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

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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

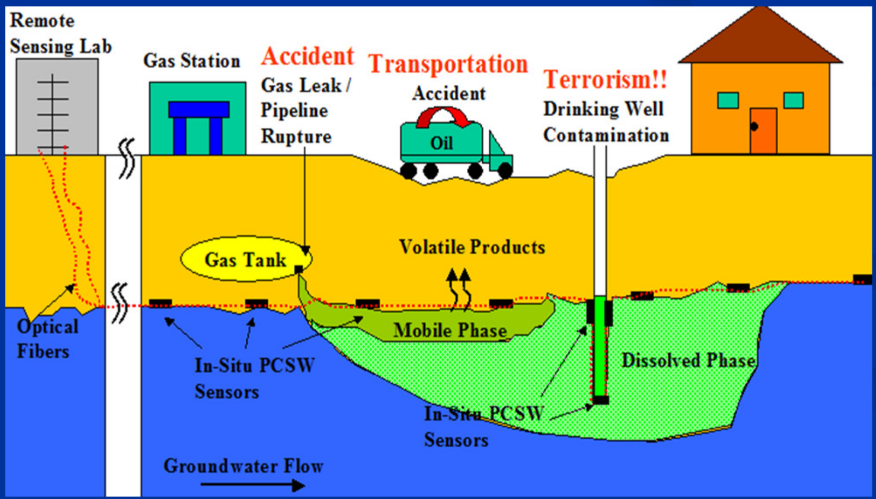
  -Continuous monitoring of water (drinking water, waste water) needed for prompt response

- Most on-chip optical sensors detect changes in refractive index

  -Infrared absorption is a fundamental molecular signature

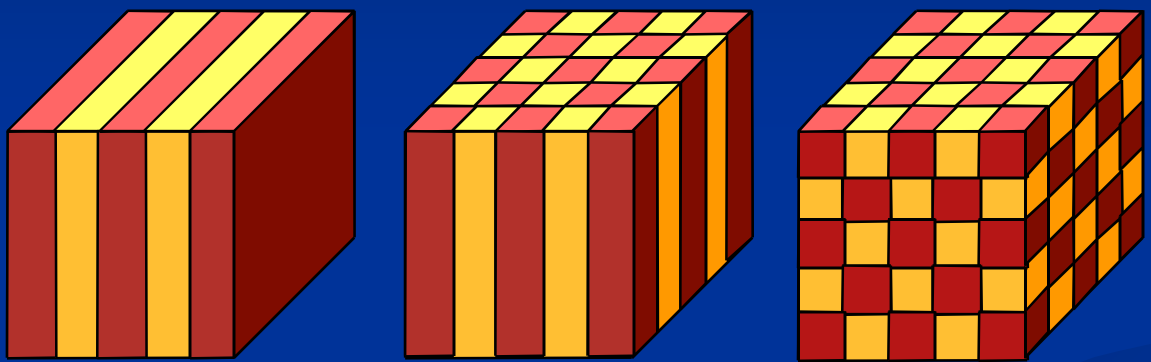
- FTIR, PAS, TDLAS, CRDS are not chip-integrated yet, usually larger than handheld devices.

  -An on-chip sensor that detects analytes by molecular absorption signatures

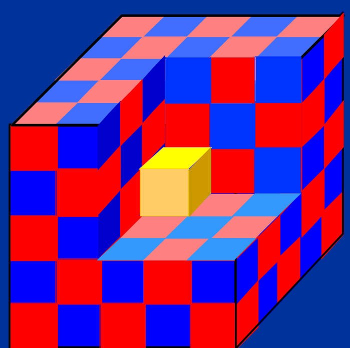


➢What is Photonic Crystal?

