Towards Photonic Biosensing using a Three-Port Mach-Zehnder Interferometer in a Silicon Nitride Platform

Student Paper

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ABSTRACT

Integrated photonics enables sensitive and label-free optical biosensors for the detection of chemical and biological substances and is therefore promising for future lab-on-chip solutions. In this article we present our current development of silicon nitride based integrated photonic biosensing devices working at telecom wavelengths. Our approach of three-port based interferometric sensing circumvents the issues of conventional Mach-Zehnder interferometers, providing a constant sensitivity, and allowing to use a fixed wavelength sensing scheme. Preliminary experimental results show that the fabricated devices work as expected from simulations.

Keywords: photonic biosensor, silicon-nitride, three-port Mach-Zehnder interferometer, refractive index sensing, phase detection

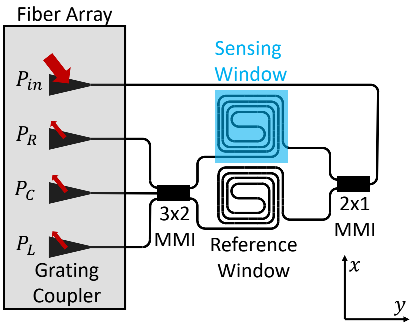
1 MOTIVATION

Integrated optical sensors, based on the interaction of the waveguide mode with the analyte, are promising candidates for lab-on-chip platforms, because they offer label-free detection, high sensitivity and low production costs [1], particularly when implemented with silicon based materials [2]. In the silicon-on-insulator (SOI) platform and at telecom wavelengths, interferometric sensors have recently been shown to achieve limits of detection below 10^{-7} refractive index units [3] when using optimized phase read-out techniques [4]. Compared to SOI, silicon-nitride waveguides offer the fundamental advantage that they remain transparent even at visible wavelength, where photo-damage to biological tissues and water absorption, which may ultimately limit sensitivity, are minimal [5]. Here we report on exploratory work on implementing advanced interferometric sensors in a silicon-nitride platform, working at telecom wavelengths as a first step to extend the operation into the visible regime.

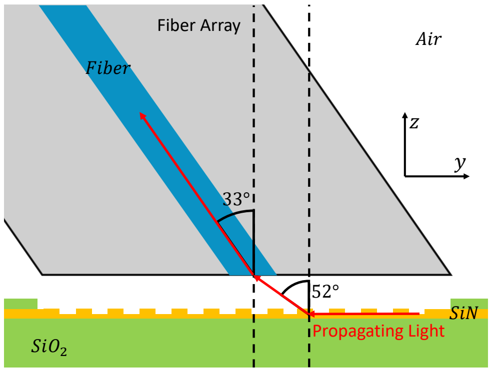
2 DESIGN

The complete sensing structure is shown schematically in Fig. 1(a). Light is coupled into the structure through a fiber array and split among the two interferometer arms with a 1x2 multimode interference coupler (MMI). Each arm consists of a spiraled waveguide, which is exposed to the analyte in the sensing arm, and covered in the reference arm. As light propagates through the sensing arm it interacts with the analyte deposited on the chip surface, thereby acquiring a phase shift with respect to the reference arm. In order to optimally detect this phase shift, light from both arms is recombined by a 2x3 MMI, which provides three output signals, shifted by 120° to each other, thereby avoiding the low sensitivity regions at the interferometric maxima and minima that arise in conventional Mach-Zehnder schemes [4]. This enables sensing without any wavelength sweeping, thus offering potentially low cost. The three output signals are coupled back to the fiber array, and can then be detected with photo-diodes. All elements were designed for TE (horizontal) polarization in 300 nm thick silicon nitride waveguides, with a refractive index of ~ 2.0 at telecom wavelengths. We briefly discuss the design of each element in the following.

Efficient and low cost light coupling is a key challenge for many integrated optical platforms. Surface grating couplers are widely used for this purpose, because they can be placed anywhere on the chip surface, and, due to their comparatively large size, offer relaxed alignment tolerances. Highly efficient grating couplers for the silicon nitride platform have been reported [6], but require complex dual etch structures with small feature



(a) Schematic of the sensing structure showing the gratings for coupling to a fiber array, the interferometer with the exposed sensing arm, and the 2x3 coupler for enhanced phase read-out.



(b) Illustration of the grating coupler angles. The grating radiates in an angle of around 52° in direction of the FA where it is coupled into the fiber mode according to Snell's Law at an angle of 33°. The FA is not drawn to scale.

Figure 1. Schematics of the sensing structure and the fiber-to-chip coupling solution.

sizes. Here, we designed a grating with one single shallow ($150\,\mu\text{m}$) etch step, and a period of $\Lambda = 2.1\,\mu\text{m}$ with a duty cycle $DC = 50\%$, which greatly simplifies fabrication. This structure provides both minimized back reflections as well as a theoretical coupling efficiency to a standard fiber of around $-5\,\text{dB}$. The resulting radiation angle into air, measured from the surface normal, is $52°$. In order to place the fiber array close enough to the grating couplers (to avoid diffraction of the radiated beam), the fiber array has to be angle-polished. As shown in Fig. 1(b), the polishing angle is $\sim 33°$ to take into account Snell's law as the light beam couples from air into the fiber with refractive index 1.45.

