Photonic Crystal Slot Waveguide Spectrometer for Detection of Methane

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 Environmental Protection Agency (EPA)
SBIR Grant #: EP-D-10-047

Motivation

No other chip based optical method for infrared molecular absorption spectroscopy of gases

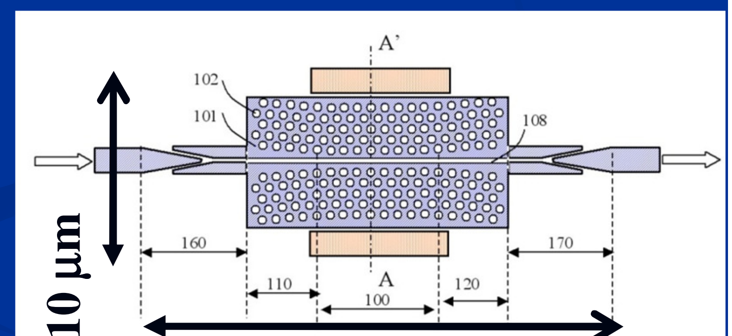
Cavity Ringdown Spectroscopy
(66lbs, ~ 3cu.ft)

← Tunable Diode Laser Absorption Spectroscopy

FTIR Spectroscopy
(24lbs, ~ 1.5cu.ft,)

Photoacoustic Spectroscopy
(33lbs, ~ 1cu.ft)

Our Device

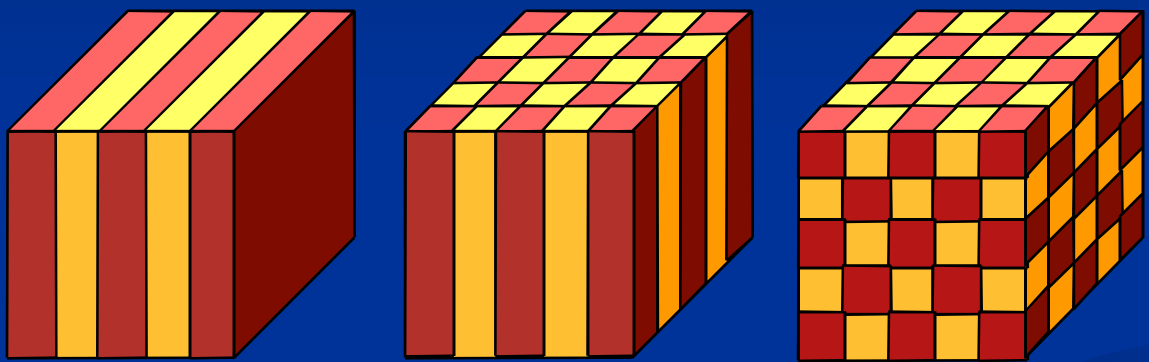


300 µm

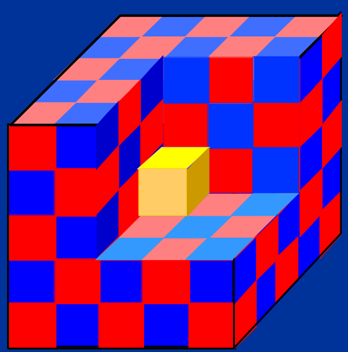
Photonic Crystal Slot Waveguide Spectrometer
(< 0.1 lbs, <10cu. cm.)

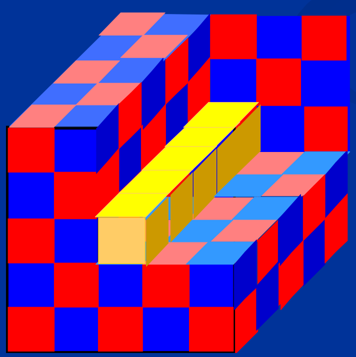
➢What is Photonic Crystal?

- **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





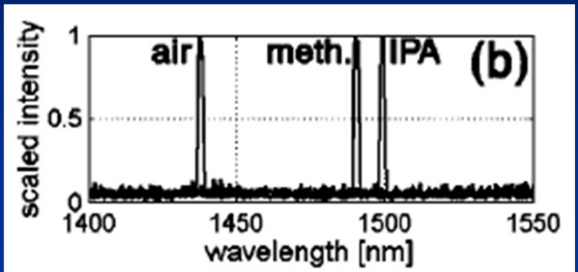
Defect structures can introduce defect mode inside the photonic bandgap
Similar to: Doping of Semiconductor

can trap light in cavities

and waveguides (“wires”)

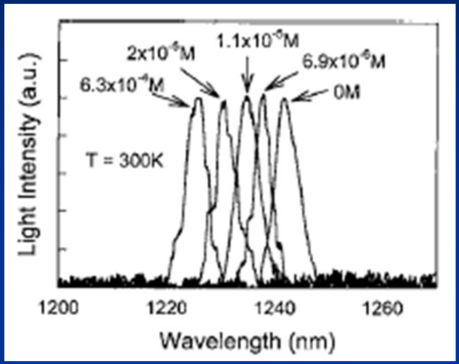
Photonic Crystal Bio-Chemical Sensors

Sensing principle based on change in refractive index



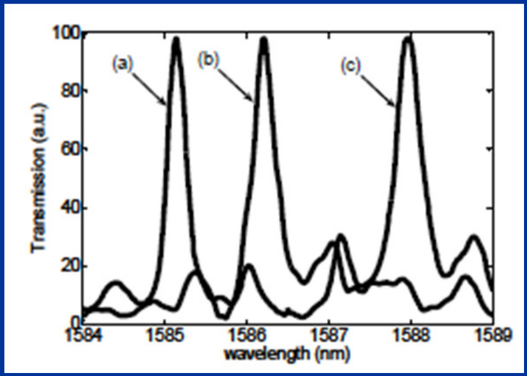
Chemical Sensing

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



Ion Sensing

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



Bio-Sensing

Lee et al, Optics Exp. **15** (8), 4530 (2007)

