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 Ottwa

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

Department of Physics and Astronomy
University of Glasgow

Plenary Presentation at OPTO, Photonics West, San Francisco CA, February 13, 2016.

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. Introduction to Nonlinear Optics and Quantum NLO
2. New Applications of "Slow Light"
3. Möbius Strips of Polarization
4. Quantum Communication with Multiple Bits per Photon

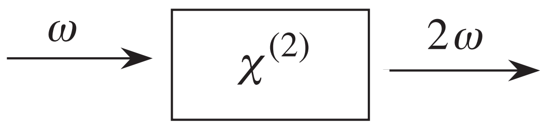
Simple Formulation of the Theory of Nonlinear Optics

$$P = \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 + \ldots$$

Here P is the induced dipole moment per unit volume and E is the field amplitude

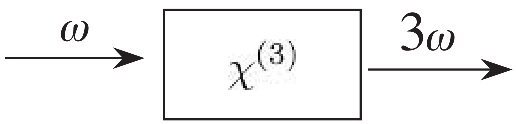
$\chi^{(1)}$ describes linear optics, e.g., how lenses work:

$\chi^{(2)}$ describes second-order effects, e.g., second-harmonic generation (SHG)

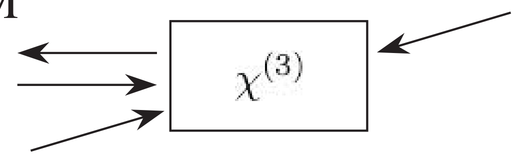


$\chi^{(3)}$ describes third-order effects such as third-harmonic generation, four-wave mixing, and the intensity dependence of the index of refraction.

THG



FWM



NL index

$$n = n_0 + n_2 I \quad \text{where} \quad n_2 = \frac{3}{4 n_0^2 \epsilon_0 c} \chi^{(3)}$$

Intense Field and Attosecond Physics

E 70, NUMBER 11 PHYSICAL REVIEW LETTERS 15 MARCH

Above Threshold Ionization Beyond the High Harmonic Cutoff

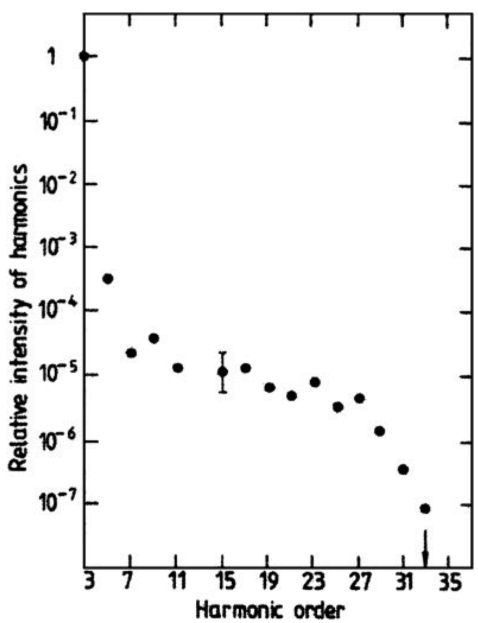
K. J. Schafer,[1] Baorui Yang,[2] L. F. DiMauro,[2] and K. C. Kulander[1]
[1] *Lawrence Livermore National Laboratory, Livermore, California 94550*
[2] *Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973*
(Received 2 December 1992)

VOLUME 71, NUMBER 13 PHYSICAL REVIEW LETTERS 27 SEPTEMBER 1993

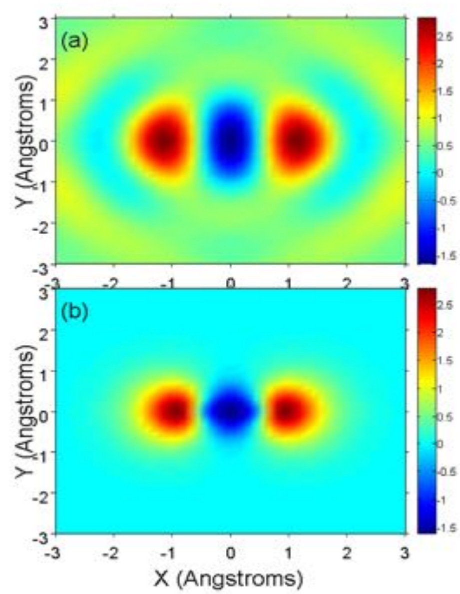
Plasma Perspective on Strong-Field Multiphoton Ionization

P. B. Corkum
National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6
(Received 9 February 1993)

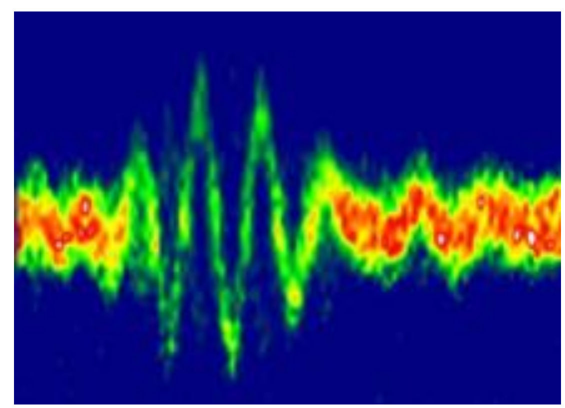
$I > 10^{15}$ W/cm^2



High-harmonic generation



Measuring the molecular nitrogen wavefunction



Attosecond pulses to sample a visible E-field

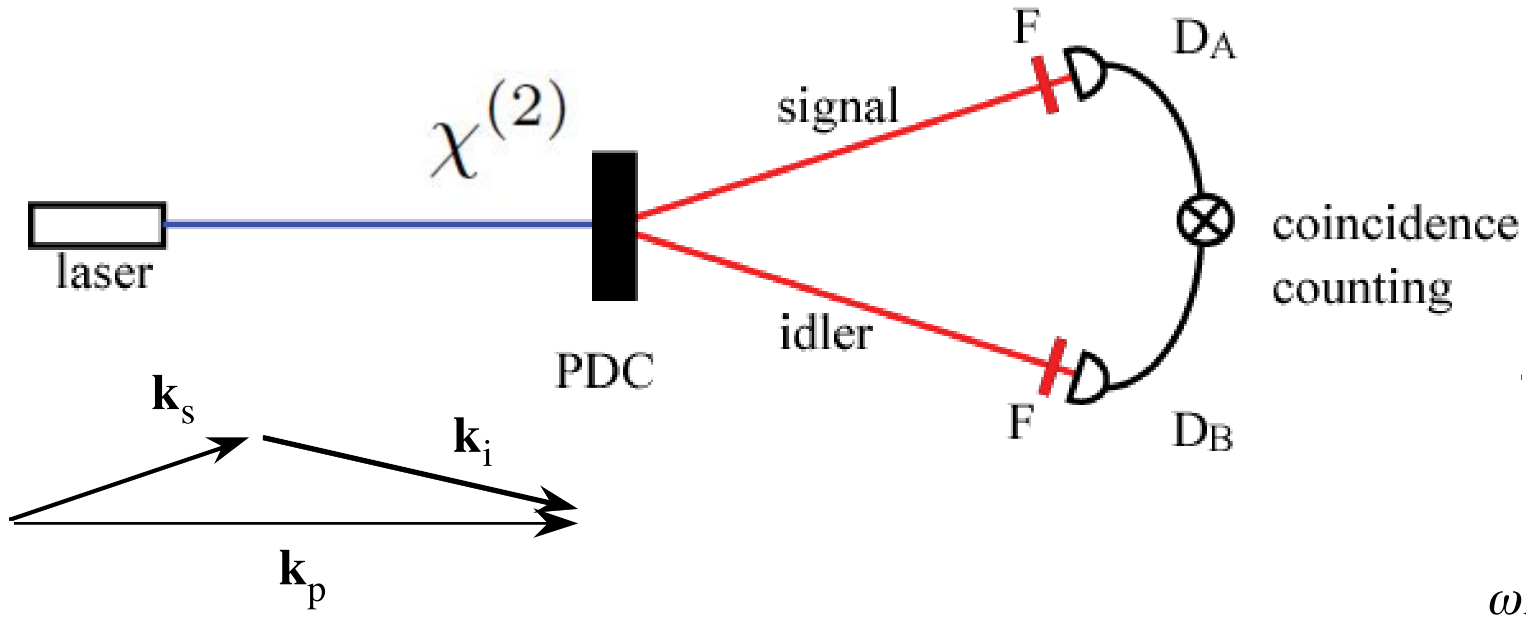
Why Interest in Quantum Nonlinear Optics?

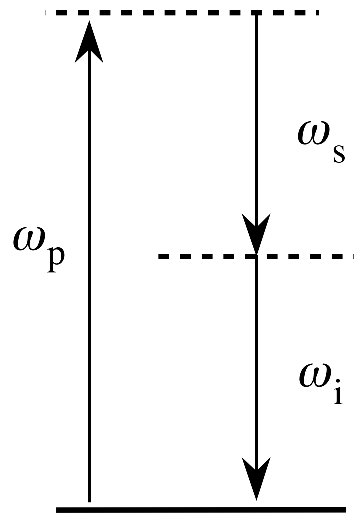
Explore the relation between traditional nonlinear optics (NLO) and phenomena in quantum information science (QIS).

QIS holds great promise for secure communication, quantum logic, quantum computing, etc.

Many processes in QIS rely on nonlinear optical interactions.

Parametric Downconversion: A Source of Entangled Photons





The signal and idler photons are entangled in:

(a) polarization

(b) time and energy

(c) position and transverse momentum

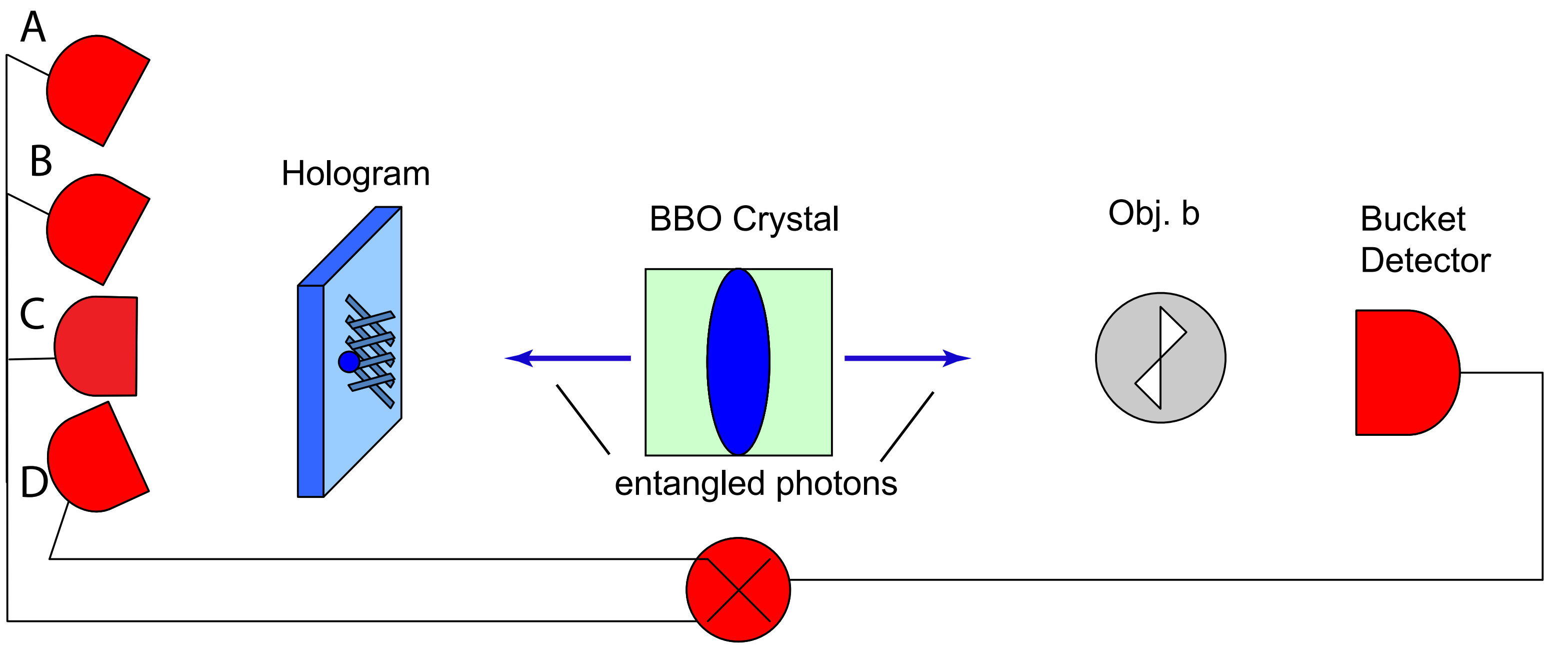
(d) angular position and orbital angular momentum

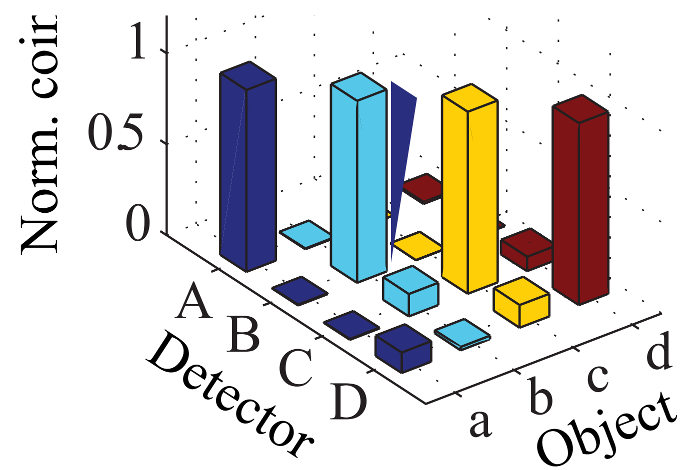
Entanglement is important for:

(a) Fundamental tests of QM (e.g., nonlocality, Bell tests)

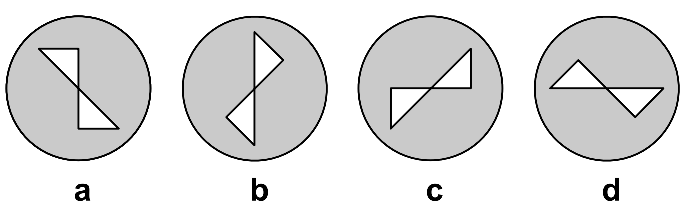
(a) Quantum technologies (e.g., secure communications, Q teleportation)

Single-Photon Coincidence Imaging





- We discriminate among four orthogonal images using single-photon interogation in a coincidence imaging configuration.



