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SENSITIVITY ENHANCEMENT OF INTEGRATED OPTICAL SENSORS BY THIN HIGH INDEX FILMS

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Abstract

Experimental measurements on waveguide Mach-Zehnder interferometers are presented which show that order of magnitude improvements in the sensitivity of planar waveguide sensors can be achieved by incorporating thin high index overlays.

Introduction

Integrated optics (IO) has increasingly found application in the field of chemical sensing [1]. A broad range of optical techniques for chemical analysis, based on absorption, refractive index variation, fluorescence and chemiluminescence for example, may be exploited and have the potential for great sensitivity. Integrated optics allows the fabrication of several different devices of one chip, offering the simultaneous measurement of several analytes, or of different optical parameters. The planar format of integrated optics is also convenient for the attachment of flowcells, enabling controlled measurements on fluid analytes.

Stewart et al. [2, 3] predicted that it would be possible to increase the sensitivity of methane gas sensors by overlaying D-fibres with high refractive index films — sensitivity enhancements of one or two orders of magnitude were predicted. It is desirable to achieve the same kind of enhancements with evanescent wave integrated optical devices. To investigate the feasibility of this approach, a similar computer model was established, allowing design of IO sensors, and devices were fabricated to measure the enhancement factor. Mach-Zehnder Interferometers (MZI's), used as refractometers, were selected as being suitable devices for testing the theoretical predictions. In this paper we report the fabrication of such interferometers incorporating high index films, and present experimental results using measurement of the refractive index of aqueous sucrose solutions to establish the sensitivity of these devices.

Theory

A computer model was constucted following the multilayer approach of Ghatak et al.[4]. Muller's method[5] was used to find the roots of the eigenvalue equation, rather than the method used in [4] of fitting Lorentzians to resonance peaks. The model was used to calculate the proportion of power in guided modes carried by the evanescent field in the superstrate region, which is directly related to the sensitivity of the effective index to bulk refrative index changes, and the change in this proportion caused by the addition of non-guiding films of various refractive indices and thicknesses. The model is of an infinite slab waveguide and as such cannot be expected to give more than qualitative predictions of the behaviour of channel waveguides. Figure 1 shows the waveguide geometry and mode profiles for the waveguide without an overlay (the dotted line) and with an overlay of 30nm of a material with index 2.1 for a wavelength of 633nm. Only the TE polarization is shown because the enhancement is much greater for the TE than the TM polarization.

The irradiance of each mode was integrated and arbitrarily normalized to $1\mu W/m$ width of guide. The power, per meter width of guide, being carried by the evanescent fields in the superstrate was calculated. The power enhancement factor was then calculated by ratioing this with the value for the non-overlaid waveguide.

Figure 2 shows the power enhancement factors predicted for a range of geometries. The curves in figure 2 only extend in the range where the effective index of the mode is less than or equal to the refractive index of the waveguide layer. This ensures that the mode is not being guided by the film, merely perturbed by it. The indices used in this model were selected as approximating those of a practical system. The thickness of the waveguide was selected as $1\mu m$ to give single moded operation over the range of overlays modelled for a wavelength of 633nm.

Experimental Setup

Channel waveguides were made by potassium ion exchange in soda-lime glass for 25 minutes at 400 ° C, giving waveguides which were single moded at 633nm wavelength. The devices that were tested consisted of a y-junction with a MZI on one arm and the other left as a reference, as illustrated by figure 3. Two samples were fabricated. Both were coated with 500nm ± 100nm of Teflon FEP as an isolation layer, with a 10mm-long window opened by lift-off over one arm of the interferometer. One slide had an intermediate step in fabrication during which 30nm ± 5nm of tantalum pentoxide (Ta_2O_5) was deposited on the surface of the slide in the region where the window in the Teflon was to be made. The Ta_2O_5 was deposited by reactive sputtering of tantalum in a mixed oxygen-argon atmosphere, yielding a film index of 2.1. The index of the film was determined by ellipsometric measurements of thicker films on separate samples.

Solutions of sucrose in de-ionized water of a range of concentrations were made to provide samples with a range of refractive indices. Samples were then pumped over the devices through a flow cell using a flow injection analyser (FIA), and the responses to index were measured by acquiring the signal and reference arm output powers on a PC. The refractive indices of the sucrose solutions were measured at 589nm wavelength using an Abbé refractometer. The de-ionized water has an index of 1.334 at this wavelength.

Results

Figure 4 shows the typical effect on the ratio of the two outputs of the Ta_2O_5 coated device of a pulse of sugar solution.

To obtain these plots a 'buffer stream' of de-ionized water was pumped through the system at constant speed and samples of sugar solution were injected into the flow. In figure 4 the trace can be seen to be initially flat corresponding to a continuous flow of de-ionized water. On injection of a test solution the output passes through one maximum and one minimum as the sugar pulse fills the flow-cell, settling to a fixed level in the centre of the sample pulse. Finally, the sample is washed out by the buffer-stream. Due to viscosity and diffusion the wash-out of the sample is slow, allowing easier counting of the number of oscillations and more accurate measurement of the maxima and minima.

From plots such as this, the phase shifts in the interaction region due to the test solutions were calculated for the different index changes, as shown in figure 5. Straight lines have been fitted to the data and comparison of the gradients shows that the overlaid device is approximately 15 times more sensitive than the non-overlaid device, in the TE polarization.

An interferometer with zero losses would result in plots such as that shown in figure 4 displaying full-scale excursion between 0 and 1. Clearly this is not the case, indicating that there are losses in the interferometer; as the ratio does not fall to zero it is clear that the Teflon window and high index film have, unsuprisingly, introduced significant losses, which are estimated to be $\sim$ 2dB. However this has not substantially compromised the operation of the sensor.

