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Optical Fiber Harsh Environment Sensors

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Abstract
Various optical fiber harsh environment sensors were reported, including the miniaturized inline Fabry-Perot interferometer sensor by femtosecond laser micro-machining, the long period fiber grating sensor and the inline core-cladding mode interferometer by CO_2 laser irradiations.

Introduction
Optical fiber sensors are very attractive for applications in harsh environment due to their proven advantages of small size, lightweight, immunity to electromagnetic interference, resistance to chemical corrosion, high sensitivity, large bandwidth, and remote operation. This paper summarizes our recent research efforts in developing optical fiber harsh environment sensors. Their applications towards measurement of temperature, pressure and strain in a high temperature harsh environment are presented. The preliminary results and potentials of using these devices as sensor platforms for measurement of various gases in high temperature environment are also briefly discussed.

Fiber Inline Fabry-Perot Interferometer (FPI)
Recently, our lab developed a miniaturized inline FPI fabricated by one-step fs laser micromachining. [1, 2] It has an all-glass structure and does not involve assembly of multiple components. As a result, the device can survive very high temperatures and has very small temperature dependence. In addition, the open FP cavity allows prompt access to gas or liquid samples for direct refractive index measurement, promising an ultra-compact gas sensor with very small temperature dependence for harsh environment applications.

The device fabrication was carried out using a home-integrated fs laser 3D micromachining system. Fig. 1a and b show the SEM images of the fabricated fiber FPI device, with cavity length ~60μm and ablation depth ~72 μm. Fig. 1c shows the interference spectrum of the device. A high quality interference signal was achieved with a fringe visibility exceeding 14dB, which is sufficient for most sensing applications. The sensor was placed in a programmable electric tubular furnace. The temperature of the furnace was increased from 50°C to 1100°C at a step of 50°C. The cavity length as a function of the temperature is plotted in Fig. 1d. The cavity length increased nearly linearly at a rate of 0.074pm/°C following the increase of temperature. Fig. 1e shows the measured refractive index of deionized water as a function of temperature. The amount and shape of the measured refractive index of water change as a function of temperature agreed well with the previously reported measurement data. The temperature cross-sensitivity induced measurement error was about 4.2×10^{-6} RIU in Fig. 1e over the temperature variation of 87°C. The temperature dependence of the device was small and contributed only about 0.04% to the total refractive index variation over the entire temperature range.

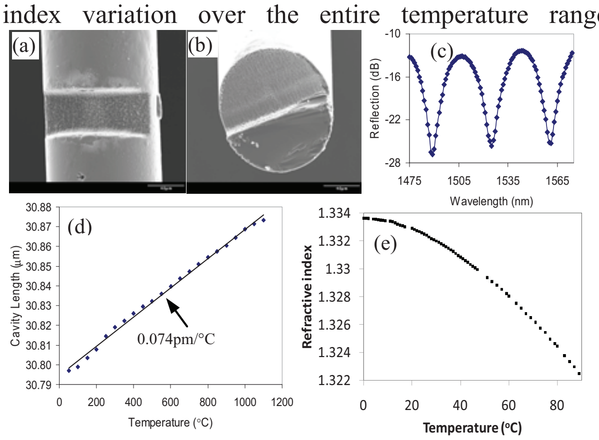

Fig. 1 Fiber inline FPI device fabricated by fs laser. (a) and (b) SEM images of the device, (c) interference spectrum, (d) cavity length as a function of temperature, (e) measured refractive index of deionized water as a function of temperature using fiber inline FPI device

Long Period Fiber Grating (LPFG)
A LPFG is a fiber device with a periodic refractive index variation along the fiber. The periodic index variation promotes energy coupling from the core mode to co-propagating fiber cladding modes at discrete wavelengths (referred to as the resonant wavelengths).

LPFGs are fabricated by point-to-point CO_2 laser irradiation method in our laboratory. By varying the period, we were able to fabricate LPFGs with different resonant cladding modes, from LP_{05} through LP_{08}. These gratings were evaluated experimentally to verify their capabilities for monitoring refractive index changes of the environment. Plotted in Fig. 2a, the resonant wavelength shifted towards the short wavelength region as the environmental refractive index increased. The response of LPFG resonant wavelength shift to refractive index change was quite nonlinear. As the environment refractive index approached that of fiber cladding, the device became more sensitive. The amounts of wavelength shift were also significantly different among different resonant cladding modes. In general, the higher the order of resonant cladding mode, the higher the sensitivity towards environmental index changes. We also tested the temperature dependence of LPFGs of different resonant cladding modes. The results are shown in Fig. 2b. The results clearly indicated the modal dependence of the device. In general, the higher the order of resonant cladding mode, the higher the sensitivity towards temperature. [3]

To facilitate LPFG sensor for chemical detection, we coated a thin layer of porous MFI type zeolite on a LPFG. The sensor operates by detecting the molecular adsorption induced refractive index change of the zeolite using the LPFG platform. Fig. 2(d) plots the dependence on resonance wavelength on toluene vapor concentration. A shifted as much as 0.7 nm was detected for a toluene vapor concentration of 0.22 ppm.

