



Quantum Nonlinear Optics: Nonlinear Optics Meets the Quantum World

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March 4, 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

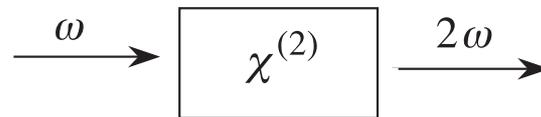
Simple Formulation of the Theory of Nonlinear Optics

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

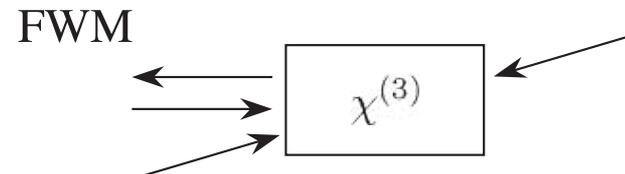
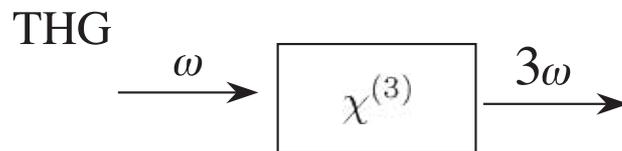
Here P is the induced dipole moment per unit volume and E is the field amplitude

$\chi^{(1)}$ 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.



NL index

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

Intense Field and Attosecond Physics

PHYSICAL REVIEW LETTERS

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13 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⁾

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(Received 2 December 1992)

VOLUME 71, NUMBER 13

PHYSICAL REVIEW LETTERS

27 SEPTEMBER 1993

Plasma Perspective on Strong-Field Multiphoton Ionization

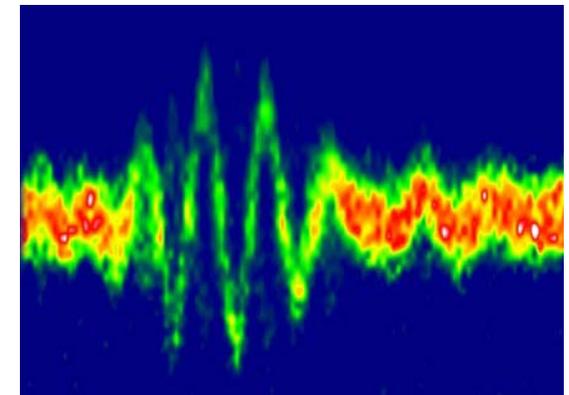
P. B. Corkum

National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6

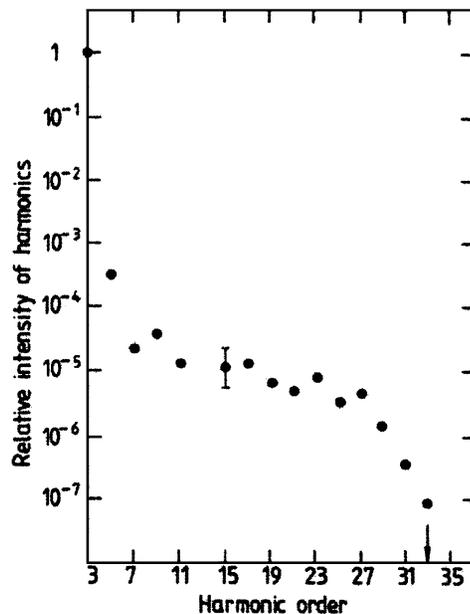
(Received 9 February 1993)



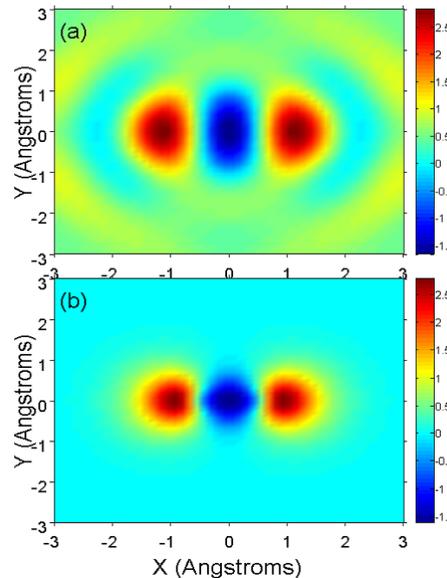
$$I > 10^{15} \text{ W/cm}^2$$



Attosecond pulses to sample a visible E-field



High-harmonic generation



Measuring the molecular nitrogen wavefunction



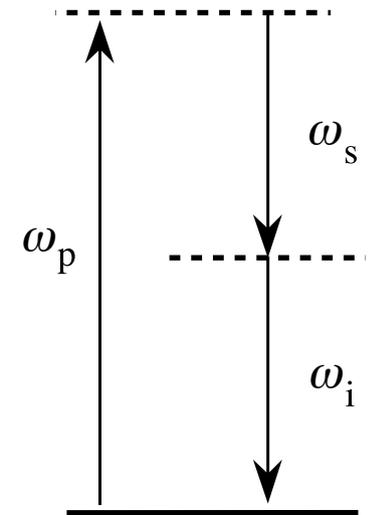
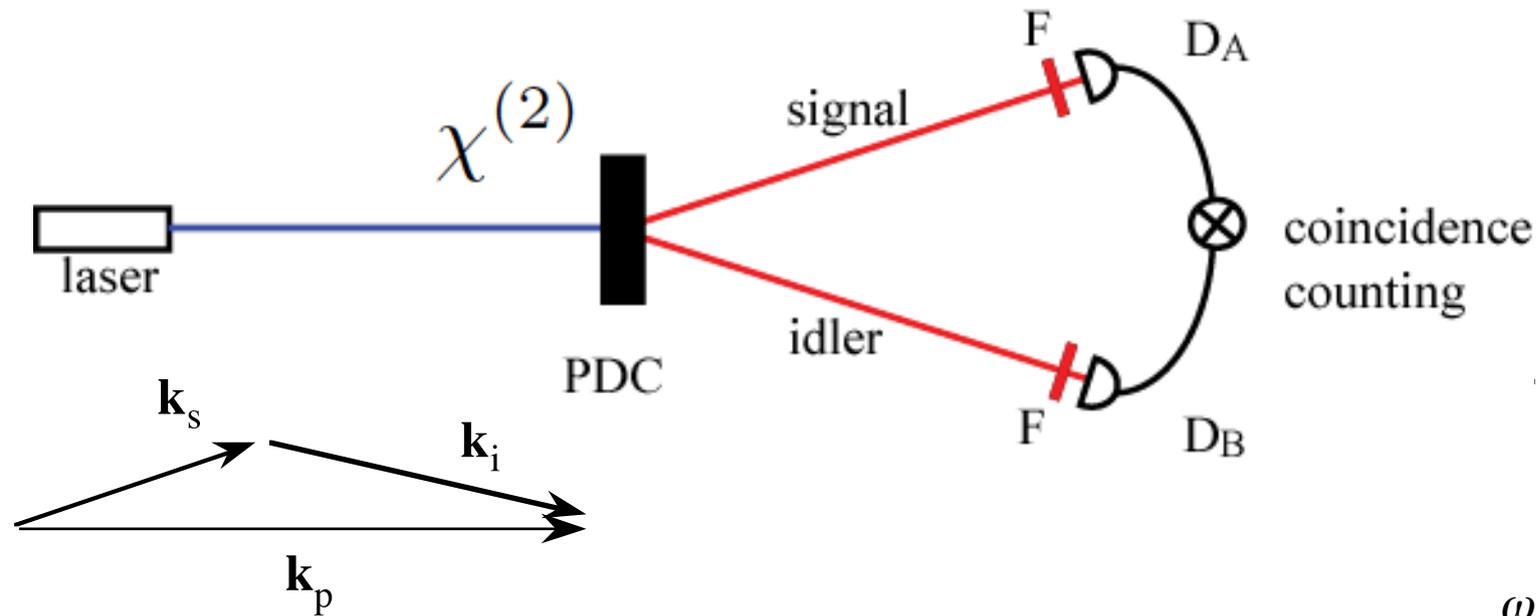
Why Interest in Quantum Nonlinear Optics?

