Design of Integrated Optical Waveguides for Highly Sensitive Sensors

A. Llobera¹, F. Prieto², L.M. Lechuga², A. Calle² & C. Domínguez¹

Centro Nacional de Microelectrónica (CNM-CSIC)
¹IMB. Campus UAB - 08193 Bellaterra, Barcelona (Spain)
²IMM. Isaac Newton, 8 - 28760 Tres Cantos, Madrid (Spain)

Abstract

Silicon based ARROW-A structures have been designed in order to obtain a high sensitive integrated optical transducer for sensing applications. The sensor has a Mach-Zehnder interferometer configuration. The optical waveguides that conform its structure have to verify two conditions: monomode behaviour and high surface sensitivity. In this paper we present a theoretical simulation of the propagation characteristics and surface sensitivity of the ARROW-A structure. According to the obtained results, several waveguides that verify the conditions mentioned above have been designed and fabricated for implementation in the Mach-Zehnder interferometer.

1. Introduction

One important step in the development of chemical sensors is the design and fabrication of a physical transducer capable of transform, in an efficient way, a chemical or biological reaction in a measurable signal [1]. There are several physical methods to obtain this transducing signal like those based on amperometric, potentiometric or acoustic systems. However, transducers that make use of optical principles offer more attractive characteristics such as the immunity to electromagnetic interference, the use in aggressive environments and, in general, a higher sensitivity. Moreover, optical sensors based on integrated optics add some other advantages as a better control of the light path by the use of optical waveguides, a higher mechanical stability and a reduced size. In the sensors based on the evanescent wave, although light travels confined within the optical waveguide, there is a part of the guided mode (called the evanescent field), that interacts with the surrounding environment. When there is a chemical reaction at the waveguide surface, as it can be understood as a refractive index variation, the evanescent field detects this change and induces a modification of the optical properties of the guided mode.

Among the different techniques to detect this variation, we have chosen an interferometric method based on the Mach-Zehnder configuration due to its higher sensitivity compared to other schemes [2]. For sensing use, the optical waveguides that conform the Mach-Zehnder interferometer, have to verify two important conditions: a monomode behaviour and a high surface sensitivity. These characteristics make crucial the design and fabrication of the optical waveguides for the development of a high sensitive optical sensor.

In this paper we will focus on the design of such integrated optical waveguides that will be fabricated with standard IC Silicon technology. The use of this well known technology will allow the integration of sources, sensors, detectors and amplifier circuitry on the same chip, important subject for mass production.

2. The ARROW structure

The optical sensor is based on the ARROW-A (AntiResonant Reflecting Optical Waveguide) structure [3]-[6]. The optical confinement of light in these waveguides is based on the total internal reflection at the air-core interface and a very high reflectivity, of 99.96%, at the two cladding layers (Figure 1). Each layer behaves as a quarter wave plate and, for a given wavelength, their refractive indexes and thickness have to be accurately selected. Therefore, this structure is a kind of leaky waveguide (it does not support guided modes) that have an effective single-mode behaviour, that is, higher order modes are filtered out by loss.
discrimination due to the low reflecting of the interference cladding. Other important features of this structure are:

- low losses for the fundamental mode
- polarization selective characteristics, that is, TM-polarized light presents higher losses than TE-polarized light
- large tolerance for the design of the refractive indexes and thickness of the cladding layers

This ARROW waveguiding concept came to solve the two main limitations of the conventional TIR (Total Internal reflection) waveguides: the reduced dimensions for monomode behaviour (an important subject for further technological development and mass-production of the sensors) and the high insertion-losses in the optical-interconnects fiber-waveguide. With ARROW structures we can have monomode behaviour with a core thickness of the same size as the core of a single mode optical fibre, suitable for efficient fire-end coupling.

2.1. Design of the optical waveguide

For a given wavelength, \( \lambda \), and refractive indexes of the interference cladding, \( n_1 \) and \( n_2 \), the thickness that verify the antiresonant condition can be expressed as:

\[
d_1 = \frac{\lambda}{4 \cdot n_1} \left[ \frac{1}{1 - \left( \frac{n_e}{n_1} \right)^2} + \left( \frac{\lambda}{2 \cdot n_1 \cdot d_{ce}} \right)^2 \right]^{-\frac{1}{2}} (2 \cdot N + 1)
\]

\[
d_2 = \frac{d_{ce}}{2} (2 \cdot N + 1)
\]

where \( N,M=0,1,2,\ldots \) and \( d_{ce} \) is the equivalent core thickness,

\[
d_{ce} = d_c + \xi_o \frac{\lambda}{2 \cdot n \cdot \sqrt{n_e^2 - N^2}}
\]

\[
\xi_o = \begin{cases} 
1 & \text{TE modes} \\
\left( \frac{n_o}{n_c} \right)^2 & \text{TM modes}
\end{cases}
\]

with \( N \) the effective refractive index of the guided mode.

