Slow-Light-Enhanced Spectral Interferometers

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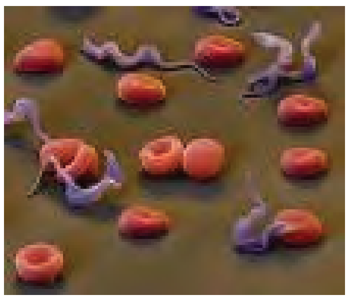
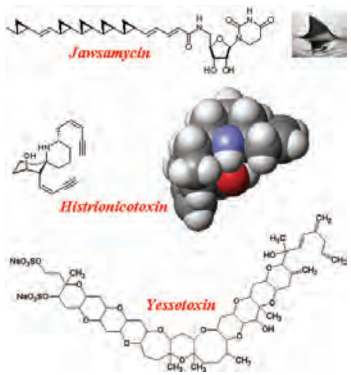
Chip-Scale Spectrometers for Chem-Bio Identification

- Spectroscopy is the standard laboratory procedure for identifying chemical species.
- Can we fabricate miniaturized, chip-scale spectrometers without sustaining a loss in resolution?

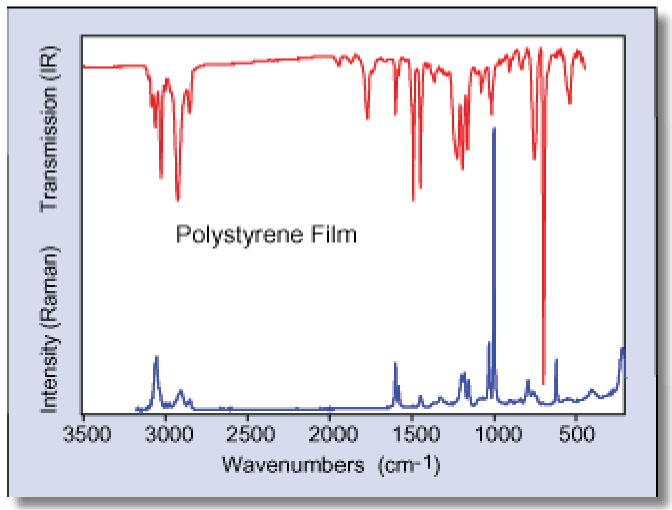
pathogens



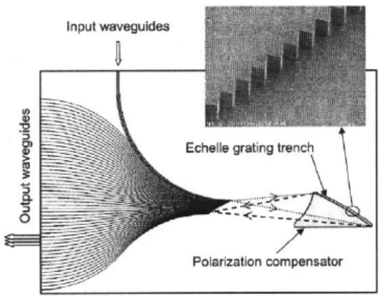
toxins



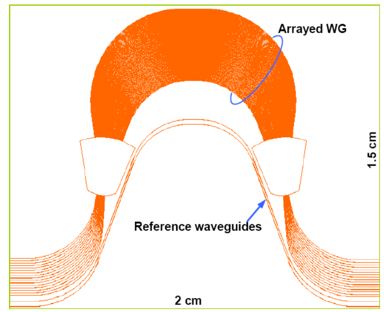
"fingerprint" Raman signature spectrum



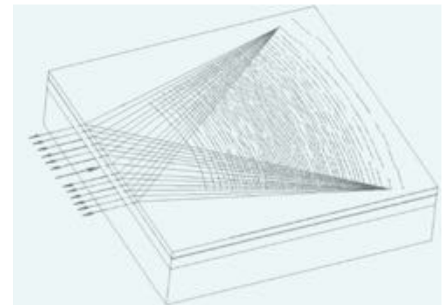
Current On-Chip Spectrometers



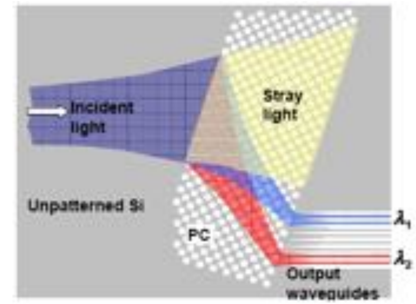
Echelle grating
(NRC, Canada)



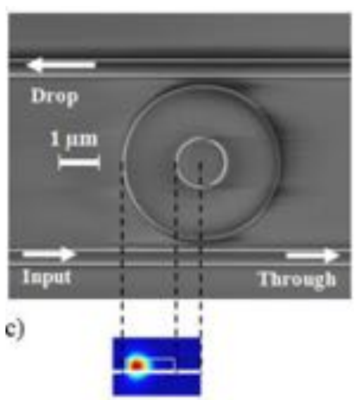
Arrayed Waveguide Grating
(UCSB)



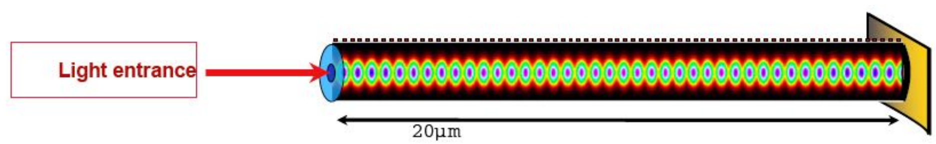
Digital Phase Holography
(LBNL *et al.*)



Super-prism
(GaTech)



Donut resonator
(GaTech)

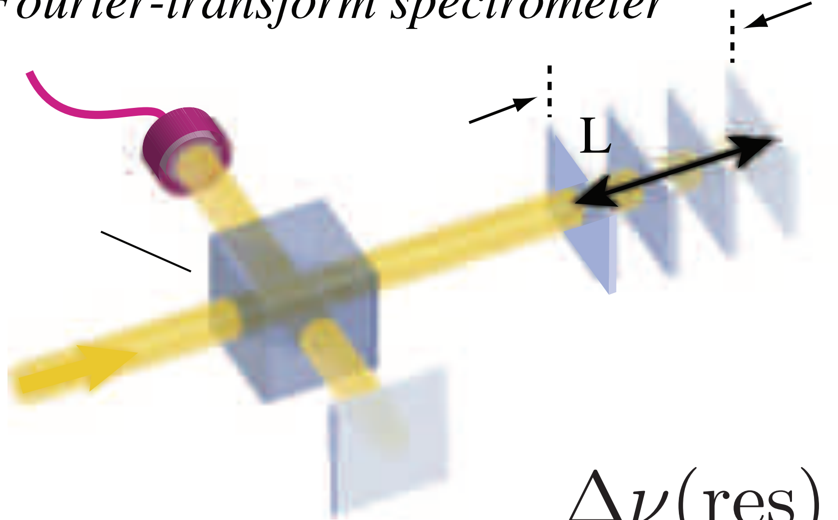


Spatial FT based (Swift)
(Université de Grenoble)

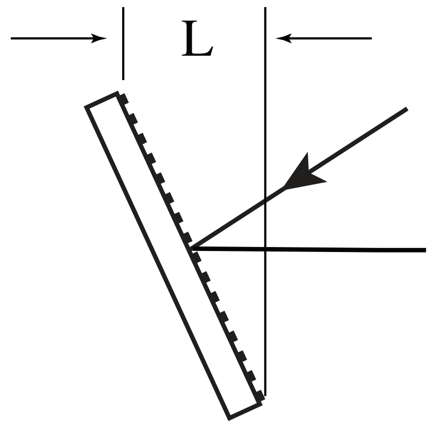
The Applied-Physics Goal of Our Project: Beat the 1/L Resolution Limit of Standard Spectrometers

- The limiting resolution of a broad class of spectrometers is given (in wave-numbers) by the inverse of a characteristic dimension L of the spectrometer.

Fourier-transform spectrometer



grating spectrometer



$$\Delta\nu(\mathrm{res}) \approx 1/L$$

- We use slow-light methods to design spectrometers with resolution that exceeds this conventional limit by a factor as large as the group index.

