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Fiber-optic Michelson Interferometer Sensor Fabricated by Femtosecond Lasers

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Abstract: The femtosecond laser is widely applied in all kinds of laser micro machining technology with its short pulse duration, high peak power, high machining accuracy and low damage threshold. A fiber optic Michelson interferometer cavity is presented by using femtosecond laser micromachining technology. The cavity has good shape of interference fringes and high contrast which is up to 15 dB. A demodulation algorithm is proposed to calculate the cavity length with high resolution. The temperature experiment shows that the interferometer cavity has sensitivity of 0.00428 μm/°C with good linearity. In addition, the micro fiber Michelson sensor is resistant to high temperature and great potential for application in harsh environments. *Copyright © 2013 IFSA.*

Keywords: Optic fiber sensor, Femtosecond laser, Fiber-optic Michelson Interferometer temperature sensor, Temperature sensing, Frequency estimation.

1. Introduction

Since the optic fiber sensor has the advantages of simple structure, electromagnetic interference resistance and intrinsic safety, it can work normally in the specific environment such as high voltage, high noise, high temperature and strong corrosion circumstances [1-4]. The optical fiber Michelson interferometer (Michelson Interferometer, MI) is a new type of optical fiber sensor with excellent performance and wide range of potential application, which has become a research hotpot in recent years [5].

The traditional all-fiber Michelson interferometer is made by dividing the incident light into two parts, and receiving the signal reflecting back by the end of the fiber through the detector. However, the refractive index of the optical fiber is susceptible to the influence of the physical quantities such as temperature and strain, so that the reference arm and the signal arm is asymmetric, which leads to the instability of the measurement. To overcome this problem, we propose a method based on femtosecond laser [6-11] processing etching fiber Michelson interferometer sensor. In the modern manufacturing, which is featured with high precision, various machining, how to ensure the quality of products is an urgent issue that particularly needs research on the answer. Femtosecond laser has the role of high peak power and short pulse duration, therefore the zone of machining is small with high positioning accuracy which can solve this problem well.

Through the femtosecond laser processing, we etch away a portion of the core to form MI

interference cavity and the remaining portion of the core is as the signal arm of the MI interferometer. The MI sensor has the characteristics of high temperature resistant with the all-fiber structure, which has a great potential in the field of optical fiber temperature sensing, and can achieve absolute measurement of physical quantities.

2. The Proposed Method

2.1. The Principle of Fiber Optic Sensor

The schematic configuration of the fiber optic Michelson temperature sensor is shown as Fig. 1. The two reflective surfaces formed by the two part of the core. When the input light reaches into the fiber, two paths of light will be reflected by the reflective surfaces, namely I_{out1} and I_{out2}. D_{core} is the depth of the core, and the depth of the remaining part is half of the core. Thus, I_{out1} is the same as I_{out2}.

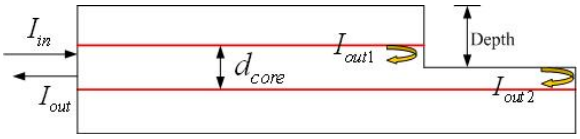

Fig. 1. Schematic configuration of the fiber-optic Michelson Interferometer.

Due to the presence of an optical path difference and the phase difference, the two reflected light will lead to an interference phenomenon. According to the principle of a multi-beam interferometer [12], the reflected light intensity can be as

$$I_{out} = \frac{2RI_{in}[1-\cos(\frac{4\pi}{\lambda}nL+\theta)]}{1+R^2-2R\cos(\frac{4\pi}{\lambda}nL+\theta)}, \quad (1)$$

where R is the surface reflectivity, L is the cavity length of the interferometer MI, I_{in} is the intensity of incident light, λ is the center wavelength of the incident light, θ is the initial phase, and n is the effective refractive index.

