Photonic Crystal Slot Waveguide for Detection of Hazardous Substances by On-Chip Infrared Absorption Spectroscopy

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Outline

- Motivation
- Introduction to On-Chip Absorption Spectroscopy with Photonic crystal Slot Waveguides
- Design and Fabrication Steps
- Current Status of Work
- Summary

Motivation

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

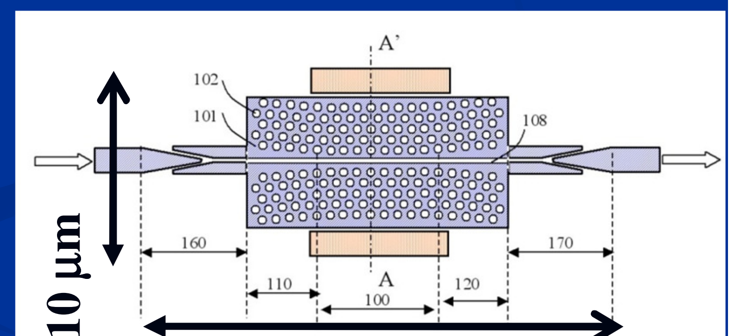
Cavity Ringdown Spectroscopy
(66lbs, ~ 3cu.ft)

← Tunable Diode Laser Absorption Spectroscopy

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

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

Our Device

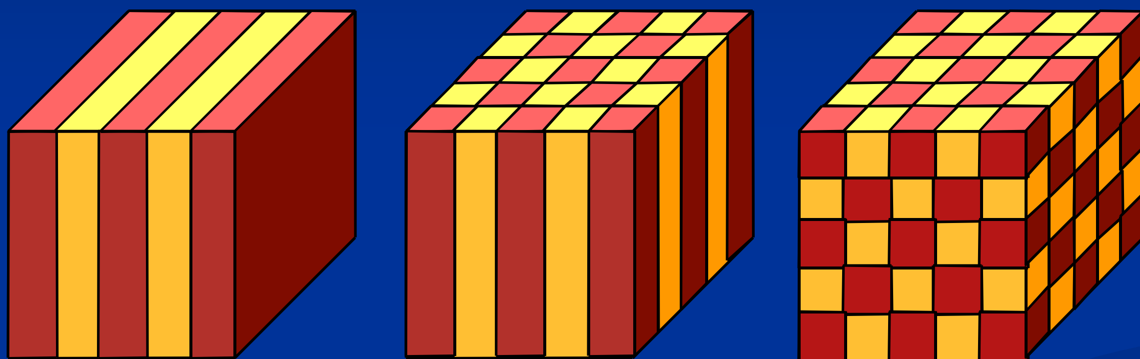


300 μm

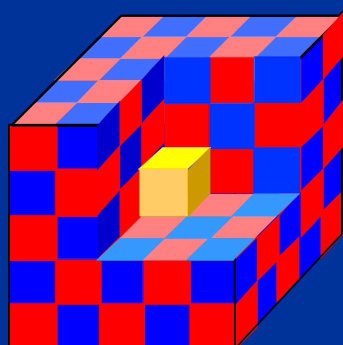
(< 0.1 lbs, <10cu. cm.)

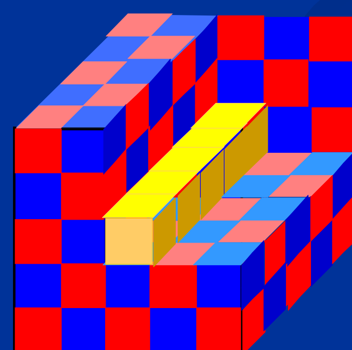
➢Photonic Crystal

- **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 Slot Waveguide Based Absorption 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

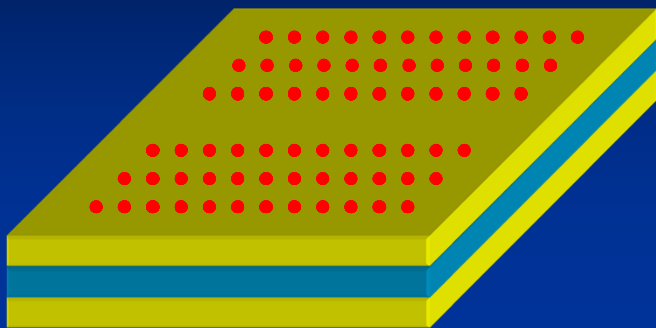
Mortensen et al, Appl. Phys. Lett. **90** (14), 141108 (2007)

