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Modal Sensitivity Enhancement of Few-Mode Fiber Bragg Gratings for Refractive Index Measurement

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Abstract—**Few-mode fibers (FMFs) offer several distinct features from single mode fibers and multimode fibers, in terms of medium core size which is capable of accommodating several transverse modes (2-6 modes). In this work, fiber Bragg grating (FBG) has been inscribed in FMF which exhibits more than one resonant Bragg wavelengths. Few-mode fiber Bragg grating (FM-FBG) can be used as sensing device because of its modal sensitivity to the changes in an ambient environment, such as temperature and refractive index in terms of concentration of the solution. To increase its modal sensitivity for solution concentration, the cladding of FM-FBG is removed, and the Bragg wavelength difference of the modes increases during the etching process. It has been observed that by decreasing the core radius through chemical etching, the Bragg wavelength difference of respective modes increases whereas the power confinement ratio in the core for the respective modes decreases. Therefore we have optimized the core radius as at approximately 7 µm for the enhancement of refractive index modal sensitivities. The fabricated sensor has been characterized with the different concentrations of sodium chloride ($NaCl_{(aq)}$) solution.**

Keywords—few-mode fiber Bragg grating; chemical etching; modal sensitivity; refractive index

I. INTRODUCTION

FMF-based devices have exhibited promising functionalities in various applications [1], such as fiber lasers [2, 3], optical filters [4, 5], add/drop multiplexers [6-9], long distance transmission channels [10, 11], FMF modal couplers [12, 13], FMF amplifiers [14, 15] and multi-parameter/discriminative sensors [16, 17]. In addition, the role of mode converters with FMFs are important for all fiber SDM technology systems [18, 19]. Therefore, FBGs inscribed in FMFs can exhibit mode conversion properties at cross-coupling wavelengths, which can be tuned by adjusting the temperature or applied strain [20].

FMF-based optical fiber sensors are inexpensive, highly sensitive, and capable of discrimination, making them preferable for most researchers [21]. Optical sensing of different parameters through FMFs can be performed using modal interference [22] and mode reflections through FM-FBGs [23]. FM-FBG sensors exhibit different modal sensitivities for concentration/refractive index by enhancing the evanescent field of the device through removing of the cladding using chemical etching [16]. These sensors can be applied in chemical industries, oil and gas industries, and biomedical applications for multi-parameter sensing due to multiple Bragg wavelengths with different sensitivities.

In this work, the chemical etching of FM-FBG has been presented and the modal sensitivity enhancement of the sensor has been elaborated. The sensor is then characterized for the different concentrations of NaCl(aq) solution. Some part of this work has presented in [16] and in Ph.D. thesis [24].

II. FABRICATION OF FM-FBG SENSOR FOR THE MEASURMENT OF REFRACTIVE INDEX

The fabrication of sensor began with inscription of Bragg grating structure inside the core of an FMF. The FMFs used are germanosilicate fibers (OFS, Denmark) with a core diameter of 19.5µm, RIs of cladding and core are 1.444 and 1.449 respectively which gives an NA of ~0.12. FM-FBG was fabricated from FMF through simple fabrication processes – UV grating inscription and chemical etching. KrF excimer laser and standard phase mask with period 1068.80 nm, were used to produce 2 cm long grating in the core of hydrogen loaded FMF. After the fabrication, FM-FBGs were annealed in a hot oven at 80 °C for 10 hours to remove the residue hydrogen and making the FM-FBG more stable in terms of Bragg wavelength and reflectivity. After FM-FBG inscription, it has been cleaved in such a way that grating part is much closed to the fiber end so that it can interact with ambient environment.

