Photonic Crystal Slot Waveguide Optical Absorption Spectrometer for Highly sensitive Near-infrared detection of Xylene in Water

Swapnajit Chakravarty ¹, Wei-Cheng Lai ², Xiaolong (Alan) Wang ¹, Che-Yun Lin ², Ray T. Chen ¹,²

¹ Omega Optics, 10306 Sausalito Drive, Austin, TX 78759
² Dept. of Electrical and Computer Engineering, University of Texas, Austin

Funded by National Science Foundation (NSF)
SBIR Grant #: IIP-0945688
Motivation

• Volatile Organic Compounds (VOCs) are undesirable pollutants in water
• Water samples are currently collected and sent to the labs, turnaround time usually few months
• Sample collection after-the-fact.
  -Real-time detection and identification of BTEX hydrocarbons in water needed
  -Remote Monitoring of BTEX hydrocarbons in water needed
  -Continuous monitoring of water (drinking water, waste water) needed for prompt response
• Most on-chip optical sensors detect changes in refractive index
  -Infrared absorption is a fundamental molecular signature
• FTIR, PAS, TDLAS, CRDS are not chip-integrated yet, usually larger than handheld devices.
  -An on-chip sensor that detects analytes by molecular absorption signatures
What is Photonic Crystal?

- **Periodic** electromagnetic media comparable to wavelength
- With **photonic band gaps**: “optical insulators”

1-D grating = 1-D PhC
2-D PhC = 2-D grating
3-D PhC = 3-D grating
Similar to:
Semiconductors

Defect structures can introduce defect mode inside the photonic bandgap
Similar to: Doping of Semiconductor

can trap light in cavities
and waveguides ("wires")
On-Chip Bio-Chemical Sensors

Sensing principle based on change in refractive index

Photonic Crystal Chemical Sensing

Photonic Crystal Ion Sensing
Chakravarty et al, Optics Lett. 30 (19), 2578 (2005)

Photonic Crystal Bio-Sensing
Lee et al, Optics Exp. 15 (8), 4530 (2007)

Ring Resonators
Robinson et al, Optics Exp. 16 (6), 4296 (2008)
Robinson et al, Optics Exp. 16 (16), 11930 (2008)
Photonic Crystal Slot Waveguide Spectroscopy

Principle is based on Beer-Lambert absorption law:

\[ I = I_0 \exp[-\gamma \alpha L] \]

where

- \( I \) = Transmitted Intensity at the output of photonic crystal slot waveguide at wavelength \( \lambda \)
- \( I_0 \) = Incident Optical power at wavelength \( \lambda \)
- \( L \) = Geometrical optical path length = 300\( \mu \)m
- \( \gamma \) = Medium-specific absorption factor determined by dispersion enhanced light-matter interaction
- \( \alpha \) = Absorption coefficient at wavelength \( \lambda \)  


\[ \gamma = f \times \frac{c / n}{v_g} \]

where

- \( c \) = Velocity of light in medium of refractive index \( n \).
- \( v_g \) = Group velocity of light
- \( f \) = Electric field intensity enhancement
Photonic Crystal Slot Waveguide

Photonic crystal period $a=460\text{nm}$

Waveguide height $h=0.52a$

Hole diameter $d=0.5a$

Slot width $w_0=0.15a$

Defect width $w_1=0.8 \times \sqrt{3}a$

Advantages:
- Slow photon group velocity
- Smaller mode profile
- Compatible fabrication processes with silicon photonics


Device Fabrication Steps

Standard silicon fabrication steps

Thermal Oxide Growth  Resist Patterning  Silicon Dioxide Hard Mask  Pattern transferred to Silicon

Structures considered with bottom SiO₂ cladding for mechanical stability for operation in harsh environments

Final Step: 8μm thick hydrophobic PDMS top cladding

PDMS serves 2 purposes:
- Avoids interference from near-infrared absorption of water
- Extracts VOCs from water into optical interaction volume in the photonic crystal slot
Photonic Crystal Slot Waveguide

- Slot in the middle of a photonic crystal waveguide
- Mode Converter for higher coupling efficiency from the ridge waveguide into slot
- Photonic Crystal Impedance Taper for higher coupling efficiency into slow light region

Experimental Setup
Xylene Detection in Water Ambient

- 100 parts per billion (v/v) (86 µg/L) detected
- In comparison:
  - PDMS disks showed 3 mg/L [1]
  - 11 meter optical fiber showed 400 µg/L [2]
- No need for salinity enhancement [3]
- Response time < 1 minute
- < 1 mW power

Summary

Photonic Crystal Slot Waveguide enables:
• On-Chip sensing by infrared absorption signatures
• VOC detection directly in water
• Generous deployment of low-cost sensors in field
• Multiple species detection simultaneously on-chip

Easily scalable to mid-IR for higher sensitivity

In-situ detection
• Remote Monitoring
• Continuous Monitoring

Application Areas:
• Waster water monitoring, groundwater monitoring, drinking water monitoring
• Process fluid monitoring
Methods to improve Optical Coupling Efficiency

- Group index varied gradually by shifting the edge air holes; from low group index at the ridge waveguide to high group index at the photonic crystal waveguide slow light regime.

$n_0 = 3.5 < n_1 < n_2 < \ldots < n_{k-1} < n_k = 100$