Micro-engineered optical fiber sensors fabricated by femtosecond laser micromachining

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Abstract: Micro-structures in optical fiber created by femtosecond laser micromachining can function as the sensing elements. Different types of micro-structures can be combined together in single optical fiber to perform multiple parameter measurement without ambiguity.
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1. Introduction

Optical fiber sensing elements can be formed by creating micro-structures along optical fiber using femtosecond (fs) laser micromachining [1-5]. Such a micro engineered optical fiber sensor has advantages such as small size, compatible with other fiber components and easy integration with each other to form a combined structure to implement multiple parameter measurement. This paper will present a number of novel micro-structures in optical fiber created by use of fs laser micro-machining and demonstrates their applications.

2. Long period fiber grating based on micro-holes

By periodically drilling micro-holes along the fiber length, long period fiber grating (LPFG) can be created by fs laser macromachining [6-8]. Such an LPFG exhibits a small dimension as it introduces a strong and asymmetric structural modulation in the fiber core and cladding, and can be formed in different types of optical fibers such as single mode fiber (SMF), photonic crystal fiber (PCF) and all-solid photonic bandgap fiber (AS-PBGF).

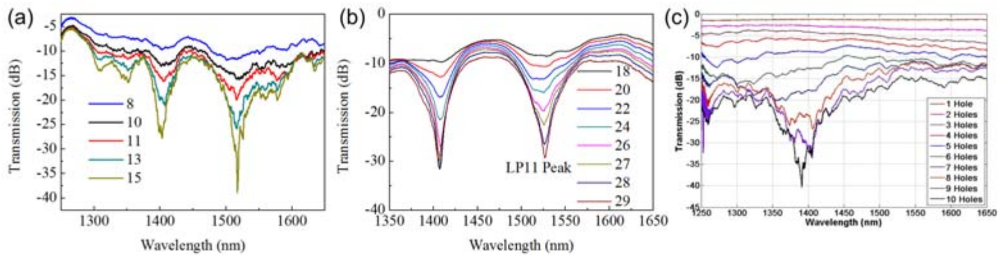

Fig. 1 Spectrum evolution of the microhole-structured LPFG in (a) SMF [8]; (b) in PCF fiber (LMA-10) [8]; (c) in AS-PBGF [6]

The micro-hole based LPFG can be used as refractive index (RI) sensor, , the sensitivity achieved is 532 nm/RIU in the region between 1.30 and 1.35 in AS-PBGF and ~190 nm/RIU between 1.31 and 1.38 in SMF.

3. Fiber in-line interferometers based on micro-cavity

3.1 Fiber in-line Mach-Zehnder interferometer

By removing part of the fiber core, a micro-cavity can be formed [9-10], and the incident light at the core-cavity wall will divide into two paths: one contains the micro-cavity and the other lies in the remaining fiber core. The interference occurs when the two output light beams are combined at the other core-cavity wall, which forms a Mach-Zehnder interferometer (MZI), as shown in Fig. 2. Such a MZI device can be used for RI sensing with an extremely high sensitivity of -9370.84 nm/RIU.

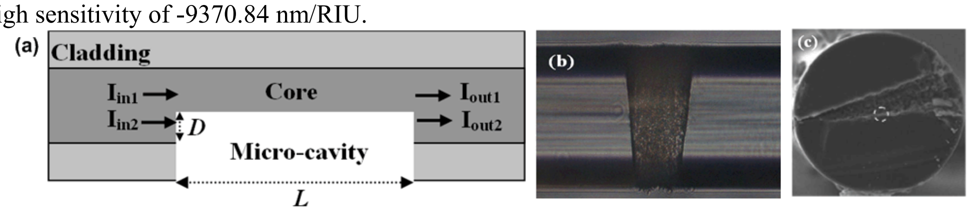

Fig. 2 (a) Schematic of the fiber in-line MZI; (b) side view; (c) cross section view [9].

3.2 Fiber in-line Michelson interferometer

By creating the micro-cavity at the fiber end instead of in the middle of fiber length, a novel Michelson interferometer can be formed as shown in Fig. 3(a). Compared with MZI described above, the fiber in-line Michelson interferometer is more compact and efficient and can be operated in a reflection mode, which is convenient in many sensor operation conditions.

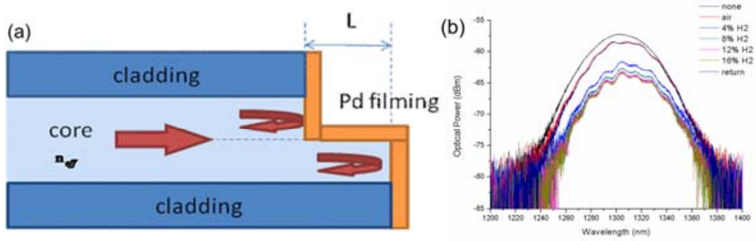

Fig. 3 (a) Schematic of fiber in-line Michelson interferometer; (b) transmission spectra of the interferometer under exposure of hydrogen

By depositing palladium (Pd) film on the micro-cavity of the device, a novel hydrogen (H_2) sensor can be created to monitor H_2 concentrations in gases. Fig. 3(b) shows the transmission spectra at different H_2 volume concentrations from 0 to 16%. When air is filled into the chamber at the end, the spectrum can be returned to its initial state. The sensitivity achieved below 4% H_2 volume concentration is 0.75 dB/% with resolution of 100 ppm.

