Slow-Light-Enhanced Spectrometers and Photon Drag in Slow-Light Media

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Presented at Photonics West OPTO, February 18, 2016

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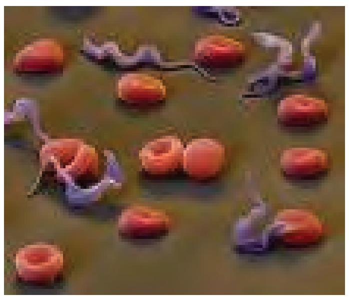
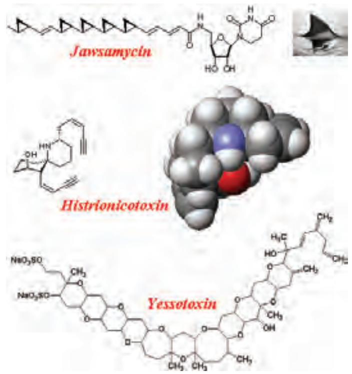
Chip-Scale Spectrometers for Chem-Bio Identification

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

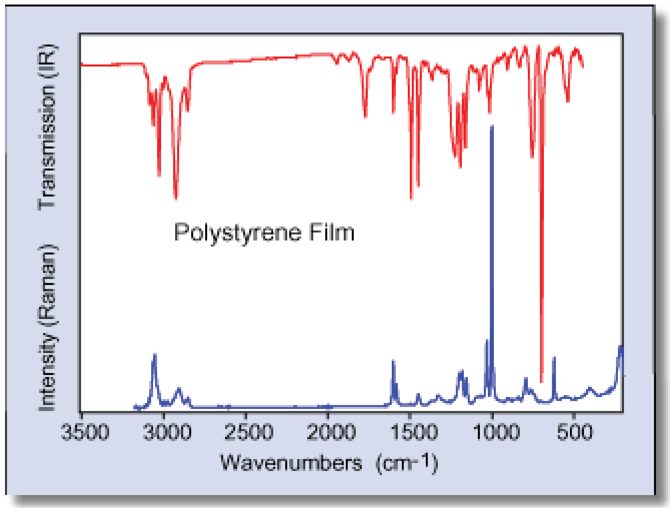
pathogens



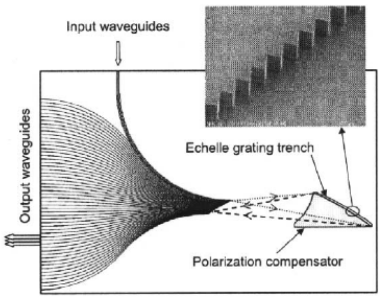
toxins



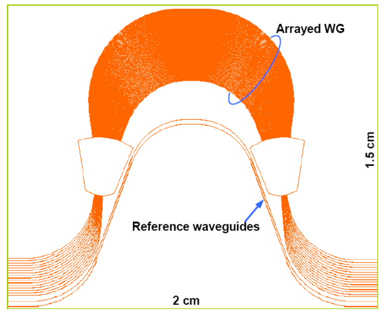
“fingerprint” Raman signature spectrum



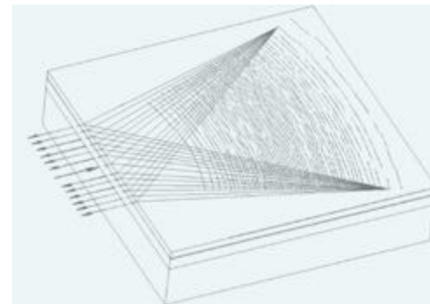
Current On-Chip Spectrometers



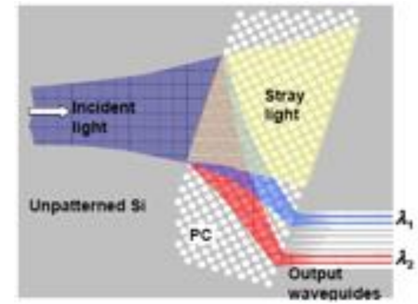
Echelle grating
(NRC, Canada)



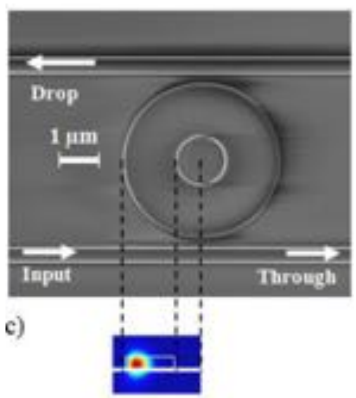
Arrayed Waveguide Grating
(UCSB)



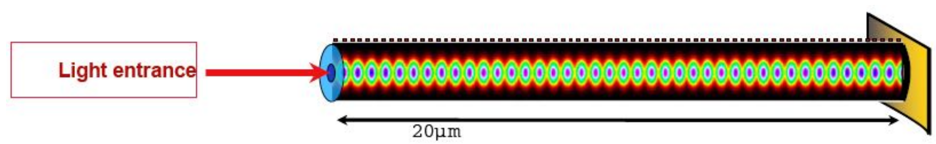
Digital Phase Holography
(LBNL *et al.*)



Super-prism
(GaTech)



Donut resonator
(GaTech)



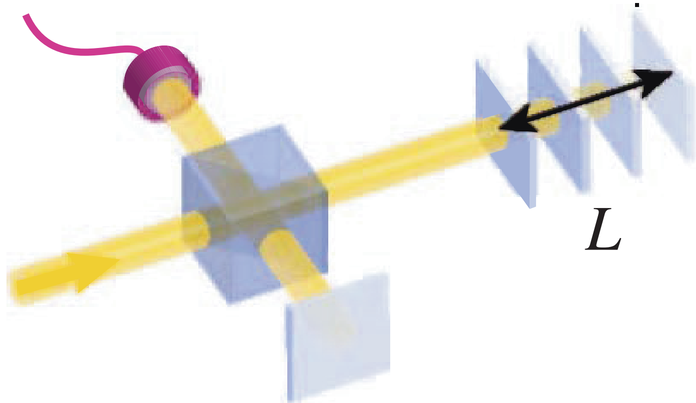
Spatial FT based (Swift)
(Université de Grenoble)

Development of Miniaturized, Chip-Scale Spectrometers

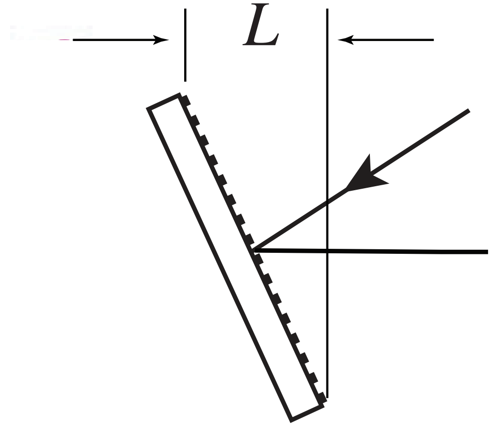
Can We Beat the $1/L$ Resolution Limit of Standard Spectrometers?

- 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:

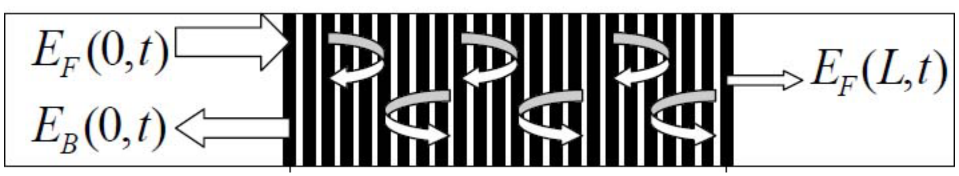
slow: $v_g << c$ (as much as 10^6 times slower!)

