Quantum Nonlinear Optics: Nonlinear Optics Meets the Quantum World

Robert W. Boyd

Department of Physics and
Max-Planck Centre for Extreme and Quantum Photonics
University of Ottawa

The Institute of Optics and
Department of Physics and Astronomy
University of Rochester

Department of Physics and Astronomy
University of Glasgow

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Quantum Nonlinear Optics: Nonlinear Optics Meets the Quantum World

Outlook: NLO is a superb platform from which to explore new physical processes and to develop photonics applications.

Prospectus

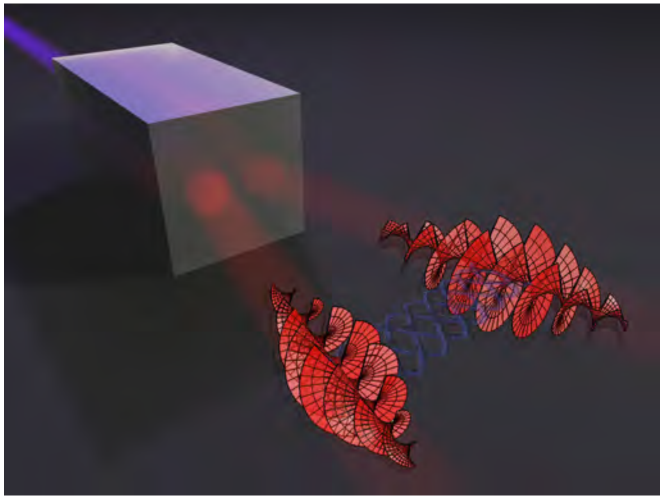
1. Quantum Communication with Multiple Bits per Photon
2. Huge Optical Nonlinearity in Epsilon-Near-Zero Materials
3. New Applications of “Slow Light”

Use of Quantum States for Secure Optical Communication

- The celebrated BB84 protocol for quantum key distribution (QKD) transmits one bit of information per received photon

- We have built a QKD system that can carry more than one bit per photon.
  - Note that in traditional telecom, one uses many photons per bit!

- Our procedure is to encode using beams that carry orbital angular momentum (OAM), such as the Laguerre-Gauss states, which reside in an infinite dimensional Hilbert space.



QKD System Carrying Many Bits Per Photon

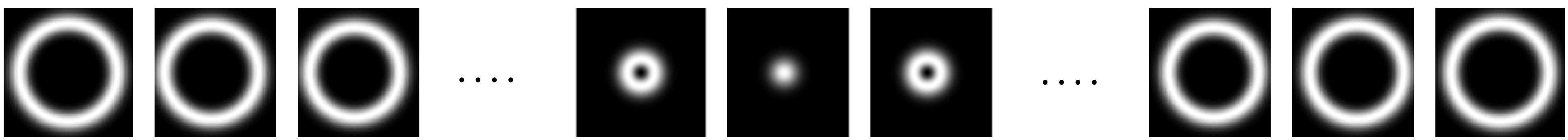
We are constructing a QKD system in which each photon carries many bits of information

We encode in states that carry OAM such as the Laguerre-Gauss states

As a diagnostic, we need to be able to measure the statevector of OAM states

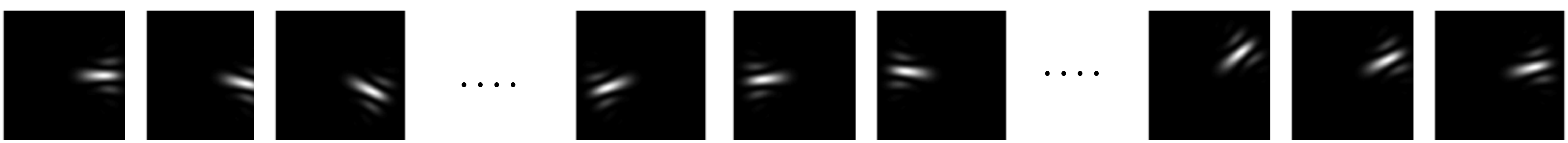
<u>Single Photon States</u>

Laguerre-Gaussian Basis $\ell = -13, \ldots, 13$



-13 -12 -11 -1 0 1 11 12 13

"Angular" Basis (mutually unbiased with respect to LG)

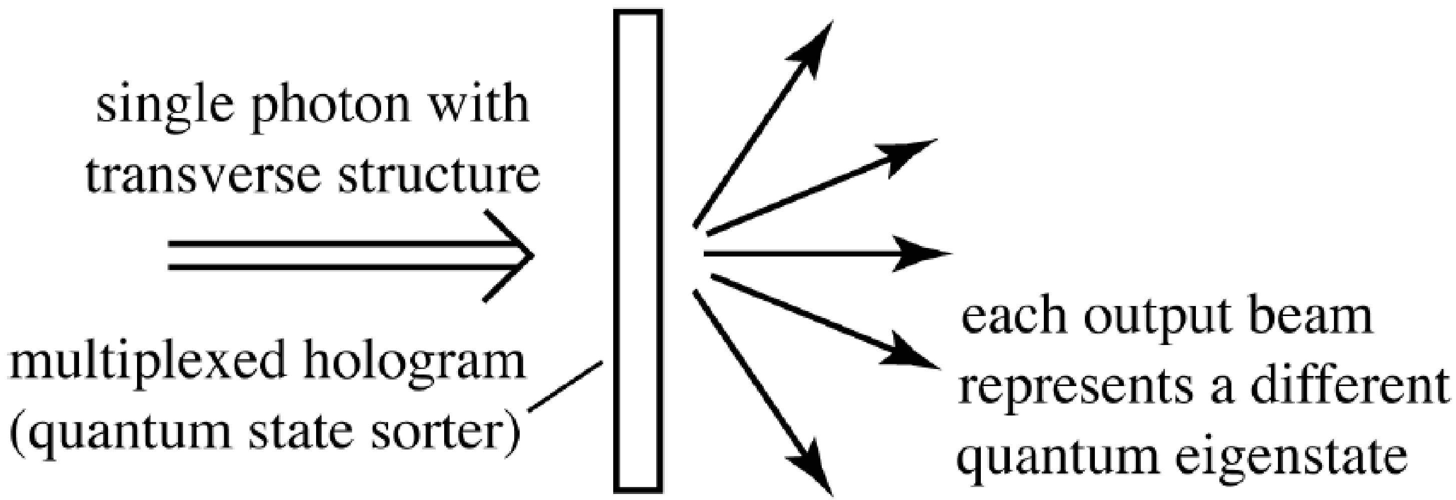


0 1 2 12 13 14 25 26 27

$$\Psi^{N}_{\mathrm{AB}} = \frac{1}{\sqrt{27}} \sum_{l=-13}^{13} \mathrm{LG}_{l,0} \exp\left(i2\pi Nl/27\right)$$

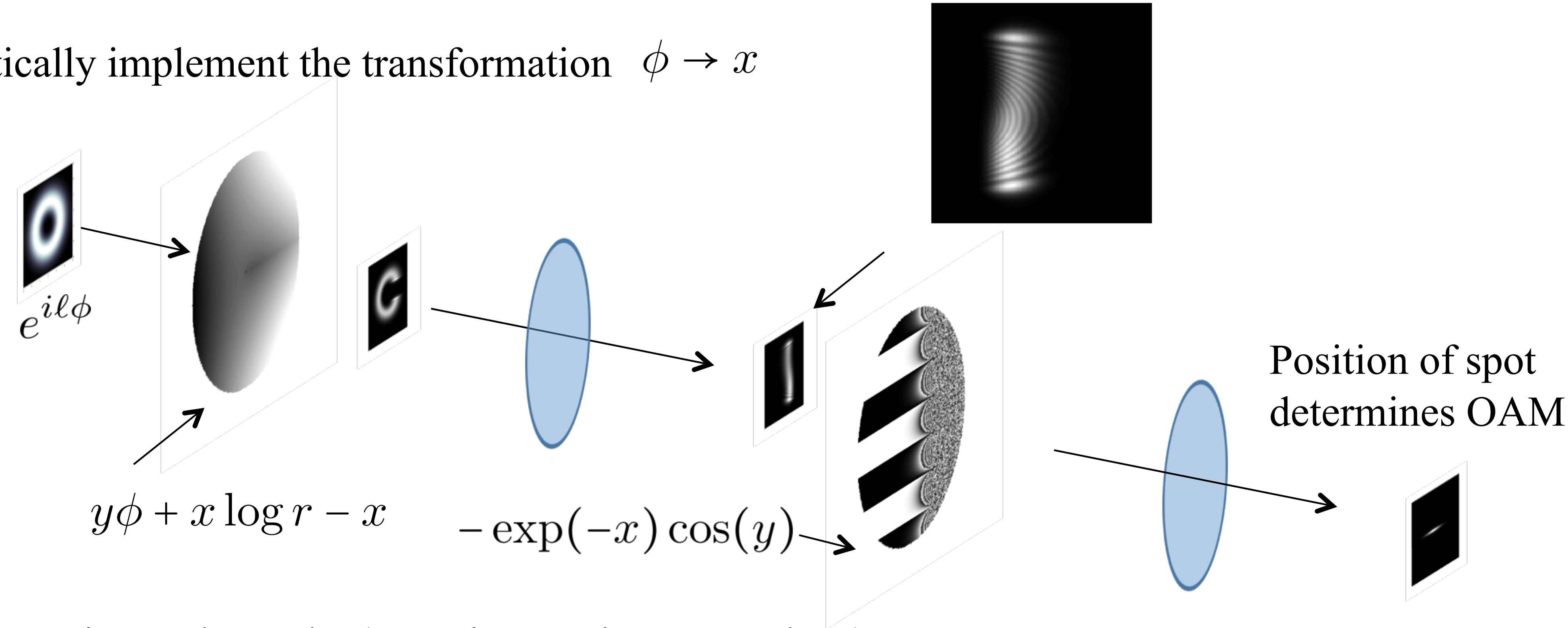
Mode Sorting

A mode sorter

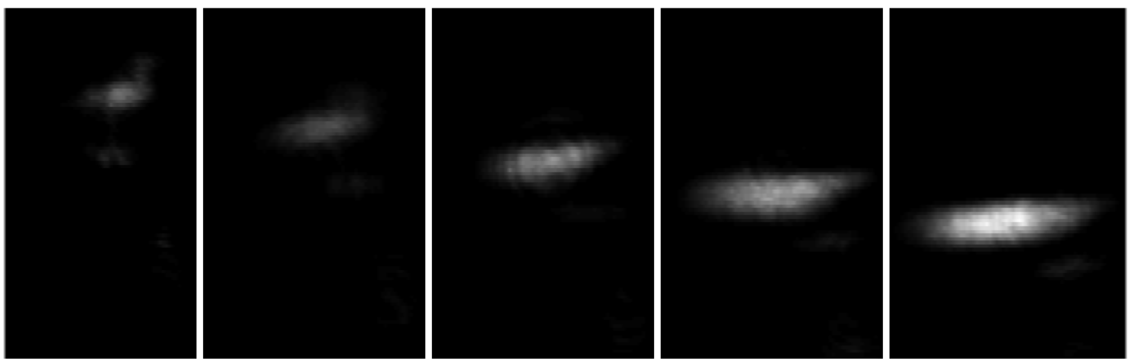


Sorting OAM using Phase Unwrapping

Optically implement the transformation $\phi \to x$



Experimental Results (CCD images in output plane)



$\ell = 1$ $\ell = 2$ $\ell = 3$ $\ell = 4$ $\ell = 5$

-Can also sort angular position states.