Frontiers in Biological Detection: From Nanosensors to Systems, Conference 7888, SPIE Photonics West 2011

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

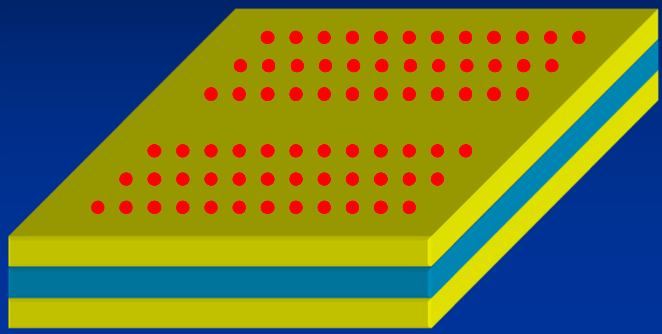
Mortensen et al, Appl. Phys. Lett. **90** (14), 141108 (2007)

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

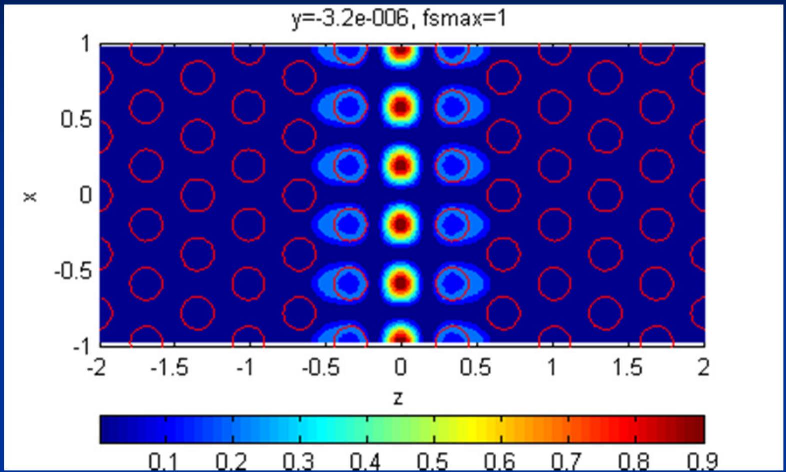
where

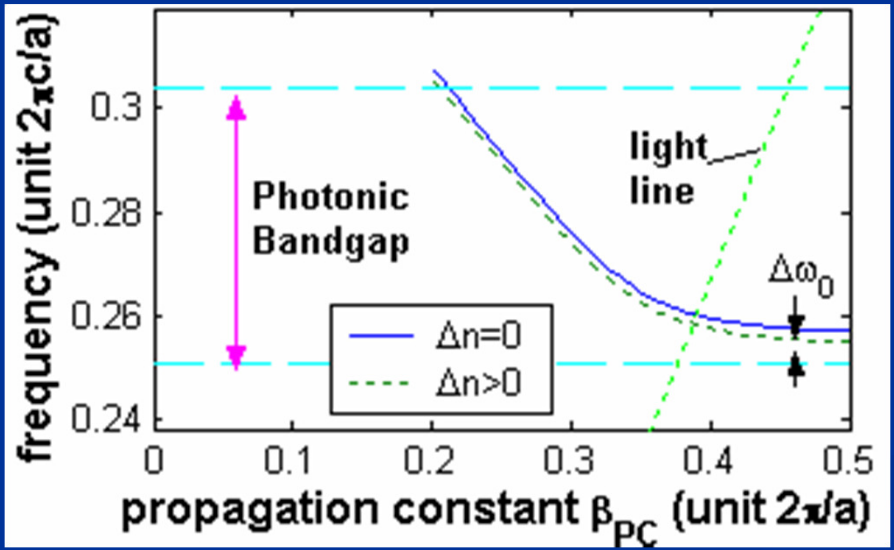
- c =Velocity of light in medium of refractive index n.
- v_g = Group velocity of light in the photonic crystal waveguide
- f = Electric field intensity enhancement in the slot