Afterwards, chemical etching was performed to remove the cladding of the fiber to enhance the evanescent wave of the core modes and to enable interaction between the core mode and ambient medium. For fast and better etching, two steps were performed. In first step the fiber end was dipped into the HF solution (48% in water) in which the silica glass is etched at a rate of ~3.05 µm/min from an original diameter of 125µm until it approaches a few µm from the cladding-core boundary. Fast etching rate may results to less desired glass surface roughness. This problem can be alleviated by continuing the etching at slower rate. In the second step, Buffered Oxide

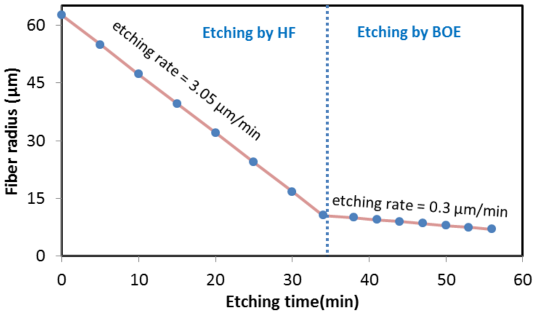

Fig. 2. Fiber radius reduction during chemical etching with Hydrofluoric acid (HF with 48% concentration in water) and buffered oxide etchant (BOE solution).

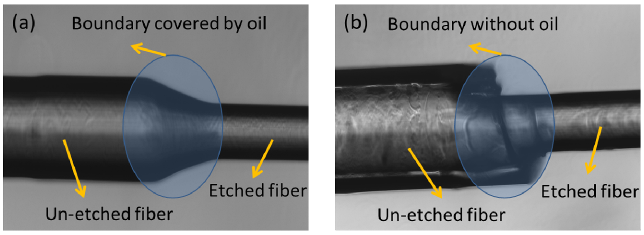

Fig. 1. Optical images of etched fiber using etchant (a) covered with oil (b) without covering with oil.

Etchant (BOE) solution with the volume ratio of NH_4F solution (40% in water) and HF solution (48% in water) was used as the etchant. The observed etching rate was 0.3μm/min and smoother glass surface was produced. In addition, it also offers the advantage of better control in etched core fiber and reduces the risk of excessive reduction in fiber radius, an irreversible process In Fig. 1, the graph illustrates the reduction of fiber radius during the etching process with HF solution at the rate of ~3.05 μm/min in the first 34 min followed by slower etching process with BOE solution at the rate of 0.3μm/min. The etchant is covered with a thin layer silicon oil to prevent the evaporation of the etchant solution. After achieving the desired fiber shape, the FM-FBG is rinsed with distilled water to remove the residual etchant. The illustration of fiber etching using etchant covered with and without the layer of oil is shown in Fig. 2 (a) and (b), respectively. It is clear that the boundary between etched and un-etched part of fiber is smooth and continuous for oil covered etchant whereas for that of uncovered with oil the boundary is discontinuous and rough. Also in case of uncovered etchant, the surface of un-etched part of fiber has become rough.

It should be notable that in chemical as well as in biological sensing applications, the core refractive index is not very close to the refractive index of tested ambient solution therefore due to large refractive index contrast the *V*-number of FM-FBG becomes also large at 1550 nm (operating wavelength) and number of modes becomes higher in the fiber. For a given fiber diameter, wavelength shift for higher order modes becomes higher with changing the refractive index of the ambient solution. This is due to the more penetration of evanescent field for higher order modes in the ambient solution as compared to the fundamental mode. Therefore the refractive index sensitivity of the FM-FBG for higher order modes can be enhanced. In the result of cladding removal, the evanescent wave is excited at the etched core-ambient boundary.

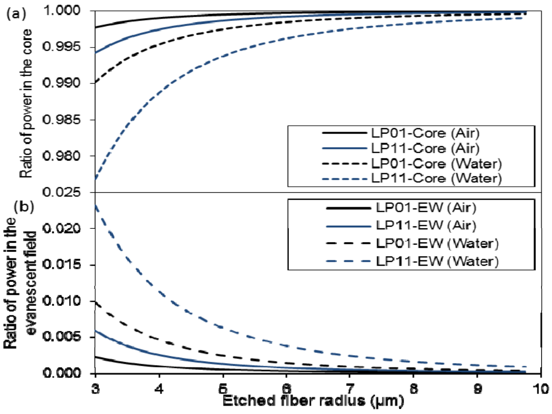

Fig. 4. Relationships between ratios of power in the (a) core and (b) evanescent field with the etched fiber radius. EW: Evanescent wave [16]

