Available online at www.sciencedirect.com
SCIENCE DIRECT®
Optics Communications 224 (2003) 237–241
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Long period gratings in multimode optical fibers: application in chemical sensing

S. Thomas Lee*, R. Dinesh Kumar, P. Suresh Kumar, P. Radhakrishnan, C.P.G. Vallabhan, V.P.N. Nampoori

International School of Photonics, Cochin University of Science and Technology, Cochin 682 022, India

Received 12 February 2003; received in revised form 25 April 2003; accepted 22 May 2003

Abstract

We propose and demonstrate a new technique for evanescent wave chemical sensing by writing long period gratings in a bare multimode plastic clad silica fiber. The sensing length of the present sensor is only 10 mm, but is as sensitive as a conventional unclad evanescent wave sensor having about 100 mm sensing length. The minimum measurable concentration of the sensor reported here is 10 nmol/l and the operating range is more than 4 orders of magnitude. Moreover, the detection is carried out in two independent detection configurations viz., bright field detection scheme that detects the core-mode power and dark field detection scheme that detects the cladding mode power. The use of such a double detection scheme definitely enhances the reliability and accuracy of the results. Furthermore, the cladding of the present fiber need not be removed as done in conventional evanescent wave fiber sensors.

PACS: 42.81.Pa; 42.79.Dj

Keywords: Fiber sensor; Evanscent wave; Grating sensor; Multimode fiber; Long period grating; Absorption

1. Introduction

Two major areas of application of optical fibers are fiber optic communication and sensing. The bridge between these two fields has become shorter by the advent of fiber gratings, both short period and long period, which are extensively used for communication as well as sensing purposes. Essentially, fiber gratings are fibers with modulated refractive index of the core and are mostly fabricated in single mode fibers [1]. However, recently, it has been reported that fiber gratings formed in multimode fibers also are useful in many applications [2]. Fiber optic chemical sensing, both extrinsic and intrinsic, has been a continuously growing field due to the scope of new sensing schemes, progress in the production of novel fiber configurations,

* Corresponding author. Permanent address: Department of Physics, St. Thomas College, Pala 686574, India. Tel.: +91-484-575-848; fax: +91-484-576-714.

E-mail addresses: lee@cusat.ac.in, thomaslees2002@hotmail.com, photonix@vsnl.com (S. Thomas Lee).

URLs: http://www.photonics.cusat.edu, http://www.stthomascollegepala.edu.

0030-4018/$ - see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/S0030-4018(03)01597-9

increasing concerns over environmental pollution, demands for safe and accurate monitoring in industrial processes, and new trends in medical diagnostics and preventive medicine [3]. Fiber optic chemical sensors can be classified in a number of ways. In one classification they are divided into three categories, namely: (1) plain fiber sensors where fibers are connected with the help of lenses to an absorption cell, (2) fiber optrodes where the working sensor chemistry is formed directly on the fiber tip, (3) evanescent wave sensor where interaction with the analyte through the cladding mode power results in a decrease in the output intensity of fiber [4]. Further they can be classified as sensors having direct optical interaction with the analyte and sensors involving indirect analysis using chemical indicators [5]. So far the most versatile of the intrinsic chemical sensing is considered to be the evanescent wave sensing which is usually carried out using an unclad multimode fiber [6–10].

Fiber gratings can be fabricated by a variety of ways. In the internal writing technique which includes the Hill gratings, rocking filters and gain saturation gratings, they are formed by the interference of two counter propagating beams in an optical fiber. The more versatile and widely used external writing techniques such as interferometric [11], phase masks, amplitude masks and point-by-point technique [12] employ external UV writing procedure. Of these techniques, the point-by-point technique has the maximum flexibility of writing where an optical fiber is exposed from the side to a tightly focused UV light. A few works related to refractometry employing long period gratings (LPG) in single mode fibers have appeared in the literature [13,14]. These have been basically used for detecting the refractive index changes of a liquid surrounding the grating region of the fiber by measuring the shift in the resonance peaks obtained for the LPG fiber. In this communication, we demonstrate a novel scheme with respect to an intensity modulated evanescent wave sensor for measuring the absorption coefficient of a chemical species rather than its refractive index of the medium surrounding the grating region of a multimode optical fiber. Moreover, it may also be noted that the idea of an evanescent wave sensor using fiber gratings which simultaneously employ both bright and dark field detection schemes has been implemented here for the first time.