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



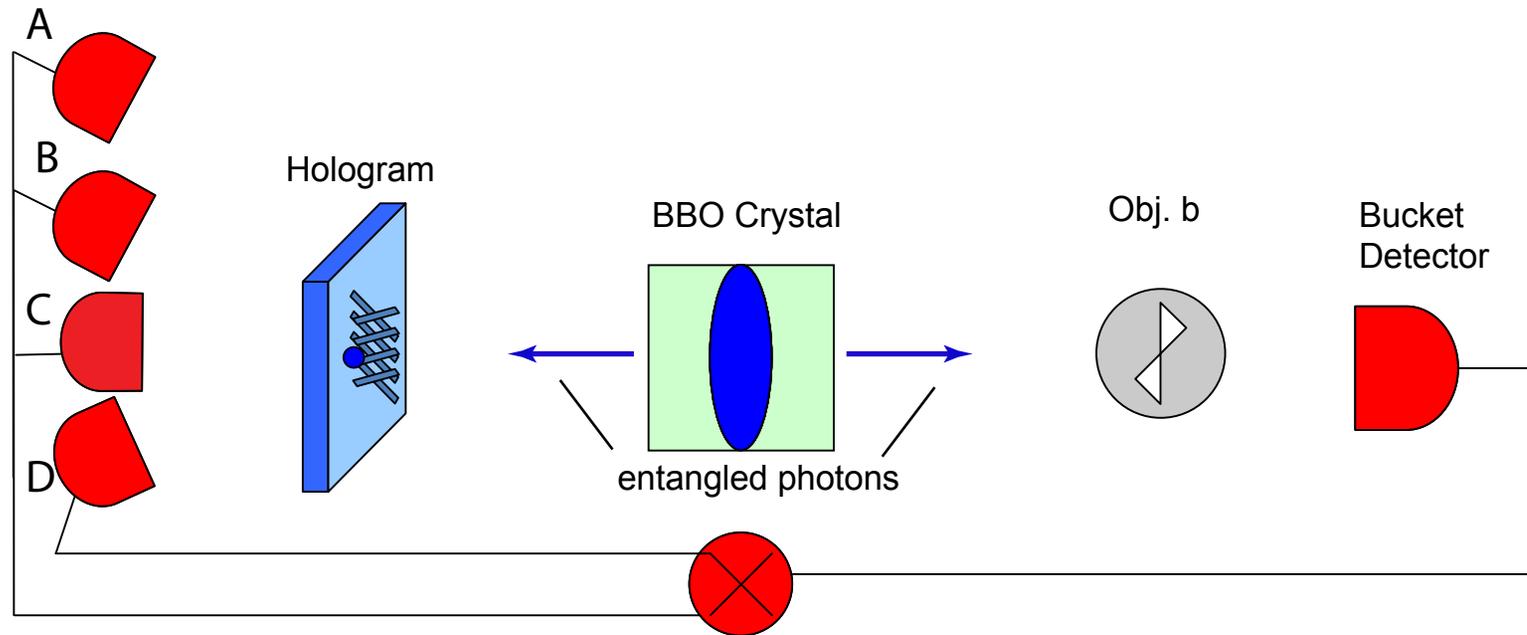
The signal and idler photons are entangled in:

- (a) polarization
- (b) time and energy
- (c) position and transverse momentum
- (d) angular position and orbital angular momentum

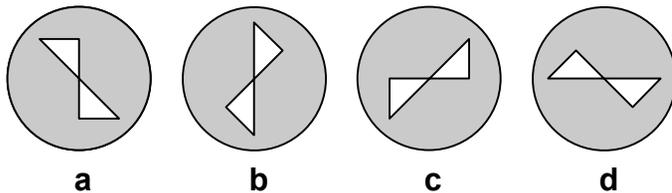
Entanglement is important for:

- (a) Fundamental tests of QM (e.g., nonlocality, Bell tests)
- (a) Quantum technologies (e.g., secure communications, Q teleportation)