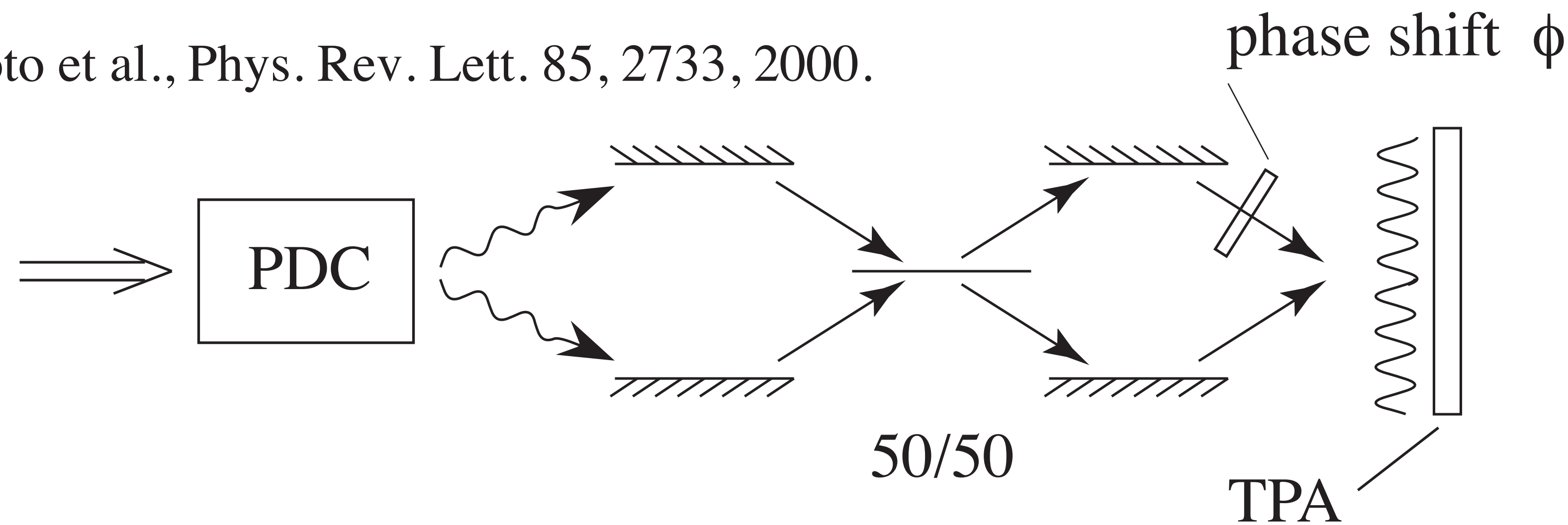
- Note that a single photon can carry more than one bit of information.

Malik, Shin, O'Sullivan. Zerom, and Boyd, Phys. Rev. Lett. 104, 163602 (2010).

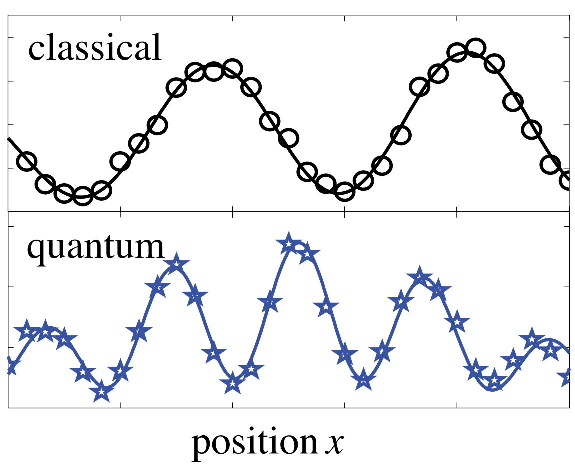
Quantum Lithography: Concept of Jonathan Dowling

- Entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit
- Resolution ≈ $\lambda/2N$, where N = number of entangled photons

Boto et al., Phys. Rev. Lett. 85, 2733, 2000.



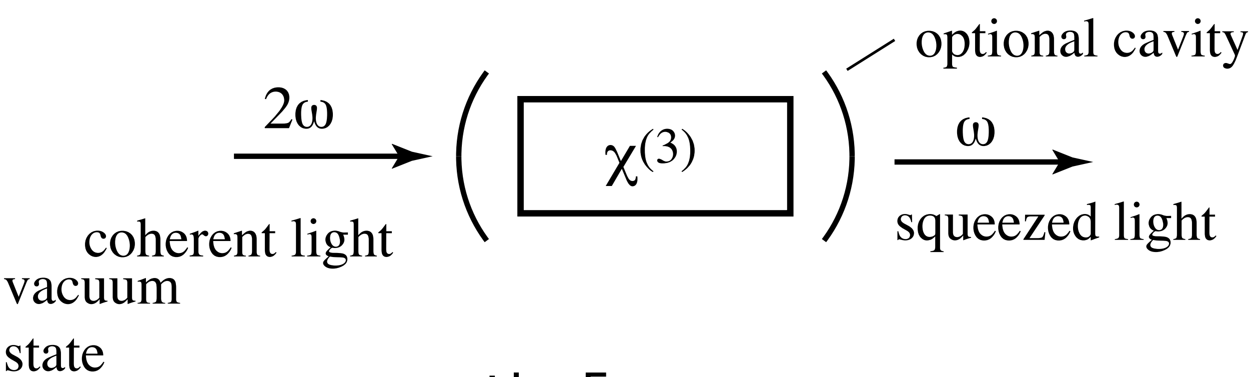
- No practical implementation to date, but some laboratory results

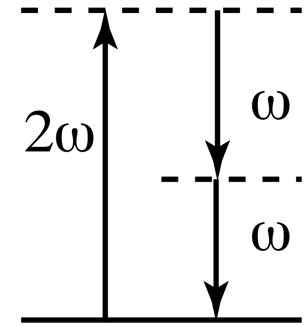


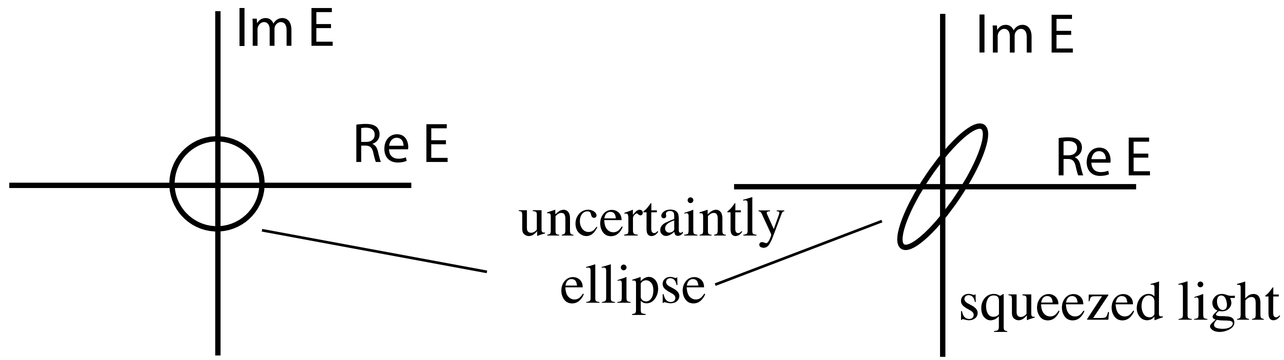
Quantum spatial superresolution by optical centroid measurements, Shin, Chan, Chang, and Boyd, Phys. Rev. Lett. 107, 083603 (2011).

See also, Quantum Lithography: Status of the Field, R.W. Boyd and J.P. Dowling, Quantum Information Processing, 11:891–901 (2012).

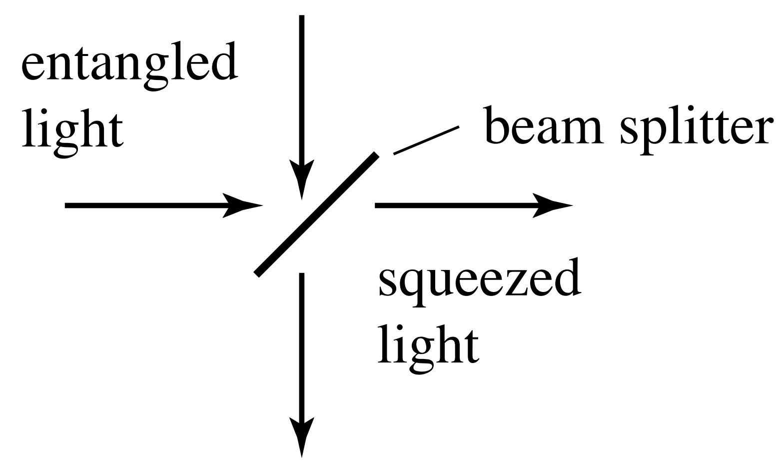
Squeezed Light Generation



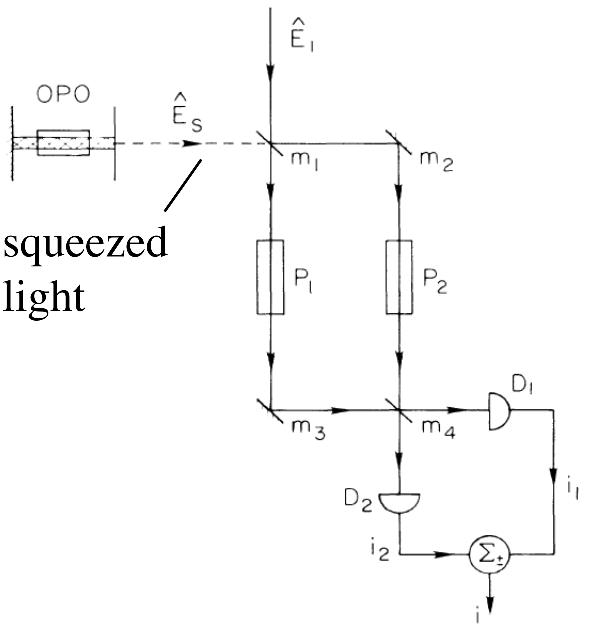




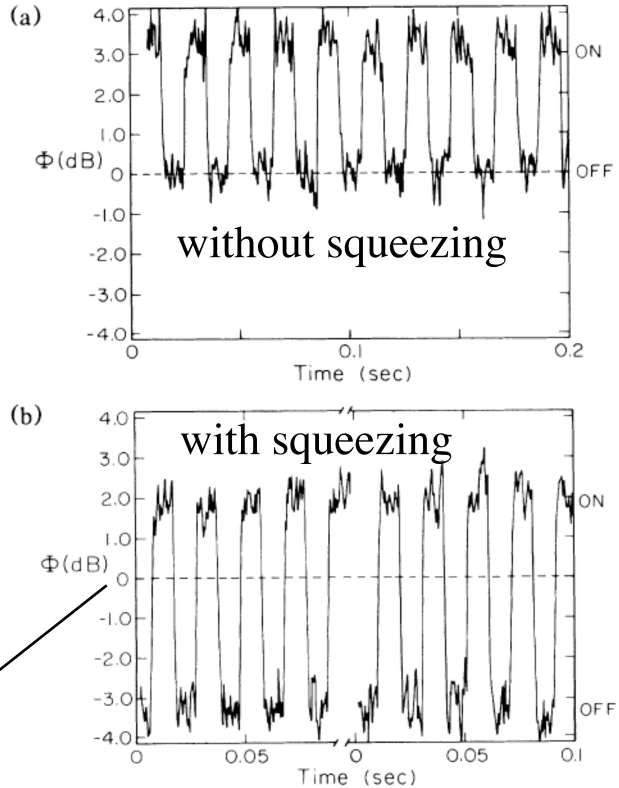
Entanglement and squeezing
share a common origin:



Precision Measurement beyond the Shot-Noise Limit



squeezed light



shot-noise limit = standard quantum limit

Xiao, M., L. A. Wu, and H. J. Kimble, Phys. Rev. Lett. 59, 278, 1987.