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

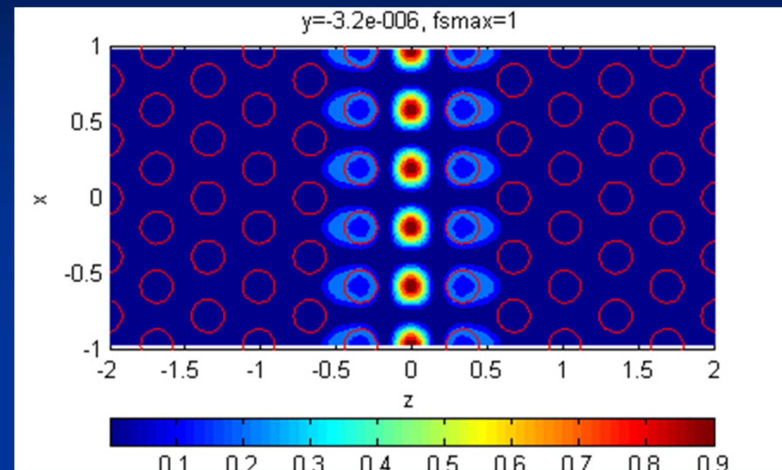
where

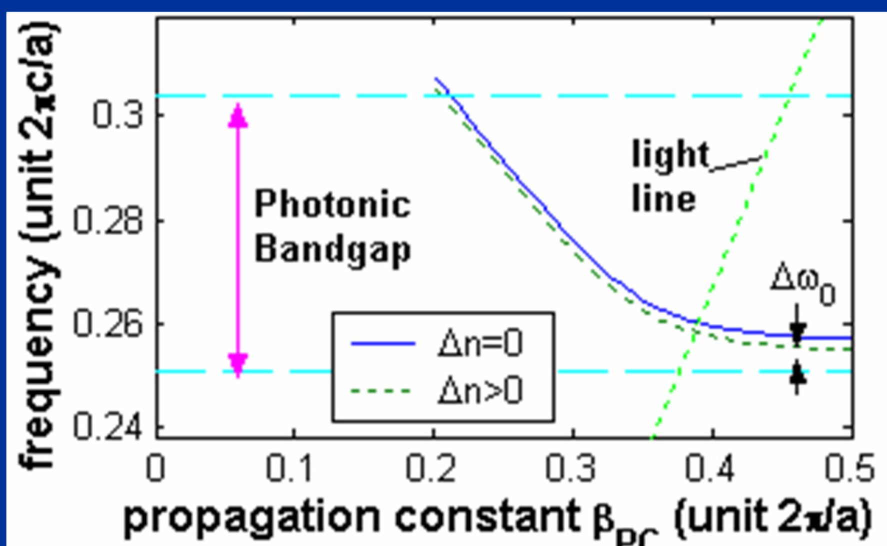
- c =Velocity of light in medium of refractive index n.
- v_g = Group velocity of light
- f = Electric field intensity enhancement