2. Experimental

The long period gratings with a period, $\Lambda = 500$ μm and length 10 mm are written in an unjacketed step index multimode plastic clad silica (PCS) fiber (Newport F-MBB) of N.A. 0.37 and core diameter 200 μm. The writing technique employed here is the point-by-point technique using the frequency tripled (355 nm, 9 ns) radiation from a pulsed Nd:YAG laser (Spectra-Physics GCR-170), which is operated in the single shot Q-switched mode. The fiber with a cladding is placed on a microtranslator, which can be moved in steps of 500 μm. The radiation from the laser is focused on to the fiber using a quartz cylindrical lens. After each irradiation process the fiber is translated through 500 μm and the pattern was generated for a total length of 10 mm. The formation of gratings is clearly indicated by a loss in transmission. Apart from this observation, when light is allowed to pass through the fiber streaks of light from the grating region can be seen on the fiber with LPG, similar to the case with a microbent optical fiber. The fiber gratings thus formed is used in evanescent wave chemical sensing. The schematic of the experimental setup for chemical sensing is shown in Fig. 1, which is similar to that of the microbent chemical sensing as already reported by Lee et al. [15].

The grating region of the unstrained fiber is immersed in a glass cell containing Methylene Blue (MB) dye solution, the absorption peak of which is at 664 nm [15,16]. This grating sensor is powered by a continuous wave He–Ne laser (Spectra Physics) operating at 632.8 nm. Detector D_1 (Newport 1815-C) measures core-mode power which is placed at the output end of the fiber. In order to detect the cladding mode power an index matching liquid (R) is placed near the grating region (G), and the emerging light is collected using another optical fiber of core diameter 1000 μm and is coupled to a Detector D_2 (Infos M-100). All the measurements have been carried out at 20 °C.

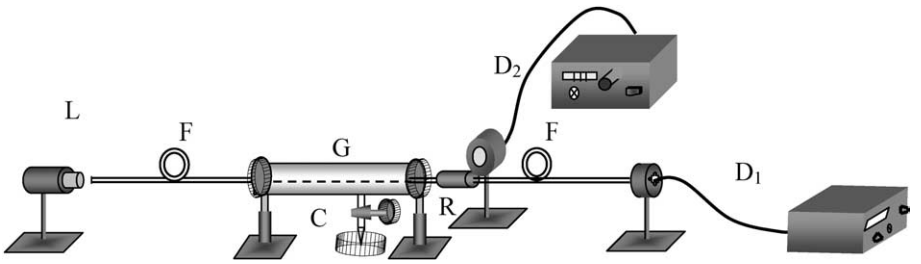

Fig. 1. L, He–Ne laser (633 nm); C, cell containing methylene blue in water; F, optical fiber; R, index matching liquid; D_1, Detector 1 (Metrologic 45-545); D_2, Detector 2 (Infos M-100); G, grating region.

3. Results and discussion

The optical power transmitted through the fiber as core modes at a wavelength λ, is coupled between core modes and cladding modes at the grating region as shown in Fig. 2. This coupling process may be expressed as [17]

$$\lambda = (n_{\text{core}} - n_{\text{clad}})\Lambda, \tag{1}$$

where Λ, n_{core}, n_{clad} are the period of the gratings, the effective refractive index of core modes and the effective refractive index of cladding modes, respectively. Since in single mode fibers there exists only one core mode (LP_{01}) and many cladding modes ($LP_{1\mu}$), the core–cladding coupling occurs at certain specific wavelengths. However, in the case of a multimode fiber with a large number of core modes and cladding modes, the core–cladding power coupling occurs at all wavelengths and the wavelength dependence is not resolved. This is experimentally verified when trace amounts of potassium permanganate is detected in another experiment by employing the same technique and using a He–Ne laser source operating at 543 nm.

To characterize the present sensor the grating is immersed in MB dye solution which is kept at 20 °C. The sensing technique used here is the bright and dark field detection schemes, the details of which are reported elsewhere [15]. The optical power contained in the core and cladding modes is measured for various dye concentrations. The variation of the core-mode intensity with concentration of the MB dye is shown in Fig. 3.

The normalization of the core mode as well as the cladding mode intensities has been made with respect to the detector output corresponding to zero concentration of the dye in pure solvent (i.e., water). This clearly indicates that the bright field detection scheme is sensitive enough to detect micromolar concentration of chemical species. Nevertheless, the dark field detection scheme that detects the cladding mode power, with the help of

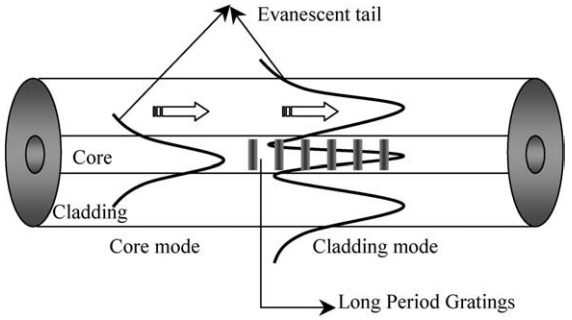

Fig. 2. Diagram showing the core mode-cladding mode power coupling and the corresponding evanescent tails.