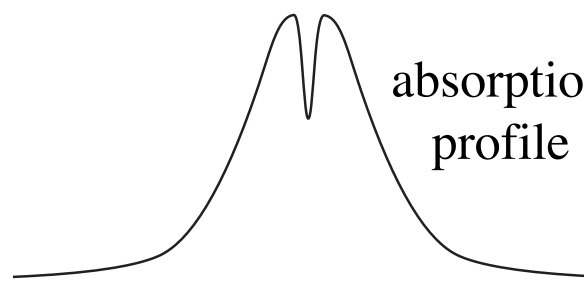
fast: $v_g > c$

backwards: v_g negative

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

– Velocity controlled by structural or material resonances

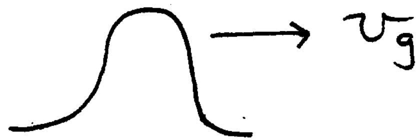




Review article: Boyd and Gauthier, Science 326, 1074 (2009).

Group Velocity

Pulse
(wave packet)



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

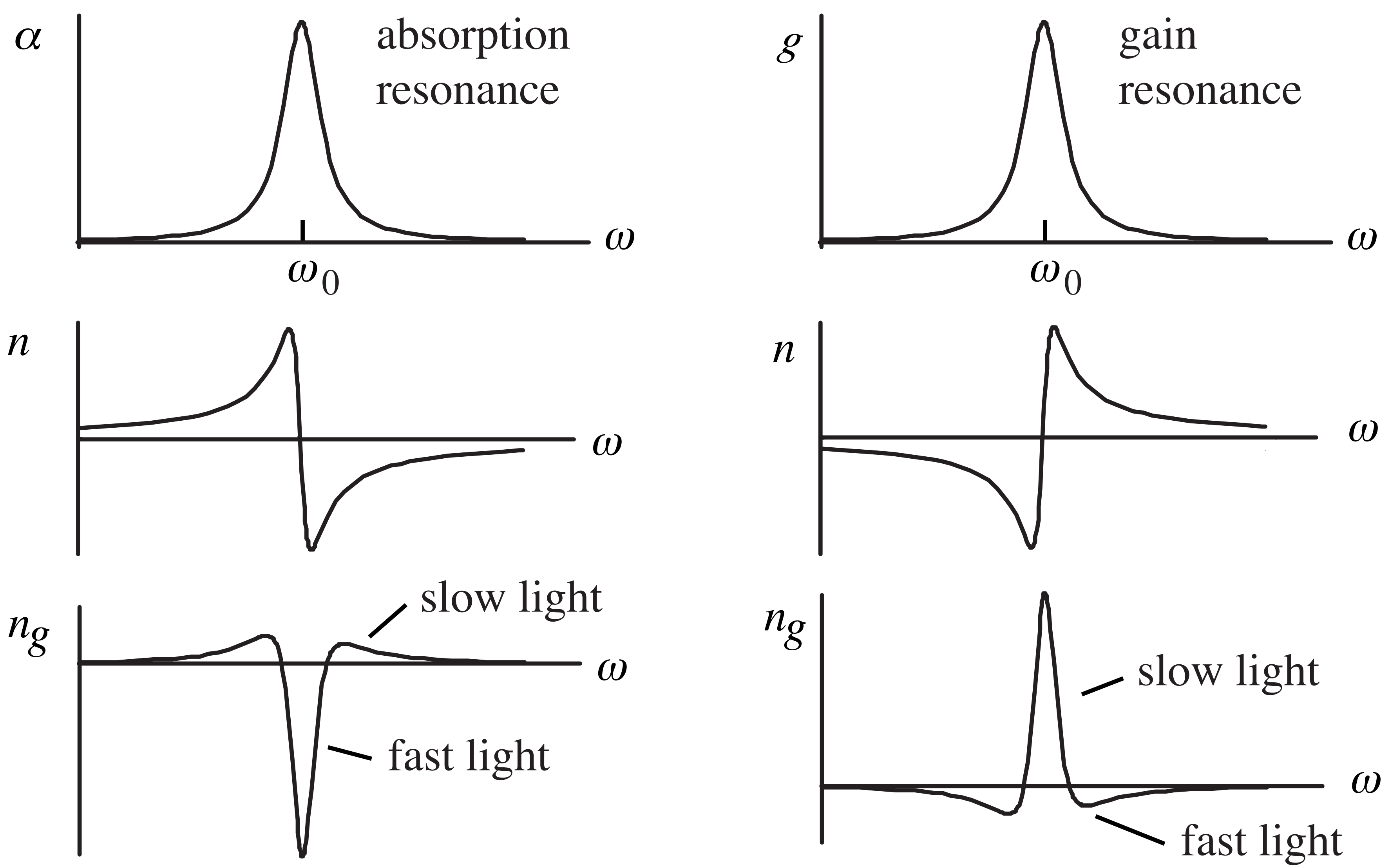
For $\quad k = \dfrac{n\omega}{c} \qquad \dfrac{dk}{d\omega} = \dfrac{1}{c}\left(n + \omega\,\dfrac{dn}{d\omega}\right)$

Thus

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

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

Slow and Fast Light Using Isolated Gain or Absorption Resonances



$$n_g = n + \omega\,(dn/d\omega)$$

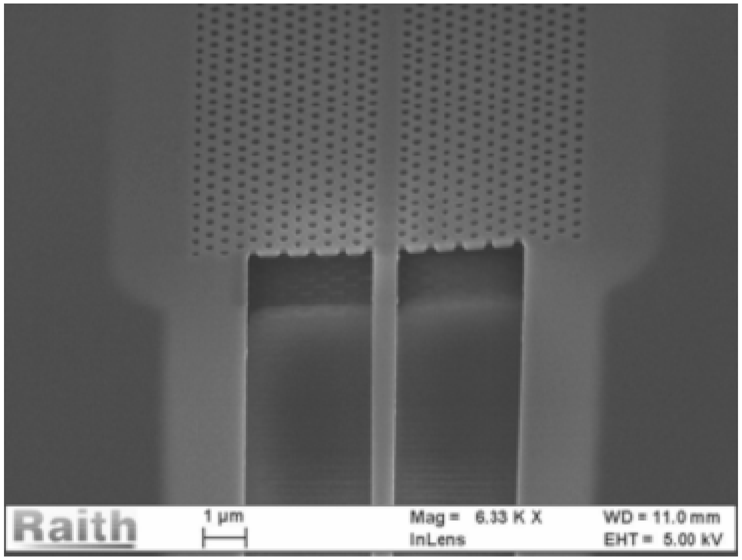
Slow-Light-Enhanced Spectral Interferometers

1. Introduction
2. What is slow light?
3. How slow light enhances spectrometers
4. Our development of a chip-scale slow-light medium for spectroscopy
5. Relation between slow light and optical resonators
6. Resonator-based spectrometer for threat reduction
7. Other work

Our Goal

Replace this:

with this:



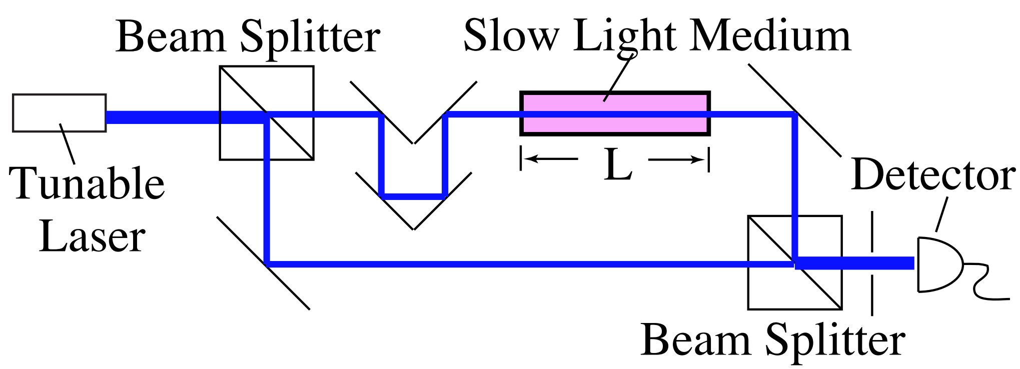
Our Approach: Chip-Scale Slow-Light Spectrometer

