

Mid-infrared Silicon Platform for Chip-scale Chemical Sensors

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ABSTRACT

Mid-Infrared optofluidics based silicon sensor platforms are demonstrated. Silicon is a great candidate for mid-infrared optofluidics for the following reasons: (1) Silicon has a broad transmission window up to 7 μm (2) Silicon offers CMOS compatible and monolithic fabrication (3) Silicon has high chemical resistance that can withstand high temperature, acid/base solution and organic solvents. (4) Silicon is a non-toxic environmentally friendly material. The fabricated mid-infrared optofluidic sensor can replace bulky instruments, such as FTIR, with a lab-on-a-chip system, while achieving much higher sensitivity.

Keywords: mid-Infrared, lab-on-a-chip, silicon microphotonics

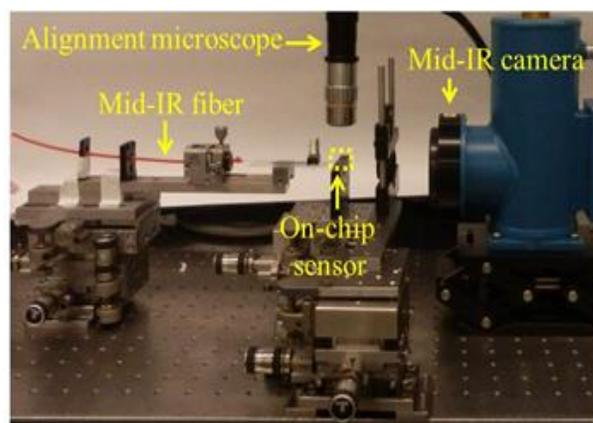
1 INTRODUCTION

Chemical sensors using integrated photonics have attracted significant attention because of their potential for large area environmental monitoring and high throughput screening for biomedical discovery.[1] Advanced technologies using absorbance, Surface Plasmon Resonance (SPR), and fluorescence detection have been developed to realize chip-scale optical sensors. For instance, chemical sensors using micro-ring resonators have been fabricated, and ppm level detectivity was demonstrated.[2] However, since these sensors are based mainly on the measurement of refractive index changes, specific identification of chemical compounds is difficult.[3] Similarly, Surface Plasmon Resonance (SPR) sensors require labeling techniques to enable specific analyte detection. Our robust air-clad pedestal silicon sensors offer a trace chemical analyte detection scheme using characteristic Mid-IR absorption spectra to simultaneously perform quantitative (target concentration) and qualitative (compound recognition) analysis.[4] Specifically, Mid-IR spectra can “fingerprint” molecular structures within functional groups present in the chemical analytes, enabling label free detection. Undoubtedly, lab-on-a-chip broadband Mid-IR sensors are

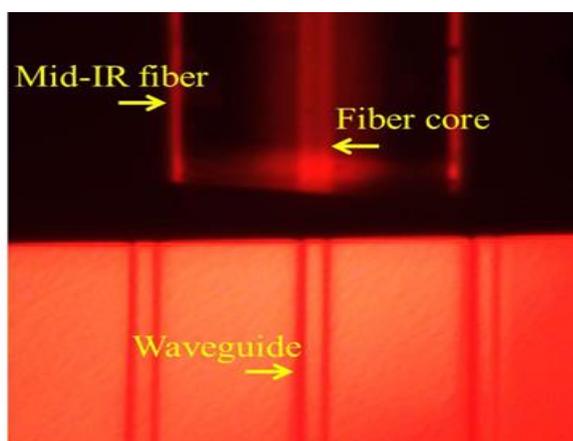
highly desirable in many applications such as remote real-time sensing of trace toxins and detection of contaminants.

2 EXPERIMENTAL SET-UP TO TEST MID-INFRA-RED OPTOFLUIDIC SENSORS

Figure 1 (a) illustrates the experimental set-up used to evaluate the performance of our chemical sensors. The light source is a pulsed laser with a wavelength tunable from $\lambda=2.4 \mu\text{m}$ to $\lambda=3.8 \mu\text{m}$, a pulse repetition rate of 150 kHz, a pulse duration of 10 nano seconds, an average power of 150 mW and a line width of 3 cm^{-1} . Using a reflective lens the probe light is collimated into a $9 \mu\text{m}$ core and $125 \mu\text{m}$ cladding single mode fluoride fiber. Light emitted from the fiber is then butt-coupled into the waveguide of the on-chip sensor as shown in Figure 1 (b), where the core of the Mid-IR fiber is lined up with the smooth cleaved front facet of the waveguide. The alignment between the optical fiber and the waveguide is performed using positioning stages with high precision adjusters that have full control of six-axes ($x, y, z, \theta, \phi, \varphi$) with $0.02 \mu\text{m}$ sensitivity. The fine adjustment is monitored by an upper microscope equipped with a long working-distance objective and high speed 800 Mbits/s CCD imager.