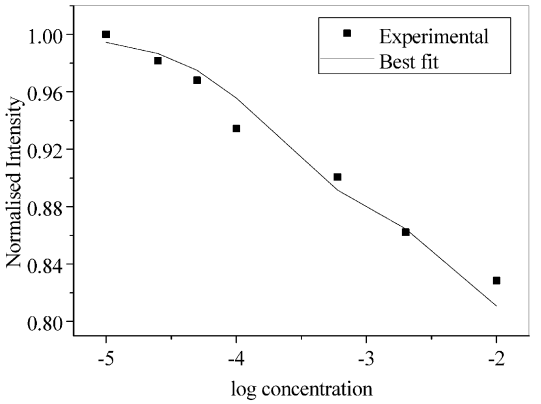

Fig. 3. Plot showing core-mode intensity variation with dye.

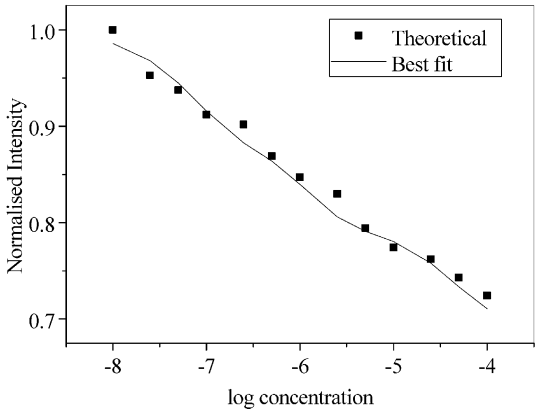

Fig. 4. Plot showing cladding-mode intensity variation with dye.

an index matching liquid that surrounds the fiber just beyond the grating region, is seen to be even more sensitive with a detection limit of 10 nmol/l as can be inferred from Fig. 4.

It may be noted that the index matching liquid has to be placed as close as possible to the grating region in order to have maximum cladding power. However, such a restriction does not impede the remote sensing capability of the present sensor which is made possible by using another optical fiber to collect the light coming out of the index matching liquid. Such a high sensitivity may be achievable with an unclad fiber also, but only with longer sensing length of about 100 mm as against 10 mm in this case [18,19]. This fact has been experimentally verified, the details of which will be reported elsewhere.

Fig. 2 throws light upon the basic mechanism of the present sensing technique. A part of the guided/core-mode power in a fiber grating gets coupled to unguided/cladding mode power at the sensing/grating region. But a part of this cladding mode power extends out of the cladding as evanescent tail, similar to the evanescent tail of core modes allowing the optical power to be absorbed by an absorbing chemical species that surrounds the cladding region. Such absorption reduces both core-mode power and cladding mode power as shown in Figs. 3 and 4, which enables a fiber with cladding to act as an evanescent wave chemical sensor. It should be noted that this explanation of the observed effect falls in line with that given in the case of microbent chemical sensing [15]. The method employed here differs from the conventionally used chemical sensing techniques employing LPG's where wavelength modulation takes place by the variations in the real part of the refractive index of surrounding medium. However, in the present case the basic mechanism behind the change in output intensity with concentration of MB dye is different. MB dye solution has a different refractive index than pure solvent, i.e., water. But the main contribution for this change will be from the imaginary part of the refractive index, which corresponds to the optical absorption. In the present case, this is due to the close match of the absorption peak of the MB dye with the propagating wavelength.

The fundamental equation that deals with evanescent wave sensing by conventional unclad fibers when power is assumed to be distributed equally among all the modes is given by [20]

$$\frac{P_{\text{out}}}{P_{\text{in}}} = \frac{1}{N}\sum_{v=1}^{N} \exp(-\alpha \eta_v C l), \tag{2}$$

where P_{out} is the output power, P_{in} is the input power of the fiber, N is the total number of modal groups where each value of N represent a group of modes having the same penetration depth, $\alpha = 1.09 \times 10^5$ mol^{-1} cm^{-1} is the molar absorption coefficient, η_v is the modal fractional power in the cladding for vth core mode and l is the interaction length between the evanescent field and absorbing species of concentration C. α is obtained by determining the absorbance of a known concentration and optical path length b of the dye, using a spectrophotometer (Jasco, V-570). However, in the present case some of the terms occurring in the above equation will have a slightly different meaning. It should be noted that, for a given wavelength, say 632.8 nm, all the core modes will not be coupled to cladding modes, but coupling takes place only for those modes which satisfy Eq. (1). Hence only a limited number of modes undergo core mode–cladding mode power coupling. η_v is the modal fractional power outside the cladding for vth cladding mode and $l = 1$ cm is the length of the grating region. In the present case a curve fitting done by assuming $\alpha = 1.09 \times 10^5$ mol^{-1} cm^{-1} and $l = 1$ cm gives the best curve fit

