Mid-Infrared Spectrometer Using Opto-Nanofluidic Slot-Waveguide for Label-Free On-Chip Chemical Sensing

Pao Tai Lin,*,† Sen Wai Kwok,‡ Hao-Yu Greg Lin,§ Vivek Singh,† Lionel C. Kimerling,† George M. Whitesides,‡ and Anu Agarwal†

†Microphotonics Center, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts, United States

‡Department of Chemistry and Chemical Biology, Harvard University, 12 Oxford Street, Cambridge, Massachusetts, United States

§Center for Nanoscale Systems, 11 Oxford Street, Cambridge, Massachusetts United States

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by,

S.Vidhya

Introduction

- Optofluidics : Research and technology area that combines the advantages of microfluidics and optics.
- Slot Waveguide : An optical waveguide that guides strongly confined light in a subwavelength-scale low refractive index region by total internal reflection.
- Mid-Infrared spectroscopy is a detection technique commonly used for identifying biochemicals and tracing of toxic molecules and is free of target labels and sensor surface functionalization.
- The use of mid-IR spectrum circumvents the need for labeling the sample, because the characteristic wavelength of absorption by many functional groups present in chemical or biological molecules falls within this region of the spectrum.

Introduction

In this paper,

- A new chip-scale optofluidic device that utilizes mid-IR techniques for label-free and surface functionalization-free chemical sensing.
- The optofluidic platform is built using CMOS processes and is capable of accomplishing broad mid-IR spectral sensing.
- Introducing an engineered slot-waveguide into the sensor generates a strong optical field and substantially improves the sensitivity of the device.
- They have demonstrated experimentally that utilizing mid-IR on-chip sensor can differentiate several organic liquids and can determine the molar fraction of components in a binary mixture of organic liquids at low concentration.
- This mid-IR slot-waveguide design can enable the