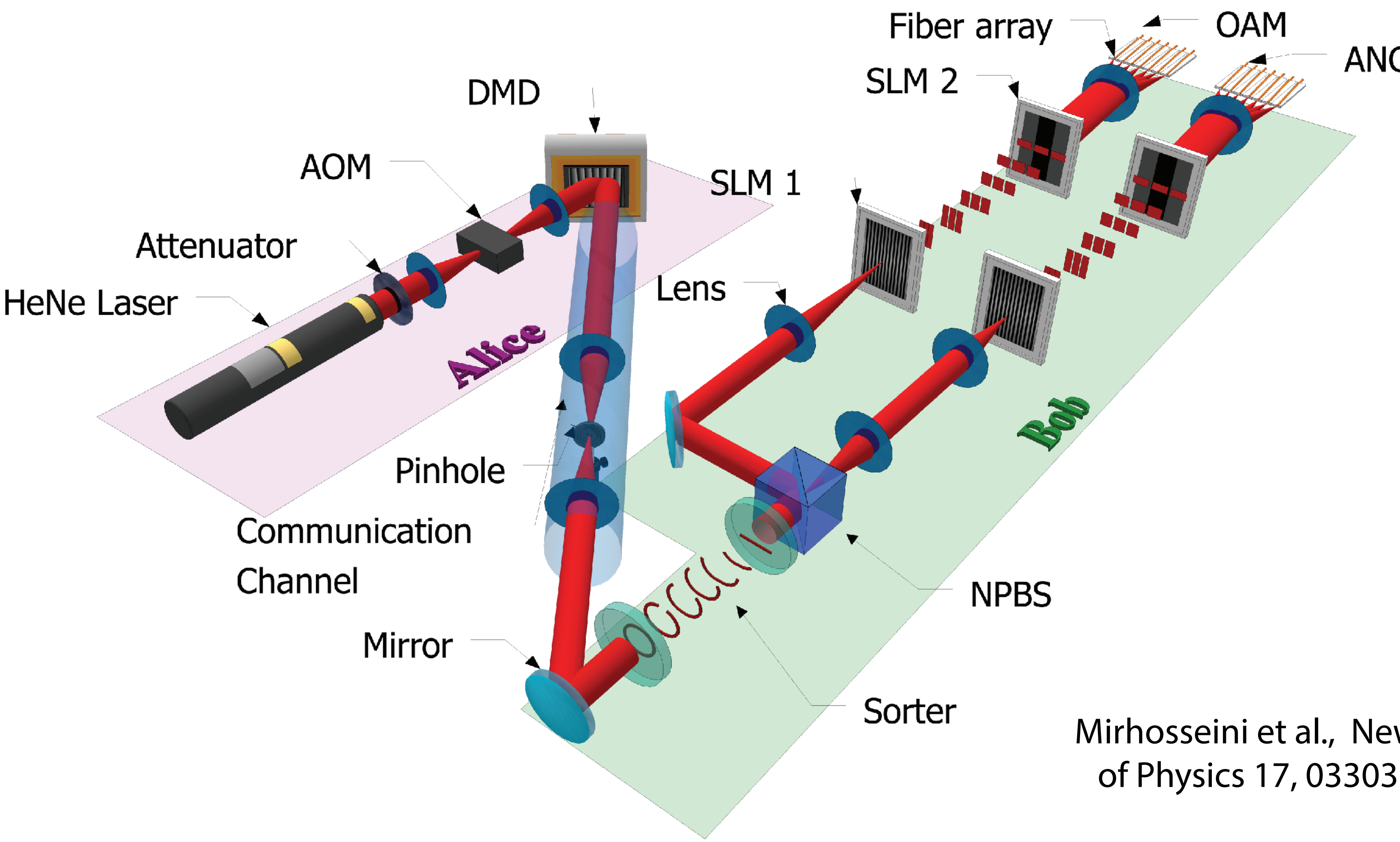
-Limited by the overlap of neighboring states.

*Berkhout *et al.* *PRL* **105,** 153601 (2010).
O. Bryngdahl, *J. Opt. Soc. Am.* **64**, 1092 (1974).

UNIVERSITY of ROCHESTER

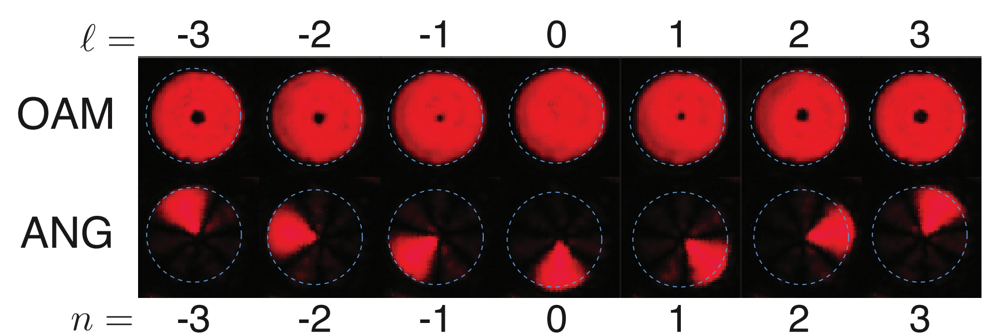
Nonlinear Optics Group

Our Laboratory Setup



Mirhosseini et al., New Journal of Physics 17, 033033 (2015).

We use a seven-dimensional state space.



Laboratory Results - OAM-Based QKD

Alice	Bob
0631336021320454444561410266455450503636030252616432155241642301466025134016132224515510 26	0630336011320214444561410266455450223536030252616432155241642301466025154036134224515510 26

Alice:
063133602132045444456141026645
545050363603025261643215524164
230146602513401613222451551026

Bob:
063033601132021444456141026645
545022353603025261643215524164
230146602515403613422451551026

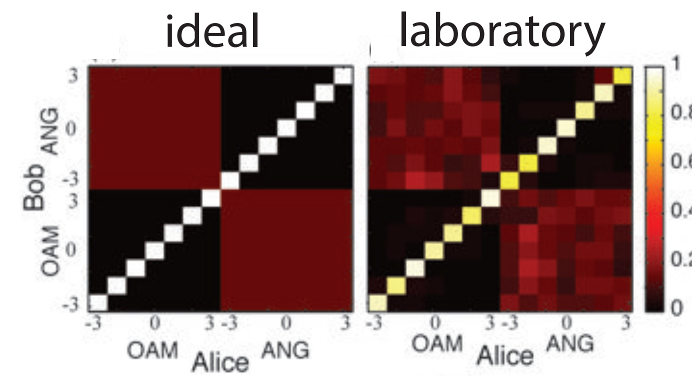
Error Correction

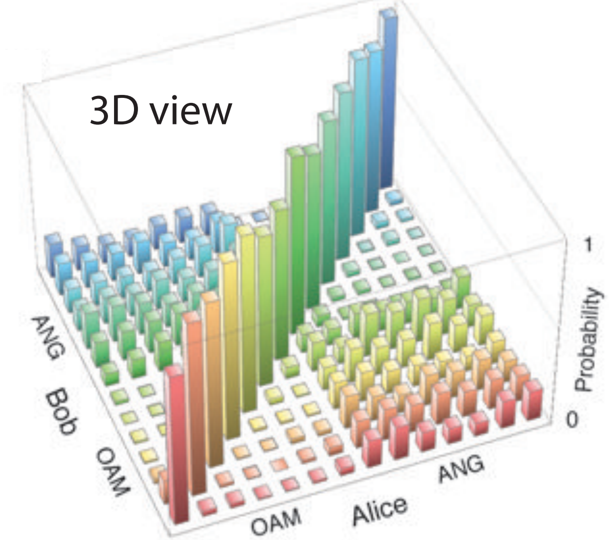
0000 0100 0111 0100 0101 0001 1100 0010 1100 1001 0010 0100 1101 0001 0000
0001 0011 0100 0000 0100 0010 0001 0001 0011 0000 0101 0010 0111 1000 0101
1101 0011 0001 1001 1011 0101 0000 0100 0111 0100 0011 0110 0101 0000 1101
0101 0010 1111 1010 1111 0010 1000

Privacy Amplification

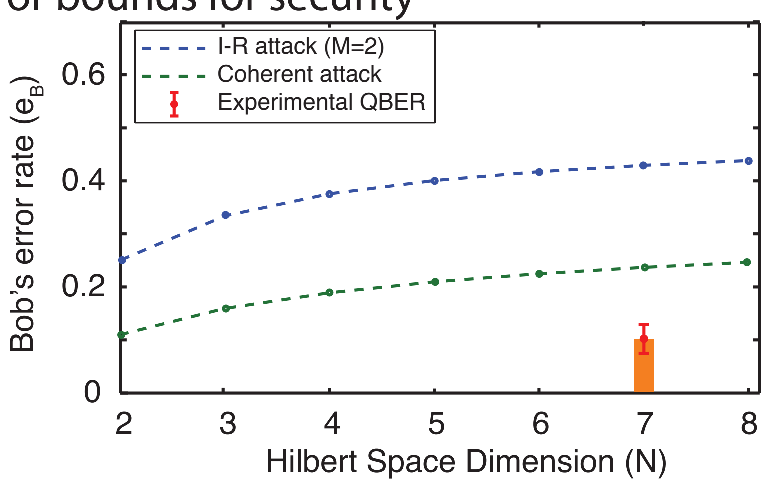
0001 0100 1011 1111 1111 1010 1010 0111 1010 1011 1111 0001 0000 1101 1111
1110 1110 1101 1110 0001 0011 1000 0101 1101 1100 0011 0111 1101 0001 1001
0100 0110 1011 0000 0110 1010 1