ARTICLE PREVIEW

view full access options ▸

NATURE PHOTONICS | LETTER

日本語要約

Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

J. Aasi, J. Abadie, B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, C. Affeldt, O. D. Aguiar, P. Ajith, B. Allen, E. Amador Ceron, D. Amariutei, S. B. Anderson, W. G. Anderson, K. Arai, M. C. Araya, C. Arceneaux, S. Ast, S. M. Aston, D. Atkinson, P. Aufmuth + *et al.*

Affiliations | Contributions | Corresponding author

Nature Photonics **7**, 613–619 (2013) | doi:10.1038/nphoton.2013.177
Received 23 April 2013 | Accepted 04 June 2013 | Published online 21 July 2013

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. Introduction to Nonlinear Optics and Quantum NLO
2. New Applications of "Slow Light"
3. Möbius Strips of Polarization
4. Quantum Communication with Multiple Bits per Photon

Controlling the Velocity of Light

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

– Light can be made to go:

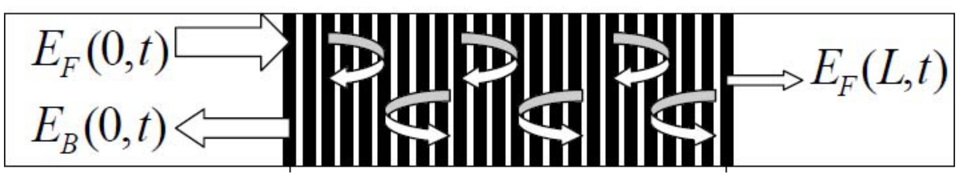
slow: $v_g << c$ (as much as 10^6 times slower!)

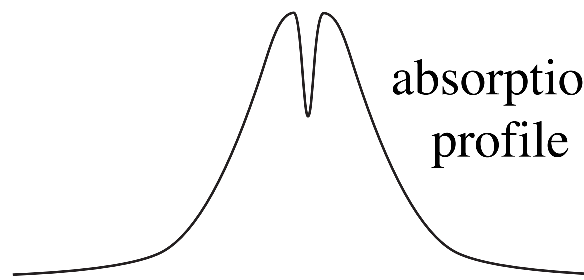
fast: $v_g > c$

backwards: v_g negative

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

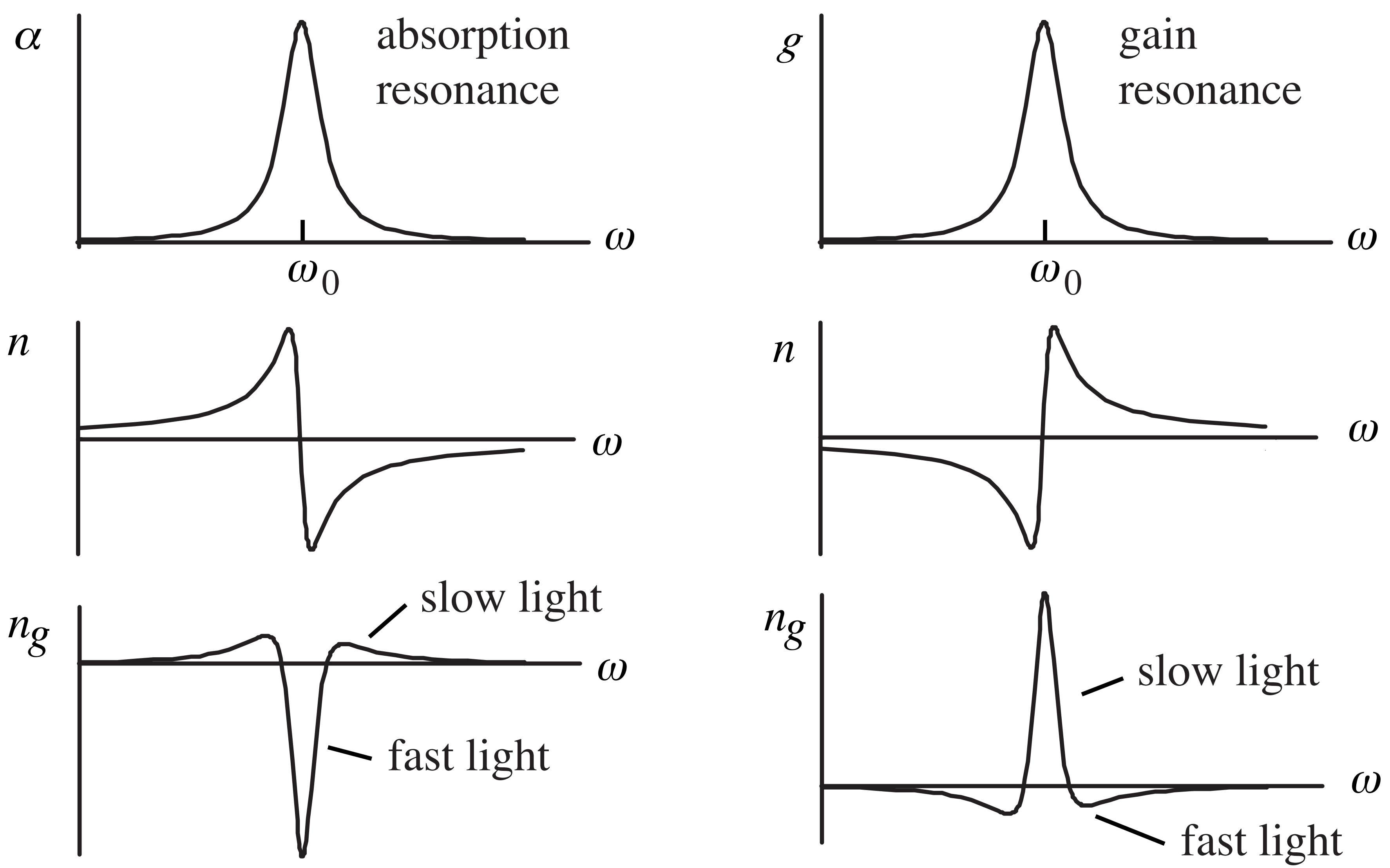
– Velocity controlled by structural or material resonances





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

Slow and Fast Light Using Isolated Gain or Absorption Resonances

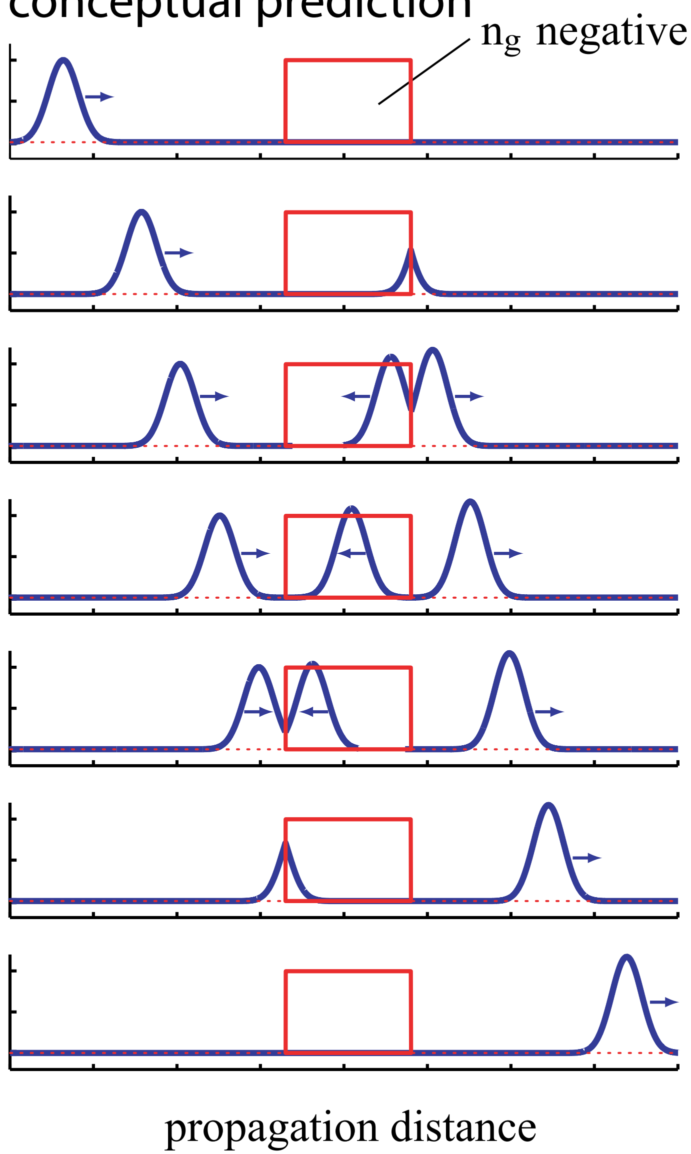


$$n_g = n + \omega\,(\mathrm{d}n/\mathrm{d}\omega)$$

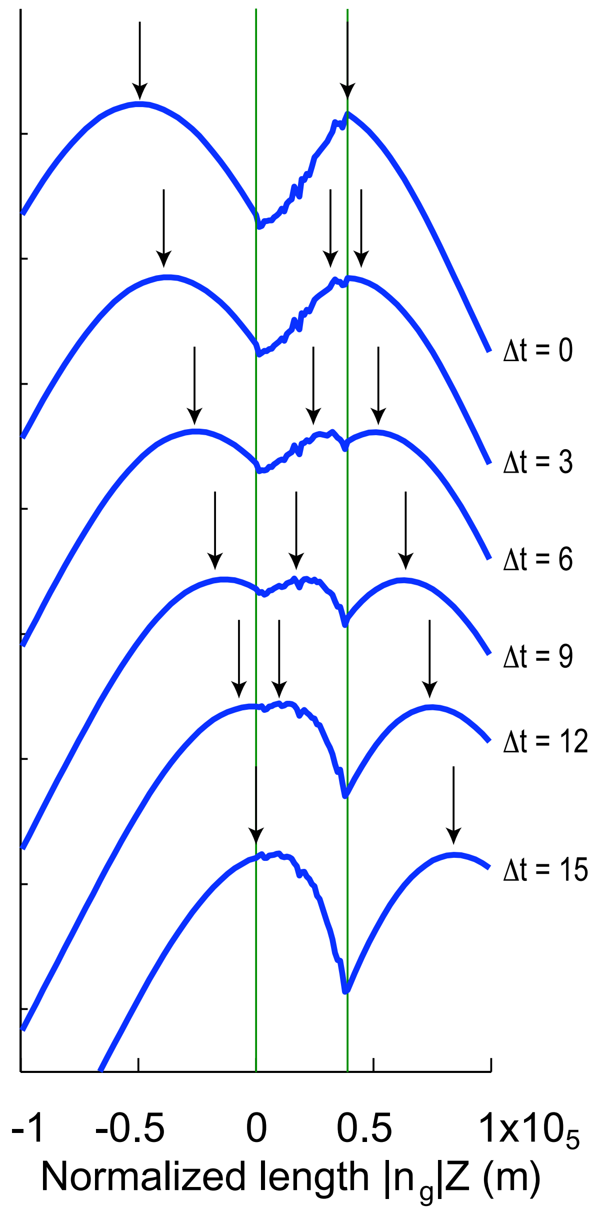
Observation of Superluminal and "Backwards" Pulse Propagation

- 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

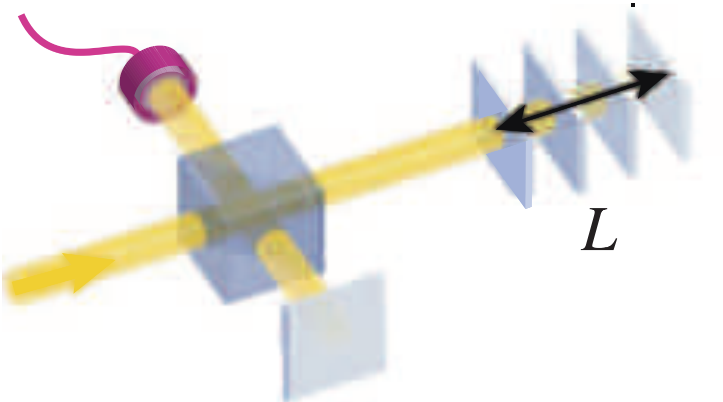


Development of Miniaturized, Chip-Scale Spectrometers

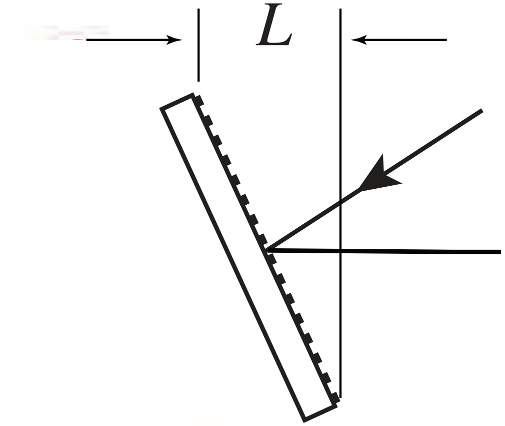
Can We Beat the $1/L$ Resolution Limit of Standard Spectrometers?

