Evanescent Wave-Based Fiber Bragg Grating Biosensors

Sang-Mae Lee and Deug Kim
R&D Division, Orientmg, Inc.
212-16 Gurodong, Gurogu, Seou, Tel:2-2107-8853; smlee@orientmg.com
Mario Dagenais , Athanasios N. Chryssis, Simarjeet Singh Saini
Department of Electrical and Computer Engineering, University of Maryland, College Park, MD-20742
Tel: 301-405-3684; dage@eng.umd.edu
Hyunmin Yi, William E. Bentley
Department of Chemical Engineering and Center for Agricultural Biotechnology, University of Maryland, College Park, MD-20742

Abstract: Etched fiber Bragg grating, Sensitivity of fiber-Bragg-grating sensors to index of surrounding, Hybridization of DNA

1. Introduction

The most common approach used in optical fiber biological sensor is to chemically modify the silica surface of the fiber allowing for immobilization of biological molecules e.g. antibody over the surface of the fiber. Some of the immobilization methods that have been reported include avidin bridging [2], covalent immobilization using heterobifunctional cross-linking agents [3], and non-covalent attachment via adsorption and gel entrapment [4]. The method to monitor biological changes is to monitor the change of refractive index that occurs in the evanescent field upon binding of the target antigen on the derivatized surface. Meltz et. al. proposed a sensing scheme for chemical sensing based upon Bragg grating in- and out-coupling for increased fluorescence excitation [5]. A sensor based upon long-period grating assisted coupling to cladding modes of a fiber was presented in [6]. A method of increased sensitivity to surrounding index by etching the fiber close to the core diameter was presented by Asseh et. al. [7]. A sensitivity of 2.66 nm/riu was achieved with the diameter of the fiber etched to 11 μm. The sensitivity was increased to 7.3 nm/riu by etching the fiber to a diameter of 8.3 μm in [8]. Schroeder et. al. [9] proposed a method of side-polishing the fiber and achieved a sensitivity of 340 nm/riu.

The maximum sensitivity is achieved when the index of the surrounding medium is close to that of the core of the fiber. Finally successful detection of hybridization of fiber is demonstrated by immobilizing probe DNA on the surface of the fiber and monitoring change of wavelength while hybridizing target DNA.

2. Theory and Characterization of Sensor

The sensitivity of the sensor depends upon the change in the effective index for the waveguided mode, which is related to the change in the refractive index of the measured solution. The propagation modes in the fiber are calculated by solving the Helmholtz equations for various boundary conditions determined by the diameter of the fiber and the index of the surrounding medium. Figure 1 shows the standard relationship between the normalized effective index "*b*" and the normalized frequency "*V*". The values of *b* and *V* can

$$b = \frac{n_{eff}^{\ 2} - n_2^{\ 2}}{n_1^{\ 2} - n_2^{\ 2}} = \frac{(\beta / k)^2 - n_2^{\ 2}}{n_1^{\ 2} - n_2^{\ 2}} \qquad (1)$$

$$V = \frac{2\pi a}{\lambda}(n_1^{\ 2} - n_2^{\ 2})^{1/2} \qquad (2)$$

for a fiber with a core diameter of "*a*" are given by where n_1 is the index of the core, n_2 is the index of the clad (surrounding medium), n_{eff} is the effective index of the propagating mode, β is the propagation constant of the mode and k is the wave number. The value of n_1 for standard single mode fiber is 1.4504. The Bragg wavelength reflected by a grating is given by

$$\lambda = 2n_{eff}\Lambda \qquad (3)$$

where Λ is the grating pitch. By substituting neff as

$$b = \frac{\left(\frac{\lambda}{2\Lambda}\right)^2 - n_2^{\ 2}}{n_1^{\ 2} - n_2^{\ 2}} = \frac{\left(\frac{\pi a}{V\Lambda}\right)^2 (n_1^{\ 2} - n_2^{\ 2}) - n_2^{\ 2}}{n_1^{\ 2} - n_2^{\ 2}} \qquad (4)$$

$\lambda/2\Lambda$ and substituting the value of λ in terms of V from (2) in (1), the effective index *b* can be written in terms of the grating parameters as Equation 4 is also plotted in Figure 1. The intersection of the two curves gives the Bragg wavelength.