cross-talk matrices





• error bounds for security



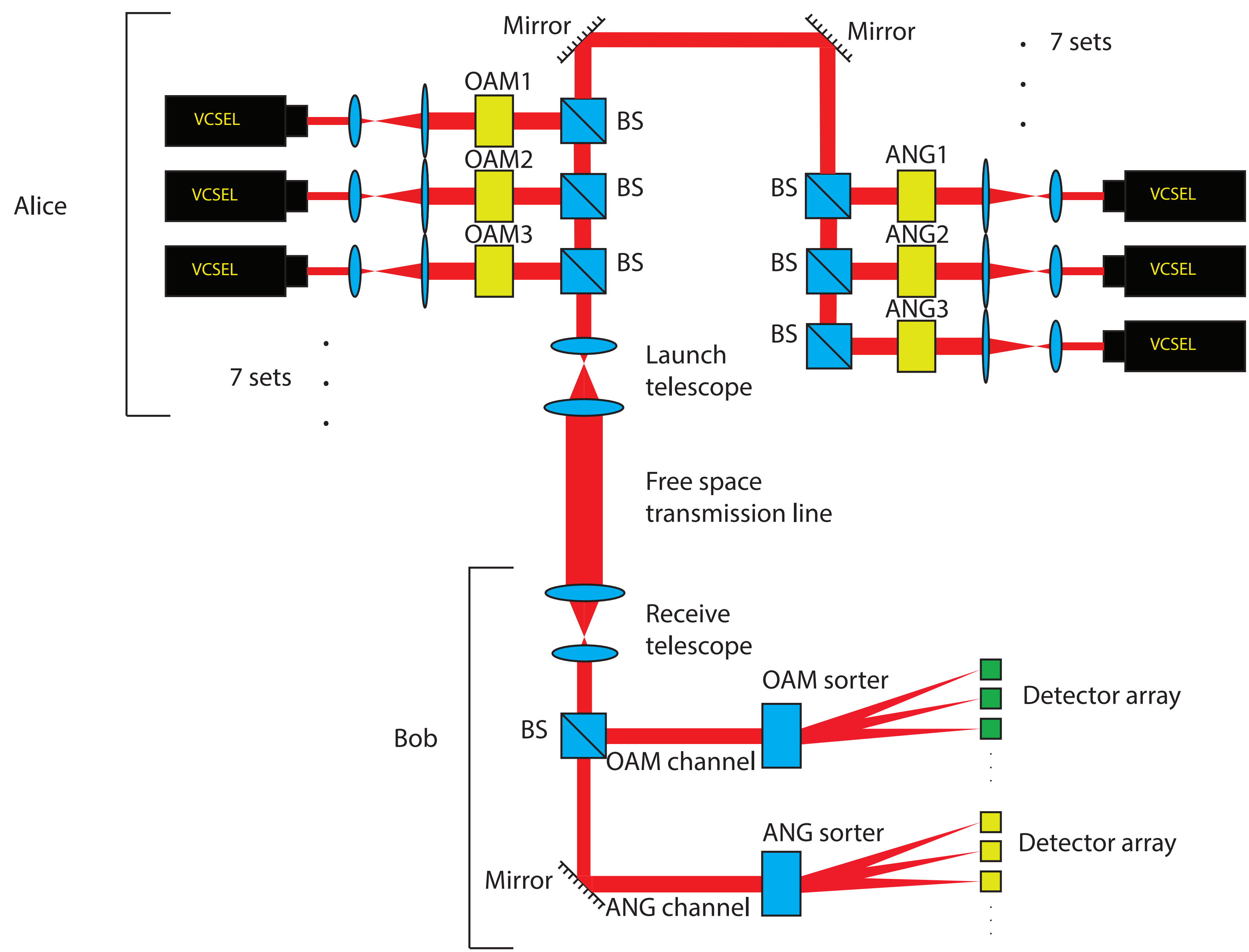
We use a 7-letter alphabet, and achieve a channel capacity of 2.1 bits per sifted photon.

We do not reach the full 2.8 bits per photon for a variety of reasons, including dark counts in our detectors and cross-talk among channels resulting from imperfections in our sorter.

Nonetheless, our error rate is adequately low to provide full security,

Next Step: gigabit-per-second OAM-based QKD system

- Use direct modulation of laser diode to encode at gigabits per sec.



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2. Huge Optical Nonlinearity in Epsilon-Near-Zero Materials
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New Nonlinear Optical Material for Quantum Information Processing

- We want all-optical switches that work at the single-photon level

- We need photonic materials with a much larger NLO response

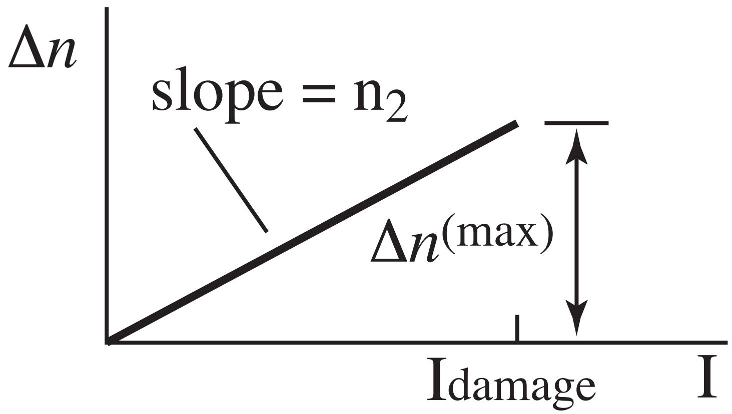
- I report a new NLO material with an n_2 value 100 times larger than any previously reported results (but with background absorption).

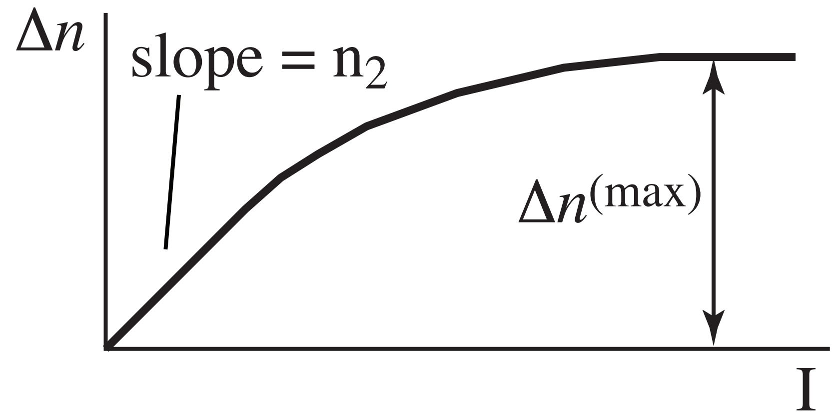
M. Z. Alam et al., Science 352, 795 (2016).

What Makes a Good (Kerr-Effect) Nonlinear Optical Material?

Want n_2 large; and also want $\Delta n^{(\max)}$ large.

These are distinct concepts! Damage and saturation can limit $\Delta n^{(\max)}$





We report a material for which both n_2 and $\Delta n^{(\max)}$ are extremely large!

For ITO at ENZ wavelength, $n_2 = 1.1 \times 10^{-10}$ cm^2/W and $\Delta n^{(\max)} = 0.8$

(For silica glass $n_2 = 3.2 \times 10^{-16}$ cm^2/W, $I_{damage} = 1$ TW/cm^2, and thus $\Delta n^{(\max)} = 3 \times 10^{-4}$)

Nonlinear Optical Properties of Indium Tin Oxide (ITO)

ITO is a degenerate semiconductor (so highly doped as to be metal-like).

It has a very large density of free electrons, and a bulk plasma frequency corresponding to a wavelength of approximately 1.24 μm.

Recall the Drude formula

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

Note that $\mathrm{Re}\,\epsilon = 0$ for $\omega = \omega_p/\sqrt{\epsilon_\infty} \equiv \omega_0$.

The region near ω_0 is known as the epsilon-near-zero (ENZ) region.

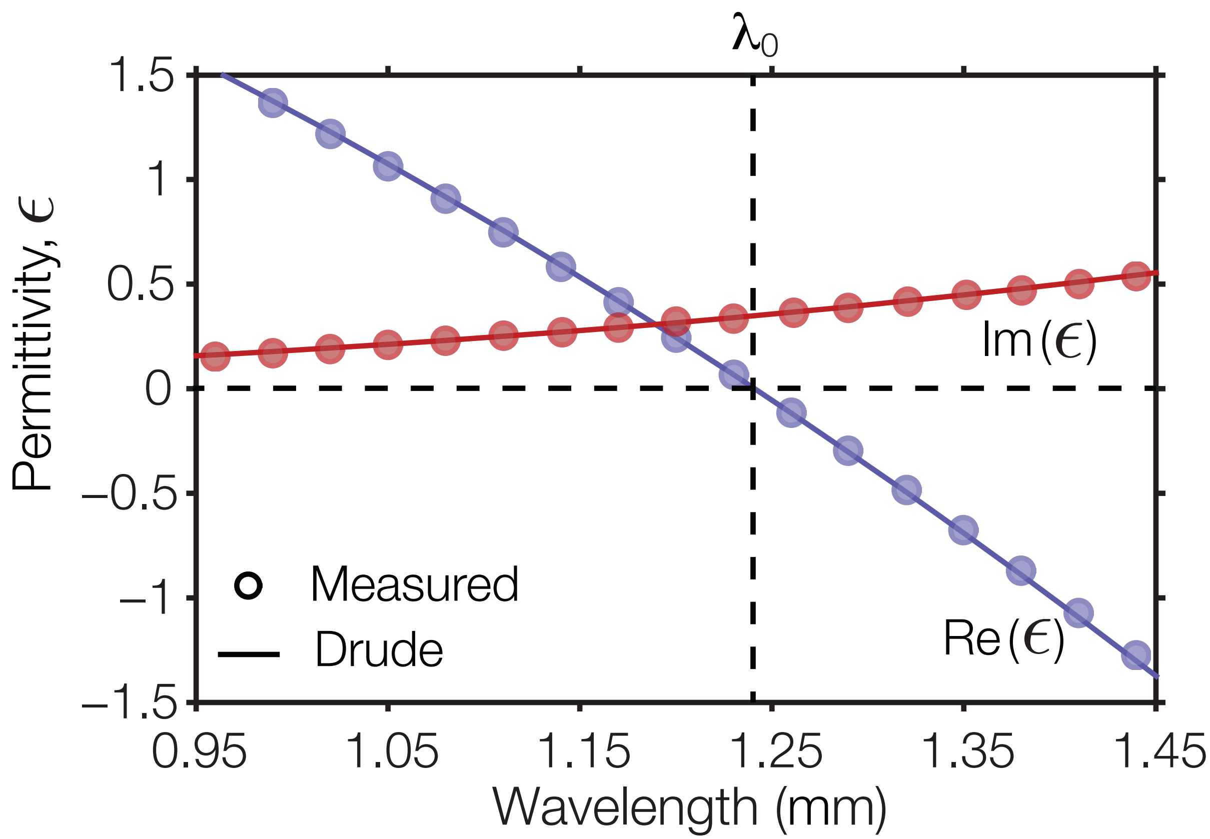
There has been great recent interest in studies of ENZ phenomena:

H. Suchowski, K. O'Brien, Z. J. Wong, A. Salandrino, X. Yin, and X. Zhang, Science 342, 1223 (2013).
C. Argyropoulos, P.-Y. Chen, G. D'Aguanno, N. Engheta, and A. Alu, Phys. Rev. B 85, 045129 (2012).
S. Campione, D. de Ceglia, M. A. Vincenti, M. Scalora, and F. Capolino, Phys. Rev. B 87, 035120 (2013).
A. Ciattoni, C. Rizza, and E. Palange, Phys. Rev. A 81,043839 (2010).

The Epsilon-Near-Zero (ENZ) region of Indium Tin Oxide (ITO)

Measured real and imaginary parts of the dielectric permittivity.

Commercial ITO sample, 310 nm thick on a glass substrate



Drude fit

$\epsilon_\infty = 3.77$

$\gamma = 0.0468\ \omega_p$

$\omega_p/2\pi = 473$ THz

Note that $\mathrm{Re}(\epsilon)$ vanishes at 1.24 mm, but that the loss-part $\mathrm{Im}(\epsilon)$ is non-zero.

