Optics Letters, 2001 December, Vol. 26, Issue 23, pp. 1840-1842

Sub-micron Fiber Optic Fabry-Perot Interferometer formed by the Langmuir-Blodgett Technique.

N.D.Rees[*], S.W.James*, S.E.Staines*, [**]G.J.Ashwell and R.P.Tatam*.

[*]Optical Sensors Group, and [**]Nanomaterials Group
Centre for Photonics and Optical Engineering, School of Engineering, Cranfield University, Cranfield MK43 0AL, UK
Tel: +44-1234-754630 Fax: +44-1234-750728
Email: r.p.tatam@cranfield.ac.uk

ABSTRACT

The fabrication of an optical cavity at the distal end of an optical fiber has been achieved by Langmuir-Blodgett (LB) deposition of tricosanoic acid, the technique allowing nanometer-scale control over the cavity length to a total thickness of ca. 0.5 μm. The cavity has been shown to act interferometrically and, thus, has potential sensing applications.

Keywords: fiber optic Fabry-Perot; interferometer; Langmuir-Blodgett.

Fabry-Perot interferometers formed at the end of optical fibers have been used as sensor elements to measure a range of measurands including temperature, vibration and pressure[1]. Particularly attractive are the short gauge lengths that provide high spatial resolution and the potential for fast response to external measurands. Several methods have been reported for the fabrication of an optical cavity, where the cavity material may be air, metal or an organic film, on the end of an optical fiber[2]. In general it is difficult to obtain high precision in the film thickness for short cavities (< 2 μm), but a recently reported method, using ionically self-assembled monolayers[3] (ISAM) has demonstrated thickness control of *ca.* 5 nm layer^{-1} to a total film thickness of 1 μm.

In this letter, we present an alternative to the ISAM process for fabricating multilayer films with nanometer thickness control. The method is based on the Langmuir-Blodgett (LB) technique which allows the layer-by-layer deposition of multilayer structures [4-6] and control of the thickness at the molecular level. It also permits the cavity to be fabricated from a single chemical species, this homogeneity not being available to other fabrication techniques, such as ISAM[3], which require alternate layers of oppositely charged materials.

Previously we have shown that LB films can be deposited onto *side*-polished optical fibers to form overlay waveguides[7]. These have been shown to act as wavelength filters[8], chemical sensors[9] and to offer an effective method for generating waveguide second-harmonic generation in non-centrosymmetric films[10]. In this letter we report the deposition of LB multilayers on the *end* of an optical fiber, thus forming an optical cavity in which the optical fiber/LB interface forms the first mirror (M_1), and the LB film/air interface forms the second mirror (M_2).

From the Fresnel equations, the reflectance (R_i), at M_1 and M_2 are given by:

$$R_1 = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \qquad\qquad R_2 = \frac{(n_3 - n_2)^2}{(n_3 + n_2)^2} \tag{1}$$

where the effective refractive index of the fiber-core is n_1, the cavity is n_2, and air is n_3. Figure 1 shows a schematic of the optical cavity and the refractive index designations. In general, if the molecular length is l and the number of bilayers is m, then the cavity length is $d = 2\ m\ l \cos\theta$, where θ is the tilt angle of the molecules when deposited onto the substrate. The optical phase change experienced by light undergoing a double pass through the cavity is

$$\varphi = \frac{4\pi n_2 d}{\lambda} \tag{2}$$

where λ is the free space wavelength of the source.

From Fabry-Perot theory, assuming a $\pi/2$ phase shift between transmitted and reflected waves (valid strictly only for lossless mirrors), the ratio of reflected to transmitted amplitude, r_{FP}, summing over multiple passes through the cavity[11] is

$$r_{FP} = jr_1 + jr_2 \; t_1 t_1 \exp^{-2\alpha d} \exp^{j\varphi} \sum_n (r_1 r_2 \exp^{-2\alpha d} \exp^{j\varphi})^n \tag{3}$$

assuming $ja r_i$ and $a t_i$ to be the reflected and transmitted amplitudes at each mirror, (where a is the amplitude coefficient), and $\exp^{-2\alpha d}$ is the attenuation due to each double pass of the cavity. As the fabricated cavity has low reflectance at both M_1 and M_2, in the limit as r_1 tends to zero, the transfer function will be cosinusoidal, of the form

$$I \approx I_0 (1 + V \cos\varphi) \tag{4}$$

where V is the visibility, as in a dual beam interferometric arrangement.

The cavity material, tricosanoic acid [$CH_3(CH_2)_{21}CO_2H$], was spread from dilute chloroform solution (0.1 mg cm^{-3}) onto the pure water subphase of one compartment of a Nima Technology LB trough (model 2022), left for 10 min at *ca.* 20^{o}C, and compressed at 0.5 cm^{2} s^{-1} (*ca.* 0.1 % s^{-1} of total surface area). Transfer on to the end of the fiber was achieved by vertical deposition, at a surface pressure of 30 mN m^{-1} and a rate of 1 cm min^{-1}. The fiber was alternately raised and lowered through the floating monolayer, with its cleaved face orthogonal to the plane of the film, using a modified dipper mechanism. Y-type structures, in which the amphiphilic molecules pack head-to-head and tail-to-tail, (Figure 2), were obtained by multiple passes through the film.