- 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



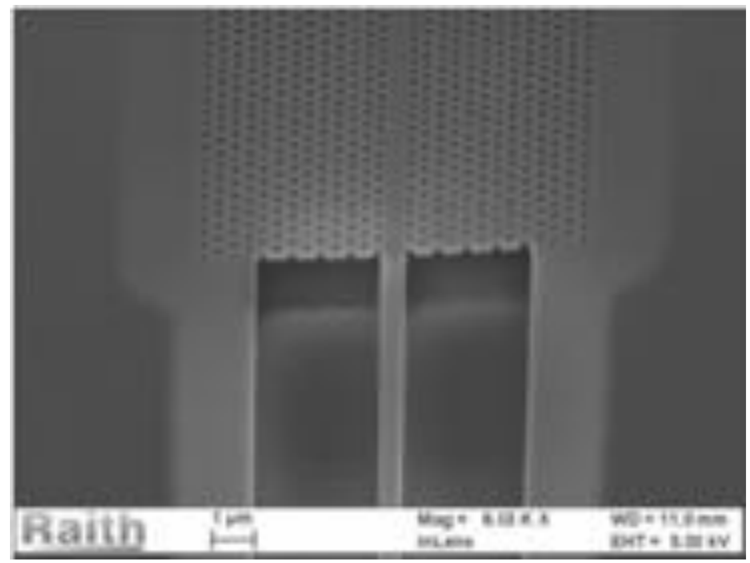
$$\Delta\nu(\text{res}) \approx 1/L$$

- 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:



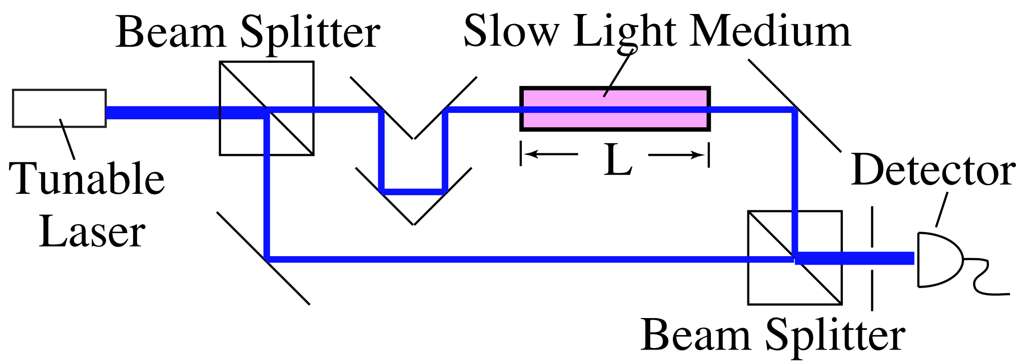
Our Approach: Chip-Scale Slow-Light Spectrometer

- 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:

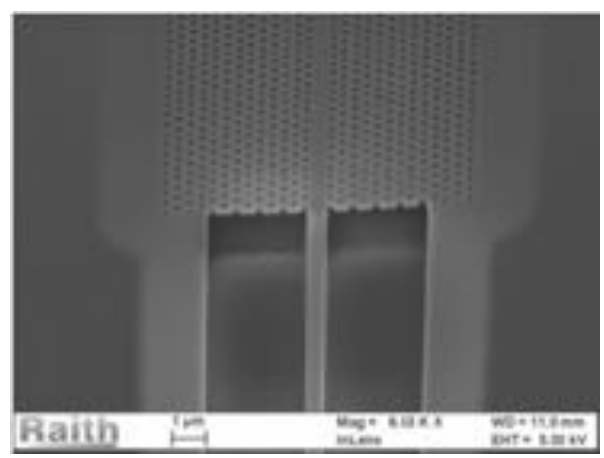


Simple analysis

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

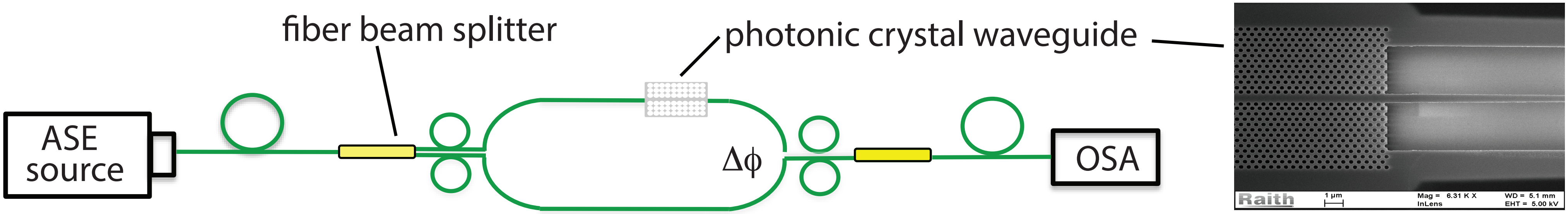
- We use line-defect waveguides in photonic crystals as our slow light mechanism

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

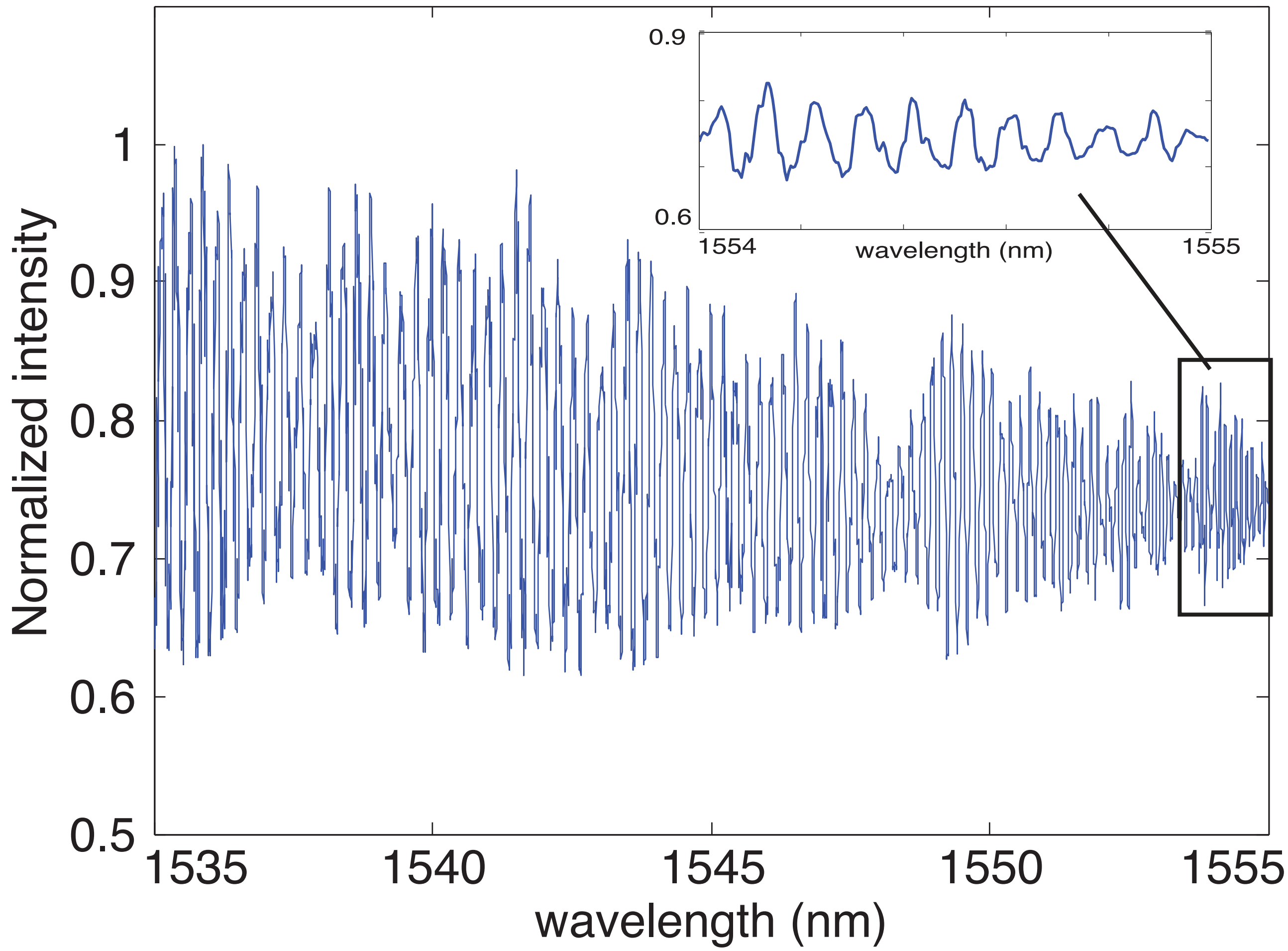


Shi, Boyd, Gauthier, and Dudley, Opt. Lett. 32, 915 (2007)
Shi, Boyd, Camacho, Vudyasetu, and Howell, PRL. 99, 240801 (2007)
Shi and Boyd, J. Opt. Soc. Am. B 25, C136 (2008).

Laboratory Characterization of the Slow-Light Mach-Zehnder Interferometer



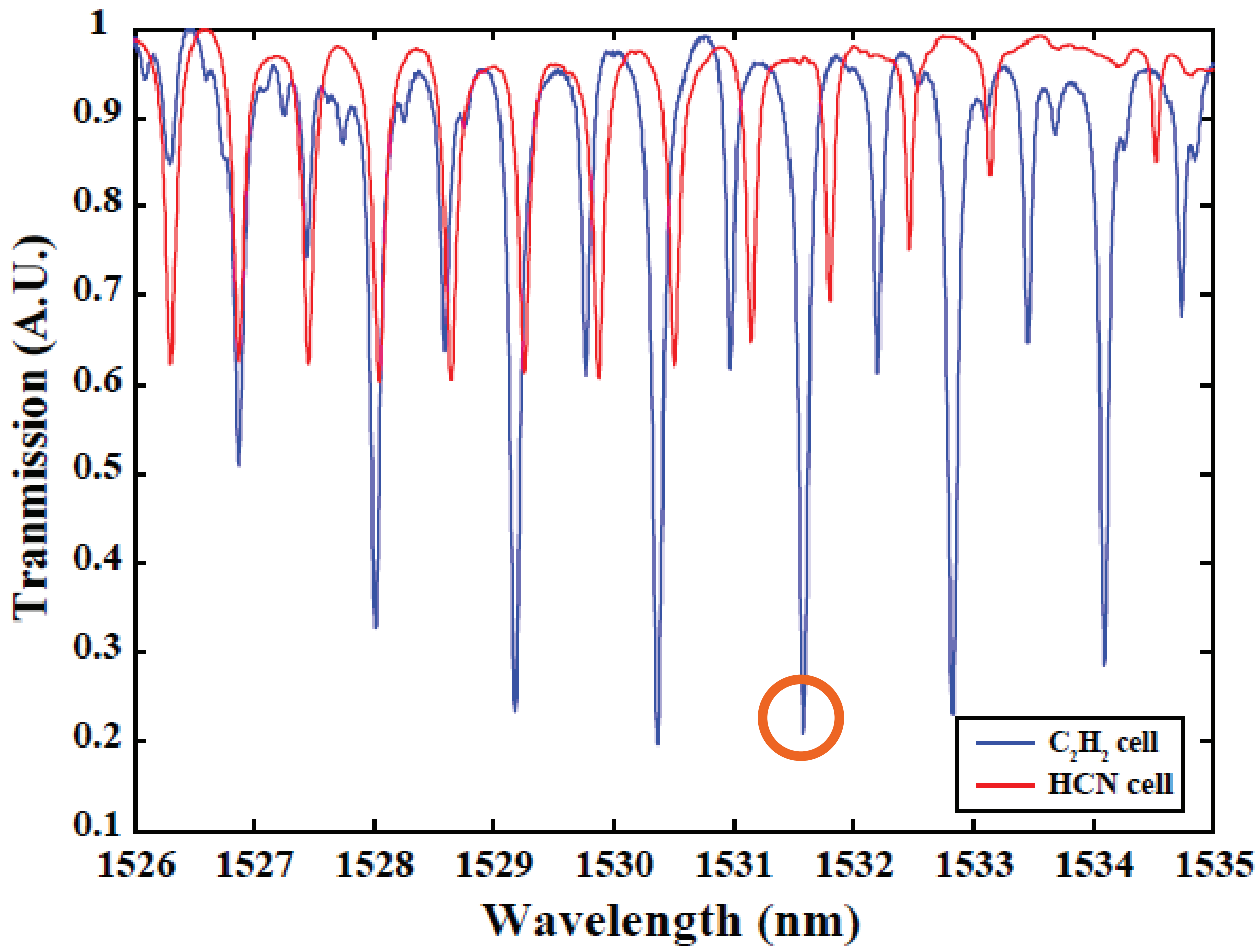
- Interference fringes



- 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.