Implications of ENZ Behavior for Nonlinear Optics

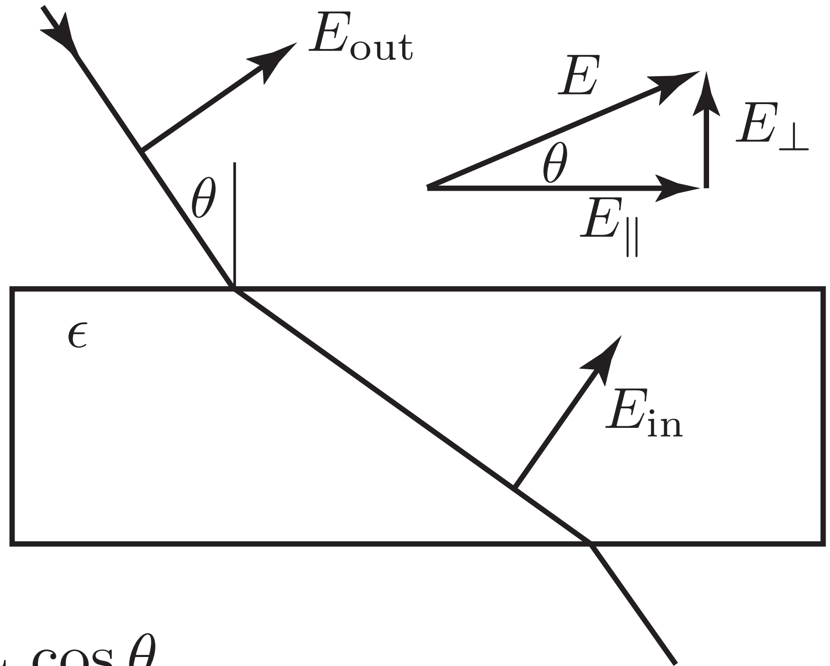
Here is the intuition for why the ENZ conditions are of interest in NLO

Recall the standard relation between n_2 and $\chi^{(3)}$

$$n_2 = \frac{3\chi^{(3)}}{4\epsilon_0 c\, n_0\, \mathrm{Re}(n_0)}$$

Note that for ENZ conditions the denominator becomes very small, leading to a very large value of n_2

The NLO Response Is Even Larger at Oblique Incidence



Standard boundary conditions show that:

$$E_{\text{in},\parallel} = E_{\text{out},\parallel} = E_{\text{out}} \cos\theta$$

$$D_{\text{in},\perp} = D_{\text{out},\perp} \quad \Rightarrow \quad E_{\text{in},\perp} = E_{\text{out},\perp}/\epsilon = E_{\text{out}} \cos\theta/\epsilon$$

Thus the total field inside of the medium is given by

$$E_{\text{in}} = E_{\text{out}} \sqrt{\cos^2\theta + \frac{\sin^2\theta}{\epsilon}}$$

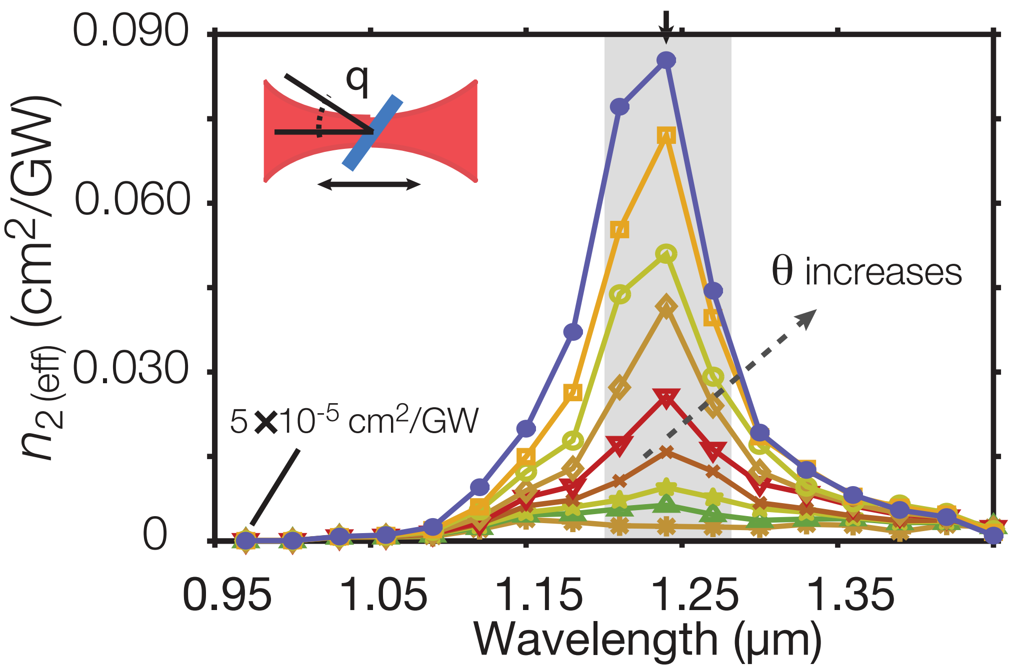
Note that, for $\epsilon < 1$, E_{in} exceeds E_{out} for $\theta \neq 0$.

Note also that, for $\epsilon < 1$, E_{in} increases as θ increases.

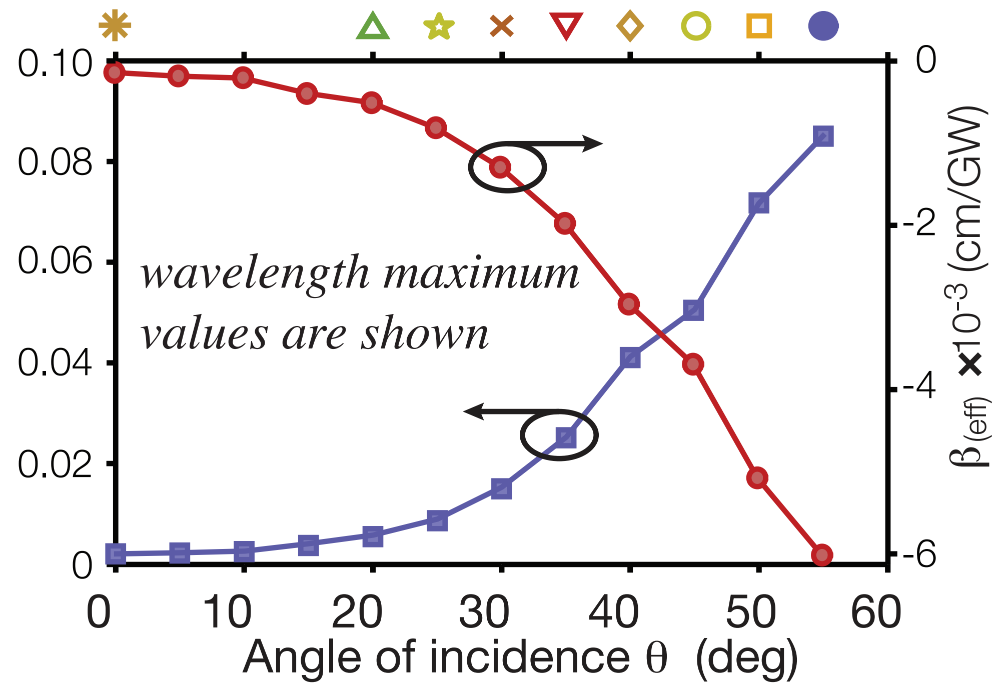
Huge Nonlinear Optical Response of ITO

Z-scan measurements for various angles of incidence

Wavelength dependence of n_2



Variation with incidence angle



- Note that n_2 is positive (self focusing) and β is negative (saturable absorption).
- Both n_2 and nonlinear absorption increase with angle of incidence
- n_2 shows a maximum value of 0.11 $cm^2/GW = 1.1 \times 10^{-10}$ cm^2/W at 1.25 μm and 60 deg.

Why is n_2 so large?

The short-wavelength value of n_2 of ITO is 6×10^{-5} cm^2/GW, which is 190 times larger that of fused silica (3.2×10^{-7} cm^2/GW).

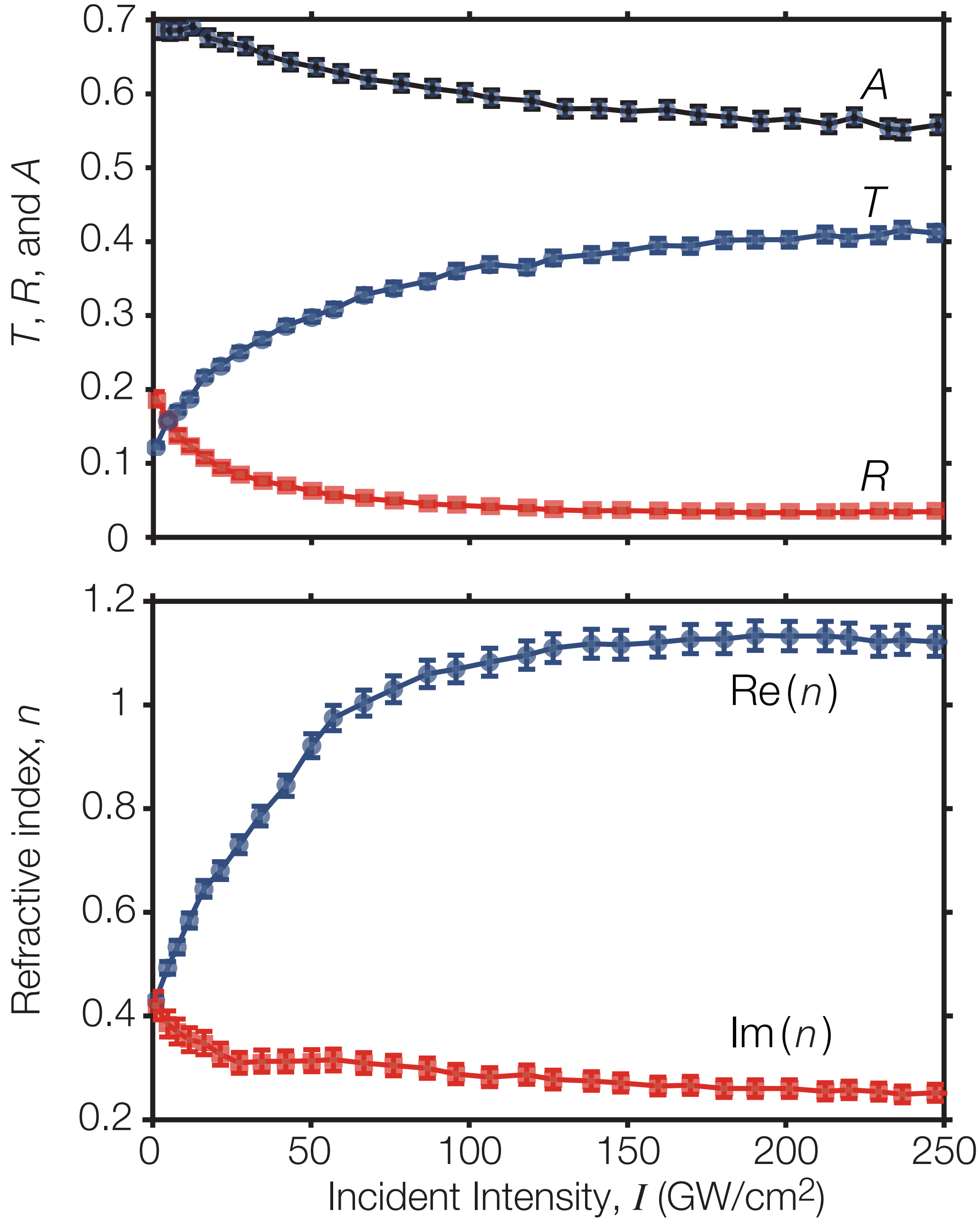
There is a 43x enhancement from working at the ENZ wavelength and an additional 43x enhancement from using non-normal incidence.

