icrobent optical fibers as evanescent wave ensors

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Abstract. Microbent optical fibers are potential candidates for evanescent wave sensing. We investigate the behavior of a permanently microbent fiber optic sensor when it is immersed in an absorbing medium. Two distinct detection schemes, namely, bright-field and dark-field detection configuration, are employed for the measurements. The optical power propagating through the sensor is found to vary in a logarithmic fashion with the concentration of the absorbing species in the surrounding medium. We observe that the sensitivity of the setup is dependent on the bending amplitude and length of the microbend region for the bright-field detection scheme, while it is relatively independent of both for the dark-field detection configuration. This feature can be exploited in compact sensor designs where reduction of the sensing region length is possible without sacrificing sensitivity. [DOI: 10.1117/1.1519243]

Subject terms: microbend; fiber optic sensor; evanescent wave.

Paper 010381 received Oct. 17, 2001; revised manuscript received Apr. 15, 2002; accepted for publication May 7, 2002.

ntroduction

ical sensing using optical fiber has a variety of applications in diversified fields such as industry, biomedicine, [1,2] Fiber optic chemical sensors exploit the inherent perties of optical fibers such as low cost, light weight, loss transmission of data, immunity to electromagnetic radio frequency interference, remote sensing capability, sensing in inaccessible locations.[3] Moreover, they have added advantage that the measurement is optical, rather physical or electrical. The simplest and easiest to fab are the intensity modulated fiber optic sensors (FOS) fall into two categories, namely, extrinsic[4] and intrinsic Evanescent wave FOS are[5] a class of intrinsic intenmodulated FOS. These work on the basis of the phemenon of attenuated total internal reflection when a light propagates through an optical fiber having a lossy ding. As is well known, the power transmitted through optical fiber is not fully confined inside the core of the e, but a fraction of it travels through the cladding.[6] This tion of the guided power in the cladding region is ed the evanescent field, and it can be utilized for fabing various types of fiber optic chemical sensors.[7] To e optical fiber in the evanescent wave sensing configuon, usually a part of the cladding is removed from a ion that is then surrounded with a medium whose absore or refractive index changes with the concentration of species.[8] The light traveling through the fiber interacts h this surrounding medium, which now acts as a lossy ding, through the evanescent field. As the surrounding ium becomes more and more opaque to the evanescent ld, the optical power transmitted through the fiber decreases.[9] Such sensors are operated by direct sensing techniques[10] or by reagent mediated sensing methods.[11] The main advantage of evanescent wave FOF is that the interaction between the optical radiation and sensing region is achieved without disturbing the fiber path. Such an interaction helps in using the fiber sensor in distributed sensing applications also.[12]

Microbent fiber sensors are[13-15] among the earliest forms of FOS. They work on the basic principle that when a fiber is physically deformed over its length, a loss in transmission takes place. This deformation is usually achieved by placing the fiber in between a pair of corrugated plates and applying pressure on it, which then modulates the output intensity. These fiber optic microbend sensors are used in measuring various physical parameters such as pressure, strain, temperature, displacement, etc.[16,17] Although, some chemical sensors based on microbending have also been reported in the literature, these essentially use an indirect method to determine the chemical concentration by using a transducer to convert the value of the chemical concentration to the pressure applied to microbend the fiber.[18] However, Lee et al. have shown that a permanently microbent optical fiber could be directly used to detect any chemical species that has optical absorption at the transmitting wavelength.[19] Two detection configurations, one for detecting the core modes and another for detecting the cladding modes of a fiber, have been proved to be viable for measuring the concentration of a chemical species. Moreover, we predicted that it could become a potential substitute for the conventional unclad optical fiber in the fabrication of evanescent wave FOS. In this paper, we report the effect of bending amplitude and bending length on the sensitivity and dynamic range of the generic sensor developed in two of its operating configurations,

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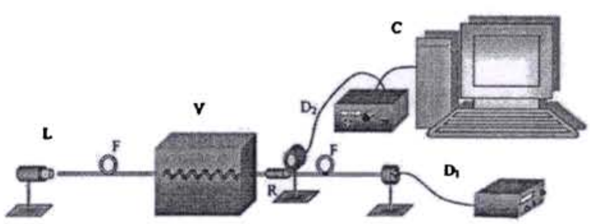


Fig. 1 Schematic diagram of the experimental setup: L; diode laser (670 nm); C; computer (Intel PIII); V, vessel containing methylene blue in water; F; optical fiber; R; index-matching liquid; D_1, detector 1 (Metrologic 45-545); and D_2, detector 2 (Newport 1815-C).

namely, the bright-field detection scheme and the dark-field detection scheme.