Introduction

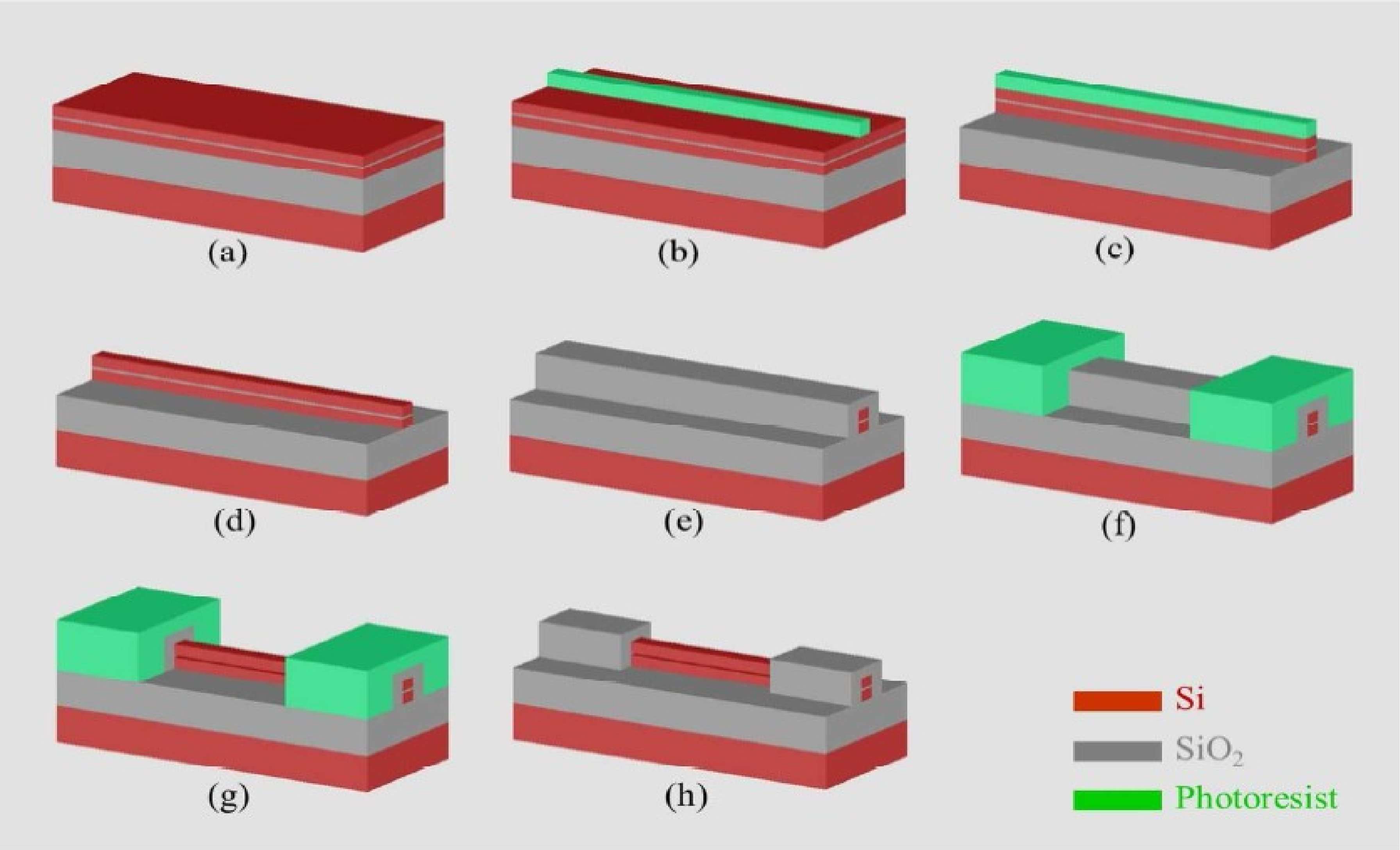
Requirements

- Platform assembled from components transparent to mid-IR radiation
- a new approach that can allow the mid-IR probe light to interact with the target analyte efficiently in the fluidic channel.

This device provides improvements over current evanescent-wave detection using fiber- or rib-waveguide in two ways:

- The availability of a broad spectral range (from λ = 2.5 µm to λ = 4 µm) enables the differentiation of multiple chemical species in the same sample
- Effective spatial confinement of the light wave in each fluidic channel significantly enhances the interaction between the probe light and the analyte and imparts high sensitivity to the device

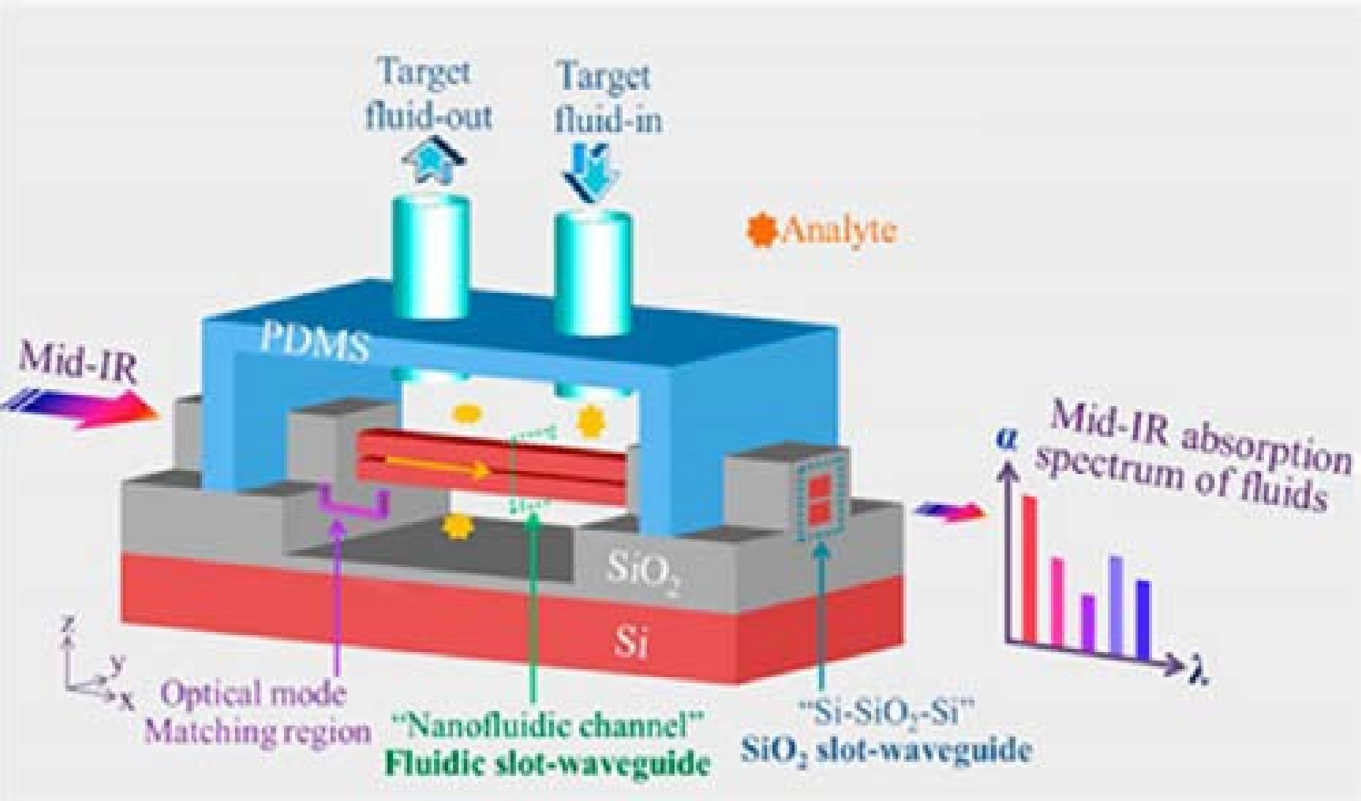
Fabrication Process



(a) Si-SiO2-Si multilayer growth by PECVD. (b) Photolithography to define waveguide and fluidic channel. (c) Pattern transfer to Si-SiO2-Si multilayer by RIE. (d) O2 plasma to remove photoresist. (e) Conformal SiO2 deposition.