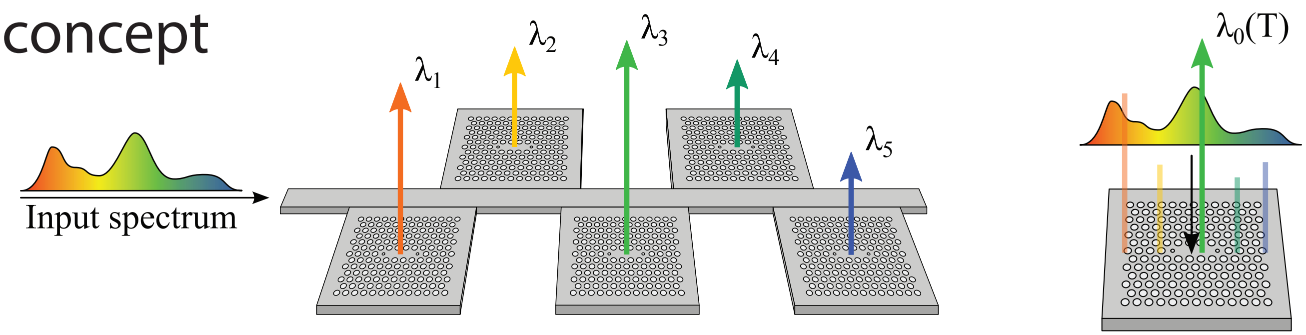
Challenge: Fabricate a chip-scale spectrometer that can discriminate acetylene (H_2C_2) from hydrogen cyanide (HCN)?



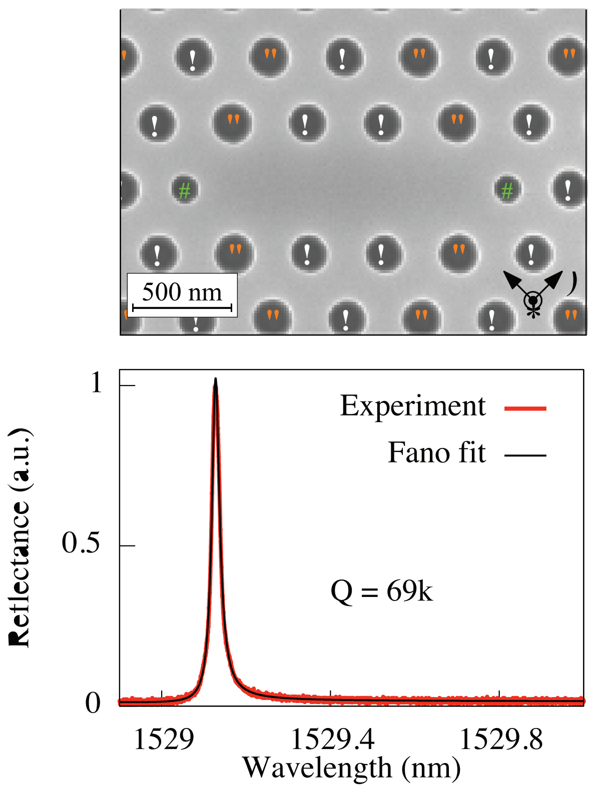
(data from our own lab)

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

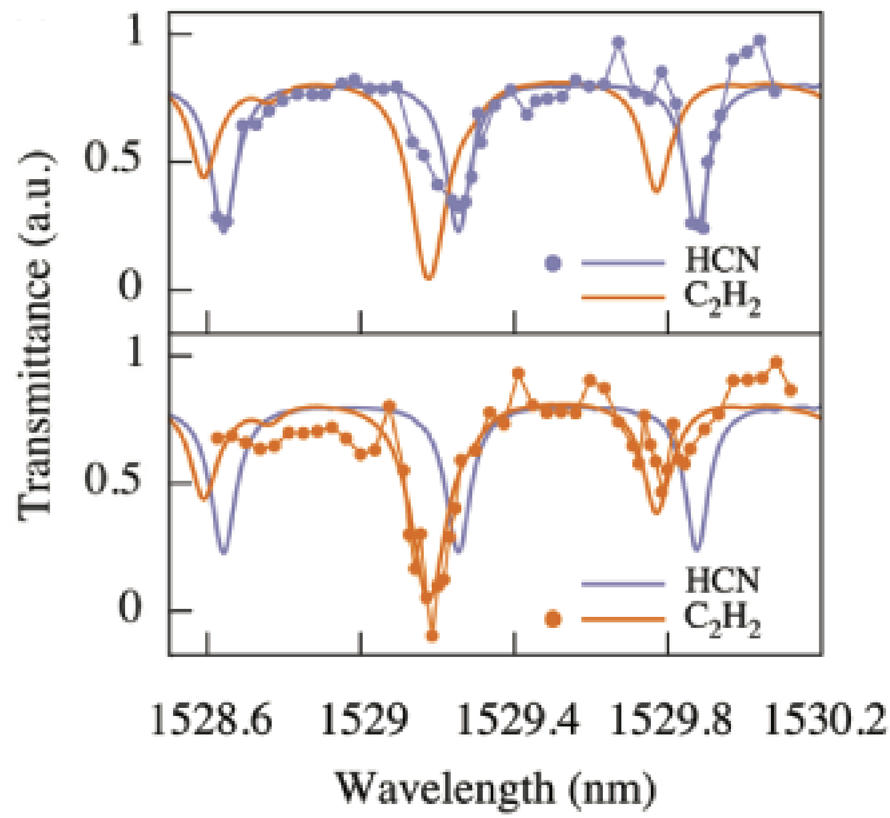
- The concept



- Cavity design



- Spectroscopy results



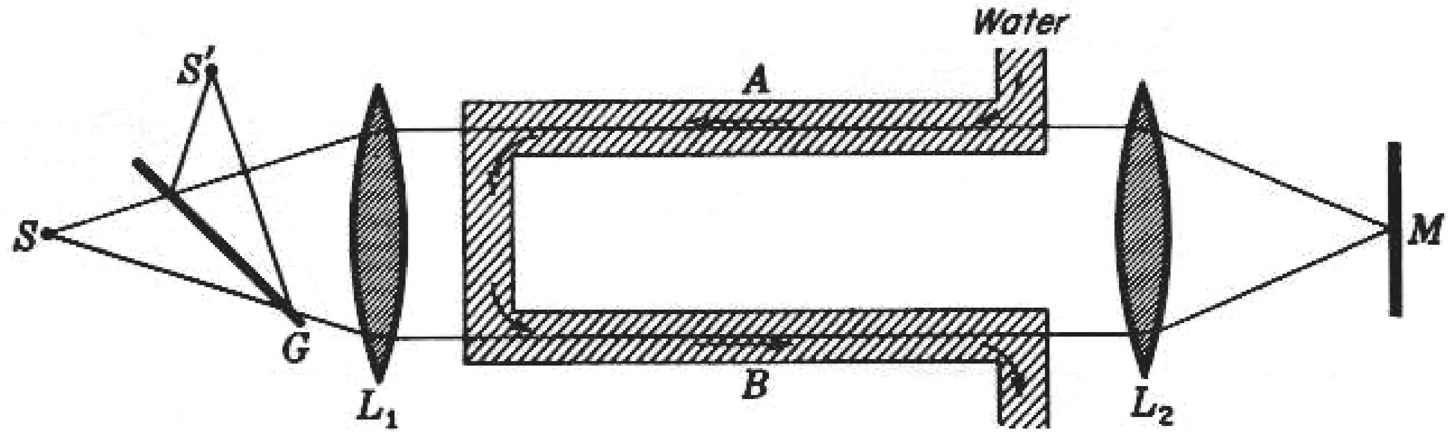
Liapis, Gao, Siddiqui, Shi, Boyd, Appl. Phys. Lett. 108, 021105 (2016).

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

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

Fresnel "drag" coefficient

- But what about slow-light media?

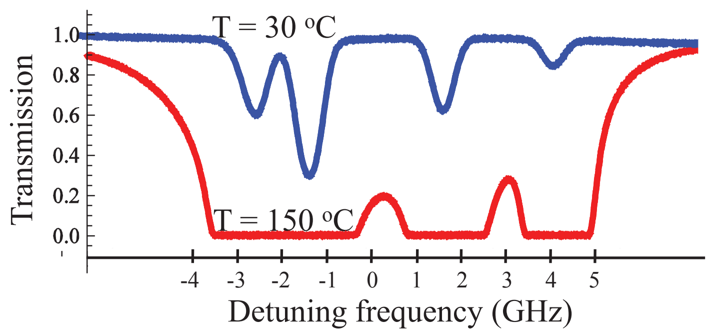
Fresnel Drag in a Highly Dispersive Medium

Light Drag in a Slow Light Medium (Lorentz)

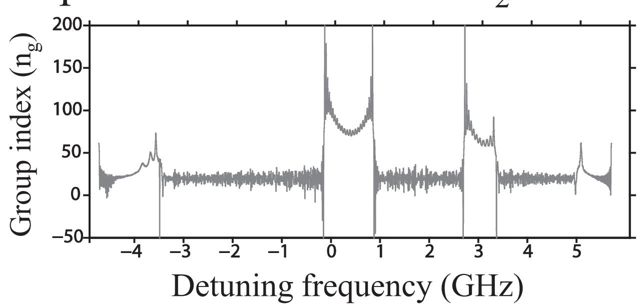
$$u \simeq \frac{c}{n} \pm v\left(1 - \frac{1}{n^2} + \frac{n_g - n}{n^2}\right)$$

We Use Rubidium as Our Slow Light Medium

- Transmission spectrum of Rb around D_2 transition:

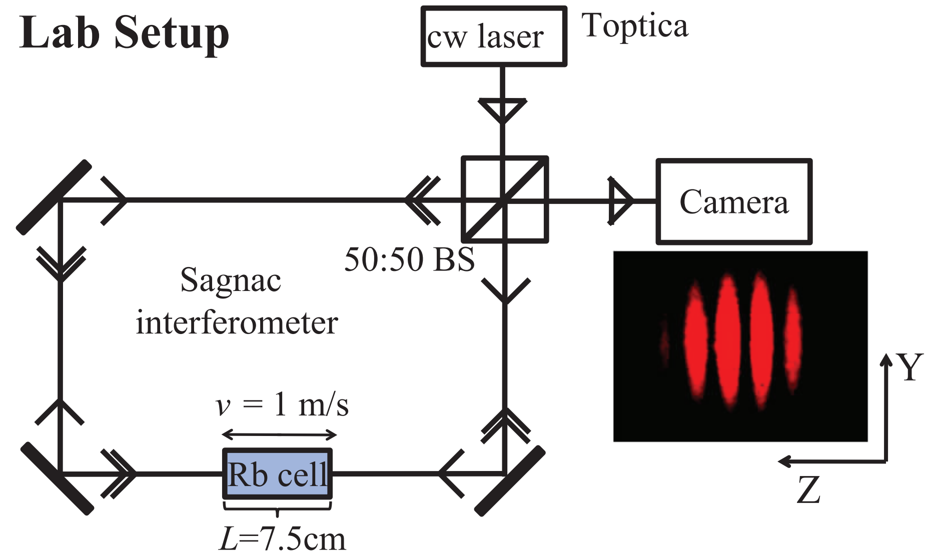


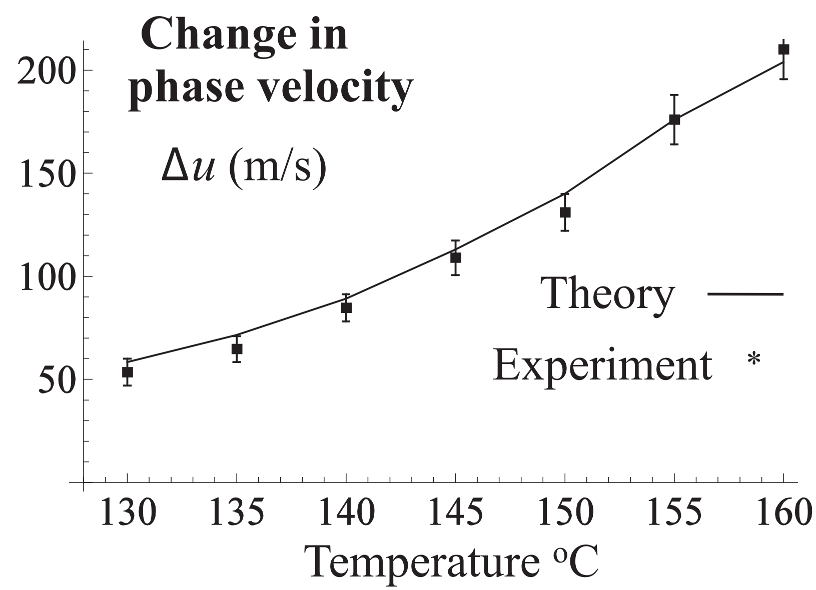
- Group index of Rb around D_2 line at T=130