For fiber-optic Michelson interferometer sensor, the OPD of the MI cavity can be shown as

$$d = 2nL, \quad (2)$$

As the reflectivity of the surface which etching by laser is low, the multiple reflections of the micro-cavity can be ignored, and therefore Eq.(1) can be simplified as

$$\begin{aligned} I_{out} &= 2RI_{in}[1-\cos(\frac{2\pi}{\lambda}d+\theta)] \\ &= 2RI_{in}[1-\cos(kd+\theta)] \end{aligned}, \quad (3)$$

where $k = \frac{2\pi}{\lambda}$ is the wave number. Since the OPD of the MI cavity will change with the temperature of the circumstance changes, which can be shown as

$$\Delta d = d(\frac{\partial n}{\partial T}\Big/ n+\alpha_T)\Delta T = d(\delta_T+\alpha_T)\Delta T, \quad (4)$$

where δ_T is the coefficient of thermal expansion with the value of $6.8\times10^{-6}/°C$, α_T is the thermo-optic coefficient.

2.2. The System of Femtosecond Laser

Femtosecond laser micromachining technology is a set of ultrafast laser technology, microscopy, high-precision 3D mobile technology and computer control technology in one of the new three-dimensional processing technology. In this study, we use the laser scanning method for processing. Femtosecond processing system is mainly composed by a light source system, a microscope, and real-time monitoring system, three-dimensional precision mobile systems and software control systems, the system is shown as Fig. 2.

The light source system includes a pump source, multiplier and regenerative amplifier which can be output femtosecond laser with wavelength of 800 nm, single pulse width of 120 fs, repetition rate a 1 HZ. According to MI interference cavity conditions and fiber parameters, the value of cavity length *L* is set as 110 μm, and the etching depth is as 55 to 60 μm, so we can ensure the physical fitness of the chamber through the core and the sensor head is not easy to break.

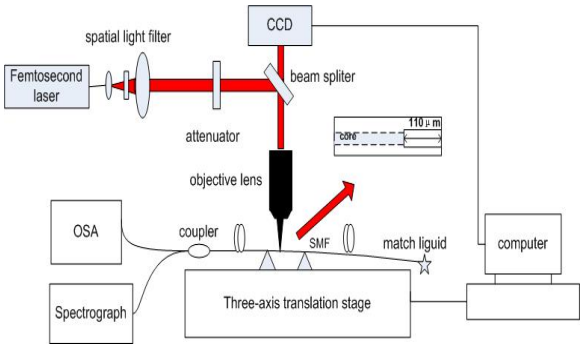

Fig. 2. The system of femtosecond pulse laser.

The parameters of the femtosecond laser system has a great influence on the machining process, for example, the laser focal spot of energy, focusing eyepiece numerical aperture, the resolution of three-dimensional precision platform and the

scanning speed the processing of the laser energy cannot be too large to avoid excessive reflection surface ablation. Different ablation will appear in material with different laser power. The greater the energy is, the more powerful ablation proposes. In this process, the laser power is proposed at ~20 mW.

2. The Fabrication Method

The processing step is as follows: Firstly, take a period of ordinary single-mode fiber (core diameter of 9 micrometers), remove the coating of the fiber end with an alcohol wipe and fiber cleaver (Furukawa S325) to cut flat. Secondly, handle the optical head affixed to the slide, and fix it on the three-dimensional precision platform. While the end of the optical fiber receiving a port of the 3 dB coupler, the two ports of the coupler are respectively connected spectrometer (YOKOGAWA AQ6370B) and a broadband light source (center wavelength of 1550 nm). Manually adjust the three-dimensional platform, when the laser beam is focused onto the surface of the fiber, the CCD imaging is the most clear. Next, while processing, control table by hand, to make sure that the laser beam spot is 10 μm away from the center of the fiber, as shown in Fig. 3(b). Then etch towards left horizontally with the speed of 135 μm/s until the good shape of the interference fringes. Fig. 3 shows the reflection spectrum of the fiber MI temperature sensor. The contrast of the interference fringes of the sensing probe up to 15 dB, and the result of processing is better. The optical microscopic image is shown in Fig. 4, wherein (a) is a side view, (b) for the end view.

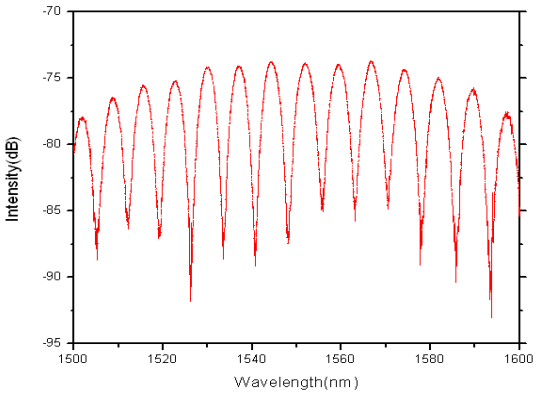

Fig. 3. Interference spectrum of the fiber-optic Michelson Interferometer.