(f) Photolithography to define optofluidic region. (g) BOE to remove the exposed SiO2

Schematic of a mid-IR opto-nanofluidic sensor



(i) A nanofluidic channel with a gap in which fluidic target analytes can fill *(labeled as a fluidic slot-waveguide)*,

(ii) A Si−SiO2−Si structure, which acts as an optical mode matching region as well as a mechanical support *(labeled as a SiO2 slot-waveguide)*

(iii) A PDMS fluidic chamber with an inlet and outlet for delivery of target analytes into and out of the fluidic slot waveguide.

Liquid analyte is injected in/out of the chamber through plastic tubes connected to the PDMS chamber. This liquid fills the nanofluidic channel and it is where the optical absorption for spectrum scanning takes place. Mid-IR light is initially coupled into the front SiO2 slot-waveguide and then passes through the optical mode matching region, the fluidic slot waveguide (nanofluidic channel), and finally into the SiO2 slot-waveguide on the exit end.

Experimental Setup

- The nanofluidic channel serves two functions in this device:

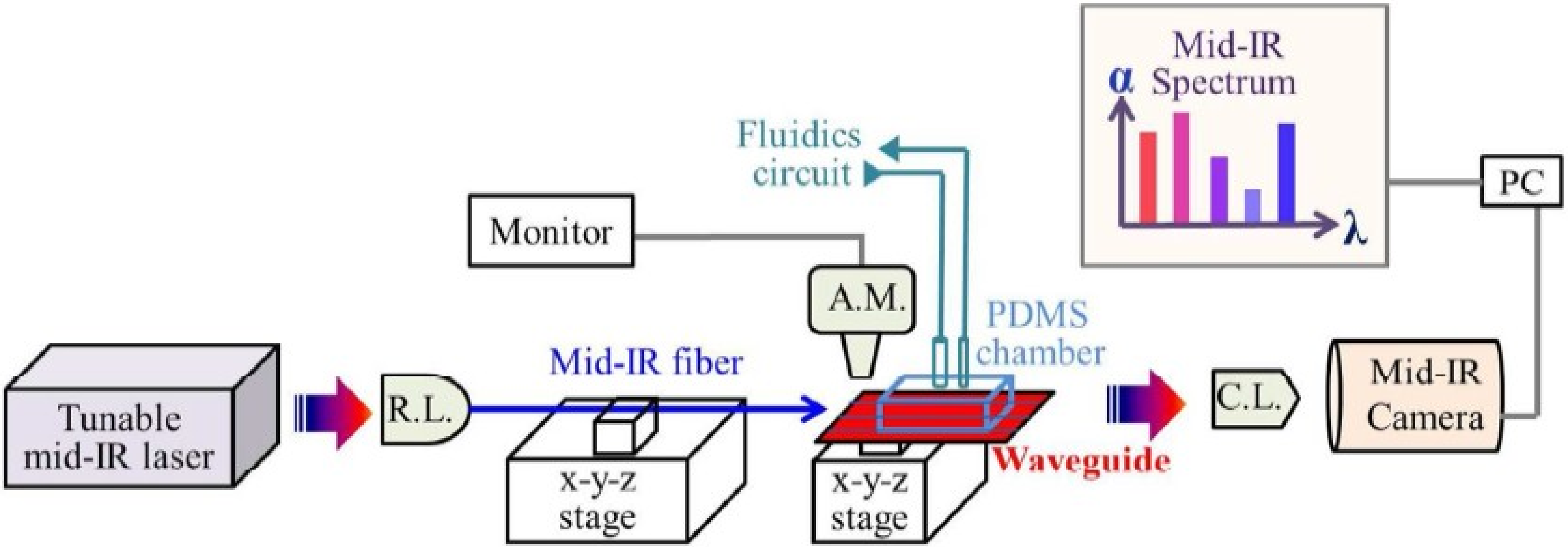
  (1) it works as a mid-IR waveguide

  (2) provides a detection zone that allows maximal spatial overlap between the analyte and the optical field.
- This interaction between the analyte and the optical field enhances the sensitivity of the device.
- The two SiO2 slot-waveguides adjacent to the fluidic slot-waveguide seal the two ends of the nanofluidic channel and prevent organic liquid from leaking out the PDMS chamber.
- Thus, the SiO2 slot-structure serves as

  (a) an efficient mid-IR medium for transmitting the mid-IR light into and out of the fluidic channel

