Displacement measurement

In contrast to the absolute distance mode, *displacement* measurement is a relative measurement that tracks the distance moved by a target relative to an arbitrary (often user defined) zero position. This mode is "blind" to the absolute distance of the target. The coupled-cavity arrangement shown schematically in FIGURE 1 forms the basis of this mode operation. A relatively broadband (moderate coherence) source provides the illumination that is split into two paths at the input of the modulator cavity. The coherence length a tradeoff between providing adequate range and eliminating the effect of spurious reflections within the system that may form other cavities. One arm of the modulator cavity modulates the frequency of the light in that arm, while the other arm introduces a fixed phase delay. The modulated and delayed light combines at the output of the cavity. The combined radiation enters a second Fizeau cavity comprised of the sensor reference surface and the target via an optical fiber. Both surfaces reflect portions of the two beams. The portions reflected by the target traverse an additional optical path due to the round-trip to the target. This additional phase delay matches the delay imposed within the modulator cavity. The result is that the optical path lengths traversed by an unmodulated beam reflected from the reference surface and a modulated beam reflected by the target match and interference occurs at the frequency of the modulation. This phase of this frequency modulated AC signal is related to the target displacement, which is extracted using phase measuring techniques. The coherence of the source and delay in the modulator cavity independently determine the measurement range and standoff respectively. This sensor configuration has a number of advantages, including:

- Accessible reference surface to register the measurement datum to a metrologically relevant point in user's metrology frame
- Independent control of standoff and measurement range
- Large standoff and high dynamic range, i.e., large measurement range with interferometric resolution.
- Elimination of all heat generating components from the sensors



Remotely located heat generating components

Passive components embedded in application

FIGURE 2. System architecture

Absolute distance measurement

The sensor is also capable of measuring the absolute distance of the target from the reference surface. This capability is a natural consequence of the operating principle of sensors such as capacitance gages and triangulation sensors and is typically not available in interferometric sensors due to fringe order ambiguity. In this sensor, the method of exact fractions (due to Michelson and Benoit [5]) forms the basis of this functionality. In this technique, the fringe fraction from the “synthetic wavelength” of (whose length is driven by the maximum distance between the target and the reference surface) provides fringe order information for shorter wavelengths (either a single wavelength or a shorter synthetic wavelength). Two shorter, closely spaced wavelengths generate the synthetic wavelength. Fringe fraction information from the synthetic wavelength resolves the fringe order ambiguity in either of the shorter wavelengths. A combination of the fringe order information from the synthetic wavelength and the fringe fraction from one of the shorter wavelengths enables the determination of the absolute position of the target relative to the reference surface. This capability provides homing capability, i.e., allows the targets to return to known starting positions in the presence of beam interruptions and power cycling. Three wavelengths generate two synthetic wavelengths to establish the absolute position.

A typical measurement sequence starts with the relatively slow (low bandwidth) measurement of the absolute initial position of the target relative to the reference surface while the target is stationary. The system then switches to the displacement measurement mode that tracks the target motion at the full bandwidth of the instrument using a single wavelength.

SYSTEM ARCHITECTURE

The system consists of five functional modules as depicted in FIGURE 2. The control unit contains the illumination, modulator, distribution and measurement electronics modules and is remotely located. This serves to isolate the measurement apparatus from the heat generated by active components within these modules. It also facilitates serviceability by confining components that may require maintenance to an area outside the machine envelope. Embedding only the high-reliability passive sensors within the machine obviates the need for entering the machine envelope for maintenance, thereby minimizing downtime. This arrangement also confines all the electronics to a remote unit, thereby eliminating a potential source of EMI. Optical fibers connect the sensors to the control unit, making it possible to place the sensors at relatively large (tens of meters) distances from the control unit.

Illumination Module

The illumination module provides the moderately coherent (when compared to a laser) radiation at multiple wavelengths, which are used to implement the method of exact fractions for the determination of absolute distance. Displacement measurements rely on a single wavelength.