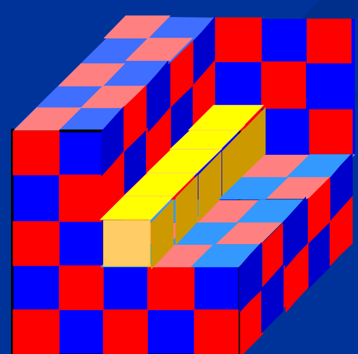
- **Periodic** electromagnetic media comparable to wavelength
- With **photonic band gaps**: "optical insulators"



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



can trap light in cavities

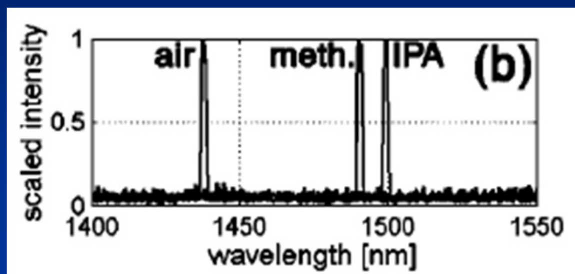


and waveguides ("wires")

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

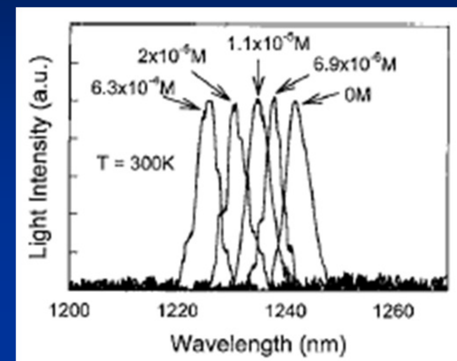
On-Chip Bio-Chemical Sensors

Sensing principle based on change in refractive index



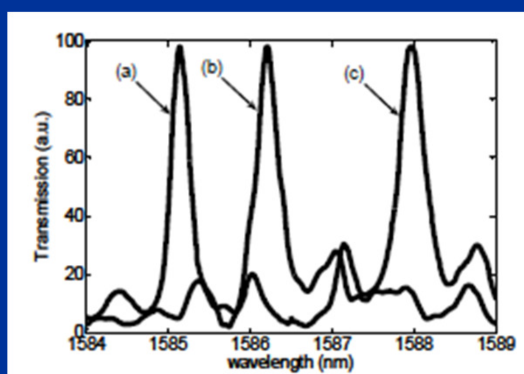
Photonic Crystal Chemical Sensing

Loncar et al, Appl. Phys. Lett.
82 (26), 4648 (2003)



Photonic Crystal Ion Sensing

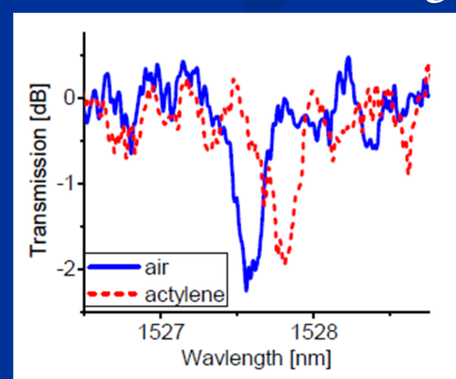
Chakravarty et al, Optics Lett. **30** (19), 2578 (2005)

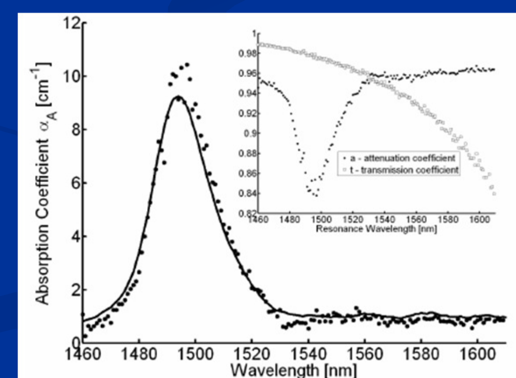


Photonic Crystal Bio-Sensing

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 λ
- I_0 = Incident Optical power at wavelength λ
- L = Geometrical optical path length = 300μm
- γ = Medium-specific absorption factor determined by dispersion enhanced light-matter interaction
- α = Absorption coefficient at wavelength λ

