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DETERMINATION OF COMPLEX REFRACTIVE INDICES OF ABSORBING MEDIA USING A DIRECTIONAL COUPLER

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Abstract

A method is presented for the simultaneous measurement of the real and imaginary parts of the refractive indices of absorbing media using an integrated-optical sensor.

Introduction

The principle of an integrated-optical sensor based on the directional coupler has been demonstrated for the determination of small changes of the refractive indices of non-absorbing bulk and thin-film media[1]. However, for applications such as the monitoring and production control of beverages in the food industry and the selective detection of analytes where changes in absorption properties are involved, it may be desirable to obtain information on the variation of both the real and imaginary parts of the refractive index. Through examination of the dual outputs of the directional coupler sensor we demonstrate that it is possible to determine both of these quantities in real time during a single measurement cycle.

Operating principle

The directional coupler sensor is illustrated in Fig. 1. The waveguides forming the coupler are single-moded at the wavelength of operation. A 'window' is present in the isolation layer material above one waveguide of the coupler (waveguide 1, with output labelled 1); refractive index changes taking place in the superstrate therefore affect the propagation constant of the mode of this waveguide while that of waveguide 2 (with output labelled 2) is unaffected. The coupling condition between the waveguides is therefore altered by index variations in the superstrate and thus the distribution of power between the two outputs changes. The waveguides of the coupler for this device are weakly coupled and so the behaviour of the sensor is described adequately for non-absorbing superstrate media by the coupled-mode theory of Taylor and Yariv[2]. A reference output for use in compensating fluctuations in input light intensity is provided in this design by splitting the light from the input using a y-junction.

The effect of superstrate media with varying complex refractive indices on the behaviour of this device was modelled using a commercially available simulation software package (CAOS) which combines the effective index method with a 2D beam propagation method (BPM) algorithm[3]. For these simulations, parameters were chosen to be representative of waveguides formed in BGG31 glass by ion-exchange ($n_{substrate}$ = 1.4722 at 633 nm, $\Delta n_{surface}$ = 0.0122) using the simplification of rectangular depth and transverse refractive index profiles; the wavelength of operation (λ) was taken as 633 nm and quasi-TE polarisation was assumed. The length of the coupling region was 10 mm, the waveguide widths and depths were 3 μm and 0.96 μm, respectively and the separation between the waveguide centres was 10 μm. Figs. 2 and 3 show the results of simulations for non-absorbing media and for media with absorption coefficients of 115 cm^{-1} at the operating wavelength.

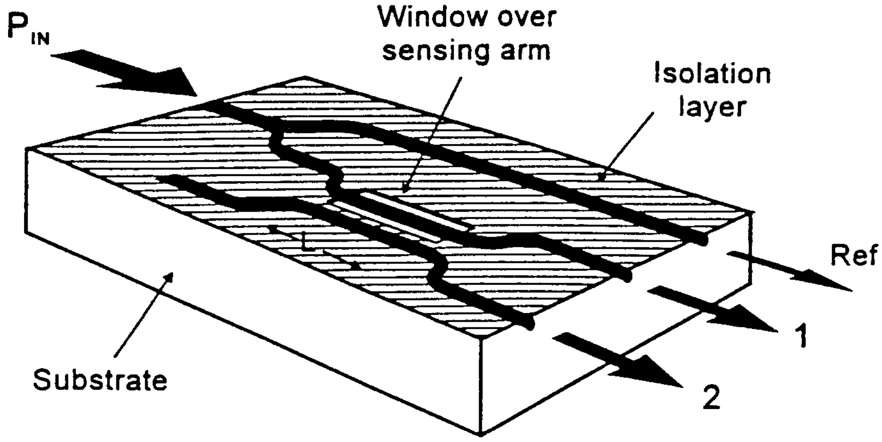

Figure 2 Directional coupler sensor.

The output powers from each waveguide (P_1 and P_2) are plotted versus the difference between the real parts of the refractive indices of analyte media (Δn) and that of the isolation material above waveguide 2 (assumed for the purposes of the model to have a refractive index of 1.33). The sums of the output powers from waveguides 1 and 2 ($P_1 + P_2$), representing the total transmission of power through the device, are also plotted. Fig. 2(a) shows the situation for input excitation of waveguide 1, while Fig. 2(b) shows that for input excitation of waveguide 2. The variation in total transmitted power is seen to be different between the two cases; for high asychronism between the effective indices of the modes propagating in the waveguides (large |Δn|) the values of transmitted power will tend towards maximum values for the case of Fig. 2(a) (because no coupling occurs and all power will be carried in the absorbing waveguide) and towards 1 for the case of Fig. 2(b) (all power carried in the non-absorbing waveguide).