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?**

Quantum Nonlinear Optics:
Nonlinear Optics Meets the Quantum World

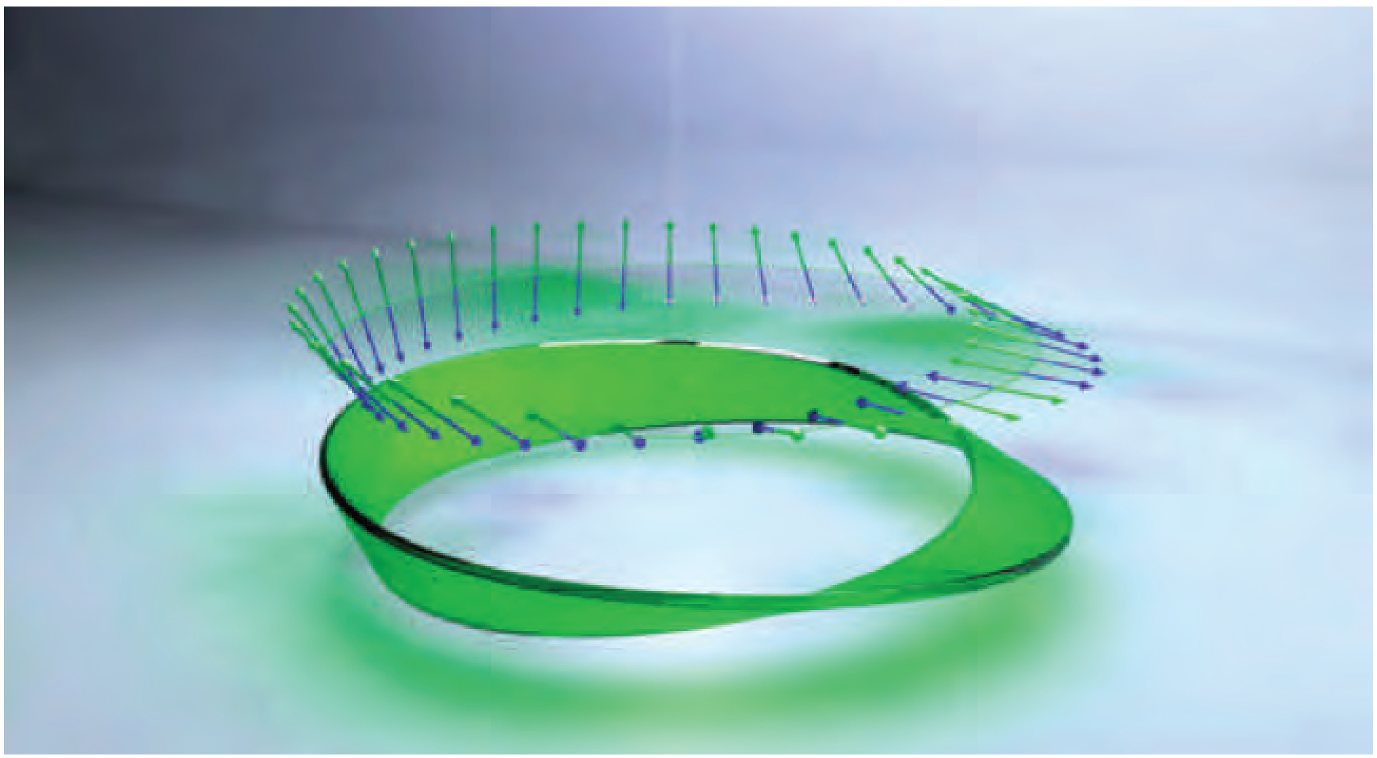
Outlook: NLO is a superb platform from which to explore new physical processes and to develop photonics applications.

Prospectus

1. Introduction to Nonlinear Optics and Quantum NLO
2. New Applications of “Slow Light”
3. Möbius Strips of Polarization
4. Quantum Communication with Multiple Bits per Photon

Observation of Optical Polarization Möbius Strips

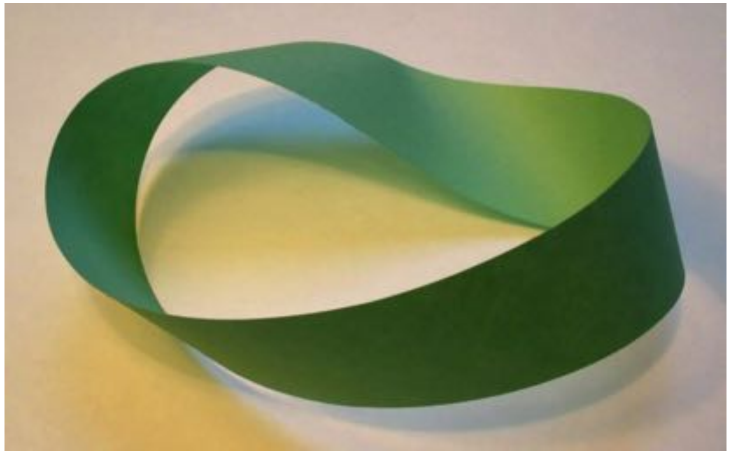
- Möbius strips are familiar geometrical structures, but their occurrence in nature is extremely rare.
- We generate such structures in the nanoscale in tightly focused vector light beams and confirm experimentally their Möbius topology.



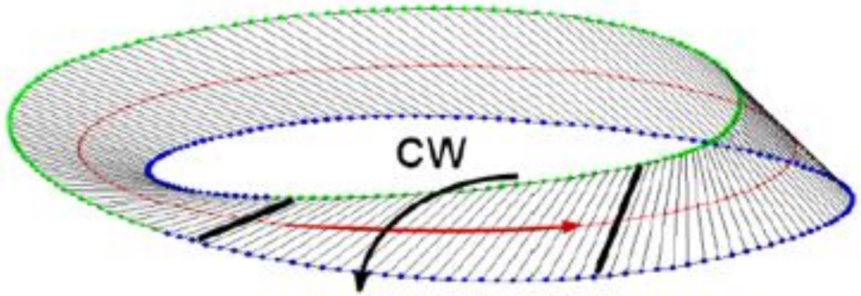
Bauer, Banzer, Karimi, Orlov, Rubano, Marrucci, Santamato, Boyd and Leuchs, Science, 347, 964 (2015)

Prediction of Optical Möbius Strips

An "ordinary" Möbius strip



A polarization Möbius strip
(introduced by Isaac Freund)



- Isaac Freund discovered, described, and investigated these unusual structures
- To observe these structures, one needs to create a very special field distribution (e.g., a Poincaré beam)
- One also needs to observe the field distribution in a very special way (measure polarization as a function of position around a very tightly focused light beam)

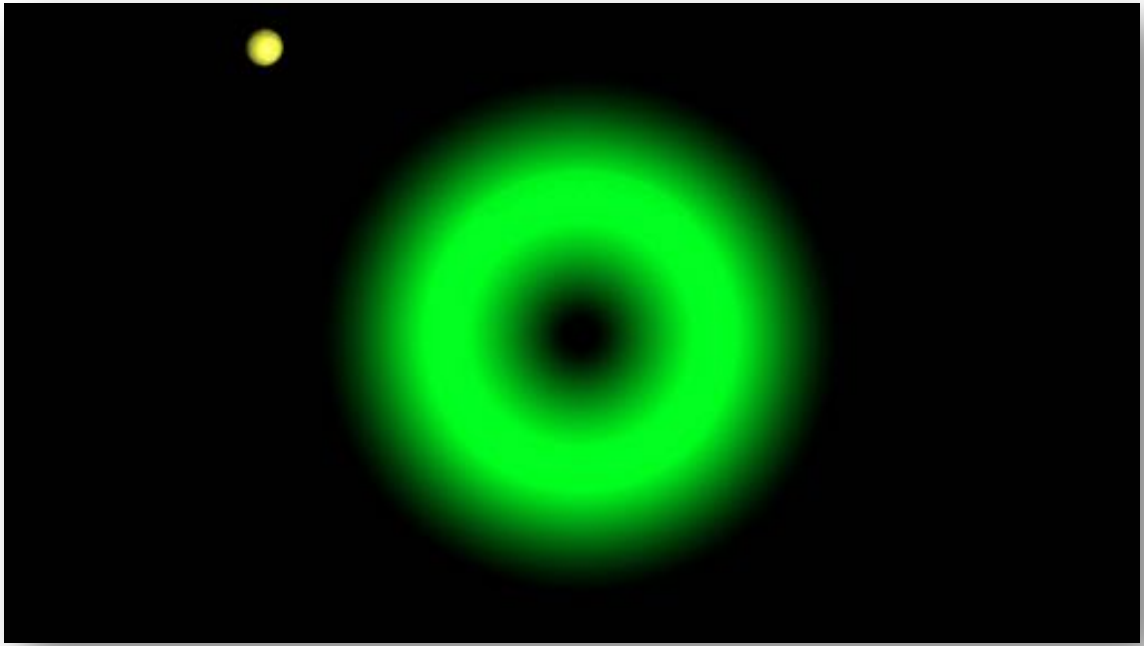
[1] Wikipedia
[2] Isaac Freund, Bar-Ilan Univ., Talk: *Optical Moebius Strips and Twisted Ribbons*, Conf. on Singular Optics, ICTP Trieste, Part II, 30 May 2011

Isaac Freund, Opt. Commun. 242, 65-78 (2004)
Isaac Freund, Opt. Commun. 249, 7-22 (2005)
Isaac Freund, Opt. Commun. 256, 220-241 (2005)
Isaac Freund, Opt. Commun. 283, 1-15 (2010)
Isaac Freund, Opt. Commun. 283, 16-28 (2010)
Isaac Freund, Opt. Lett. 35, 148-150 (2010)
Isaac Freund, Opt. Commun. 284, 3816-3845 (2011)

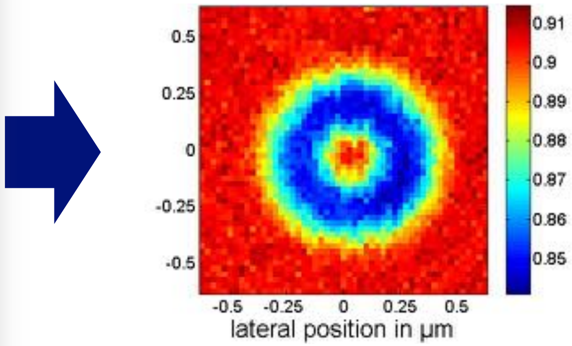
Full vectorial beam measurement on the nanoscale

Nanoparticle-based probing technique for vector beam reconstruction

1. A dipole-like spherical nanoparticle (90 nm diameter) is scanned through the beam
2. The forward- and backward-scattered light for each position of the nanoparticle relative to the beam in the focal plane is measured

