Nano-structured fibre-to-chip grating coupler for bio-sensing applications

R. Halir[1], P. Cheben[2], J. H. Schmid[2], R. Ma[2], S. Janz[2], D.-X. Xu[2], A. Densmore[2], J. Lapointe[2], and Í. Molina-Fernández[1]

[1]Departamento Ingeniería de Comunicaciones, Universidad de Málaga, Málaga, Spain
[2]Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Canada
robert.halir@ic.uma.es

Direct monitoring of molecular reactions in real-time is key to many aspects of biochemical research. Intermediate labeling steps hamper detection reliability, which is why optical biosensors, which enable label-free monitoring, are advantageous. The most established optical monitoring method is surface plasmon resonance, which is based on probing the material with a lightwave travelling along a metal surface. However, the precision of this method is fundamentally limited by the short propagation length (~30 µm) along the metal surface [1]. Due to their low propagation loss (~3 dB/cm), dielectric based, integrated optical sensors do not suffer from this limitation [2]. Use of the high index contrast silicon-on-insulator platform furthermore allows for drastic sensor size miniaturization, thus enabling parallel probing of several samples in a single device [3]. Detection limits of 0.5 pg/mm^2 have been reported for devices with a sensing area smaller than 130 µm x 130 µm in the silicon platform, yielding a minimum detectable mass of 0.5 fg [3], thus readily competing with commercial surface plasmon resonance techniques. The operation of these photonic biosensors is based on evanescent field sensing: part of the waveguide mode travels outside the actual guiding region and thus experiences different phase velocities depending on the refractive index of the material that is deposited on the waveguide surface. This phase velocity change can be exploited for biosensing by defining Mach-Zehnder interferometers or ring resonators with these waveguides [2-4]. Both configurations produce strong intensity variations at their outputs as a result of refractive index changes on the waveguide surface, which can be measured with photodetectors. Fig. 1 shows the fundamental TM (vertically polarized) mode of a silicon wire waveguide. The substantial evanescent tails make this polarization highly sensitive to changes of the refractive index of the material on the waveguide, and thus particularly suitable for biosensing [5].

Practical photonic biosensing chips must be compatible with large scale, low cost fabrication, and should present efficient and robust light coupling interfaces with standard optical fibres. In Si-wire waveguides the latter is especially challenging because of the large size mismatch between optical fibres (8 µm core size) and the miniaturized waveguides (~ 250 nm x 450 nm core size). Diffractive grating couplers, as shown on the left of Fig. 2, are widely used for coupling TE (horizontally polarized) light into these waveguides. However, this solution is not directly applicable to biosensors, not only because the TM polarization is not injected efficiently, but mainly because the gratings are etched only ~70 nm into the waveguide layer. This shallow etch is necessary to reduce the discontinuity between the alternating strips of the grating, thereby matching the large fiber mode to the field diffracted by the coupler. However, the second etch step, added to the full etch needed for waveguide definition, increases fabrication costs. Here we present our latest findings on a novel fibre-to-chip coupler that can be fabricated in a single etch step and offers efficient light coupling for TM polarization. The coupler uses nano-structures to synthesize effective materials, which are used to optimize coupling efficiency [6,7].

A schematic view of the proposed coupler is shown on the right of Fig. 2, with the optical fibre positioned above it, and the polarization states indicated with arrows. The device couples light coming from the optical fibre into the waveguide along the *z* axis, and into the vertical (*y* direction) polarization state, as required for biosensing. The fully etched, periodic nano-structures along the *x* axis have a pitch of 450 nm, which is small enough to create an equivalent homogenous medium at the operation wavelength of 1550 nm. By tuning the width of the silicon tooth in the sub-wavelength structure, effective media with refractive indexes ranging from air (no silicon tooth) to silicon (no air gap) can besynthesized. Specificially, if the size of the silicon tooth is set to 185 nm, an effective medium with a refractive index of 2.73 is created. For a uniform grating, this intermediate refractive index provides a near optimum match of the diffracted field and the fiber mode. Furthermore, it is readily fabricated, since the 185 nm minimum feature size is fully compatible with large volume deep ultraviolet lithography.