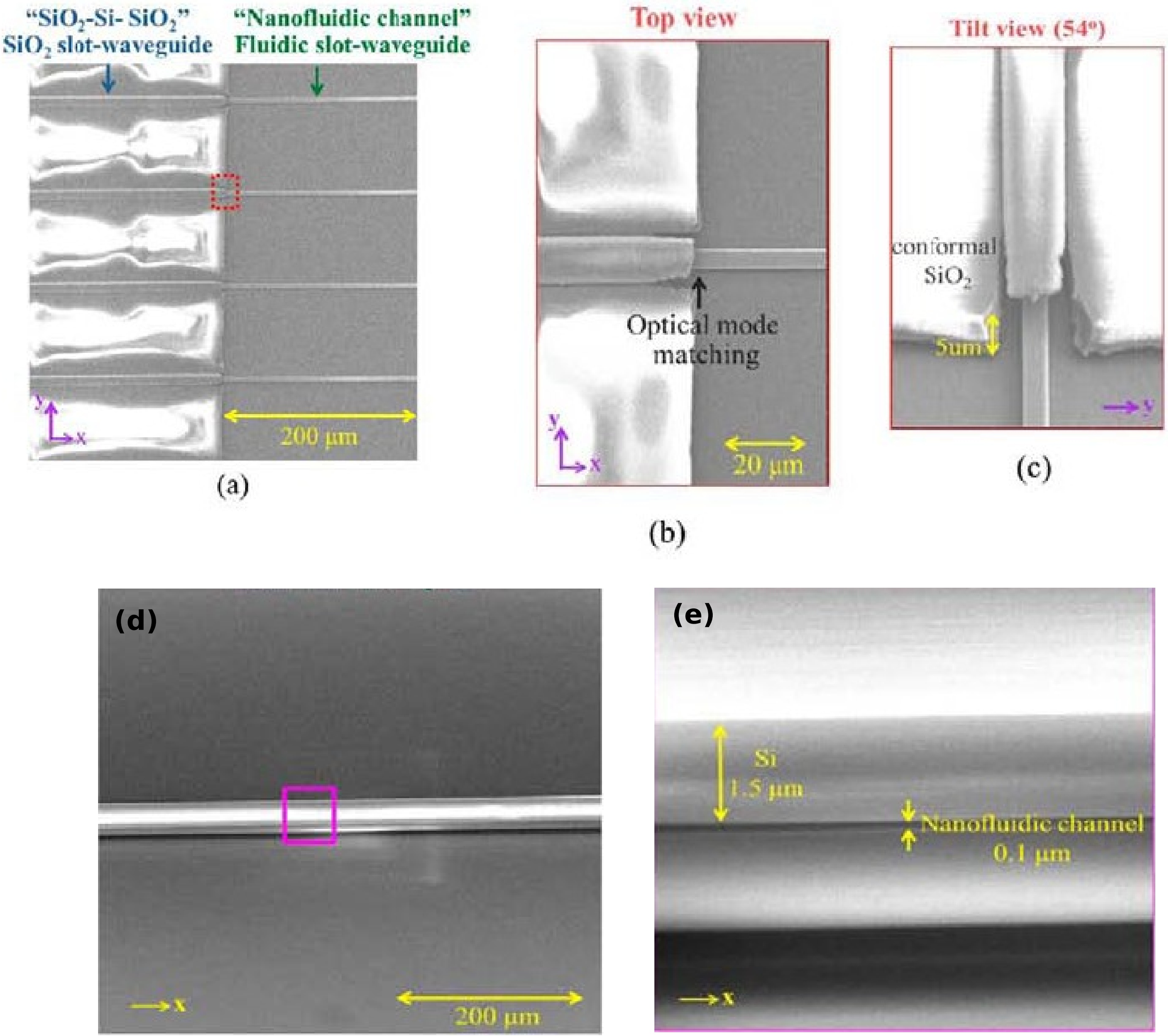
  (b) a fluid-stopping element.
- After passing through the nanofluidic channel, the mid-IR probe light propagates into the second SiO2 slot-waveguide at the other end.
- It is subsequently transmitted from the second SiO2 slot-waveguide into free space and is immediately captured and recorded by a mid-IR (InSb) camera detector outside the PDMS chamber.
- The transmitted light is encoded with the absorption spectrum of the analyte in the fluid because the absorption of probe light by the

Experimental Setup



A schematic of MIT's characterization system for evaluating an on-chip mid-IR spectrometer. Mid-IR probe light is first collimated into the mid-IR fiber through a reflective lens (R.L.) and then coupled into the Si-SiO2-Si slot waveguide. Fine alignment is monitored by an overhead alignment microscope (A.M.) to improve the coupling efficiency. In parallel, analytes are delivered into the PDMS chamber through plastic pipes. The light transmitted from waveguides is focused by a convex lens (C. L.) and captured by the mid-IR camera for spectral analysis.

