Reliability of grating couplers incorporated on integrated interferometric biosensors

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***Abstract*—Sub-micronic grating couplers have been integrated on optical waveguides for efficient light in-coupling into interferometric biosensors. Design and fabrication processes are presented as well as the results of the optical characterization and the sensing evaluation.**

Keywords-Grating couplers; interferometers; biosensors; integrated optics.

I. Introduction

Among the different existing biosensing technologies photonic sensors based on integrated optics (IO) have emerged as one of the most promising candidates for lab-on-a-chip (LOC) platforms due to their high sensitivity, miniaturized size, multiplexed format for array implementation and CMOS compatible fabrication processes. However, the way to couple light into the photonic chip is still a critical aspect for the implementation of a complete LOC platform. Common coupling techniques are based on end-fire method, prism coupling and grating assisted coupling. The two first methods are commonly used in laboratory environment as they are quite versatile and efficient. However, they usually require bulky equipments and critical alignment, making them inconvenient for LOC applications. On the contrary, grating couplers appear to be the most suitable solution as they provide better integration, better alignment tolerance and do not require polishing steps.

Diffraction gratings are fundamental building blocks for integrated optical devices. They have been extensively studied over the last decades and a solid platform for their modeling and fabrication has been built. Nevertheless, up to now very few publications have demonstrated biosensing capabilities of IO sensors incorporating grating couplers.

Taking into account the above considerations, we are seeking to develop highly sensitive IO biosensors incorporating grating couplers with a view to implement a complete LOC platform. Two sensor configurations are employed: the Mach-Zehnder interferometer (MZI) and the bimodal waveguide interferometer (BiMW) which have both demonstrated their capacities for highly sensitive and label-free biosensing [1,2]. In the following, we will show our last results regarding the fabrication and evaluation of the grating couplers for efficient light in-coupling into the interferometric sensors.

II. Device design and fabrication

In the integrated MZI, a first Y-junction splits the guided light into two arms, the sensing and the reference arms. After a certain distance, the two signals are recombined into an output waveguide via a second Y-junction, producing the interference of both beams. In the BiMW interferometer, two guided modes of the same polarization interfere in a single channel waveguide: TE polarized light is coupled into a waveguide that supports a single transversal mode TE_{00} and, after a certain distance, the guided beam reaches a modal splitter that splits the first guided mode in two transversal modes, the fundamental TE_{00} and the first order TE_{10} modes [2]. Both interferometric devices are formed by Si_3N_4 rib waveguides, enabling precise control of light path and modal behavior. To maximize the sensor sensitivity and to ensure lateral single-mode behavior, the rib height has to be below 2 nm for a waveguide width of 3 μm. For biosensing applications, the protective cladding is removed from a portion of the interferometers, the sensing area, where the evanescent field can probe the external medium.

Due to the dimensions of the interferometers and to the operating wavelength (600-700 nm), the diffractive grating length does not exceed 100 μm with a sub-micronic period. In order to optimize the coupling efficiency, the gratings are designed on wide waveguides (from 20 to 100 μm) which will be then reduced to 3 μm by a width-tapered waveguide. The resonant coupling between the guided mode and the grating is obtained when the following phase matching condition is verified,

$$\sin\theta = n_{eff} + m\frac{\lambda}{\Lambda} \quad (1)$$

with θ the incidence angle, n_{eff} the effective refractive index of the guided mode, m the diffraction order (here m = -1), λ the wavelength (600-700 nm) and Λ the grating period. The effective index depends on the material and of the dimensions of the waveguide. It has been calculated for each structure under evaluation by the effective index method.

Equation (1) was used to design gratings with incidence angles ranging from 5º to 15º. This range of angles enables an efficient coupling but, above all, it is an important requirement for the implementation of a complete LOC platform where the different units have to be integrated all together in a minimum of space and without disturbing each other. Taking into account these considerations, the grating period Λ was set to 400 nm for the MZI and to 450 nm for the BiMW. To maximize the coupling, efficiency the grating profile should have a rectangular shape with a duty cycle of 0.5 and depth around 50 nm for both types of devices.