➢Photonic Crystal Waveguide



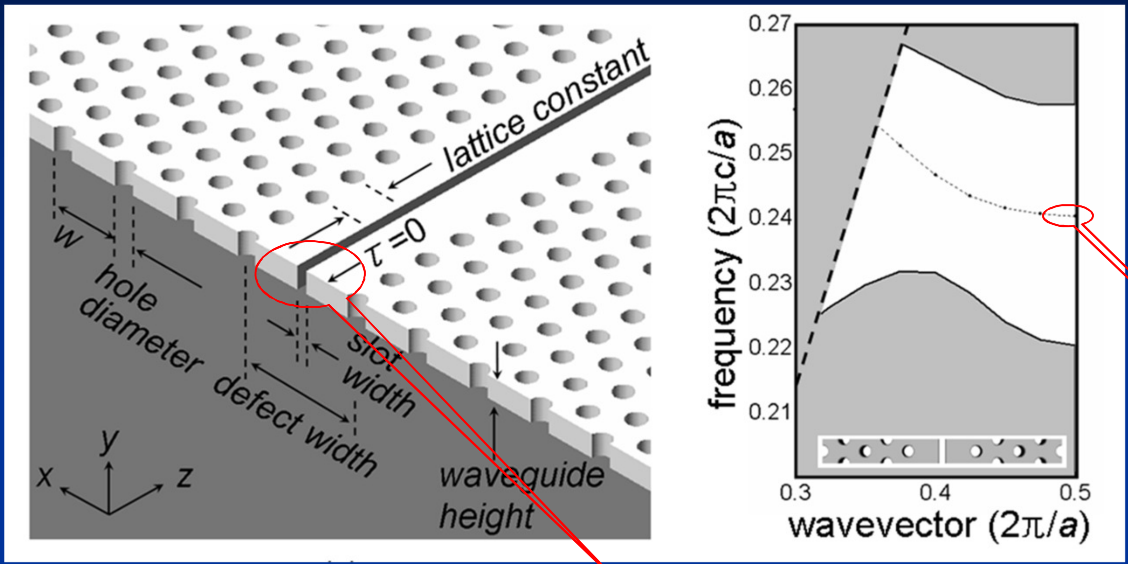
W-1 PCW





- Normalized dispersion diagram
- Scaled in wavelength by scaling the lattice constant of the photonic crystal

