Chemical sensing with microbent optical fiber

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Received May 29, 2001

We propose and demonstrate the possibility of using a permanently microbent bare optical fiber for detecting chemical species. Two detection schemes, viz., a bright-field detection scheme (for the core modes), and a dark-field detection scheme (for the cladding modes) have been employed to produce a fiber-optic sensor. The sensor described here is sensitive enough to detect concentrations as low as nanomoles per liter of a chemical species, with a dynamic range of more than 6 orders of magnitude. © 2001 Optical Society of America

OCIS codes: 060.2370, 060.2300.

Microbend loss has always been an undesirable effect that causes problems in fiber-optic communication links. However, this phenomenon has been exploited profitably in the fabrication of a variety of fiber-optic sensors[1–5] to measure, e.g., pressure, temperature, and displacement. Essentially, microbend sensors are based on coupling and leakage of modes that are propagating in a deformed fiber. Usually one achieves this deformation by employing corrugated plates that deform the fiber into a series of sharp bends with small bending radii. Such periodic bending causes coupling of energy among various guided modes as well as between guided modes and leaky modes; the latter causes a loss in transmission. In most cases these bends made in the fiber are temporary inasmuch as the deformations in the fiber will vanish if the pressure applied to the corrugated plates is removed, provided that the pressure applied is within the elastic range of the fiber. However, a few investigations have been carried out with permanent microbend fibers also.[6,7] But those studies were essentially an extension of what has been done with temporary microbend fibers and were used mainly for measuring physical parameters. It would be interesting to examine the losses in such a permanently bent fiber when it is subjected to various chemical environmental conditions. In the present Letter we describe the use of such a permanently deformed fiber for the development of a chemical sensor.

We introduce a series of permanent microbends into a bare plastic multimode step-index fiber of 30-cm length and a numerical aperture of 0.3 by sandwiching the fiber with a pair of corrugated plates and applying sufficient pressure, as shown in Fig. 1. The pitch of the corrugations is 1 mm, and the total length of the plates is 60 mm. In the research reported in this Letter we use such a permanently bent optical fiber to detect those chemical species that have optical absorption at the operating wavelength. A schematic diagram of the experimental setup is shown in Fig. 2. The bent portion of the fiber is immersed in a cell containing Methylene Blue (MB) dye in water, the absorption peak of which is at 664 nm. This value is near the operating wavelength of the diode laser (670 nm, 5 mW) that is used to power the sensor. To detect the cladding modes we surround the cladding of the optical fiber just beyond the bent portion with index-matching liquid, which acts as the sensing region. The power carried by the core modes and that carried by the cladding modes in the fiber sensor are independently measured for various concentrations of MB dye by two powermeters, D_1 (Metrologic 45-545) and D_2 (Newport 1815-C).

The measurements are carried out in two detection configurations. The first one is the bright-field detection scheme in which we measure the core mode's intensity by using detector D_1.[2] Figure 3 shows the variation of core mode intensity from the microbent fiber as a function of the logarithm of concentration of the absorbing species (MB dye) surrounding the bent portion of the optical fiber. From the figure it is clear that the dynamic range of the sensor is ~6 orders of magnitude. The observed effect may be explained as follows: It has been proved theoretically[8] as well as experimentally[9] that, when periodic microbends are induced along the fiber axis, light is coupled between modes with propagation constants k and k', satisfying the relationship

$$k - k' = 2\pi/\Lambda\,, \tag{1}$$

where Λ is the distance between two consecutive deformations, which is 1 mm in the present case. Conventional microbend sensors work on the principle that, when a fiber is subjected to squeezing between a pair of corrugated plates, a loss of transmitted intensity takes place as a result of mode coupling

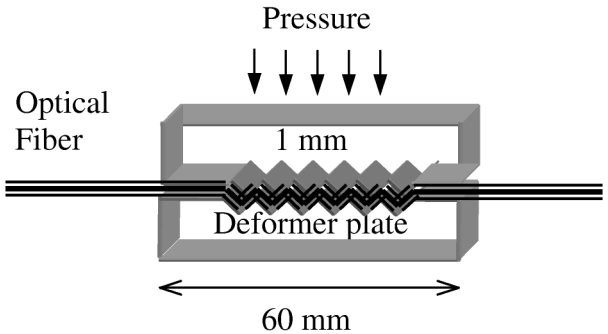

Fig. 1. Schematic diagram of the setup used to deform the optical fiber.

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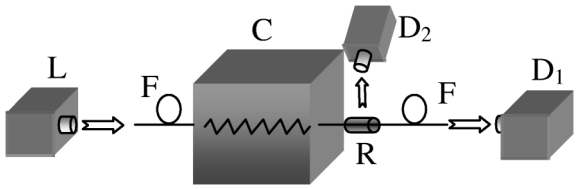

Fig. 2. Schematic diagram of the experimental setup: L, diode laser (670 nm); C, cell containing MB in water; Fs, optical fibers; R, index-matching liquid; D_1, detector 1 (Metrologic 45-545); D_2; detector 2 (Newport 1815-C).

