Simple and compact integrated silicon interferometer device for biosensing platforms devices

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***Abstract*—We have recently implemented a new interferometric device based on silicon photonics to be employed as a highly sensitive and label-free biosensor. We show here the working principle, theoretical design, fabrication, and optical and biosensing characterization of the integrated bimodal waveguide interferometer (BiMW), based on two-mode interference.**

Keywords - Bimodal Waveguide Interferometer; biosensor; two-mode-interference; integrated optics.

I. INTRODUCTION

Current diagnostic tests are expensive, require specialized personnel and equipment, and employ indirect detection methods that involve a long analysis time. Integrated optical (IO) biosensors represent an attractive alternative to these devices due to its high sensitivity and the use of a label-free detection scheme. Such devices are the most suitable candidates as transducer elements for its integration in portable lab-on-a-chip platforms (LOC) as they can be miniaturized and mass-produced, obtaining cost-effective devices. Among them, interferometric transducers present the highest sensitivity, achieving detection limits (LOD) around 10^{-7} RIU [1]. Mach-Zehnder (MZI) and Young (YI) Interferometers has been the most usual configurations. In these transducers, the Y divisor is used to split or recombine light, a critical process in order to obtain highly coherent devices. Due to the standard tolerances of current fabrication techniques, the Y-shape splitter is the most complex component of these configurations.

To overcome this limitation, we have developed [2] a simpler configuration using a single waveguide where two modes of the light interfere and we have named this new sensor bimodal waveguide interferometer (BiMW) [3]. In this device, the Y-divisor is replaced by a modal splitter consisting in a jump of the thickness of the waveguide core of several nanometers, a simple process totally compatible with standard fabrication techniques. In this work, the fundamental working principle, design of the structure, fabrication, and optical and biosensing characterization of the BiMW device are discussed.

II. WORKING PRINCIPLE

In a BiMW biosensor (see Fig. 1), the light is coupled into a single-mode rib waveguide. After some distance, the light is coupled into a thicker waveguide which supports two transversal modes. Due to the vertical asymmetry of the junction, fundamental mode of light splits in two, fundamental and first order modes which propagate till the output of the chip. In the bimodal part of the waveguide device, the cladding (cladd) is etched exposing a region of the core to the external medium, the sensor area. An interferometric pattern is obtained at the exit of the waveguide due to the different response of both modes to external changes through the evanescent field.

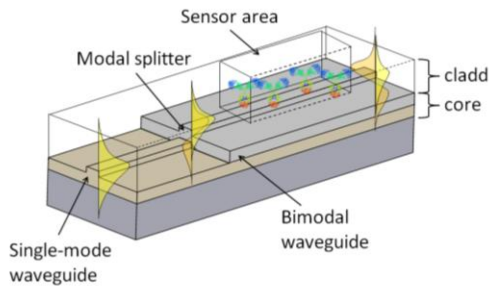

Figure 1. Scheme of a BiMW sensor.

III. SIMULATIONS AND DESIGN

The modal behavior of the light in a waveguide will depend on the thickness of the core, the width and the height of the rib, the refractive index difference between the materials of the cladding and the core, and the wavelength. Using silicon-based materials for the waveguide fabrication and visible wavelengths, our previous modelization indicates that employing SiO_2 as cladding (n=1.46) and Si_3N_4 as core (n=2.00) layers, single-mode behavior will be obtain for a core thickness down to 300 nm, a width of 4 µm, and a rib height down to 4 nm.

Taking account these previous results, we have employed the transfer matrix method to select the thickness of the core of the single and the bimodal mode part of the sensor. This approach was used to represent the profiles of the electric fields of the modes in the bimodal transversal direction (see Fig. 2). By integrating the intensities of the fields at the exit over the upper and the lower half-planes, the modulation of the output signal as a function of the phase shift between modes can be calculated. The results indicate that in order to obtain more than 70% modulation, the single mode part must have a thickness below 160 nm. The confinement factors for both, the fundamental and first order modes in the bimodal part were calculated as 0.94 and 0.67, respectively.

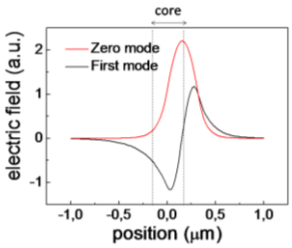

Figure 2. Distribution of the electric field of both modes in the bimodal waveguide.

