Optics and Lasers in Engineering 88 (2017) 60–64

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Fiber-optic Michelson interferometer fixed in a tilted tube for direction-dependent ultrasonic detection

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ARTICLE INFO

Article history:
Received 2 December 2015
Received in revised form
27 June 2016
Accepted 27 June 2016

Keywords:
Fiber-optic Michelson interferometer
Ultrasonic detection

ABSTRACT

A fiber-optic interferometer is proposed and demonstrated experimentally for ultrasonic detection. The sensor consists of a compact Michelson interferometer (MI), which is fixed in a tilted-tube end-face (45°). Thin gold films are used for the reflective coatings of two arms and one of the interference arms is etched serving as the sensing arm. The spectral sideband filter technique is used to interrogate the continuous and pulse ultrasonic signals (with frequency of 300 KHz). Furthermore, because of the asymmetrical structure of the sensor, it presents strong direction-dependent ultrasonic sensitivity, such that the sensor can be considered a vector detector. The experimental results show that the sensor is highly sensitive to ultrasonic signals, and thus it can be a candidate for ultrasonic imaging of seismic physical models.

1. Introduction

Compared with a traditional piezoelectric transducer (PZT), fiber-optic ultrasonic sensors have several merits such as good anti-electromagnetic disturbance capability, small volume, easy installation, high detection precision, wide dynamic range, fast response, and accurate discernment of ultrasound. With the above-mentioned advantages, fiber-optic ultrasonic sensors have attracted great interest for applications in submarines, medical therapy, medical imaging [1], and imaging of physical models [2]. So far, the majority of the reported fiber-optic ultrasonic sensors are based on conventional interferometers such as the Mach-Zehnder interferometer (MZI), Fabry–Pérot interferometer, and Sagnac interferometer, and fiber grating techniques [3,4]. Among these schemes, a Pi-phase-shifted Fiber Bragg grating (PS-FBG) sensing system based on the Pound-Drever-Hall (PDH) technique has been proposed and experimentally demonstrated for ultrasonic detection [5]. The proposed system presents properties of high-sensitivity and great stability, therefore, this grating-based fiber device can be regarded as a favorable sensor for ultrasonic detection. In addition, as another type of fiber sensor, conventional fiber-optic interferometers are also capable of detecting ultrasound with high-sensitivity [6]. For example, Guo has proposed and demonstrated an extrinsic Fabry–Pérot sensor based on a thin silver film and applied it to ultrasonic detection [7]. Although the device exhibited a high-sensitivity and a high-response frequency range, its instability limits applications because the silver film is easily oxidized in air. A Mach-Zehnder interferometer has been proposed to detect ultrasound, in which an interference arm is tapered to improve the sensitivity of detection. The interferometer showed good performance, however, the transmission structure of the sensor still limits its wide application. The fiber-optic Mach-Zehnder interferometer for directional ultrasonic detection has also been proposed by Berer et al. [8] and Bauer-Marschalliner et al. [9]. They make use of the mechanical flexibility of the fibers to form ring-shaped fiber-optic detectors. These rings are mainly sensitive to signals, which come from the ring axis [8,9]. Although the fiber-optic Mach-Zehnder interferometer (MZI) and fiber-optic Sagnac interferometer can detect ultrasound, the transmission configuration of MZI and some properties of the Sagnac interferometer such as high-sensitivity to temperature, polarization-dependence, and instability limit their application for imaging compared with MI. In addition, the induced phase shift in MI is double compared to MZI, which also limits the application of MZI.

The fiber-optic Michelson interferometer (FMI), as another well-known interference technique [10–12], due to the merits of high stability, micro-size, and simple fabrication, which has been widely used to measure diverse physical parameters (e.g., vibration [13,14], refractive index [15–17], and magnetic field [18]) through the recovery of interference wavelength information. The underlying principle of optical detection of ultrasound relies on variations in pressure, which in the optical fields of the medium transmitting, leads to changes in the phases they accumulated

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http://dx.doi.org/10.1016/j.optlaseng.2016.06.024
0143-8166/

[19]. Therefore, the FMI can be employed in detecting ultrasound. Due to its micro-size, the compact reflection configuration makes the MI viable as a probe for ultrasonic imaging with high precision of seismic physical models.

In this paper, we propose an MI sensor to detect ultrasound with a higher sensitivity compared to earlier studies, which presents the properties of great stability and direction-dependence due to the sturdy tilted packaging. An interference arm is etched to improve the ultrasonic-induced strain sensitivity. The spectral sideband filter technique is employed to demodulate the detection signals. In our experiments, the reflected ultrasonic signals of physical models are detected in the water tank using the proposed interferometer, making it a good candidate for ultrasonic imaging of seismic physical models.