- This ability allows us to miniaturize spectrometers with no loss of resolution, for "lab-on-a-chip" applications.

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Controlling the Velocity of Light

"Slow," "Fast" and "Backwards" Light

– Light can be made to go:

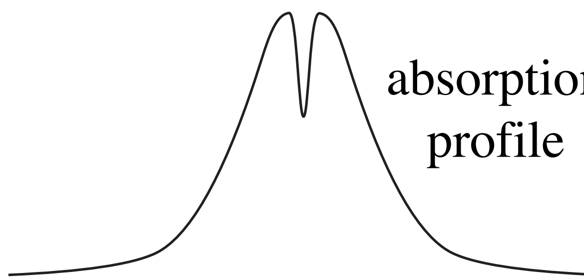
slow: $v_g << c$ (as much as 10^6 times slower!)

fast: $v_g > c$

backwards: v_g negative

Here v_g is the group velocity: $v_g = c/n_g$ $n_g = n + \omega\,(dn/d\omega)$

– Velocity controlled by structural or material resonances



Review article: Boyd and Gautier, Science 326, 1074 (2009).

Group Velocity

Pulse
(wave packet)

Group velocity given by $v_g = \dfrac{d\omega}{dk}$

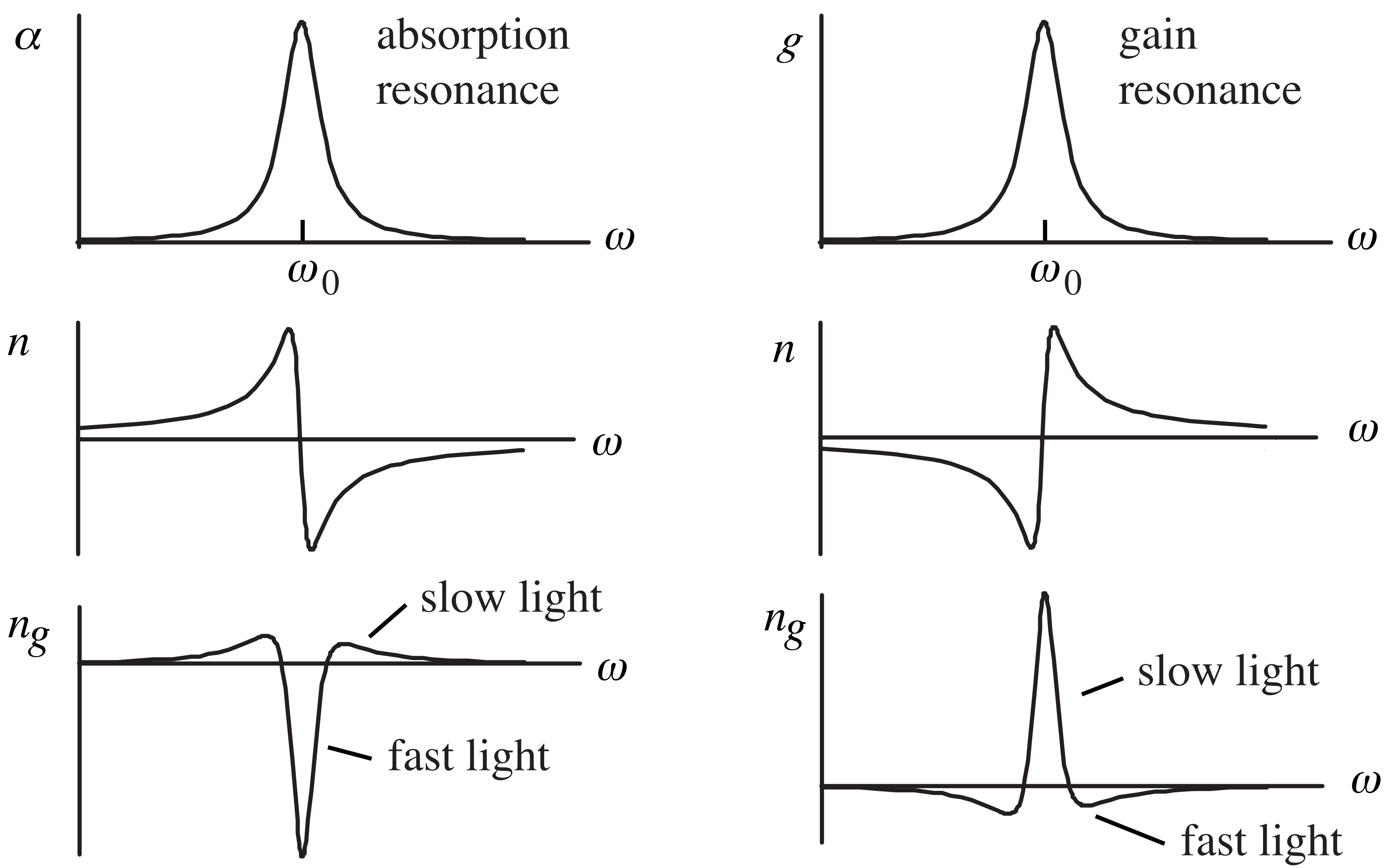
For $k = \dfrac{n\omega}{c}$. $\dfrac{dk}{d\omega} = \dfrac{1}{c}\left(n + \omega\,\dfrac{dn}{d\omega}\right)$

Thus

$$v_g = \frac{c}{n + \omega \frac{dn}{d\omega}} \equiv \frac{c}{n_g}$$

Thus $n_g \neq n$ in a dispersive medium!

Slow and Fast Light Using Isolated Gain or Absorption Resonances



$$n_g = n + \omega\,(\mathrm{d}n/\mathrm{d}\omega)$$

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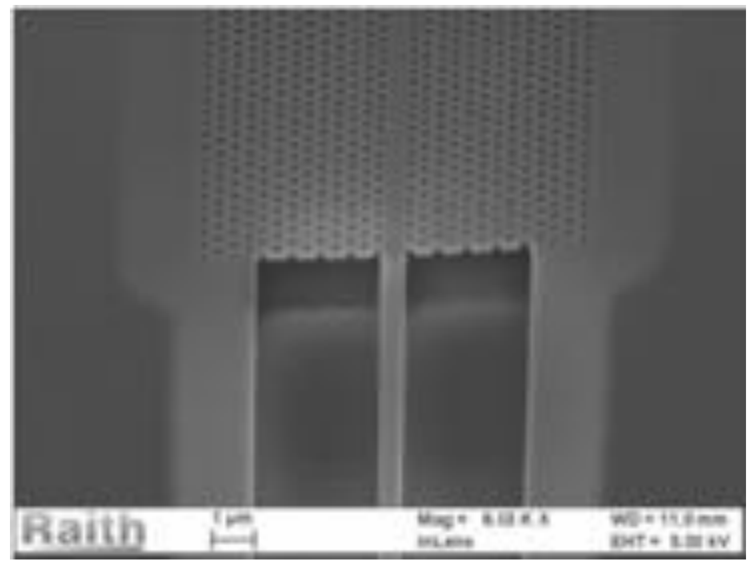
Our Goal

Replace this:

with this:



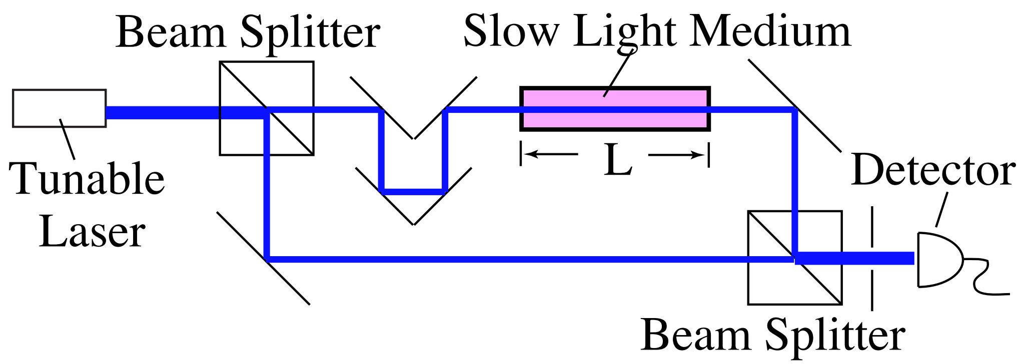
Our Approach: Chip-Scale Slow-Light Spectrometer

- The spectral sensitivity of an interferometer is increased by a factor as large as the group index of a material placed within the interferometer.