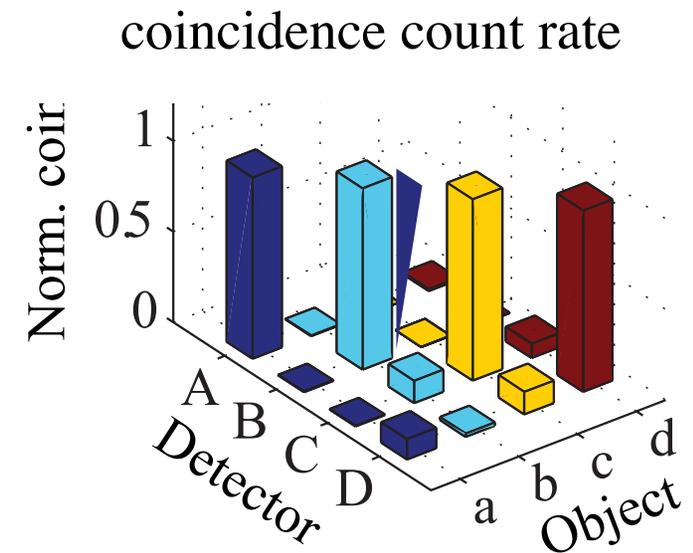
Single-Photon Coincidence Imaging



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



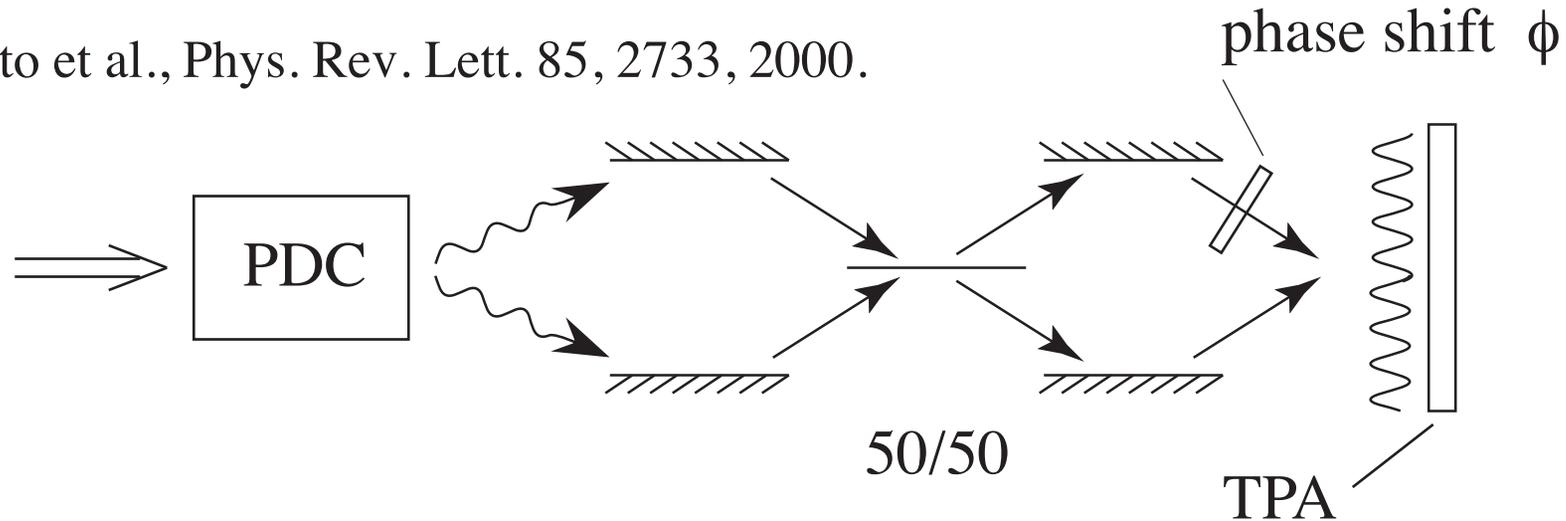
- Note that a single photon can carry more than one bit of information.



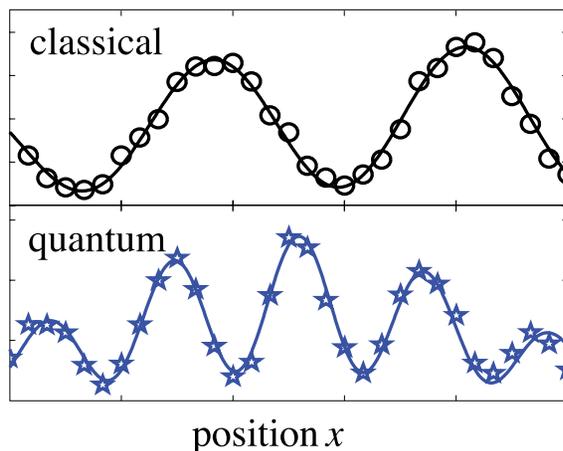
Quantum Lithography: Concept of Jonathan Dowling

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

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



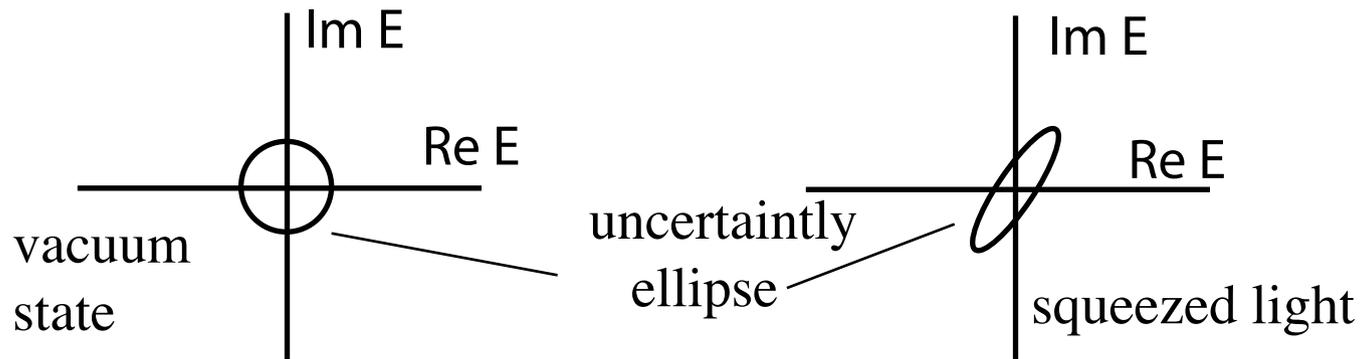
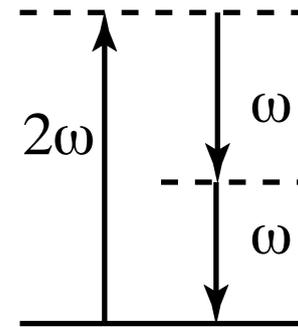
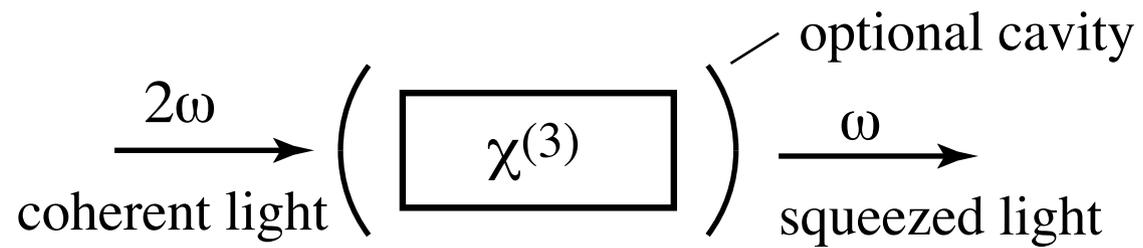
- No practical implementation to date, but some laboratory results



