Silicon Nitride Bimodal Waveguides for High Sensitivity Biosensors

K. E. Zinoviev, C. Dominguez
Micro and Nanosystems Department,
Instituto de Microelectronica de Barcelona, CNM (CSIC)
Campus UAB, 08193, Cerdanyola del Valles, Barcelona
Spain
kirill.zinoviev@imb-cnm.csic.es

L. M. Lechuga
Nanobiosensors and Bioanalytical Applications Group
CIN2 (CSIC-ICN)
Campus UAB, 08193, Cerdanyola del Valles, Barcelona
Spain
laura.lechuga@cin2.es

Abstract—**The fundamental properties of a bimodal waveguide interferometer were studied to evaluate its suitability for high sensitive biosensing applications.**

Keywords- Bimodal waveguide, biosensors,, integrated optics, multimode waveguides, optical waveguides

I. Introduction

Among the interferometric devices widely used for sensing applications the most common are the ones based on Mach Zehnder and Young interferometers. These devices have two separated in space single mode waveguide branches, one of which is provided with a sensing window. The speed of the light propagation along the sensing arm of the waveguide depends on the optical properties of the analyte deposited over this waveguide window. The relatively simple design, high integration level, well developed read out techniques, and high sensitivity (2×10^{-8} refractive index unit (RIU) [1]) made these devices very attractive for label-free biosensing applications. Y-shape junction or more complicated structures are employed to deliver the light in the two branches with 3 dB split ratio in order to achieve 100% modulation at the output. Fundamentally, the sensitivity is limited by the length of the sensing window, but in practice is limited by other factors, such as the noise in the detection system, the accuracy of sensor fabrication, by the stability of the light coupling. In order to make the device insensitive to temperature fluctuations, the waveguide branches are placed very close to each other, ~50 µm, thus, the temperature fluctuations affect both waveguides simultaneously. A substrate made of a material with high thermal conductivity, silicon for example, is preferred; so that no significant temperature gradients are expected to appear over the chip.

The devices dealing with modal interference employ single waveguide supporting the interfering modes [2, 3]. The modes propagating with different velocities create at the exit an interference pattern where the intensity distribution depends on the physical parameters of the structure, and, in particular, on the refractive index of the cladding layer. The sketch of the device is presented in Fig.1. The simplicity of the design of bimodal waveguide (BW) devices is attractive for fabrication of biosensors on their basis; there is no need for the design and fabrication of Y-shape splitters, which are the most complex component of MZI device responsible for the modulation depth of the output signal and, subsequently, for the sensitivity.

For implementation of the BW device a light source with a narrow spectral line, stable in time, and with a coherency length of several millimeters is required. This allows creating a high contrast interference at the output of the BW. Temperature sensitivity of BW device is an intrinsic property resulting from the fact that propagation constants of the modes are differently affected by temperature changes. To take advantage of this, the temperature might be used for initial adjustment of the interference pattern.

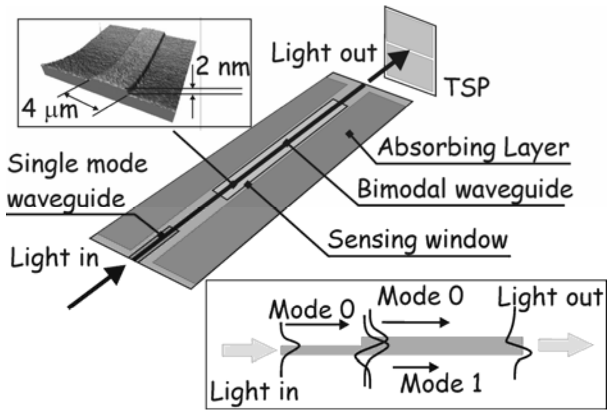

Figure 1. Sketch of the device. Top inset: an AFM image of the ridge designed for single mode operation of the waveguide in lateral direction. Inset below: the principle of mode splitting is sketched.

The interference pattern is independent on the light intensity and the output signal is not sensitive to fluctuations in coupling efficiency. The quality of the end facet, either polished or cleaved, should be good enough to register the interference of the modes. Both modes, once excited, are suffering of scattering on surface imperfections. The first order mode is normally scattered more than the zero order mode, because the concentration of the electromagnetic field of this mode is stronger at the interface waveguide-cladding. The waveguide should be maintained defects-free as much as possible in order to reduce scattering. Relatively strong defects might result in regeneration of the modes with additional phase shifts.

In this work we discuss the above mentioned issues which are important for the implementation of a BW device as a high sensitive biosensor.