➢Photonic Crystal Slot Waveguide



Photonic crystal period a=460nm

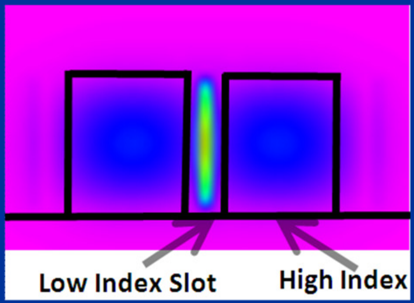
Waveguide height h=0.5a

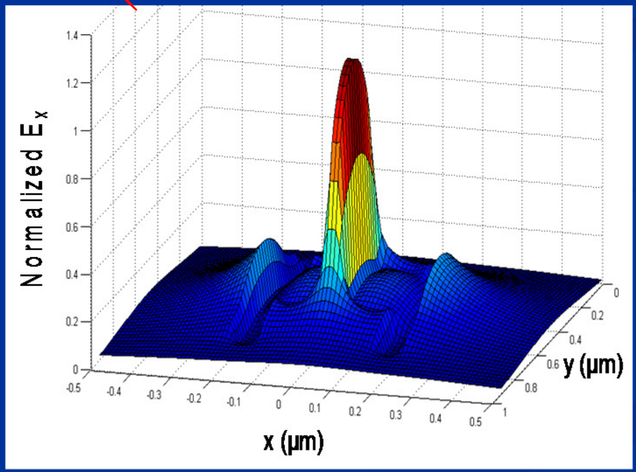
Hole diameter d=0.5a

Slot width w_0=0.2a

Defect width w_1=1.3 √3a

Slot Enhancement



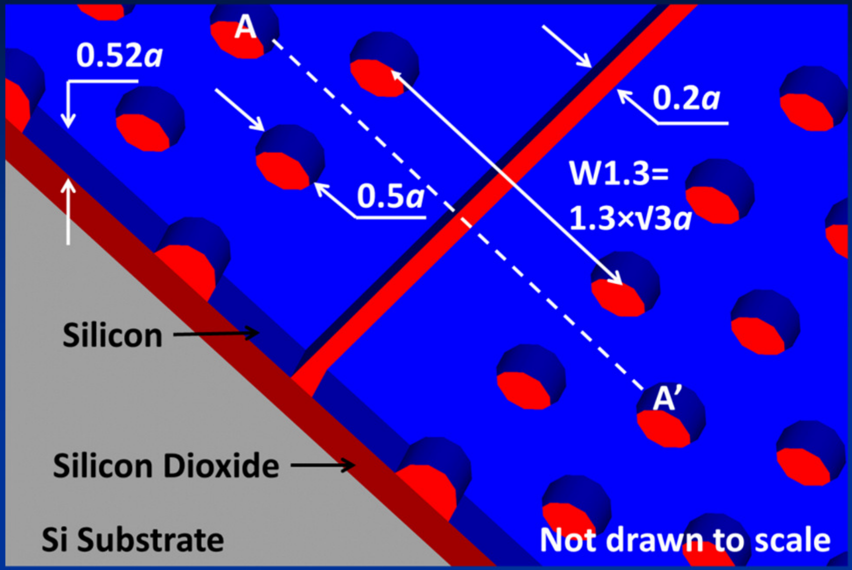


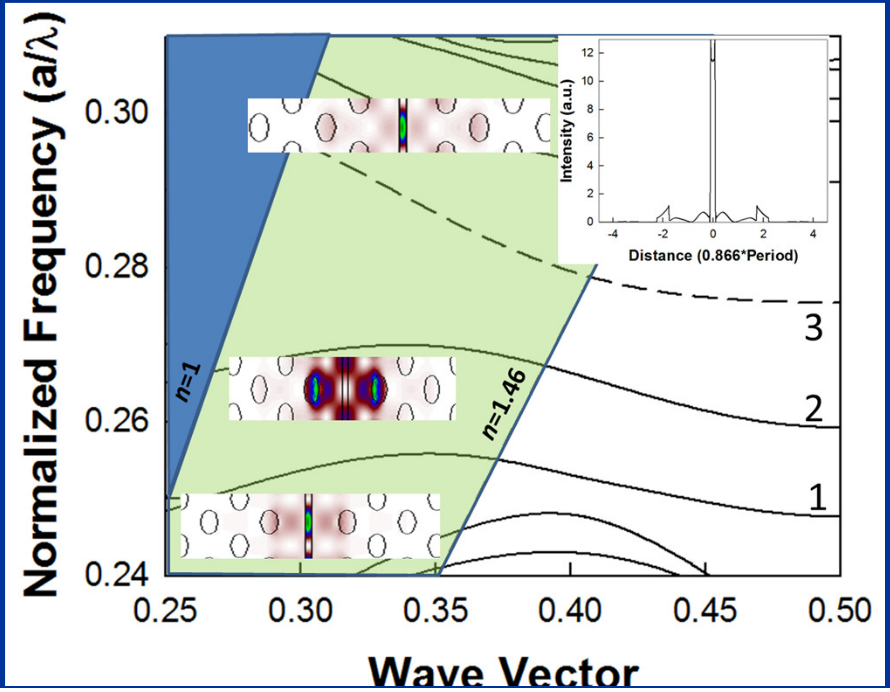
Advantages:

- 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





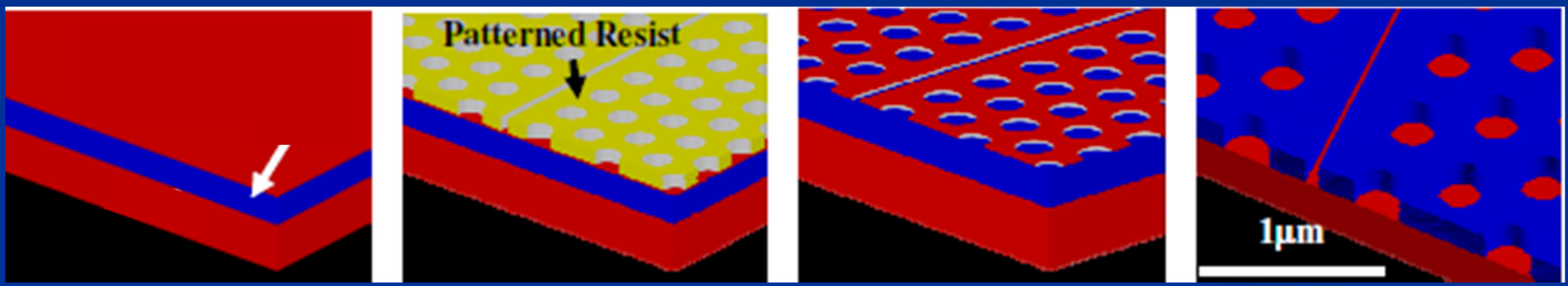
W-C. Lai, S. Chakravarty, X. Wang, C-Y. Lin, and R. T. Chen, "On-chip methane sensing by near-IR absorption signatures in a photonic crystal slot waveguide," Opt. Lett. 36, 984-986 (2011)

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 fabrication steps to create an optical waveguide