The losses at the modal splitter junction were studied by two computational electrodynamics modeling algorithms, the beam propagation method (BPM) and the finite-difference time-domain method (FDTD). In BMP, only light dispersed in an angle smaller than 30-40° in the propagation direction is displayed. However, FDTD can show dispersed light for higher angles as well as retrodispersed light. Logarithmic representations of the electromagnetic fields for both algorithms (see Fig. 3) indicate that at the transition junction the quantity of dispersed light is very small, the retrodispersed light is negligible, and that the light is well-confined within the waveguide structure.

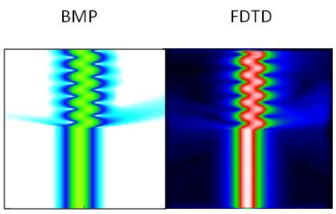

Figure 3. Logarithmic representations of the electromagnetic field in the splitter region of a BiMW device by BMP and FDTD methods.

IV. Fabrication and Characterization

The devices were fabricated using silicon-based standard microelectronics technology at Clean Room facilities. A thermal SiO_2 cladding layer (2 μm) was grown over a silicon wafer. A core layer of 340 nm of Si_3N_4 was deposited by LPCVD technique. The rib channel waveguide was defined by BHF etching using conventional photolithography. Then, the thickness of the single mode part of the waveguide was decreased to 150 nm. The wafer was covered by a protective SiO_2 layer deposited by PECVD technique. A sensing window (15 mm x 50 μm) was opened by wet etching in this layer. The wafer contains 12 chips; the size of each chip was 30 × 10 mm^2 in size and contains 16 BiMW devices.

We have done a structural characterization of the 16 rib waveguides in the same chip by Atomic Force Microscopy (AFM). An average rib width of 4.45 ± 0.02 μm and a height of 1.22 ± 0.03 nm were evaluated. The high reproducibility of the results indicates the quality of the fabrication process. A 3D AFM image of one of the waveguides is shown in Fig. 4a.

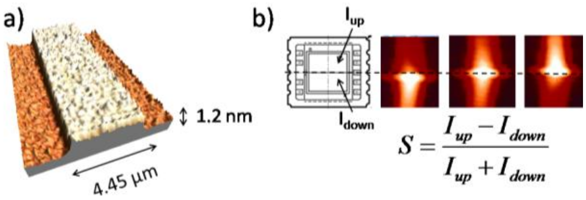

Figure 4. a) 3D AFM image of a rib waveguide and b) output signal.

For the optical characterization of the devices, TE light from a He-Ne laser (15 mW) was coupled into the waveguide using a microscope objective (40×). The interference pattern at the end of the waveguide (see Fig. 4b) was monitored using a two sectional photodiode. The light at the output generates currents I_{up} and I_{down} at the photodetector. The intensity values were used to calculate the normalized output signal (S). The system provided temperature stabilization of the chip with 0.01 degrees accuracy. Using these conditions, the fluctuations of the S parameter did not exceed 1 % during 2 h.

V. Biosensing Evaluation

A 4-channel fluidic cell was fabricated by molding PDMS with a master of PMMA (see Fig. 5a). By using a syringe pump and an injection valve, different solutions were flowed over the sensor surface to functionalize it. In this way, we have immobilized human growth hormone (hGH) by covalent bonding. Then, a 3 nM concentration of the monoclonal antibody against hGH (mAb hGH) was flowed, producing a specific biomolecular interaction which is detected in real-time by the sensor (Fig. 6). The same concentration of a nonspecific antibody (mAb BSA) gives a negligible signal.

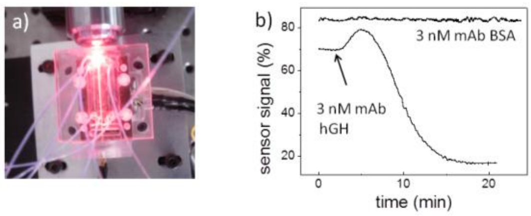

Figure 5. a) 4-channel fluidic cell and b) interferometric detection of a 3 nM of mAb hGH.

Acknowledgment

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