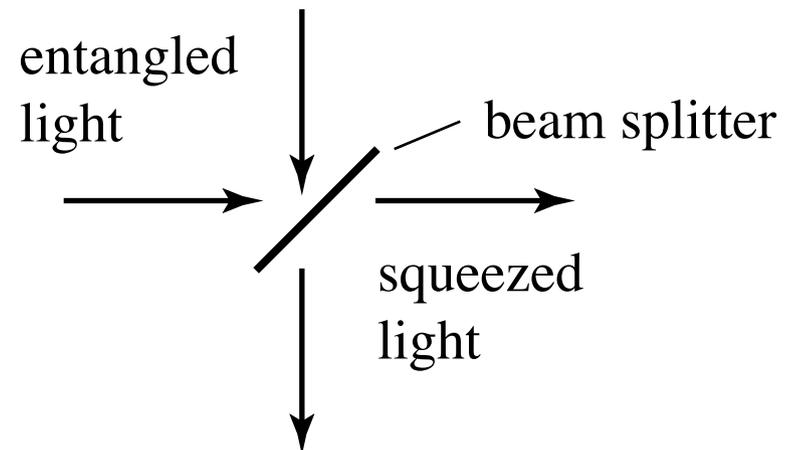
Quantum spatial superresolution by optical centroid measurements, Shin, Chan, Chang, and Boyd, Phys. Rev. Lett. 107, 083603 (2011).

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

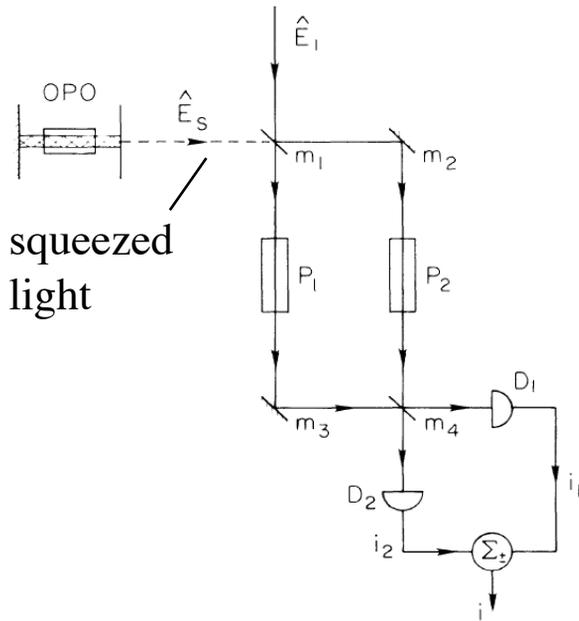
Squeezed Light Generation



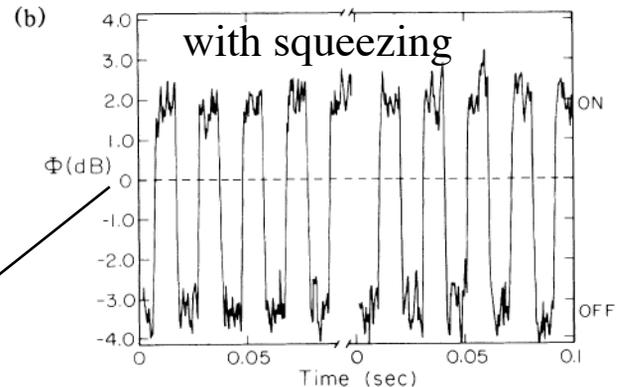
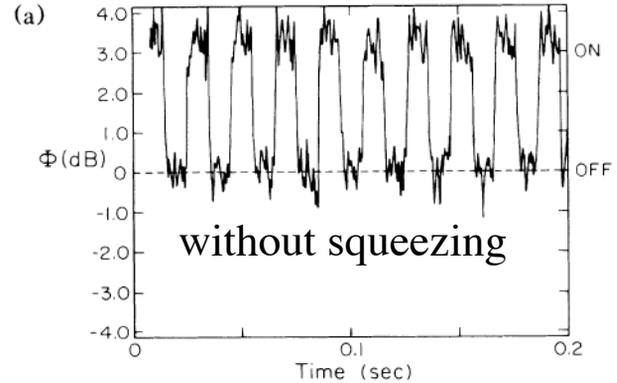
Entanglement and squeezing share a common origin:



Precision Measurement beyond the Shot-Noise Limit



shot-noise limit =
standard quantum limit



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

(See also Slusher, Hollberg, Yurke, Mertz, and Valley, Phys. Rev. Lett. 55, 2409, 1985)

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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

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Controlling the Velocity of Light

“Slow,” “Fast” and “Backwards” Light

– Light can be made to go:

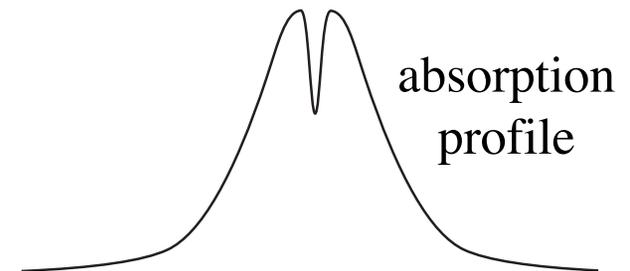
slow: $v_g \ll c$ (as much as 10^6 times slower!)

