DIRECTIONAL COUPLER SENSOR USING A LOW-INDEX FLUOROPOLYMER ISOLATION LAYER

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A novel integrated optical sensor based on an asymmetric directional coupler structure is described. A patterned low-index fluoropolymer film is used to define the sensing region. The response of the device with respect to small changes in refractive index is demonstrated, and its potential for detecting antibody-antigen reactions is considered.

Introduction

Integrated opical devices are increasingly finding application in the area of chemical sensor/biosensor technology. When used as transduction elements for specific bioreactions (such as antibody-antigen binding) the potential exists for the creation of highly sensitive, rugged and portable sensors capable of rapid screening or accurate quantitive assessment of a vast range of possible analytes. Integrated optical sensors reported so far include those based on the Mach-Zehnder Interferometer[1] and on surface plasmon resonance[2]. The present performance of MZI devices appears to be limited by the lack of suitable low-index isolation layers. Here, we describe a new type of sensor based on the directional coupler; this sensor has the advantage of two outputs, resulting in improved signal/noise characteristics and the potential to provide simultaneous measurement of both the real and complex components of the refractive index of an analyte. Devices were fabricated in BGG31 glass using Ag^+ - Na^+ ion-exchange, and a new low-index fluoropolymer material (Teflon AF 1600) was deposited and patterned for use as the isolation layer. We report measurements on the characteristics of a device with respect to changes in the refractive index, and consider the response of the device to the addition of a monomolecular layer on its surface such as would occur during antigen-antibody binding in an aqueous environment.

Operating principle

The operation of the directional coupler sensor is based on adjusting the coupling condition via a sensing layer above one of the guides, which changes its effective index with respect to the second guide which has a protective cover layer and is not affected by the medium in which the sensor is immersed. Information on the sensing reaction is obtained by measuring the intensity and distribution of power at the two outputs of the coupler. The structure of the device is shown in Figure 1.

Sensor design

If a difference in propagation constant between the two guides of a directional coupler is introduced and the input waveguide is guide 1 (Figure 1), then, from coupled mode theory, the output power from guide 2 is given by

$$P_2 = \frac{\sin^2[\sqrt{(\kappa L)^2 + (\Delta\beta L/2)^2}]}{1 + (\Delta\beta/2\kappa)^2}$$

where $\Delta\beta = \beta_1 - \beta_2$ is the difference in propagation constants, L is the length of the device and κ is the coupling coefficient, which expresses the strength of the coupling between the two guides and depends on the overlap between the two modal fields[3]. It can be seen from the above equation that the maximum power coupled to guide 2 is reduced as the difference in propagation constant increases, and the coupling length changes. The power emerging from guide 1 is given by $P_1 = 1 - P_2$. Complete power transfer (assuming $\Delta\beta = 0$) occurs at $\kappa L = \pi/2$, $3\pi/2$, $5\pi/2$ etc, with values above $\pi/2$ corresponding to light coupling fully between the guides more than once over the length L. However, the case $\kappa L = \pi/2$ shows the most rapid change of output with $\Delta\beta$; this case was therefore chosen for the sensor design. Note also that large values of L are also advantageous. Further, the maximum of sensitivity is achieved at the point of maximum slope of the main peak of the power curve; it is therefore necessary to shift the operating point of the device to near this position. This can be achieved by introducing an initial difference in propagation constant $\Delta\beta$ by varying the width of one of the guides. The asymmetry due to the initial difference in superstrate index for the two guides also has to be considered in the calculation; in some cases (as in the example below) this asymmetry is sufficient to shift the operating point by the required amount, and the widths of the two guides can be the same.

The change in effective index of a waveguide with respect to superstrate index is greater for TE polarization and greater the more symmetric the guide in the depth direction[4]. For the latter reason, a low index glass, BGG31 (n = 1.4722 at 632.8 nm), was chosen as substrate; further, the surface index change of waveguides formed in this glass following ion-exchange is controllable by varying the $AgNO_3/NaNO_3$ melt composition[5]. The choice of this glass, however, imposes a limited choice of possible isolation layers, as the index of the layer must be less than that of the waveguide. After some investigation, a new material, Teflon AF 1600 amorphous fluoropolymer (n = 1.31 at 632.8 nm) was found to have suitable optical properties[6].