SEM images of the mid-IR spectrometer

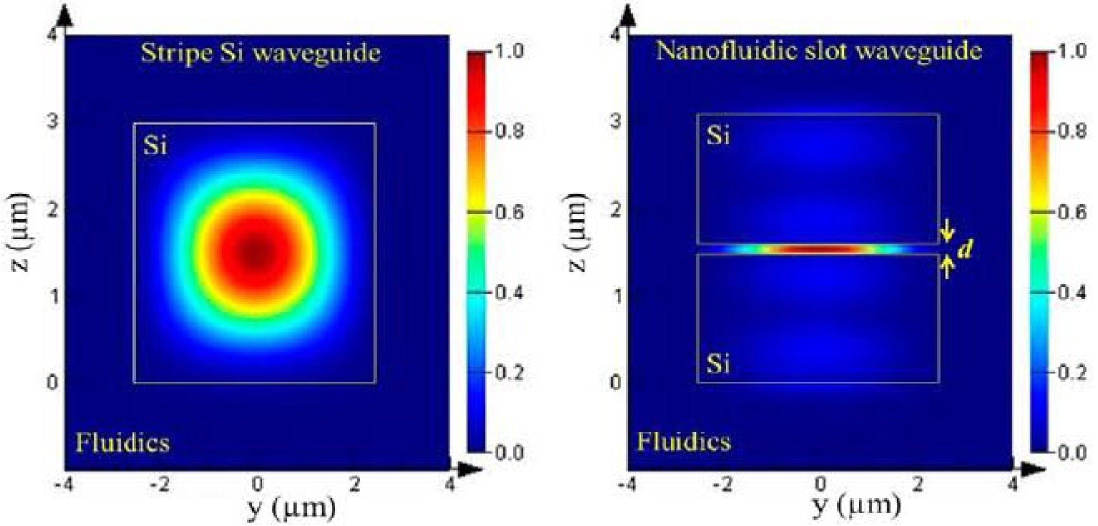


a) An array of “Si−SiO2−Si” SiO2 slot-waveguides (left) and nanofluidic channels (right). The red dashed box indicates the optical mode-matching region.

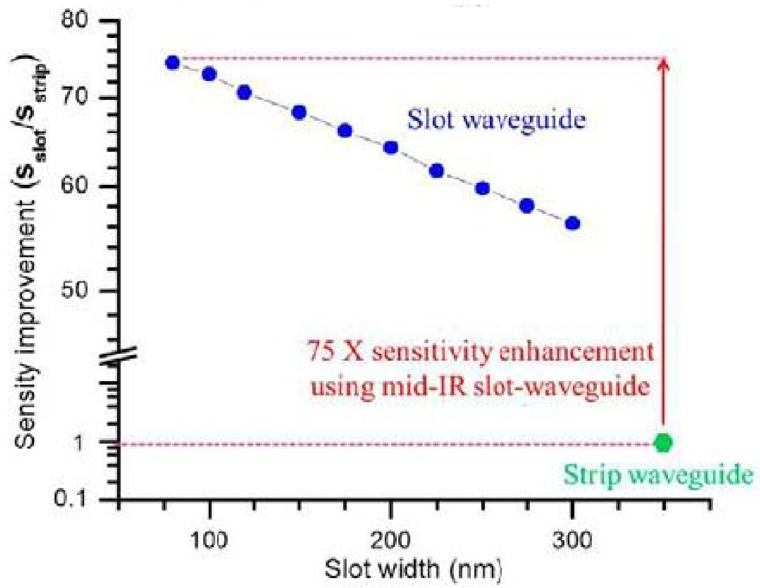
(b) Top view of a magnified image of the mode matching region, showing that the slot waveguide has a width of 5 µm.

(c) Tilted view of the optical mode-matching region. A 5 µm thick conformal layer of SiO2 is seen above the Si−SiO2−Si slot waveguide.

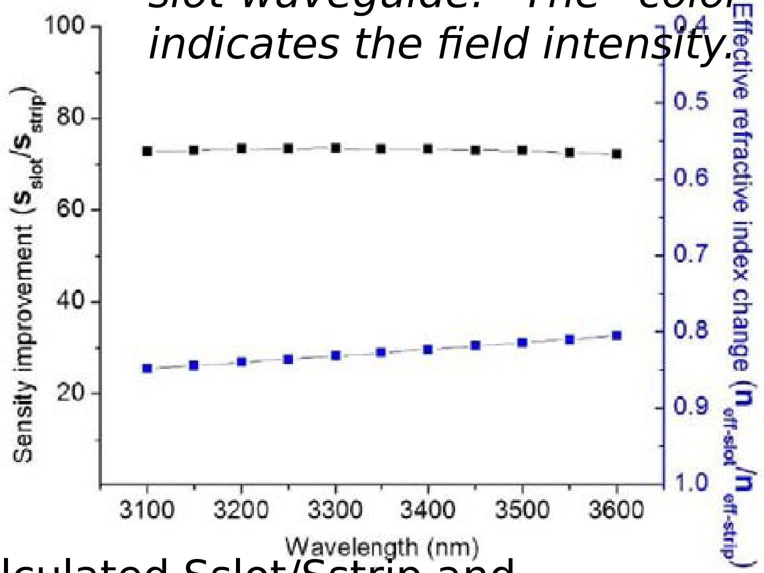
FDTD and FEM modeling of the nanofluidic slot-waveguides