fast: $v_g > c$

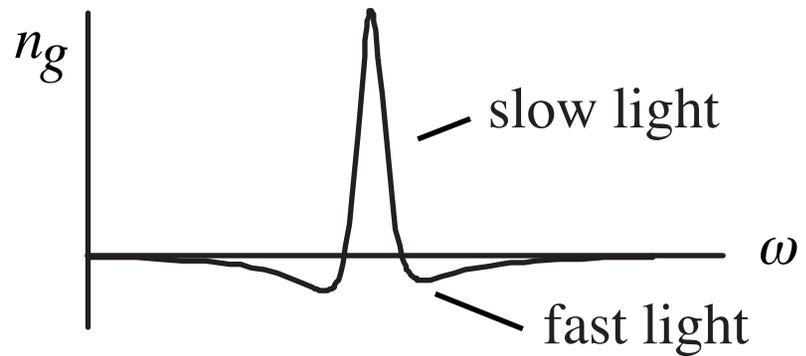
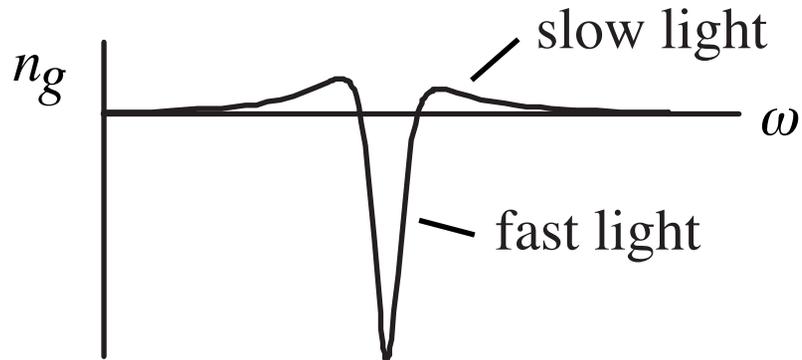
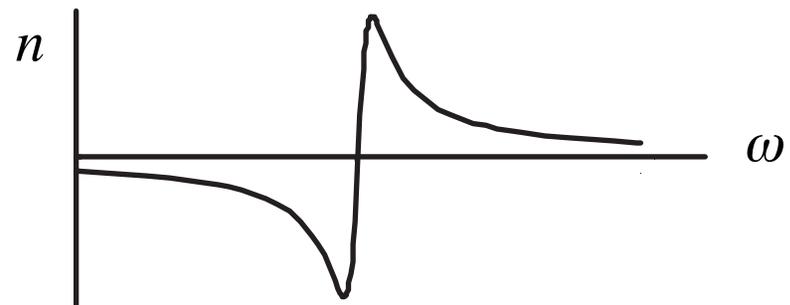
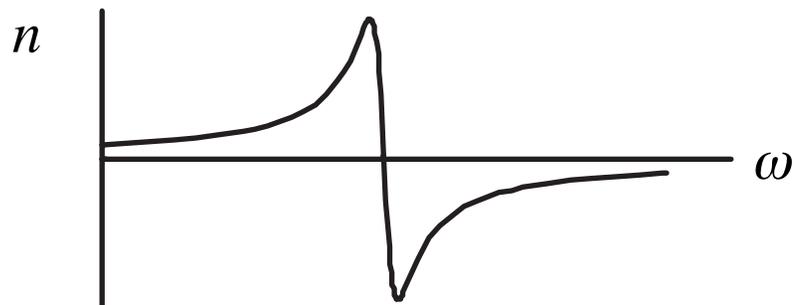
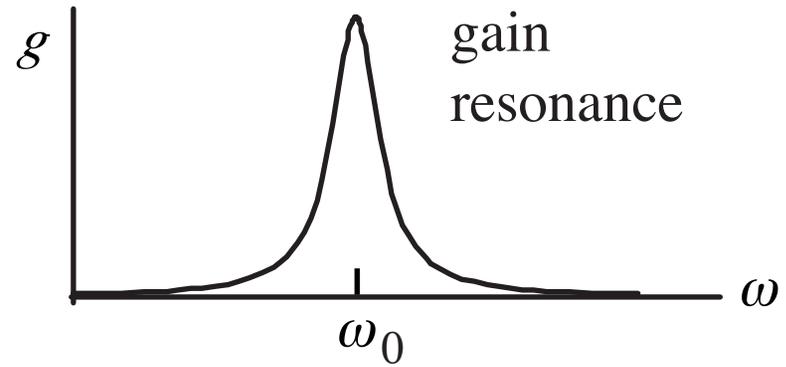
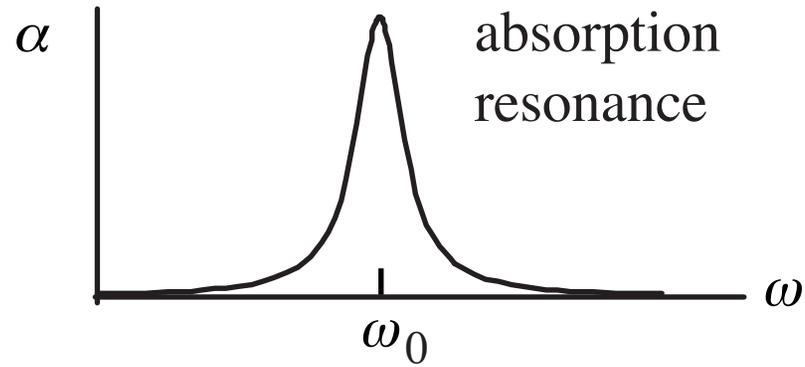
backwards: v_g negative