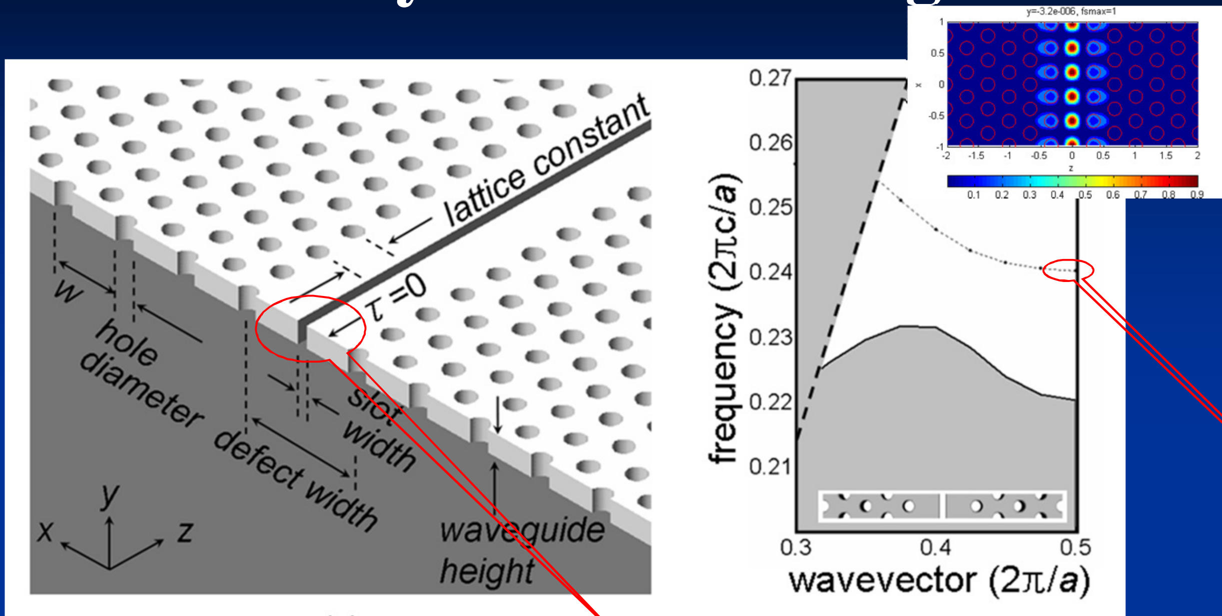
Mortensen et al, Appl. Phys. Lett. **90** (14), 141108 (2007)

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

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=460nm

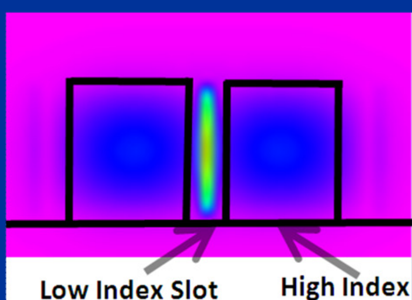
Waveguide height h=0.52a

Hole diameter d=0.5a

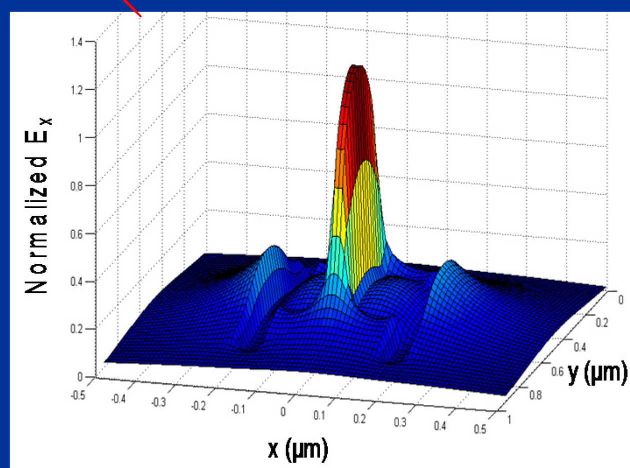
Slot width w_0=0.15a

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

Slot Enhancement



Xu et al, Optics Lett. **29** 1626 (2004)