Taking the above considerations into account, devices were modelled fully using CAOS BPM (Beam Propagation Method) software[7], which is able to analyse coupling between ion-exchanged waveguides. The wavelength of operation of the device was chosen for convenience as 632.8 nm and the interaction length L was set at 10 mm. Y-junctions were incorporated into the inputs of the devices to split the input signal and provide a reference to compensate for variations in input coupling. BGG31 glass and parameters for the refractive index profiles of ion-exchanged waveguides in this glass were supplied by IOT (Waghausel, Germany).

Device fabrication

Directional coupler structures were fabricated in BGG31 glass using titanium as the masking material for the ion exchange. The waveguide patterns were produced in the titanium using standard photolithographic techniques and etching. The ion-exchange took place in a 10 mol% $AgNO_3/NaNO_3$ mixture at 310°C; the exchange time was 450 s. This melt composition produces a surface index change of 0.011. Following mask removal, an 800 nm thickness layer of Teflon AF 1600 was deposited
by thermal evaporation[8] and patterned using a liftoff technique to open windows of dimensions 150 μm x 10 mm over one of the coupler waveguides as shown in Figure 1.

Results and discussion

Figure 2 shows the variation of output power from each output of a directional coupler sensor as a function of superstrate index. The dimensions of the coupler in this example were: $w_1 = w_2 = 3\ \mu m$, $s = 7.4\ \mu m$. Chopped TE polarized light from a feedback-stabilized He-Ne source was coupled into the device via a microscope objective; the three outputs (including reference) were expanded using another objective and measured simultaneously using three photodiode detectors and lock-in amplification. A flow cell was clamped to the device. Solutions of various refractive indices were pumped around the system using a peristaltic pump. Distilled water with added sucrose (0 - 25% by weight) was used to obtain indices in the range 1.334 to 1.373; refractive indices were measured using an Abbé refractometer at 589 nm. A further point below the index of water was obtained by using methanol (n = 1.329).

The measured variation with index is comparable to that predicted using the BPM model, which is shown in Figure 3. The actual device is not quite at the optimum operating point and so displays slightly reduced sensitivity; it is possible to move the device to nearer the required point by slightly varying the device dimensions or by altering the operating wavelength. The measurements demonstrate that the device offers sufficient sensitivity to detect monolayers of biomolecules adsorbed on its surface. Figure 4 shows the predicted variation in output power of output P_2 as a function of layer thickness expected when a non-absorbing layer of index 1.4 is added to the sensing region; output P_1 will show a similar variation but the power will change in the opposite direction. The values of refractive index and thickness are chosen to be typical of this type of biological material.

Conclusions

A novel type of integrated optical sensor based on the directional coupler has been demonstrated. High sensitivity has been achieved through careful choice of substrate material and design parameters. The choice of substrate necessitated the use of a new low-index material (Teflon AF) as an isolation layer and the development of techniques to pattern it lithographically; this material should be useful in many other integrated optical applications. The use of the device for detecting antibody-antigen binding reactions has been considered.

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References

1. G. Gauglitz and J. Ingenhoff, Fresenius J. Anal. Chem., **349**, 355 (1994).
2. R. D Harris *et al*, submitted to ECIO 1995.
3. A Yariv, Optical Electronics, 4th ed. Saunders College Publishing (1991).
4. H. Kogelnik and V. Ramaswamy, Applied Optics, **13**, 1857 (1974).
5. L. Ross, Glastech. Ber., **62**, 285 (1989).
6. J. H. Lowry *et al*, Optical Engineering, **31**, 1982 (1992).
7. Dipartimento di Elettronica, Politecnico di Torino, Italy.
8. T. C. Nason, J. A. Moore and T.-M. Lu, Appl. Phys. Lett., **60**, 1866 (1992).