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



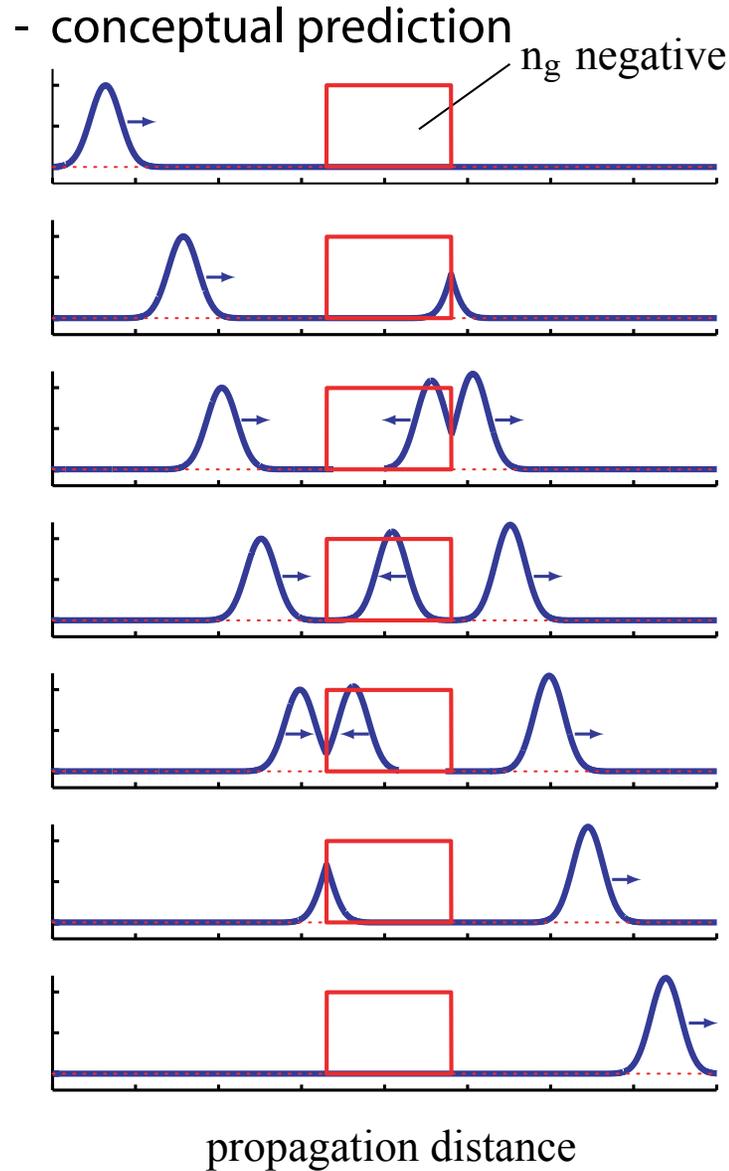
Slow and Fast Light Using Isolated Gain or Absorption Resonances



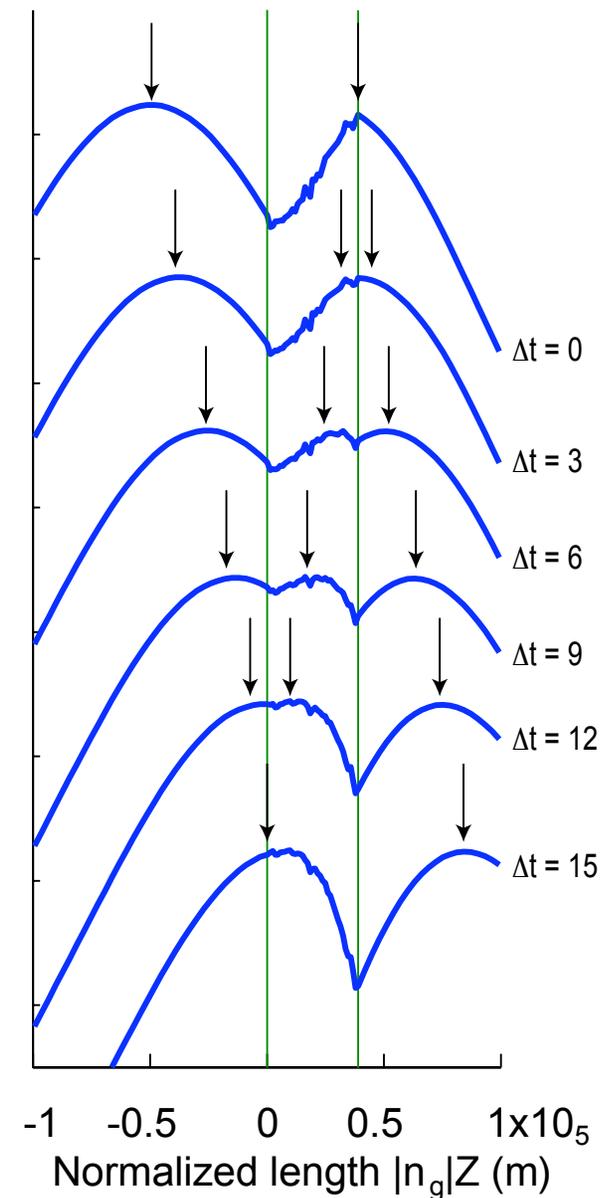
$$n_g = n + \omega (dn/d\omega)$$

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.



- laboratory results

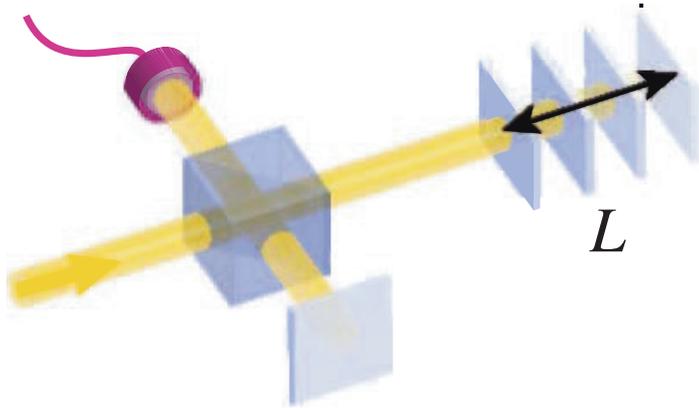


Development of Miniaturized, Chip-Scale Spectrometers

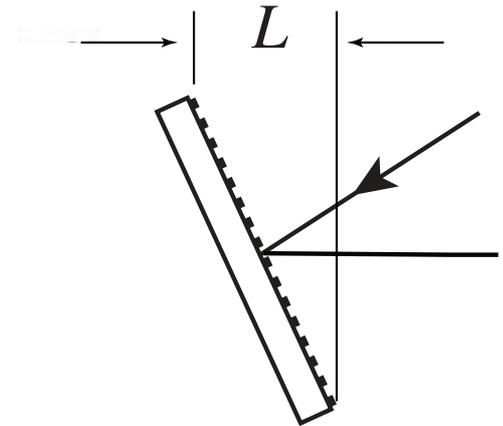
Can We Beat the $1/L$ Resolution Limit of Standard Spectrometers?

