Temperature referenced high sensitivity point-probe optical fiber chem-sensors based on cladding etched fiber Bragg gratings

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ABSTRACT

Point-probe optical fiber chem-sensors have been implemented using cladding etched fiber Bragg gratings. The sensors possess refractive index sensing capability that can be utilized to measure chemical concentrations. The Bragg wavelength shift reaches 8 nm when the index of surrounding medium changes from 1.33 to 1.44, giving maximum sensitivity more than 10 times higher than that of previously reported devices. More importantly, the dual-grating configuration of the point-probe sensors offers a temperature reference function, permitting accurate measurement of refractive index encoded chemical concentrations.

1. INTRODUCTION

Fiber Bragg gratings (FBGs) have been demonstrated as optical sensors to measure a wide range of physical parameters including temperature, strain, pressure, loading, bending and vibration [1,2]. FBGs possess many desirable sensing properties such as immunity to EM interference, linear responsivity, small size and lightweight, and most importantly, wavelength multiplexing capability. These advantages, usually unmatched by other types of sensor, have made FBGs one of the most popular optical sensing devices, have been widely explored for smart sensing applications in monitoring engineering structures and systems in the oil, civil, maritime and aerospace industries [3]. However, unlike long-period fiber gratings (LPFGs), normal FBGs are intrinsically insensitive to the surrounding-medium refractive index (SRI), since the light coupling takes place only between well-bound core modes that are well screened from the influence of the SRI by the cladding. In order to make FBGs sensitive to surrounding medium, core-exposed FBG devices have been used [4,5,6]. The evanescent field of the light propagating along the core-exposed fiber can be extended to the surrounding medium region, giving rise to the dependence of the effective index of the core modes on SRI. Based on this principle, the existence of certain chemicals and their chemical properties can be detected by monitoring Bragg wavelength shift of the core-exposed FBG. Such FBGs have been made by side-polishing standard fibers [4,5] or chemical etching D-fibers [6]. However, due to limited exposure of the core to the surrounding, the SRI sensitivity of these FBG based sensors is generally lower than that of LPG based devices.

Despite inherently high SRI sensitivity, LPFGs, however, exhibit several disadvantages as deployable sensor devices. LPFGs possess much higher temperature and bending cross-sensitivities, thus being severely influenced by their environmental conditions. Another disadvantage is that their spectral responses can be measured only in transmission with poor resolution due to the broad (typically tens of nanometers) transmission loss-type resonance. To reduce the bandwidth of the LPFG, the device length has to be increased substantially, limiting its usage as a localized or point sensor device.

In this paper, we propose and demonstrate an optical chem-sensor device based on deep-etched FBG structures in standard telecom fiber. Unlike our previous work [6] where we etched off just the cladding of the FBG, we further etched off part of the core, achieving significantly improved SRI sensitivity. In addition, we have adopted a dual-grating configuration to the point-probe FBG sensors by concatenating etched and unetched gratings, realizing simultaneous measurement of SRI and temperature.

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2. EXPERIMENTS AND RESULTS

2.1. GRATING FABRICATION AND ETCHING

The dual-grating configuration is illustrated in figure 1. Two gratings (G1 and G2) of 2mm length were UV-inscribed with a 7mm separation at one end of an H_2-loaded standard telecom fiber using a phase mask and a frequency doubled Ar laser. Figure 2 22 shows the transmission spectra of G1 and G2 before the etching treatment. The Bragg wavelengths of G1 and G2 are at 1561nm and 1568nm with similar reflection strength of 17dB.

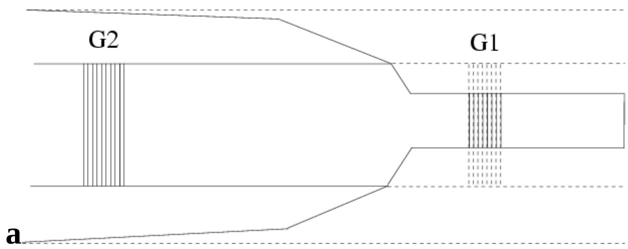

Figure 1 Schematic diagram of the dual-grating chem.-sensor device: G1 and G2 are the etched and un-etched gratings.