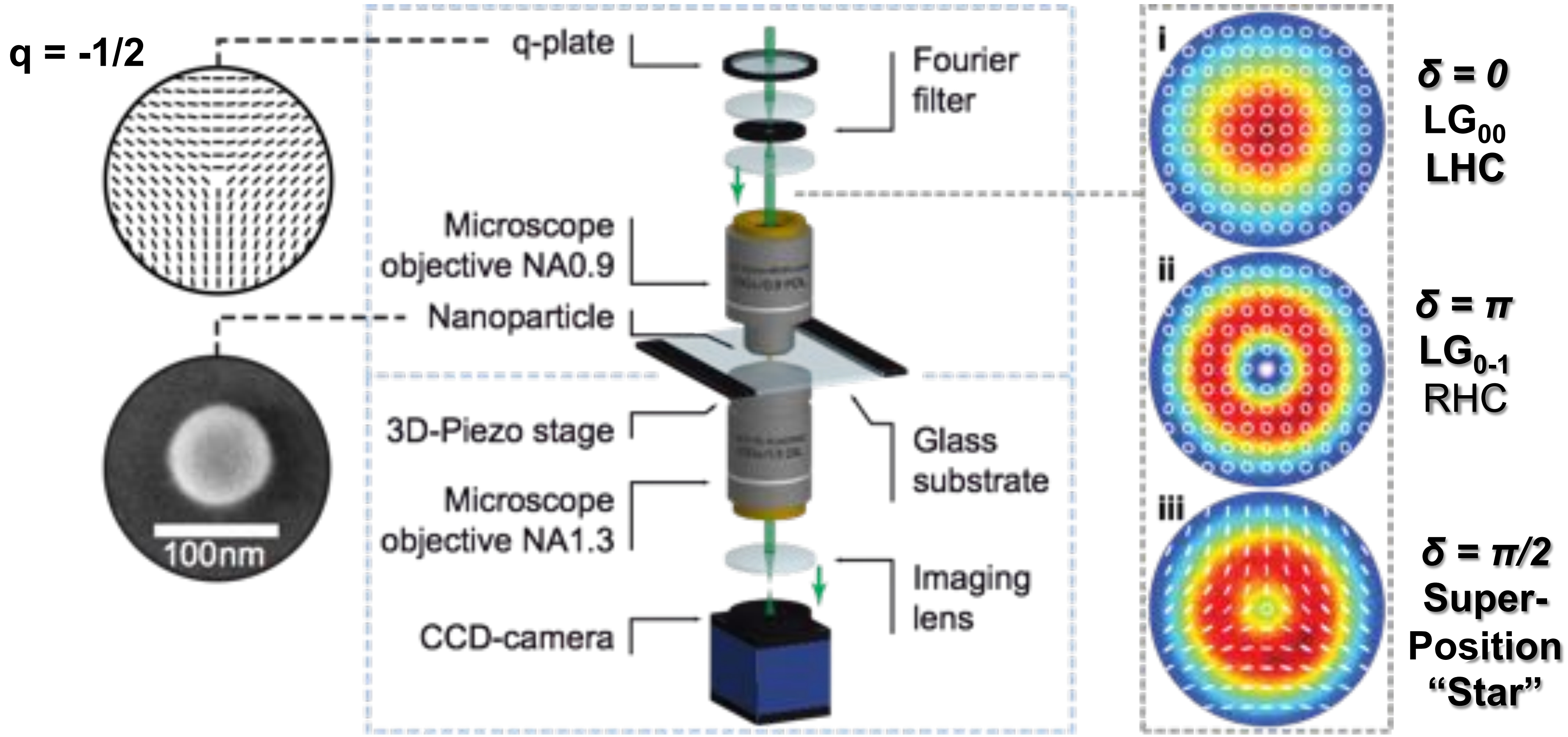


measured intensity (can also measure polarization and phase)



Full amplitude and phase reconstruction scheme:
T. Bauer, S. Orlov, U. Peschel, P. B. and G. Leuchs, "Nanointerferometric Amplitude and Phase Reconstruction of Tightly Focused Vector Beams", Nat. Photon 8, 23 - 27 (2014).

Lab Setup to Observe a Polarization Möbius Strip



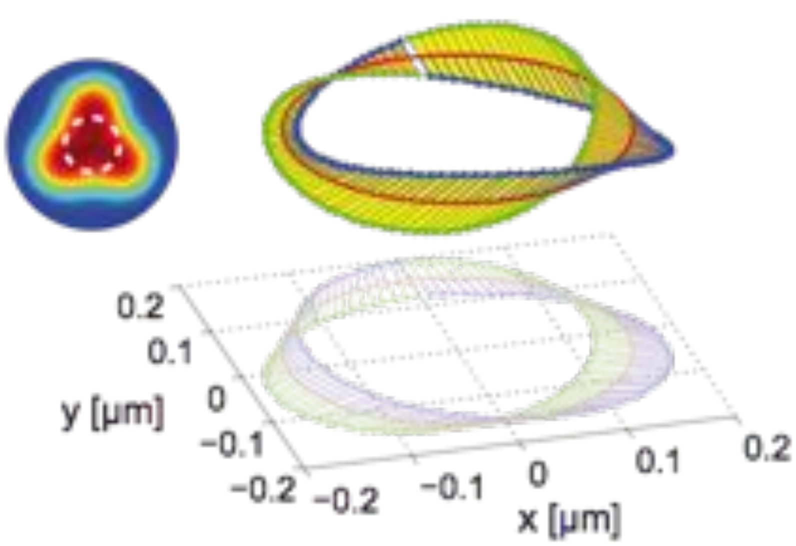
- q-plate: waveplate with a spatially varying orientation (q is the topological charge)
- output beam has a spatially varying state of polarization (vector beam, Poincaré beam, etc.)

Tight focusing enhances the Möbius effect,which depends on the z component of the field

Observation of Polarization Möbius Strips

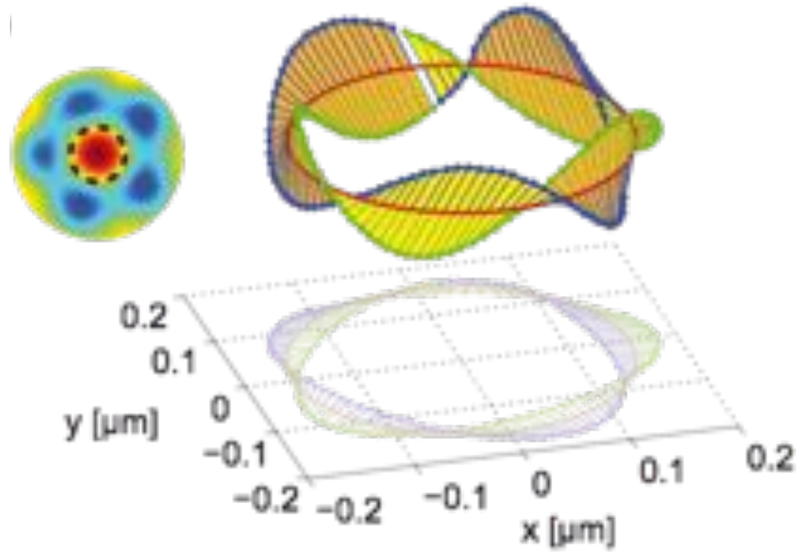
q =-1/2

3/2 twists



q = -3/2

5/2 twists



structure possesses |q|+1 half twists

Remarks

- First observation of a polarization Möbius strip
- Light fields can possess rich spatial structure on subwavelength scales
- Current technology is capable of controllably creating beams with such structures and measuring it at subwavelength distances.

Bauer T, Banzer P, Karimi E, Orlovas S, Rubano A, Marrucci L, Santamato E, Boyd RW, and Leuchs G. Science, 2015.

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

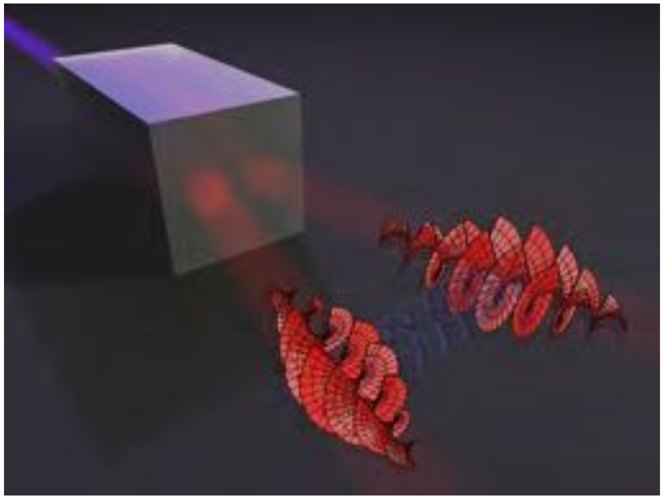
1. Introduction to Nonlinear Optics and Quantum NLO
2. New Applications of "Slow Light"
3. Möbius Strips of Polarization
4. Quantum Communication with Multiple Bits per Photon

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

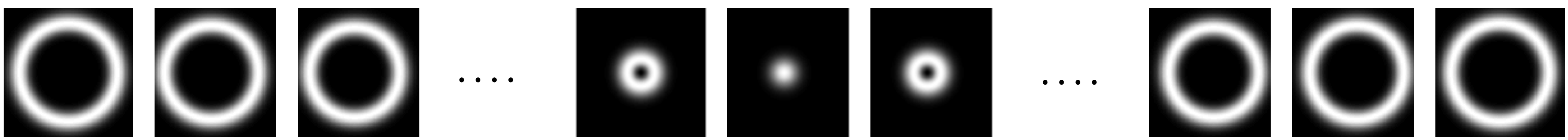
We are constructing a QKD system in which each photon carries many bits of information

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

We also need a second basis composed of linear combinations of these states

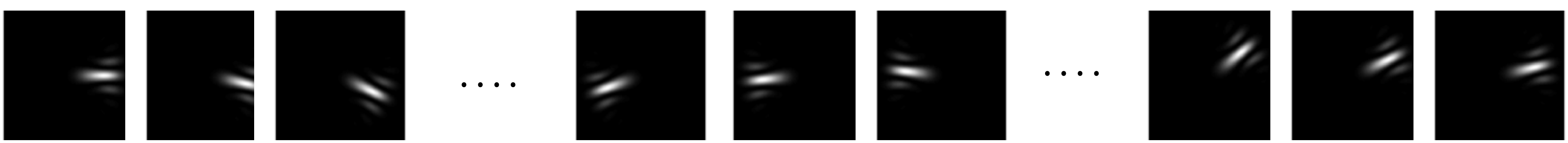
<u>Single Photon States</u>

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



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

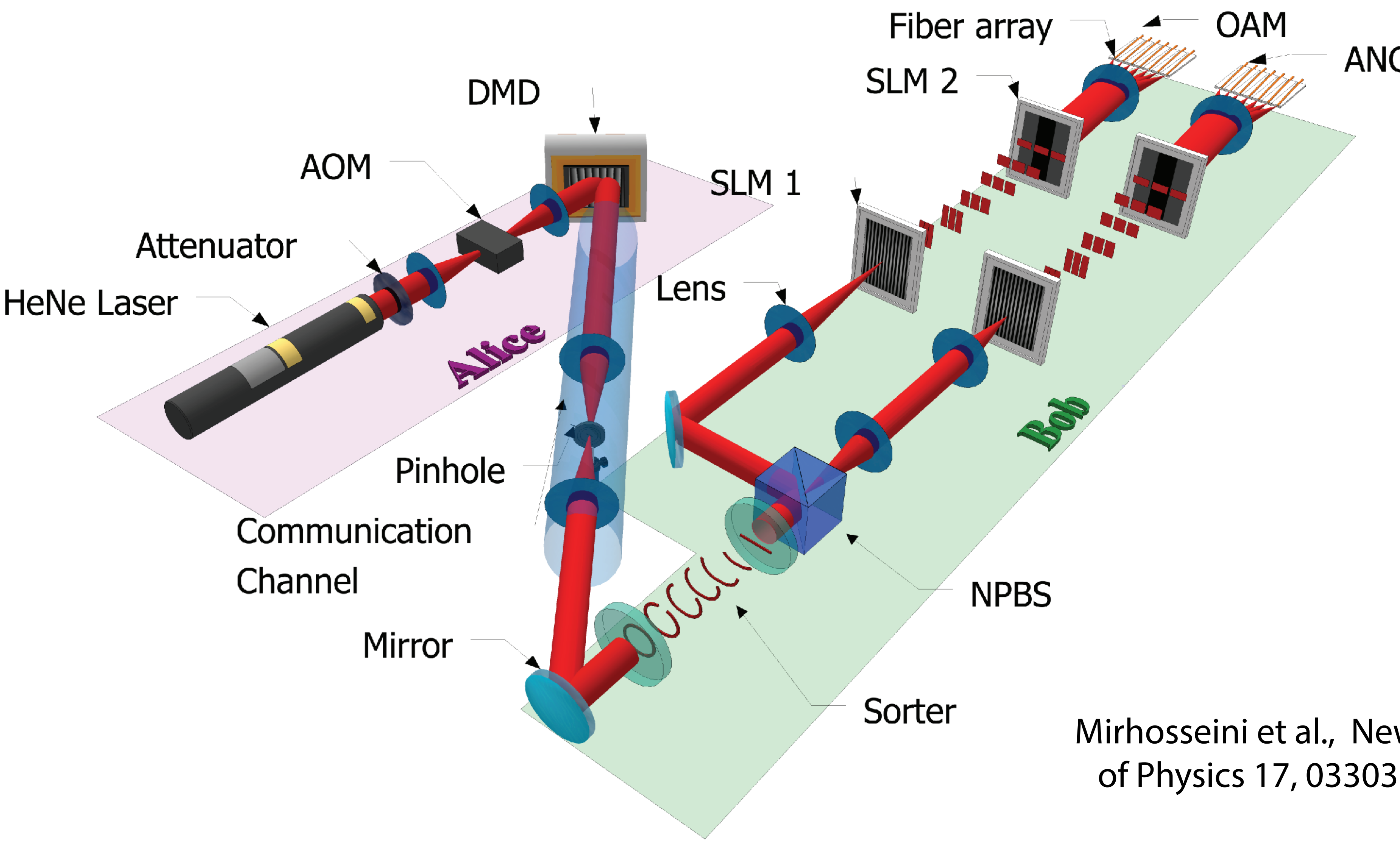
"Angular" Basis (mutually unbiased with respect to LG)