The spirals forming the inteferometer should, in principle, be as long as possible to increase the interaction length of light with the analyte placed on the sensing arm. Keeping bending losses low is crucial to minimize the overall losses of the spirals. We found by simulation that a bending radius of $50\,\mu\text{m}$ should yield negligible losses.

Finally, the dimensions of the multimode interference couplers were designed according to the procedure detailed in [7]. The 1x2 device used for equally splitting the power into the MZI arms is fully etched and has a footprint of $9\,\mu\text{m} \times 44\,\mu\text{m}$. The 2x3 MMI used for the recombination of the sensing and reference arm with $120°$ phase shift among the outputs, was also fully etched with a footprint of $13.5\,\mu\text{m} \times 264\,\mu\text{m}$.

3 FABRICATION

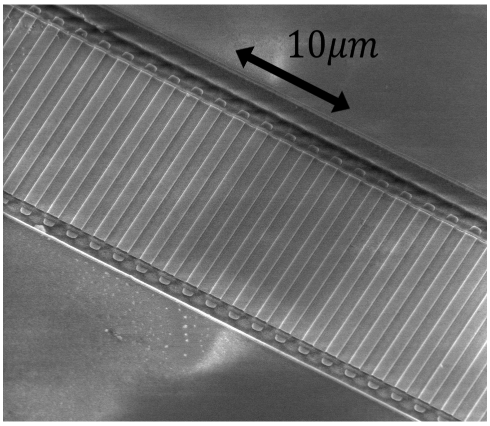
The sensing chip was fabricated at the Instituto de Microelectrónica de Barcelona, Centro Nacional de Microelectrónica (IMB-CNM), CSIC [8] through a Multi Project Wafer approach offered by VLC photonics. The $300\,\text{nm}$ thick silicon nitride layer was fully etched to define the single-mode waveguides, while a shallow ($150\,\text{nm}$ deep) etch was employed for the fiber-to-chip grating couplers. The material surrounding the waveguides, the 1x2 and the 2x3 MMIs is silicon-dioxide (SiO_2), whereas for the gratings and sensing arms the SiO_2 cladding is removed by two additional dry etching steps, so that light propagating in the sensing arm is able to interact with the analyte on top of it. Fig. 2(a) shows a SEM picture of the fabricated grating coupler.

4 PRELIMINARY OPTICAL CHARACTERIZATION

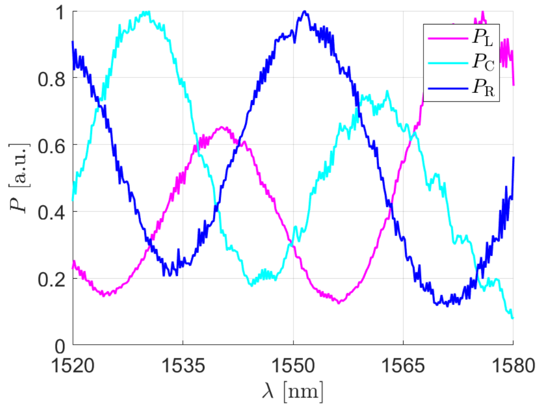
A preliminary characterization was carried out to verify the optical functionality of the chip. A tunable near infra-red laser source ($1520\,\text{nm}$ to $1580\,\text{nm}$) is connected to a polarization controller, wherefrom light is coupled into a fiber array which is positioned above the grating couplers (see Fig. 1(a)). The polarization of the input light is adjusted to match the TE (horizontal) polarization state required for efficient coupling. The output fibers are attached to optical power meters.

First we measured four different test spirals with lengths ranging from $3\,\text{mm}$ up to $21.5\,\text{mm}$, to estimate waveguide and bending losses. We found very low bending losses of $\sim 0.15\,\text{dB}/90°$ and $\sim 0.12\,\text{dB}/90°$ for curvature radii of $50\,\mu\text{m}$ and $75\,\mu\text{m}$, respectively. Waveguide losses were found to be below $1.5\,\text{dB/cm}$ but could not be measured accurately with these test structures.

In a second experiment, the complete sensing structure as shown in Fig. 1(a) was measured, recording all three output ports (P_L, P_C, P_R) simultaneously, as the wavelength was swept. This causes a phase shift between the sensing and reference arm of the sensor, emulating a sensing experiment. The normalized measurements in Fig. 2(b) demonstrate that the three outputs show the expected sinusoidal behavior, with a phase shift of approximately $120°$ to each other.



(a) Scanning electron micrograph of the shallowly etched grating coupler.



(b) A wavelength swept measurement confirming the the chip provides the desired 120° phase shift between the three output signals of the interferometer.

Figure 2. Preliminary experimental results on the optical functionality of the chip.

5 CONCLUSIONS

The combination of SiN with a three-port phase read-out of the MZI is a promising approach for high sensitivity biosensing. We have designed, fabricated and experimentally demonstrated the optical functionality of the fabricated chips thereby paving the way for detailed sensing experiments which will be carried out in the near future.

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