16036

Integrated optical sensor utilising a 1D CCD array for multiple output addressing

B. J. Luff*, K. Kawaguchi† and J. S. Wilkinson*

*Optoelectronics Research Centre, University of Southampton, Southampton
SO17 1BJ, UK
† Kyoto Electronics Manufacturing Co., Ltd., 68 Ninodan-cho, Shinden, Kisshoin
Minami-ku Kyoto 601, Japan

Abstract. An inexpensive and robust method for acquiring multiple outputs from integrated optical sensor devices using a 1D CCD array is described in this paper. An example is given of the development of an instrument based on the use of an integrated optical Mach-Zehnder interferometer (MZI) refractive index transducer. The technique is especially promising for application to multianalyte sensors where several outputs need to be interrogated simultaneously. The high sensitivity and low noise demonstrated by the system will enable the use of cheap, stable LED light sources in practical instruments.

1. Introduction

Integrated optical transducers for the real-time measurement of interactions between biological molecules and for the specific detection of chemical and biochemical species are the subject of growing interest. Applications of this technology include environmental pollution monitoring, industrial process control and medical diagnostics. Integrated optical sensors provide the high detection sensitivity achievable using optical transduction techniques in a compact and robust format. This approach also offers advantages for the fabrication of multianalyte sensors through the integration of multiple transducers on a single chip by straightforward scaling of the photolithographic production process. Several types of integrated optical sensor have been described (e.g. [1-3]), but no commercially viable multianalyte system currently exists and, in order to fully exploit this technology in practical instrumentation, inexpensive and reliable techniques for addressing the multiple outputs of waveguide devices must be found. Fibre-to-chip pigtailing of integrated optical devices formed in 'passive' materials such as glass, where it is difficult to truly integrate monolithic light sources and detectors, is not the best solution when dealing with multiple outputs due to the necessity of producing and pigtailing fibre arrays. For single input devices, however, fibre input coupling is still a viable option as only a single pigtail needs to be made.

In this paper we present measurements on multiple-output integrated optical sensor

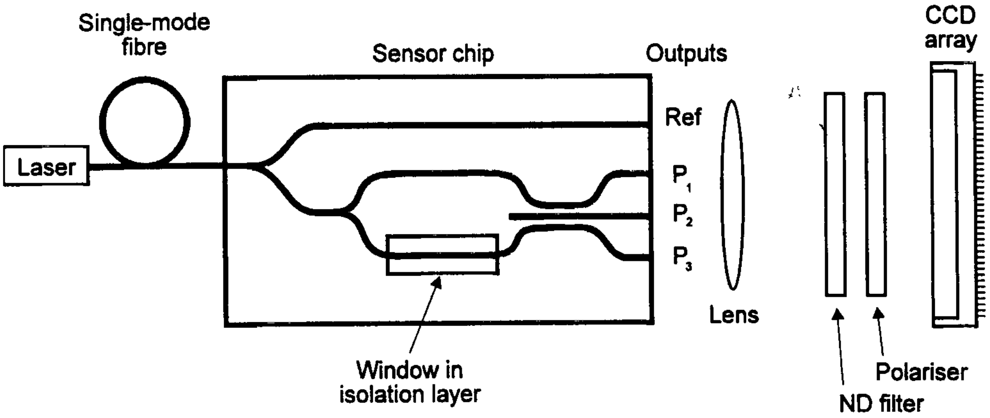

Figure 1 Experimental sensor system

devices using fibre input coupling and a cheap, readily available, 1D CCD array detector to simultaneously address all outputs. A lens is used to focus the waveguide outputs onto the array, resulting in a compact unit that can be housed in a standard instrument package. A further advantage of this arrangement is that other optical elements such as filters and polarisers can readily be inserted into the beam path.

2. Transducer design

The sensor transducer chip is shown as part of the experimental setup in Figure 1: for this work we used an integrated optical Mach-Zehnder interferometer (MZI) device fabricated in BGG36 glass (Schott) by Ag^+-Na^+ ion-exchange [1]. The sensor utilises a three-waveguide coupler to produce three phase-shifted outputs and responds to refractive index changes occurring above the transducer surface within the waveguide evanescent field. Sputtered silica was used as an isolation layer material to isolate the reference arm of the Mach-Zehnder, the input and output transition regions, and the independent reference waveguide, from the analyte. A window was opened in the silica layer using a photolithographic liftoff technique to define the sensitive region of the waveguide. The sum of the intensities of the three outputs of the device potentially yields further information on analyte absorption as the sum reflects the total power loss through the interferometer. The separation between the output waveguides was 250 μm; the chip length was 40 mm. Comparison of the relative intensities of the three outputs enables unambiguous determination of refractive index over one full period of the output interference function.

3. Experimental system

Figure 1 shows the experimental sensor system. Light from a 10 mW 633 nm He-Ne laser was coupled into a single-mode fibre and the fibre was coupled to the sensor chip; the waveguides on the chip were single-mode at 633 nm. A 10X objective lens was used to focus the output signals on a Toshiba 1D CCD array (cost around $40US). The distance from the CCD to the objective lens was 18 cm, giving a total magnification of 14 times. The CCD array has 3648 pixels; the pixel width and height were 8 μm and 200 μm, respectively. A 40 dB neutral density filter was placed between the lens and the detector to reduce the signal so that the CCD array was not saturated and a polariser was used to select TE polarisation. The extremely high