- 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:

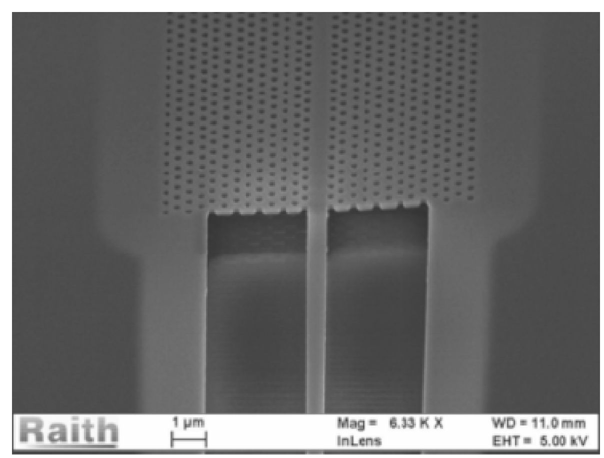


Simple analysis

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

- 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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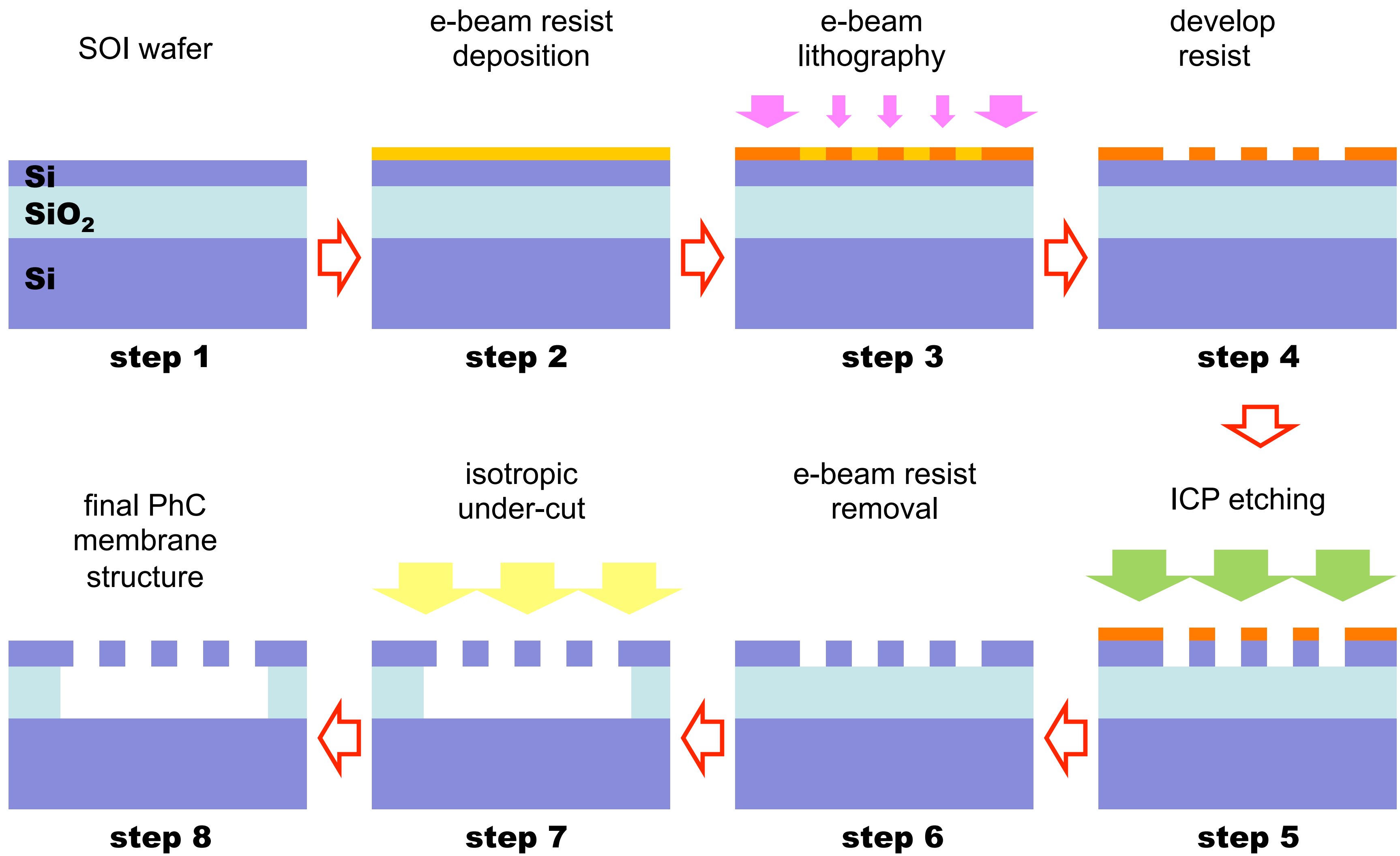
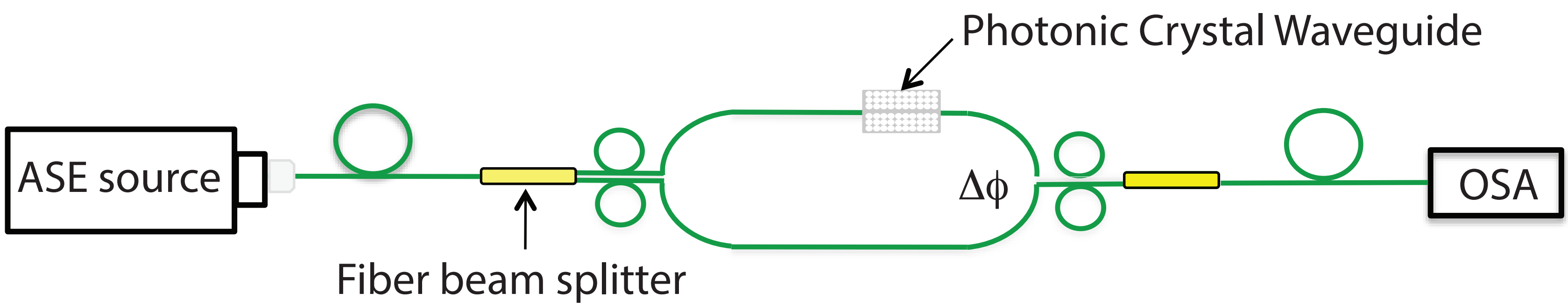
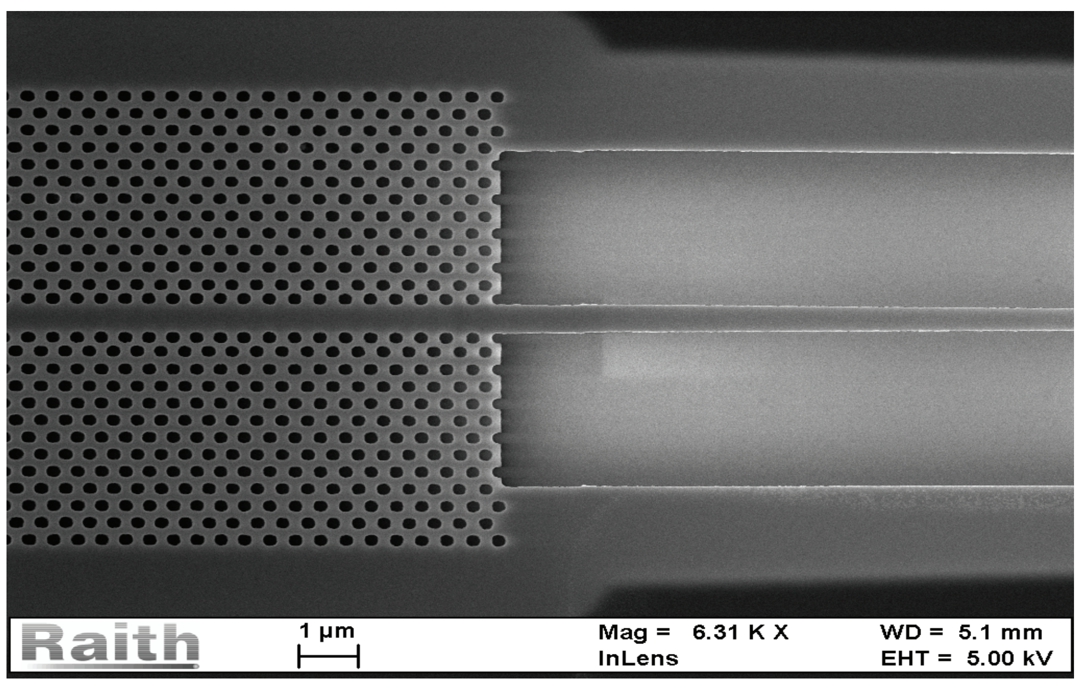
Nano-fabrication process

