Analysis of homogeneous sensitivity of rib-waveguides for Mach-Zehnder interferometer

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Abstract— **The Mach-Zehnder interferometer has successfully been employed for biosensing with a minimum detectable change of about 10^{-7} in the refractive index. In this paper we use numerical simulations to study the influence of waveguide parameters on the sensitivity. The waveguides considered are rib waveguides made of Si_3N_4, with a sensitive layer of doped PDMS for gas sensing. The sensitivity is found to be strongly dependent on the core thickness relative to the wavelength, and to some extent on the polarization. Maximum sensitivity is obtained for a core thickness of 120 nm for TM-polarized light of wavelength 780 nm and 100 nm for TM-polarized light of wavelength 632.8 nm. The sensitivity does not depend significantly on the height of the ribs or on their width, for the shallow ribs considered (0.5 to 5 nm height).**

Keywords-component; rib waveguide; homogeneous sensitivity; Mach-Zehnder interferomter.

I. INTRODUCTION

We present a study of sensitivity for the development of a waveguide gas sensor. As light propagates in a waveguide, the evanescent field interacts with the cover medium. A change in the refractive index of the cover medium therefore influences the effective refractive index of the guided mode. To make a gas sensor, the refractive index of the cover medium (the sensitive layer) must change when it is exposed to gas. By depositing the sensitive layer on one of the branches of a wave-guide Mach-Zehnder interferometer (MZI), changes in the effective index of the mode can be measured and thus indirectly the gas concentration.

The Mach-Zehnder interferometer has previously been used for environmental sensing [1] and biosensing [2]. Two important features are required for the Mach-Zehnder interferometer: single mode behavior and high sensitivity. In this work we present a study of the mode behavior for three different sensitive layers: water (n = 1.33), silica (n = 1.46) and doped PolyDiMethylSiloxane (PDMS, n = 1.412). Doped PDMS will be used as the sensitive layer for gas detection. We will show how the geometrical parameters of a rib waveguide influence the sensitivity of the Mach-Zehnder interferometer. As the sensitive layer will be thicker than the evanescent field, we are restricting the analysis to a homogeneous change in the refractive index of the sensitive layer.

II. MODE BEHAVIOUR

The waveguide considered for this MZI design has a waveguide core of Si_3N_4 ($n_c = 2.00$) with variable thickness, on top of a silica layer (2 μm thick, $n_s = 1.46$). The rib height is a few nanometers (see Fig. 1), while the rib width is a few micro-meters. For the mode analysis, a 2D simulation is made with the Finite Element Method, using Comsol Multiphysics. Fig. 2 shows the mode behaviors for different rib widths and rib heights, for a core thickness of 150 nm, wavelength of 632.8 nm and TE-polarization.

The simulations show that the waveguide is single mode for rib widths less than 3 μm for rib heights around 5 nm. For even more shallow ribs, the waveguide can be single mode up to 5 μm width. These very shallow ribs will not guide light unless they are several micrometers wide. The effective index of the waveguide changes little with the rib width and the rib height, while it is strongly dependent on the core thickness (not shown).

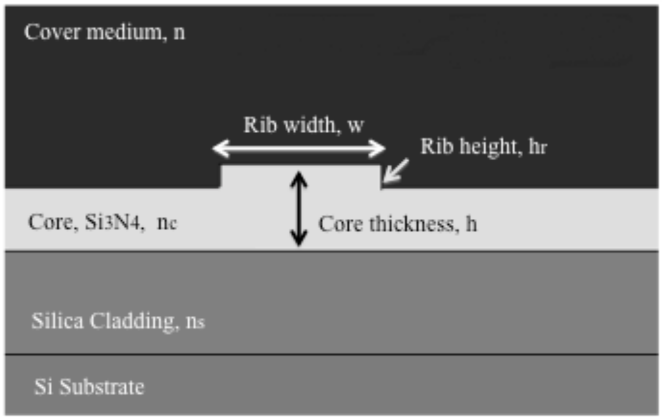

Figure 1. Cross-section of the waveguide, with the different parameters used for the 2D mode analysis.