Thus $n_2 = 0.11$ cm^2/GW, which is 3.4×10^5 times that of fused silica.

Incidentally, for arsenic trisulfide glass, $n_2 = 2.4 \times 10^{-4}$ cm^2/GW. which is 750 times larger than that of fused silica.

R.E. Slusher et al., J. Opt. Soc. Am. B 21, 1146 (2004).

Beyond the $\chi^{(3)}$ limit



The nonlinear change in refractive index is so large as to change the transmission, absorption, and reflection!

Note that transmission is increased at high intensity.

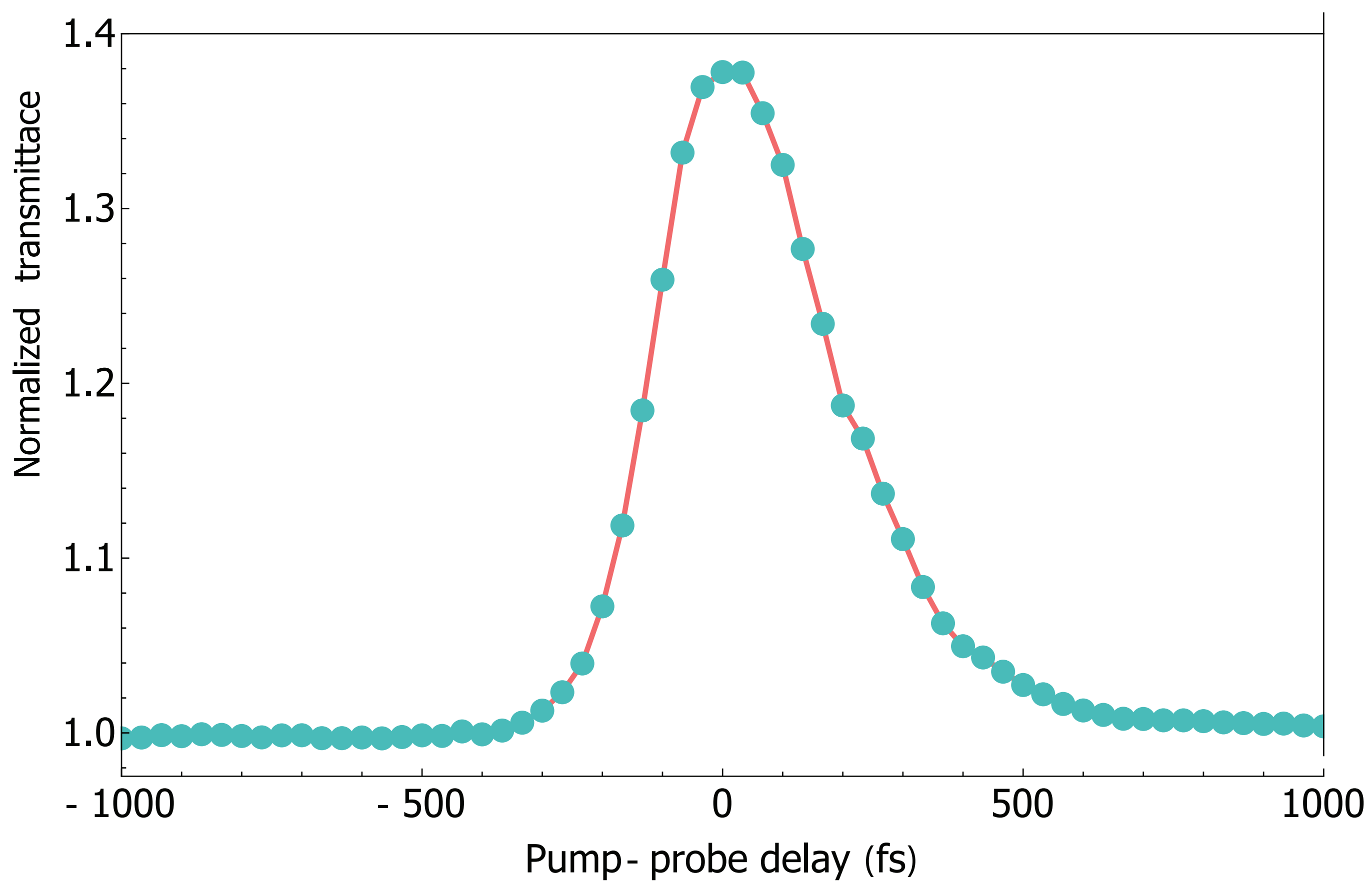
Here is the refractive index extracted from the above data.

Note that the total nonlinear change in refractive index is $\Delta n = 0.8$.

The absorption decreases at high intensity, allowing a predicted NL phase shift of 0.5 radians.

Measurement of Response Time of ITO

- We have performed a pump-probe measurement of the response time. Both pump and probe are 100 fs pulses at 1.2 μm.
- Data shows a rise time of no longer than 200 fs and a recover time of of 360 fs.
- ITO will support switching speeds as large as 1.5 THz



Implications of the Large NLO Response of ITO

Indium Tin Oxide at its ENZ wavelength displays enormously strong NLO properties:

n_2 is 3.4×10^5 times that of fused silica
Nonlinear change in refractive index as large as 0.8

Note that the usual "power-series" description of NLO is not adequate for describing this material. (We can have fun reformulating the laws of NLO!)

Some possible new effects
Waveguiding outside the "weakly-guiding" regime
Efficient all-optical switching
No need for phase-matching

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Controlling the Velocity of Light

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

– Light can be made to go:

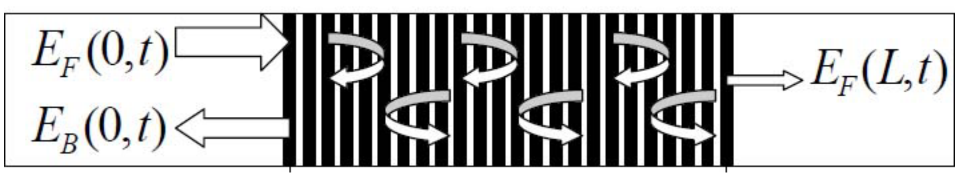
slow: $v_g << c$ (as much as 10^6 times slower!)

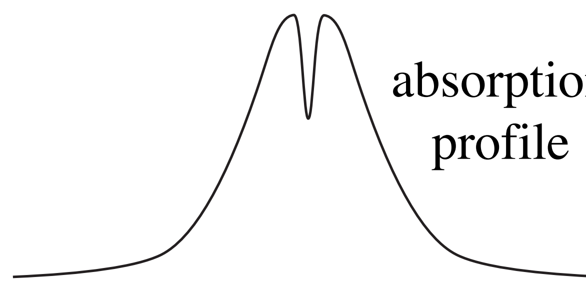
fast: $v_g > c$

backwards: v_g negative

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

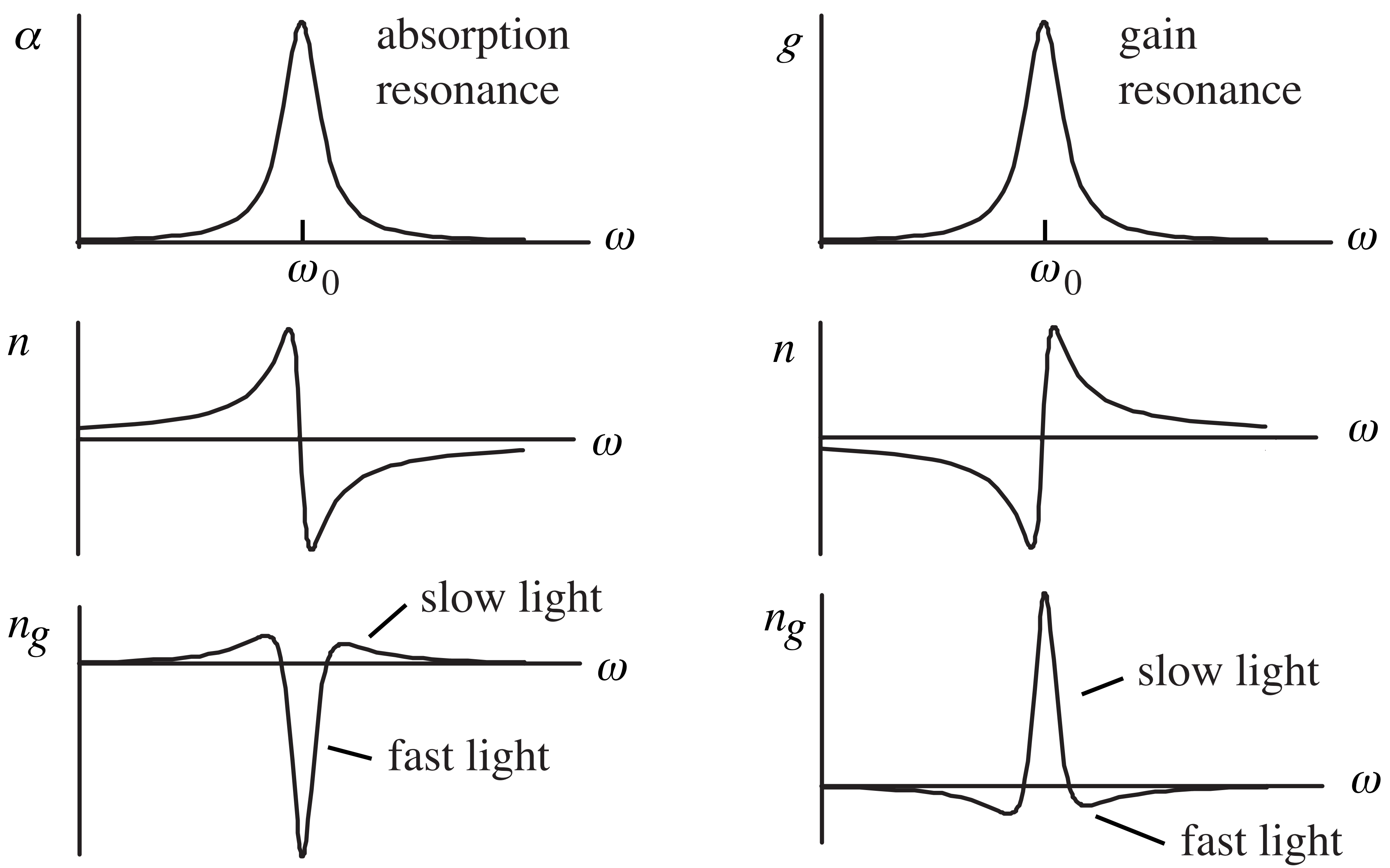
– Velocity controlled by structural or material resonances