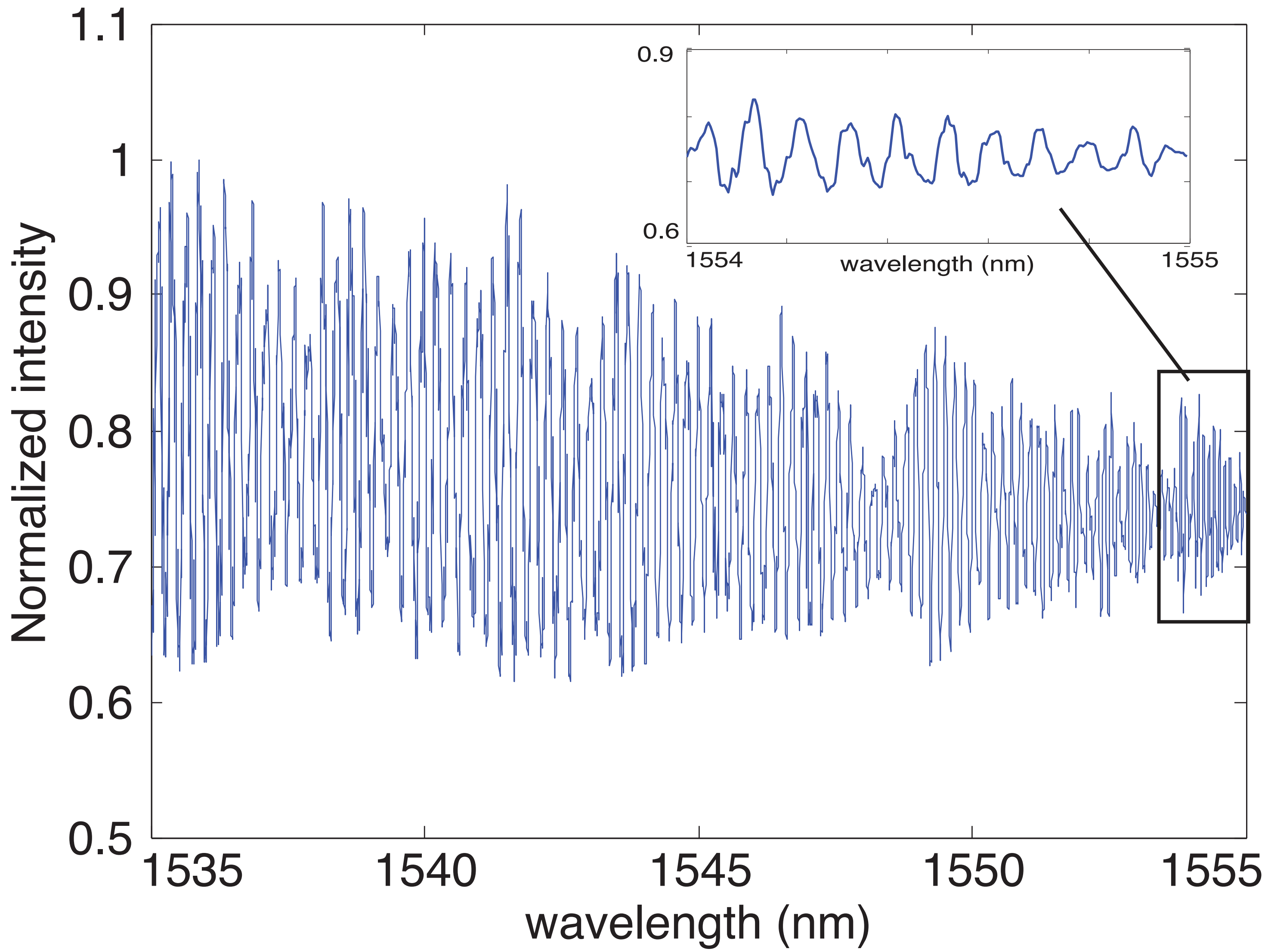


Laboratory Characterization of Slow-Light Mach-Zehnder Interferometer





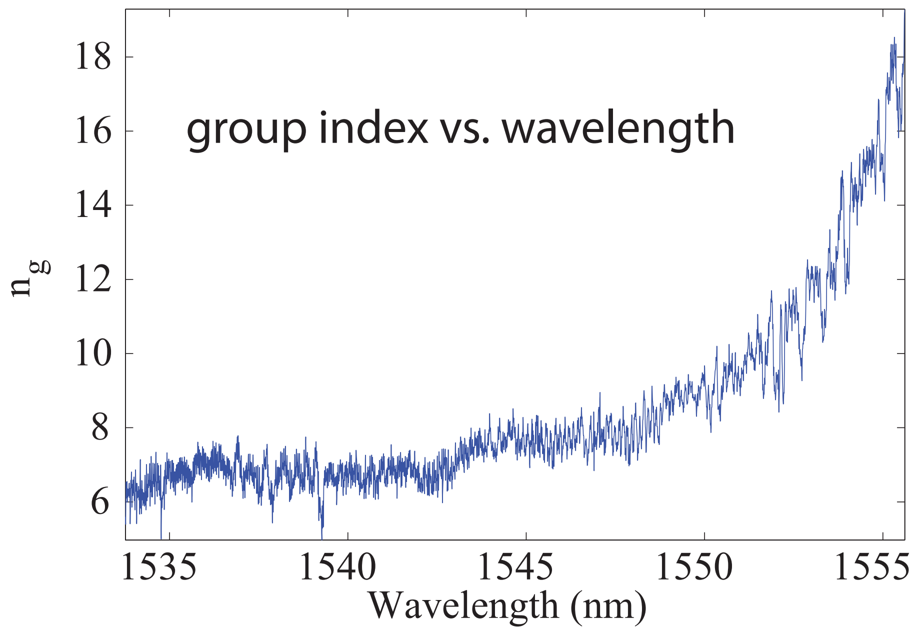
Interference Pattern Produced by the Photonic-Crystal, SLow-Light Spectrometer

