EFFECTS OF THE SENSING REGION REFRACTIVE INDEX IN FIBER OPTIC EVANESCENT FIELD ABSORPTION SENSORS

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ABSTRACT

The response of a fiber optic sensor based on evanescent field absorption has been calculated with respect to the refractive index (RI) of the sensing region by using the weakly guiding approximation (WGA). For the same absorption conditions, the response of the sensor varies to 26.9%, while the RI of the sensing region varies to 4.19%. In this study, the effect of fluctuations in the sensing region RI on the sensor response has been investigated and it has been shown that it is necessary to use the effective RI of the matrix (cladding + chemical) instead of the cladding RI.

1. INTRODUCTION

In last twenty years, fiber optic sensors (FOSs) for sensing of various chemical parameters, species, and compounds have been developed [1-2]. The advantages of very small size, flexibility, immunity to electromagnetic interference and inherent possibility for remote measurements make them useful for chemical, biomedical and environmental sciences. In first chemical sensing applications, optical fibers have been used for light transferring from the source to sensing tip and from sensing tip to the detector. In these sensors, the sensing tip was formed by a bulk structure surrounding the reagent interacted with the light. This optical probe is also known "optrode".

Optrodes have some practical limitations due to poor reagent and mechanical stability, and long response times. This limitations can be eliminated if optical fibers are directly used as the sensing element. The most efficient method serving this aim is to constitute an interaction (especially absorption) between the chemical sensed and the evanescent field that is exist in the cladding along the fiber. In the chemical sensing, trends tend to fiber optic sensors based on evanescent field absorption (EFA) [3-15].

Absorption of the evanescent field by a chemical species can be achieved by use of two kind of optical fibers: Singlemode D-fibers (mostly for gas absorption) [14-15], and multimode plastic cladding silica (PCS) fibers (for sensing of liquid chemicals) [4-7, 9, 11-13].

At suitable wavelengths, D-fibers can carry optical signals for long distances. However, some drawbacks of them are problems associated with splicing and connecting, and poor evanescent field.

In sensors used PCS fibers the interaction between the evanescent field and the chemical can be accomplished by various ways including to immobilize a suitable polymer, to coat sol-gels around the core, and to remove the plastic cladding. It has been reported that, high sensitivities can be obtained if the cladding is removed [4-5, 8].

Since the light transmission in optical fibers depends on the total internal reflection (TIR), there is an evanescent field that penetrates into the cladding and is carried along the fiber (see Figure 1). This field is given by

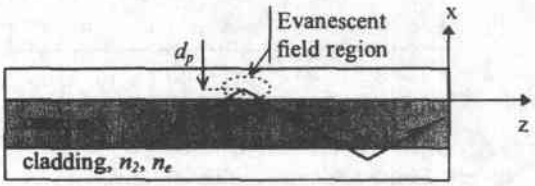
$$E = E_0 \exp(-x / d_p). \qquad (1)$$

d_p is the penetration depth and is determined by

$$d_p = \frac{\lambda}{2\pi n_1 \left[\sin^2 \theta - \left(\frac{n_2}{n_1} \right)^2 \right]^{1/2}}, \qquad (2)$$

where λ is the free space wavelength of the optical source, θ is the incident angle to the core/cladding boundary, and n_1 and n_2 are refractive indices of the core and the cladding, respectively.

If the fiber core is surrounded by an absorbing material, the evanescent field is attenuated due to absorption and the total optical power reached to the fiber end decreases. This is the sensing principle of EFA FOSs. In these sensors, the quality of the interaction between the evanescent field and the chemical surrounding the core depends on the value of the effective RI of the sensing region (n_e) because of d_p. Some researches have been used in their calculations the cladding RI instead of that the chemical [5, 8, 10]. In fact, the n_2 of the fiber used in sensor system is constant while the n_e may be variable. For example, fluctuations in temperature and concentration and different wavelengths may be caused changes in n_e. In this work, it has been shown the effects of varying n_e on the sensor response by theoretical calculations.



n_e; cladding refractive index after the diffusion of the chemical

Figure 1. Evanescent field and geometry of the sensing region

2. THEORY

Normalized frequency is an important parameter determining the sensitivity of EFA FOSs and is given by

$$V = \frac{2\pi}{\lambda} a\left(n_1^2 - n_2^2\right)^{1/2} = \frac{2\pi}{\lambda} a\, n_1 (2\Delta)^{1/2}, \quad (3)$$

where a is the fiber core radius and Δ is the relative RI difference.

For a uniform distribution of power among the fiber modes, the total fraction of guided power contained in evanescent fields is given by [16],

$$\eta = \frac{4}{3V}. \quad (4)$$

The normalized frequency also determines the total number of guided fiber modes (N). For a step index profil, the N is approximately given by [16],

$$N = \frac{V^2}{2}. \quad (5)$$

For a uniform modal power distribution, the total power guided by a multimode optical fiber of length l with a lossless core and a cladding with its bulk absorption coefficient α is given by [8],

$$P_{out} = \frac{P_{in}}{N} \sum_{\nu=1}^{N} \exp(-\alpha \eta_\nu l), \quad (6)$$

where η_ν is the power fraction in the cladding of the νth mode (i.e. $P_{\nu\text{-}clad} / P_{\nu\text{-}core}$) and is given by Equation (3.3.41) of ref. [17]. The WGA solution has been used in order to determine the η_ν.