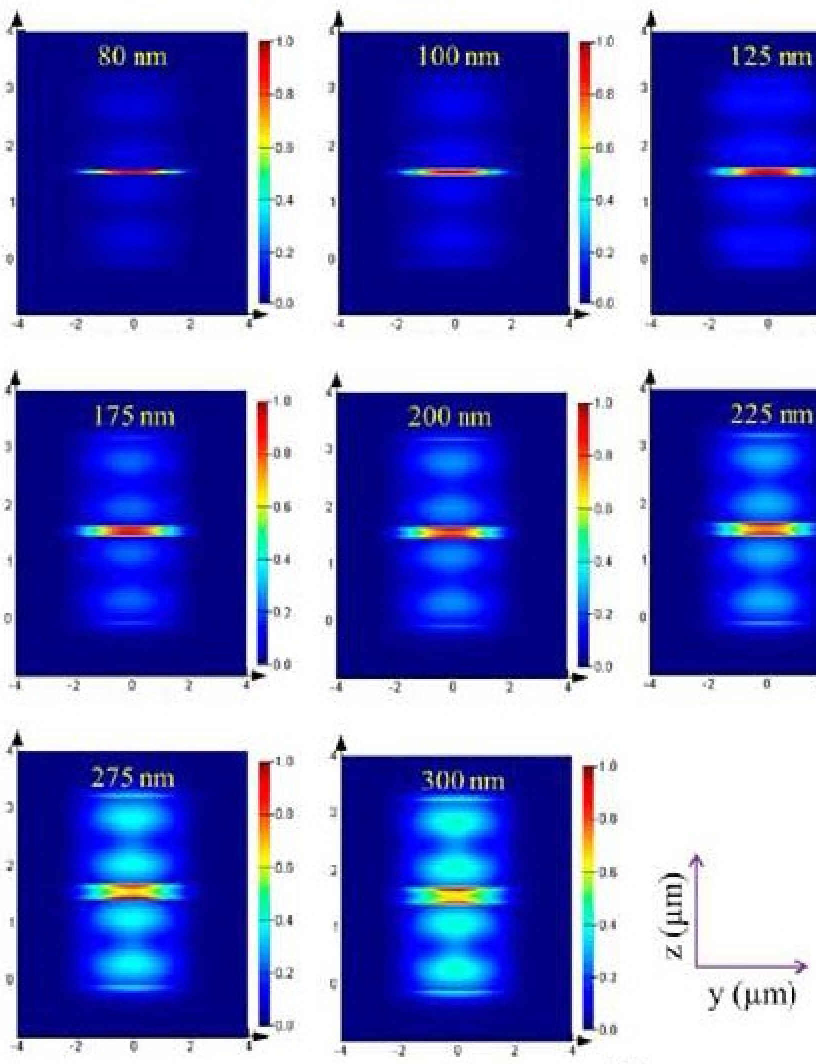
The field intensity profile of a strip Si waveguide (left) and nanofluidic slot-waveguide (right) at λ = 3300 nm. For a strip-waveguide, light is guided by the Si medium, whereas strong light confinement inside center fluidic channel is obtained using a slot-waveguide. The color bar indicates the field intensity.



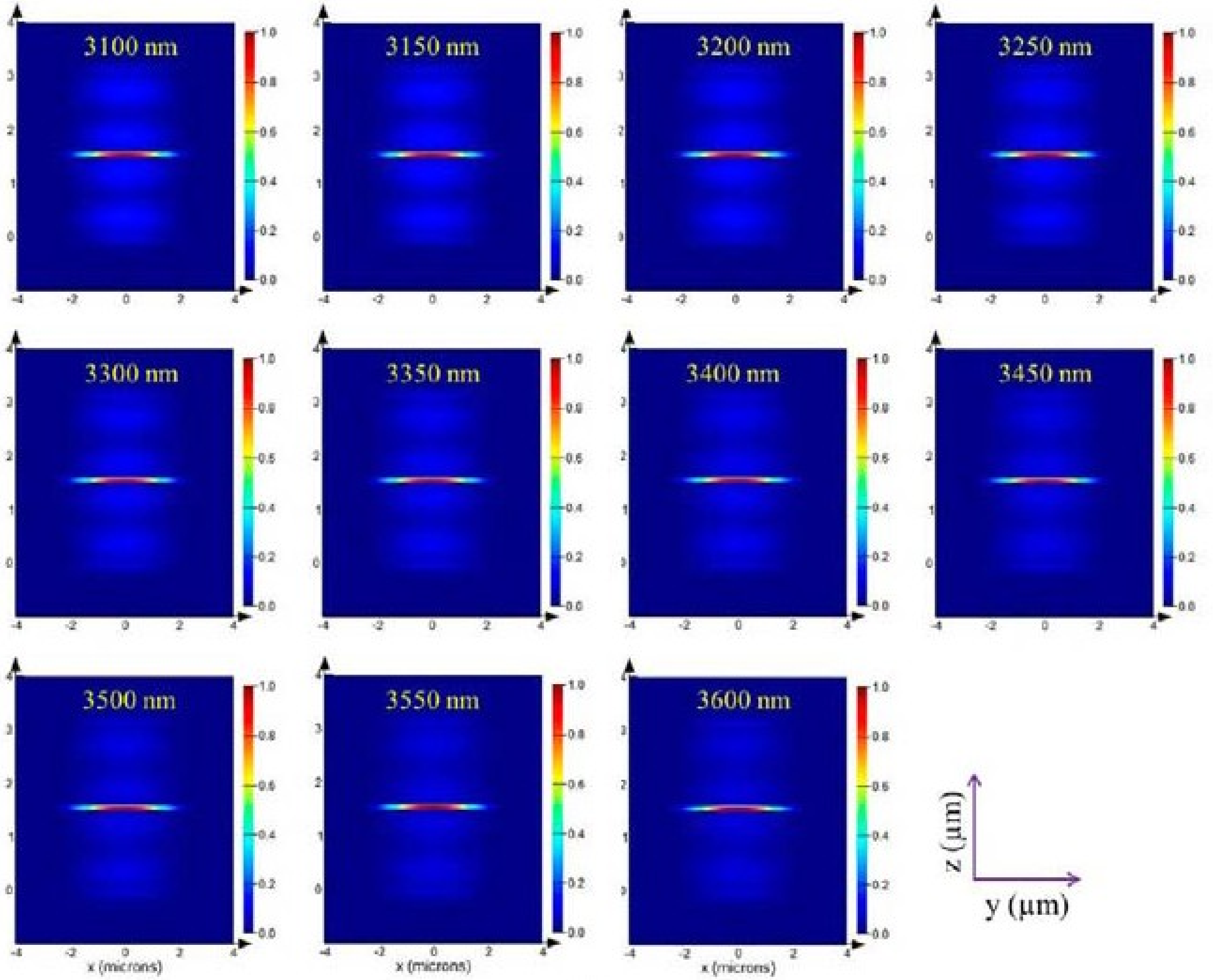
Calculated Sslot/Sstrip ratio (sensitivity improvement) at different slot-width, d. A 75× enhancement is obtained when slot width d reaches 80 nm



