Optics and Lasers in Engineering 110 (2018) 207–210

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Fiber-optic micro vibration sensors fabricated by a femtosecond laser

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ARTICLE INFO

Keywords:
Fiber-optic sensors
Extrinsic Fabry–Perot interferometer
Femtosecond laser fabrication
Vibration measurement

ABSTRACT

Fiber-optic micro vibration sensors fabricated by a femtosecond laser are proposed and experimentally demonstrated. The proposed sensor is an extrinsic Fabry–Perot interferometer (EFPI), which is the three-section structure sandwiched by a single mode fiber (SMF), a hollow core fiber (HCF) and a coreless silica fiber (CF). A femtosecond laser is employed to fabricate the cantilever beam. The ablation process does not affect reflectivity of the mirrors of the EFPI, resulting in the high visibility of the interferometric fringe. The vibration can be interrogated by using the quadrature passive demodulation. The experimental results show that the sensitivity of 20.678 mV/g@500 Hz is achieved in the acceleration range of 0–10 g. The frequency response of the ANSYS simulation and the experimental results are compared with the frequency range from 100 Hz to 3000 Hz, and the resonant frequency is 1920 Hz.

1. Introduction

Vibration sensors have found wide applications in the monitoring of equipment and structures. Compared with electrical sensors, fiber-optic vibration sensors offer many advantages, such as high sensitivity, light weight, fast response and immunity to electromagnetic interference, etc. [1]. Fiber-optic vibration sensors can be classified into three types: intensity-based sensors, fiber Bragg grating (FBG) -based sensors and interferometer-based sensors. Intensity-based vibration fiber sensors, which are usually based on the principle of fiber-fiber coupling [2–4], detect the power changes of the reflected or transmitted light. However, practical applicability of such sensors is limited due to power fluctuations of the light source and the leading fiber. Several designs of the FBG-based vibration sensor have been investigated [5–8]. Cantilever-based designs are commonly used [5–7]. The cantilever converts the vibration to the strain of FBGs which are embedded in or bonded to the cantilever. The wavelength shift of the FBG is proportional to the strain and hence to the vertical acceleration. An inertial mass to the cantilever tip is usually designed to increase the extent of bending and, hence, the sensitivity [6]. However, the configuration of the FBG attached cantilever decreases the reliability because the FBG may be debonded from the cantilever. Interferometer-based sensors, such as extrinsic Fabry–Perot interferometer (EFPI), Mach–Zehnder interferometer (MZI), and Michelson interferometer (MI), provide a high-resolution measuring technique. The key skill of these sensors is the fabrication of two interference arms or a semi-reflective mirror. An EFPI, which was fabricated by using focused ion beam (FIB) technology and chemical etching, was reported [9]. The vibration sensor can detect the vibration in the range of 1 Hz–40 kHz. Another accelerometer based on a micro cantilever is fabricated onto the side of a single mode optical fiber using a combination of ps-laser machining and FIB processing [10]. Acceleration up to 6 g was measured with a resolution of ∼0.01 g and a frequency range from dc to 500 Hz has been demonstrated. However, FIB technology is time consuming and expensive. The femtosecond laser is a more efficient tool for micro/nano fabrication because of its highly accurate material processing capability [11]. In recent years, a number of fiber-optic sensors have been fabricated by the femtosecond laser for measurements of refractive index [12], temperature [13], pressure [14], magnetism [15], vibration [4,16], etc. For EFPI sensors fabricated by the femtosecond laser, interference signals are formed by the reflections at the glass/air interfaces, which are directly ablated by the femtosecond laser [14,17]. However, the reflectivity is usually low due to the rugged surface caused by sputtered remains adhering to the surface machined, resulting in a low interferometric fringe visibility. The interferometric fringe with low visibility makes it difficult to demodulation.