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

Slow and Fast Light Using Isolated Gain or Absorption Resonances

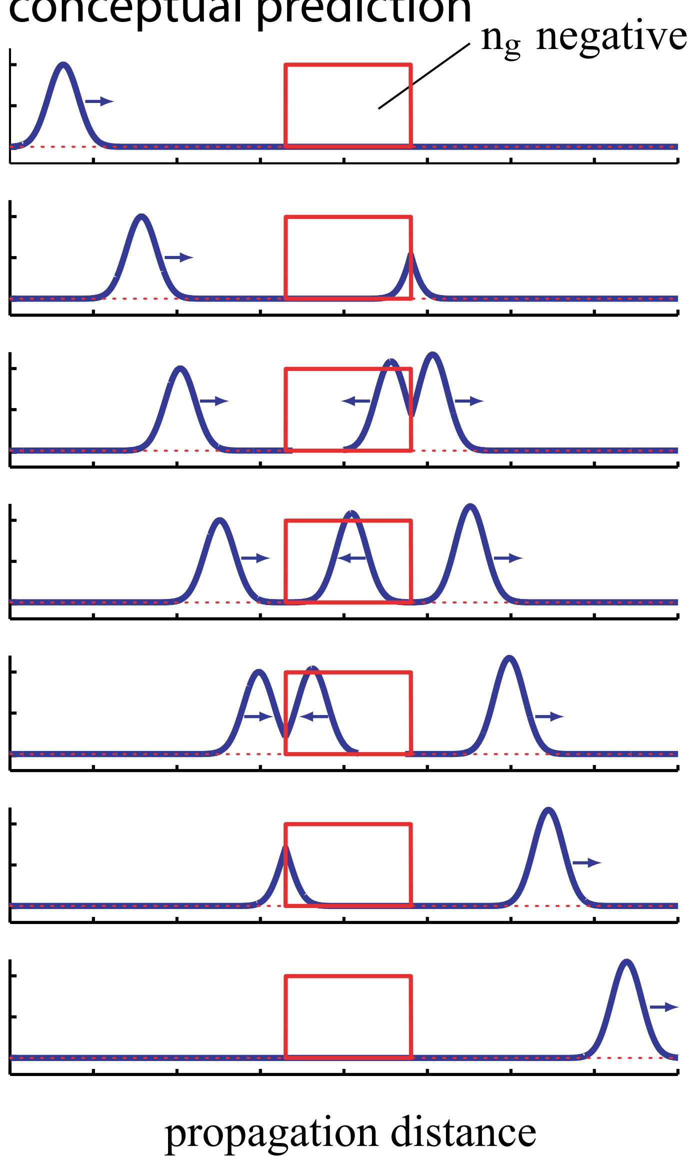


$$n_g = n + \omega\,(dn/d\omega)$$

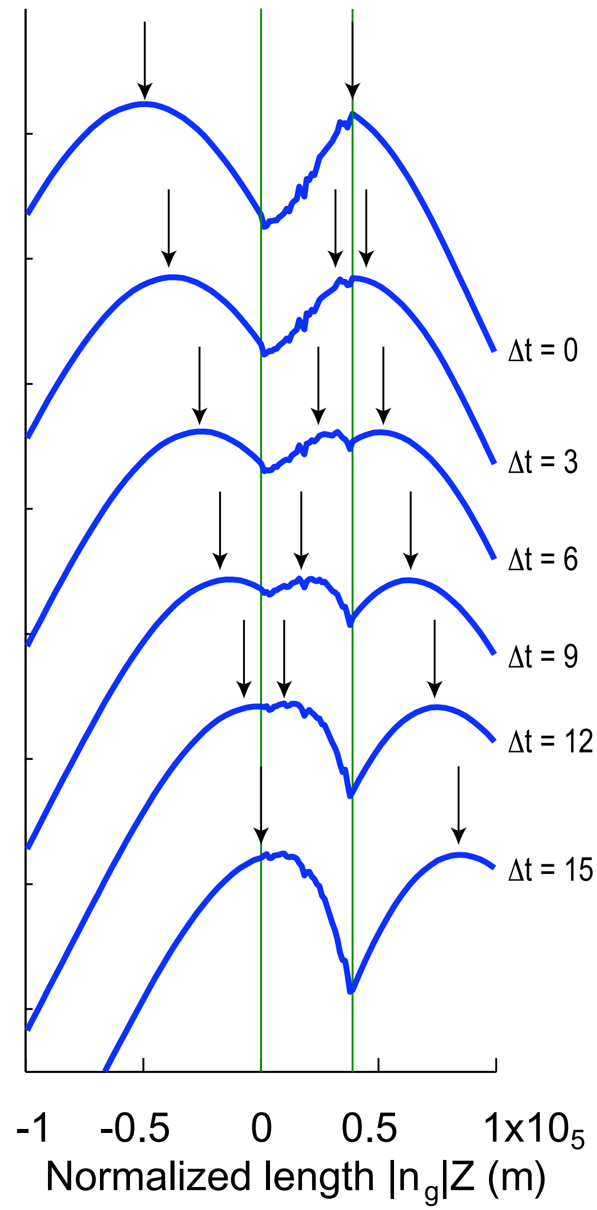
Observation of Superluminal and "Backwards" Pulse Propagation

- A strongly counterintuitive phenomenon
- But entirely consistent with established physics
- Predicted by Garrett and McCumber (1970) and Chiao (1993).
- Observed by Gehring, Schweinsberg, Barsi, Kostinski, and Boyd Science 312, 985 2006.

- conceptual prediction



- laboratory results

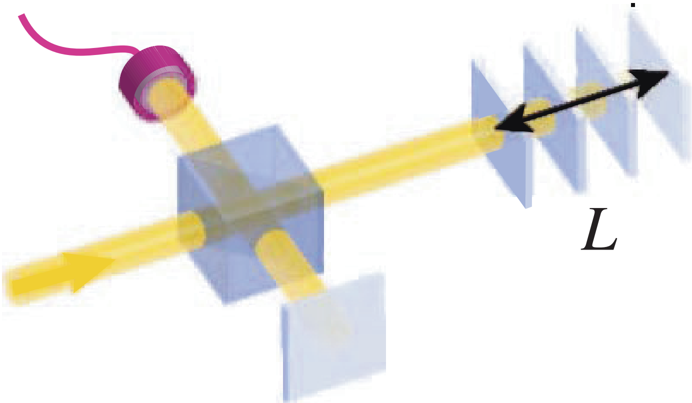


Development of Miniaturized, Chip-Scale Spectrometers

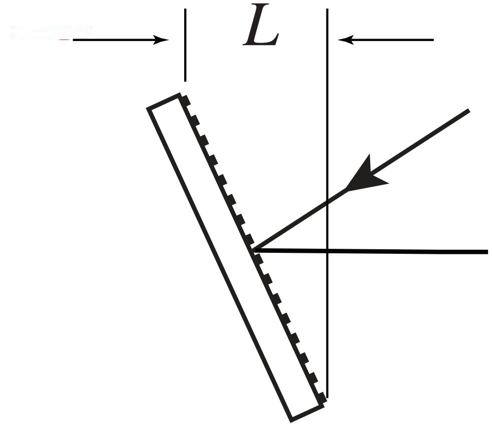
Can We Beat the 1/*L* Resolution Limit of Standard Spectrometers?

- 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



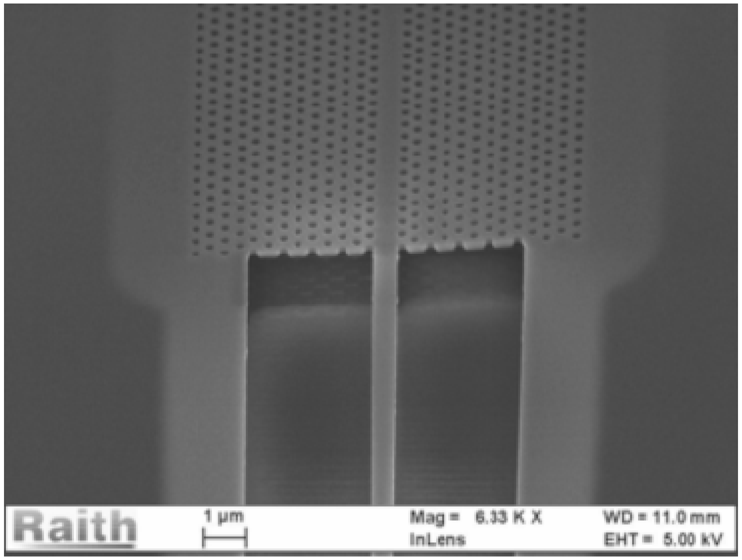
$$\Delta\nu(\text{res}) \approx 1/L$$

- 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.

Our Goal

Replace this:

with this:



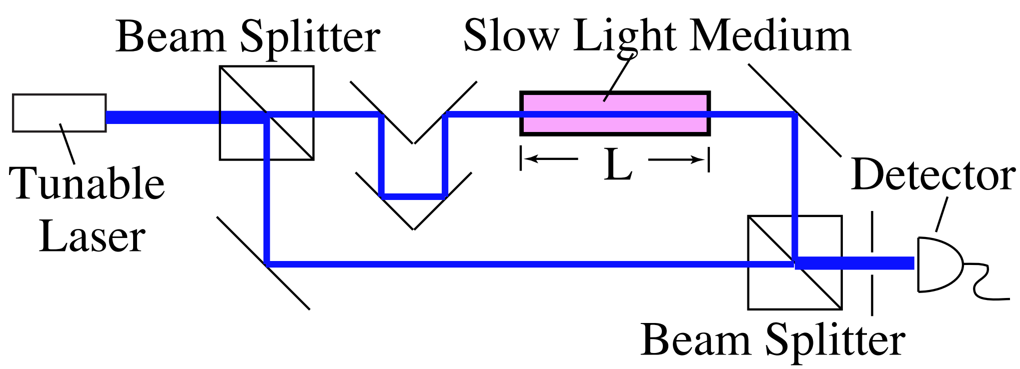
Our Approach: Chip-Scale Slow-Light Spectrometer

- 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:

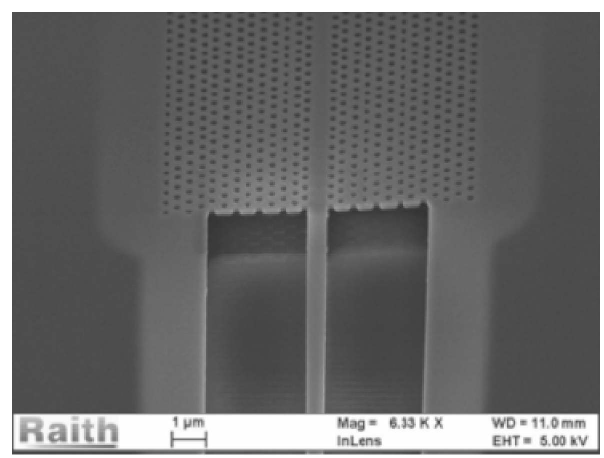


Simple analysis

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

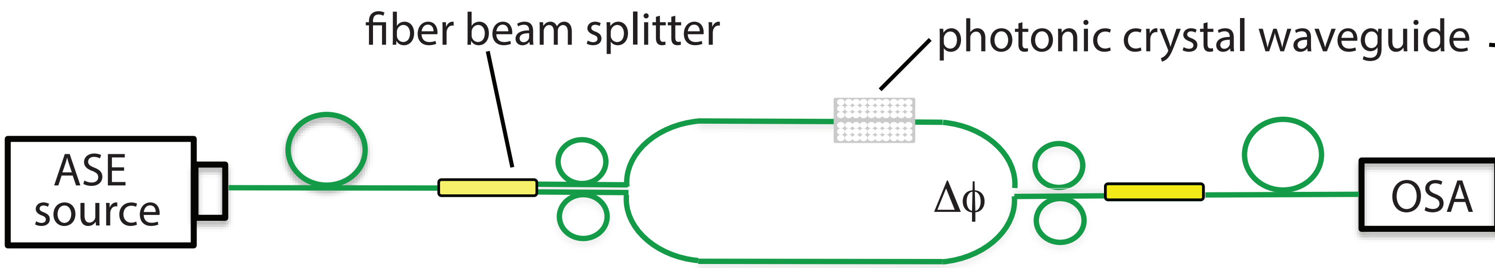
- We use line-defect waveguides in photonic crystals as our slow light mechanism

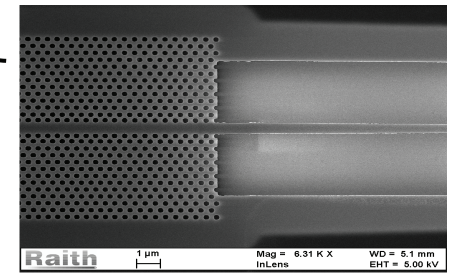
Slow-down factors of greater than 100 have been observed in such structures.