(a)



(b)

Figure 1 (a) Experimental set-up used to characterize the performance of fabricated Mid-IR chemical sensors. The probe light is collimated into the Mid-IR fiber and then coupled into the on-chip sensor. The waveguide mode is captured by the Mid-IR Camera. (b) Alignment between the Mid-IR fiber and the waveguide. To improve the coupling efficiency, the fiber core position (6-axis stage) is adjusted so it is optimally aligned with the waveguide.

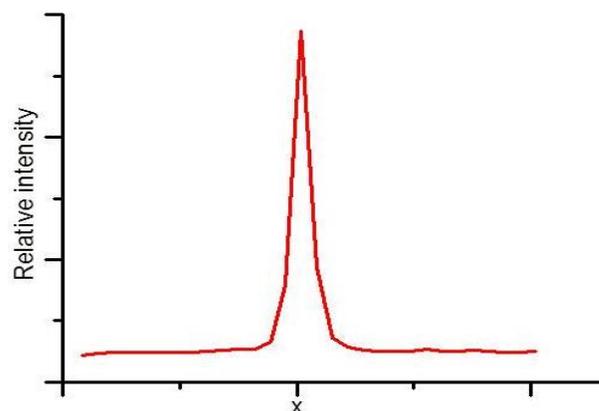
The Mid-IR signals from the on-chip sensors are captured by a liquid nitrogen cooled 320 x 256 pixel InSb camera. A calcium fluoride bi-convex lens with 25 mm focal length is placed between the on-chip sensor and the InSb camera to sharpen the image of the observed waveguide mode.

3 EXPERIMENTAL SILICON WAVEGUIDE MODE FIELD PROFILES

The waveguide modes of the on-chip sensors are experimentally characterized through the Mid-IR set-up described in Figure 1. Figure 2 (a) shows the mode image captured at $\lambda=3.3 \mu\text{m}$ and its intensity profile is plotted in Figure 2 (b). A sharp fundamental mode is clearly resolved showing no scattering or distortion which implies that the Mid-IR probe light is well confined inside the pedestal Si waveguides as predicted by the simulation. The mode profiles are also evaluated between $\lambda=3.1 \mu\text{m}$ to $\lambda=3.7 \mu\text{m}$ and fundamental modes are obtained within this wide spectral range. The broadband guided waves provide a steady light source for this application of chemical sensing and monitoring. Especially for chemical screening, to accurately identify the compounds, recording multispectral intensities are vital since each chemical has a characteristic absorption spectrum. Consistently monitoring the fundamental mode over the entire spectrum prevents undesired false positives caused by waveguide mode alteration.



(a)



(b)

Figure 2 (a) A single mode is observed for wavelengths between $\lambda=3.1 \mu\text{m}$ to $\lambda=3.7 \mu\text{m}$. As an example, the experimental optical waveguide mode captured by the Mid-IR camera at $\lambda=3.3 \mu\text{m}$ is shown (b) The intensity profile in the x direction confirms excitation of the fundamental mode.

4 TRANSIENT RESPONSE OF ON-CHIP MID-IR DETECTION AT $\lambda=3.3 \mu\text{m}$

The time-resolved response of Mid-IR detection is investigated by recording the waveguide intensity upon exposing the sensor to toluene. The probe light has wavelength $\lambda=3.3 \mu\text{m}$, and the results are illustrated in Figure 3. The intensity decreases as the toluene reaches the waveguide. After 5 s the toluene covers the entire surface of the sensor and the signal is stabilized. The waveguide intensity remains stable and low until most of the toluene evaporates - between 370 s and 400 s the intensity increases sharply as the toluene liquid layer, which is directly above the waveguide and absorbs the Mid-IR evanescent wave, has now evaporated. Increase in intensity after 400 s becomes slow because the surface tension at the toluene-silicon interface tends to retain the toluene layer on the waveguide. Eventually the intensity recovers to the original intensity at 0 s when there is no toluene on the sensor. The

transient characteristics of the toluene solvent demonstrates that the fabricated Mid-IR sensor is capable of in-situ monitoring of a chemical analyte, highly desirable for applications such as pollution control and early alarm systems.

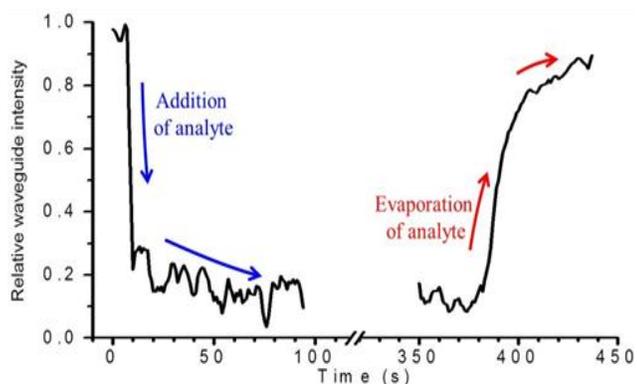


Figure 3 Real-time trace of toluene measured using our fabricated Mid-IR sensor. The waveguide intensity drops instantly as the analyte reaches the sensor, where the intensity variation is indicated by the blue arrow. After 370 s, the intensity starts to recover because the analyte evaporates as denoted by the red arrow.

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