➢Photonic Crystal Waveguide



W-1 PCW

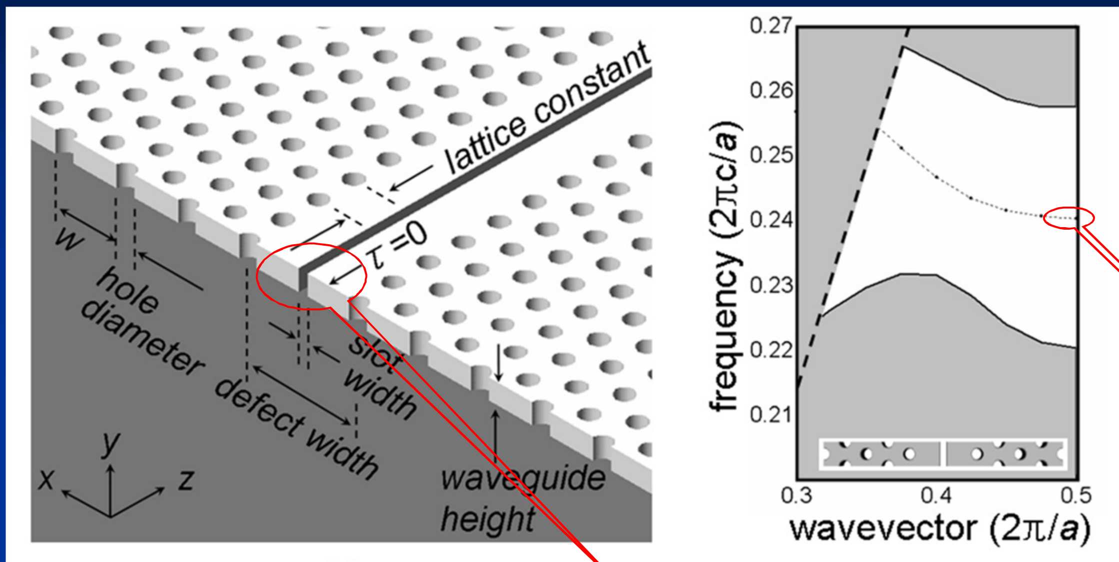




•Normalized dispersion diagram

• Scaled in wavelength by scaling the lattice constant of the photonic crystal

➢Photonic Crystal Slot Waveguide



Photonic crystal period a=460nm

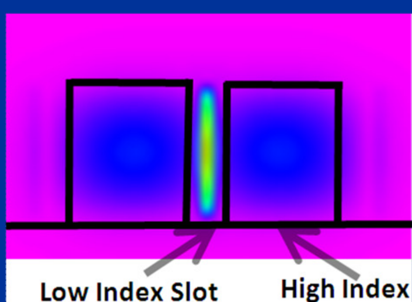
Waveguide height h=0.5a

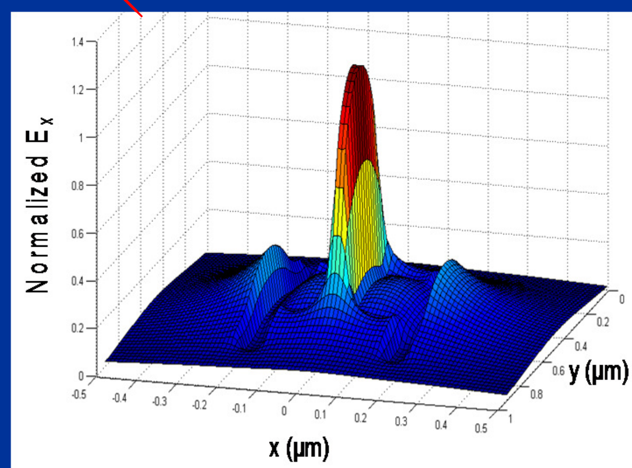
Hole diameter d=0.5a

Slot width w_0=0.2a

Defect width $w_1=1.3\sqrt{3}a$

Slot Enhancement



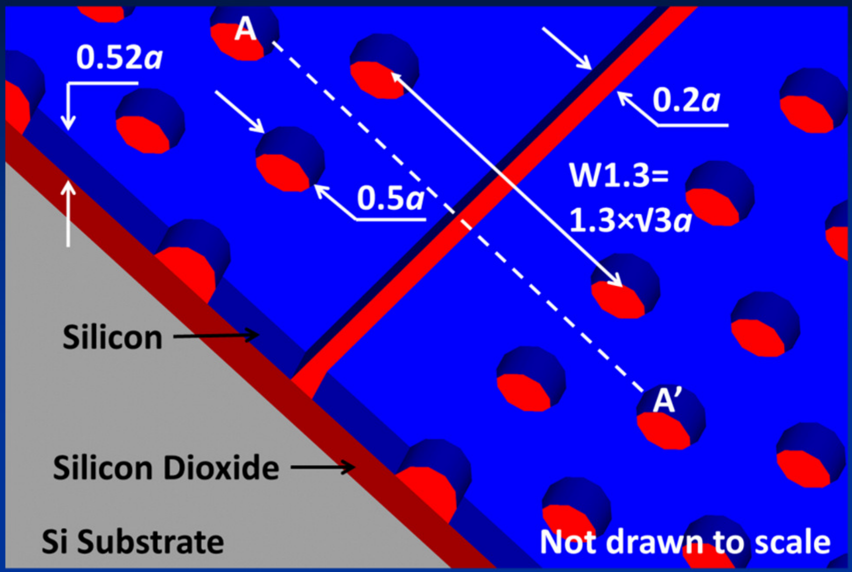


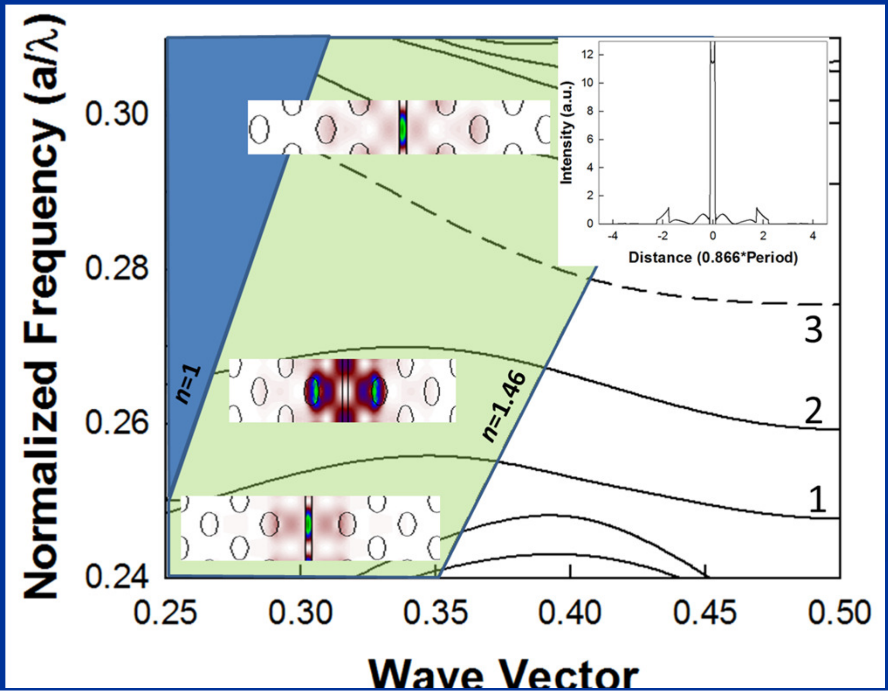
Advantages:

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