2. Sensor fabrication

The proposed interferometer is based on a typical MI, which consists of two arms of different lengths, 1 cm and 3 cm. In fact, the length difference between the two interference arms, which dictates the interference pattern can be precisely determined by mathematical calculation. By increasing the length difference, the free spectrum range decreases owing to the phase difference increase, resulting in the narrow spectral slope. Although it will improve the sensitivity of the sensor, the large length difference also leads to a fringe contrast decrease in the interference spectrum, poor stability, and temperature sensitivity. These unexpected drawbacks limit the dynamic range of the sensor, ultrasonic detection repeatability, and application field (a stable temperature field is required). There may be a suitable length difference for ultrasonic detection. By trial and error, we have detected the ultrasonic signal with large signal-to-noise ratio at the length difference (only taken a case) used in the experiment. The facet reflectivity of single-mode fiber (SMF) is only 4% and the interferential intensity between SMFs cannot reach the dynamic range of the photoelectric transducer (PD). In order to improve reflectivity, the end-faces of two arms are coated with gold films using the magnetron sputtering technique. The response to the ultrasonic field of the sensor mainly presents a phase difference change, which is attributed to the sum of two contributions: modulation of the length of the fiber-sensing region under the strain wave (supposing no shear strain), and a change in refractive index via the elasto-optic effect which is small and can be ignored. It is well-known that by decreasing the diameter of the sensing region, the same strain-induced length variation increases. However, the smaller the etching region diameter is, the less sturdy the sensing region will be. In this work, for equipping the etching fiber region on the tilted tube and keeping the sensor sturdy, the fiber is etched for 50 min, and a 25.6 μm-diameter sensing region (measured using microscope) is achieved as shown in Fig. 1(a). In addition, the use of graded index polymer optical fibers can also increase the sensor's sensitivity to ultrasound because of their small intrinsic Young's modulus [20]. A polypropylene tube of 5 mm radius diameter is employed to hold the post-process sensor, whose end-face is oblique, cut to 45°. Both sides of the sensing arm are glued on the tilted end-face by epoxy resin adhesive and the corrosion region is suspended with a pre-stress which can also improve the strain response sensitivity of the sensor. A certain thickness of epoxy resin adhesive mixed with tungsten powder is coated on the polypropylene tube to stabilize the pigtail fiber and absorb the residual ultrasonic field. The schematic diagram and the zoomed photograph of the packing structure are shown in Fig. 1(b) and (c), respectively. In Fig. 1(b), the red and blue lines on behalf of the reference arm and sensing arm are shown, respectively. The reference arm is placed in the tube, which can avoid ultrasonic effects in the reference arm. Gluing the sensor arm at two points as shown in Fig. 1(c) can make the sensing fiber coupled with ultrasound better and avoid chirp effectively.

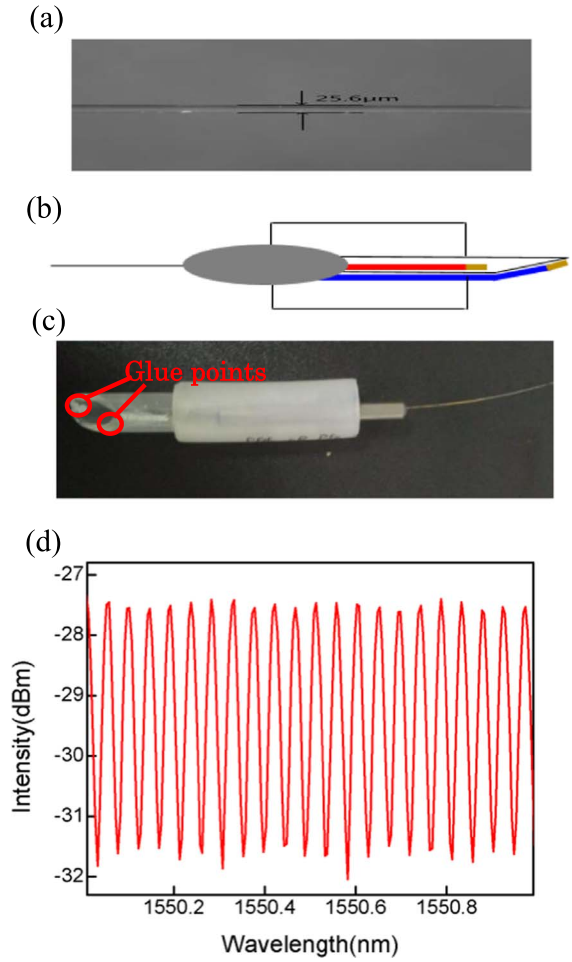

Fig. 1. (a) Photograph of the fiber corrosion region, (b) schematic of packing structure, including sensing arm (blue line), reference arm (red line), and gold film (yellow line), (c) photograph of packaging structure, (d) experimentally measured interference spectrum of the interferometer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

As the sensor is employed, a broadband source and an optical spectrum analysis are utilized to demonstrate the reflection spectrum of the sensor probe. Light is coupled into the fiber as the arms of a 3 dB coupler, and then reflected by the end-faces of two arms. Because of the length difference (inducing phase difference) between the two arms, a well-defined interference spectrum is achieved, as shown in Fig. 1(d).

MI is based on the mechanism of two-wave interference. According to interference theory, the free spectral range (FSR) between two interference dips can be expressed as:

$$FSR = \frac{\lambda^2}{n\Delta L} \tag{1}$$

where n is the refractive index of fiber, ΔL is the length difference between two arms, and λ is the operation wavelength. Eq. (1) shows that the FSR is proportional to the wavelength square, in additional inverse proportion to the length difference and refractive index of fiber. Thus, the length difference between the two arms can be precisely controlled to design sensors with the expected FSR [21]. In the experiment, the wavelength separation between two interference peaks is close, thus the sensor presents the property of high-sensitivity. When strain is applied to the