Silicon-on-sapphire waveguides design for mid-IR evanescent field absorption gas sensors

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Abstract: We investigate three types of SOS waveguides suitable for evanescent field absorption based gas sensing in mid-IR. Rib and slot waveguide shows greater quasi-TE evanescent field than strip waveguide. 1.33ppm resolution is achievable.
OCIS codes: (130.2790)Guided waves; (130.6010)Sensors (130.3060) Infrared

1. Introduction

Silicon-on-insulator (SOI) based evanescent field sensors have been investigated intensively [1, 2]. These sensors are compatible with CMOS IC and capable of achieve chip-scale integration. However, buried oxide loss has hindered this type of sensors applying to mid-IR spectrum. Since, the mid-IR contains absorption peaks for a wide variety of gas including CO, CO_2, NO, N_2O and NO_2, this spectral range is of great importance. As a mid-IR alternative of SOI, silicon-on-sapphire (SOS) waveguide can be utilized to solve this problem [3, 4]. In this study, we investigate three types of SOS waveguides which would be used in absorption based gas sensing in mid-IR. The wavelength of 4.23um is used in the design, which corresponding to the absorption line of CO_2 in mid-IR.

2. Waveguide Design

We define the evanescent power fraction (EPF) as the ratio of evanescent field power in the cladding to the total modal power. In order to improve sensitivity, we want to maximize EPF so that the interaction between light and target material will be strengthened. In this report, three main types of waveguides are investigated for this purpose, including strip, rib and slot waveguides as shown in Fig. 1. *W* and *H* are the width and height of waveguide. *T* is the thickness of the long dielectric layer in rib waveguide and *S* is the width of the slot in slot waveguide. We fix H to 0.6um to accommodate the parameters of commercial SOS wafer we purchased from market. No pure TE or TM mode exists in these waveguides and we denote hybrid modes according to Goell's convention [5].

In strip waveguides (Fig. 2), E_{11}^{x} mode is supported with W>0.85um and EPF deceases as W increases due to the decrease on side-wall interaction. This mode shows good confinement and the tendency is straightforward. The case in E_{11}^{y} is more complicated. Mode analysis shows that the E_{21}^{x} onsets and becomes dominant at W=1um and W=1.9um respectively, each corresponding to a slope change. Large EPF in this mode is due to normal electrical displacement conservation at the top-wall boundary. In rib waveguides, E_{11}^{y} mode is not supported and EPF of E_{11}^{x} mode follows a similar fashion as in strip waveguide. However, the film layer thickness T plays an important role here. Firstly, the introduction of the film layer renders a supported E_{11}^{x} mode at a smaller width and enhances the EPF. Secondly, a too thin film layer may result in early cut-off in E_{11}^{x} mode. In slot waveguides, modes with electrical field in perpendicular to the slot will lead to a greater EPF and the optimized waveguide width is positively dependent on the slot width. Generally, special waveguides like rib and slot waveguide can support better evanescent field sensor performance, but their fabrications are more challenging.

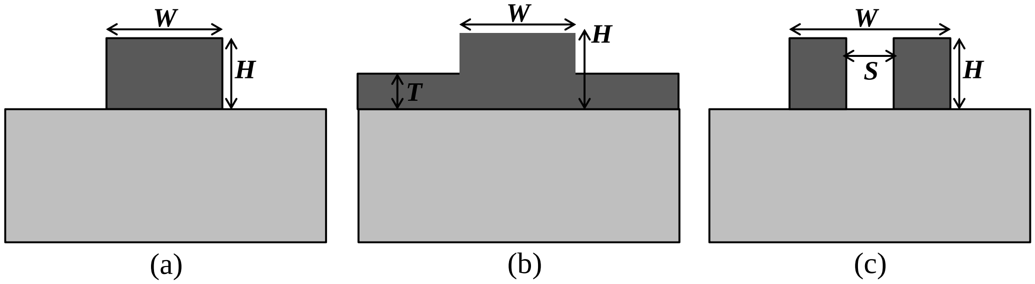

Fig. 1. Three main types of waveguides investigated: (a) strip; (b) rib; (c) slot waveguide