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

Photonic Crystal Slot Waveguide Design



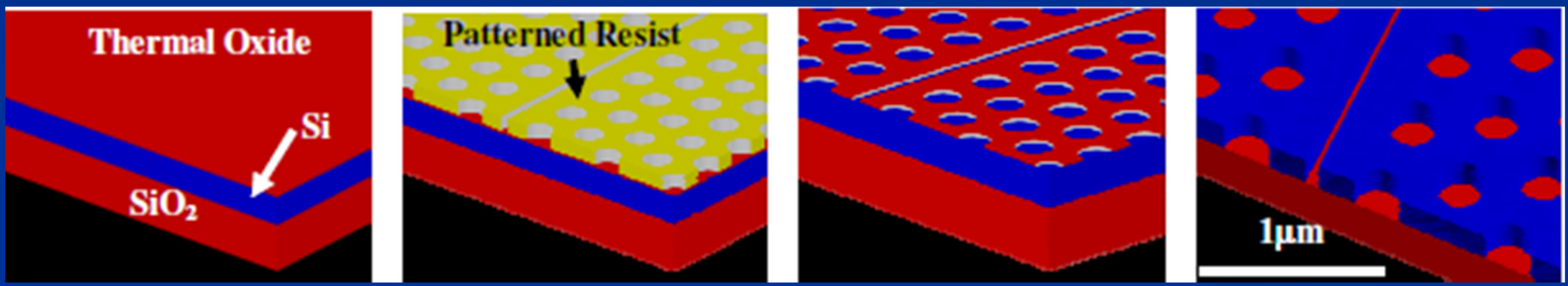


Device Parameters on a SOI wafer

- Guided mode design in SOI wafer
- Factor of 12 enhancement in slot with mode 3.
- Designed for wavelength at which mode 3 has group index n_g=40, which coincides with the peak of the near-infrared absorption spectrum of methane at 1665.5nm.

Device Fabrication Steps

Standard silicon fabrication steps

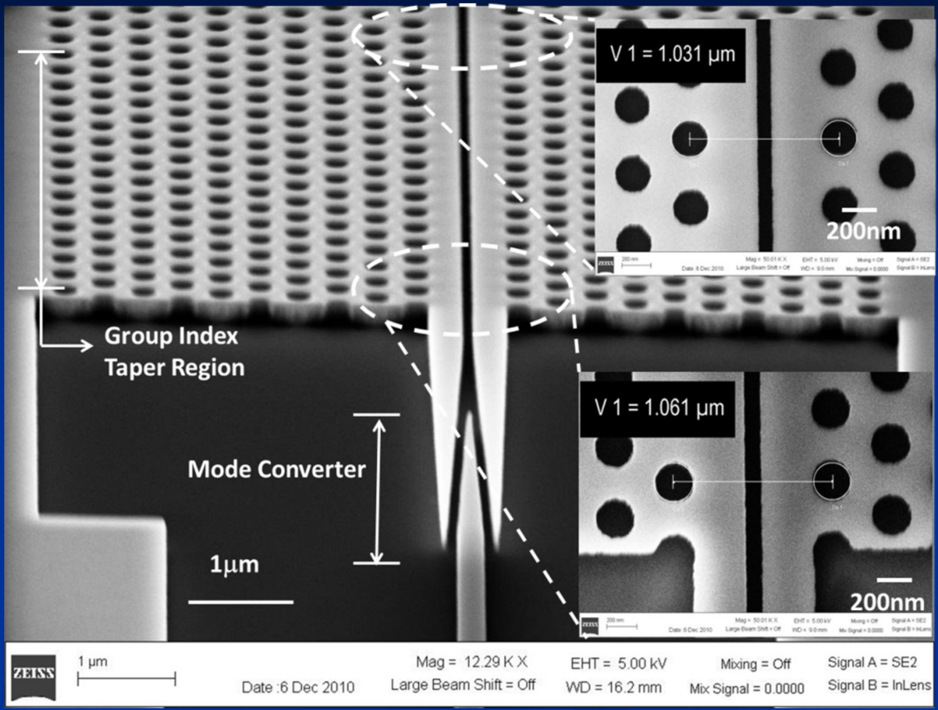


Thermal Oxide Growth	Resist Patterning	Silicon Dioxide Hard Mask	Pattern transferred to Silicon

