Anti-Resonant Reflecting Optical Waveguides (ARROWS) as Optimal Optical Detectors of µTAS Applications

ANTI-RESONANT REFLECTING OPTICAL WAVEGUIDES (ARROWS) AS OPTIMAL OPTICAL DETECTORS FOR MICROTAS APPLICATIONS

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Abstract

Anti-Resonant Reflecting Optical Waveguides (ARROW) have been developed for integrated optical devices, as they permit waveguiding in low-index layers fabricated from materials such as silicon dioxide. They have been developed mainly for integrated optics applications, as they are compatible with standard silicon processing techniques [1,2]. The main feature of ARROW waveguides is that light confinement is by Fabry-Perot anti-resonant reflectors, rather than total internal reflection (TIR). As a result of the light confinement mechanism, ARROWs can be constructed such that the light is confined in a low refractive index medium surrounded by high refractive index reflecting boundaries. ARROWs have been proposed as optical sensors [3], but the configuration suggested used the evanescent field outside the ARROW waveguide to perform sensing, leading to very low sensitivity.

ARROWs are extremely well suited to MicroTAS applications, since they permit waveguiding in a low index medium such as an aqueous solution. A simple refinement of the basic ARROW structure permits simple in- and out-coupling of light by frustrated total internal reflection (FTR), eliminating the need for complex coupling arrangements such as end-fire or grating couplers. ARROWs can be used to monitor optical absorption and refractive index, as well as to excite fluorescence.

Keywords: Optical waveguide sensors, fluorescence, refractive index sensing.

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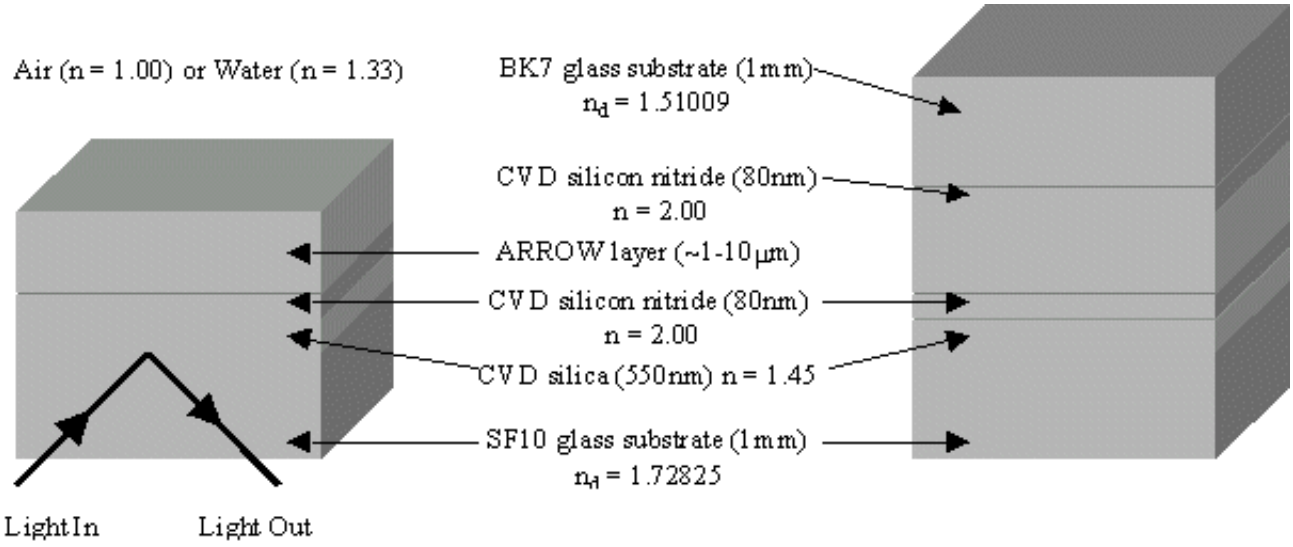
1. Introduction

Optical detection in MicroTAS systems has usually taken place through the depth of the microfabricated channels, which has resulted in a large body of work on the fabrication of high aspect ratio channel structures. Recently, the use of optical waveguides as detectors in MicroTAS systems has been reported [4]. In these systems, a high-index waveguide forms the top or bottom wall of the channel, permitting optical detection via the evanescent field present at the channel-waveguide boundary. While this scheme has many advantages, it has the major disadvantage of only sensing a thin layer (about half a wavelength) at the channel wall. If the channel is much deeper than half a wavelength, much of the material in the channel cannot be sensed. To overcome this disadvantage requires a structure that permits waveguiding in a low index medium (the normally aqueous medium in the channel) bounded by higher index materials (the MicroTAS substrate).