- We want to exploit this effect to build chip-scale spectrometers with the same resoluation as large laboratory spectromters

- Here is why it works:

Slow-light interferometer:

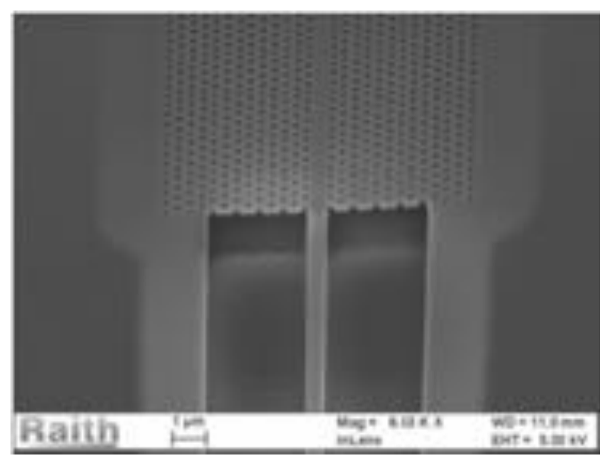


Simple analysis

$$\frac{d\,\Delta\phi}{d\omega} = \frac{d}{d\omega}\frac{\omega n L}{c} = \frac{L}{c}\left(n + \omega\frac{dn}{d\omega}\right) = \frac{L n_g}{c}$$

- We use line-defect waveguides in photonic crystals as our slow light mechanism

Slow-down factors of greater than 100 have been observed in such structures.



Shi, Boyd, Gauthier, and Dudley, Opt. Lett. 32, 915 (2007)
Shi, Boyd, Camacho, Vudyasetu, and Howell, PRL. 99, 240801 (2007)
Shi and Boyd, J. Opt. Soc. Am. B 25, C136 (2008).

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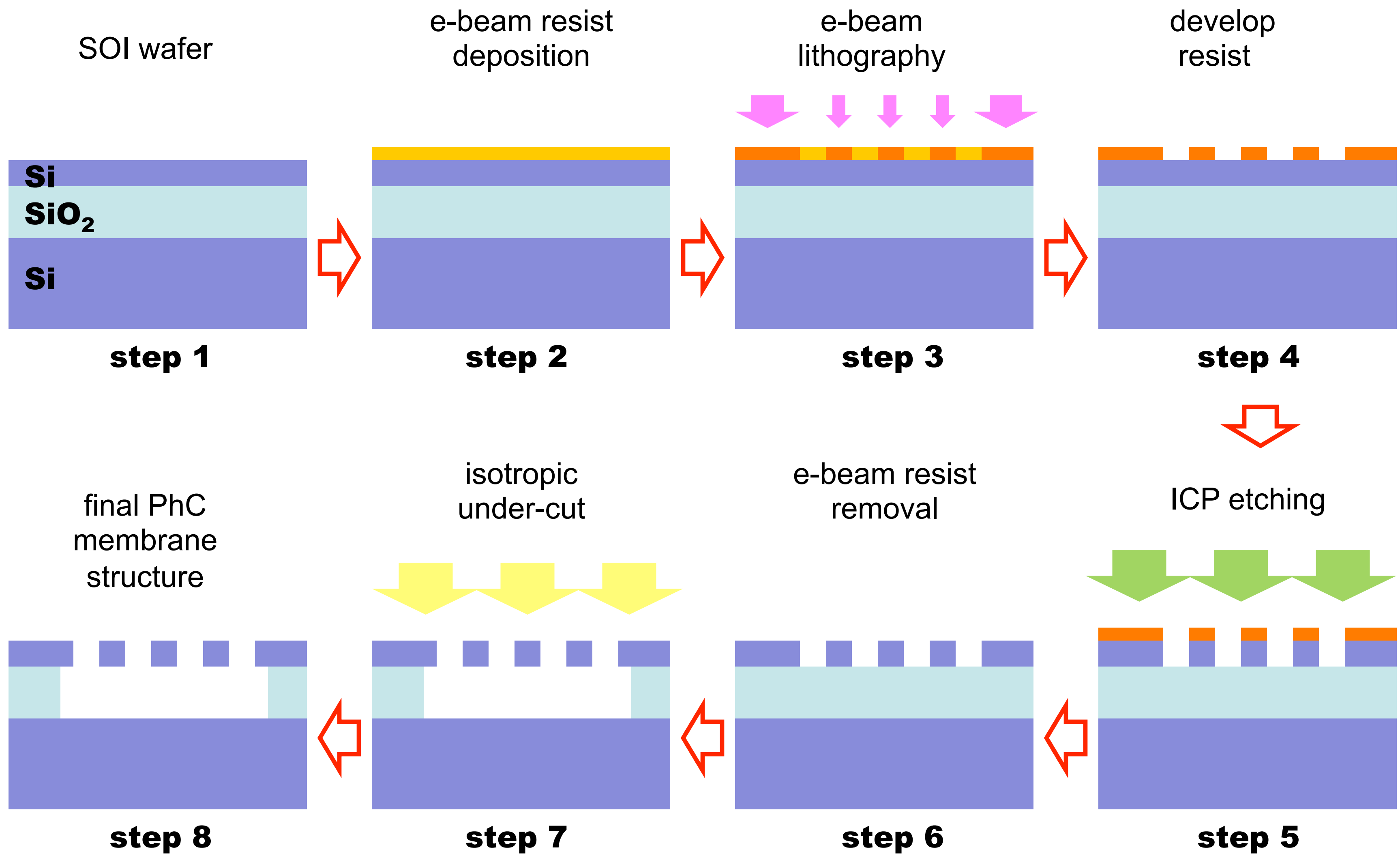
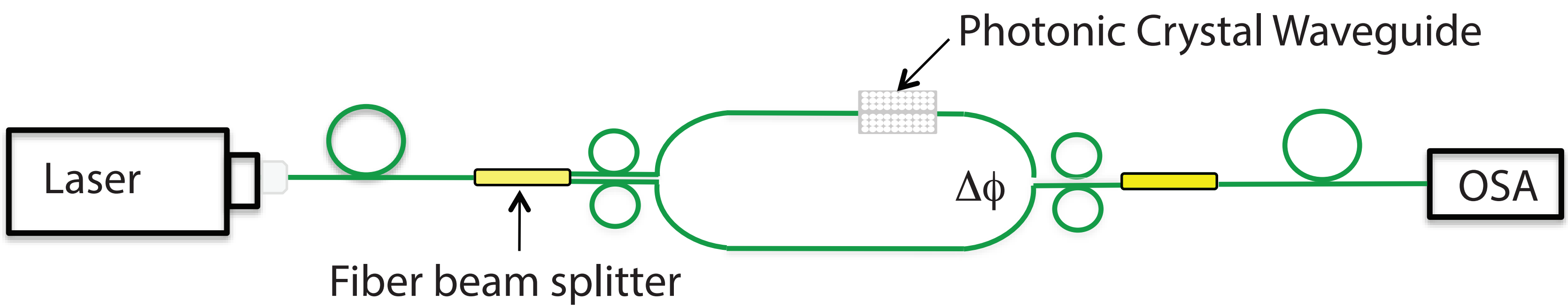
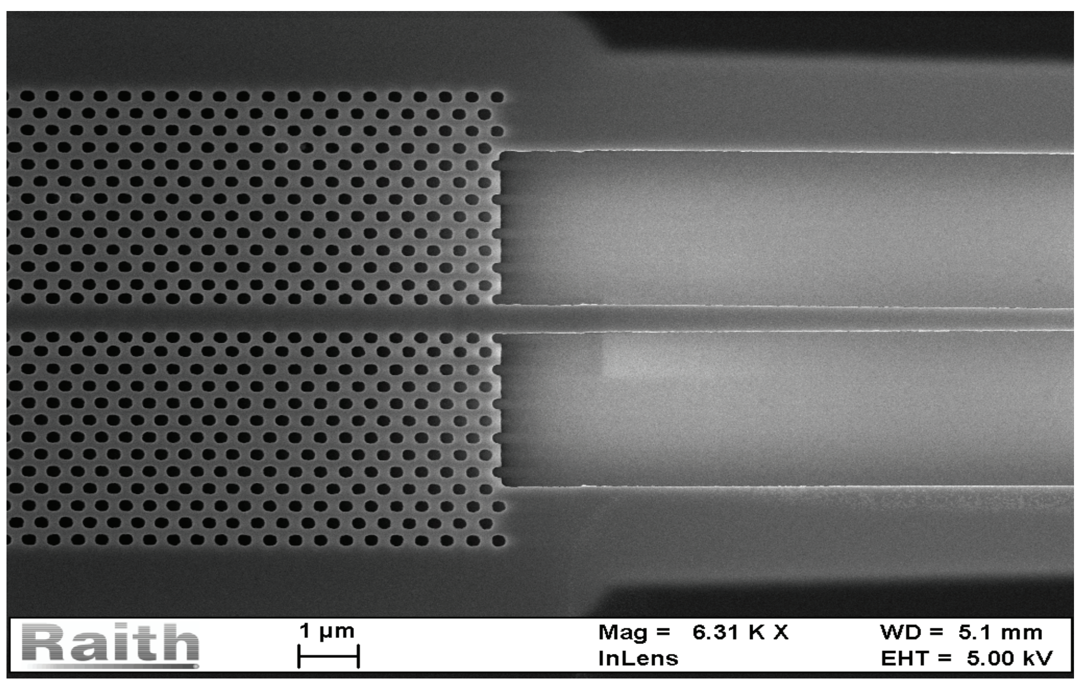
Nano-fabrication process