The experimental layout shown in Figure 1 was used to monitor the formation of the cavity, the light source being a super-luminescent diode with a central wavelength of 830 nm and a 3 dB bandwidth of 30 nm. This was coupled to the cavity via a 3 dB directional coupler using single mode optical fiber (Fibercore PS750, cut-off wavelength 730 nm). As the cavities formed were of the order of 1 μm in length, a broad band source with a coherence length of 15 μm was sufficient to monitor their fabrication. The optical power of the source and the reflected signal from the cavity were monitored on separate matched photo-detectors. Following the deposition of each bilayer, at an incremental thickness of *ca.* 5 nm, the ratio of the reflected to incident intensity was recorded. This ratio is plotted versus number of bilayers in Figure 3.

The reflected signal varies with the cavity thickness, having a period of ~ 49 ± 1 bilayers, assuming transfer upon every pass through the floating monolayer, and clearly showing the interferometric nature of the cavity, (Figure 3). From this period and the refractive indices of fatty acids, i.e. $n = 1.43 \pm 0.02$ from reflectometry studies[12], the calculated thickness is 2.9 ± 0.2 nm layer^{-1}. This is in reasonable agreement with the thickness from X-ray synchatron diffraction measurements[13], i.e. 2.68 nm layer^{-1} for films deposited under identical conditions on to silicon wafers. In this case, the slight difference may result from variations in the thickness when films are deposited on to large planar substrates and the end of an optical fiber.

The optical fiber data are similar to those reported for ISAM[3], showing attenuation with cavity thickness owing to absorption and scattering within the film. There is some asymmetry, (Figure 3), probably resulting from incomplete deposition of the multilayer, and this should affect thickness calculations. Assuming transfer upon every pass through the floating monolayer, 96 bilayers were deposited to a cavity thickness *ca.* 0.5 μm.

The visibility is dependent on the refractive index difference between the LB/fibre and LB/ air interfaces. In this experiment the refractive index of the LB film was approximately 1.43 giving a theoretical visibility of approximately 0.06. The measured visibility is approximately 0.03. The discrepancy arises due to the difficulty in obtaining accurate refractive index values for the fibre and LB film at the wavelengths used and also due to scattering loses in the cavity. Future work will investigate materials with with higher refractive indices to create cavities with higher visibility. Knowledge of the dispersion of the material would allow the cavity to be monitored at different wavelengths and thus facilitate signal processing of the cavity when deployed as a sensing element. The facility to control the optical thickness of the cavity on a nanometer scale permits the formation of high spatial resolution optical fiber sensors and the potential for sensors with fast response times.

In addition to the above, LB film-forming materials may be designed to form non-centrosymmetric films and change their optical characteristics when reacting to a particular chemical species. Such materials have been synthesised and deposited on side-polished optical fibers[7-10]. Using the technique presented here, optical cavities of such materials could be fabricated on the end of an optical fiber opening up the potential for non-linear optics based sensing.

In this letter, the deposition using the LB technique of tricosanoic acid with an estimated thickness of 2.9 nm layer^{-1} has allowed the fabrication of an optical cavity *ca.* 0.5 μm in length at the end of an optical fiber. The LB technique permits nanometer-scale control over the cavity length. The cavity has been shown to act interferometrically. This technique may facilitate the fabrication of novel optical sensing devices with high spatial resolution.

We are grateful to Dr. I.R.Gentle (University of Queensland) for calculating the layer thickness of the LB film from the X-ray synchatron diffraction data and the

Engineering and Physical Sciences Research Council (EPSRC), UK for financial support.

REFERENCES

---

1 D.A.Jackson, Meas. Sci. Technol. **5**, 621 (1994)

2 E.Udd *Fiber Optic Smart Structures* Wiley Interscience NY (1994)

3 F.J.Arregui, I.R.Matais, Y.Liu, K.M.Lenahan and R.O.Claus, Opt. Lett. **24**, 596 (1999)

4 A.Ulman, *An Introduction to Ultrathin films: from Langmuir-Blodgett to Self-Assembly,* Academic Press, San Diego, (1991)

