Novel Optical Sensors Based on Integration of Fiber Micro-machining with Sensitive Thin Films

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Abstract: The combination of fiber optics with micro-structure and sensitive thin films offers great potential for novel sensor concepts. This paper reviews some works on the integration of thin films with fiber micro-structures for sensing application.

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1. Introduction

Optical fiber sensor has attracted more and more attention in academic and industrial community. The advantages provided by the optical fiber sensor include small size, light weight, high sensitivity and immunity to electromagnetic interference, which facilitate the measurement of a variety of physical, chemical, and biomedical parameters. Femtosecond (fs) laser processing is an emerging field with important application prospects. Fs laser has been widely used for micromachining because of its good beam quality, high precision and excellent spatial resolution, which are particularly suitable for fabricating micro-cavity in the optical fiber. However, the sensing principles of these micro-structured fiber sensors are based on the variations of airy cavity under different conditions of temperature and stress, which is in fact a physical length change of airy cavity. When sensitive thin films are employed in the cavity as sensing elements, refractive index change of sensitive thin film due to environment will generate a change of optical length, but not physical length of the micro-structure cavity, thus sensing of environment can be correlated to with the shift of interference fringe with thin films as sensing media.

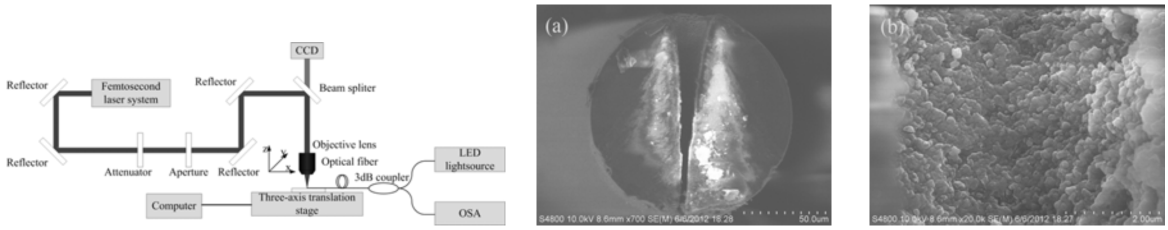

Fig.1: femtosecond laser system for fiber micro-machining and coating on micro-structured fiber

2. Mach–Zehnder Interferometer Hydrogen sensors based on Femtosecond laser micro-machining

A fs laser fabricated micro Mach-Zehnder Interferometer (MMZI) fiber hydrogen sensor is proposed and developed. A palladium (Pd) film is deposited on the MMZI by magnetron sputtering process to be used as the transducer layer. The MMZI coated with the Pd film is analyzed and discussed under different conditions such as different micro-cavity lengths and different hydrogen concentrations. In principle; there are two main light transmission paths on the MMZI coated with the Pd film according to the traditional theory of MZI. Fig.2 shows the schematic structure and digital microscope (VHX-100) images of the MMZI which are fabricated by fs laser ablation.

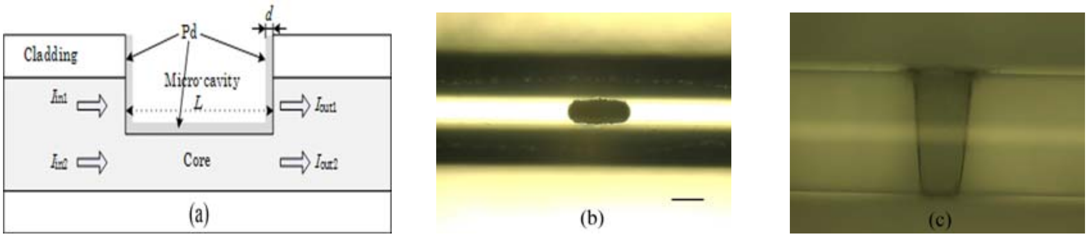

Fig.2. Schematic structure and digital microscope images of MMZI fabricated by fs laser ablation with a 50 μm scale bar.(a) Structural illustration; (b) top view; (c) side view.

The interference intensity can be expressed by: $I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\varphi$, where I_1 and I_2 are the intensities along the two light paths, and φ is the phase difference to be defined as: $\varphi = 2\pi\Delta n_{eff} L/\lambda + \varphi_0$,where Δn_{eff} is the RI difference between the fiber core and the micro-cavity; λ is the wavelength; L is the length of the micro-cavity, and φ_0 is the initial interference phase $\Delta n_{eff} L = 2(n_{film} - n_{core})d_{film} + (n_{cavity} - n_{core})(L - 2d_{film})$, where n_{film} is the RI of the Pd film; n_{core} is the RI of the fiber core; n_{cavity} is the RI of the micro-cavity and d_{film} is the thickness of the Pd film.