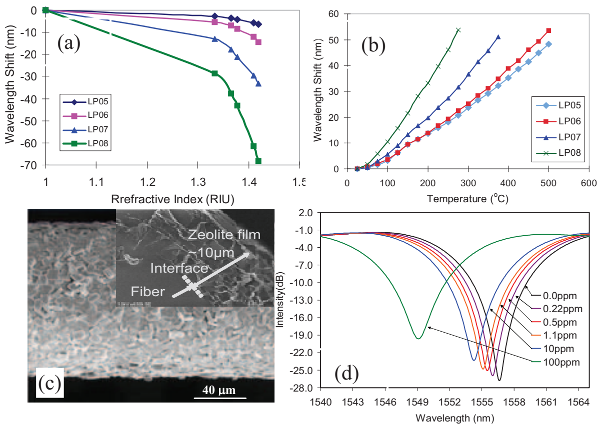

Fig. 2 LPFG as chemical sensor. (a) resonant mode dependent response of LPFG towards refractive index change, (b) temperature variations for LP_{05-08} cladding modes, (c) SEM image of zeolite-LPFG surface. Inset: fracture cross-section, (d) zeolite-LPFG transmission spectrum displacement and a function of toluene vapor concentration in air.

To investigate the high temperature stability, we placed such device in electric furniture at a temperature of 550°C to evaluate its long-term stability. The resonant wavelength continuously drifted towards short wavelength. Within the total test time of 60 days, the cumulated drift was about 52nm. We believe that the drift is caused by the inherent difference in temperature dependence of the core and cladding modes.

LPFGs have also been investigated for gas detection in high temperatures. Various nanocrystalline ceramic thin films were investigated for coating the LPFG for gas sensing. For example, proton conducting perovskite-type $Sr(Ce_{0.8}Zr_{0.1})Y_{0.1}O_{2.95}$ (SCZY) nanocrystalline thin film was synthesized on the LPFG surface. At a high temperature, the defect states in the SCZY crystal lattice change upon reacting with hydrogen that varies its refractive index. The SCZY-coated LPFG sensor was successfully demonstrated for monitoring bulk hydrogen concentration at 500 ºC by straightforward measurement of the resonant wavelength shift ($\Delta\lambda_R$) [5].

Fiber Core-Cladding-Mode Interferometer (CCMI)

Fiber CCMI sensors operate based on the interference between the core mode and the cladding modes. Mach-Zehnder interferometer (MZI) and Michelson interferometer (MI) type CCMI sensors can be fabricated by CO_2 laser irradiation. [4] The laser irradiation induced a micronotch on the fiber structure (Fig. 3a), causing light coupling from the core mode to cladding modes, and vice versa. Fig. 3b shows the interference spectrum of MZI-CCMI with the length of 10mm with a fringe visibility of ~20dB. Fig. 3c compares the sensitivity of a 5mm MZI-CCMI with that of two LPFGs (LP_{04} and LP_{05} cladding mode) for ambient refractive index measurement. The sensitivity of the CCMI is smaller than, but every close to LPFG-LP_{04}. This suggested that the order of the cladding mode excited in this CCMI was lower than but every close to LP_{04}. Fig. 3d shows the wavelength shift of the interference minimum as a function of the furnace temperature where the relation is nonlinear. The linear fit of the experiment data indicated that the temperature sensitivity of the device was about 0.11nm/°C.

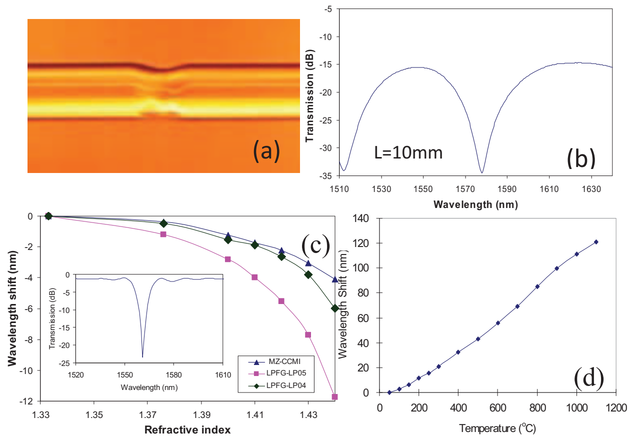

Fig. 3 Fiber CCMI fabricated by CO_2 laser irradiation. (a) microscopic image of CMMI coupler, (b) inteference fringe of 10mm fiber MZ-CMMI, (c) wavelength shift as a function of refractive index in a MZ-CCMI and LPFGs with LP_{04} and LP_{05} cladding modes. Inset: transmission spectrum of LPFG with LP_{05} cladding mode)

Conclusions

This paper summarized our recent research progresses in developing several new fiber sensor platforms that can be used to develop various physical and chemical sensors. The reported new devices have been tested to survive high temperatures up to 1100°C. Their capabilities for refractive index monitoring have also been experimentally verified.

References

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