G2, as the temperature reference grating, was coated with material (Desolite from DSM Desotech Inc) in order to be kept intact from the chemical etching. The whole device was then mounted on a Teflon chassis and the end of the fiber containing G1 and G2 was then bathed in hydrofluoric acid (HF) of 15% concentration. During the etching process, the Bragg reflections of G1 and G2 were monitored using a broadband light source and an optical spectrum analyzer. As expected, in the beginning, the reflection peak of G1 did not move as the core was still confined by the cladding. When the remaining cladding was several μm, the reflection peak of G1 started shifting towards shorter wavelengths due to the evanescent wave penetration effect. The fiber was further etched to reduce the core diameter from 8μm to 4μm. During the whole etching process, the reflection peak of G2 remained at the same position.

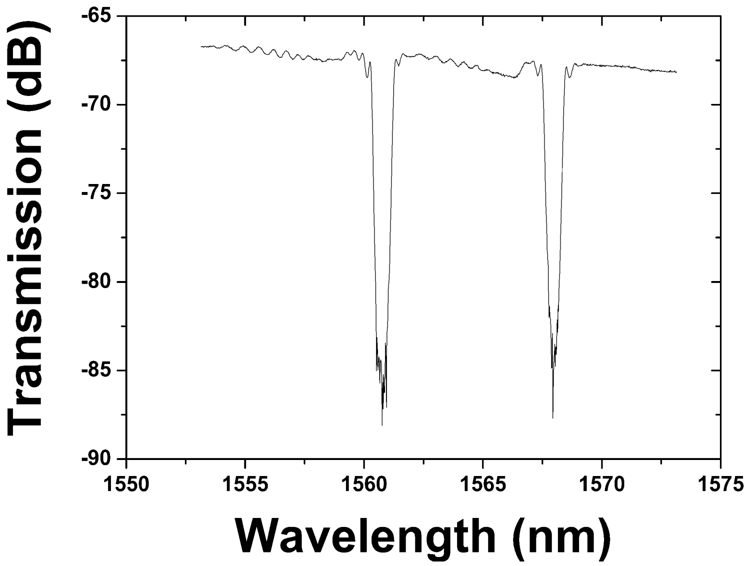

Figure 2 The transmission spectrum of the dual-grating chem.-sensor before G1 subjected to etching. The central wavelength for G1 is 1561nm and for G2 is 1568 nm.

2.2. SRI SENSING

The SRI sensitivities of three fiber grating samples with core-etching levels of shallow, medium and deep were evaluated using sugar solutions with concentrations from 0% to 60%. Figure 4a and 4b show λ_B shift of G1 with respect to the sugar concentration and SRI (using the calibration in table 1) of the solution, respectively, for the three etching levels. It is clear that more the core is etched, larger the shift rate of λ_B is, giving higher SRI sensitivity. The maximum sensitivities for shallow, medium and deep etched fiber devices are 0.58nm/%, 1.02/%, 1.47nm/%, much higher than previous reported result of 0.11nm/% obtained from the D-fiber FBG with its cladding being etched off only. Figure 3 shows the spectral evolution of the deep-etched dual-grating sensor under the variation of sugar concentration. Clearly, the G2 is totally insensitive to the SRI changing. It can be also noted from figure 3 that the reflection strength of G1 decreased as the core was exposed directly to the surrounding medium.

We have also simulated the effect of the core size to the SRI sensitivity of FBGs without cladding. Figure 5 shows the Bragg responses of three gratings with core radius of 2.5μm, 3μm and 3.5μm to SRI changes. It can be seen that when the core size is reduced the sensitivity of the grating to SRI enhances. The simulation results agree very well with the experiment ones.

Table 1: Correlation between refractive index and concentration of sugar solutions

Sugar concentration (%)	0	10	20	30	40	50	60
Refractive index	1.333	1.3478	1.3639	1.3812	1.3999	1.4201	1.4419