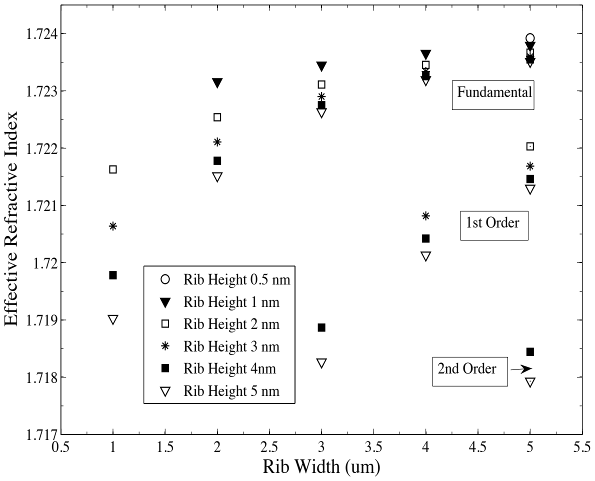

Figure 2. The effective index of the modes of the rib waveguide, versus rib width for six rib heights. The cover medium is doped PDMS (n = 1.412). Core thickness is 150 nm thick, guided by TE-polarized light of wavelength 632.8 nm. The figure shows up to three modes, depening on width and rib height.

III. HOMOGENEOUS SENSITIVITY

The homogeneous sensitivity is defined as the rate of change the effective refractive index of the guided mode, to the rate of change of the refractive index of the cover medium. The homogeneous sensitivity can be expressed as [3,4]:

$$\frac{dN}{dn} = \frac{n}{N}\left[2\left(\frac{N}{n}\right)^2 - 1\right]^{\rho} \cdot \frac{P_o}{P_T} \qquad (1)$$

where n is the cover medium refractive index, N is the effective refractive index of the guided mode in the waveguide, P_o is the power of the guided mode in the cover medium, and P_T is the total power of the guided mode. Here ρ is equal to zero for TE modes and one for TM modes. We have used simulations with the RF module of COMSOL Multiphysics to determine the parameters in (1) for various rib parameters, and used (1) to find the corresponding sensitivity.

Fig. 3 shows the calculated homogeneous sensitivity as function of the core thickness for a waveguide of 1 μm width and 5 nm height and for two wavelengths, 632.8 nm and 780 nm. The analysis shows that the sensitivity is very dependent on the core thickness and to some degree on the polarization of the guided light. The homogeneous sensitivity increases as the core thickness decreases, due to less confinement in the guided core, which implies more power in the cover medium. For even less core thickness, the sensitivity decreases as the mode approaches cut-off. In general, for TE-polarization maximum sensitivity is obtained with a thinner waveguide than for TM-polarization. The maximum sensitivity is highest for TM-polarization. Changing the wavelength merely gives a shift of the curves, as expected.

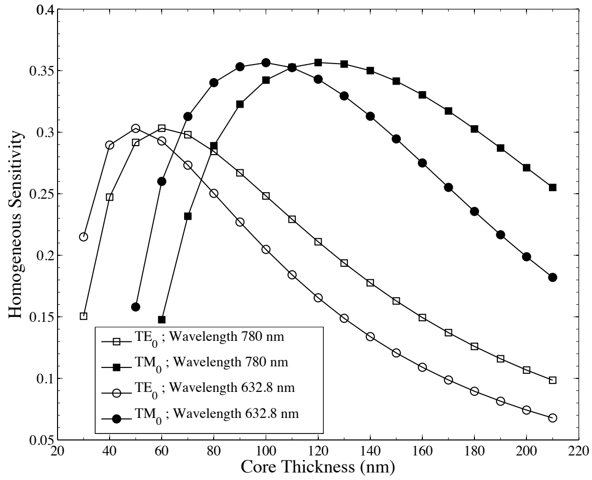

Figure 3. The homogeneous sensitivity as function of core thickness for a cover layer of PDMS (n = 1.412) for a rib waveguide of 1 μm width and 5 nm height. The waveguide were single mode for this rib width.

We have also found that the sensitivity does not vary much as function of the rib width and rib height (not shown). This can be expected from the small change in effective index relative to these parameters in Fig. 1.

In conclusion, the main factors for the sensitivity are the core thickness relative to the wavelength of light, the polarization of the light and the refractive index of the core and cover medium.

IV. FURTHER WORK

We would like to include losses due to sidewall and surface roughness in the numerical simulations.

ACKNOWLEDGMENT

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