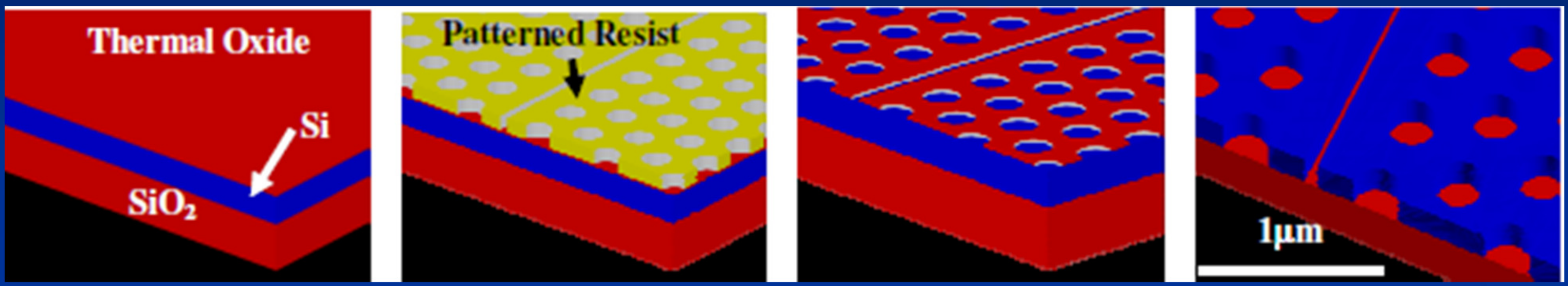
Chen et al, Appl. Phys. Lett. **91, 091111** (2007)

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

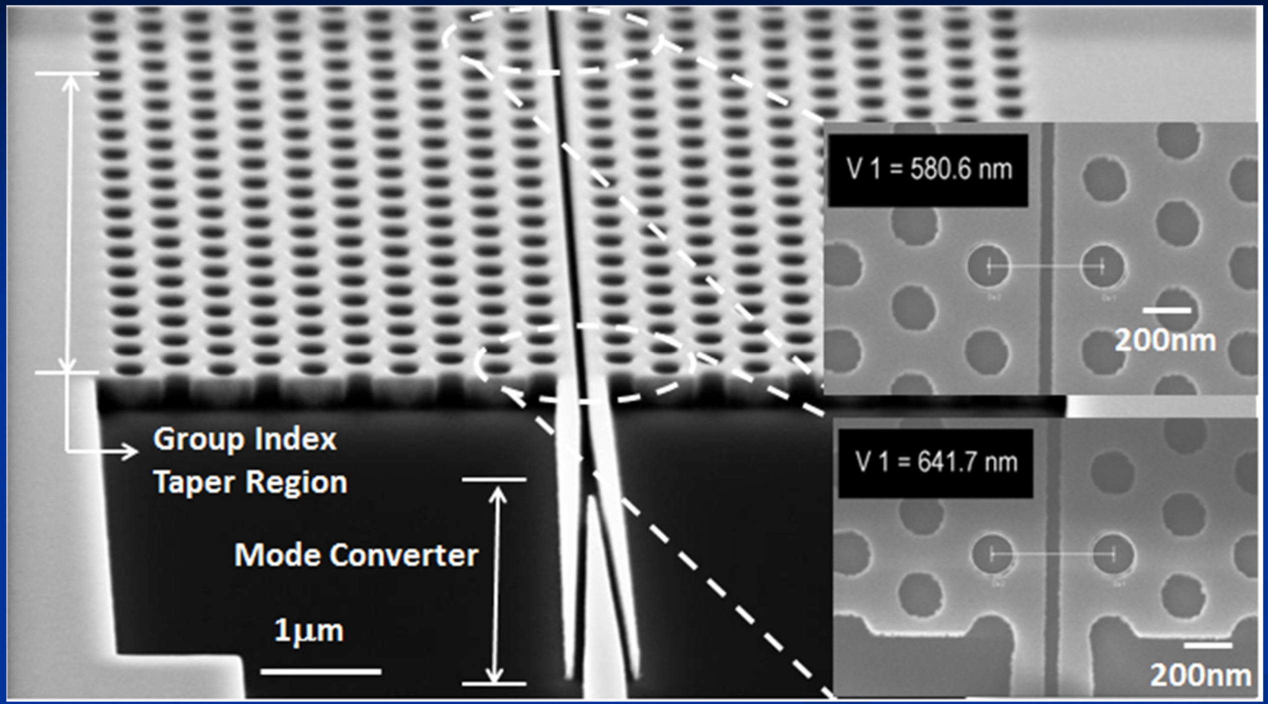
Structures considered with bottom SiO_2 cladding for mechanical stability for operation in harsh environments