II. Experiment

The sensor is fabricated over a silicon substrate. A silicon nitride layer with thickness of 340 nm was deposited using LPCVD technique on a thermally grown silicon dioxide buffer layer. A ridge type channel waveguide with ridge height of 2 nm was formed by BHF etching through a photoresist mask patterned by conventional photolithography. We used a step junction in order to excite two modes inside the BW. The fundamental mode propagating down a single mode waveguide in the beginning is split in fundamental and first order modes on the junction. According to our calculations in order to obtain more than 70% modulation, single mode part must be less than 160 nm thick. It is difficult to achieve 100% modulation using this method. In the experiment the single mode part of the waveguide was 150 nm thick.

Light exiting the waveguide is projected on two sectional photodetector (TSP). The signals U_{up}, U_{down} generated by correspondingly the upper and the lower sections of the photodetector are recalculated into a parameter S_r, according with the expression:

$$S_r = \frac{U_{up} - U_{down}}{U_{up} + U_{down}} \tag{1}$$

The chip was mounted on a thermoelectric element with temperature stabilization of 0.001 degrees. Light from He-Ne (633 nm) laser was coupled into the chip using direct focusing of light by an objective lens to a polished waveguide facet. The temperature of the chip support was constantly monitored together with the parameter S_r.

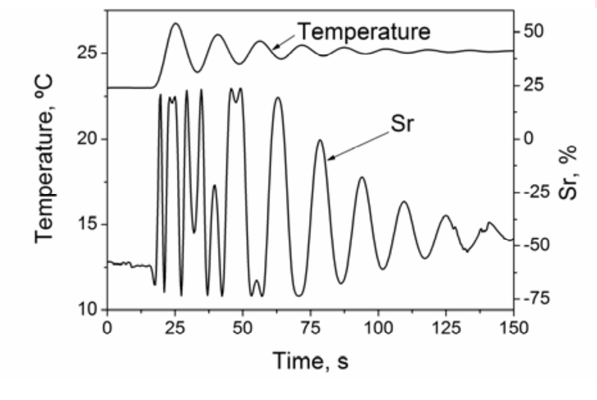

Figure 2. Response of the sensor to the temperature changes

Temperature fluctuations resulted in a chip displacement which can affect the coupling efficiency, but this did not affect the modulation depth and the sensitivity of the device. The time diagram of temperature and the readout signal are shown in Fig. 2. The parameter S_r changed by 14.3 % per 0.1 degree of temperature change.

Experiments on sensitivity to the changes in the refractive index of the cladding layer were performed by injecting a varying water:glycerin solution over the sensing window. For this purpose the chip was mounted in a PMMA fluidic cell connected to a peristaltic pump. Prior to the measurements, the signal was stabilized by injection of deionised water. Afterwards, two solutions with refractive indexes different from one of water by 1.4×10^{-4} and 5.2×10^{-4} were injected into the channel, respectively.

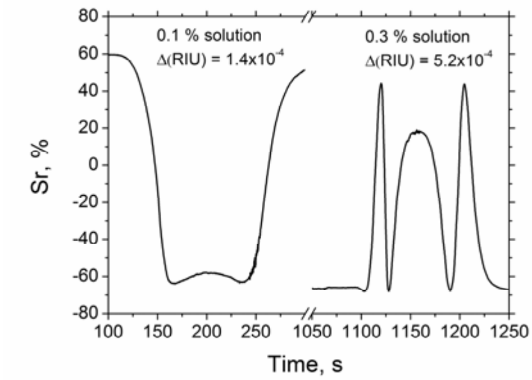

Figure 3. Response of the sensor to injection of glycerin solutions with concentrations of 0.1 % and 0.3 % (both by volume)

Fluctuations of S_r with amplitude of more than 60% can be observed in Fig.3. A phase change of more than π radian per 0.00014 cladding RIU change was observed. At the most sensitive position, where the curve slope is at the maximum, detection of a refractive index change of 10^{-6} is possible if the accuracy in detection of the parameter S_r is better than 1%.

In order to prove the expected sensitivity of the biosensor, experiments are in progress for the immunodetection of two pituitary peptide hormones with relevant biological interest and diagnostic value. We are evaluating the human growth hormone (hGH) and the follicle stimulating hormone (hFSH), which have been previously evaluated with our commercial SPR biosensor (Sensia SL., Spain).

Acknowledgment

Authors acknowledge the financial support from Fundación M. Botín and the SENA project (TSI-020301-2008-11) from the Spanish Ministry of Industry.

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