# SOI Slot Waveguide Based on-Chip Trace Gas Sensor in the Mid-IR

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**Abstract:** We numerically propose design of a silicon-on-insulator slot waveguide based $NO_2$ gas sensor with evanescent field fraction as high as ~ 41% at a wavelength of 3.4 μm.

## 1. Introduction

Recently, integrated *siliconized* photonics, made an excellent entry to the label-free optical sensing domain owing to their CMOS fabrication compatibility, low energy consumption, extremely low foot prints, and infrared (IR) to mid-IR transparency. This mid-IR transparency of silicon-on-insulator (SOI) waveguides (WGs) can be exploited for hazardous trace gas sensing [1] through evanescent field absorption (EFA)-based scheme [2]. Nitrogen oxides ($NO_x$) are some of the more damaging pollutants that impact the environment as well as public health in multiple ways. Here we propose an efficient SOI based slot-WG for environmental $NO_2$ gas sensing at 3.4 μm. Among various SOI-WG structures the slot WG of moderate dimension offers maximum evanescent field fraction (EFF), which is the key performance parameter of an EFA-based sensor. EFF as high as ~ 41% is achievable with the proposed WG.

## 2. Theory, Proposed Structure and Results

*EFA-Based Sensing*

The evanescent tail of WG interacts with the surrounding gas medium and the transmission of the propagating light will change at the corresponding absorption lines of the gas. According to Beer-Lambert's law [1], the transmitted intensity at the output can be written as

$$I_{out} = I_0 \exp(-\eta \varepsilon c_g L - \alpha L) \qquad (1)$$

where, $I_0$ is input intensity, $\varepsilon$ is absorption coefficient, $L$ is WG length, $c_g$ is gas concentration, $\alpha$ is intrinsic loss of WG and $\eta$ is the EFF [2]. By differentiating Eq. (1) with respect to $c_g$, we can get the sensor's sensitivity ($S$) as

$$S = \frac{dI_{norm}}{dc_g} = -\eta \varepsilon L \exp(-\eta \varepsilon c_g L - \alpha L) = -\eta \varepsilon L I_{norm} \qquad (2)$$

*Proposed Structure*

A full-vectorial, commercially available FIMMWAVE software® is used to analyze the 2-D WG. Our proposed structure is a Si-vertical slot WG with $SiO_2$ substrate and gas medium as forming the cover and the slot region (cf. Fig. 1(a)). The intensity profile is shown in Fig. 1(b), where maximum evanescent field lies in the slot region.

*Results and Discussions*

We have checked that among various options for a SOI WG, slot WG offers maximum EFF. We studied the variation of EFF for the slot WG [cf. Fig.1(a)] by varying its two widths ($W$, $W_s$) and height ($H$). For different values of $W_s$ and $H$ an optimum $W$ exists at which $\eta$ becomes maximum. We have calculated that maximum $\eta$ as high as ~ 41% is achievable for $W = 0.5$ μm, $W_s = 0.15$ μm and $H = 0.6$ μm.

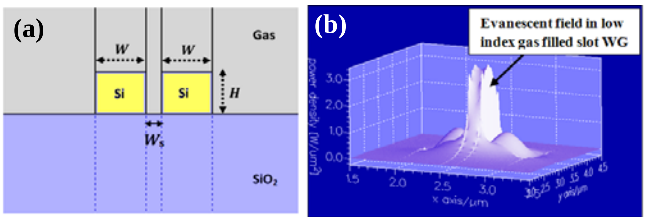


**Fig. 1.** (a) Cross-sectional view of the proposed Si-slot WG with gas as a cover and filling the slot and $SiO_2$ as the substrate. (b) Power density plot of slot WG. Evanescent field inside the low index slot region is very high.

In the next step, we used this structure to study the detection sensitivity of $NO_2$ gas. Atmospheric $NO_2$ concentration lies between 20 - 200 ppm. We choose our base $c_g$ value as 50 ppm and studied the variation in $S$ with $L$ for different values of $\eta$ and $\alpha$. For each set, $S$ attains a maximum at a certain optimum $L$ ($L_{opt}$). With $\eta = 0.41$ and $\alpha = 5$ dB/cm (typical loss of Si slot WG), $L_{opt} \approx 8$ mm. Then variations of output intensities ($I_{out}$) for three different values of $c_g$ (10, 50 and 100 ppm) were studied with wavelength ($\lambda$) and shown in Fig. 2. We assumed an input power ($P_0$) of 20 mW for this study. By boosting this input power level we can always counter the intrinsic loss of the WG.

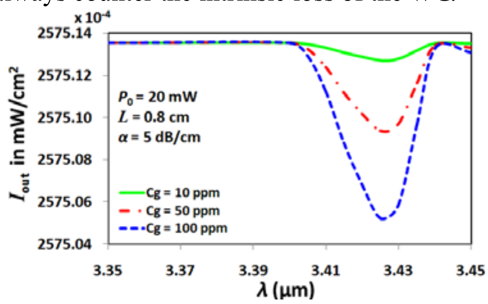


**Fig. 2.** Variation of $I_{out}$ with $\lambda$ at the end of $L = L_{opt} = 8$ mm.

## 3. Conclusions

In conclusion, design of a SOI-based slot WG is proposed to sensitively detect atmospheric $NO_2$ at ~ 3.4 μm wavelength for on-chip gas sensing application. EFF as high as ~ 41% can be achieved. Detection at low levels down to about few 10's of ppm including WG loss should be feasible with just 8 mm length of our proposed structure.

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**References**

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[2] Y. Huang et al., Opt. Com. **313** (2014) 186-194.