ARROWs are leaky optical waveguides where waveguiding occurs in a thick low refractive index layer, rather than in a thin high index layer [1,2]. The confining mechanism is not total internal reflection; instead anti-resonant Fabry-Perot reflectors are used. ARROWs are also inherently leaky, and can thus use frustrated total internal reflection for in- and out-coupling. Optimisation of the coupling efficiency and propagation length can be performed by coupling through a thin low index spacer layer on a high index substrate as shown in figure 1. They are also non-dispersive, and can even use white light from an incandescent source instead of a monochromatic laser or LED. This means that the light throughput can be much greater than other waveguide sensors. The sensitivity of ARROWs is also much higher than high index waveguide sensors, as virtually all the light is confined in the sensing (low-index) layer, which in the ARROW is the waveguide. Typically, we would expect anything from twice to five times the sensitivity of conventional high index waveguides. When the peak widths are compared, the sensitivity of ARROWs is enhanced still further.

Figure 1

Asymmetric FTR-coupled ARROW   Symmetric FTR-coupled ARROW



ARROWs may be symmetrical, where confinement at both boundaries is by anti-resonant reflectors, or asymmetrical, where confinement is by anti-resonant reflector at one boundary and total internal reflection at the other. Asymmetrical ARROWs are most useful as direct chemical and biochemical sensors, as the TIR boundary can be between the chemically selective layer and the sample. Symmetrical ARROWs are most appropriate to MicroTAS applications, as the channel can be bounded entirely by anti-resonant reflector layers. By using substrates identical to the Resonant Mirror (RM) devices used in earlier work [4,5], we can simultaneously excite conventional high-index waveguide and ARROW modes, giving a direct comparison of the peak widths and sensitivities of both modes.

2. Experimental

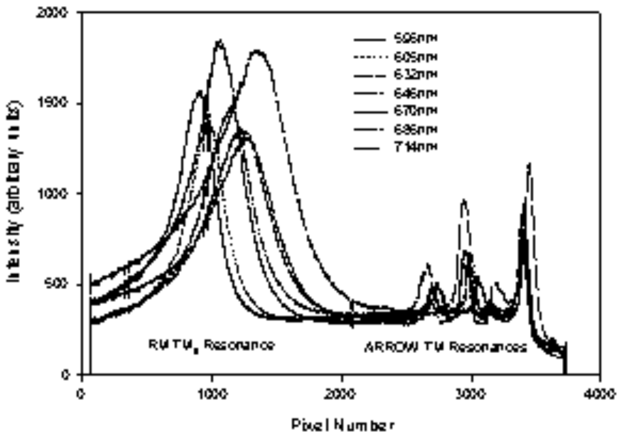
Sensor chips were fabricated on 1mm thick Schott SF10 glass substrates, optically polished on both sides (Gooch and Housego Ltd, Ilminster, UK). The substrates (1mm thick SF10 glass, Schott Glass) were cleaned successively in Decon-90 solution and acetone, then dried at 80?C for 30 minutes. Deposition of silica spacer layers and silicon nitride waveguide layers was performed using chemical vapour deposition (CVD) (Affinity Sensors Ltd, Cambridge, UK). To form channels, photoresist (SJR5740 high-viscosity positive photoresist, Shipley, Coventry, UK) was spin-coated onto the substrate. The photoresist was soft-baked at 105?C for 5 minutes, followed by UV exposure through a film phototool for 5 minutes . The pattern was then developed for 60 seconds using potassium hydroxide solution. Finally, a top cover was bonded to the photoresist by heating the two pieces together under pressure from a clamp.

The instrumentation consisted of a 12V, 20W tungsten-halogen lamp with condensing lens, a 350?m pinhole and collimating lens to produce a substantially collimated beam of white light. This beam was used directly for the constant angle, variable wavelength experiments. Interference filters (10nm FWHM bandwidth) (Ealing Electro-optics,Watford, UK) were used to provide a reasonably monochromatic light source for the dispersion measurements. Fluorescence measurements were performed using a Laser 2000 10mW 473nm solid-state frequency-doubled blue laser. A 3648 pixel CCD (Toshiba TCD1301D) was used with a 12-bit analogue-to-digital converter to monitor angle changes. The CCD had a pixel pitch of 8microns and a pixel height of 200microns. A frame-transfer CCD camera (Model TM1001, Pulnix Inc, USA) was used to capture images of fluorescence emission excited using ARROW modes.

3. Results and Discussion

Initially, asymmetric ARROW sensors were used to verify ARROW operation, to monitor refractive index changes and to excite fluorescence. An approximately 8 ?m thick layer of cellulose acetate was deposited on the substrate by spin-coating from acetone solution. The TM RM and ARROW resonances were visualised using crossed input and output polarisers [5] at a number of wavelengths as shown in figure 2. The RM resonance is strongly dispersive, as shown by the large changes in peak position with wavelength. The ARROW resonances are much less dispersive, and remain virtually stationary.