Modulator Module

The output of the illumination module feeds the modulator module, which imposes the frequency modulation on the incoming radiation and generates a phase delay between the modulated and unmodulated components. This module also contains stable etalons that track any phase drift in the modulator cavity and changes in the calibrated value of the illumination wavelengths.

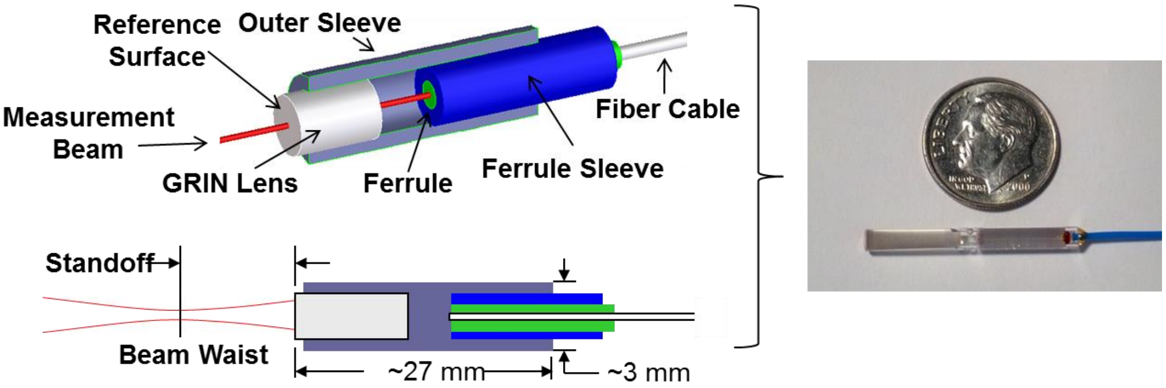


FIGURE 3. Details of sensor construction

Distribution Module

The modulated and phase-shifted output of the modulator reaches the sensors via the distribution module. This module also serves to collect the reflected light from the reference and target surfaces and returns it to the detectors in the measurement electronics.

Measurement Electronics

This module converts the optical interference signal into an electrical signal. The signal from each sensor is processed using phase measuring techniques to extract the displacement. The processing also factors in the refractive index data from the refractometers (specialized sensors that directly measure index of refraction). A high-speed data interface makes the digital position data available to the end-user.

Sensor System

The sensor system is comprised of the sensors embedded in the application. The sensors are constructed from standard telecom fiber components and exploit the reliability of the components and assembly processes developed for this industry. FIGURE 3 shows the details of sensor construction and the approximate dimensions of these extremely compact sensors.

The basic sensor is a fiber collimator, with a gradient index (GRIN) lens serving to collimate the light emanating from the fiber. This lens also couples the reflected light back into the fiber. Sensor reliability stems from the simplicity of the construction and the small number of passive components. The exposed surface of the GRIN lens (the reference surface) reflects part of the incoming light to form the reference beam for the interferometer. This surface provides a well-defined measurement datum, i.e., measurements are made relative this surface. This surface is accessible to the end user to facilitate registration of this datum with the reference frame of the user's metrology system. This in contrast to other displacement sensors of this type where the sensor mount becomes part of the metrology loop thereby making mount instabilities a source of measurement uncertainty.

The collimated beam exiting the sensor has a waist located at the standoff distance of the sensor. This feature provides tolerance to target tilt of a few mrad (to accommodate angular error motions of the mirror, intentional tilts or alignment errors) over the measurement range of the sensor.