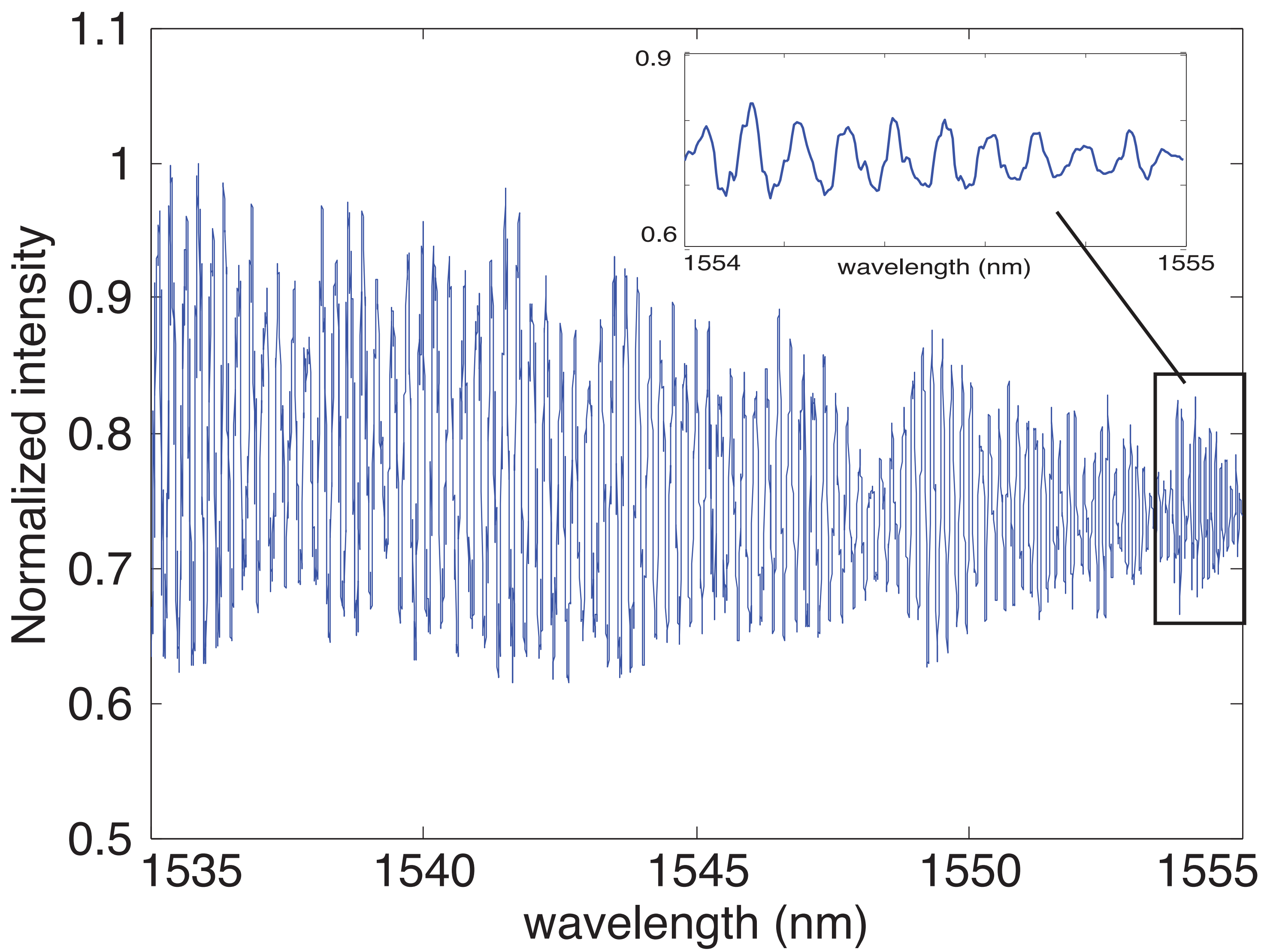
UNIVERSITY of ROCHESTER

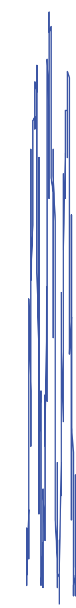
Laboratory Characterization of Slow-Light Mach-Zehnder Interferometer





