Force Measurement by Visibility Modulated Fiber Optic Sensor

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Abstract

The birefringence of optic fiber is sensitive to external physical changes. This produces an undesirable effect of reducing fringe visibility for an interferometer made up of ordinary single-mode fibers. In this work, we actively modulate the reference arm of a Mach-Zehnder interferometer with a PZT drum. Force sensing is achieved by measuring the visibility of the fringes produced with respect to the force applied to a portion of the sensing arm. Ordinary single-mode fiber is used and no expensive polarization components are necessary. In addition, the visibility measurement is not sensitive to the ambient temperature fluctuation and no additional control measures are necessary to eliminate the effect of thermal drift.

Introduction

Traditional interferometric fiber optic sensors using ordinary single-mode optical fibers with circular cores have an intrinsic problem of fluctuating visibility, known as polarization-induced fading (PIF). The origin of PIF is the birefringence change within the fibers,[1,2] resulting from lateral stress, bending, transverse electric field, axial magnetic field, and twisting of the fibers. Birefringent single-mode fibers were therefore developed for accurate applications to preserve the states of polarization (SOP) of the transmitted light.[3] A typical birefringent fiber pressure sensor requires complex alignment and sophisticated instrumentation. Furthermore, birefringent fibers and the ancillary optical components are very expensive, and the fibers are sensitive to temperature changes.[4] In this work, the undesirable effect of PIF is exploited to measure an external force applied to an ordinary single-mode fiber. A modulating signal is applied to a PZT drum coupled to the reference arm of a Mach-Zehnder fiber optic interferometer. The fringe visibility of the output signal is a measure of the force applied to the sensing arm. This method gives the force induced SOP in the fiber and does not involve any complex alignment.

Working Principle

The fringe visibility of a Mach-Zehnder interferometer, V, can be written as[5]

$$V = V_o \cos(\eta + \Delta\phi),$$

where 2η is the angle in Poincaré sphere representation between the SOP of the light in the signal and reference arms at the output coupler, $\Delta\phi$ is the additional change of SOP due to induced birefringence, and V_o is the polarization-free visibility that depends on the intrinsic fiber and coupler characteristics.

When a lateral force F is applied to a fiber, the refractive indices of both orthogonal modes change, resulting in an induced birefringence. The change of birefringence per unit length, β, is given by[1] $\beta = 4K(F/\pi r l E)$, where

- r = radius of the fiber
- F = force acting on fiber of length l
- E = Young's modulus of fiber material
- K = strain optical coefficient

The original position representing the SOP of light in the fiber on the Poincaré sphere will shift. The resulting $\Delta\phi$ depends on βl and hence on F.

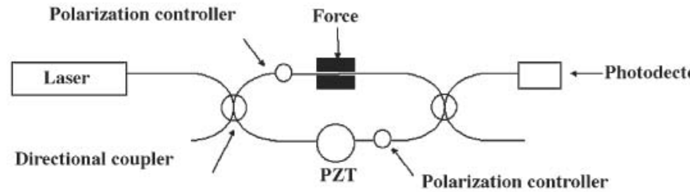


Figure 1. Schematic layout of VMFOS for force detection.

Sensor set-up

The visibility modulated fiber optic sensor (VMFOS) shown in Figure 1 is made up with single-mode optic fibers (Newport F-SV-500) connected to two directional couplers (F-506A) through finger splices (AMP F-SK-SA). A stabilized HeNe laser (Newport NL-1) is used as the linearly polarized source. Application of a modulation signal (4V-ramp at 650 Hz) through a PZT drum in the reference arm results in a 20 kHz intensity modulation at the optic fiber output, which is picked up by the photodetector. Mode scramblers (Newport FM-1) coupled to the arms are used as polarization controllers. Adjustment of the mode scramblers will change the visibility of the interference. The peak-to-peak value of the photodetector output is a measure of the visibility. In the actual experiment, the SOP of the sensor arm is set to maximize the birefringence effect of the applied force and visibility is initially set to zero by adjusting the polarization controllers. Under this setting, it was shown that $V = V_o \sin(2KF/\pi r E)$.