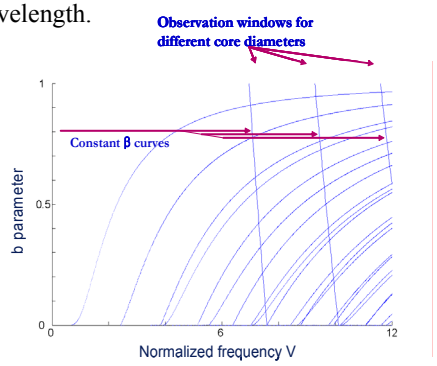
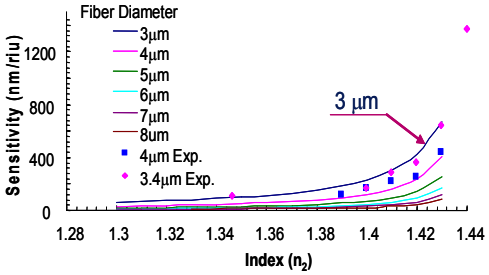


Figure 1. Normalized propagation versus V of a fiber. Constant b curves for the grating are also plotted. The intersection gives the Bragg wavelength of the grating

The simulation results for different situations will be discussed in the talk and are briefly summarized. As the grating is etched down to the core, the cladding index changes from 1.447 to 1.33 (index of etchant) forcing the fiber to be multimoded. However, as the fiber is etched further, the value of V again decreases to less than 2.405 and the single mode condition is again restored. Decreasing index and diameter also lowers the Bragg wavelength and this can be used for in-situ monitoring of the core diameter. The sensitivity which is defined as the change of Bragg wavelength as the index is changed, increases as the core is decreased. The sensitivity is also higher when the index of the surrounding medium is close to that of the core. This is shown in Figure 2.



Two sensors with diameters 3.4 μm and 4.0 μm were used for the measurements. Very stable known index fluids from Cargille were used as the surrounding medium. The indices of the fluids were calculated at the wavelength region of 1.55 μm using Cauchy relationships. Theoretical calculations are also plotted in the figure. A maximum sensitivity of 1394 is achieved for a 3.4 μm sensor which is at least four times larger than previously reported values [9]. A minimum change of the surrounding index of 7.2×10^{-6} can be resolved by the sensor assuming a wavelength resolution of 0.1 nm. Sensitivity of a higher order mode was also measured for fiber grating with a diameter of 4 μm. The first order mode achieves the absolute maximum sensitivity. However, this high sensitivity is achieved only when the surrounding index is close to that of the core of the fiber. This may not always be possible in chemical and biological sensing where the index of the chemical and biological reagents can be less.

3. Detection of Hybridization of DNA

The sensor was used to detect hybridization of target DNA with probe DNA immobilized on the surface of the fiber. A grating was etched to a diameter of 4 μm. The surface of the fiber was chemically treated in order to immobilize the probe DNA on the fiber. In the first step, silanization of the fiber grating surface was performed by immersion in fresh 1% 3-Aminopropyl-triethoxysilane (APTS) in water for 30 minutes at room temperature. The sensor was then rinsed in DI water and immersed in 5 ml of 0.1 % glutarahyldehyde solution for 30 minutes at room temperature. The sensor was again rinsed in DI water and then equilibrated in a saline sodium citrate (SSC) buffer (20x concentrated, molecular biology grade) with 0.1 M $MgCl_2$ for 10 minutes. For the rest of the experiment, the SSC buffer was used to rinse the fiber instead of DI buffer. After equilibrating the sensor in SSC buffer, it was immersed in a 3 ml solution containing 20 μg/mL of the amine-terminated ssDNA surface probe. Specifically; the ssDNA was a 20-base sequence complementary to a region in the *dnaK* gene of *E. coli*. The sensor was kept immersed overnight at 4° C. The fiber was then rinsed in SSC buffer to remove any unattached probe DNA from the fiber surface. Hybridization reactions were performed with a purified 20-base ssDNA targets. The first immersion was in a non-complimentary DNA and the change of Bragg-wavelength was measured. Before the immersion, the sensor was rinsed with Sigma PerfectHyb hybridization buffer to remove any traces of the SSC buffer and also to equilibrate the sensor. No change in Bragg wavelength was observed as shown in Figure 3. This shows that no modification of the surface of the fiber takes place as expected with the non-complimentary DNA. The sensor was then immersed in a complimentary target DNA specifically 20-base *E-coli dnaK* target was used. This time a decrease of approximately 46 pm in the Bragg wavelength was observed as shown in Figure 3. This is because hybridization of DNA takes place on the surface of the fiber altering the index causing a change in wavelength. It was confirmed that the index of the target DNA was less than that of the hybridization buffer by measuring the Bragg wavelength using a bare etched core fiber grating. So the decrease in wavelength due to hybridization is expected.

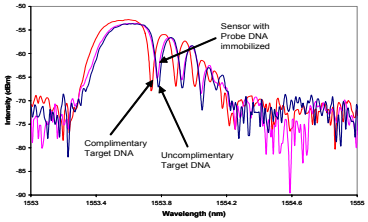


Figure 3. Reflected Bragg spectrum

4. References

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