Interference Pattern Produced by the Photonic-Crystal, SLow-Light Spectrometer

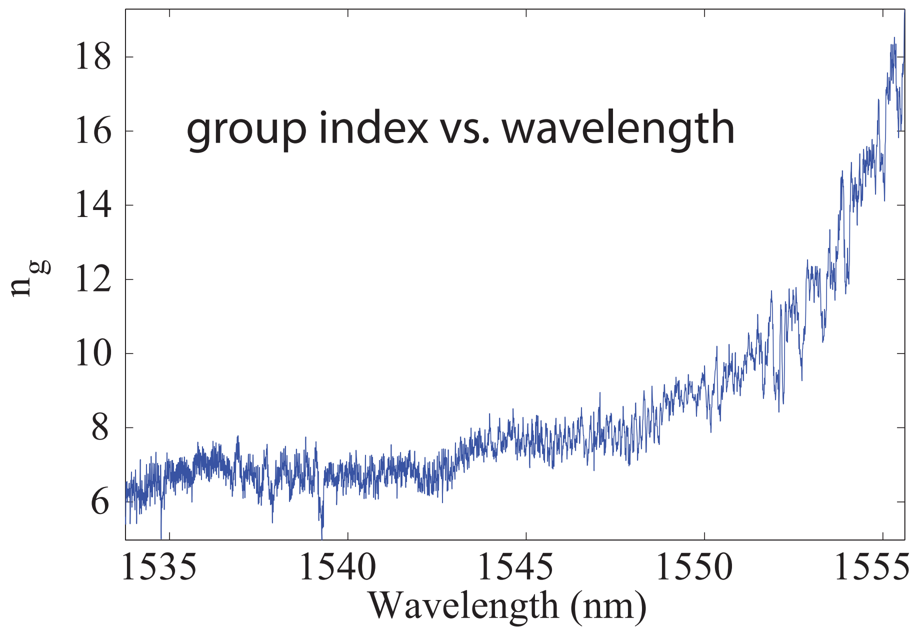


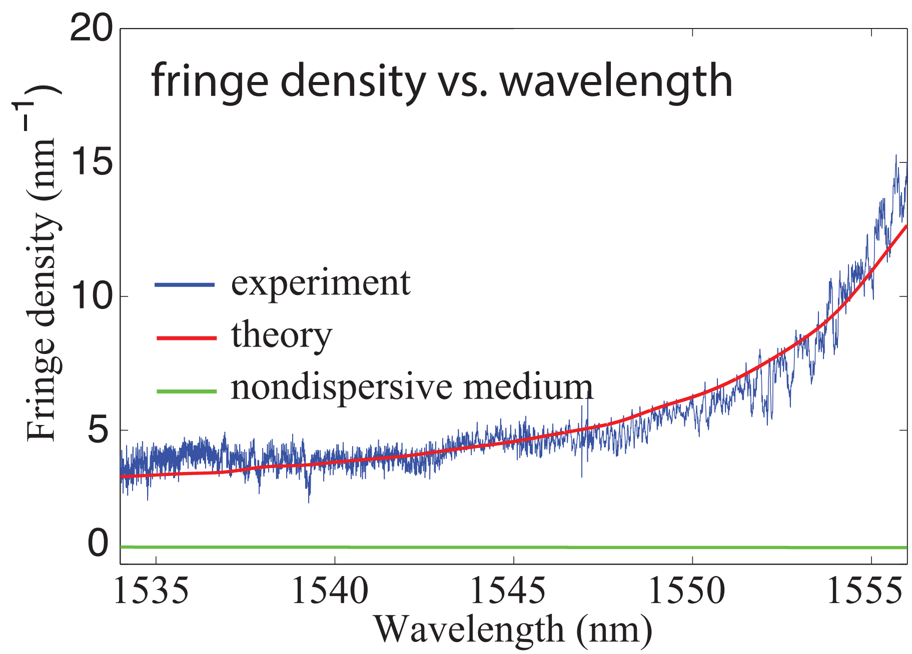


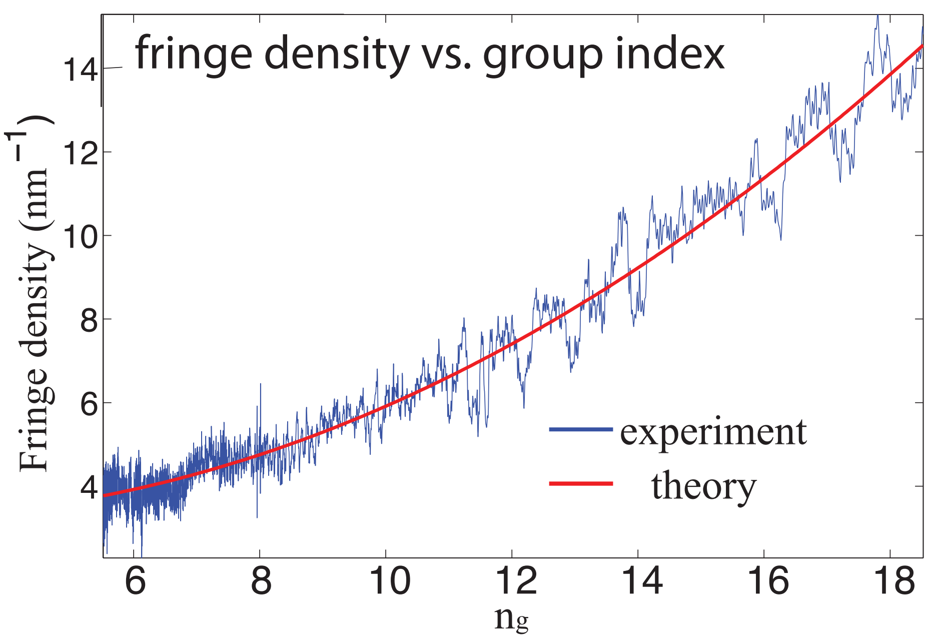
Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm^{-1}

(Slow-light waveguide is only 1 mm long!)