Summary

A computer model was constructed for waveguides with high index overlays which produced results in agreement with those of Stewart and Culshaw. This model was used to design IO interferometers with which to verify the theoretical approach experimentally. For the MZIs tested, an enhancement in sensitivity of 15 times was caused by addition of a 30nm film of Ta_2O_5. This supports the predictions of the computer model and suggests that it may be possible to obtain similar increases in the sensitivity of a broad range of integrated optical sensors employing evanescent fields. The device tested is a sensitive refractometer and could also be applied to biochemical sensing, for example, where thin films specific to the analyte of interest are attached to waveguide surfaces.

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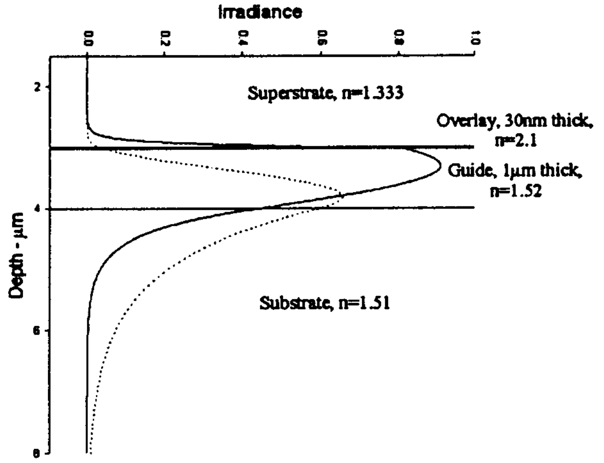

Figure 1: Examples of computed mode profiles for coated and uncoated waveguides

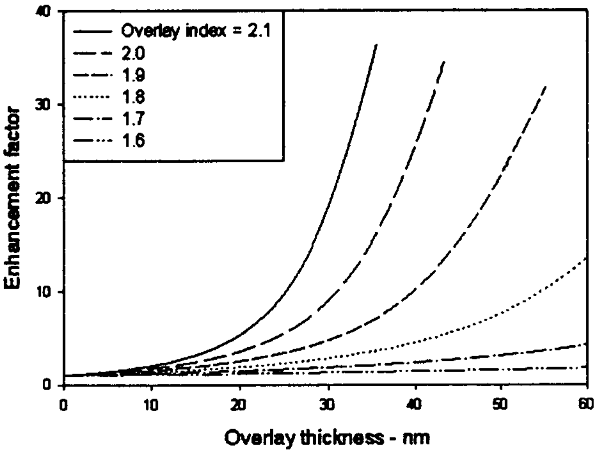

Figure 2: Enhancement of superstrate evanescent fields by films of different refractive indices

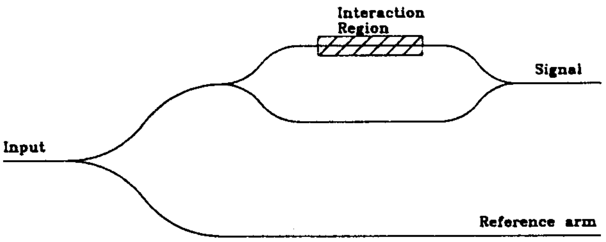

Figure 3: Schematic diagram of experimental IO device

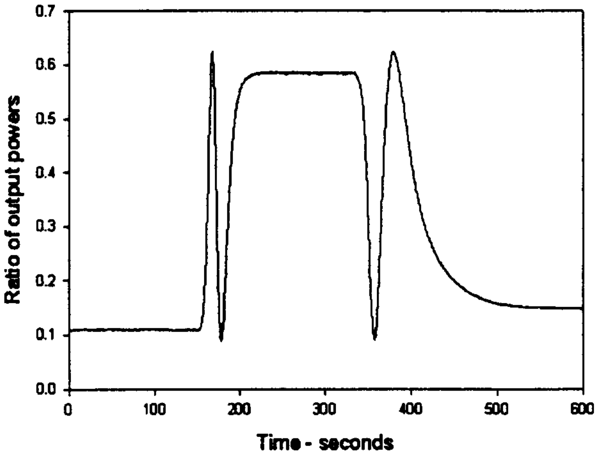

Figure 4: Response of interferometer to a pulse of sugar solution, n=1.338

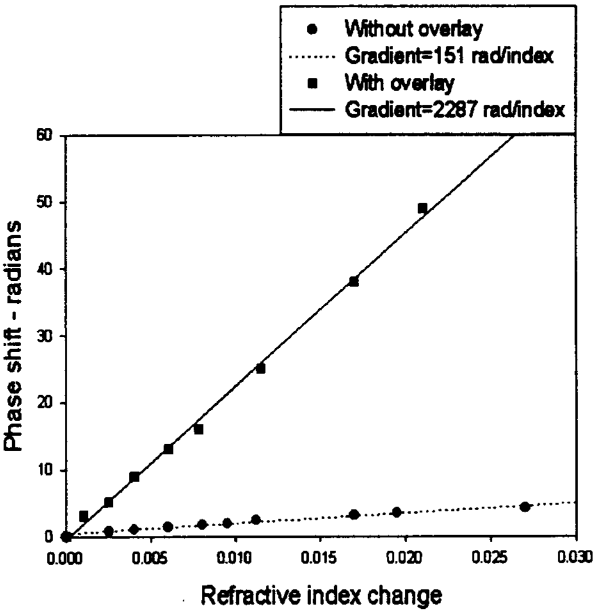

Figure 5: Change in phase of output of MZI with refractive index