The interferometers were fabricated using standard silicon technologies. The silicon nitride waveguide layer ($n_{Si3N4} = 2.00$ at 633 nm, thickness between 75 and 350 nm depending on the device) is deposited using LPCVD technique and the rib structure is defined by photolithography and wet etching. The top cladding, a silicon dioxide layer ($n_{SiO2} = 1.48$ at 633 nm, 2 µm), is then deposited by PECVD. The final wet etching step defines the sensing areas (15 x 0.05 mm^2) and the 2 mm-long grating windows. The gratings are then directly written onto the Si_3N_4 input waveguide by electron beam lithography and reactive ion etching. The gratings have a length of 100 µm and a width equal to the one of the taper (20 to 100 µm).

III. Optical characterization

To measure the coupling efficiency of the gratings, a light beam from an HeNe laser (λ = 632.8 nm, 5 mW) is coupled into the chip mounted on a rotation stage by focusing the beam on the grating with a lens of 50 mm focal distance. The coupled light propagates in the waveguide until the edge of the chip where it is collected by an objective (x40 and NA=0.65) and monitored by a photodiode connected to a current amplifier. We define the coupling efficiency as $\eta = I_g / I_0$, with I_g the intensity at the output and I_0 the incident intensity. This expression is valid as long as propagation losses are negligible, which is the case with Si_3N_4 rib waveguides. Fig. 1 shows the coupling efficiency measured as a function of the incident angle for a grating with a period of 400 nm written on a MZI device (width taper: 20 µm). The resonant coupling is obtained at 9º35' for the TE_{00} mode (η = 6.4%) and at 1º15' for the TM_{00} mode (η = 2.1%). The coupling efficiency for the TE_{00} mode is quite satisfactory but a more exhaustive development is currently being done to improve it. For example, we have already achieved an efficiency of 12% for the coupling of the TM_0 mode in a planar waveguide.

Moreover, a quite large angle tolerance of about 1º at - 3dB has been measured. This is an important parameter when dealing with portable LOC platform.

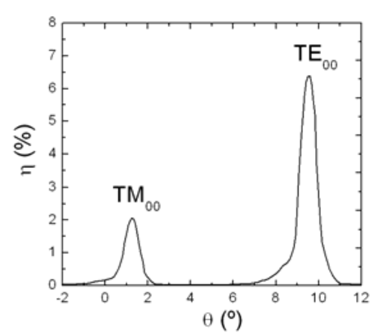

Figure 2. Coupling efficiency at 632.8 nm as a function of the incident angle for a grating (Λ = 400 nm) incorporated on a integrated MZI.

IV. Sensing evaluation

The sensitivity of the integrated interferometers incorporating grating couplers is evaluated by measuring the phase changes $\Delta\varphi$ induced by refractive index variations Δn in the sensing area. A microfluidic header made of PDMS and PMMA is used to control the liquid flow. To achieve truly portable LOC platform, cheap and easily integrated laser diodes are now used. A fiber pigtailed laser diode (λ = 658 nm, 2 mW, TE polarization) is placed above the chip and finely positioned at the excitation angle to reach the coupling.

Fig. 2 shows a calibration curve of a BiMW sensor obtained with a set of solutions of HCl (indices ranging from 1.3332 to 1.3376). Light coupling was achieved via a 450 nm-period grating on (width taper: 20 µm). The inset shows the response of the system to an injection of a solution of HCl 0.2 M with milli-Q water as running buffer ($\Delta n = 1.9 \cdot 10^{-3}$). With these results, a detection limit of $5.9 \cdot 10^{-7}$ in refractive index unit has been achieved.

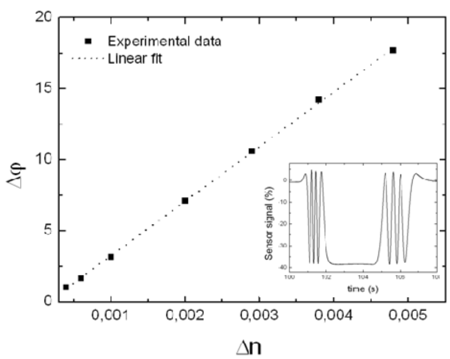

Figure 1. Calibration curve obtained with a BiMW excited via a grating coupler (Λ = 450 nm, TE polarization, 658 nm, θ = 9º50'). Inset: BiMW response to the injection of a solution of HCl 0.2 M.

The detection limit of our system (gratings incorporated in integrated interferometric sensor), obtained with a cheap and easily integrated laser diode, is comparable to the one demonstrated in our previous study using HeNe laser and end-fire method [2]. This strongly supports the adoption of the grating coupler method for the achievement of a truly portable and sensitive LOC platform. Work is in progress to evaluate the surface sensing limit of detection through an immunoassay test.

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