Quantitative Results: Photonic-Crystal, SLow-Light Spectrometer

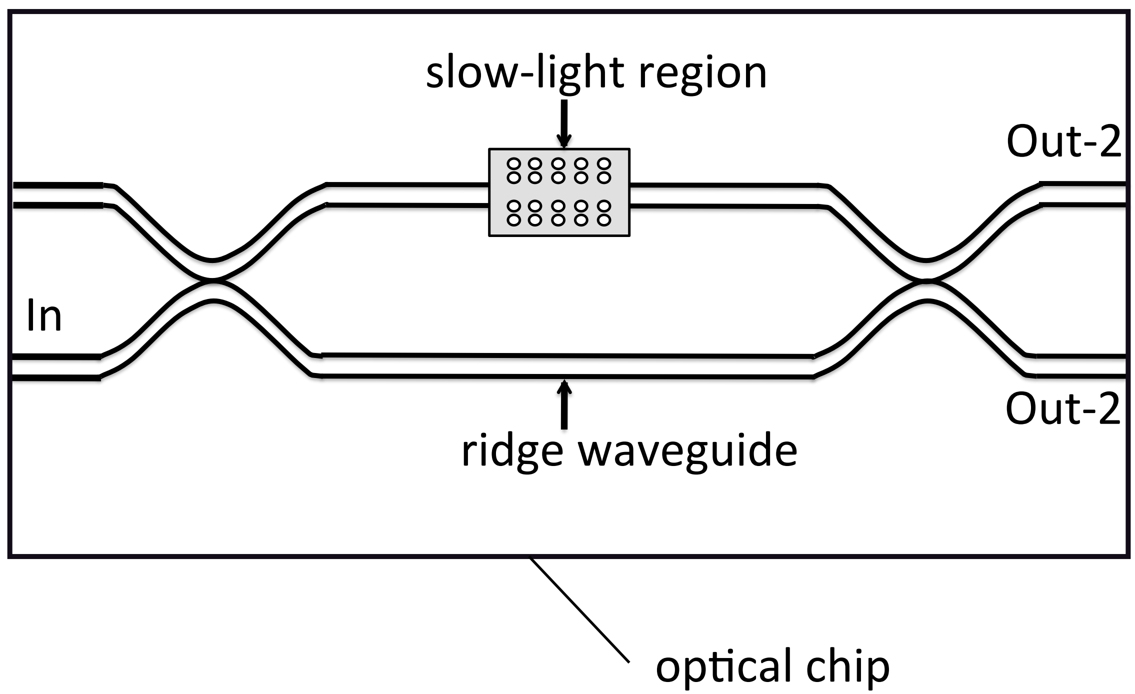




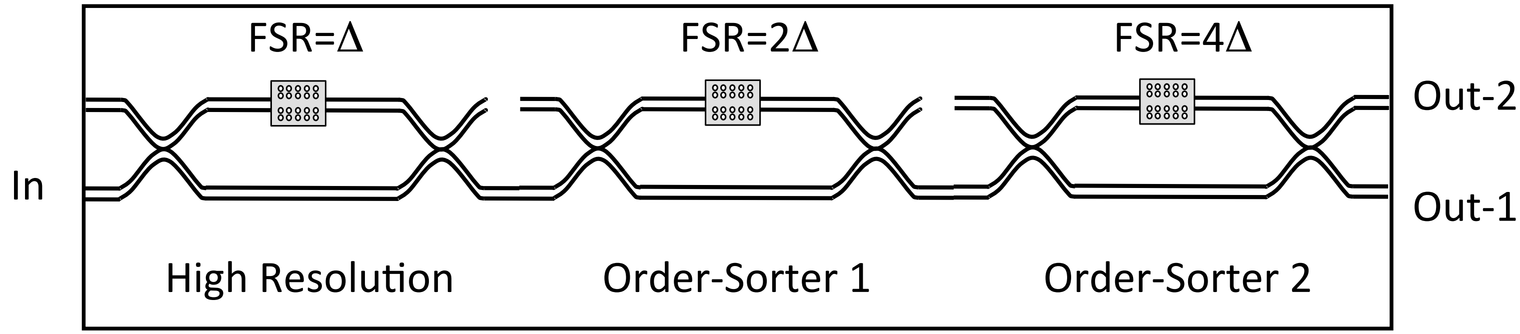


- Spectral resolution is proportional to fringe density
- Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm^{-1}
- Slow-light waveguide is only 1 mm long

Next Step: All-On-Chip Slow-Light Spectrometer



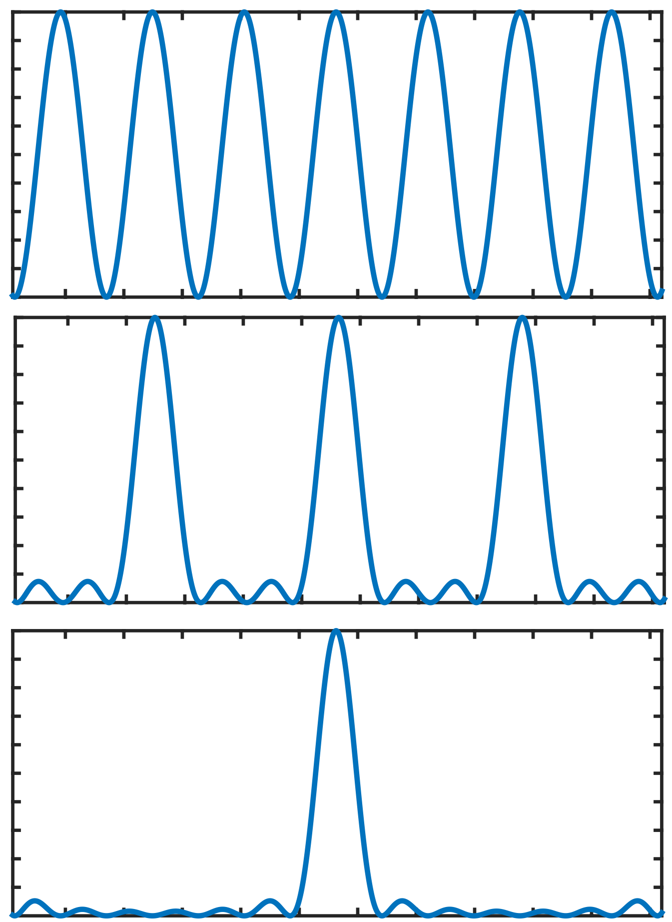
Long-Term Goal: All-On-Chip Spectrometer with Order Sorting



After Stage 1

After Stage 2

Output



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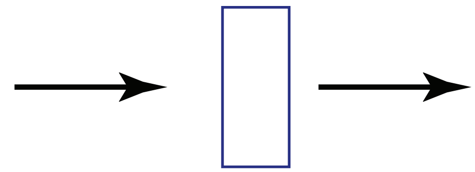
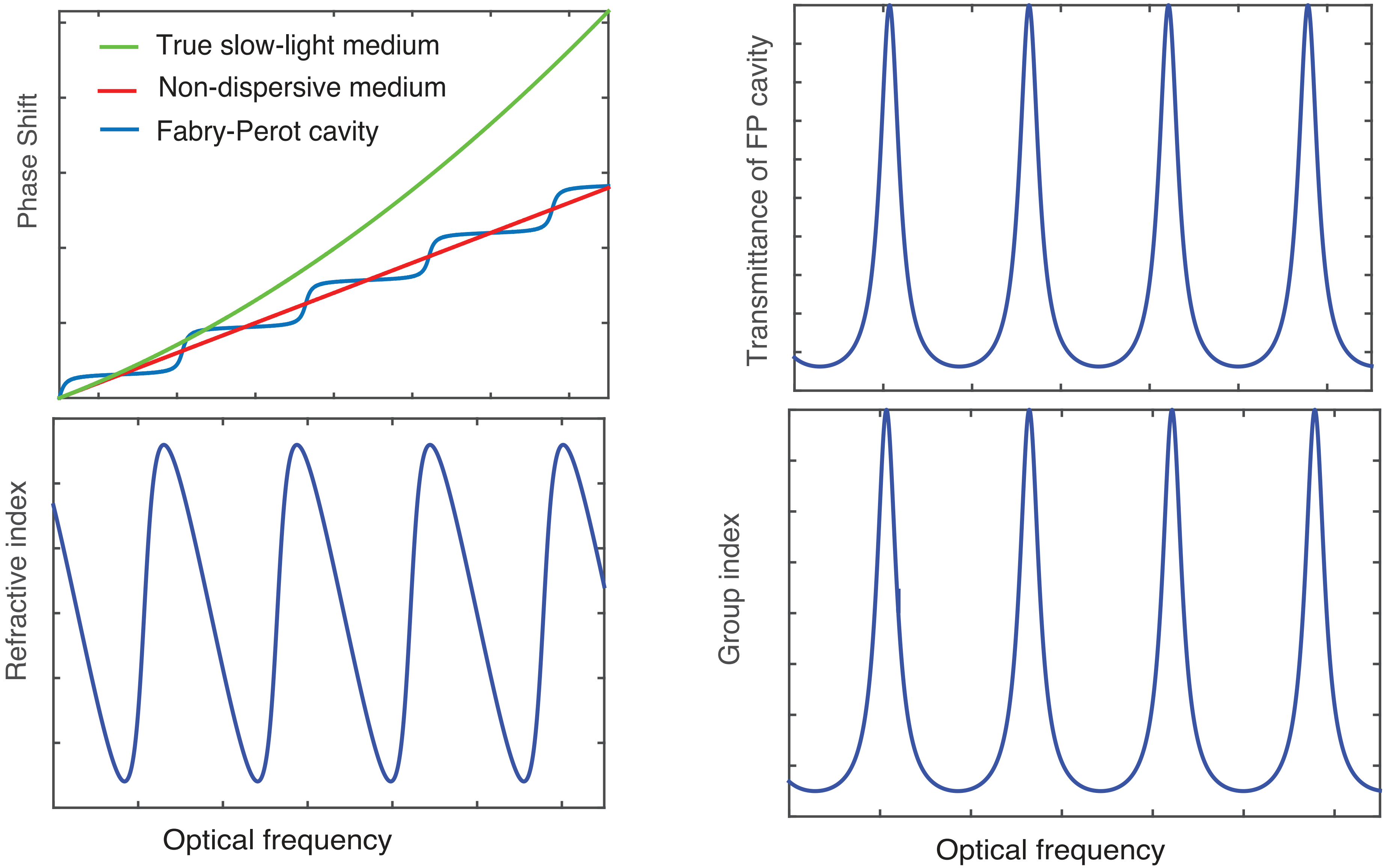
Relation between Slow Light and Resonator Structures