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

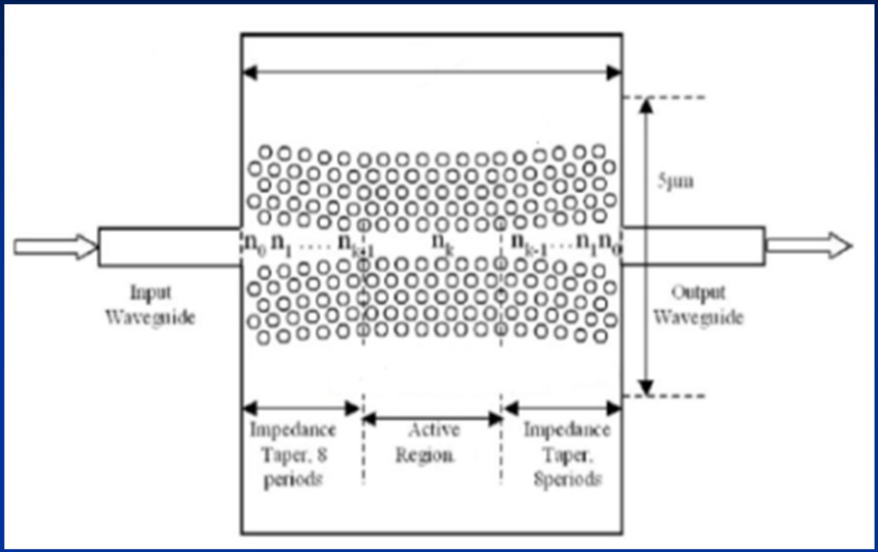
Minimum feature sizes easily achievable by 193nm photolithography

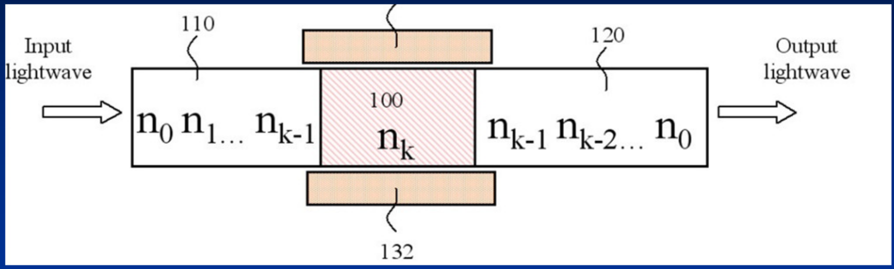
Photonic Crystal Slot Waveguide



- 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

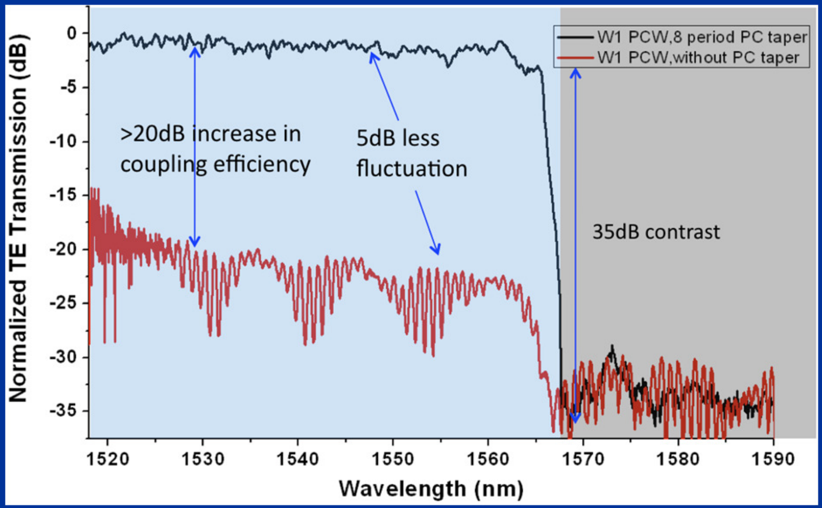
Methods to improve Optical Coupling Efficiency