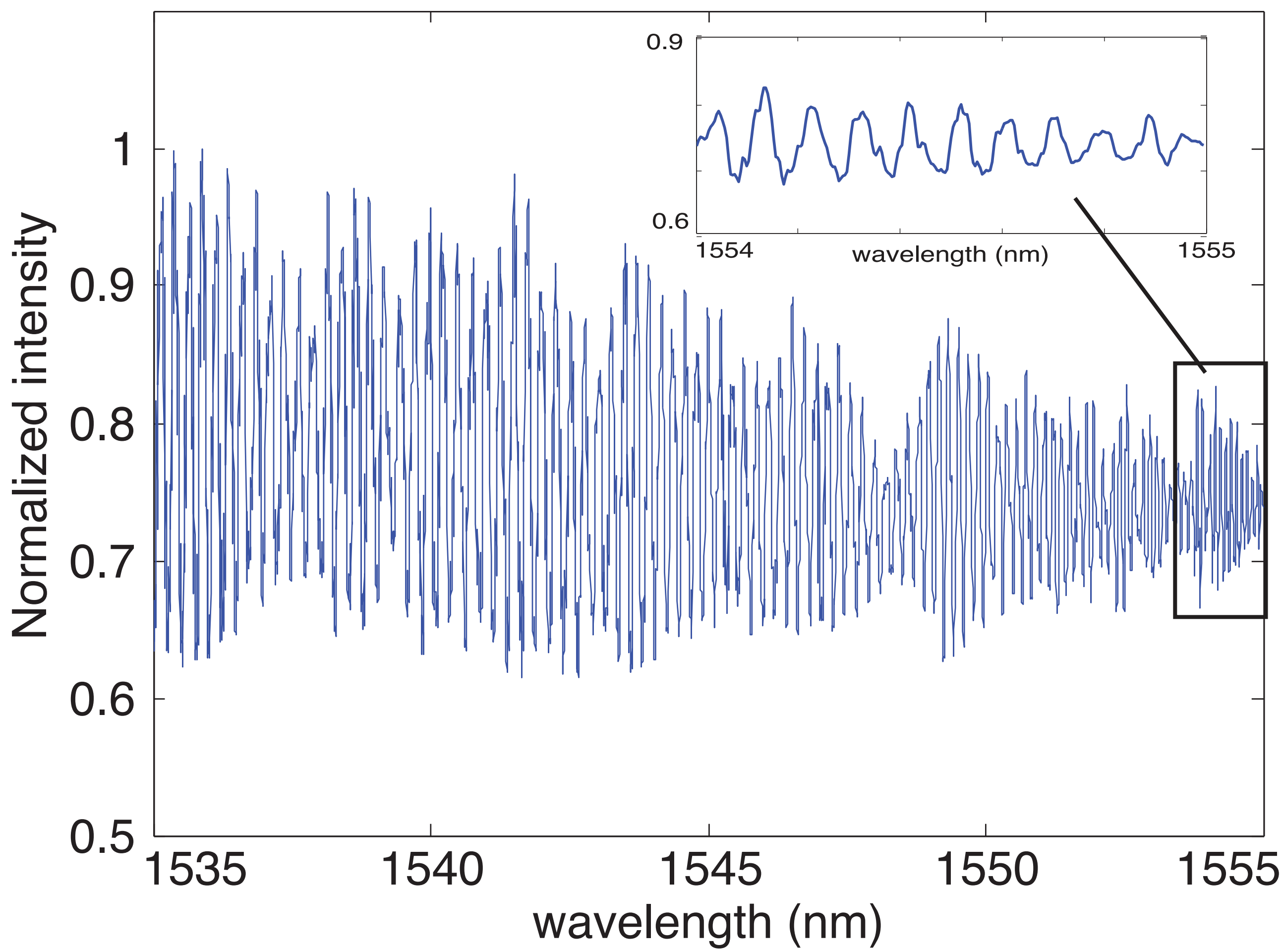
Shi, Boyd, Gauthier, and Dudley, Opt. Lett. 32, 915 (2007)
Shi, Boyd, Camacho, Vudyasetu, and Howell, PRL. 99, 240801 (2007)
Shi and Boyd, J. Opt. Soc. Am. B 25, C136 (2008).

Laboratory Characterization of the Slow-Light Mach-Zehnder Interferometer





- Interference fringes

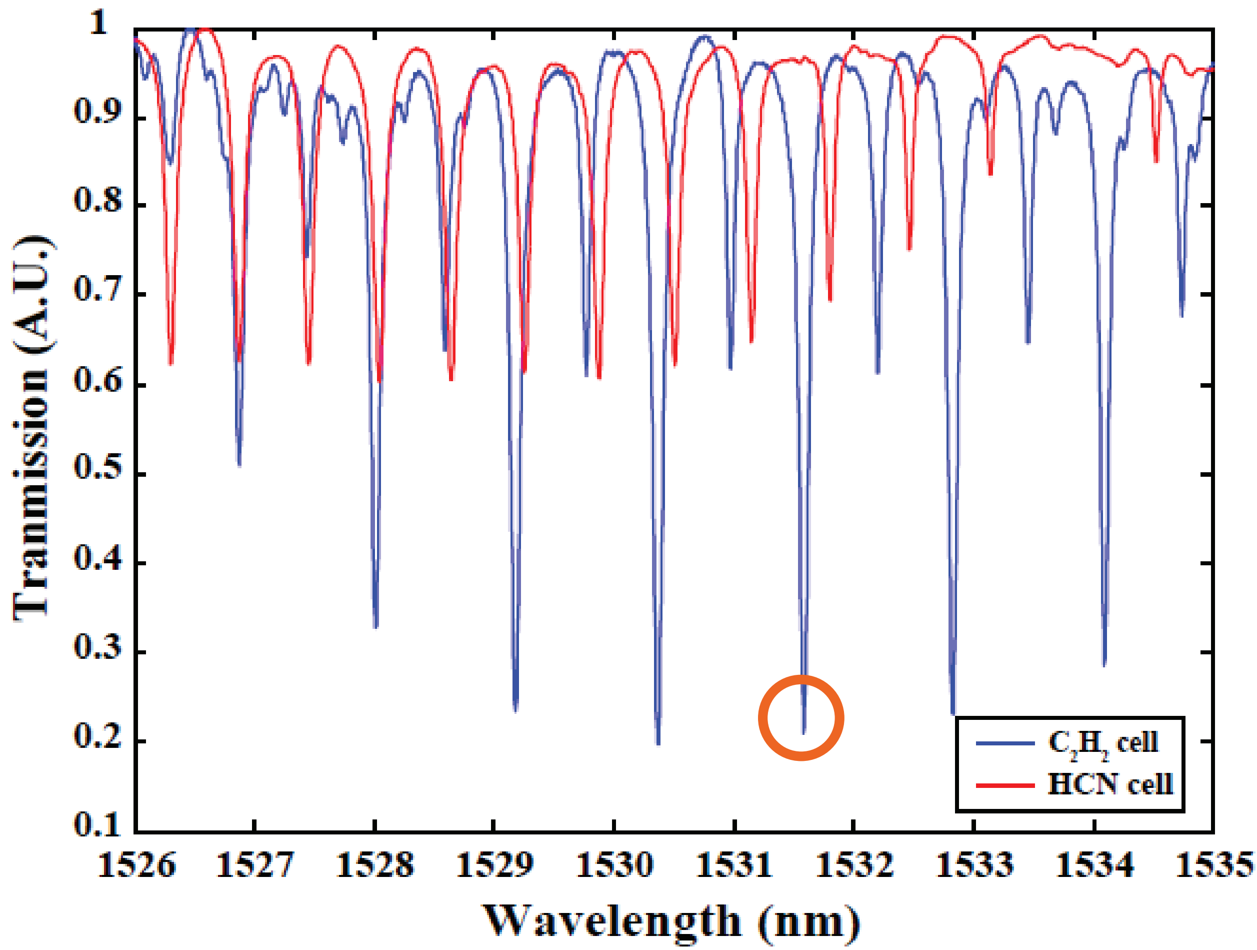


- Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm^{-1}

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

Magaña-Loaiza, Gao, Schulz, Awan, Upham, Dolgaleva, and Boyd, in review.

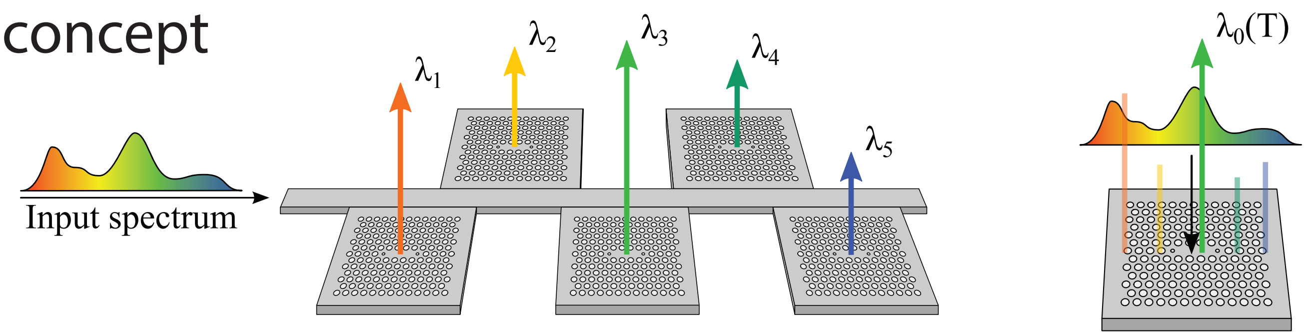
Challenge: Fabricate a chip-scale spectrometer that can discriminate acetylene (H_2C_2) from hydrogen cyanide (HCN)?