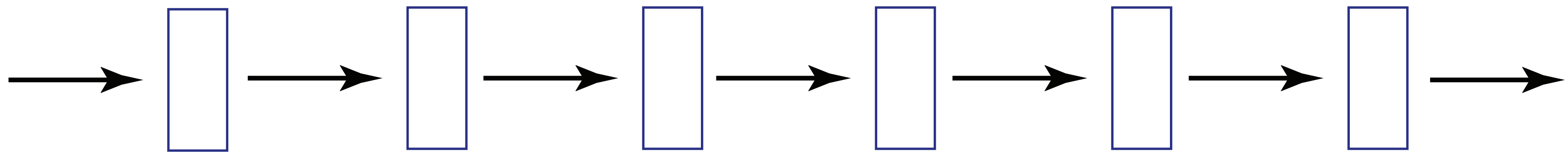
A Fabry-Perot étalon mimics some of the properties of a slow-light medium





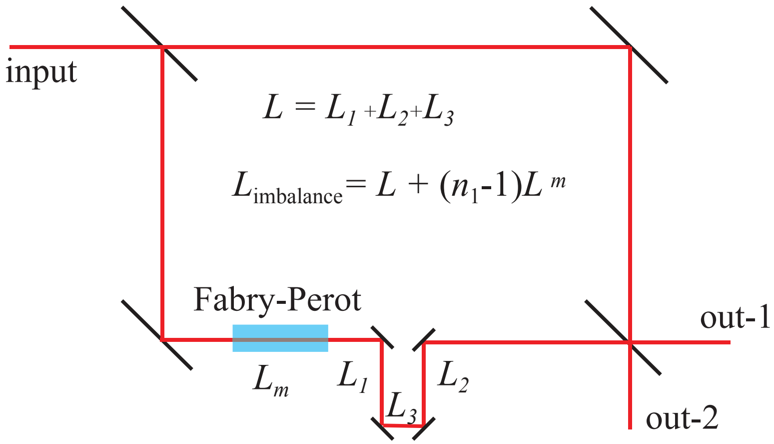
Relation between Slow Light and Resonator Structures

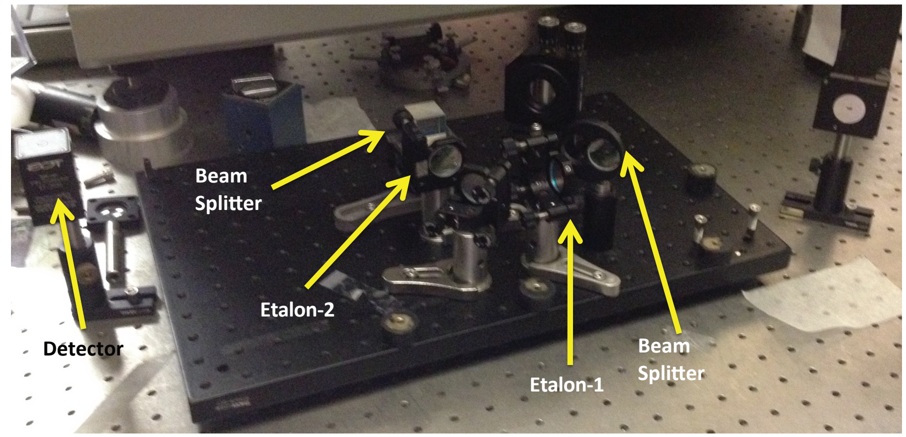
A sequence of Fabry-Perot étalon acts like a true slow-light medium.



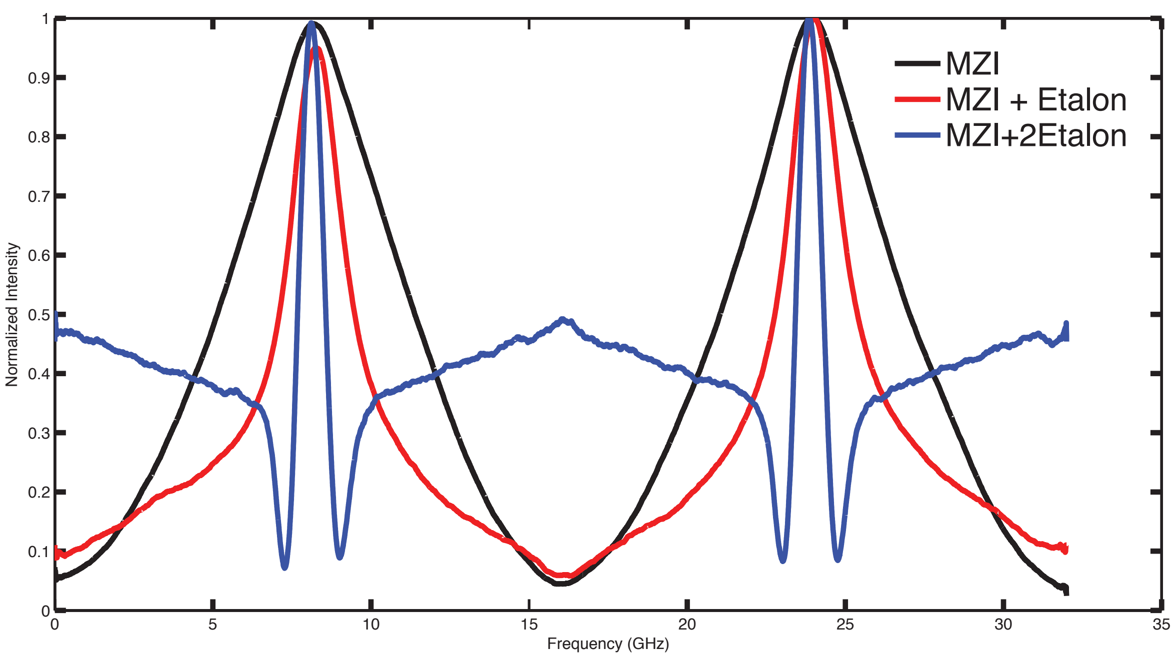
Laboratory Studies of a Hybrid Interferometer

Place one or more Fabry-Perot étalons inside of a Mach-Zehnder interferometer





- Laboratory results



Resolution is improved as more interferometers are cascaded.