5 M.C.Petty, *Langmuir-Blodgett Films: an Introduction,* Cambridge University Press, (1996)

6 G.J.Ashwell, J.Mater.Chem. **9**, 1991 (1999)

7 R.B.Charters, S.E.Staines and R.P.Tatam, Opt. Lett. **19**, 2036 (1994)

8 R.B.Charters, A.P.Kuczynski, S.E.Staines, R.P.Tatam and G.J.Ashwell, Electron. Lett. **30**, 594 (1994)

9 D.Flannery, S.W.James, R.P.Tatam and G.J.Ashwell, Opt. Lett. **22**, 567 (1997)

10 S.S.Johal, S.W.James, R.P.Tatam and G.J.Ashwell, Opt. Lett. **24**, 1194 (1999)

11 C.E.Lee, W.N.Gibler, R.A.Atkins and H.F.Taylor, J. Lightwave Technol. **10** 1376 (1992)

12 CRC Handbook of Chemistry and Physics (69th Edition) (1988-1989) Ed. R. C. Weast C.R.C Press Florida USA

---

13 I.R.Gentle, personnal communication to G.J.Ashwell.

Captions to Figures

Figure 1

(a) Experimental setup, where SLD is a superluminescent diode light source, OPM 1 and OPM 2 are the inputs of a dual channel optical power meter, C is the 3 dB directional fiber coupler and the cavity is fabricated using the LB trough. (b) The cavity formed at the end of the fiber, and the designated refractive indices.

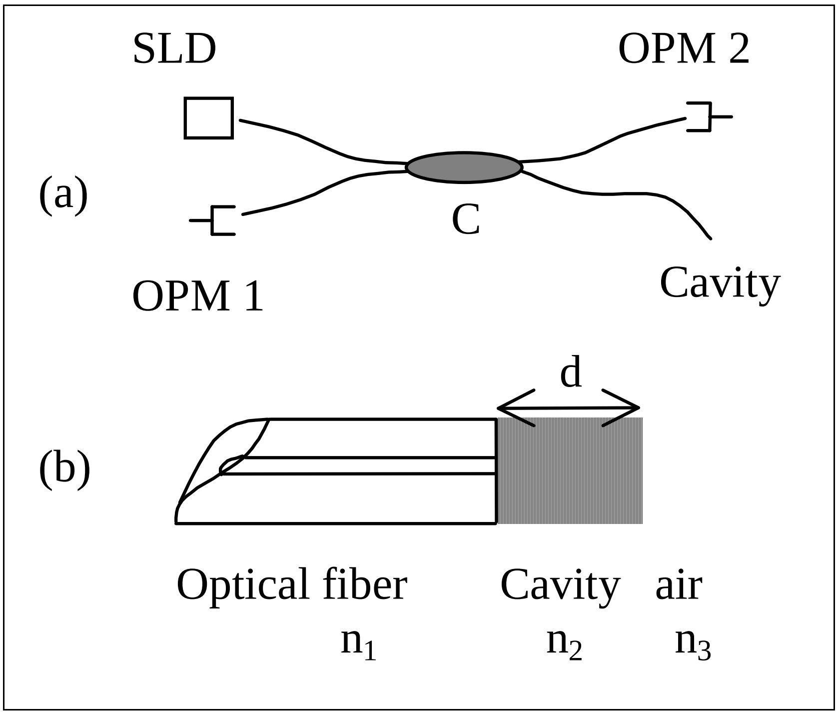
Figure 2

The Langmuir-Blodgett technique (a) a monolayer film of aliphatic molecules – represented by hydrophilic circles and hydrophobic rods - is formed on the pure water surface. (b) The fiber is passed up through the film, depositing one layer. (c) Deposition of the seventh layer after six passes though the film.

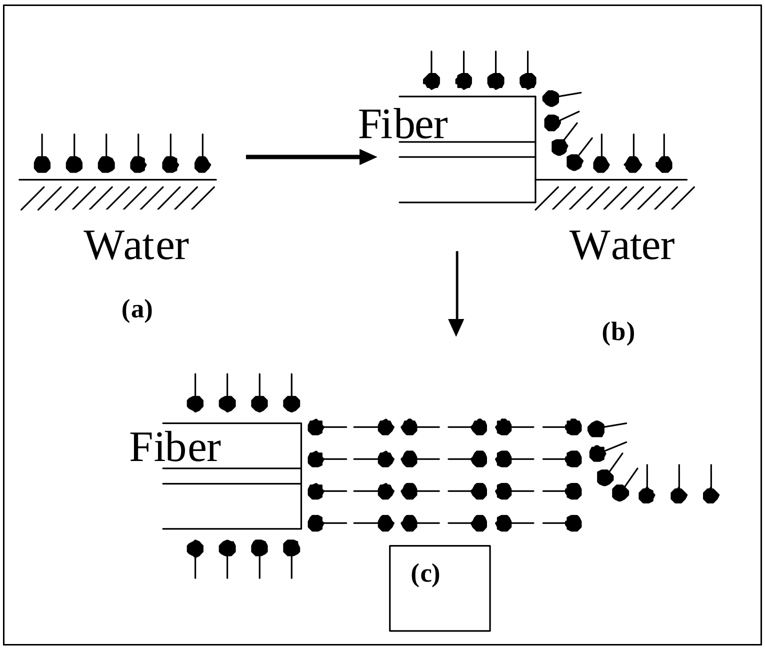
Figure 3

Plot of reflected optical power against number of bilayers deposited.

(top) Figure 1, N.D.Rees, Optics Letters



(top) Figure 2, N.D.Rees, Optics Letters



(top) Figure 3, N.D.Rees, Optics Letters