Evanescent wave can be further enhanced by reducing the etched fiber radius at the expense of reducing the ratio of power confined within the core [25], as illustrated in Fig. 3 (a) and (b). Compared with the LP_{01} mode, LP_{11} presents a greater gain in the evanescent wave power during fiber radius reduction, as depicted by the blue curves in Fig. 3 (a). However, the medium RI affects the evanescent wave generation. The ambient medium with RI closer to that of fiber glass produces stronger evanescent wave as a result of smaller etched fiber NA. This finding explains the increase in the etched fiber's ratio of power in evanescent wave when the medium is changed from air (solid curves in Fig. 3 (b)) to water (dotted curves in Fig. 3 (b)). Fig. 4 shows the simulation results on the sensitivity of Bragg wavelengths λ_{01} and λ_{11} in the function of etched fiber radius. The high RI sensitivity of λ_{11} can be attributed to the extended mode profile and relatively higher power ratio in evanescent wave for LP_{11} mode. Therefore, LP_{11} mode has stronger interaction with the ambient medium compared with the LP_{01} mode. Theoretical simulation results have been verified experimentally as shown in Fig. 5, when the optical fiber radius is decreased by etching, the wavelength difference increases and the power of higher order mode decreases. Also the location of Bragg wavelength has been found through intersection of the functions as $g(\lambda) = \lambda$ and $f(\lambda) = 2n_\mu \Lambda$ where n_μ is the effective refractive index of the μ^{th} mode. It can be observed in Fig. 5, at r = 7 μm, the power of LP_{11} is very less but reflection peak is visible and the wavelength difference is higher therefore it shows the more sensitivity to the refractive index of ambient solution.

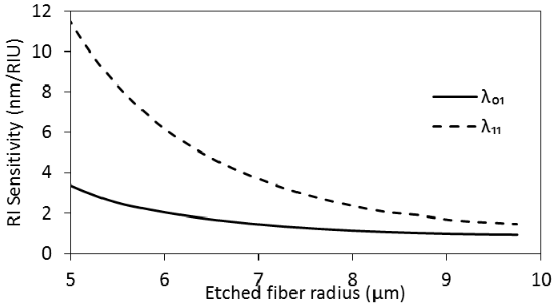

Fig. 3. RI sensitivity of Bragg wavelengths λ_{01} and λ_{11} to ambient refractive index [16]