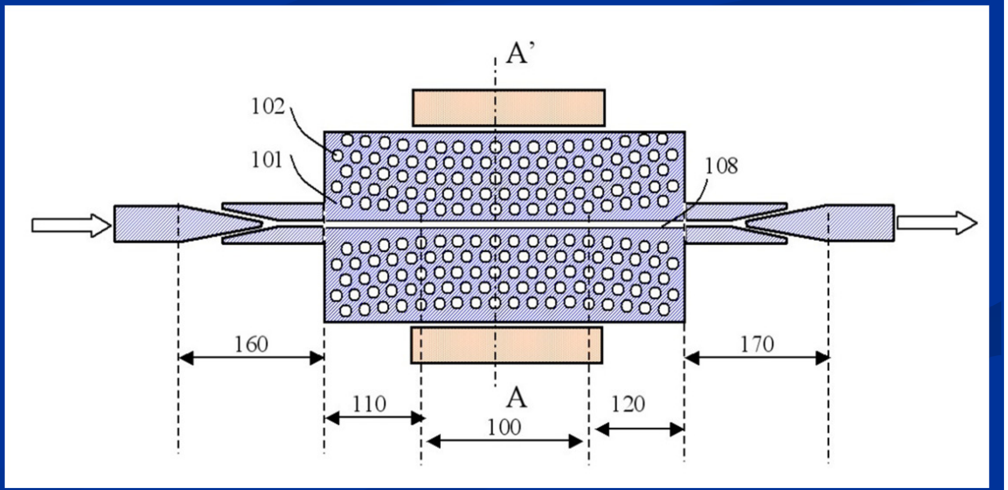




$$n_0=3.5<n_1<n_2<\ldots<n_{k-1}<n_k=100$$

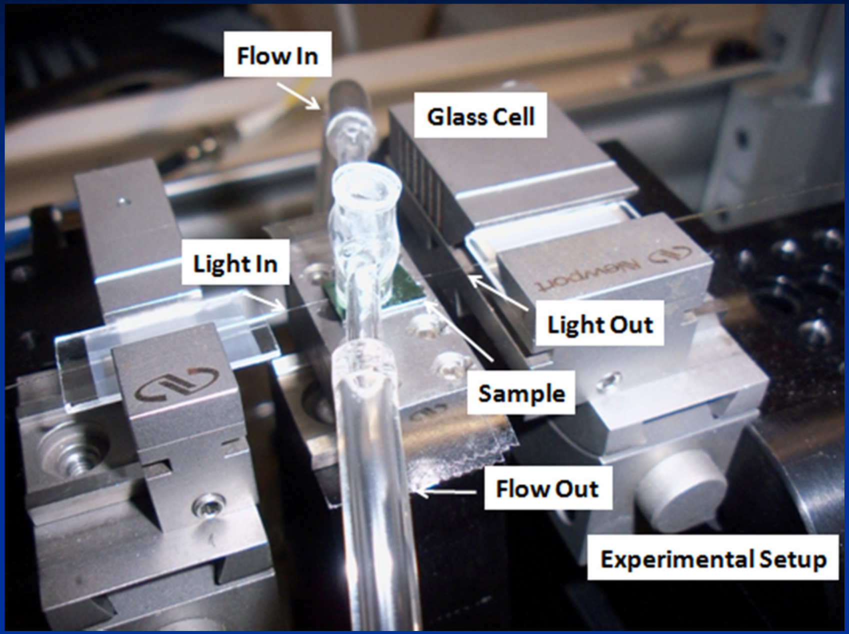
- **Group index varied gradually by shifting the edge air holes; from low group index at the ridge waveguide to high group index at the photonic crystal waveguide slow light regime.**

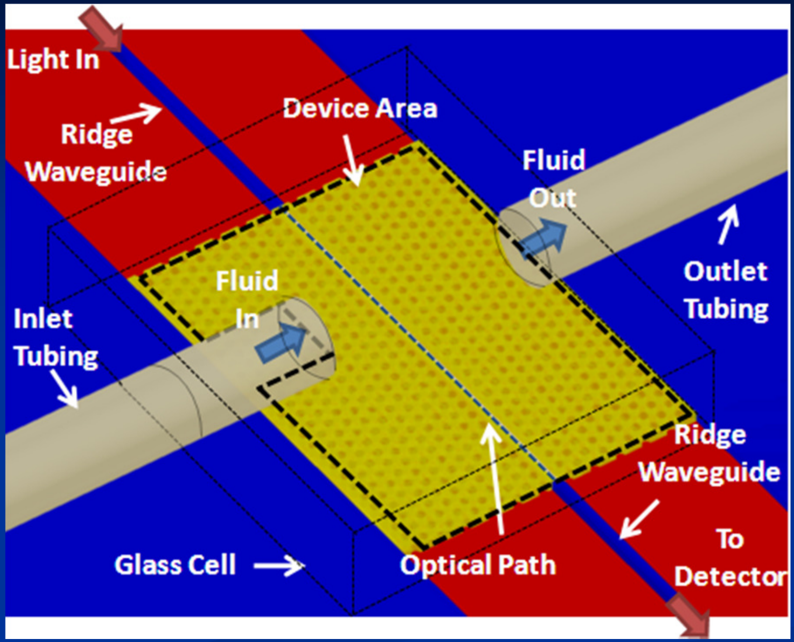


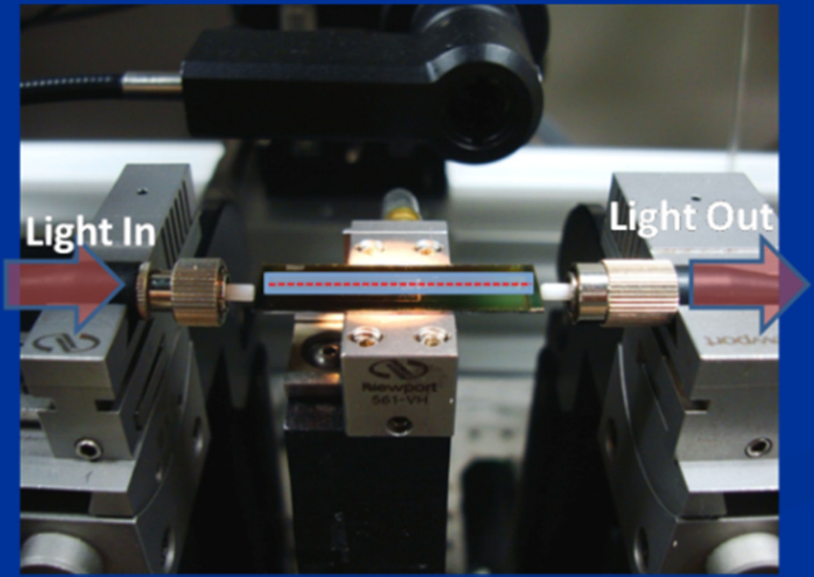


•Xiaolong Wang, Ray T. Chen, "Photonic Crystal Band-Shifting Device for Dynamic Control of Light Transmission," U.S. patent 455,791 (2009)