There are several theoretical methods to simulate the propagation characteristics of the ARROW structure: Multilayer Analysis [7], Perturbative Methods [8], Spectral Index [9] or Non-Uniform Finite Difference Method [10]. The latter has demonstrated to have a greater computational efficiency compared to others and was used to calculate, for a design wavelength of 0.633 \( \mu \text{m} \), the effective refractive index and attenuation losses for the following ARROW structure (Figure 2):
- substrate: Silicon
- second cladding: SiO\(_2\), \( n_2 = 1.46\)
- first cladding: Si\(_3\)N\(_4\), \( n_1 = 2\)
- core: SiO\(_2\); \( n_c = 1.46-1.49\)

Figure 3 shows the attenuation losses of the first four TE modes versus the thickness of the second cladding layer, \( d_2 \), assuming that the thickness of the first cladding layer satisfy the antiresonant condition. When \( d_2 \) is nearly equal to the half thickness of the core, the attenuation of even order modes reaches its minimum value, while attenuation for the odd order modes is maximum. This is the antiresonant condition for the second cladding layer.

![Fig. 2. ARROW structure](image)

![Fig. 4. Attenuation versus core thickness for ARROW-A waveguides](image)
We also evaluated the attenuation losses for the fundamental TE<sub>0</sub> mode as a function of the thickness and refractive index of the core. Results can be seen in Figure 4. As the refractive index of the core increases, attenuation for the fundamental mode decreases. However, higher order modes also present lower losses, being possible that the ARROW structure would lose its single mode behaviour. This fact would be a drawback for sensing applications and, therefore, the refractive index of the core has to be precisely controlled.

Finally, in order to obtain a lateral confinement of light, a rib structure has to be designed (Figure 2). Propagation characteristics, as well as single mode behaviour, will depend on the width and depth of the rib. Experimentally, we have observed a good lateral confinement for rib depths of the order of 75% of the core thickness. Regarding the rib width, a lateral dimension lower than 5 μm would be enough to obtain a single mode behaviour.

3. Sensitivity calculations

For sensing purposes, the optical waveguide structure has to be designed to assure a high sensitivity, that is, the sensor response for changes in the optical properties of the cover medium has to be as high as possible. This sensitivity depends on the strength and distribution of the evanescent field in the outer medium [12], [13].

We can distinguish between two different sensor sensitivities depending on how is the refractive index change in the outer medium:

a) if this change is homogeneously distributed in the cover (homogeneous sensing), sensitivity is related to the integral of the squared evanescent field in the outer medium.

b) if there is an adsorption of molecules from a gaseous or liquid sample on the waveguide surface (surface sensing), sensitivity is related to the squared field magnitude at the waveguide-core interface.

In the first case, sensitivity is evaluated as the rate of change of the effective refractive index of the guided mode, \( N \), with respect the thickness of the adsorbed film, \( d_1 \). For a slab waveguide, surface sensitivity is expressed as,

\[
\frac{\partial N}{\partial d_1} = \frac{n_0^2 - N^2}{n_c^2 - n_0^2} \frac{2}{N/n_c} \left\{ \frac{(N/n_o)^2 + (N/n_1)^2}{(N/n_o)^2 + (N/n_c)^2} - 1 \right\} \]

\[
\rho = \begin{cases} 0 & \text{TE mode} \\ 1 & \text{TM mode} \end{cases}
\]

3.1. Sensitivity of ARROW's

Numerical simulations of the sensitivity for a slab ARROW structure were performed for the homogeneous and surface sensing cases. The ARROW consisted on a SiO<sub>2</sub> core with a refractive index of 1.485 and a two cladding layers of Si<sub>3</sub>N<sub>4</sub> (n<sub>1</sub>=2) and SiO<sub>2</sub> (n<sub>2</sub>=1.46), respectively. Calculations were done for the fundamental TE mode and results can be seen in Figure 5.

![Fig.5. a) Homogeneous sensitivity. b) Surface sensitivity.](image-url)
confinement of light within the core which implies an increase of the penetration depth of the evanescent field in the outer medium. Therefore, the sensor response to a homogeneous refractive index change increases as it is directly related to the integral of the squared evanescent field in the outer medium.

For the adsorption of a homogeneous layer from a gaseous or liquid phase on the waveguide surface, results are very similar to those from the homogeneous sensing case. As it may be seen in Figure 5, surface sensitivity increases as the core thickness decreases, because the electric field of the guided mode at the interface between the waveguide and the cover medium is stronger.

In both cases, for thick waveguides, the guided mode flows mainly within the core and we have $d_{\text{eff}} = d_c$. Consequently, the sensitivities $\frac{\partial N}{\partial n_r}$ and $\frac{\partial N}{\partial d_f}$ decrease to zero proportionally to $\frac{1}{d_{\text{eff}}}$.

4. Conclusions

ARROW structures are promising waveguides for the development of high sensitive integrated optical sensors. Their fabrication process, based on standard IC Silicon technology, and the large tolerance for the design of the refractive indexes and thickness of the waveguide layers, makes them very appropriate for low-cost mass production. Moreover, they have an effective single-mode behaviour even when the core thickness is of the same order of magnitude as the core of a monomode optical fibre; this characteristic makes them suitable for efficient connection with optical fibres.

For sensing applications, ARROW structures must verify two conditions: they have to be monomode and they should show a high surface sensitivity. To obtain a single mode behaviour, we must assure large attenuation losses for the higher order modes. For that reason, the refractive index of the core should be kept under a certain value, i.e. 1.485.

Concerning the second condition, sensitivity increases as the core thickness diminishes. However, we are limited by the attenuation losses when the size of the core is lower than a certain value, i.e. 1 μm.

Taking into account these results, we have decided to design and fabricate ARROW structures with a core refractive index of 1.485 and different thickness of 1.5, 2, 3 and 4 μm. Optical characterisation of the fabricated structures are in progress.

References