- 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



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

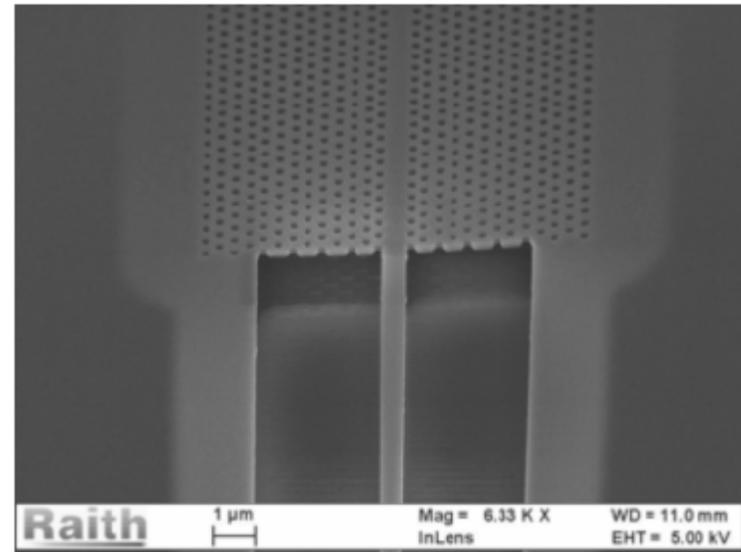
- We use slow-light methods to design spectrometers with resolution that exceeds this conventional limit by a factor as large as the group index.
- This ability allows us to miniaturize spectrometers with no loss of resolution, for “lab-on-a-chip” applications.

Our Goal

Replace this:



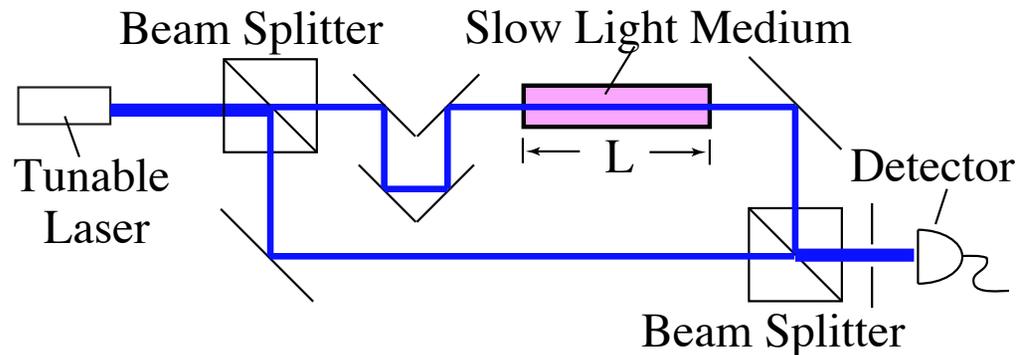
with this:



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 resolution as large laboratory spectrometers
- Here is why it works:

Slow-light interferometer:

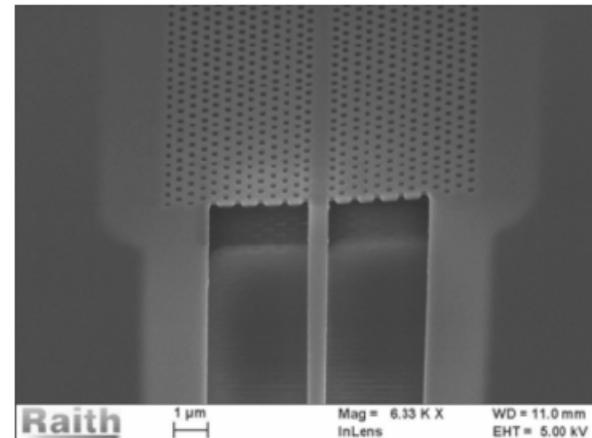


Simple analysis

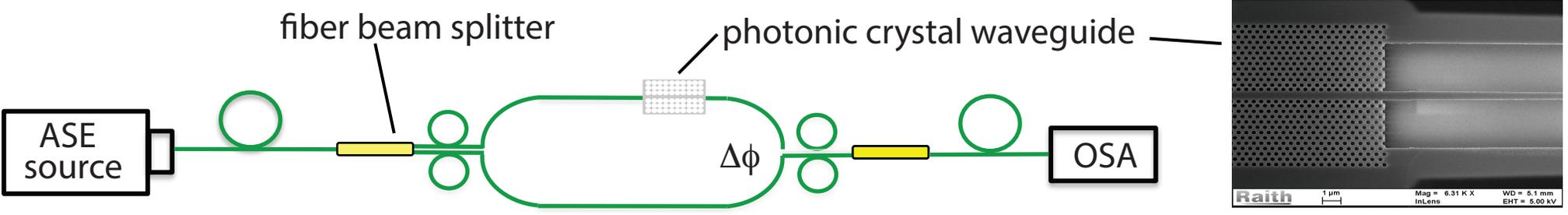
$$\frac{d \Delta\phi}{d\omega} = \frac{d}{d\omega} \frac{\omega n L}{c} = \frac{L}{c} \left(n + \omega \frac{dn}{d\omega} \right) = \frac{L n_g}{c}$$