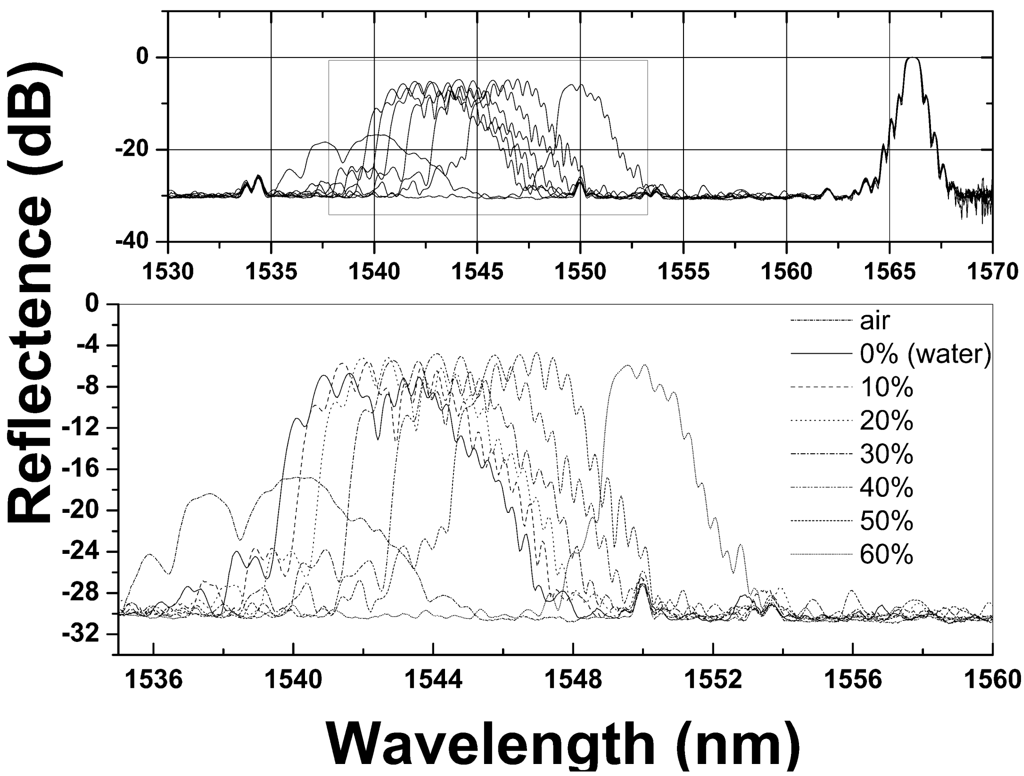

Figure 3 Evolution of reflection spectrum of the etched dual-grating device when it was immersed in sugar solutions with different concentrations.

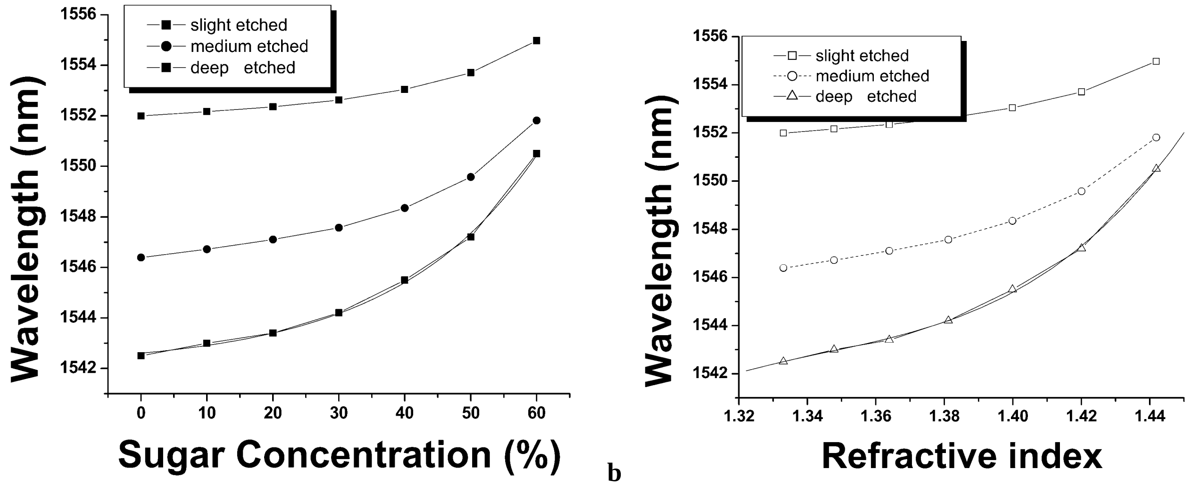

Figure 4: The wavelength shifting of G1 with respect to (a) sugar concentration and (b) SRI of sugar solution for 3 different etching levels

