Highly Sensitive Photonic Crystal Optical Fiber Based Immunosensor For Bacteria Detection In Water

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***Abstract*—In this paper a novel and highly sensitive immunosensor for bacteria detection in water based on a photonic crystal optical fiber is presented. The presented sensor is an evanescent wave type. High sensitivity is obtained by enhancing the evanescent field intensity near the sensing region by using a careful material selection and a precise geometry design of the photonic crystal fiber (PCF).**

Keywords; photonic crystal fibers; biosensors; immunosensors; bacteria detection; full-vector finite element method.

I. Introduction

Water analysis is important as life itself, when coming to drinking water, bacteria presence may threaten human life. Most conventional bacteriological water analyses are based on culture methods which take a long time before getting results. Rapid, portable and highly sensitive methods for pathogenic organisms detection are necessary in order to response properly to pathogenic infections [2].

Over the Past decade, Photonic crystal fibers technology earned more attention in biosensing applications field, beside advantages that conventional optical fibers present such as flexibility, small size, robustness, EMI (Electromagnetic interference) immunity and ability for remote monitoring, PCFs offer more design flexibility and possibility of greater wave field profile control thanks to the various influential geometry parameters, they also can be made of one material. Even more they provide the possibility of guiding light in a hollow core [3]. In this work, the design of a PCF based immunosensor for bacteria detection in water is presented. The immunosensor's performance is improved by manipulating the fiber's geometry parameters. The sensor's design is characterized by the intensity of the evanescent part of the optical field near the sensing region, i.e the propagating light inside the fiber can interact with analytes within the penetration depth of the wave [4]. Certainly, sensor's sensitivity is directly related to the evanescent field intensity.

A precise design of the fiber's geometry is critical in order to meet some requirements such as making the fiber single mode and improving the evanescent field optical power [1]. Indeed the PCF's guiding properties is directly affected by light's wavelength, the distribution of air holes over the fiber's cross section, the size of air holes and the hole to hole pitch.

The sensor's performance is verified through (FV-FEM) Full-Vector Finite Element Method. The scope of the modeling refers to enhance sensitivity by trying to find the optimal values of the fiber's geometric parameters and making a good selection of used materials.

II. Theory

The sensing principle of this sensor is related to refractive index change of the biosensitive layer induced by bacteria being bound to the immobilized antibodies on the PCF's external surface. This will lead to an effective index variation of the propagating wave, which can be detected later by an interferometer, the amount of this variation depends on how strong the evanescent field is. The optimal design is achieved by finding the right combination of the PCF's different geometry parameters, and this is the design that achieves the highest evanescent field intensity.

Selectivity is another issue in biosensing applications, selectivity depends on how specific antibodies are against target analytes. Antibodies are naturally made in the bodies of living species for defense against foreign microorganisms. The highly specific bio-recognition property of antibody with antigen has made it one of the most indispensable molecules for broad applications [5]. The selection of a suitable antibody is essential in immunosensing applications.

Despite the long assay time, culture based methods are still considered as the gold standard [5] [6]. Though antigen-antibody reactions are considered as the most rapid bacteria detection techniques [5], they are usually employed only to confirm the results of other methods [7] [6].

PCF technology has opened new perspectives to immunosensing methods with all the advantages they offer. In biosensing applications PCFs are usually used by inserting materials (liquids or gases) in air holes, this may offer better light-analyte interaction which will eventually enhances sensitivity, but it also requires some cumbersome procedures, and hence increases cost and consumes time.

Immobilizing analytes on the outer surface of the fiber drives away analytes from the fiber's core, but also makes the sensing process much simpler by just dipping the PCF into substances to be analyzed. Antibodies are immobilized on the PCF's outer surface using a linker then antigens bind to antibodies after been recognized.

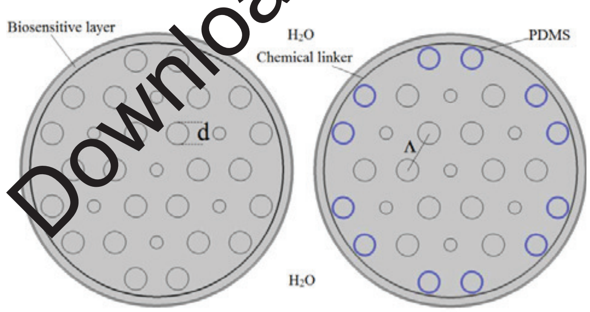
Because of the inhomogeneous nature of the cladding, PCFs cannot be studied using conventional analytical methods, so numerical methods are used. The Full-Vector Finite Element Method is one of the most widely used techniques in optical fiber analysis. This method consists of dividing the fiber's cross section into a finite number of elements and studying and characterizing each element separately and then summing-up all elements in one global matrix.