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

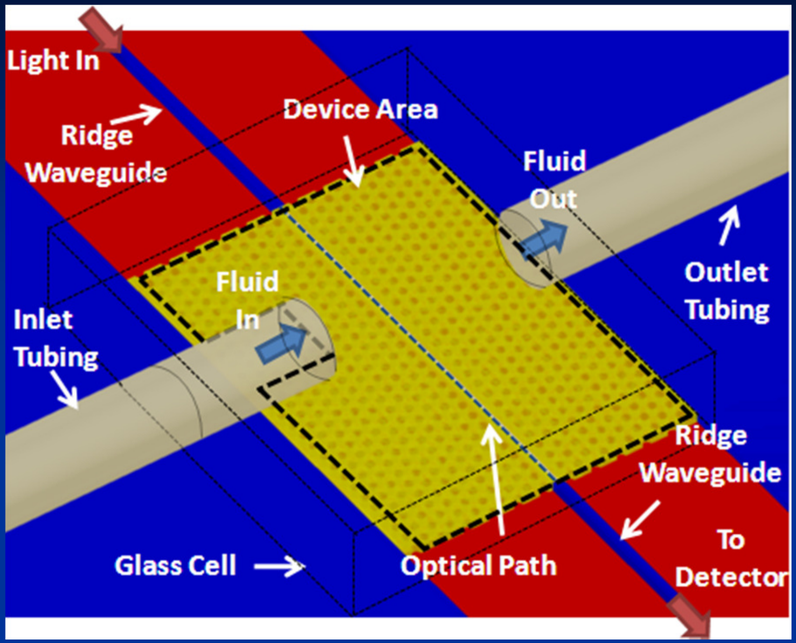
Photonic Crystal Slot Waveguide

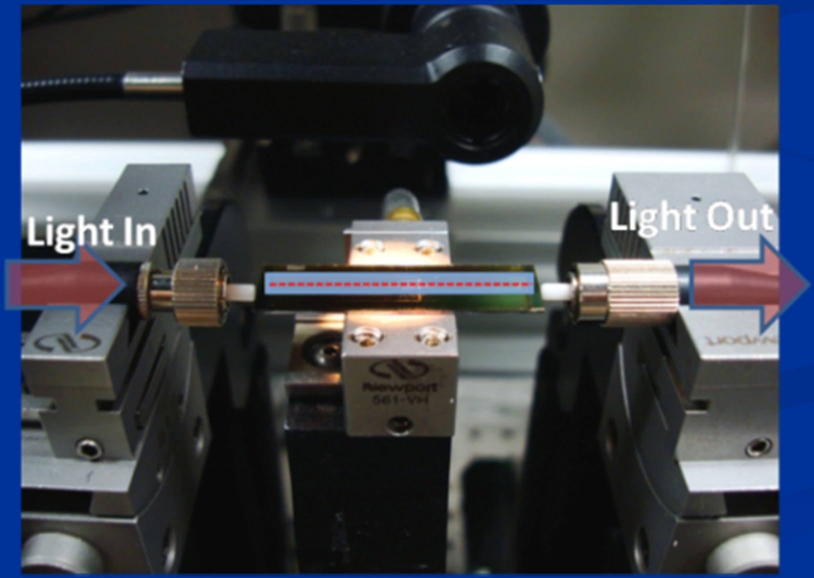


- **Slot in the middle of a photonic crystal waveguide**
- **Mode Converter for higher coupling efficiency from the ridge waveguide into slot**