0 1 2 .... 12 13 14 .... 25 26 27

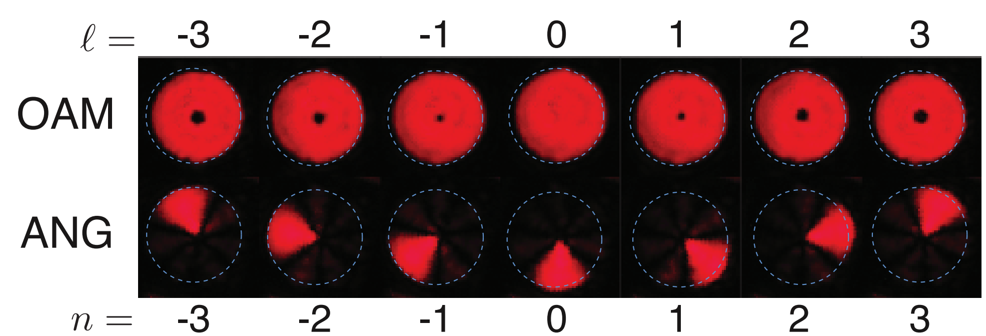
$$\Psi_{\mathrm{AB}}^{N} = \frac{1}{\sqrt{27}} \sum_{l=-13}^{13} \mathrm{LG}_{l,0} \exp\left(i 2\pi N l / 27\right)$$

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

06313360213204544445614102664 5
54505036360302526164321552416 4
23014660251340161322245155102 6

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

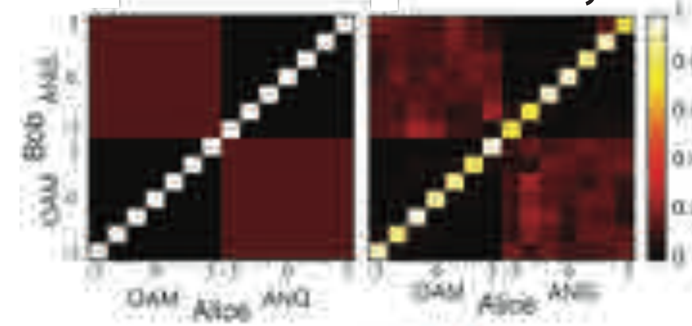
0001 0100 1011 1111 1111 1010 1010 0111 1010 1011 1111 0001 0000 1101 1111
1110 1110 1101 1110 0001 0011 1000 0101 1101 1100 0011 0111 1101 0001 1001
0100 0110 1011 0000 0110 1010 1

Alice Encrypts

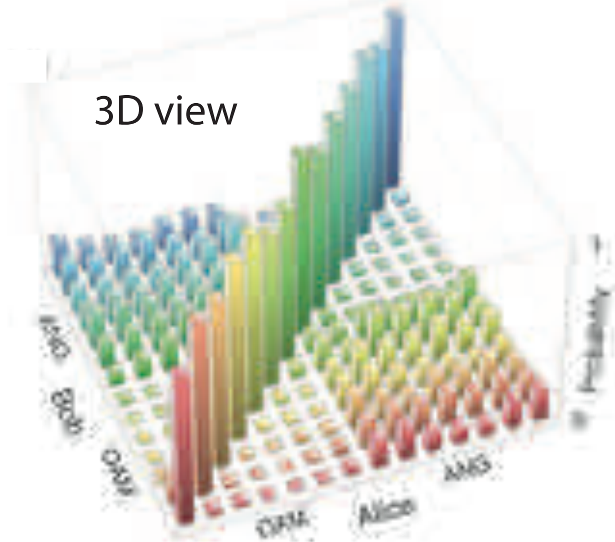
Bob Decrypts

cross-talk matrices

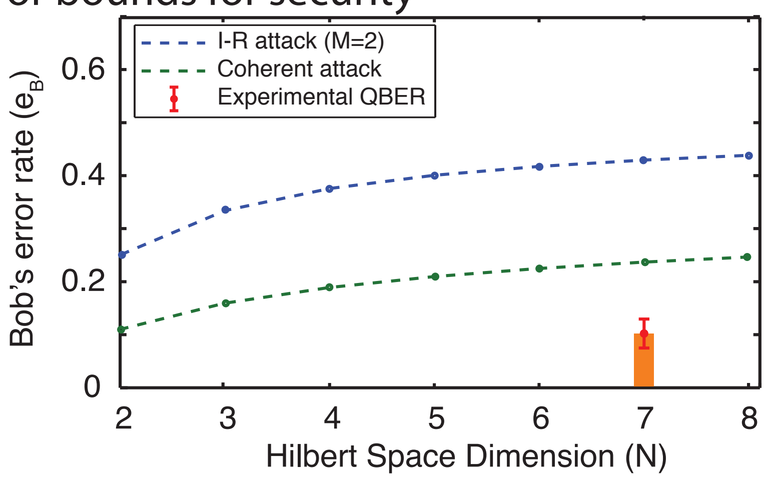
ideal laboratory



3D view



- 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,

Quantum Nonlinear Optics:
Nonlinear Optics Meets the Quantum World

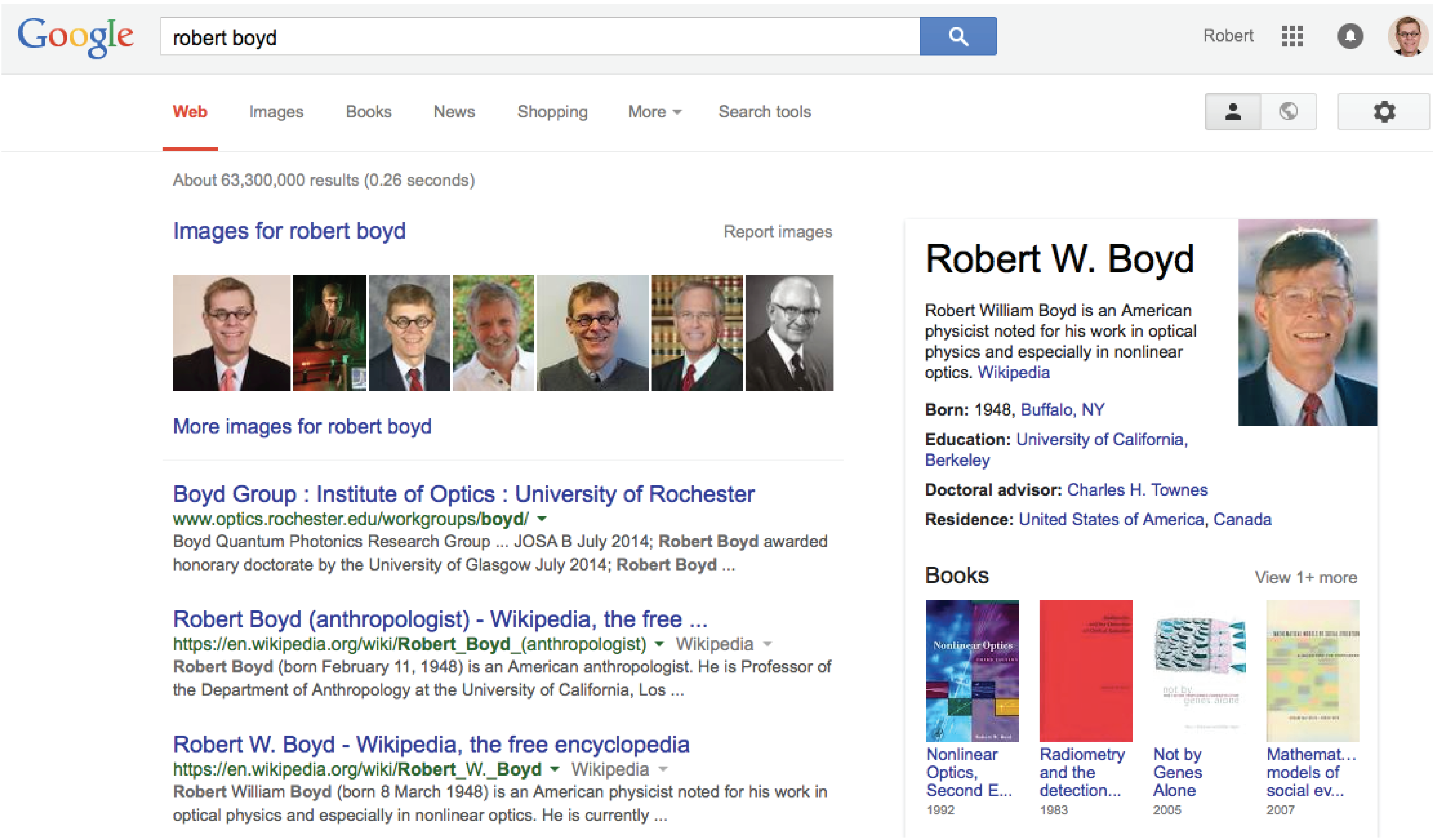
Summary: NLO is a superb platform from which to explore new physical processes and to develop photonics applications.

Prospectus

1. Introduction to Nonlinear Optics and Quantum NLO
2. New Applications of “Slow Light”
3. Möbius Strips of Polarization
4. Quantum Communication with Multiple Bits per Photon

Thank you for your attention!

Why We Shouldn't Always Trust Google



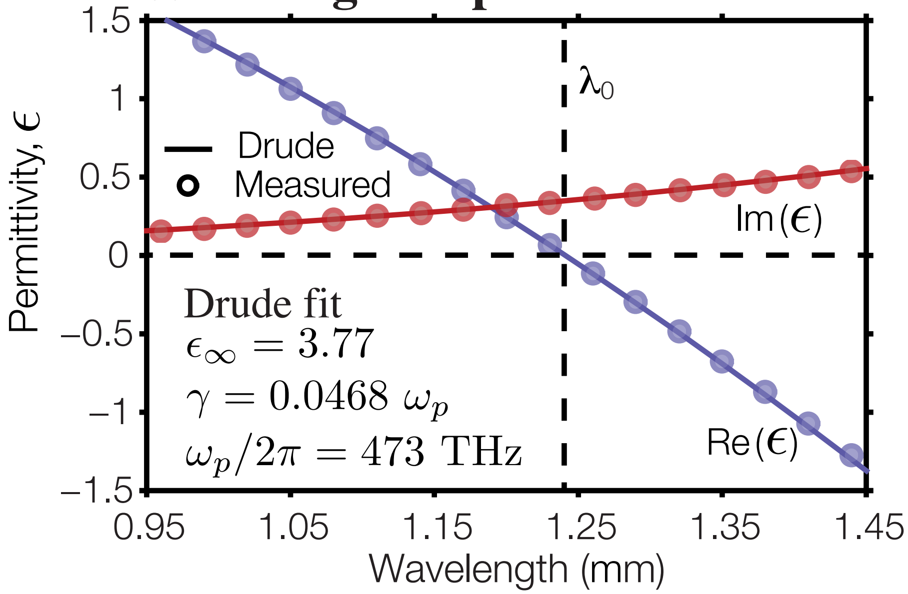
Huge Nonlinear Optical Response of ITO near its Epsilon-Near-Zero Wavelength

Indium Tin Oxide (ITO) displays enormously strong NLO properties:

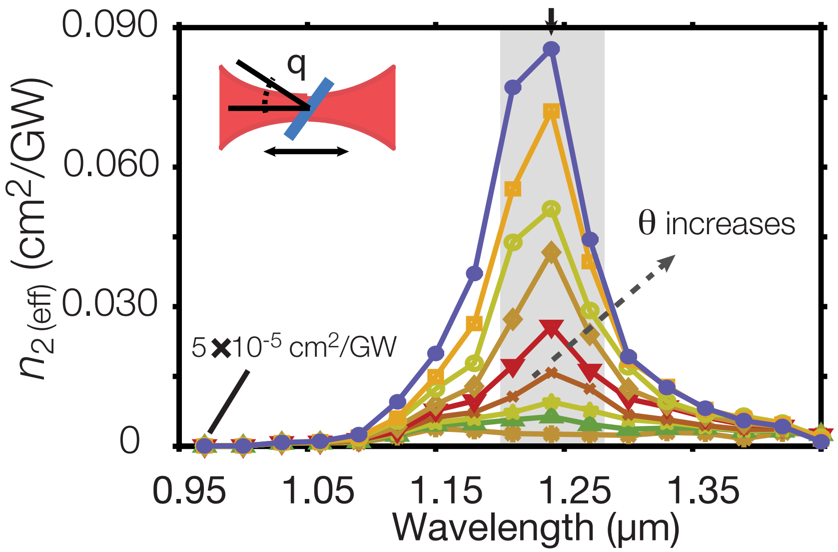
- n_2 is 2.5 x 10^5 times that of fused silica
- nonlinear change in refractive index as large as 0.8
- response time of 270 fs

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

Wavelength dependence of ε



Wavelength dependence of n_2



Some possible new effects

- Waveguiding outside the “weakly-guiding” regime
- Efficient all-optical switching
- No need for phase-matching

Alam, De Leon, Boyd