INTEGRATED INTERFEROMETRIC BIOSENSOR BASED ON OPTICAL WAVEGUIDES CMOS COMPATIBLE

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Abstract: We have fabricated using silicon technology an integrated Mach-Zehnder nanodevice based on Total Internal Reflection (TIR) waveguides with a very high detection limit in changes of the refraction index $\Delta n_0, \text{min} = 2.5 \times 10^{-6}$. Some examples of biosensing applications are shown.

Keywords: Integrated Optics, Mach-Zehnder nanodevice, biosensing applications

INTRODUCTION

There is an increasing interest in systems based on micro/nanotechnologies for ultrasensitive and miniaturised biosensors. Genomics and proteomics sensing are fields where new laboratory analysis (faster, direct, multianalyte, more accurate, smaller and cheaper than conventional methods) are demanded. Integrated optical Mach-Zehnder interferometer (MZI) devices fabricated with micro/nanotechnologies are highly sensitive bio/chemical sensors. Due to their high sensitivity, mechanical stability and microelectronics fabrication, these devices are quite suitable for further integration in a microsystem. The hybrid integration of sources, sensors, photodetectors, CMOS electronics and fluidic functions on the same microsystem will render in a complete lab-on-a-chip.

TIR WAVEGUIDES

We have fabricated an integrated Mach-Zehnder nanodevice based on Total Internal Reflection (TIR) waveguides. An input optical waveguide is split in two arms which, after a certain distance, recombine again in an output optical waveguide. The sensor is completed covered with a protective layer and only in one of the arms, a sensor area of length $L$ is opened to bring into contact the waveguide and the environment. When a chemical or biochemical reaction takes place in the sensor area, light traveling in this branch will experience a phase shift in comparison with the guided light in the other branch. Finally both beams will be combined showing a sinusoidal variation in the intensity that depends on the difference of the effective refraction indexes of both arms and on the interaction length. Due to the evanescent sensing approach employed by the sensors, the optical waveguides must be monomode and must be designed to assure high surface sensitivity

$$ S_{\text{sup}} = \frac{\Delta \Phi}{2 \pi d}, $$

which is defined as the rate of change of the phase shift of the guided mode, $\Delta \Phi$, as the thickness of the homogeneous molecular adlayer, $d$, varies. The fabrication is performed on our clean room facilities using a CMOS compatible process. The general structure of these optical waveguides (Fig 1) is: (i) a Si substrate, (ii) a cladding of SiO$_2$ (2 μm thick, $n=1.46$), grown by thermal oxidation of the Silicon substrate, iii) a core of Si$_3$N$_4$ of 200 nm thickness and a refractive index of 2.00 deposited by Low Pressure Chemical Vapor Deposition (LPCVD). To achieve monomode behaviour is needed to define a rib structure, with a depth of only 4 nm, on the core layer by a lithographic step. Finally, a 2 μm silicon oxide protective layer ($n=1.46$) is deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) at 300°C. In one of the arms (sensor arm) the SiO$_2$ layer was etched in a 50 μm wide and 15 mm large to define such area. A structural characterization of these layers was done by atomic force microscopy (AFM). Silicon nitride has a Mean Roughness (RMS) of 2 Å and silicon oxide of 5 nm. Figure 2 shows the width and height of the rib waveguide.

EXPERIMENTAL SET-UP

We have used a fiber coupled laser source ($\lambda = 635$ nm, $W_{\text{max}}=4.5$ mW) connectorized to a monomode optical fiber. The polarization of the guided light through this fiber was controlled by a fiber polarization controller. The polarized light guided through the monomode fiber was end-fire coupled to the MZI. The output light from the MZI core was collected by another optical fiber that was connectorized to a PIN silicon photodiode and amplified. Precise translational stages are used for the accurate alignment of all the components.

STUDY OF THE SENSITIVITY

The sensor has been designed for the detection of biochemical interactions between a receptor molecule and its complementary analyte. The effect of this reaction is comparable to a change of the bulk refractive index of the outer medium. Therefore, the use of solutions with different refractive indexes is useful for studying the sensor...
sensitivity. Several solutions were prepared with different concentrations of alcohol in water, with refractive index varying from 1.3328 to 1.3388 (± 0.0002). With these measurements, a calibrating curve was constructed where the phase response of the sensor is plotted versus the variation in the refractive index. Results for the transversal magnetic (TM) polarization are shown in Figure 3 for an interferometer with a sensor area of length L=15 mm. The experimental sensitivity measured for this device is $\frac{d\Delta \phi(2x)}{dn} = 4057$ and the minimum change the refractive index detected is $\Delta n_0, \text{min} = 2.5 \times 10^{-6}$. This value corresponds to a Surface Sensitivity around $S_{\text{sup}} = \frac{d\Delta \phi(2x)}{dd_0} = 10$ nm$^{-1}$, a value close to the maximum surface sensitivity reported up to now.

As an example of biosensing application we have analysed the detection of the pesticide carbaryl with immunoassays technics. The surface of the sensor area (silicon nitride) is previously modified by a silanization process to bind covalently the receptor molecules. Figure 4 shows the binding of the hapten derivative on the sensor surface. The total phase change corresponds to the adsorption of a homogeneous antigen monolayer of average thickness $d_i = 3.2$ nm (surface coverage of 1.6 ng.mm$^{-2}$).

In Figure 5 the calibration curve of the sensor for different concentrations of carbaryl is shown. The limit of detection for the carbaryl is around 0.06 µg/l.

Another example of biosensing application is the hybridization of the DNA sequences showing a sensitivity of 12 nM that means an estimation of $4 \times 10^9$ DNA molecules hybridated along the sensor area of the interferometer.

REFERENCES