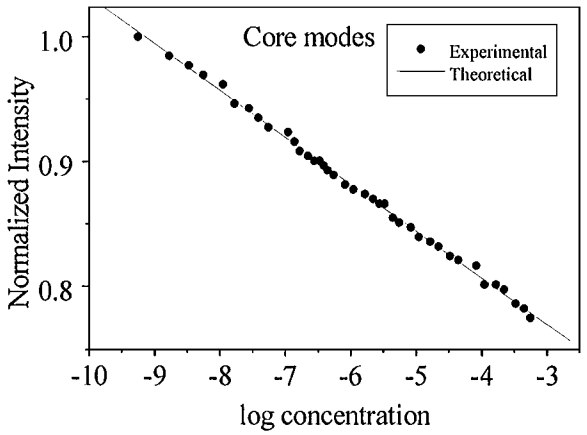

Fig. 3. Core-mode intensity variation with dye concentration.

between guided modes that consist of the core and leaky modes that comprise both cladding modes and radiation modes. The radiation modes will leak out of the fiber core as well as cladding, into the surrounding medium; the cladding modes will travel through the fiber. A similar kind of behavior has already been reported for long-period grating fibers; the dependence of the cladding field on the refractive index of the surrounding medium has been described.[10] The functioning of this sensor can be attributed to the absorption of an evanescent wave that penetrates from the cladding to the surrounding medium. Hence the behavior of this sensor may be similar to that of an evanescent-wave fiber-optic sensor, which is usually fabricated by removal of the cladding from a portion of the optical fiber.

The intensity of light transmitted through a conventional uncladded multimode fiber that is immersed in an absorbing fluid obeys the relationship[11]

$$P = P_0 \exp(-\gamma CL), \tag{2}$$

where P and P_0 are the power transmitted through the fiber with and without an absorbing liquid over the uncladded portion, respectively. γ is the molar evanescent-wave absorption coefficient [$\mathrm{mol}^{-1}\ \mathrm{cm}^{-1}$] given by $\gamma = r_f \alpha_m$, where r_f is the effective fraction of the total guided power in the sensing region and α_m is the molar absorption coefficient of the absorbing species. C is the concentration of the absorbing medium, and L is the length of the sensing region, which is usually a constant. The fraction r_f could be different for different modal groups, so an expression of the form of Eq. (2) will give a better fit with the experimental results:

$$P = P_0[\exp(-\gamma_1 CL) + \exp(-\gamma_2 CL) + \exp(-\gamma_3 CL)], \tag{3}$$

where γ_1, γ_2, and γ_3 are three effective molar evanescent-wave absorption coefficients. Fortunately, this kind of behavior makes it possible for the sensor to act as a logarithmic detector with a fairly large dynamic range, as shown in Fig. 3. However, the mode-coupling process is a reversible phenomenon, so the power transferred to the cladding modes will again be coupled back to the core modes.[12] The radiation intensity thus coupled back will depend on the absorption of the medium that surrounds the cladding. This recoupling of the cladding-mode power is considered to be the major contributing factor to the observed effect of variation of guided-mode intensity with change in absorbance of the surrounding medium.

It should be noted that the amount of power recoupled from cladding modes to core modes need not be 100%. Hence beyond the sensing region some power will be transmitted through the fiber as cladding modes also, and such power is utilized for detection in the second configuration; this is the dark-field detection scheme. To detect the power carried by the cladding modes, we surround the bare optical fiber just beyond the sensing region with an index-matching liquid. A part of the power that leaks out through the index-matching liquid is detected by detector D_2. Figure 4 shows the dependence of the intensity of the cladding modes on species concentration. It can be clearly seen that the sensitivity with the dark-field detection scheme is high, in the concentration range 10^{-7} to 10^{-5} mole/L, compared with the result for the bright-field detection technique. Within this range the agreement with the theoretical model is good, though outside this range deviations begin to appear. This result is presumably due to the fact that significant radial anisotropy exists for the cladding modes beyond the microbends, which are all in a single plane. Comparison of Fig. 3 with Fig. 4 shows that

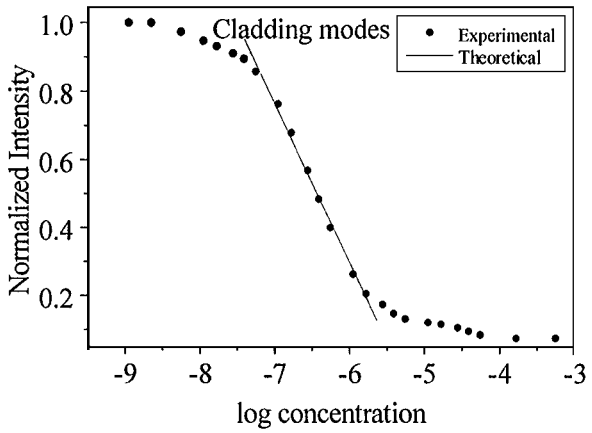

Fig. 4. Cladding-mode intensity variation with dye concentration.

the bright-field detection configuration has a larger dynamic range.

In conclusion, we have demonstrated a simple technique for fabricating a highly sensitive chemical sensor by inducing permanent microbends on a bare plastic optical fiber. To the best of our knowledge such a sensing scheme is reported here for the first time. The output intensity is found to be linearly dependent on the logarithm of concentration of the absorbing species surrounding the bent portion of the fiber. Moreover, the sensor is found to be highly sensitive and can even detect very low concentrations, of the order of nanomoles per liter. The dynamic range is found to be greater than 6 orders of magnitude. The results show that this new present sensor is far more sensitive than the conventional evanescent-wave fiber-optic sensor and can replace the latter in many sensing applications. The technique described here has the added advantage that it is a double detection scheme that is different from the conventional single detection schemes. Hence the accuracy and reliability of measurement with this fiber sensor are much greater than those offered by most the conventional sensors. We observed that with suitable reagents the microbend sensor can detect traces of nitrites and iron; we intend to report these results elsewhere. Further, we have verified a similar kind of behavior for unsheathed multimode plastic-clad silica fiber.

The authors are grateful to Holmarc Pvt. Ltd. (Cochin, India) for providing some of the components required for the experiments. T. Lee S expresses his gratitude to the Council of Scientific and Industrial Research (New Delhi) for the financial support. The authors are grateful to Netherlands Universities Funding for International Collaboration for partial financing of this project. T. Lee S's e-mail address is lee@cusat.ac.in.

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