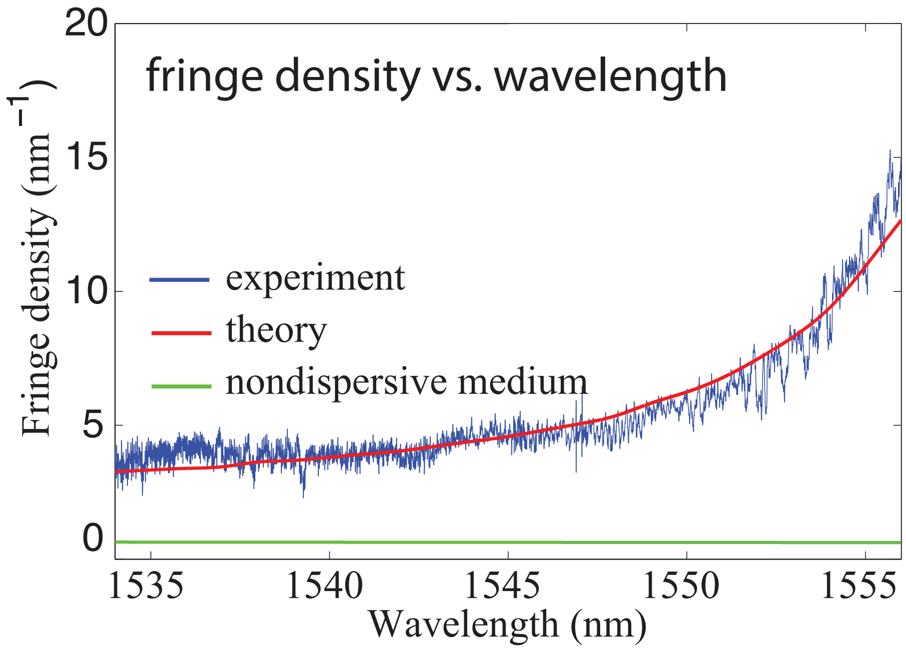


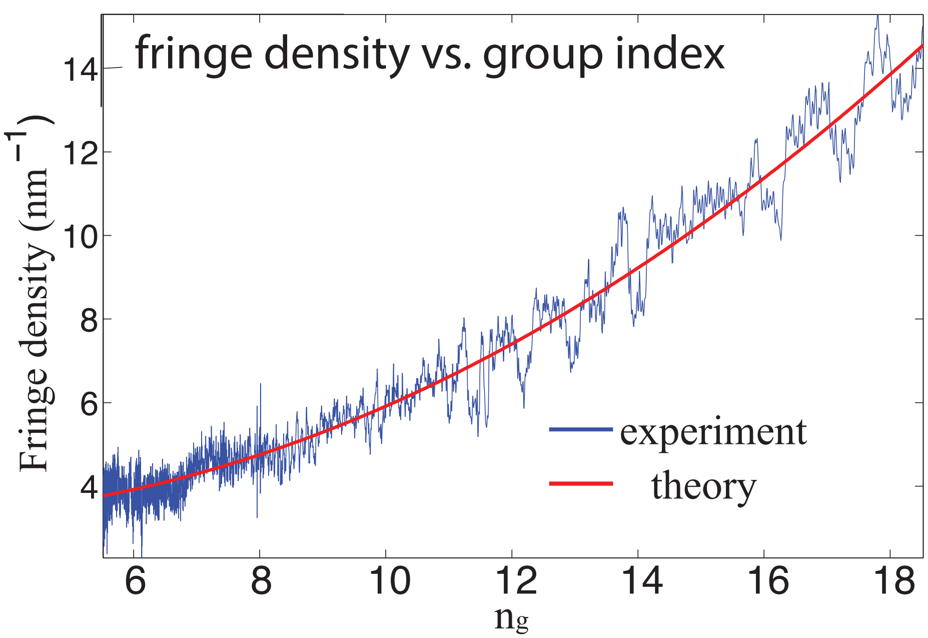
Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm^{-1}

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

Quantitative Results: Photonic-Crystal, SLow-Light Spectrometer

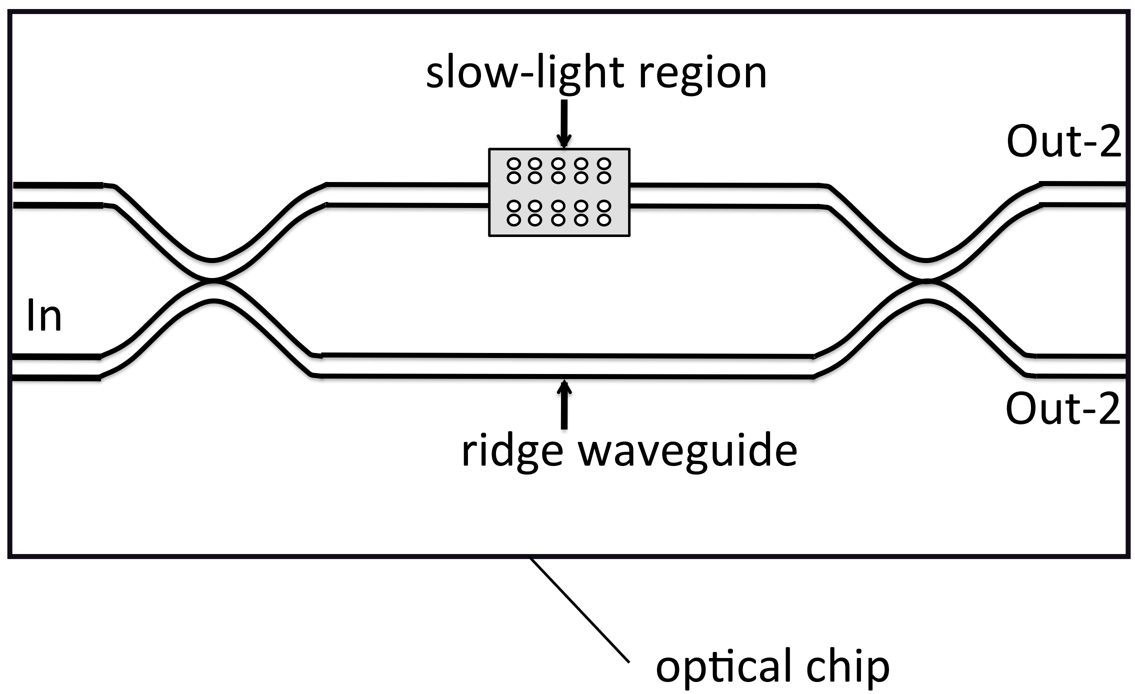




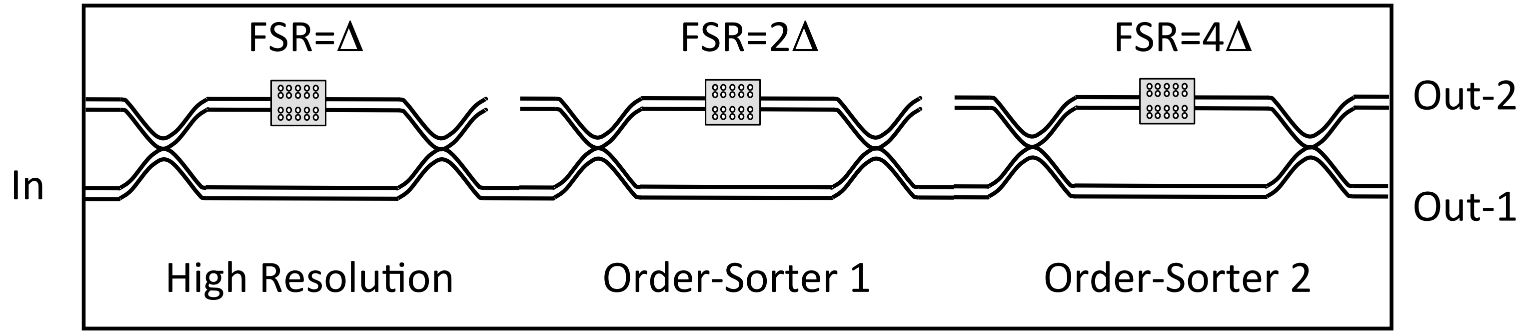


- Spectral resolution is proportional to fringe density
- Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm^{-1}
- Slow-light waveguide is only 1 mm long