Figure 2. ARROW and RM Dispersion Figure 3. ARROW and RM Vapour Sensing



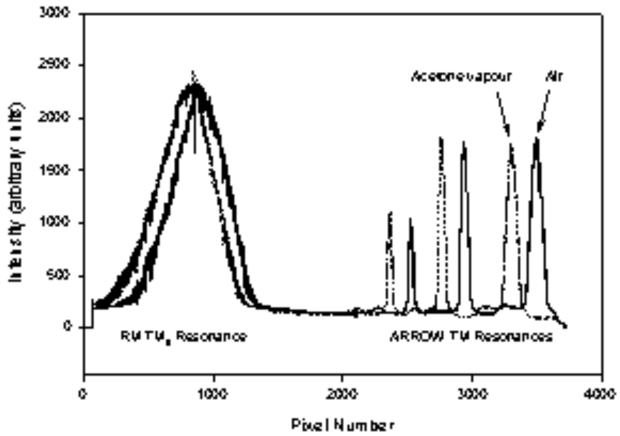


Figure 3 shows the effect of acetone vapour on the RM and ARROW resonance positions using a 660nm LED as the light source. As the acetone vapour diffuses into the cellulose acetate the refractive index of the polymer changes, causing a change in the resonance angles. The shift in position of the ARROW resonances is 1.8 times greater than that of the RM mode. This figure can be improved by modification of the layer thicknesses, as the coatings were optimised for maximum RM sensitivity. It should be noted that the ARROW resonances are much narrower than the RM resonance, making the change in position much easier to detect. Finally, a test of fluorescence sensing was performed by doping a cellulose acetate layer with fluorescein and exciting fluorescence from both the RM TM0 and ARROW modes. An Schott GG495 glass filter was used to remove scattered 473nm excitation light and an optical power meter was used to measure the fluorescence intensity. The waveguide was rotated to the maxima of emission for both the RM and ARROW resonances. The fluorescence intensity was found to be 11.0 times higher for ARROW than for the RM mode.

Symmetric ARROWs can also be used to monitor the optical properties of solutions in ?TAS channels, provided the channel depth and width are of the appropriate dimensions. Typically, the depth would be between 3 and 10 ?m and the width between 100 and 500 ?m. To provide better confinement, the structure was not completely symmetrical, as there was no silica spacer layer on the top glass substrate. This largely eliminates light leakage from the top surface of the channel. Initially, a fluorescein solution was pumped through the channel and fluorescence excited at 473 nm. Figure 4 shows the channel, which was 300 ?m wide, 10 ?m deep and 30 mm long and Figure 5 shows the fluorescence emission at the first ARROW resonance. The propagation length is the full channel length from excitation with a beam of ~1mm diameter.

Figure 4

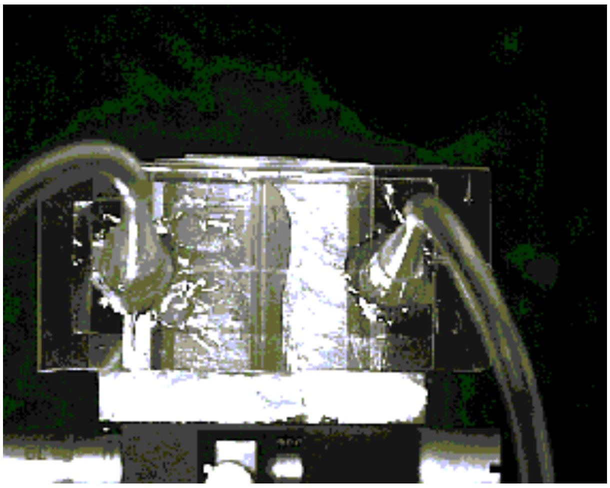
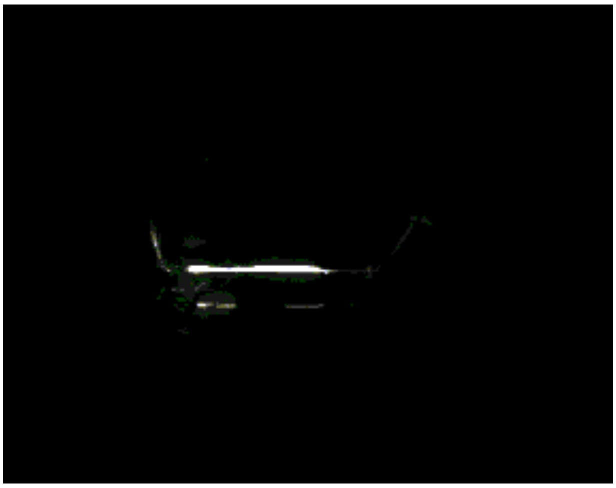


Figure 5



4. Conclusions

The predicted increase in sensitivity of ARROW sensors compared to conventional high-index waveguides (such as the Resonant Mirror) has been demonstrated for both refractive index and fluorescence sensing. The ability of symmetric ARROW devices to monitor the optical properties of solutions in microfabricated channels has also been demonstrated. The properties of ARROWs have also been shown to be compatible with ?TAS channels.

5. Referances

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Back to Home Page