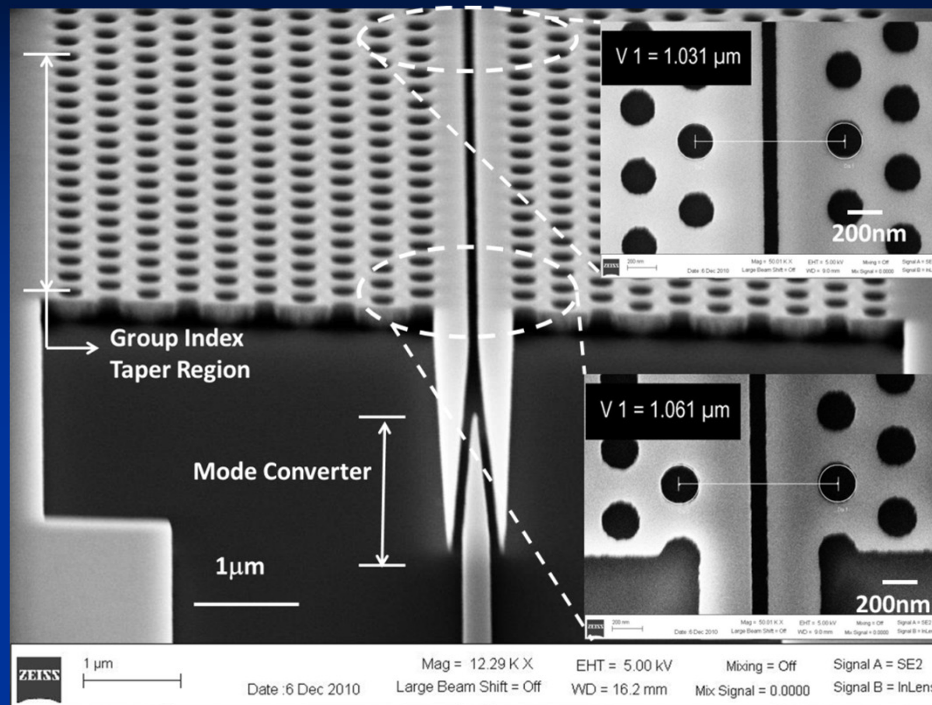


Hard Mask Growth	Resist Patterning	Hard Mask Patterning	Pattern Transfer to Core Material

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

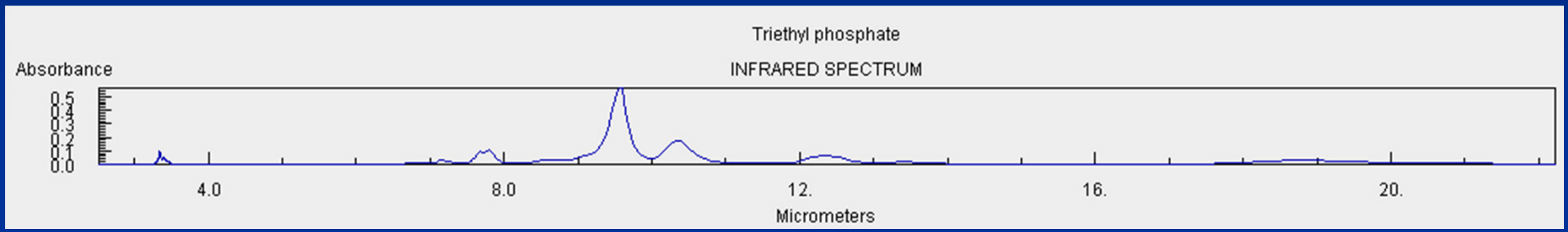
Minimum feature sizes easily achievable by 365nm photolithography