- **Photonic Crystal Impedance Taper for higher coupling efficiency into slow light region**

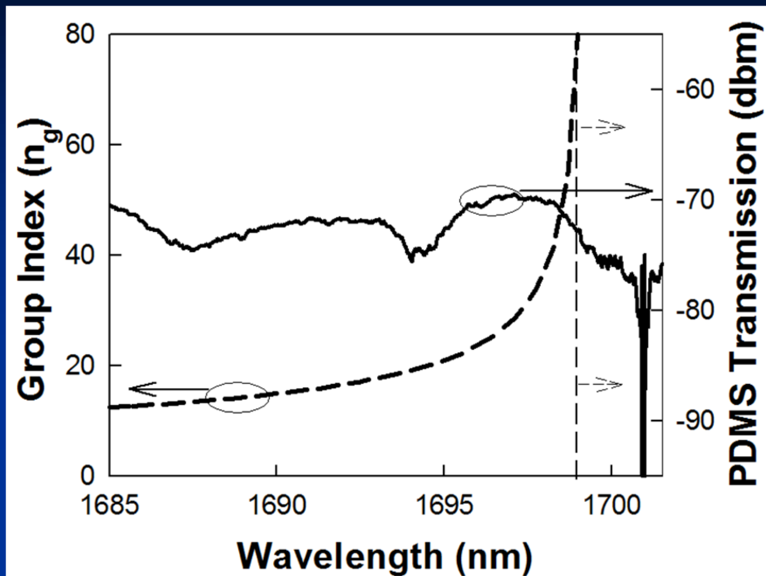
•Xiaolong Wang, Ray T. Chen, "Photonic Crystal Band-Shifting Device for Dynamic Control of Light Transmission," U.S. patent 455,791 (2009)