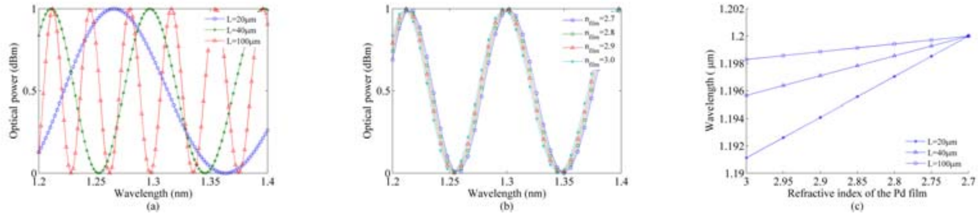

Fig.3: (a) Transmission spectra of MMZI with different micro-cavity lengths; (b) transmission spectra of MMZI coated with Pd of nfilm between 3 and 2.7, L=40 μ m, d_{film} =110 nm; (c) wavelength versus the refractive index of the coated Pd film.

Fig. 3 illustrates the shifts of the wavelength coated with 110 nm Pd film under different hydrogen concentrations, while Fig. 4 shows the normalized transmission spectra of MMZI coated with different Pd film and the relationship between the wavelength shift and the hydrogen concentration. The slope for the 40 μm micro-cavity length is ~0.155 nm/%, which is larger than that of the 100 μm micro-cavity (~0.042 nm/%). This means that the MMZI with 40 μm micro-cavity length has larger wavelength shift than that of the 100 μm micro-cavity.

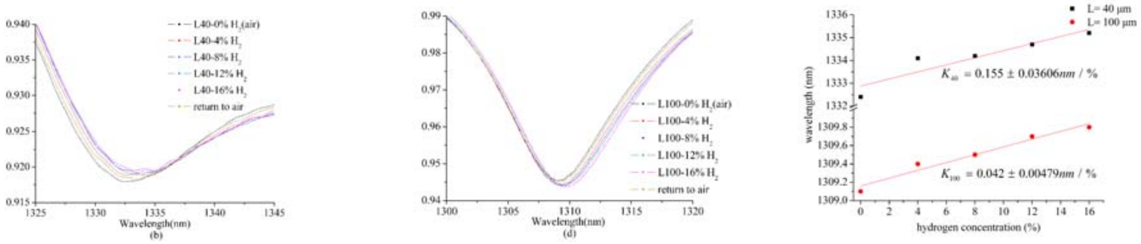

Fig.4: Normalized transmission spectra of MMZI coated with Pd film of 110 nm in thickness (a) L=40 μ m; (c) L=100 μ m, and wavelength versus hydrogen concentration in different micro-cavity lengths of L=40 μ m and L=100 μ m.

3. Fiber in-line Michelson interferometer tip sensor

A novel fiber in-line Michelson interferometer (MI) hydrogen sensor is proposed, which is fabricated by fs laser micromachining and thin-film coating. The MI is formed by removing part of the fiber core and hence the light propagating in the fiber core is along two paths. One is reflected by the cut end of the removed fiber core and the other that travels along the remaining fiber core is reflected back by the fiber tip. Palladium (Pd) film is deposited on the end of the fiber, acting as the transducer for hydrogen gas sensing. Fig.5 shows the structural schematic and the digital microscope images of the fabricated fiber in-line MI. It can be found that part of the fiber core is removed and Pd film is deposited on both the cut end of fiber core and the fiber tip.

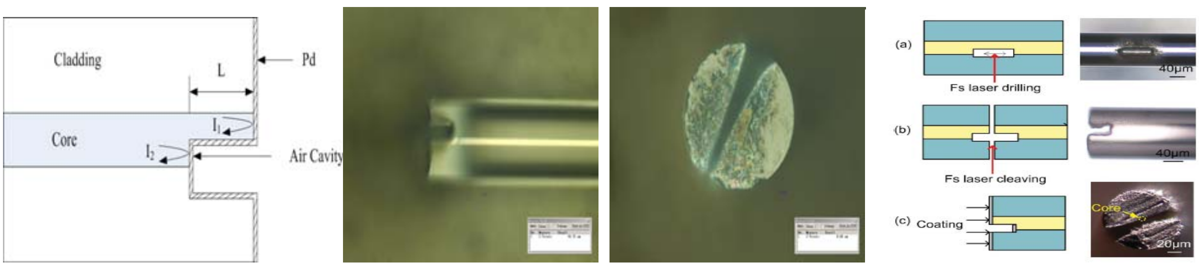

Fig.5: The structural schematic and digital microscope images of micro interferometer.