In this paper, we demonstrate a fiber-optic micro vibration sensor. The sensor is based on the configuration of EFPI, where two mirrors are the glass/air interfaces of SMF-HCF and HCF-CF. Parts of the HCF are removed by a femtosecond laser and a cantilever beam is obtained. The ablation process does not affect reflectivity of the mirrors of the EFPI, resulting in the high visibility of the interferometric fringe. Quadrature passive demodulation is used to recover the vibration signal.

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https://doi.org/10.1016/j.optlaseng.2018.06.003
Received 26 March 2018; Received in revised form 6 June 2018; Accepted 6 June 2018

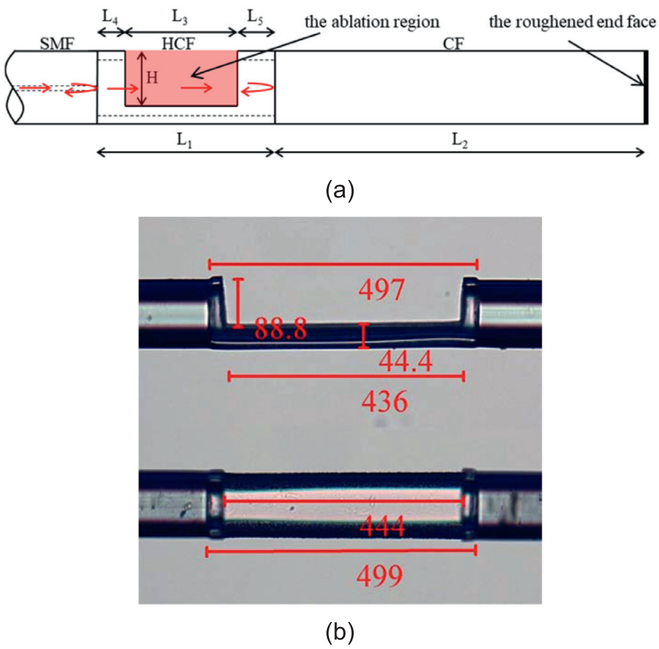

Fig. 1. The configuration (a) and the microphotographs (b) of the sensor.

2. Fabrication of sensors

The fabrication of the fiber-optic Fabry–Perot vibration sensor contains three steps: the fabrication of the SMF-HCF-CF sandwich structure to form an EFPI, the roughing process of the end face of the CF to decrease the Fresnel reflection, and the ablation of the HCF to form a cantilever beam by using the femtosecond laser. Fig. 1(a) shows the schematic configuration of the proposed sensor where L_1 is the length of the HCF, L_2 is the length of the CF, L_3 is the length of the ablation region, H is the depth of the ablation region and L_4 and L_5 are the length of the unprocessed region of the HCF. Fig. 1(b) shows microphotographs of the sensor.

First, the SMF-HCF-CF sandwich structure was fabricated. We spliced a section of the HCF to a SMF (SMF-28e, Corning) using a fusion splicer. The inner/outer diameter of the HCF is 93/125 µm. Fusion parameters are optimized to form a flat end face on the SMF. A section of the HCF was cleaved, and the remaining length of the HCF, L_1, is ~500 µm. A short cavity length will limit the length of the cantilever beam and reduce the vibration sensitivity. However, a long cavity length will reduce the contrast of the interference fringe. Then, a section of the cleaved CF was spliced to the end of the HCF. The diameter of the CF is 125 µm. After that, part of the CF was cleaved away, leaving the CF with a length of ~2000 µm. Thus, a SMF-HCF-CF sandwich structure is fabricated to form an EFPI sensor.

Second, the end face of the CF was roughened. When a laser light is injected from the leading SMF, Fresnel reflections occur at the SMF-HCF interface, HCF-CF interface and the end face of the CF. The three-beam interferometer makes it difficult to demodulate the vibration signal. The CF, instead of SMF, was used to increase the transmission loss. We roughened the end face of the CF by using the femtosecond laser to decrease the reflectivity. A layer of 2 µm thickness was ablated from the CF, and the reflectivity of the end face of the CF was reduced from 3% to less than 0.01%. By the roughing process, the Fresnel reflection at the end face of the CF was almost eliminated, and a typical two-beam interference was obtained, as shown in Fig. 2.