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



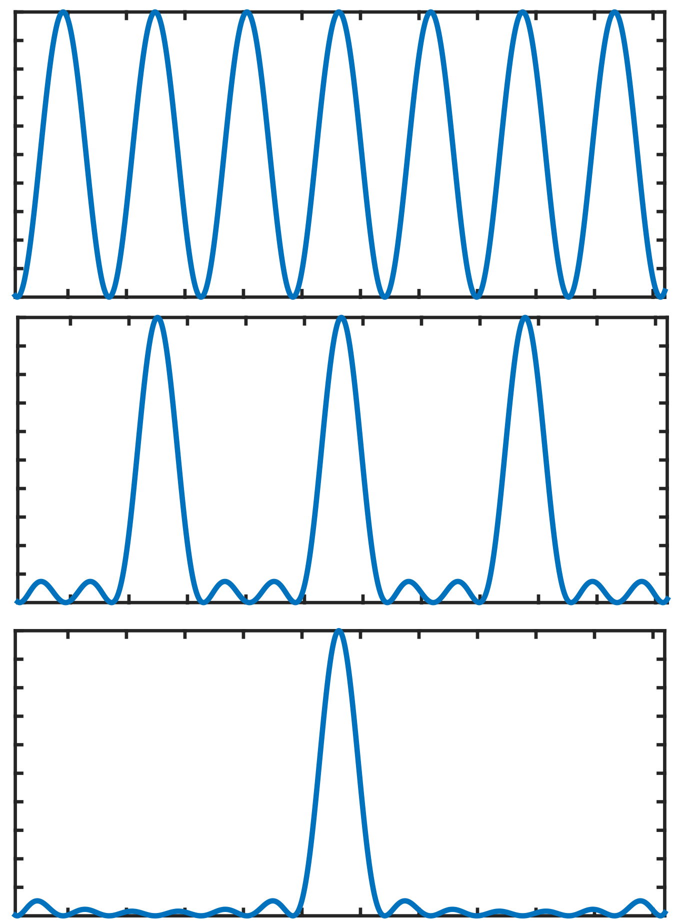
Long-Term Goal: All-On-Chip Spectrometer with Order Sorting



After Stage 1

After Stage 2

Output



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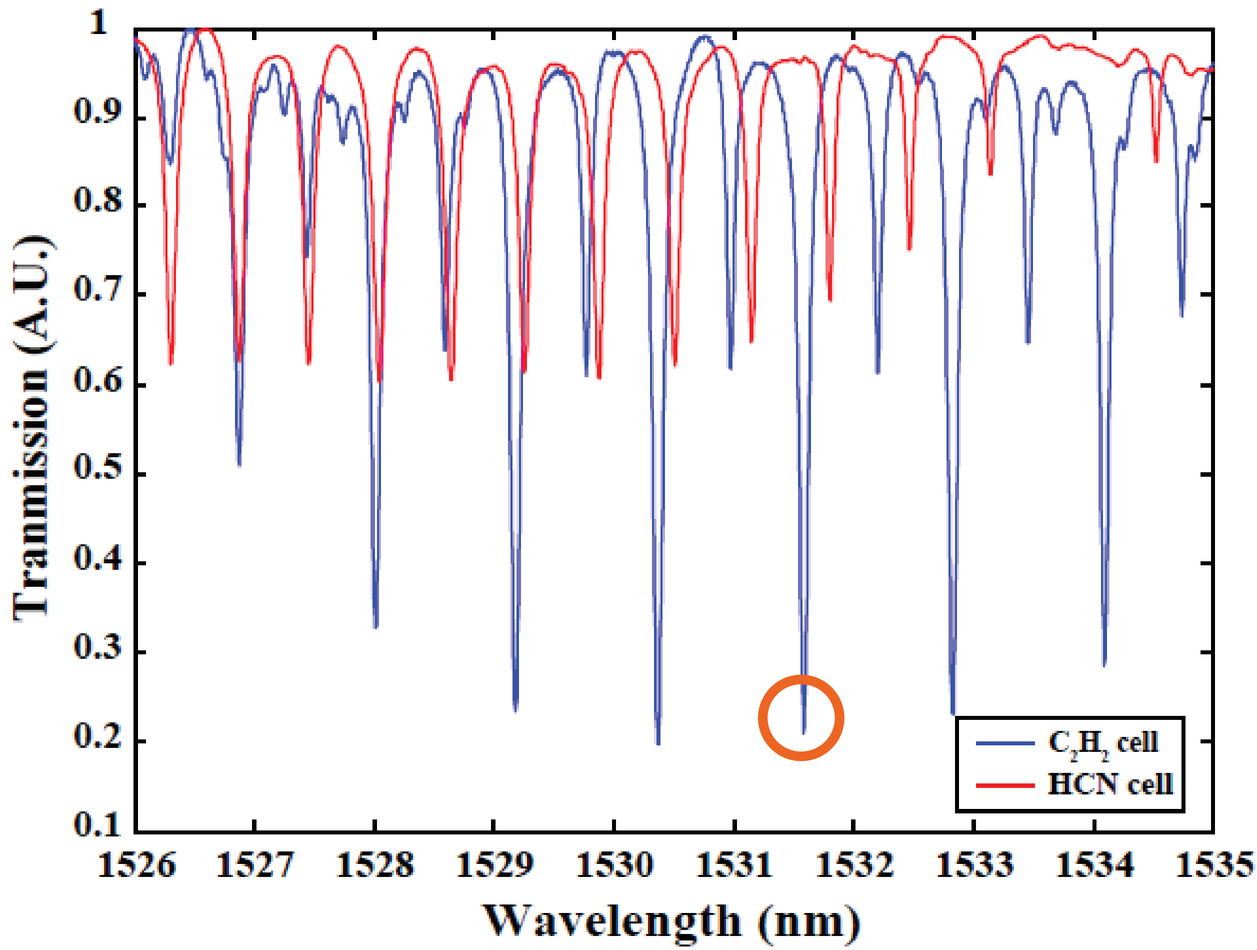
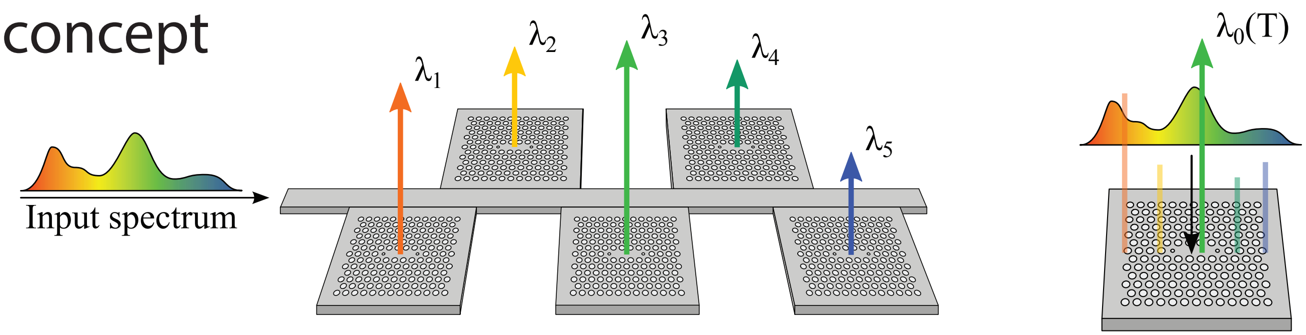
Challenge: Fabricate a chip-scale spectrometer that can discriminate acetylene (H_2C_2) from hydrogen cyanide (HCN)?