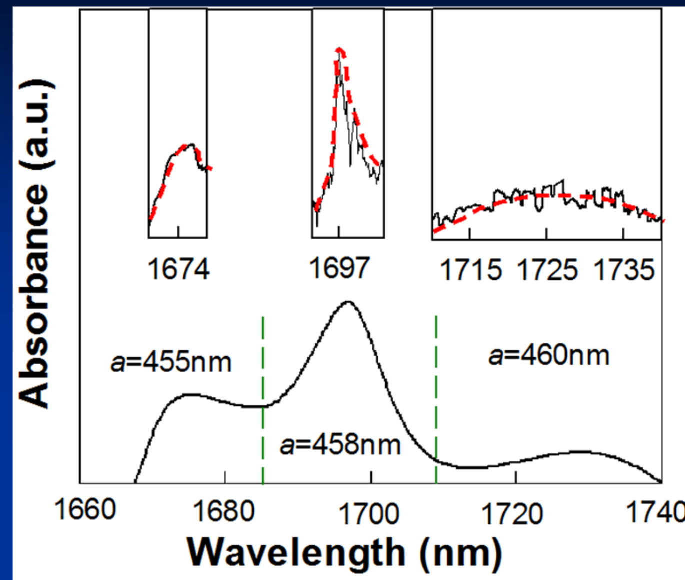
Experimental Setup

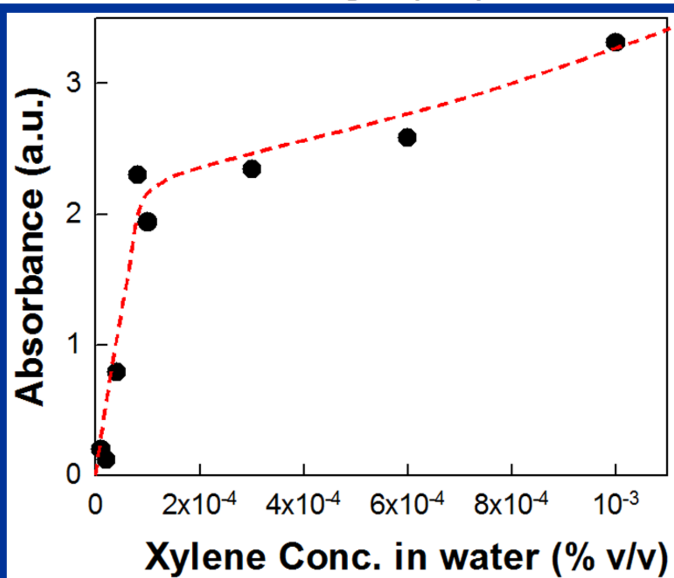




Xylene Detection in Water Ambient







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

[1] Albuquerque et al, Anal. Chem. 77 (1), 72 (2005)
[2] Burck et al, J. Hazard. Mater. 83, 11 (2001)
[3] Lima et al, Sens. & Actuators B-Chem 125 (1), 229 (2007)

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

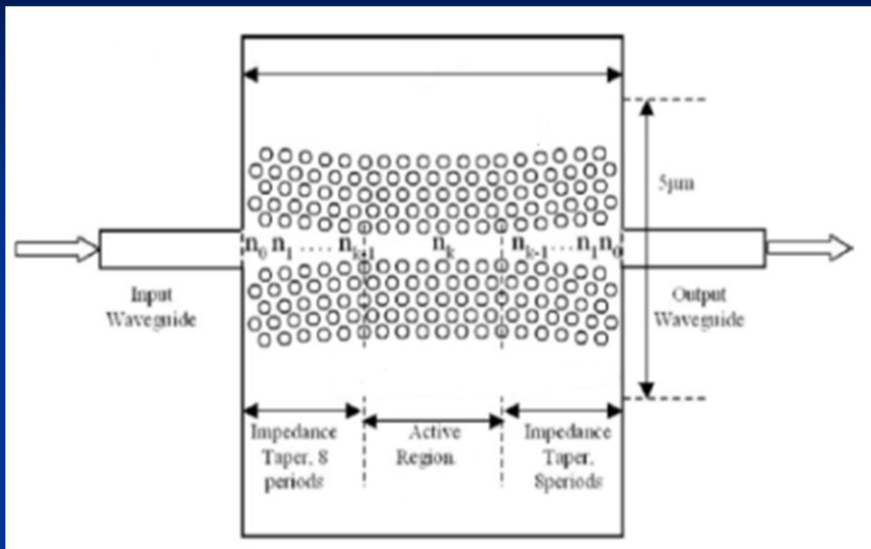
- **Remote Monitoring**
- **Continuous Monitoring**