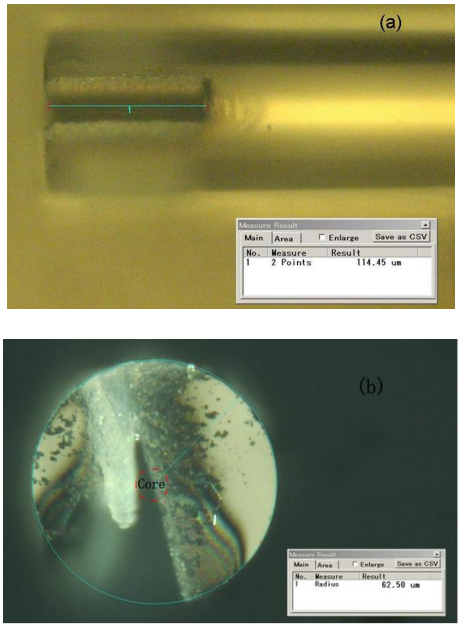

Fig. 4. The optical microscopic image of the MI (a) side view (b) end view.

4. Experimental Results and Discussion

4.1. Analysis of The Mi Reflection Spectrum at Room Temperature

Before the start of the experiment, measure the reflection spectrum of the MI at room temperature. In general, the OPD can be calculated by the interference fringes of the interference spectrum. Though this method has been successfully applied to a single optical fiber sensing system, a high signal-to-noise ratio is needed to determine the stripe order and peak position. In order to improve the accuracy of the demodulation algorithm, a frequency estimation based on the demodulation algorithm is described as following.

According to Eq.(4), the reflection spectrum is constituted by the incident light and $I_k = 2RI_{in}\cos(k_n d + \theta)$, in order to obtain the value of d, I_k should be calculated, in addition, the value of d and θ can be obtained by the least squares method. Square error between the calculated data and actual data is

$$S = \sum[\varphi_n - k_n L^* - \theta^*]^2, \tag{5}$$

When the S is smallest, the solution is

$$\begin{bmatrix} L^* \\ \theta^* \end{bmatrix} = (a^T a)^{-1} a^T \phi, \tag{6}$$

where

$$a = \begin{bmatrix} k_1 & k_2 & k_3 \cdots k_n \\ 1 & 1 & 1 \cdots 1 \end{bmatrix}^{\mathrm{T}}, \tag{7}$$

and

$$\phi = \begin{bmatrix} \varphi_1 & \varphi_2 & \varphi_3 \cdots \varphi_n \end{bmatrix}^{\mathrm{T}}, \tag{8}$$

L^* is the calculated OPD, θ^* is the initial phase.

The reflection spectrum of the fiber MI temperature sensor at room temperature is shown in Fig. 5(a), and the fast Fourier transform (FFT) is shown in Fig. 5(b). The initial incident light intensity falling into a low-frequency part, and the peak represent OPD of the fiber MI sensor. In order to obtain a signal containing phase information, a FIR band-pass filter is proposed to filter out the low frequency component. After filtering, linear scale spectrum in wavenumber domain is obtained as shown in Fig. 5(c). By the algorithm below, OPD is calculated as 327.236 μm, namely, the cavity length L = 111.304 μm, consistent with the designed and actual measured cavity length.

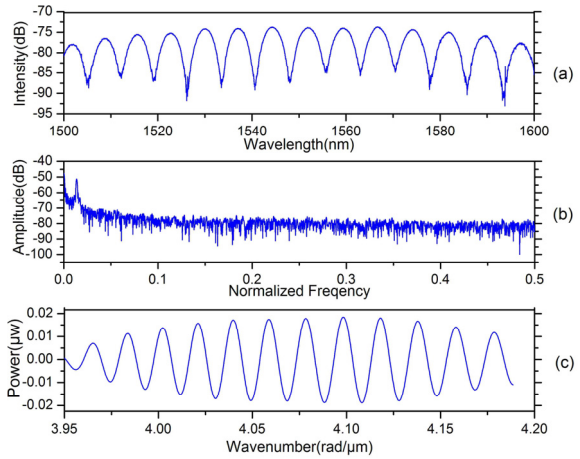

Fig. 5. (a) The initial reflection spectrum of the MI (b) Fast Fourier transform of the spectrum (c) Linear scale spectrum in wavenumber domain after filtering.