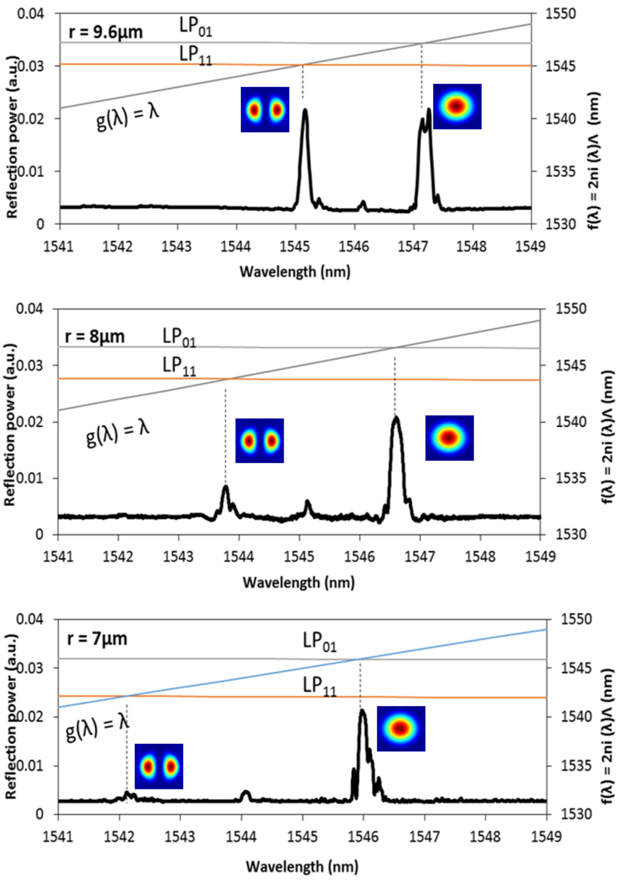

Fig. 7. From (a)-(c). Theoretical estimation of the Bragg wavelengths of two-mode FM-FBG, and variation of peak wavelength difference versus reduced fiber radius in air media, i.e., air (n=1).

III. RESULTS AND DISCUSSION

For characterization of the etched FM-FBG sensor, the reference refractive indices of the used $NaCl_{(aq)}$ solutions were considered, which were achieved using prism coupler method. Prism coupler method was used at the wavelengths of 632.8 nm and 1550 nm for the measurement of refractive index of $NaCl_{(aq)}$ solution (grams dissolved in 100 ml of water) as shown in Fig. 6. The fabricated etched FM-FBG sensor is then characterized as shown in Fig. 7, where the Bragg wavelength shift has been plotted against the refractive index values of solution. It can be seen that the higher order mode has higher sensitivity as it has more evanescent wave interaction with ambient solution at fiber core boundary. However the sensitivity of fundamental mode is less as most of the modal power is focused at the center of the fiber core. The sensor performance is measured by repeating the experiments and it has been seen that the sensor has good stability, and repetivity. On the basis of literature [26] and the current presented work, it is obvious that the higher order modes in FM-FBG can be utilized for higher sensitive refractive index sensor.

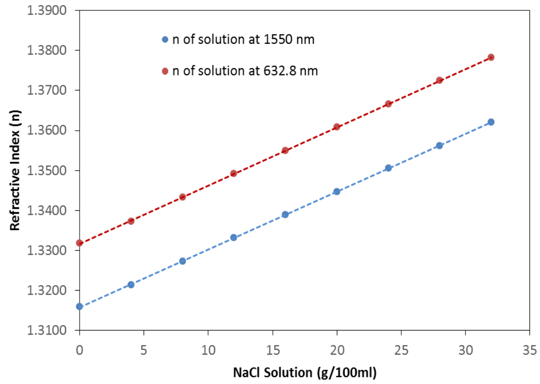

Fig. 6. Refractive index of NaCl solution (grams dissolved in 100 ml of water) obtained by prism coupler method at the wavelengths of 632.8 nm and 1550 nm, used for the characterization of proposed sensor.

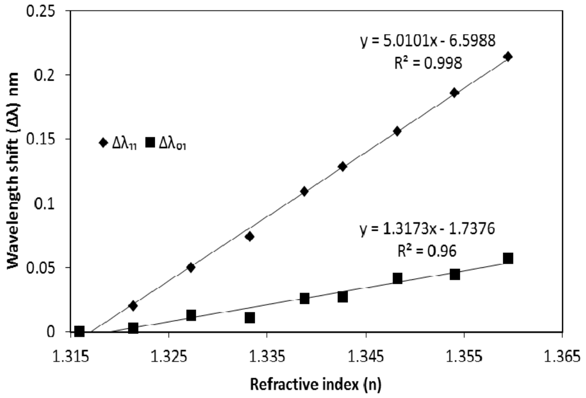

Fig. 5. Wavelength shift (Δλ) for both modes LP_{01} and LP_{11} versus refractive index of used NaCl solutions at room temperature (~22 °C)

IV. CONCLUSION

In this work, FM-FBG was fabricated and to enhance the modal sensitivities, it has been chemically etched until the core radius is left up to 7µm where the sensitivity of higher order mode LP_{11} is much higher than the fundamental mode LP_{01} due to it evanescent wave interaction with ambient solution. The fabricated sensor has good stability, and repetivity. Furthermore the sensor can be used in biomedical applications for the measurements of concentration of cells or refractive index of biological solutions.

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