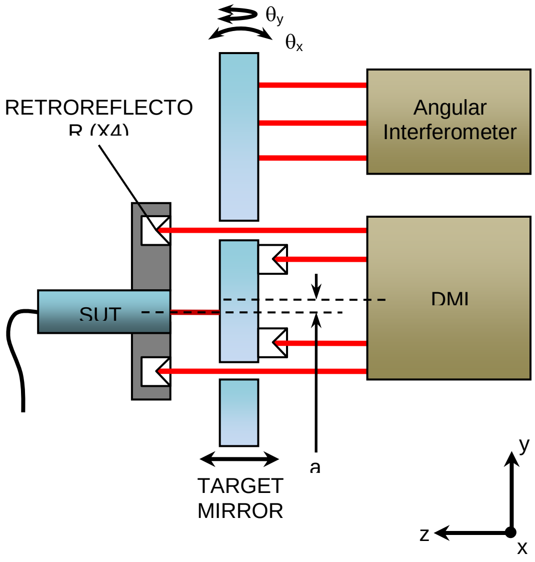


FIGURE 4 Sensor calibration setup

TABLE 1. System specifications

Parameter	Value	Parameter	Value
Number of channels	64	Bandwidth	100 kHz
Measurement range	1.2 mm	Noise over full stroke (3σ)	0.014 nm-Hz$^{-1/2}$
Standoff	3.5 mm	Drift	1 nm/day
Scan-to-scan repeatability	1 nm	Linearity	2 nm

The accuracy of the interferometric measurement depends on knowledge of the refractive index of the medium in which the sensor operates. Index data comes from one or more refractometers that continuously monitor the index. The refractometer is a modified sensor with a built-in etalon of known length whose cavity communicates with the ambient atmosphere. The absolute phase difference between the beams reflected from the two surfaces of the etalon provides a measure of the absolute refractive index. Unlike index measurement methods that rely on the “weather station” approach, this technique can measure the index of any medium, i.e., does not require knowledge of the environmental parameters and the index, and is also sensitive to changes in the composition. High accuracy applications may require several refractometers to mitigate the influence of index gradients.

SYSTEM CALIBRATION

The system is calibrated by comparison against a stabilized He-Ne laser. A custom setup (FIGURE 4) is used to perform the calibration [6]. The arrangement makes simultaneous measurements of displacement of a common target with the sensor under test (SUT) and a differential measurement between the sensor mount and target with a He-Ne based displacement-measuring interferometer (DMI). Errors due to any residual Abbe offset are corrected using information provided by an angular interferometer that monitors the target’s angular error motions. This calibration establishes the length metric, i.e., provides a traceable transfer of the unit of length through a NIST traceable standard and establishes the illumination wavelengths and other system parameters.

SYSTEM PERFORMANCE

The system performance as it relates to displacement and distance measurement is evaluated by several different methods. *TABLE 1* summarizes the system specifications and performance.

Linearity & scan-to-scan repeatability

Linearity is measured on the calibration setup and is the deviation from the linear fit that establishes the calibration constant of the system. Multiple scans are performed to establish the scan-to-scan repeatability.

Noise performance & stability

System noise performance and stability are characterized by recording the output of the system over different sampling rates and time scales while monitoring a mechanically, thermally and temporally stable measurement cavity. Coupling the reference surface and the target through a small rigid spacer to form an etalon ensures mechanical stability (eliminates relative vibration between the reference and target surfaces). The optical contacts between the spacer and the two surfaces and spacer ensure temporal stability at a level adequate for this test and the low coefficient of thermal expansion of the spacer material ensures thermal stability. The standard deviation of the data collected at a sampling rate appropriate to the desired bandwidth over a short time period is a measure of the system noise. The maximum variation of sparsely sampled data (in the temporal sense) over an extended period (~10 hours) is a measure of the long-term stability of the system. These data are also a measure of the repeatability associated with the determination of the absolute distance.

SUMMARY

We describe a compact, multi-channel, fiber-based Interferometer system capable of both displacement measurement and absolute distance measurement. This sensor technology offers several advantages over similar displacement measuring technologies, notable among which are the small sensor size, large dynamic range at a large standoff, an accessible measurement datum, low noise and exceptional stability.

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