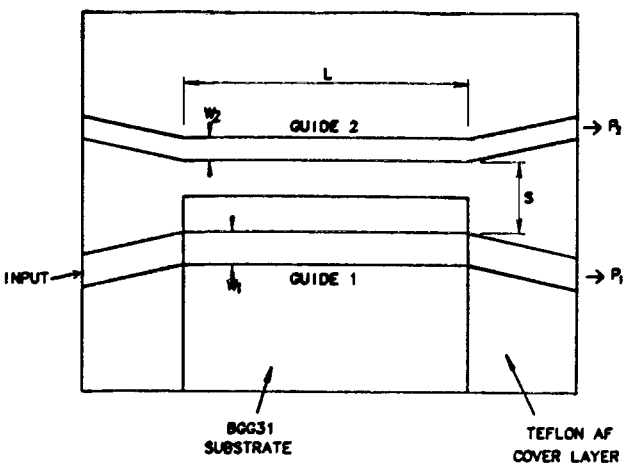

Figure 1: Structure of directional coupler sensor

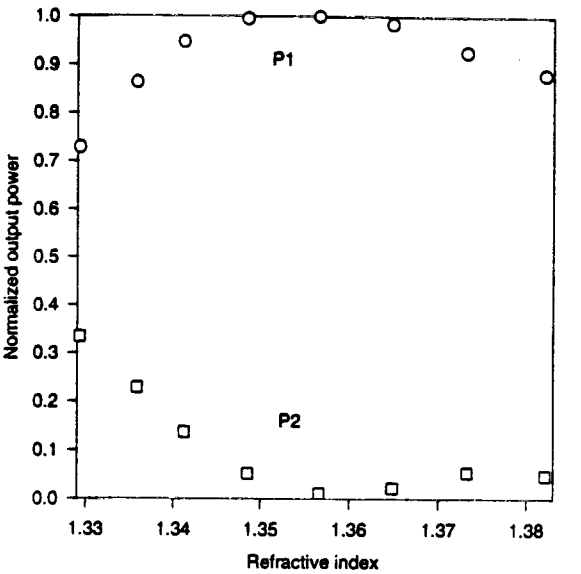

Figure 2: Measured variation of sensor output against refractive index

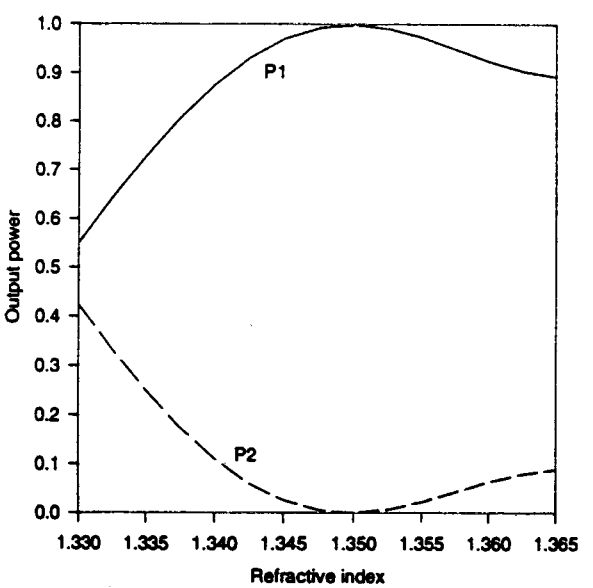

Figure 3: BPM simulation of sensor output against refractive index

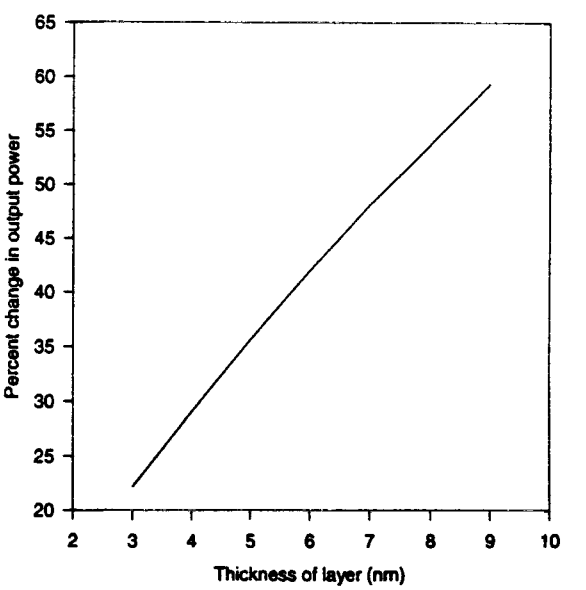

Figure 4: Calculated change in output power (P2) of a directional coupler sensor upon addition of a biolayer (n = 1.4)