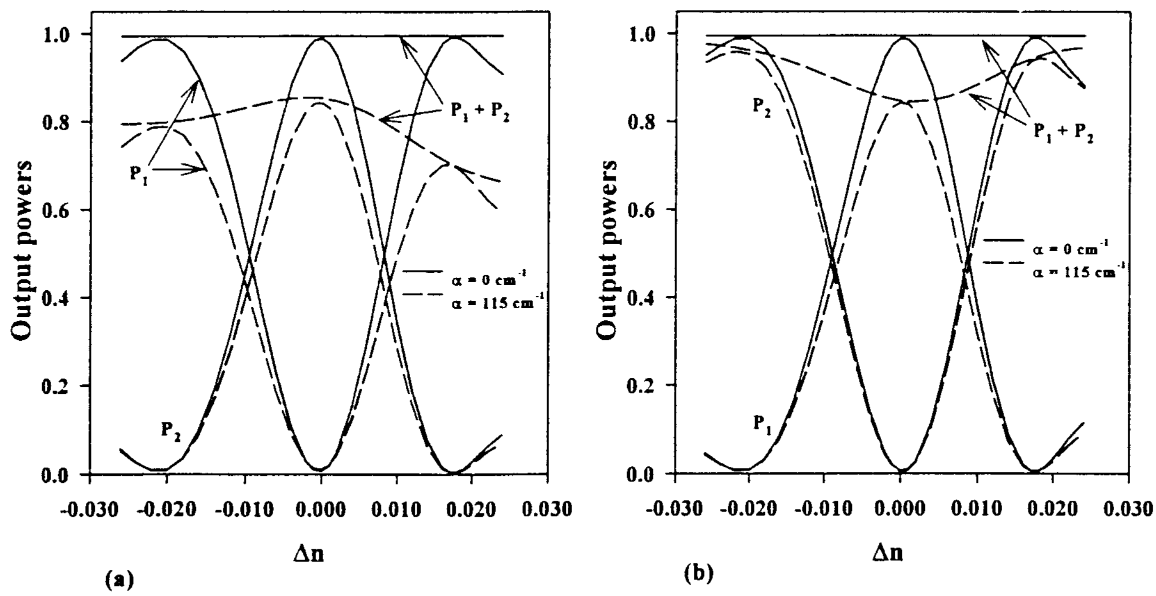

Figure 1 Simulation of the response of a directional coupler sensor to non-absorbing (α = 0 cm^{-1}) and absorbing (α = 115 cm^{-1}) media (a) with input power (P_{IN} = 1) into waveguide 1 and (b) with input power into waveguide 2.

Experimental

The device used for this work was fabricated by Ag-Na ion-exchange in a BGG31 glass substrate. A thermally evaporated polymer film derived from a Teflon FEP source (thickness 700 nm) was used as the isolation layer material; ellipsometric measurements determined the film index as 1.31 at 633 nm. The windows in the isolation layer (of dimensions 10 mm × 150 μm) were patterned using a standard resist liftoff technique. The width of waveguide 2 (w_2) was adjusted in order to obtain suitable coupling conditions for the analyte refractive index range of interest. In the

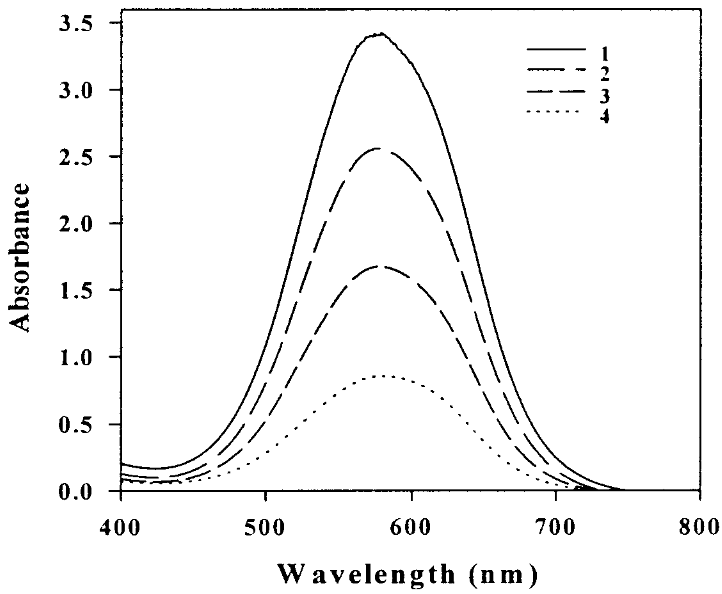

Figure 3 Absorption spectra of ink solutions used in the measurements (path length = 0.5 mm).

final design w_1 = 3 μm, w_2 = 3 μm, and the separation between the centres of the waveguides was 10.1 μm. TE-polarised light from a He-Ne laser (633 nm) was coupled into the device using a microscope objective and light from the three outputs focussed using another microscope objective onto three separate Si photodetectors. Data from the three device outputs were collected simultaneously and the coupler output values normalised to the reference signal.