2 Experimental Section

A series of permanent microbends is introduced onto a 30-cm bare step-index plastic fiber of core diameter 380 μm and numerical aperture 0.3, by sandwiching the fiber with a pair of corrugated plates and applying moderately high pressures of, a few kilograms per square centimeter. The lengths of three different corrugated plates used to bend the fiber are 20, 40, and 60 mm each having a pitch of the corrugation as 1 mm. A schematic diagram of the experimental setup is shown in Fig. 1. The bent portion of the fiber is immersed in a cell containing methylene blue dye (Qualigens, India) in water, the absorption peak of which is at 664 nm. A 5-mW laser diode (Imatronic, United Kingdom) operating at 670 nm is used to power the sensor since this wavelength is near the peak absorption wavelength of methylene blue (MB) dye. The cladding modes generated at the sensing region are detected by placing a liquid crystal (BL-35, Merck, United Kingdom) that acts as an index matching liquid, just beyond the sensing region. The power carried by the cladding modes and core modes are independently measured for various concentrations of MB dye by two laser power meters D_1 (EG&G Gamma Scientific 460-1A) and D_2 (Metrologic 45-545), respectively. The outputs from the multimeters are connected to a digital multimeter (Hewlett Packard—34401A) and the data acquisition is carried out using the GPIB (IEEE—488) card and LabVIEW software (National Instruments).

3 Theory of Operation

When a fiber is bent into a periodic series of bends having small radii, optical power transmitted through the fiber is coupled between the m'th and the n'th mode so that the spatial frequency of the perturbation satisfies the condition[20]

$$\lambda=\frac{2\pi}{\beta_m-\beta_n}, \tag{1}$$

where each mode has a propagation constant $\beta_m = n_1 k \cos(\theta_m)$, with θ_m representing the angle which the mode's equivalent ray makes with the fiber axis; n_1 is the core refractive index; and k is the free-space propagation constant. Each m represents a modal group with nearly identical propagation constants. The distance in β space between adjacent guided modes in a step-index fiber is given by

$$\beta_{m+1}-\beta_m=\frac{2\sqrt{\Delta}}{a}\frac{m}{M}, \tag{2}$$

where M is the total number of modal groups. This means that the separation of modes in β space depends on the order of the modal groups m. We can see that higher order modes having large m can be coupled with small periodicity λ. The critical value of λ that is required for coupling of guided power to leaked power occurs when $m=M$, giving

$$\lambda_c=\frac{\pi a}{\sqrt{\Delta}}=\frac{\sqrt{2}\pi a n_1}{\text{NA}}, \tag{3}$$

where NA is numerical aperture.

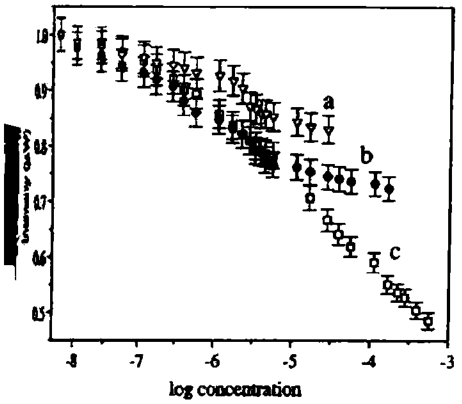
This approach to mode coupling between neighboring modes is valid for small bending amplitudes only. But for larger bending amplitudes, the guided power from even lower order modes can be coupled to leaky modes and back.[20] Since the bending is periodic, this coupling from the core to the cladding modes is oscillatory in nature. The leaky modes thus generated consist of both cladding and radiation modes. The radiation modes escape out of the core and the cladding, whereas the cladding modes continue to propagate along the fiber. After the bent portion of the fiber there is little power coupling between guided and unguided modes, and they continue to propagate without much interaction. This power in the cladding modes is measured by placing an index-matching liquid over the cladding of the fiber just beyond the bent portion. Such a measurement scheme is termed the dark-field detection configuration.[21] The power that is carried by the core modes is determined using the bright-field detection configuration. The experimental observations confirm the fact that the bent portion of the fiber essentially behaves as an unclad region of a multimode fiber that is conventionally used for evanescent wave spectroscopy. The behavior of such a fiber in the bright-field configuration can be approximated by the relation[17]

