An Integrated Optofluidic Bragg Grating Device to Measure the Dynamic Composition of a Fluid System

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Strong transitional mixing effects were observed by a planar Bragg grating sensor within a microfluidic system. This property was used to develop an integrated optofluidic sensor for detection of the composition of mixed solvent systems.

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We demonstrate a temperature compensated microfluidic optical Bragg grating sensor capable of operating within a wide range of solvent systems. We show how we can detect subtle solvent intermixing effects and how these can be used to create an optical sensor capable of unambiguously establishing the solvent composition.

Bragg gratings, incorporated within a two-dimensional planar waveguide can be written directly into a photosensitized silica-on-silicon substrate by careful modulation of a pair of interfering UV-laser beams [1]. These Bragg gratings are inherently sensitive to both strain and temperature. However, if the cladding is etched away, the evanescent field of the optical mode within the grating is exposed, making the grating sensitive to the refractive index of the environment. Changes in this environment alter the effective index of the Bragg grating and the corresponding shift in the reflected peak Bragg wavelength can be used to detect this change [2]. The sensitivity of the device to changes in refractive index is strongly dependent on the fraction of the evanescent field that penetrates into the analyte (Figure 1). A thin layer of a high index material, such as tantalum pentoxide, over the etched region of the waveguide increases this sensitivity by pulling the guided mode up into the analyte [3].

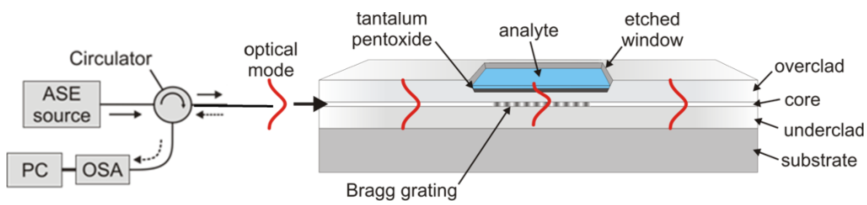
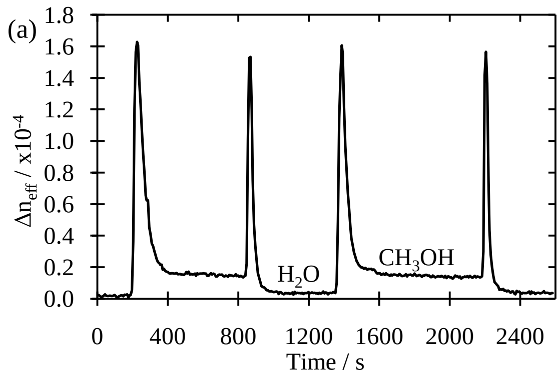


Fig. 1 – A schematic of an etched, fiber coupled Bragg grating sensor, showing the exposed Bragg grating within the window.

Several of these highly sensitive Bragg refractive index sensor regions can be fabricated simultaneously within a single waveguide. Such integrated optical sensors can be readily incorporated within a microfluidic system to allow *in situ* monitoring of a dynamic fluid system. To be able to develop sophisticated microfluidic sensors, it is necessary to first have a good understanding of the behaviour of simple fluids flowing within the system. To this end, a simple microfluidic system was fabricated from perfluorinated components; this allowed for the use of harsh solvents and reagents that are unsuitable for PDMS microfluidic systems.

Investigation into cycling between different solvents, both miscible and immiscible, within the microfluidic system showed a reproducible change in the effective index of the grating between bulk solvents. However, it was found that the previous solvent impacted the measurement of the next solvent and that the nature of the transition was dependent on the solvents being mixed. For example, isopropanol and water gave a square wave like response but with a small mixing transient while mixing water with other alcohols, such as methanol or ethanol, produced a "spike" in the refractive index during the transition (Figure 2.a).