Calculated Sslot/Sstrip and neff-slot/neff-strip between λ = 3100 nm and λ = 3600 nm. Sslot/Sstrip is wavelength independent and the variation

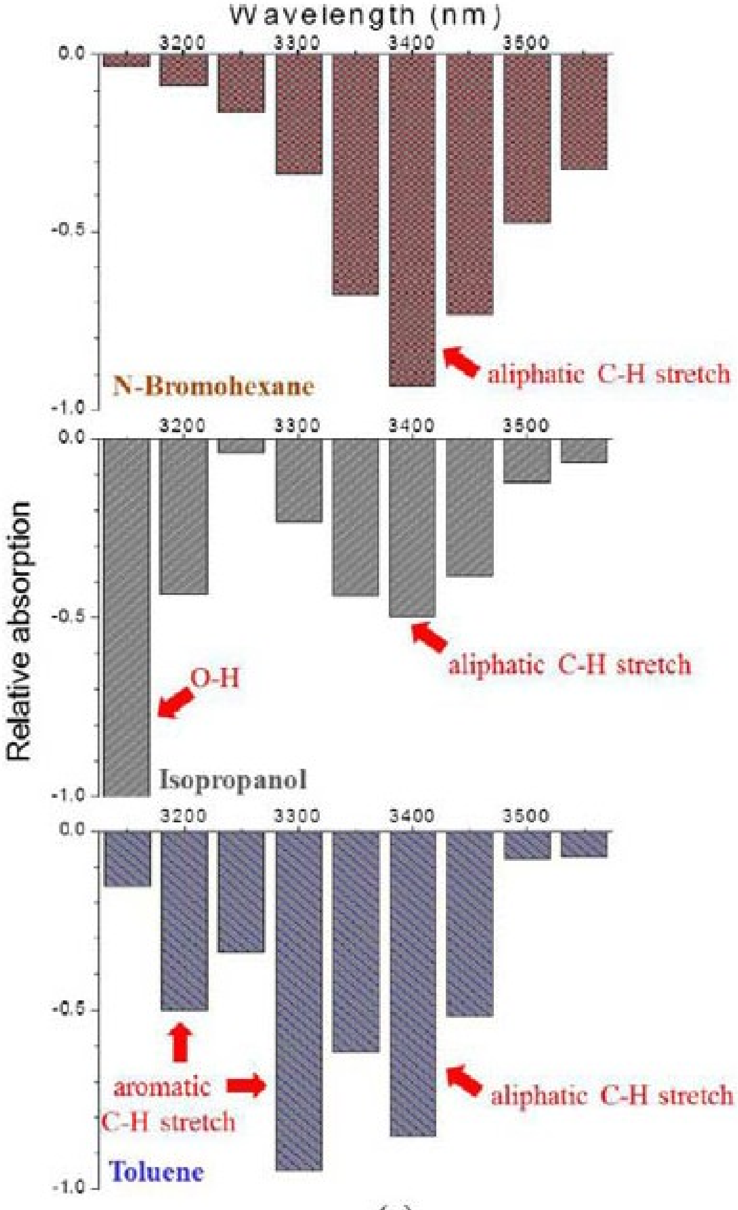


Mid-IR slot waveguide modes as slot width d increases from 80 to 300 nm. The wavelength λ is 3300 nm and silicon thickness is 1.5 μm. The intensity of slot waveguide mode decreases and its peak splits



Mid-IR slot waveguide modes as wavelength increases from λ = 3100 nm to λ = 3600 nm. The slot width d = 100 nm and silicon thickness of 1.5 μm remain constant. No changes of mode profiles are found as the wavelength increases.