$$P(l)=P_0\left[\sum_i \exp(-\gamma_i C l)\right], \tag{4}$$

where P_0 is the output power obtained without any absorbent surrounding the sensing region that is the bent/unclad portion, γ_i are the molar evanescent wave absorption coefficients[22] of different modal groups in a multimode fiber having different penetration depths, C is the concentration of the absorbing species, l is the length of the sensing region, and $P(l)$, is the power output in the presence of an absorbent. The conventionally used expression for evanescent wave spectroscopy is[23]

$$P(l)=P_0\exp(-\gamma C l). \tag{5}$$

This is valid only in a small range of operation of approximately one order of magnitude. This can be readily seen a



Influence of bent length on the sensitivity of the sensor in the bright-field detection scheme (a=20 mm, b=40 mm, c=60 mm).

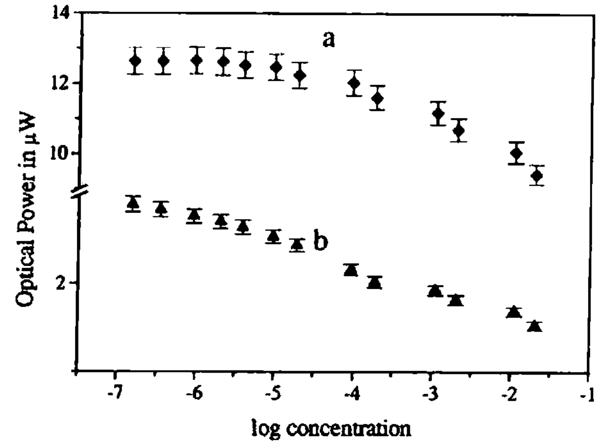


Fig. 3 Effect of bending amplitude on the sensitivity of the microbent fiber optic sensor in the bright-field detection configuration for a sensing length of 60 mm (curve a, low pressure, and curve b, high pressure).

approximation of Eq. (4). Thus, in a short range of op- Eq. (5) is valid, but the value of γ changes with the range of concentration.

Results and Discussions

Figure 2 shows the variation of the bright-field intensity as a logarithmic function of concentration of MB dye. The minimum detectable limit of the sensors for various lengths of the microbent region is about 10 ppb. Note that the variation in the output power is a logarithmic function of concentration and hence the sensitivity is range dependent. The sensitivity for a 60-mm microbent fiber in the concentration range 10 to 100 ppb is about 10 ppb, whereas in the concentration range 100 ppb to 1 ppm it is 100 ppb and in the 1 to 10 ppm range the sensitivity is 1 ppm. Moreover, the sensitivity of the sensor changes with the length of the microbent region of the fiber. The sensitivities for 60-, 40-, and 20-mm microbent fibers in a typical range of 100 to 1 ppm are 100, 150, and 200 ppb, respectively.

The coupling strength of optical power between the guided modes and leaky modes is dependent on the period of deformation and the amplitude of deformation,[24] but not on the length of deformation or the total number of bends. However, mode coupling is a periodic phenomenon such that as the number of bends increases the number of the core modes get coupled to clad modes also increases. The evanescent field of these cladding modes determines the sensitivity of the device, which will definitely also increase with the deformation length. Thus, the sensitivity in a particular range of the sensor can be expected to be directly proportional to the number of bends, which in turn is determined by the length of the corrugations.

Furthermore, the bending length seems to influence the working range of the sensor as well. The range increases with the increase in length of the microbent portion of the fiber. This can be attributed to the adsorption of solute molecules on the bent portion of the fiber. The influence of the adsorbed molecules on the light transmission properties of the sensor will be inversely proportional to the length of the bent portion. Therefore the concentration range at which saturation sets in increases with the microbend length.

Figure 3 shows the effect of bending amplitude on the sensitivity in the bright-field detection scheme. The sensitivity of the sensor at two typical bending amplitudes in the range of concentration 1 to 10 ppm are 0.7 and 5 ppm. We observe that the sensitivity increases with the bending amplitude. This may be because, as the bending amplitude increases, more and more lower order guided modes get coupled to cladding modes. Hence the evanescent field at the cladding-absorbing solution boundary increases, resulting in a larger attenuation of evanescent field of cladding modes, which in turn provides a better sensitivity.