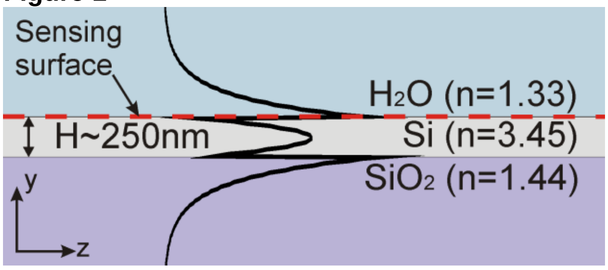
Fig. 3 shows a scanning electron microscope image of a fabricated, uniform coupler, with the diffractive grating along the *z*-direction and the stripes of effective media along the *x*-direction. By coupling light into the waveguide through one grating, and extracting it with an identical grating, the coupling efficiency of the grating can be determined. As shown on the right hand side of Fig. 3, an experimental peak coupling efficiency of 4 dB is achieved, which exceeds the coupling efficiency of traditional dual etch gratings by almost 1 dB [8].

Simulations show that using an apodized design, i.e., by varying the refractive index of the effective medium along the grating, coupling efficiencies of up to 3 dB can be achieved.

In summary, we present a novel fibre-to-chip grating coupler optimized for bionsensing applications, that is fabricated in a single etch step and fully compatible with high volume production. Using nano-structure effective media, this coupler achieves an experimental coupling efficiency of 4 dB.

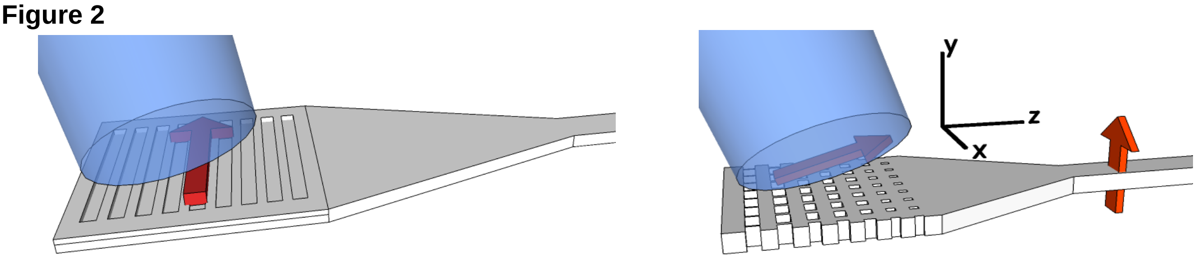
References
[1] Homola, J.; Yee, S. S. & Gauglitz, G, Sensors and Actuators B: Chemical, **54** (1999), 3-15
[2] Laura M. Lechuga, et al, SPIE Newsroom, December 2008
[3] Densmore, A, *et al*, Opt. Lett., **34** (2009), 3598-3600
[4] Xu, D.-X., *et al*, Opt. Express, ***16*** (2008), 15137-1514
[5] Densmore, A., *et al*, IEEE Photonics Technol. Lett., **18** (2006), 2520-2522
[6] Halir, R., *et al*, Opt. Lett., **34** (2009), 1408-1410
[7] Halir, R., *et al,* Opt. Lett., **35** (2010), 3243-3245
[8] Roelkens, G., *et al,* IEEE J. Sel. Top. Quantum Electron. (2010), forthcoming

Figure 1



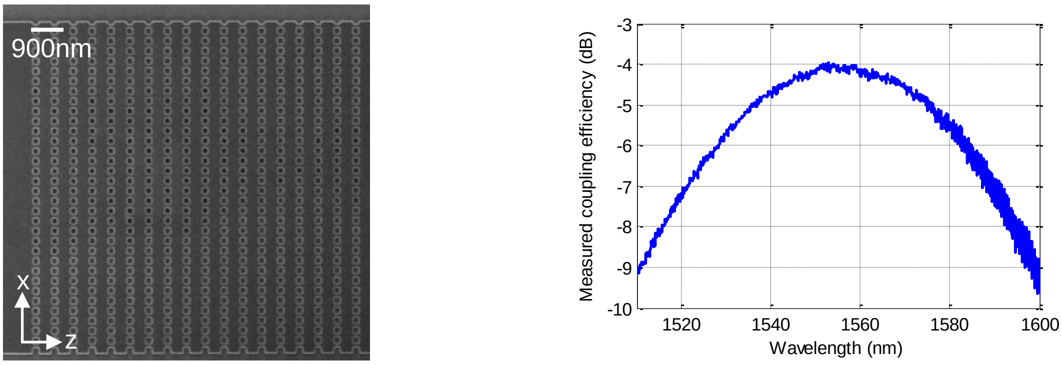
Electrical field (E_y) of the fundamental TM (vertically polarized) mode of a silicon-wire waveguide. Refractive indexes are given at λ=1.55µm.

Figure 2



Left: Schematic view of traditional fibre-to-chip grating coupler. Right: Proposed coupler. In both figures the arrows indicate the polarization state.

Figure 3



Left: Scanning electron microscope structure of the fabricated structure. Right: Measured coupling efficiency.