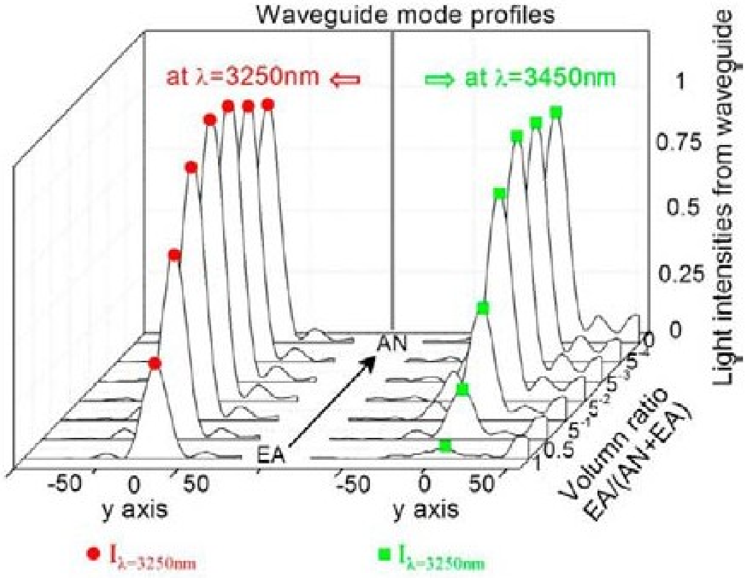
Results



(a)

(a) Mid-IR spectrum characterization of n-bromohexane, isopropanol, and toluene using our on-chip nanofluidic slot waveguide mid-IR spectrometer. Absorption bands are highlighted and assigned to chemical functional groups.

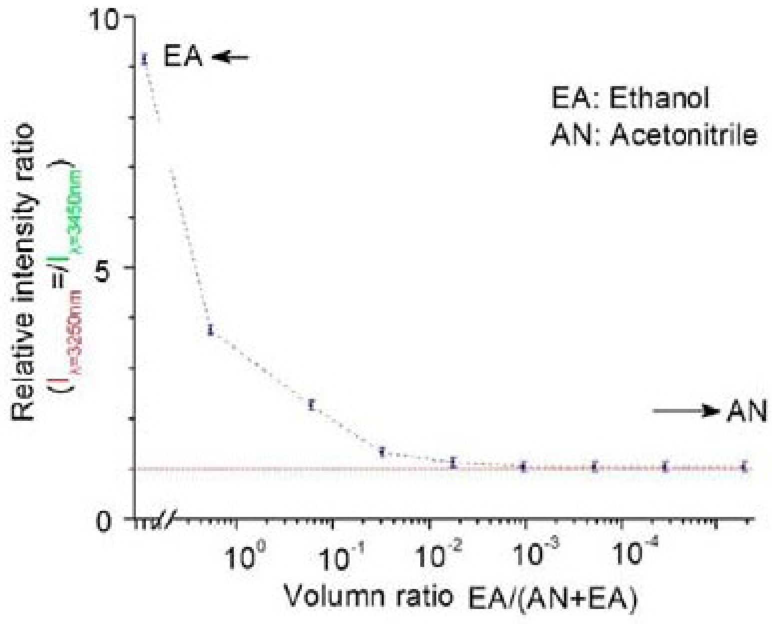
Results



(b)

(b) Intensity profiles of waveguide mode along the y-axis
at λ = 3250 nm (left) and λ = 3450 nm (right) from solutions with different AN/EA volume ratio, where the intensities of peaks, Iλ=3450 nm and Iλ=3250 nm, at different volume ratios are labeled by red circles and green squares respectively.

(c) Waveguide intensity ratio between λ = 3250 nm
and λ = 3450 nm (Iλ=3450 nm/Iλ=3250 nm) at different EA/AN concentrations. A chemical tracing limit of 5−4 is obtained and highlighted by the red line with error bars present.



(c)

Conclusion

- They have demonstrated a hybrid chip-scale integrated mid-IR spectrometer that can achieve label-free and surface-functionalization-free chemical identification of several compounds.
- The sensor can also detect the concentration of solutions.
- The miniaturized chemical sensor integrates optonanofluidics with engineered slot-waveguides, and it achieves optical-waveguide mode-matching.
- Owing to direct interaction of light with sample and strong nanoscale light-confinement a 50 times enhancement of sensitivity over a strip-waveguide evanescent-wave based optofluidic sensor device is accomplished.
- The mid-IR opto-nanofluidics platform establishes a new approach in developing compact, high throughput, and in-field chemical monitoring.

Prospectives

- This paper provides a good example of how microfluidics and nanofluidics platform can be utilised for downsizing benchtop equipments and apply them for in-field sensing applications.

Thank you...