Experimental Setup

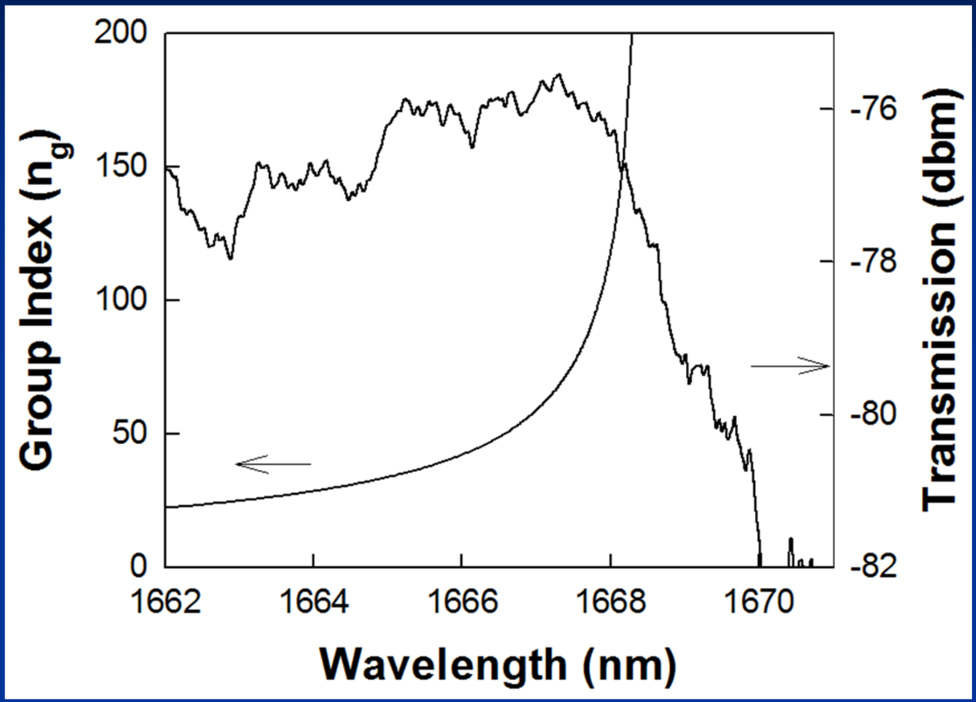


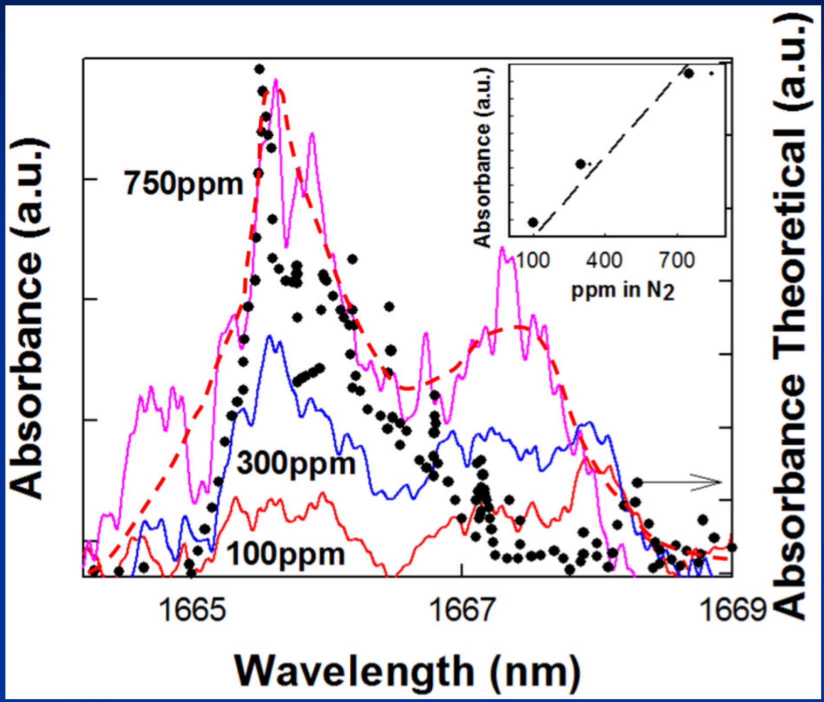




- **Light is guided in and out of the photonic crystal waveguide by optical fibers**
- **Light propagates in direction perpendicular to flow of fluid**
- **Sample cell for controlled environment during experiments; not required for final product**

Methane Detection in N_2 Ambient by Spectroscopy





- At 1.665μm, detection sensitivity of methane achieved for a 300μm long photonic crystal slot waveguide= 100ppm =0.03ppm-m (=0.2% PEL)
- Experimentally, n_g ~30; Slot enhancement ~12
- More than an order of magnitude higher sensitivity can be achieved with wavelength/frequency modulation spectroscopy in near-IR (1ppm), on chip-integrated platform