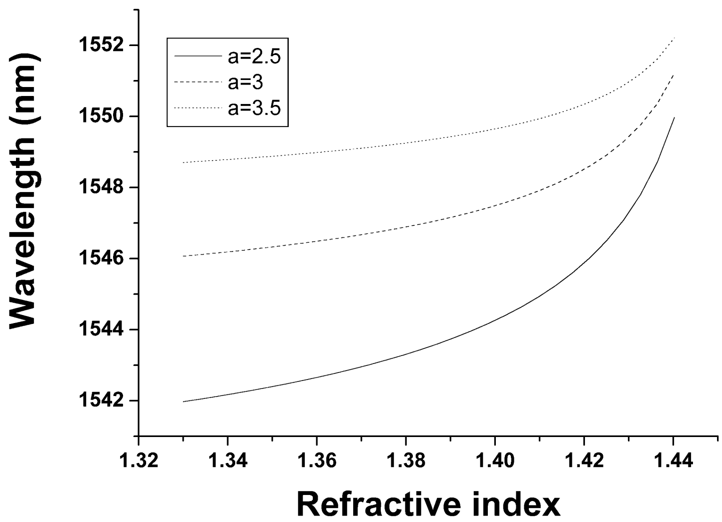

Figure 5: Simulated wavelength shifting of the cladding-off gratings with core radius of 2.5µm, 3µm and 3.5µm against SRI change.

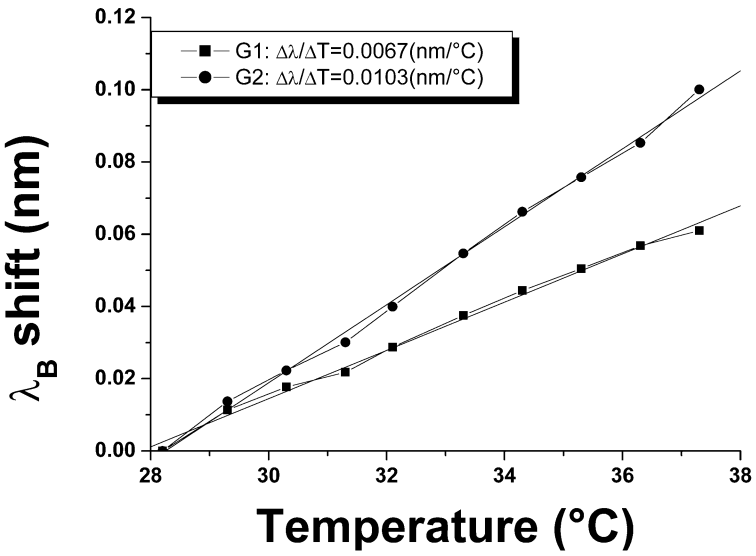

Figure 6 Temperature sensitivities of G1 and G2.

2.3. TEMPERATURE EFFECT COMPENSATION

Due to the temperature-SRI cross-sensitivity, a single etched FBG cannot be used to monitor SRI change accurately if the environmental temperature fluctuates. For practical applications, it is important to monitor temperature and SRI simultaneously and thus to obtain SRI information by decoupling the thermal effect from the total wavelength shift of the grating sensor. The proposed dual-grating structure is for this purpose. Since the thermal-optic coefficient of the fiber may change after HF etching treatment, we have evaluated the temperature responses of the deep-etched G1 and unetched G2 and the results are plotted in figure 6. It can be seen clearly that the temperature sensitivity of etched G1 (0.0067nm/°C) has been reduced significantly in comparison with the unetched G2 (0.0103nm/°C). As shown in figure 3, the reflection spectrum of G2 remained intact when the dual-grating was subjected to sugar solutions, indicating its total insensitivity to SRI. Thus, we can use G2 as a temperature reference grating to monitor thermal condition of the environment and extract the SRI information from the total reflection shift of the G1 using the temperature reference provided by G2.

3. CONCLUSIONS

We have fabricated core-exposed fiber Bragg gratings to work as a point-probe optical fiber chem-sensors. The sensitivities of the devices were characterized by measuring Bragg reflection shift with respect to concentration of sugar solution. The deep etching treatment enhances SRI- and reduces temperature-sensitivity significantly. More importantly, we proposed a dual-grating configuration concatenating an etched and unetched gratings. The total immunity to SRI of the latter makes it as an ideal temperature referencer, thus allowing thermal effect to be decoupled from the SRI response of the sensor grating. The demonstrated temperature referenced high sensitivity point probe optical chem.-sensors could be attractive for many chemical/biochemical and environmental monitoring applications.

4. REFERENCE

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