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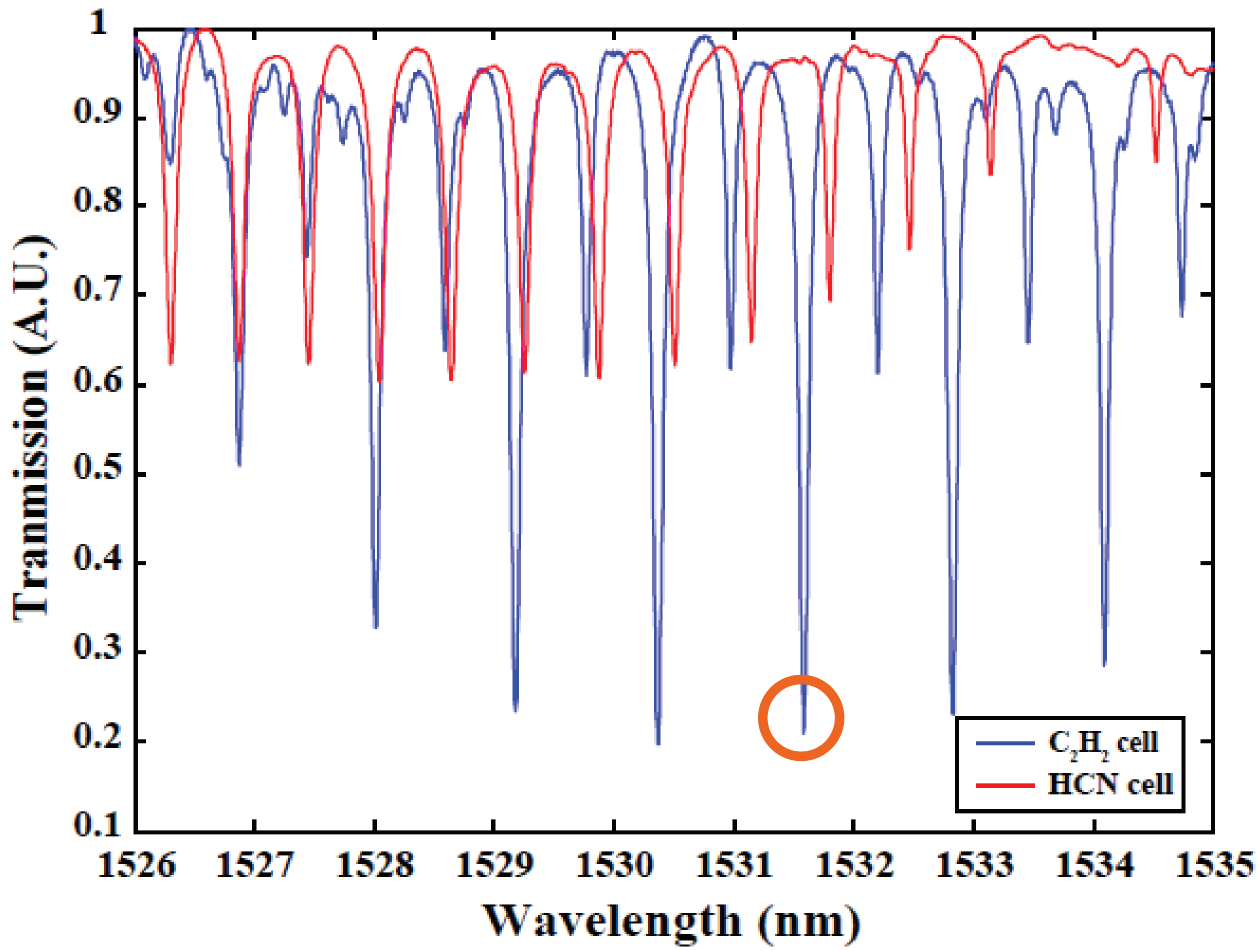
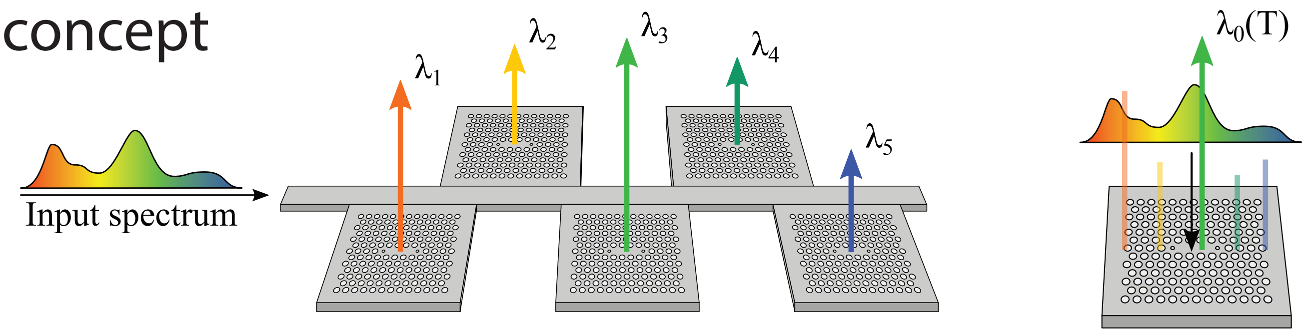
Challenge: Fabricate a chip-scale spectrometer that can discriminate acetylene (H_2C_2) from hydrogen cyanide (HCN)?



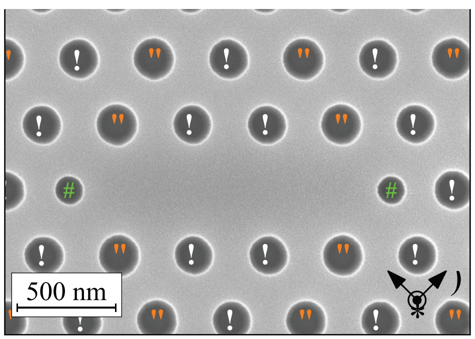
(data from our own lab)

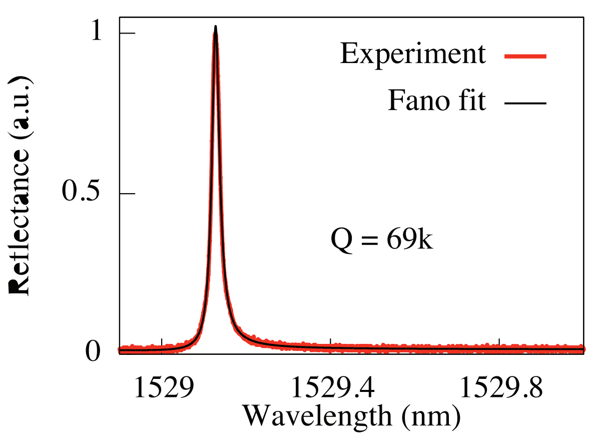
On-chip spectrometer based on high-Q photonic crystal cavities

- The concept

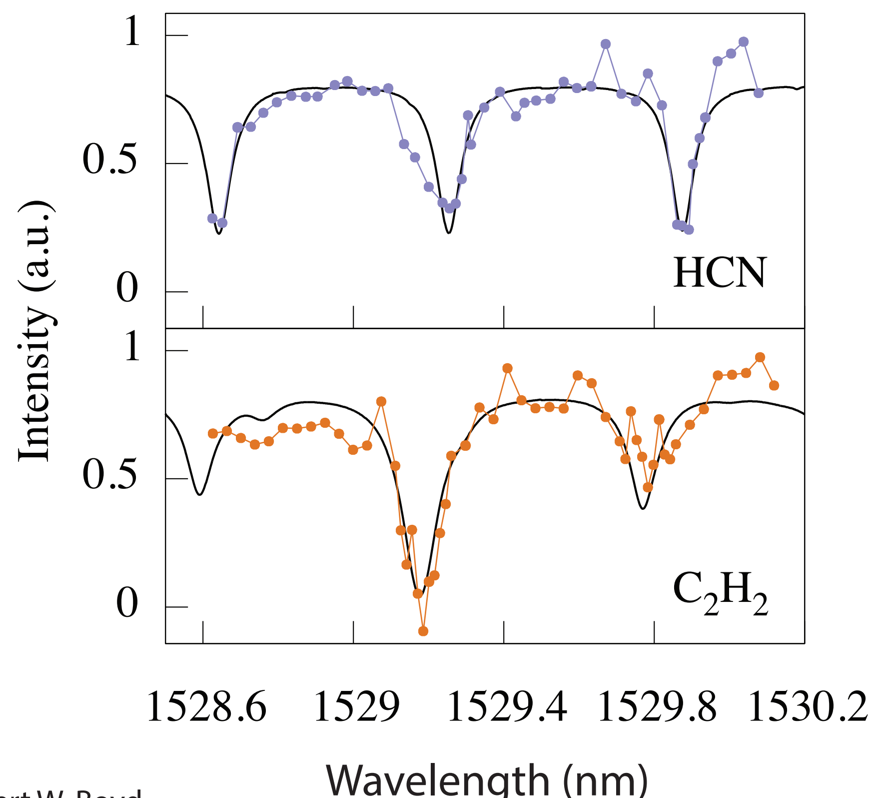


- Cavity design





- Spectroscopy results



Andreas C. Liapis, Boshen Gao, Mahmudur R. Siddiqui, Zhimin Shi, and Robert W. Boyd

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