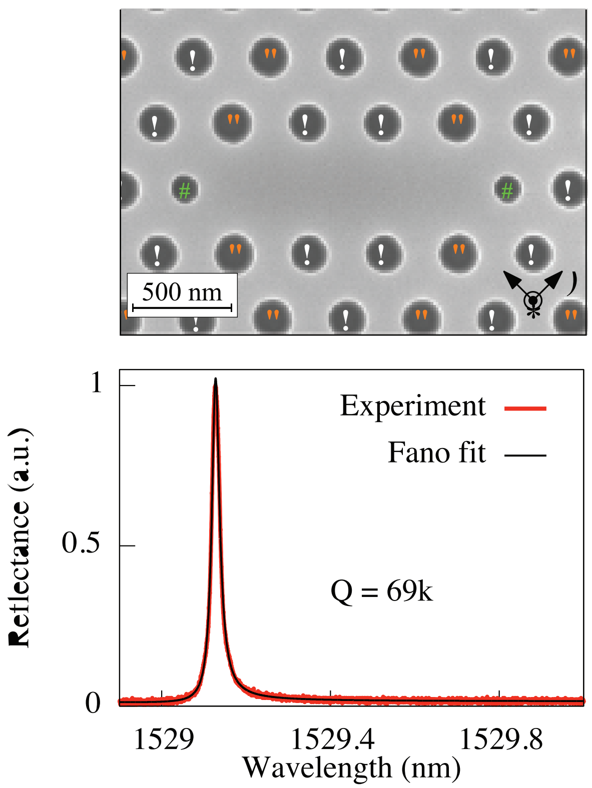
(data from our own lab)

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

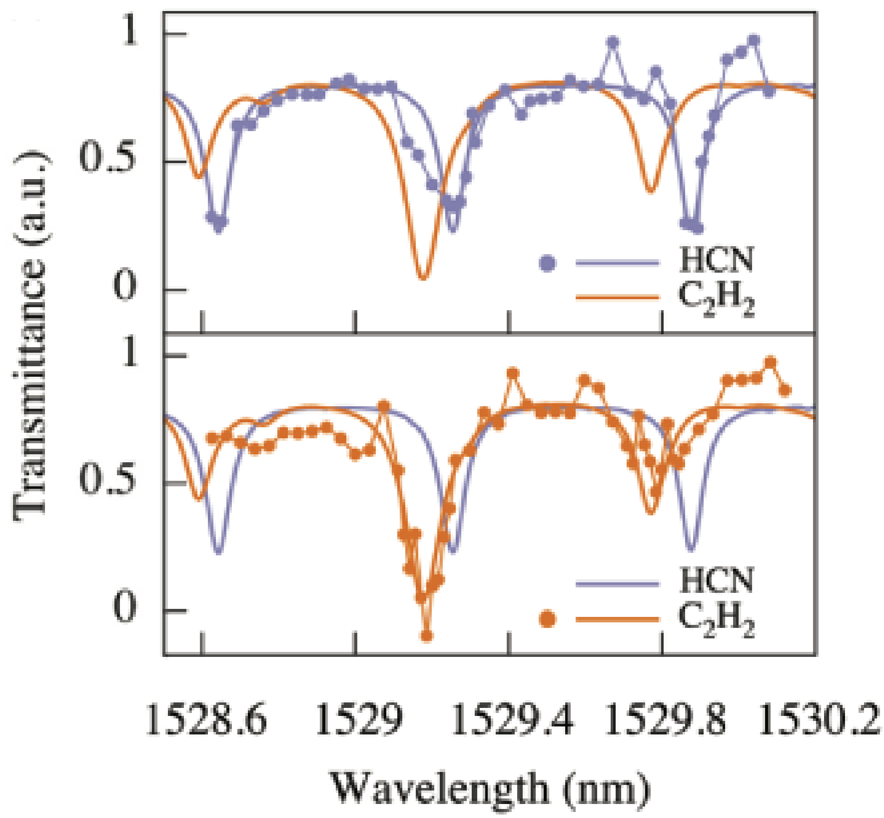
- The concept



- Cavity design

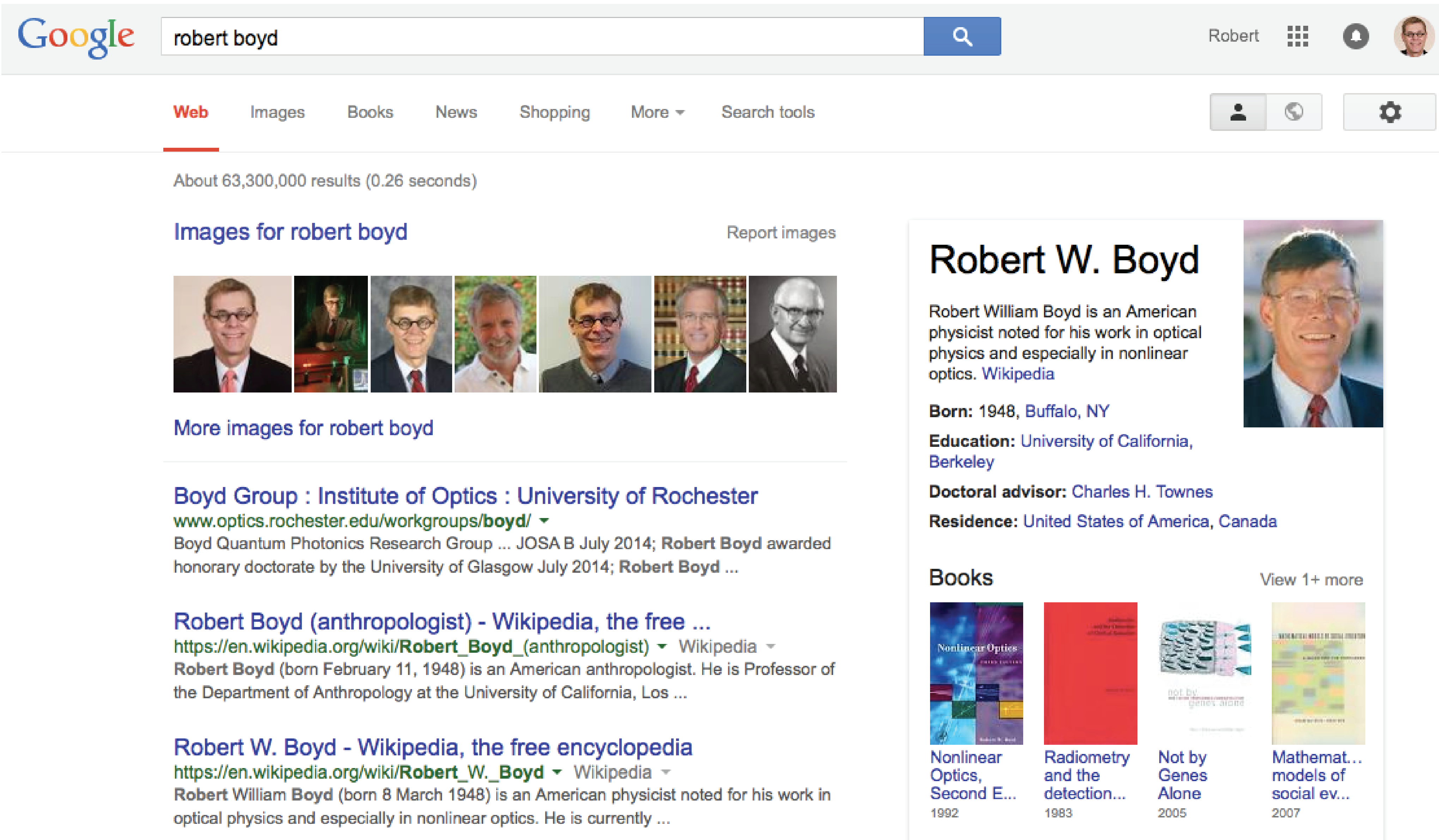


- Spectroscopy results



Liapis, Gao, Siddiqui, Shi, Boyd, Appl. Phys. Lett. 108, 021105 (2016).