Photonic Crystal Slot Waveguide

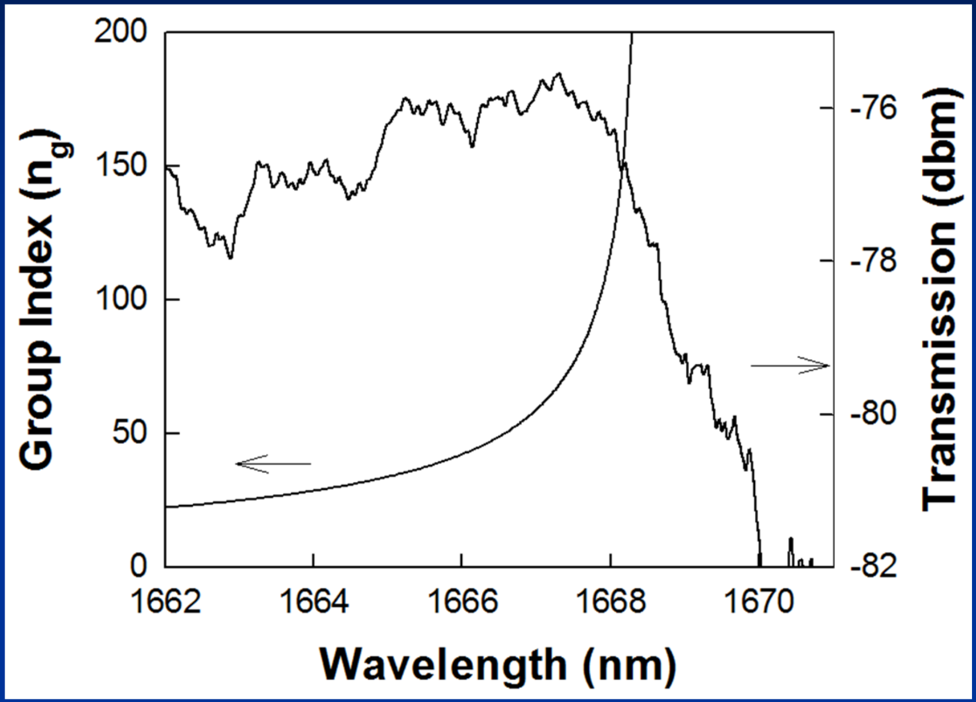


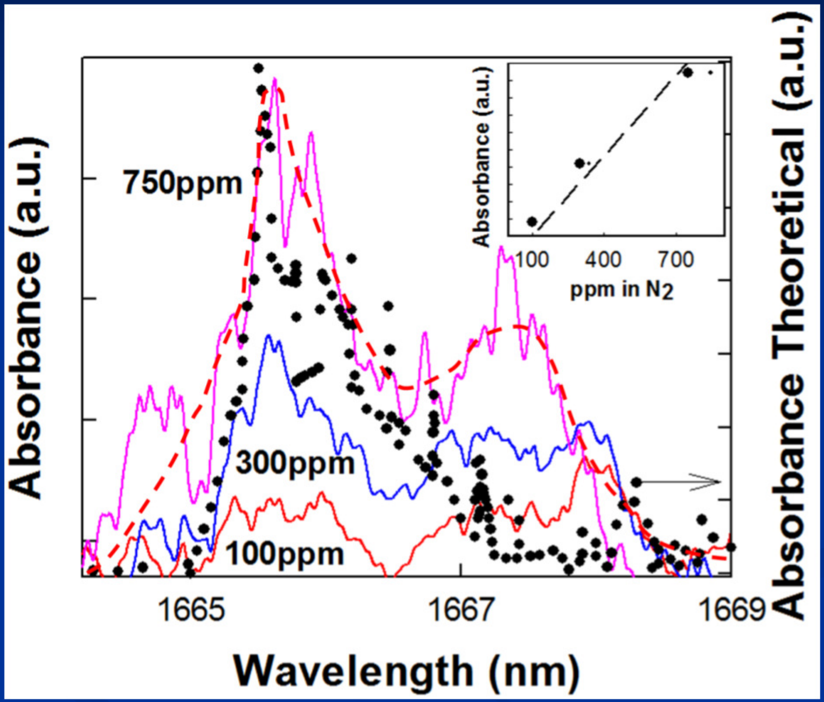
- Slot in the middle of a photonic crystal waveguide
- Mode Converter for higher coupling efficiency from the ridge waveguide into slot
- Photonic Crystal Impedance Taper for higher coupling efficiency into slow light region

Theoretical Absorbance Spectrum



On-Chip 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

Summary

Photonic crystal slot waveguides enable:

- **Miniaturization of sensors using absorption spectroscopy for chemical detection**
- **Multiple species detection on-chip**

Small size enables minimum interference with existing processes

In-situ detection and remote monitoring

Measurements still in progress for triethylphosphate