Requirements from Gas Sensors

Property	Requirement	Photonic Crystal Slot Waveguide Spectroscopy
Cost	< $50/unit for single gas CH_4 sensor	High volume manufacturing in on-chip CMOS platform (< $20)
Detection Sensitivity	<1% of LEL (500ppm for CH_4)	Function of absorption cross-section (~40ppm Near-IR, ~400ppb Mid-IR)
Device Reusability / Longevity	5 years without recalibration or ~12 hours if battery-operated	No electronic components, longevity determined by silicon
Cross-Talk / False Positives/ Specificity	Minimum interference from other substances with signatures in similar wavelengths	Specificity achieved by multiple detection on-chip

- Sensitivity sufficient for most practical purposes
- More than an order of magnitude higher sensitivity can be achieved with wavelength/frequency modulation spectroscopy in near-IR (1ppm), on chip-integrated platform
- Absorbance cross-sections in mid-IR are 2 orders of magnitude larger (10ppb), on chip-integrated platform

Comparison with other Technologies

Property	CRDS *	TDLAS **	FTIR †	PAS ↕	PC Slot Waveguide
On-Chip	No	No	No	No	Yes
Size	~1 cu. ft.	~0.5 cu. ft.	~1.4 cu. ft.	~1 cu. ft.	~0.015 cu. ft
Weight	~28lbs	~6lbs	~24lbs	~33lbs	< 0.1lbs
Power	200 Watt	0.5 Watt	40 Watt	90 Watt	<0.1Watt
Portability	No	No	No	No	Yes
Sensitivity	0.002 ppm-m	1ppm-m (handheld)	0.05ppm-m	0.05ppm-m	0.012ppm-m (near-IR) # 0.12ppb-m(mid-IR)

*CRDS: Cavity Ring-Down Spectroscopy; **TDLAS: Tunable Diode Laser Absorption Spectroscopy; †FTIR: Fourier Transform Infrared Spectroscopy; ↕PAS: Photo-acoustic Spectroscopy; PC: Photonic Crystal

Summary

Photonic crystal Absorption spectrometers enable:

- **Very low cost of ownership**
- **Sensitivity sufficient for most practical purposes**
- **Generous deployment of sensors in field**
- **Multiple species detection on-chip**
- **Less chance for false positives**

Small size enables minimum interference with existing processes

In-situ detection and remote monitoring

Application Areas :

- **Industrial process gas monitoring & quality control**
- **Air quality control & monitoring (Greenhouse and Hazardous Gases)**
- **Explosives detection**

Discussion: Minimum Detectable Sensitivity

Smallest number density that can be determined by absorption spectroscopy

$$N_{\min} = (\frac{dI}{I_0}) / S(\nu) L$$

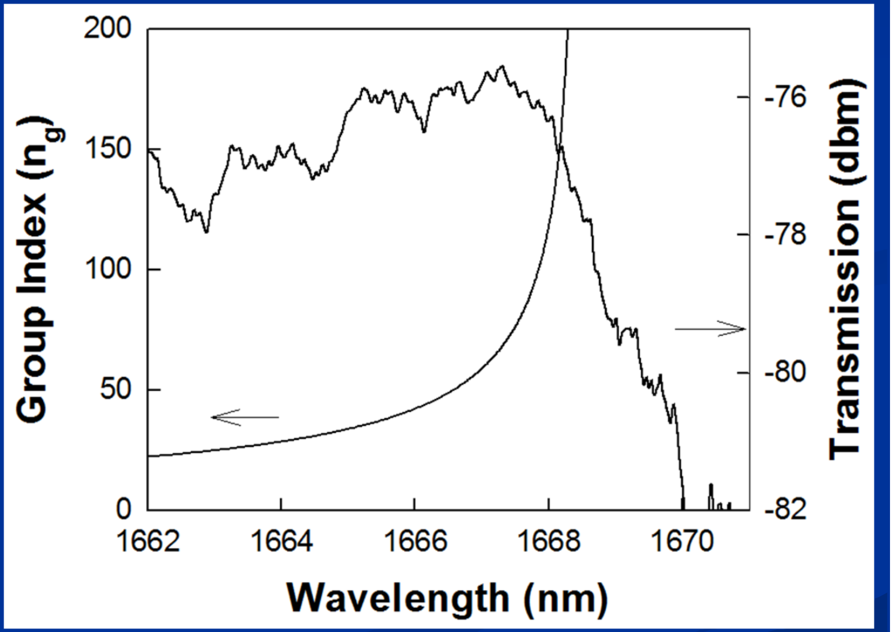
where

- dI/I_0 = smallest fractional change in light intensity that can be detected = 5×10^{-4}
- L = effective absorption path length = 300μm $\times$ 1000= 30cm
- $S(\nu)$ =absorption cross section of methane at 1.665μm = 1.6×10^{-20} cm^2 [HITRAN]

$N_{min} = 1.04 \times 10^{15}$ per cm^3

At 1.665μm, detection limit of methane for a 300μm long photonic crystal slot waveguide= 40ppm (=0.15% LEL)

Experimentally, n_g ~30; Slot enhancement ~12



Experimentally detected: 100ppm =0.03ppm-m