Why We Shouldn’t Always Trust Google



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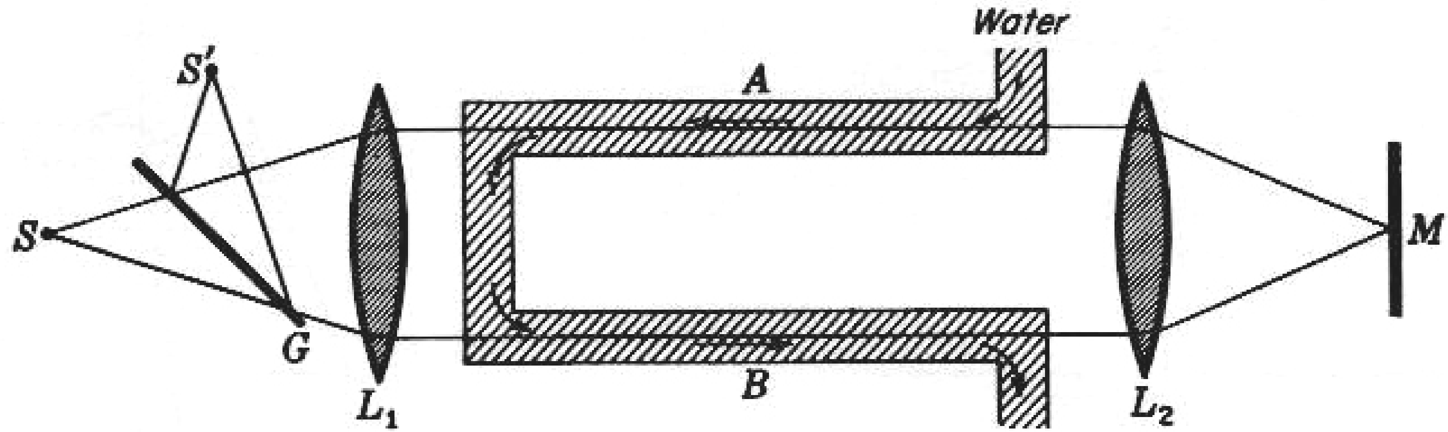
The Velocity of Light in Moving Matter: Fresnel Drag (or Ether Drag) Effects

- Fizeau (1859): Longitudinal photon drag:

  Velocity of light in flowing water.

  V = 700 cm/sec; L = 150 cm; displacement of 0.5 fringe.



- Modern theory: relativistic addition of velocities

$$\text{v} = \frac{\text{c}/n + V}{1 + (V/\text{c})(1/n)} \approx \frac{c}{n} + V\left(1 - \frac{1}{n^2}\right)$$

Fresnel "drag" coefficient

- But what about slow-light media?

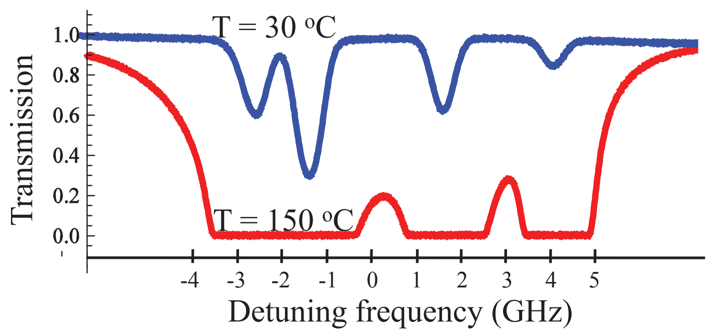
Fresnel Drag in a Highly Dispersive Medium

Light Drag in a Slow Light Medium (Lorentz)

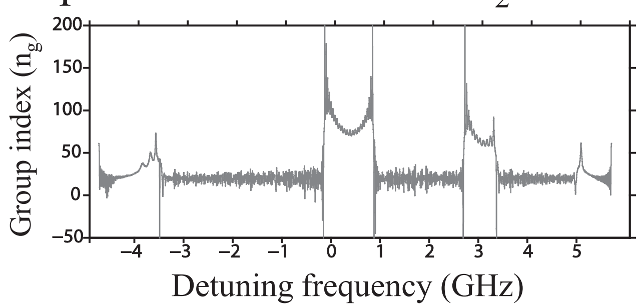
$$u \simeq \frac{c}{n} \pm v\left(1 - \frac{1}{n^2} + \frac{n_g - n}{n^2}\right)$$

We Use Rubidium as Our Slow Light Medium

- Transmission spectrum of Rb around D_2 transition:

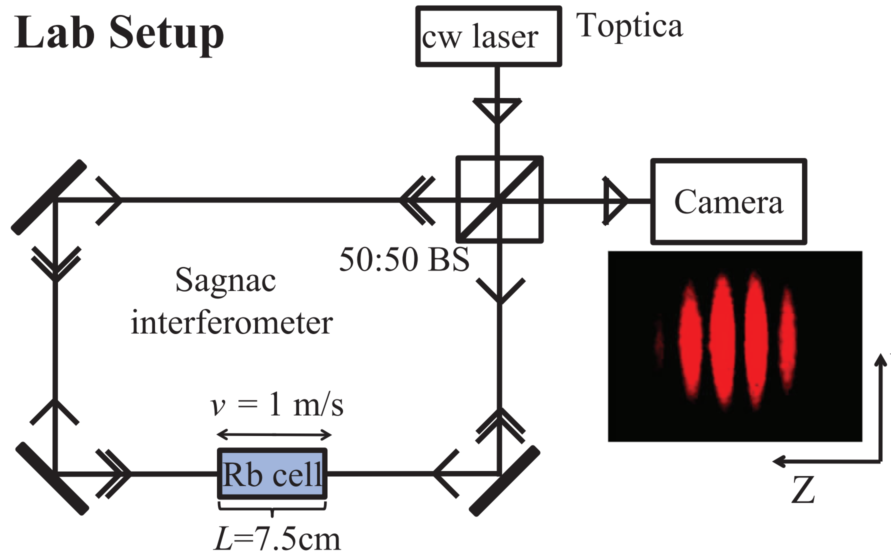


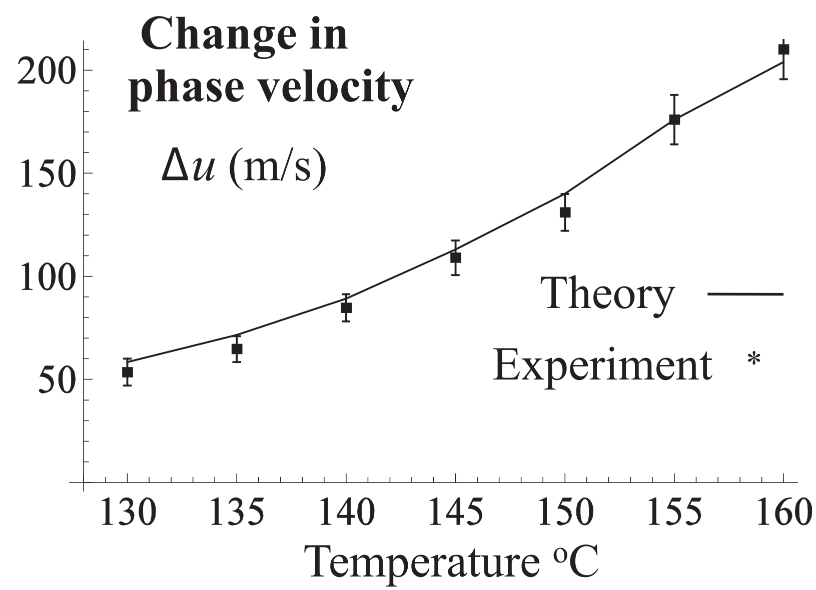
- Group index of Rb around D_2 line at T=130



Safari, De Leon, Mirhosseini, Magana-Loaiza, and Boyd
Phys. Rev. Lett. 116, 013601 (2016)

Lab Setup





- **Change in phase velocity is much larger than velocity of rubidium cell. Implications for new velocimeters?**

Thank you for your attention!