The normalized reflection spectra and wavelength shift under different hydrogen concentrations are shown in Fig.6. It can be concluded that the reflection intensity decreases while the reflection spectrum experiences a blue shift with the decrease of RI from 2.5 to 1.972 due to the increase of hydrogen concentration. The normalized reflection intensity sensitivities of the two peaks are calculated to be -0.0294 and -0.0365/%, while the hydrogen concentration sensitivities are -0.155 and -0.1625 nm/%.

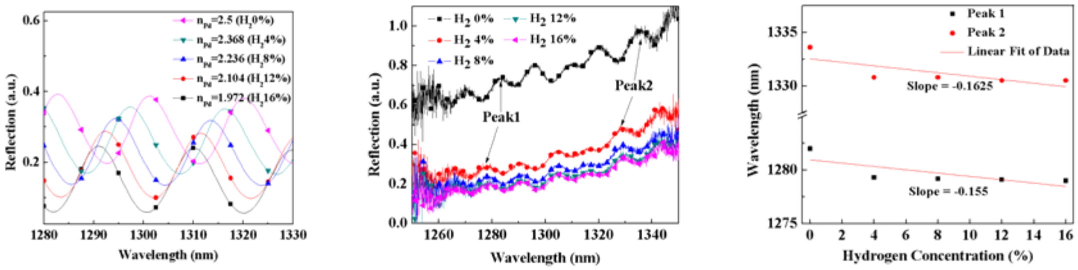

Fig.6: Normalized reflection spectra and wavelength shift versus hydrogen concentration.

4. Fabry-Perot Interferometer Sensor Fabricated by Femtosecond Laser for Hydrogen SensinG

Furthermore an optical fiber hydrogen sensor integrated of Fabry-Perot micro-interferometer and sensitive material is proposed. Matlab program is utilized to simulate the reflection spectra of the interferometer under different hydrogen concentrations. The FPI with micro-cavity length of 20 μm coated with 20 nm Pd film is measured in the hydrogen volume ratio range of 0-8%. The compact optical fiber sensor developed in this work is easy to fabricate and has high potential in hydrogen sensing.

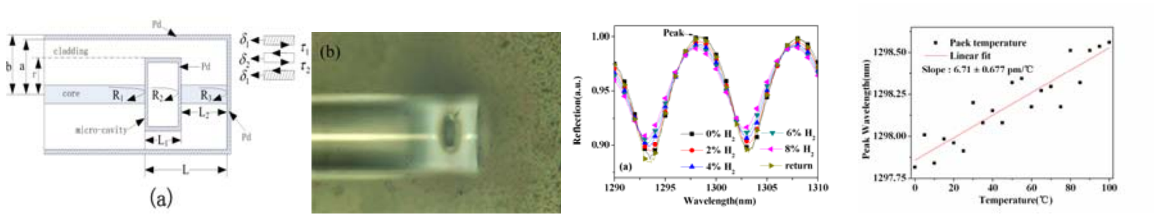

Fig.7: F-P interferometer micro-structured hydrogen sensor, its normalized reflection spectra response

Fig. 7 illustrates the proposed F-P micro-structured fiber sensor for hydrogen concentration detection. It can be found that the reflection spectrum experiences a blue shift and its intensity decreases with the increase of the hydrogen volume ratio. The experimental results show that the reflection spectrum shift of the sensor depends on the micro-cavity length change and the RI variation induced by hydrogen concentration, and an increase of the hydrogen concentration leads to a blue shift of reflection spectrum. The experimental results demonstrate that the wavelength shifts of the FPI hydrogen sensor are 10, 30, 100, and 150 pm respectively, corresponding to the hydrogen concentration of 2%, 4%, 6 %, 8%, respectively. The proposed sensor is compact, easy in fabrication and has high potentials in hydrogen detection.

5. Conclusions and remarks

Fs laser has been widely used for micromachining, and it is especially suitable for fabricating micro-cavity in the optical fiber. If sensitive thin films can be integrated with micro-machining, when sensitive thin films are deposited in the micro-cavity as sensing elements, refractive index change of sensitive thin film due to environment will generate a change of optical length, but not physical length of the micro-structure cavity, therefore the sensing principle is different from that of air cavity. The combination of fiber optics with micro-structure technologies and sensitive thin films offers great potential for the realization of novel sensor concepts.

6Acknowledgments

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7. References

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