3.2 Fiber in-line Fabry-Perot interferometer

A cone slot is firstly fabricated in the center of the cross section of a SMF by using fs laser, followed by splicing the fiber facet to another SMF by high-intensity arc discharge. The ultra-high temperature and pressure of the arc discharge softens the fiber material and blow up an elliptical air cavity with smooth inner wall, as shown in Fig. 4(a). Two micro-channels are drilled to allow fluid flows through the inner air cavity, as shown in Fig. 4(b).

The air cavity forms a fiber Fabry-Perot interferometer, in which light is reflected by the two walls respectively. The results of RI measurement performed by use of such a device are displayed in Fig. 4(c). where the inset shows the reflection spectra corresponding to different RI liquids filled in the cavity. The fabricated micro-channels are wide enough to ensure the smooth flow of the liquid. The RI sensitivity is measured as ~88.5nm/RIU.

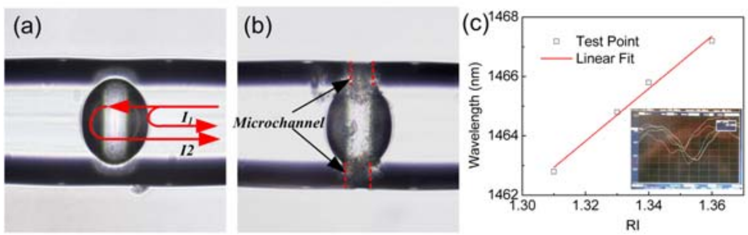

Fig. 4 (a) Fiber in-line Fabry-Perot interferometer based on an air cavity formed in fiber; (b) fs laser drilled micro-channel in the Fabry-Perot interferometer; (c) RI response and reflection spectra of the interferometer in different RI oils.

4. Combined micro-structures in optical fiber

Different types of micro-structures can be fabricated in the same location of the optical fiber to form a combined structure to implement multiple parameter measurement.

4.1 Mach-Zehnder interferometer embedded in fiber Bragg grating (FBG)

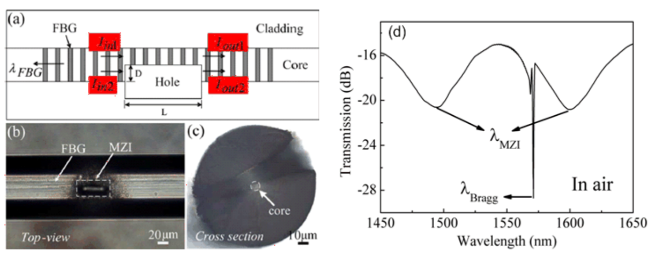

Fig. 5 (a) Schematic of MZI embedded FBG sensor; (b) top view; (c) cross section view; (d) transmission spectrum of the sensor [11].

By fabricating micro-structure embedded in FBG as shown in Fig. 5 [11], a simultaneous and unambiguous RI and temperature sensing could be achieved. Since the micro-structure is usually a RI sensitive element itself, when embedded in FBG sensor head, both the temperature and RI can be detected at the same time. The simultaneous measurement of RI and temperature can be carried out by tracing two characteristic wavelengths: one of the interference fringe dips/peaks λ_{MZI}.and the FBG resonant wavelength λ_{Bragg}.

4.2 Micro-holes integrated with FBG

Another micro-structure embedded FBG sensor is achieved by placing micro-holes along the fiber length as shown in Fig. 6 [12]. Such a device can achieve simultaneous and independent temperature and RI sensing by direct detecting the FBG resonant wavelength shift and its intensity variation. The two parameters can be determined by tracing only one characteristic wavelength, which can largely simplify the detection system.

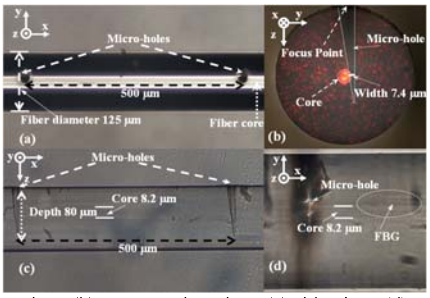

Fig. 6 Morphology of the device (a) Top view; (b) cross-section view; (c) side view; (d) top view (focused at the fiber core) [12].

5. Conclusion

In this paper, a number of micro-structures fabricated in optical fibers by use of fs laser micro-machining are presented. Compared with conventional optical fiber sensors, these devices possess the advantages of compact device dimensions, relative high sensitivities and capable of performing unambiguous multiple parameter measurement. This opens opportunities for new optical fiber devices with increased functionality.

Acknowledgement

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4. References

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