This work aims to characterize and to enhance the sensitivity of an evanescent field PCF's immunosensor through a FV-FEM.

III. Numerical Modeling

Two photonic crystal fibers designs are shown in Fig.1.a and 1.b. The first PCF design was presented by L. Mescia, et al [1]. Our design is illustrated in Fig.1.b, it differs from the first one by the polydimethylsiloxane (PDMS) rings inserted inside the last layer of air holes (Hybrid PCF). Both designs are solid core index-guiding PCFs with a silica (SiO_2) core and three rings of air holes. The refractive index of silica and PDMS were taken 1.444 and 1.420 respectively at an operating wavelength of 1.55 µm.

A chemical linker Mercapto Undecanoic acid (MUDA) surrounds the previous designs and helps to immobilize antibodies on the PCF's external surface, its refractive index is 1.463 with a 50 nm thickness [8], then a second layer acting as the biosensitive layer, models antibodies and the bound antigens, its average refractive index value is 1.37 with a 500 nm thickness. The fiber's radius (R) is equal to 8.0 µm and the thickness (t) of the PDMS rings is equal to 165 nm.



a.Conventional PCF b.Hybrid PCF

Fig.1 Hexagonal-lattice PCFs cross sections

The surrounding medium is water, its refractive index was taken 1.31.

The central air hole in the core helps to improve the evanescent field intensity interacting with the biosensitive layer [1].

A comparison has been made between the two designs by varying the holes distribution parameters, hole diameter (d) and hole to hole pitch (Λ), and then the performance of the sensor is investigated by calculating two parameters, the first parameter is the effective mode area (A_{eff}), which shows how much the mode field profile is extended outside the core. A_{eff} is calculated by means of the following equation [9]:

$$A_{eff} = \frac{\left(\iint_S |E_t|^2 \, dxdy\right)^2}{\iint_S |E_t|^4 \, dxdy} \qquad (1)$$

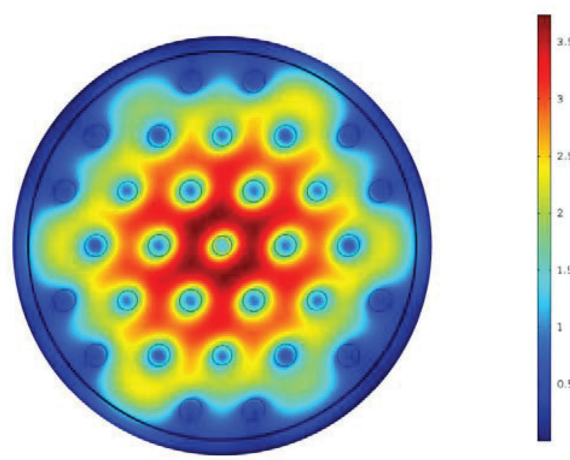
Where E_t is the transverse component of the electric field.

The second parameter is sensitivity, which is calculated by simply investigating the amount of effective index (n_{eff}) variation induced by refractive index change of the biosensitive layer (n_b), this change is directly proportional to bacteria concentration in water:

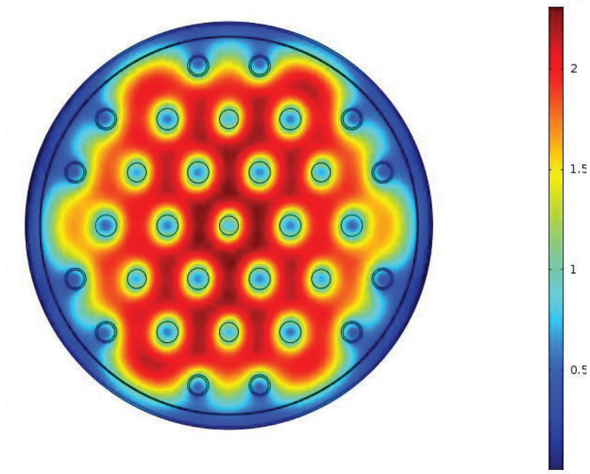
$$S = \frac{dn_{eff}}{dn_b} \qquad (2)$$

IV. Results and Discussion

Fig.2.a and 2.b shows the transverse electric field profile of the fundamental mode (HE_{11}) for the conventional and hybrid PCFs respectively for the same geometry parameters.



a. Conventional PCF



b. Hybrid PCF

Fig.2 Transverse electric field profile of the fundamental mode (HE_{11})

By comparing the two figures, we can easily notice the difference between the two mode profiles where the evanescent field is clearly enhanced in the hybrid PCF.