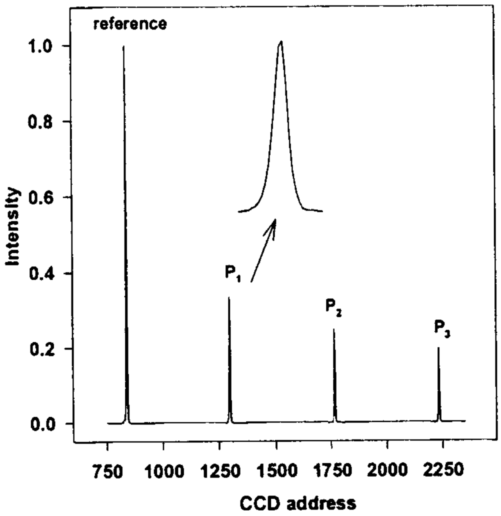

Figure 2 Spatial output on CCD array

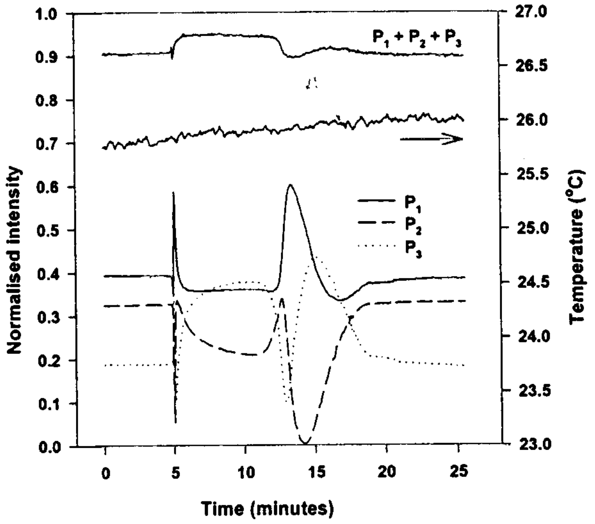

Figure 3 Sucrose solution test cycle

sensitivity of the detector allows less stringent fabrication tolerances as regards waveguide loss when using laser sources; it also opens up the possibility of using other sources that are less intense or which couple poorly to single-mode fibre, such as LEDs. A temperature sensor was placed near the flow cell to monitor ambient temperature during a measurement.

A flow-cell was clamped to the sensor surface and sucrose test solutions of varying refractive indices were applied using a flow-injection system. The refractive indices of these solutions, which are a function of the sucrose concentration, were determined using a KEM refractometer at a wavelength of 589 nm at 20°C.

4. Results and discussion

Figure 2 shows the spatial distribution of the sensor output intensities when water is applied to the chip surface (n = 1.33299). The half power full width (HPFW) of the intensity profile of the light from a single waveguide output falling on the array is 34 μm. As the vertical dimensions of the mode profiles are of a similar magnitude, all the light from each output is incident on the 200 μm-high array. The measured signal for each output is taken as the sum of the intensities falling on the pixels within a region surrounding each feature. A background signal measured close to each feature was subtracted for each output. The integration time was 40 ms; for each data point in sucrose solution test cycle measurements several integrations were collected and averaged.

Figure 3 shows the temporal response of the sensor to a sucrose solution of refractive index n = 1.41045. Each output P_1, P_2 and P_3 of the three-waveguide coupler is divided by the independent reference output to compensate fluctuations in the input light intensity. Also shown is the ambient temperature and the sum of the three referenced outputs. The sum does not remain constant throughout the measurement due to the redistribution of power taking place between the waveguides of the coupler, which each exhibit somewhat different loss characteristics due to the presence of bends and fabrication errors. Corrections to the measured data to eliminate this effect will be made following further characterisation of the sensor. The sucrose pulse is injected into the flow stream and pumped at a constant rate through the flow cell during the measurement. Equilibrium levels are reached at around t = 10 minutes as the pure water is displaced completely from the cell and replaced with the sucrose solution; the sucrose solution is then washed out and replaced with water, and the signals return to their original levels.

The demonstration system shown here is not yet temperature stabilised and therefore there is some drift due to variations in ambient temperatures. However, this setup provides an indication of the limit of detection by calculating the smallest detectable signal change considering the noise in the system: the minimum detectable refractive index change was determined to be 7×10^{-5}. However, the sensor chip employed in this demonstration was not optimised for maximum sensitivity. Work is now in progress to package the transducer and detector in a permanent housing, with temperature control of the active region of the transducer, employing localised temperature sensors, and pigtailed fibre input. The use of more compact and inexpensive light sources is being investigated, particularly 635 nm laser diodes and visible LEDs. Initial experiments indicate that sufficient light is coupled from standard packaged LEDs to single mode fibres to render their use with the current instrumentation a practical possibility. Ultimately, the present test transducer design will be replaced with arrayed MZI devices having more than four outputs and the instrument will be used to probe selective thin films for the detection of specific analytes in solution.

5. Conclusions

An inexpensive and robust technique for the addressing of multiple outputs from integrated optical transducers has been described. The performance of the demonstrator setup indicates that further development of the method and application of low-cost light sources will lead to the first truly practical integrated optical multisensor instrument.

Acknowledgements

This work was funded by Kyoto Electronics Manufacturing Co., Ltd., Japan. The Optoelectronics Research Centre is an Interdisciplinary Research Centre funded by the UK EPSRC.

References

[1] Drapp B, Piehler J, Brecht A, Gauglitz G, Luff B J and Wilkinson J S 1997 *Sensors and Actuators B* **38-39** 277-282

[2] Ch. Fattinger, Koller H, Schlatter D and Wehrli P 1993 *Biosensors and Bioelectronics* **8** 99-107

[3] Mouvet C, Harris R D, Maciag C, Wilkinson J S, Luff B J, Piehler J, Brecht A, Gauglitz G, Abuknesha R and Ismail, G 1997 *Analytica Chimica Acta 338* 109-117