These "spikes" are particularly significant for the interchange between methanol and water, where the peak index change is over an order of magnitude larger than the difference in the bulk fluids. On switching from methanol to water a shorter narrower spike was observed, while the reverse transition produced a broader spike. A comparison of the TE mode with that for the relatively insensitive TM mode shows that the ratio of the magnitude of the spikes to the change in refractive index between the bulk solvents was consistent for both. Surprisingly it was found that turning off the pump during the transition allowed these "spikes" to be frozen for up to several hours without change or degradation. On re-engaging the pump the spike profile continued unperturbed. The duration of these spikes are much longer than expected, with the effective index taking 2-5 minutes to normalise to the bulk value. In To put this in context, the diaphragm pump pulls through thirty times the volume of the sensor channel with each pump every 1.5 seconds, indicating an additional intermixing mechanism.



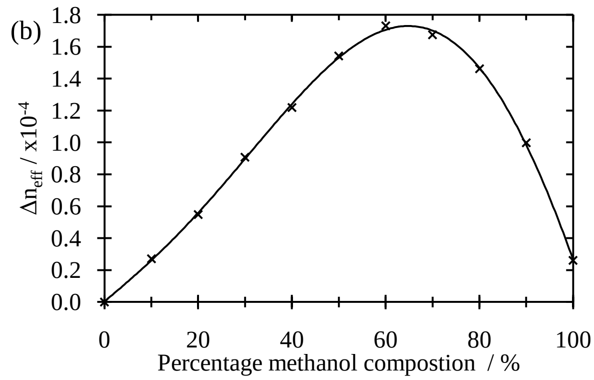


Fig. 2.a) – The change in effective index upon cycling between methanol and water within a microfluidic flow cell, showing the spikes caused by transitional solvent mixing.
Fig. 2.b) – The effective index of the grating changes with the composition of the methanol-water binary mixture.

Measuring the effective refractive index for a series of methanol-water solutions showed that the refractive index of methanol-water binary mixtures are much higher than their constituent parts (Figure 2.b). The higher refractive index is due to a ternary mixture of associated water, associated methanol and water associated with methanol producing a significantly different structure [4]. The peak refractive index found in an aqueous solution containing 60% methanol is consistent with the peak height of the "spike". This confirms that this is a genuine refractive index change formed by a slow moving concentration gradient along the microfluidic channel as the solvent is switched.

For continuous monitoring of a dynamic fluid system, such as within a chemical reactor, an understanding of these mixing effects is crucial to be able to extract conclusions from the observed changes in effective index. However, this property can also be exploited to produce a real-time sensor that is capable of accurately detecting the fluid composition of a dynamic mixture. As demonstrated in Figure 2.b), it would be impossible to differentiate between an aqueous solution containing 30% methanol from one containing 90% with a single measurement of refractive index. However if the fluid mixture is mixed with water and a second measurement is taken, the resultant dynamic response will be very different for the two solutions, for a 90% solution a large "spike" is observed, while for 30% a smooth transition is observed. Using this effect the concentration of the original mixture can be ascertained.

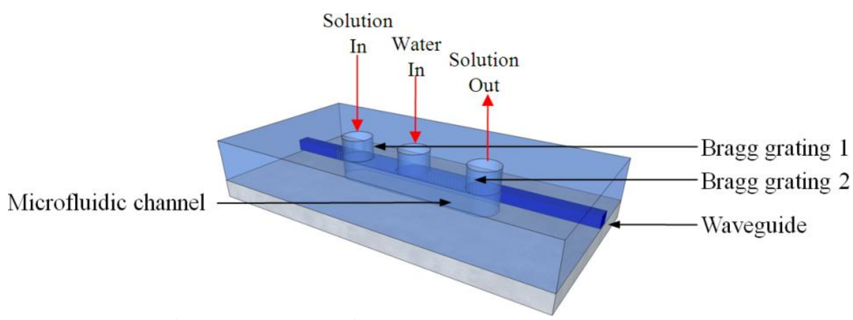


Fig. 3 – A schematic of the Integrated Optofluidic Bragg Grating Device acting as a concentration sensor

We show that a highly sensitive optical Bragg grating can be used to detect subtle dynamic fluid effects within a microfluidic system. If these transitional solvent mixing effects are not accounted for, these anomalies can cause significant problems for refractive index based sensors. We will show that this property can be used to develop an integrated optofluidic sensor for detection of the composition of dynamic mixed solvent systems using a novel dilution technique.

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