Table 1 demonstrates the calculated effective mode area for both geometries.

TABLE 1 Effective mode area for different values of *d* and ʌ

	Hole diameter d (μm)	*Optimal pitch* Λ_{opt} (μm)	A_{eff} (μm^2)
Conventional PCF	*0.9*	*2.56*	*140.5*
	1.1	*2.60*	*134*
	1.4	*2.65*	*122.5*
Hybrid PCF	*0.9*	*2.61*	*154*
	1.1	*2.65*	*146*
	1.4	*2.72*	*127*

For each value of *d*, a corresponding optimal pitch Λ_{opt} is calculated, A_{eff} is then calculated using equation (1).

The single mode nature of the two waveguides is maintained in each case [9].

Table 1 shows how much sensor's performance is affected by the PCF's geometry parameters, it clearly shows the dependence of the mode field profile on the hole diameter (*d*) and hole to hole pitch (ʌ), the effective mode area is inversely proportional to *d*/ʌ ratio, this is due to the fact that the mode field diameter (MFD) is inversely proportional to refractive index contrast Δ*n* between the core and the cladding [9][10]. The hybrid PCF presented wider effective mode area than conventional PCF, thanks to PDMS rings that help to extend the mode field profile outside the core.

Fig.3 depicts the guided mode effective index (n_{eff}) variation with respect to biosensitive layer's refractive index (n_b) for both PCFs designs (n_b is proportional to bacteria concentration).

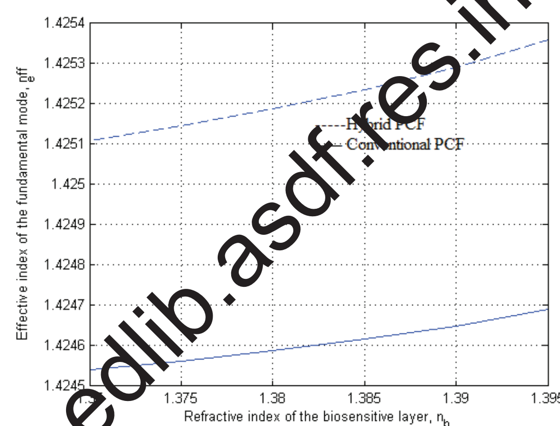


Fig.3 Fundamental mode effective index versus refractive index of the biosensitive layer, with d = 0.9μm and ʌ=2.66

Fig.4 illustrates the calculated sensitivity for both designs.

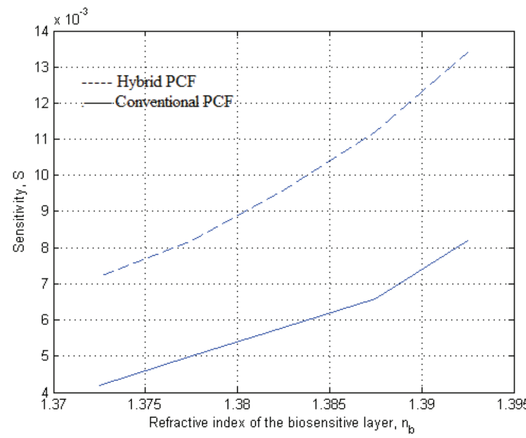


Fig.4 Sensitivity of the sensor versus refractive index of biosensitive layer

The last figure depicts the calculated sensitivity, it is obvious that Hybrid PCF is more sensitive than conventional one.

It is very important to emphasize the difference that 165 nm thick PDMS rings in the last layer of air hole can make, PDMS with its smaller refractive index (smaller than silica's refractive index) helps to increase the average refractive index near the sensing region (and hence decreases Δn and increases MFD), which extends the effective mode area towards the sensitive layer and enhances the evanescent field, offering better light-analyte interaction.

V. Conclusion

The design of an evanescent field PCF-based immunosensor is presented in this paper. Two PCFs designs are compared by varying the hole diameter (d) and the hole to hole pitch (Λ). The hybrid PCF has proved better performance than conventional one, however it is important to note that the implementation of the hybrid design requires some extra experimental work compared to conventional PCF.

The presented sensor can be a good alternative to conventional methods for determining bacteria concentration in water, it is also important to note that a better enhancement can be added by trying new geometries or by using new materials.

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