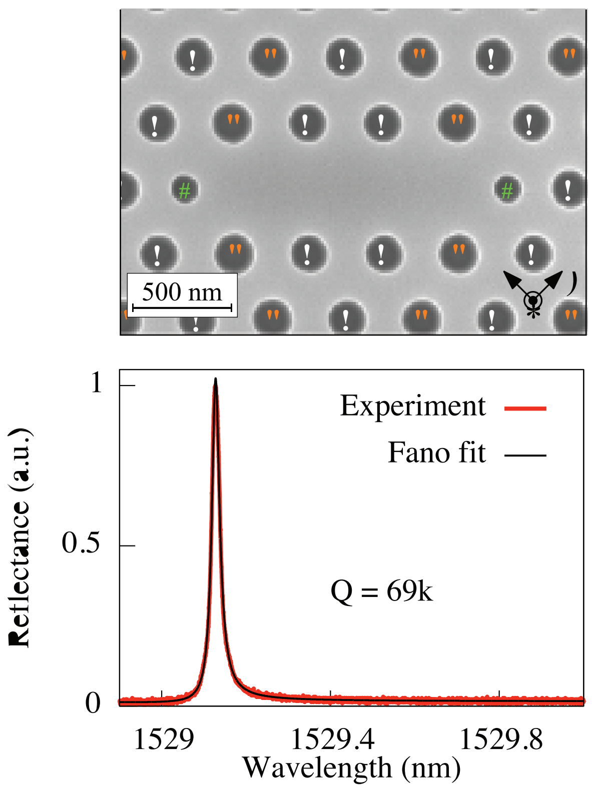
(data from our own lab)

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

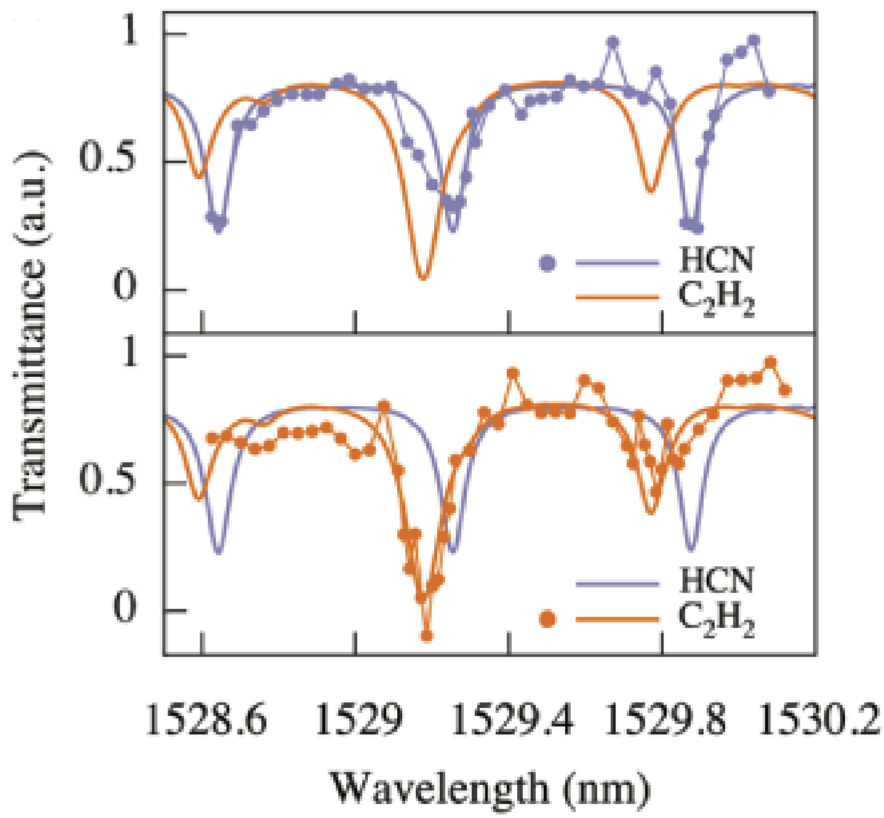
- The concept



- Cavity design



- Spectroscopy results



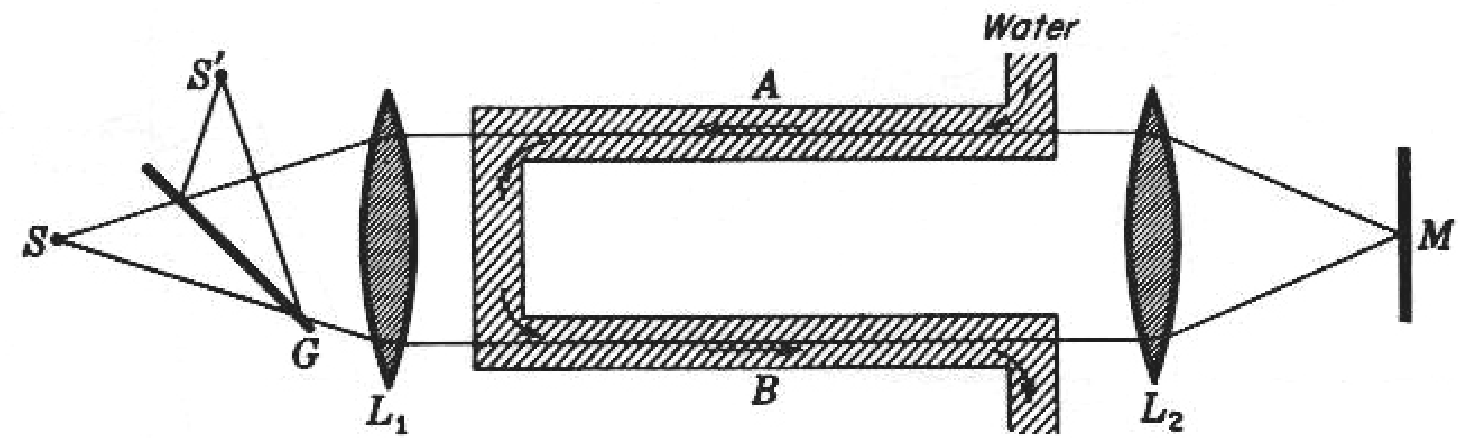
Liapis, Gao, Siddiqui, Shi, Boyd, Appl. Phys. Lett. 108, 021105 (2016).

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

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

Fresnel "drag" coefficient

- But what about slow-light media?

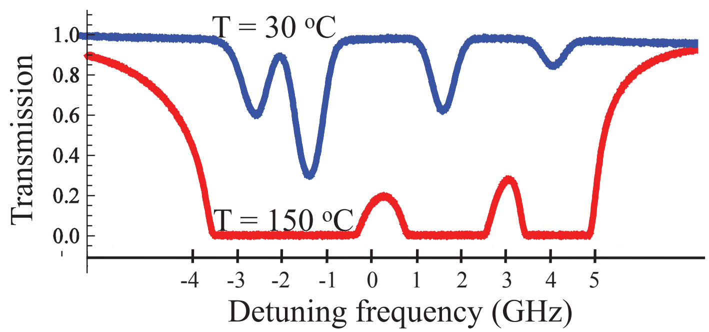
Fresnel Drag in a Highly Dispersive Medium

Light Drag in a Slow Light Medium (Lorentz)

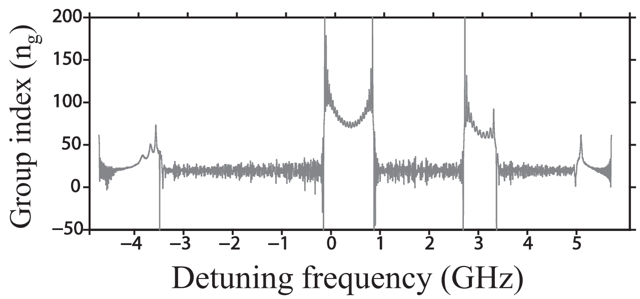
$$u \simeq \frac{c}{n} \pm v\left(1 - \frac{1}{n^2} + \frac{n_g - n}{n^2}\right)$$

We Use Rubidium as Our Slow Light Medium

- Transmission spectrum of Rb around D_2 transition:

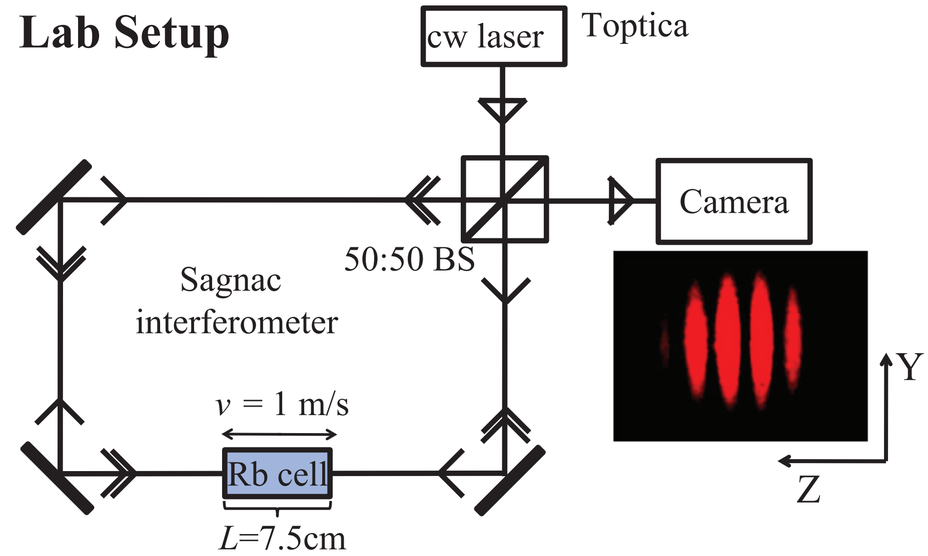


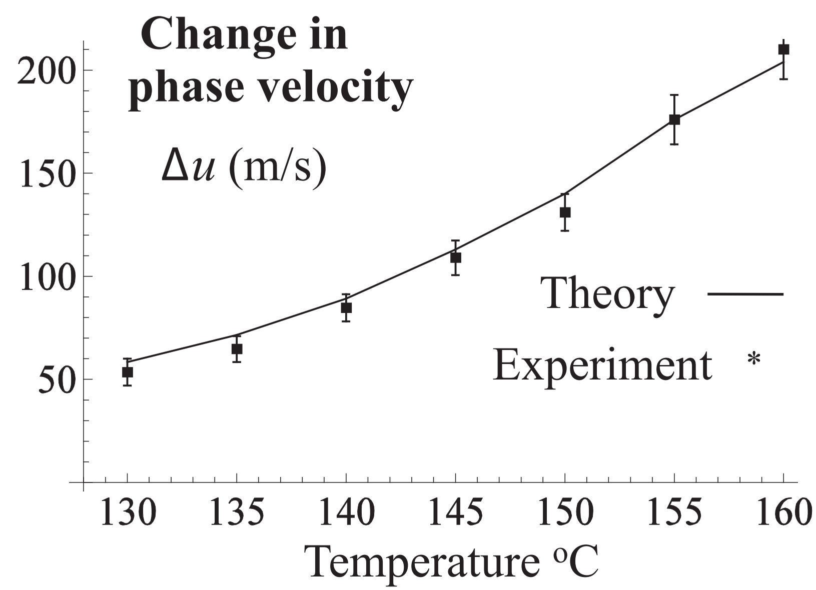
- Group index of Rb around D_2 line at T=130



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?**

Boyd Name Origin

(Road outside Glasgow)

Why We Shouldn’t Always Trust Google