4.2. The System of Temperature Experiments

The system consists of a broadband light source (center wavelength of 1550 nm), a spectrometer (YOKOGAWA AQ6370B), sorts of 3 dB coupler and temperature chamber. The system of experimental measurement is shown in Fig. 6.

The optical fiber sensing probe is placed horizontally in the temperature chamber, and the light from light source enters into the sensing probe through the 3 dB coupler. Then the optical signal is reflected back through the coupler into the spectrometer, the temperature variation is obtained by signal processing and analysis.

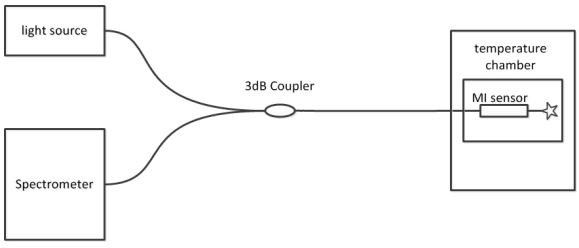

Fig. 6. The system of temperature experiments.

4.2. Temperature Experimental Results and Analysis

In the temperature experiment, the sensor head is tested in a temperature chamber with range of 0 °C~100 °C. The temperature is increased steadily from 20 °C to 100 °C with the interval of 5 °C, the time of each interval is 1 h. As the same with the increasing round, a decreasing round is proposed. The shift curves of increasing round are shown in Fig. 7 (a). The figure shows that the reflection spectrum moves toward the long wavelength with increasing temperature. In addition, during the heating process, the interference fringes are kept in good shape. The OPD shift corresponding to different temperature between 35 °C and 95 °C are demonstrated in Fig. 7 (b), where a linear fit of the experimental data is implemented and an extremely high sensitivity of 0.00428 μm / °C is obtained.

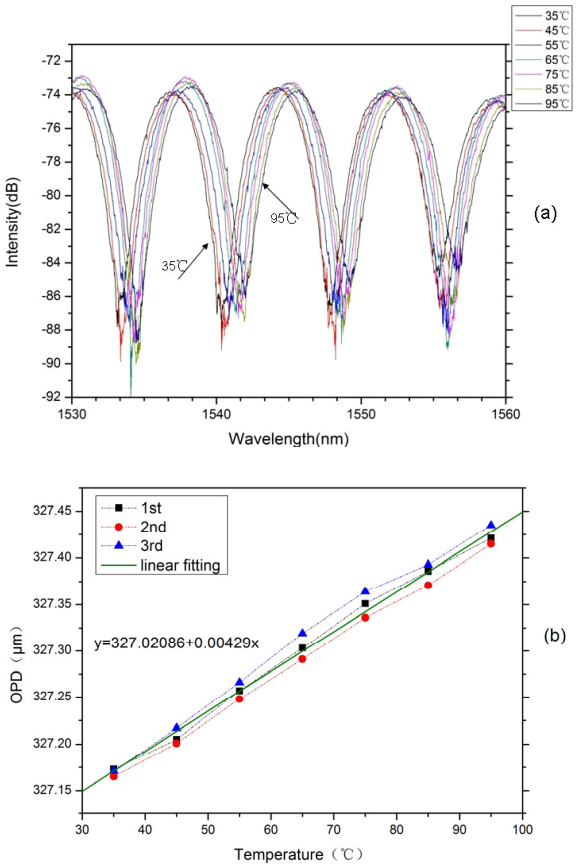

Fig. 7. (a) The shift curves of increasing round (b) Linear fitting of increasing-decreasing round.

5. Conclusions

A simple and compact fiber MI sensor has been presented. The interference cavity is formed by etching away a portion of the core through femtosecond laser. And the remaining portion of the core is as the signal arm of the MI interferometer.

The MI sensor has the characteristics of high temperature resistant with the all-fiber structure, which has a great potential in the field of optical fiber temperature sensing, and can achieve absolute measurement of physical quantities.

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