A wall-jet flow cell was fixed on the sample and test solutions were introduced using a flow injection system. The test solutions used were mixtures of water-soluble blue ink (Quink), sucrose and water; by varying the concentrations of the ink and sucrose solutions a wide range of values of complex indices was obtained. The absorption spectra of the four concentrations of ink solution used (without any added sucrose) are shown in Fig 3. The absorption coefficients (α) at 633 nm were 101.4, 77.0, 50.2 and 25.9 cm^{-1}, respectively, for the concentrations 1- 4 shown in the figure. The imaginary parts of the indices corresponding to these values are 5.1×10^{-4}, 3.9×10^{-4}, 2.5×10^{-4} and 1.3×10^{-4}. After applying the ink/sucrose solutions to the sample for a measurement, the solution was washed from the sample using distilled water. The real parts of the refractive indices of the absorbing solutions were measured using a Abbe refractometer at 589 nm. Input power was coupled into waveguide 2.

Results

Figs. 4(a) and (b) show measured values of $P_1 + P_2$ and P_2 versus the real parts of the refractive indices of the test solutions for the four ink concentrations and for sucrose solutions alone (zero absorption). These plots follow qualitatively the behaviour expected from the simulations of Fig. 2(b). However, some absorption takes place for zero absorbance solutions; this is likely to be due to small amounts of absorbing material remaining on the surface of the waveguide after washing (the zero absorbance measurements were carried out last). The plots define values of the two

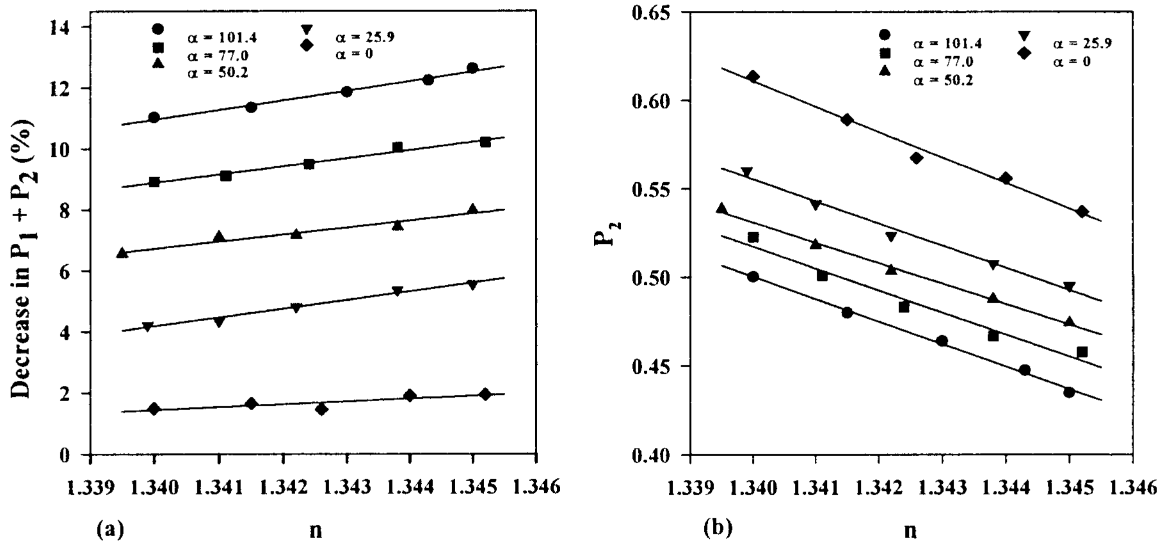

Figure 4 Measured values for the quantities $P_1 + P_2$ and P_2 for solutions of varying complex index; n is the real part of the index.

measured quantities ($P_1 + P_2$ and P_2) as functions of the real and imaginary parts of the complex refractive index; it is therefore possible to use these plots together as calibration curves and to determine the values of the real and imaginary parts of the complex indices of unknown solutions from the measured output powers.

Conclusions

We have demonstrated a method for for the determination of complex refractive indices of bulk media. The measurement can be carried out in real time and is also applicable to the determination of absorption changes in thin films, rendering it a potentially useful technique for a broad range of sensor applications. Further theoretical and experimental details will be discussed in the presentation.

References

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