3. ANALYSIS

We consider a PCS fiber whose geometry is given by Figure 1. Length l of the cladding is immersed into the chemical. The effective RI after diffusion of the chemical is n_e and bulk absorption coefficient is α. For calculating of the output power of the sensor, it is usual to use fiber parameters. However, d_p, V and η have different values in the unremoved part of the fiber and in the sensing region (removed part) because n_e may not equal to n_2. Consequently, the output power calculated with initial fiber parameters differs from that with the sensing region since absorption only takes places in there. This effect has been accounted for by some workers adding a term representing the NA changing in the sensing region [6].

For analysis we consider a standard (i.e. commercially available) PCS fiber whose core RI is 1.46 and numerical aperture (NA) is 0.2. We choose the other parameters so that the V number of optical fiber equals to 100. The sensor response (P_{out}/P_{in}) calculated against the αl by using Equation (5) will be as given in Figure 2.

If the n_e equals to n_2 the response will be the same as that of initial fiber parameters. In fact, fiber parameters cannot be used for calculations because the n_e may differ from n_2. The n_e must be measured during the power measurements and its dependence on the αl must be determined if it is variable.

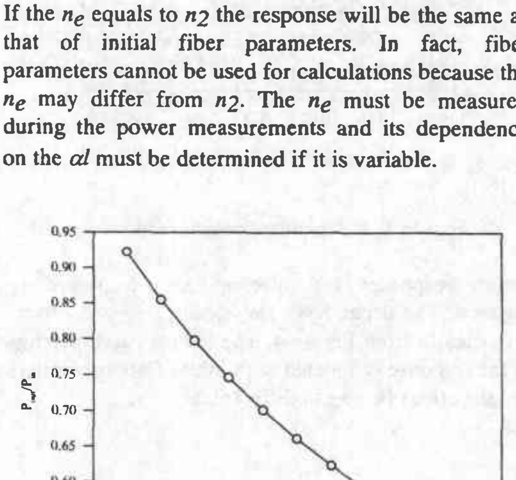


Figure 2. The sensor response for V=100 and Δ=0.0094 (NA=0.2).

In order to test the effects of changes in the n_e (i.e. when different chemicals are used) on the response we have changed the n_e from 1.446 to 1.386. This correspond to a change of 4.19% in the n_e, a change from 0.0094 to 0.0494 in the Δ, and a change from 0.2 to 0.46 in the NA. The last value of the V number is 230 while its starting point is 100.

Changes in the V also affect the d_p, η, N and hence the response. The response varies from 0.922 to 0.965 for αl=10 and from 0.534 to 0.731 for αl=100. In other words, sensor responses will be calculated as 0.922 instead of 0.965 (with a 4.46% difference) and as 0.534 instead of 0.731 (a 26.9% difference).

Δ-dependent sensor responses are shown in Figure 3. As can be seen from Figure 3 the difference between responses increase for large αls while they remain approximately constant for small αls.

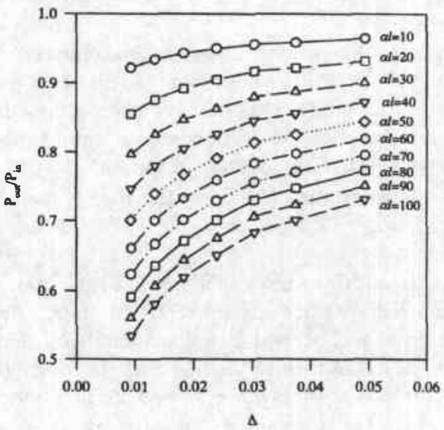


Figure 3. Δ-dependent sensor responses.

Sensor responses for different Δs are plotted in Figure 4. The dependence on sensing region Δ can be seen clearly from Figure 4. The lowest curve belongs to the response calculated with initial fiber parameters and the others belong to different Δs.

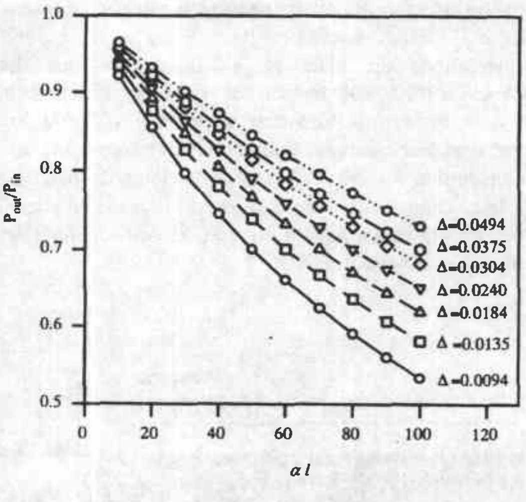


Figure 4. Sensor responses against αl for various Δs.

CONCLUSIONS

The WGA solution used in our calculations is independent from Δ. But this doesn't mean that the output power is independent from Δ, too. In EFA FOS, the output power greatly depends on the Δ.

Hence, for the output power analysis of the sensor, it must be used the sensing region RI instead of fiber cladding RI. Furthermore, since RI is a wavelength-dependent parameter, this dependence must be determined in spectroscopic measurements.

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