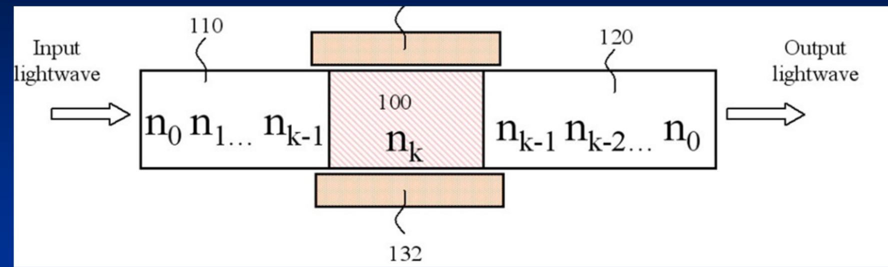
Application Areas :

•Waster water monitoring, groundwater monitoring, drinking water monitoring

•Process fluid monitoring

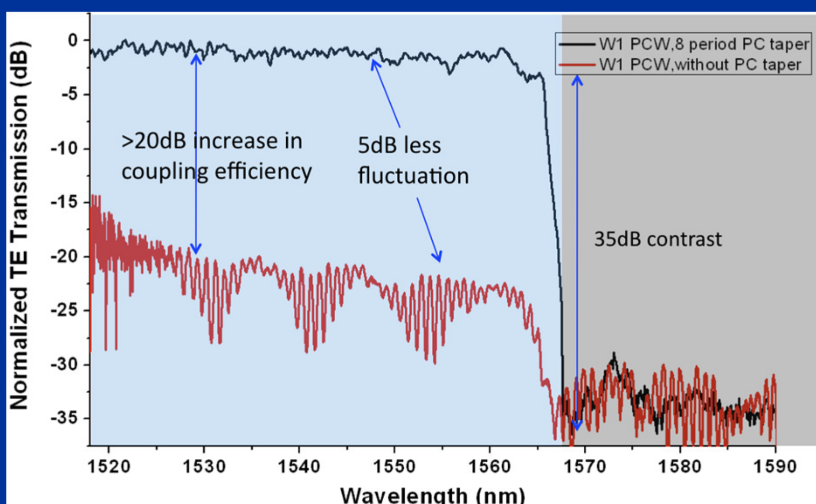
Methods to improve Optical Coupling Efficiency

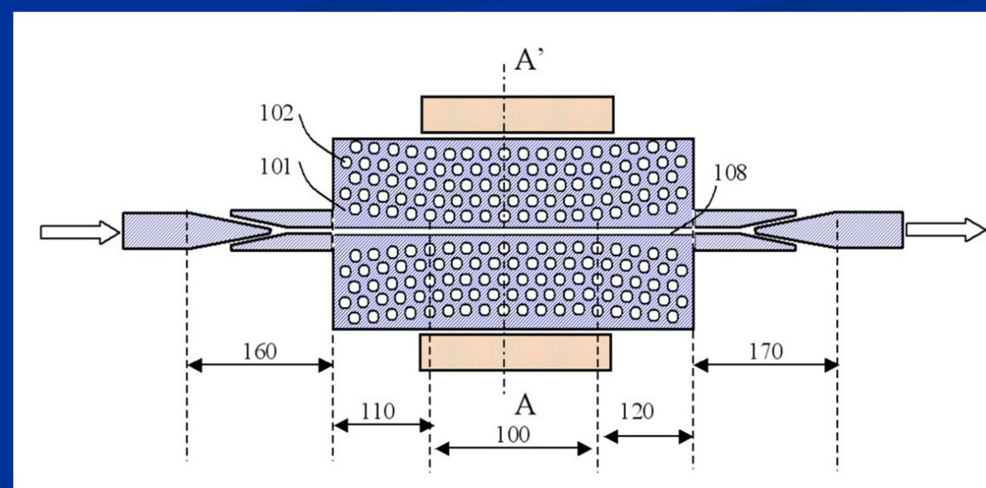




$n_0=3.5<n_1<n_2<\ldots<n_{k-1}<n_k=100$

- **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.**





•Xiaolong Wang, Ray T. Chen, "Photonic Crystal Band-Shifting Device for Dynamic Control of Light Transmission," U.S. patent 455,791 (2009)