for $N = 25$ by taking different values for η_v. It can be seen from Figs. 3 and 4 that the theoretically obtained data by curve fitting fits fairly well with the experimentally observed data, which clearly establishes the validity of the given relationship. It is observed that the present sensor shows detectable output variation, even with a dye concentration of a few nmol/l.

4. Conclusions

To conclude, we have presented the performance of a very sensitive evanescent wave chemical sensor by creating long period gratings in a multimode step index fiber. To the best of our knowledge such a technique is not yet reported anywhere else. The output intensity is found to be approximately linearly dependent on the logarithm of concentration of the absorbing species surrounding the grating region of the fiber in both bright and dark field detection configurations. Moreover, the sensor is observed to be highly sensitive and can even detect very low concentrations of the order of 10 nmol/l using the dark field detection scheme. Furthermore, the dynamic range of operation is found to be greater than 4 orders of magnitude. A comparative study with a conventional unclad evanescent wave sensor reveals that the present sensor is superior in many aspects, such as short sensing length and use of double detection scheme to facilitate more reliable and accurate measurements.

Acknowledgements

The authors are grateful to NUFFIC, The Netherlands and AICTE, India for the partial financing of this work. The help rendered by Unnikrishnan K.P. for the fabrication of the gratings is acknowledged. The first author expresses his gratitude to CSIR, India for the research fellowship. V.P.N. is thankful to UGC (India) for financial assistance through a Research Award Project.

References

[1] G. Meltz, W.W. Morey, W.H. Glenn, Opt. Lett. 14 (1989) 823.
[2] T. Mizunami, T.V. Djambova, T. Niiho, S. Gupta, IEEE J. Lightwave Technol. 18 (2000) 230.
[3] O.S. Wolfbeis, Anal. Chem. 74 (2002) 2663.
[4] B. Culshaw, J. Dakin, Artec House (1996) 69.
[5] J. Dakin, B. Culshaw, Artec House (1997) 69.
[6] P.H. Paul, G. Kychakoff, Appl. Phys. Lett. 51 (1987) 12.
[7] V. Ruddy, B.D. MacCraith, J.A. Murphy, J. Appl. Phys. 67 (1990) 6070.
[8] B.D. Gupta, C.D. Singh, A. Sharma, Opt. Eng. 33 (1994) 1864.
[9] A. Messica, A. Greenstein, A. Katzir, Appl. Opt. 35 (1996) 2274.
[10] S.T. Lee, G. Jose, V.P.N. Nampoori, C.P.G. Vallabhan, N.V. Unnikrishnan, P. Radhakrishnan, J. Opt. A 3 (2001) 355.
[11] C.G. Askins, T.E. Tsai, G.M. Williams, M.A. Putnam, M. Bashkansky, E.J. Gfriebele, Opt. Lett. 17 (1992) 835.
[12] B. Malo, K.O. Hill, F. Bilodeau, D.C. Johnson, J. Albert, Electron. Lett. 29 (1993) 1668.
[13] V. Bhatia, A.M. Vengsarkar, Opt. Lett. 21 (1996) 692.
[14] H.J. Patrick, A.D. Kersey, F. Bucholtz, IEEE J. Lightwave Technol. 16 (1998) 1606.
[15] S.T. Lee, N.A. George, P. Suresh Kumar, P. Radhakrishnan, C.P.G. Vallabhan, V.P.N. Nampoori, Opt. Lett. 26 (2001) 1541.
[16] C.A. Villarruel, D.D. Dominguez, A. Dandridge, Proc. SPIE. 798 (1987) 225.
[17] T. Erdogan, IEEE J. Lightwave Technol. 15 (1997) 1277.
[18] P. Suresh Kumar, C.P.G. Vallabhan, V.P.N. Nampoori, V.N. SivasankaraPillai, P. Radhakrishnan, J. Opt. A 4 (2002) 247.
[19] P. Suresh Kumar, S. Thomas Lee, C.P.G. Vallabhan, V.P.N. Nampoori, P. Radhakrishnan, Opt. Commun. 214 (2002) 25.
[20] O.G. Saracoglu, S. Ozsoy, Opt. Eng. 41 (2002) 598.