Sensor characteristics

Masses were loaded to a length of the sensing arm fiber and the corresponding output visibility (peak-to-peak voltage)

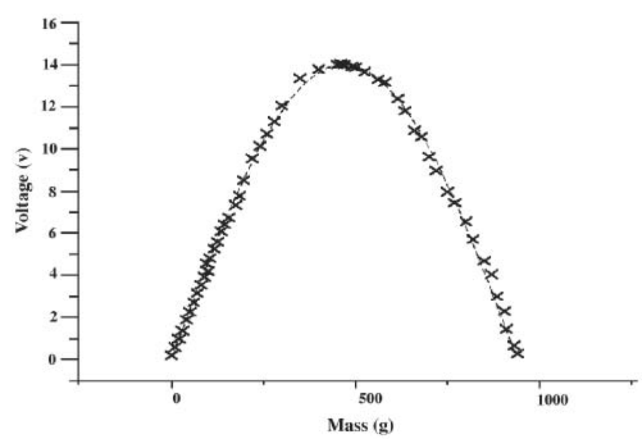
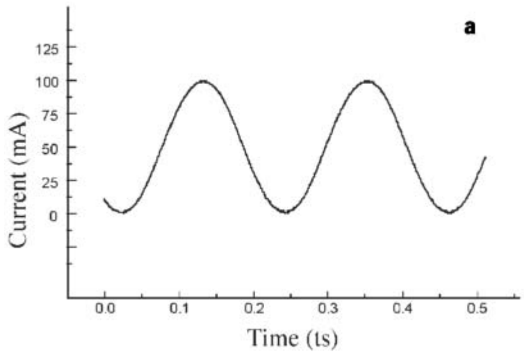


Figure 2. VMFOS characteristics under static loading.



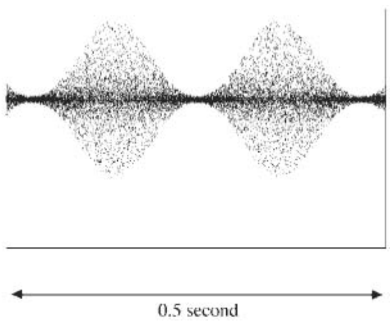


Figure 3. Dynamic response of the VMFOS. (a) The input magnetizing current, and (b) the output visibility profile.

was measured. The visibility change was independent of length, in agreement with theoretical expectation. Figure 2 is a plot of sensor output (visibility) against static loading. The experimental points follow closely to a portion of a sine curve. For loading less than 0.15 kg, the plot is essentially linear. The sensitivity of the sensor is 0.33 rad/N, in good agreement with the calculated value based on the values of E and K quoted in Ref. 1.

Dynamic force is introduced by placing the sensing fiber between an iron bar and the flat pole-piece of an electromagnet. Figure 3 shows the sinusoidal magnetizing current and the resulting visibility, which is an overlaying of 25 oscilloscope captures. It is apparent from the figures that the envelope of the output visibility profile follows closely to the input signal. To test the temperature response of the sensor, 15 mm of the sensing arm was sandwiched between two steel bars. Visibility remained unchanged when the bars were heated from 25°C to 90°C .

Conclusion and discussion

The VMFOS involves a new concept of sensing mechanism that exploits the polarization sensitivity of ordinary single-mode fibers. Application of force measurement demonstrates that VMFOS is a direct, simple, and practical set-up that has high sensitivity and good thermal stability. The sensor is particularly useful for thermally unstable environments and for systems that involve both stress and thermal change. The sensor, however, responds only to asymmetric stress introduced by radial forces and the visibility modulation depends on the SOP of the laser source. The stability and repeatability of the sensor have yet to be improved to extend the dynamic frequency range of the sensor.

Acknowledgment

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A Transfer Standard for Optical Fiber Power Metrology

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Abstract

We have developed and evaluated a transfer standard for the calibration of optical fiber power meters over the wavelength range from 750–1800 nm. The transfer standard is an optical-trap detector consisting of two germanium (Ge) photodiodes, and a spherical mirror. The photodiodes and mirror are contained in a package that is thermally stable and accepts a variety of optical fiber connectors. Spatial uniformity measurements indicate that the variation of detector response as a function of beam position is less than ±0.15%. Comparison of the absolute responsivity for three different input conditions indicates that the detector responsivity is nearly the same for collimated beams transmitted through air, as for diverging input from an optical fiber. Small measurement-result differences between collimated and diverging inputs still remain and are discussed briefly.

Design description

The transfer standard achieves the accuracy and ease-of-use of previous trap designs, while also being suitable for optical power measurements using either a single-mode fiber or monochromator (f/# ≅ f/4, divergence ≅ 15°), over the wavelength range from 750–1800 nm. In the wavelength range from 450–1000 nm, a similar trap-design has been successful for high accuracy radiometers, which use three, high quantum efficiency, silicon PIN photodiodes. This transfer standard, unlike its Si-trap predecessors, is not intended to be an absolute radiometer because there is no reason to expect to measure unit quantum efficiency from the Ge photodiodes at room temperature. Nonetheless, because of the optical-to-electrical conversion efficiency and good spatial uniformity, the trap configuration has been useful for our calibration measurements.

The optical configuration is loosely referred to as a "corner-cube arrangement." In fact, the diodes do not form a cube corner, but the optical path traces (and retraces) three edges of a cube. Reflections occur at three adjacent cube corners defined by a diode location. Two diodes are