Figures 4 and 5, respectively, give the effect of number of bends and bending amplitude on the sensitivity in the dark-field detection scheme. The profiles for the dark-field configuration at different bending amplitudes and bent lengths are more or less the same. This suggests that the sensitivity is independent of both these parameters at least in the range of values used in the present investigation. This is understandable because the total power coupled to the cladding modes is governed by the bending amplitude and the number of times this coupling takes place is deter-

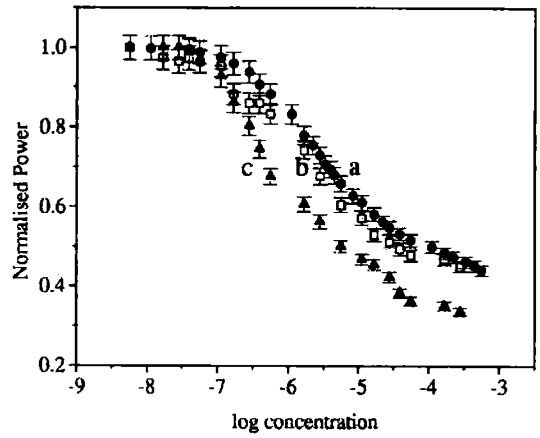


Fig. 4 Effect of bent length for the sensor in the dark-field detection configuration (curve a, 60 mm; curve b, 40 mm, and curve c =20 mm).

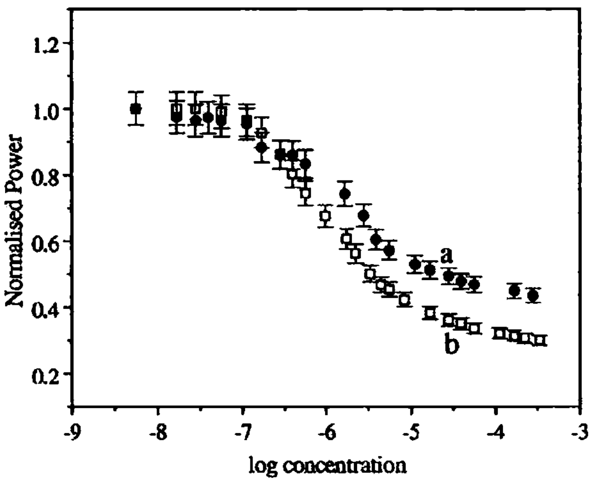


Fig. 5 Effect of bending amplitude on the sensor response for the dark-field detection configuration (relatively low pressure and high pressure).

mined by the bend length. But the fraction of the cladding power that will be modulated by varying the absorbance of the medium surrounding the bent portion is independent of both these parameters. This may be the reason for the observed nondependent nature of sensitivity on the bending amplitude and bent length in the dark-field detection technique.

Again, we can see that the shape of the curves obtained using bright-field and dark-field detection schemes are different. If we attribute γ_i to the different penetration depths of various modal groups, it can be argued that the amount of power coupled to the various cladding modes may be different, which results in the appearance of three regions with different slopes for the dark field detection scheme.

5 Conclusion

We designed, fabricated, and characterized a permanently microbent fiber optic sensor that is of generic nature. It can be applied to any chemical sensing configuration provided the sample has optical absorption at the operating wavelength of the sensor. The sensor presented employs a double detection scheme and consequently the reliability of the measurement should be high, which is certainly an advantage compared to conventional evanescent wave sensors. Moreover, the sensitivity in the bright-field detection scheme is dependent on the amount of deformation and also on the length of deformation, while that in the dark-field detection scheme is independent of both these parameters. This is an advantage over the conventionally used evanescent wave FOS where the sensitivity is directly related to the length of the sensing region. However, for the present sensor in the dark-field detection configuration the sensitivity is least dependent on the length of the sensing region, so that reducing the sensing length does not affect the sensitivity noticeably. This feature will definitely help in the fabrication of very compact FOS.

Acknowledgments

S. Thomas Lee expresses his gratitude to the Council for Scientific and Industrial Research (CSIR, New Delhi) for the research fellowship. He also acknowledges the help rendered by Sebu Thomas for setting up LabVIEW. Again thanks are due to Shaji S and Joseph Mathai, Department of Physics, Cochin University of Science and Technology, for rendering a helping hand at various stages of this work. The authors are grateful to All India Council for Technical Education (AICTE) and Netherlands Universities Funding for International Collaboration (NUFFIC) for the partial financing of this project.

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