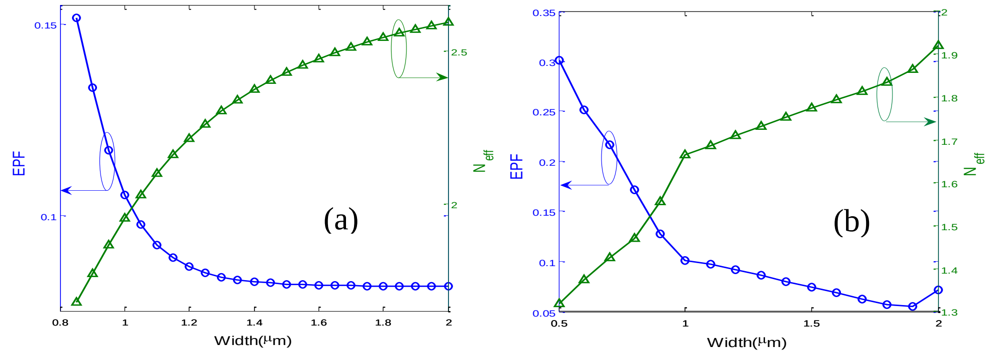

Fig. 2. EPF and effective index for the guided modes in strip waveguide: (a) E_{11}^{x} mode; (b) E_{11}^{y} mode

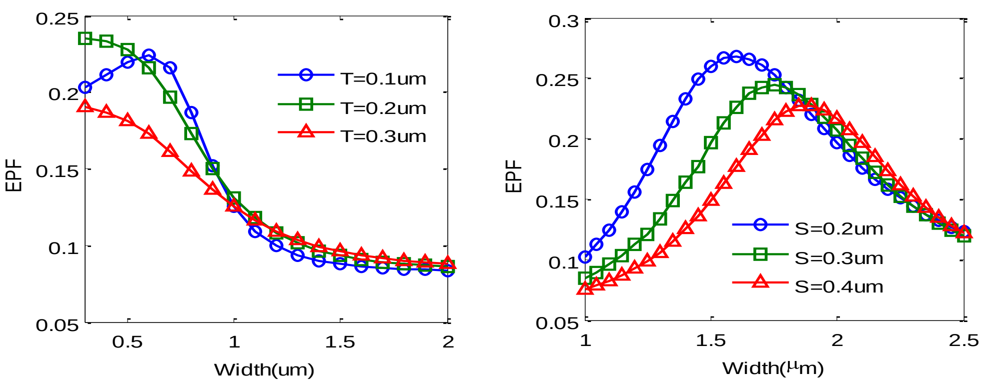

Fig. 3. EPF and effective index for E_{11}^{x} modes in (a) rib; (b) slot waveguides

3. Evanescent Field Sensing

The attenuation in evanescent field depends on the concentration of target gas in the cladding surroundings. From [6], the output optical intensity will $I \;\; c \; = I_0 \exp(-\eta\varepsilon cl - \alpha_w l)$ and for convenience we normalize this intensity as $I_{norm} \;\; c \; = I \;\; c \; / I \;\; c = 0 \; = \exp(-\eta\varepsilon cl)$. We can further derive the sensitivity S and resolution Δc of the sensor as

$$S = \frac{dI_{norm}}{dc} = -\eta\varepsilon l \exp(-\eta\varepsilon cl) \tag{1}$$

$$\Delta c = \frac{NEP\sqrt{B}}{SI(0)} = \frac{NEP\sqrt{B}}{SI_0 e^{-\alpha l}}, I(0) > NEP\sqrt{B} \tag{2}$$

Assuming a waveguide with EPF=0.2 and waveguide length of 10cm. We characterize the system using commercial HCT detectors and IR sources at room temperature and standard pressure. We can get a 1.33ppm resolution of CO_2 with a standard CO_2 concentration in the atmosphere. This indicates the sensor's capability of monitoring the dynamic CO_2 concentration in the atmosphere.

4. Acknowledgement

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5. References

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