Third, part of the HCF was ablated. In this process, the sample was glued on a glass slide and the femtosecond laser irradiated perpendicularly to the fiber axis. The size of the ablation region should be optimized: on the one hand, a short length of L_3 (less than 300 µm) or a shallow depth of H (less than 70 µm) will decrease the vibration sensitivity of the sensor, and the cantilever beam will be very frail if the ablation region is too deep (over 100 µm). On the other hand, the reflectivity of two mirrors of the EFPI is decreased if the length of the milling region (L_4 and L_5) is too short, because the ablation process may pollute the reflectors. Hence, the L_3 and H are optimized as 450 µm and 90 µm in order to balance the sensitivity, the strength and the signal intensity. The spectrum of the sensor after the ablation process is shown in Fig. 2. A redshift of the spectrum after the ablation process was detected because of the bending effect of the cantilever beam.

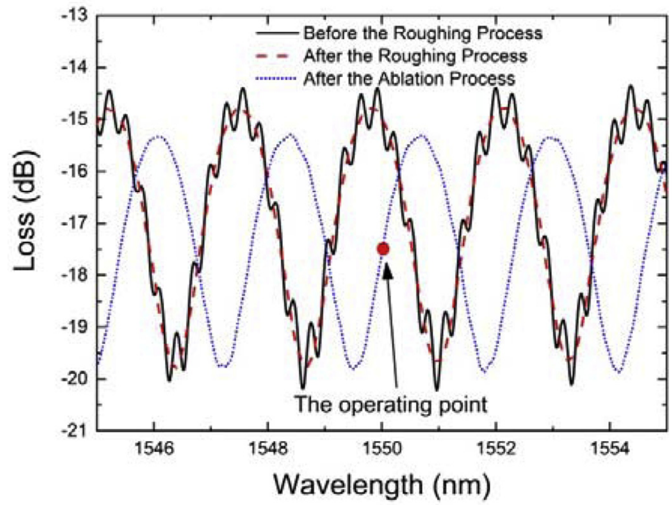

Fig. 2. The spectra before the roughing process, after the roughing process, and after the ablation process.

3. Experiments and discussion

When a laser light is injected into the leading SMF, the light is reflected at two glass/air interfaces due to the Fresnel reflection, forming an EFPI. A section of CF, acting as the inertial mass, oscillates vertically when the sensor is applied with the vibration. The oscillation of the cantilever beam causes a periodic change in the cavity length. The vibration, therefore, can be measured by quadrature passive demodulation. Typically, the operating point is chosen in the center region of the sinusoidal interference signal to achieve a linear response with high sensitivity.

The experimental setup for evaluating the vibration sensor is shown in Fig. 3. The laser from a distributed feedback (DFB) laser injects the sensor through a coupler, and the reflected light is detected by a photoelectric diode (PD). The center wavelength of the DFB laser is 1550.02 nm. The signal is sampled by the data acquisition card (DAC), and the sampling frequency is 15 kHz. A signal generator outputs a sinusoidal signal to a power amplifier, and the amplified sinusoidal signal drives a shaker. The fiber vibration sensor is fixed on the shaker tightly, and the cantilever beam is perpendicular to the vibration direction. A piezoelectric vibration sensor (YD84T, Amphenol), connected to the meter (VT-63, Shanghai Wujiu, China), is placed near the fiber vibration sensor in order to calibrate the acceleration value.,

The demodulated signal and its frequency spectrum are shown in Fig. 4(a) and (b) after the input signals of 200 Hz and the acceleration of 2 g were applied to the shaker. The demodulated signal and its frequency spectrum are shown in Fig. 4(c) and (d) after the input signals changed to 500 Hz and the acceleration was 2 g. The frequency spectra include the original signal, the second harmonic signal and the higher-order frequency signal. The demodulated signal frequency is the same as the input signal frequency, and the signal-to-noise ratio (SNR) is 55 dB/$\sqrt{\text{Hz}}$.