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

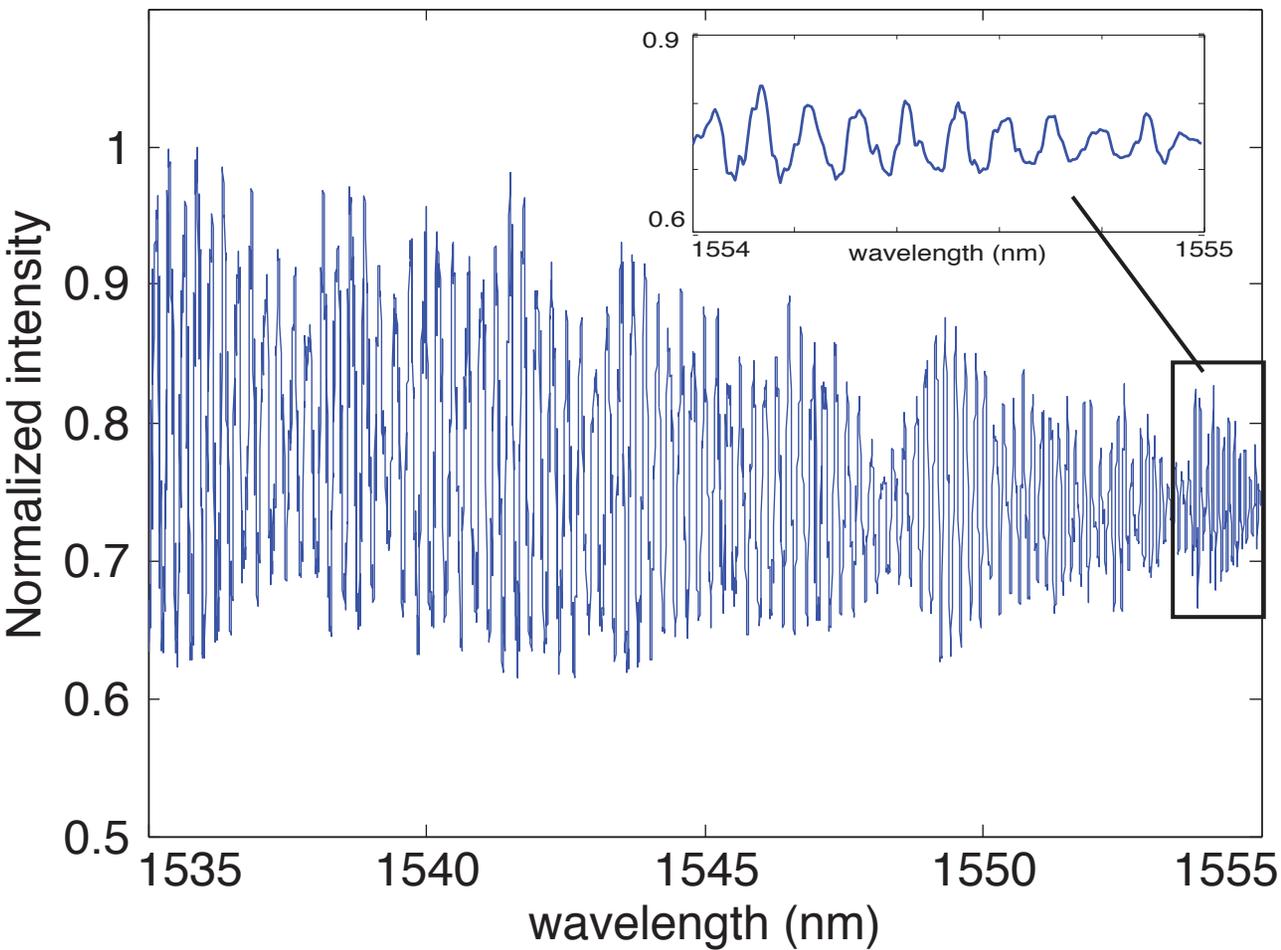
Slow-down factors of greater than 100 have been observed in such structures.



Laboratory Characterization of the Slow-Light Mach-Zehnder Interferometer



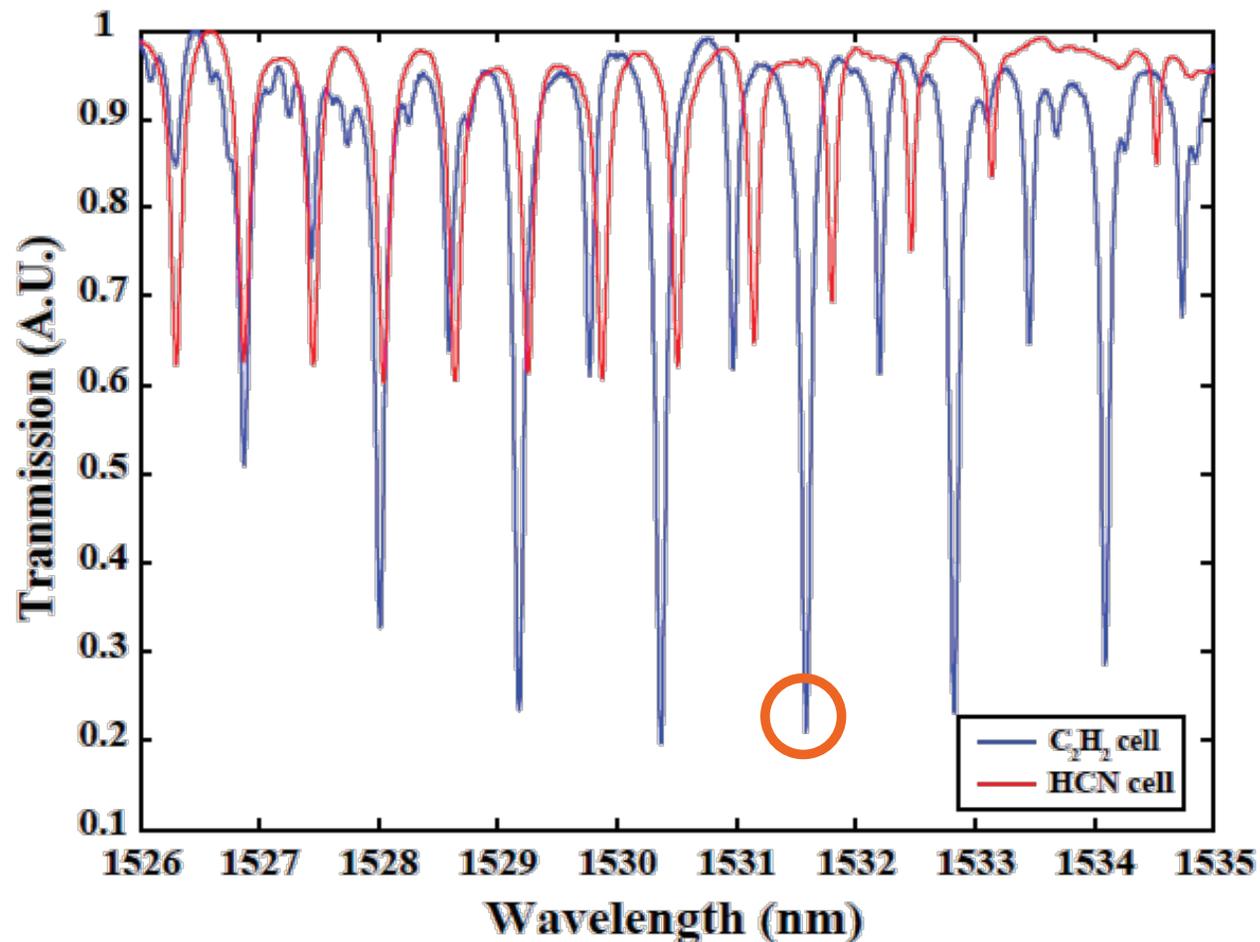
- Interference fringes



- 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.

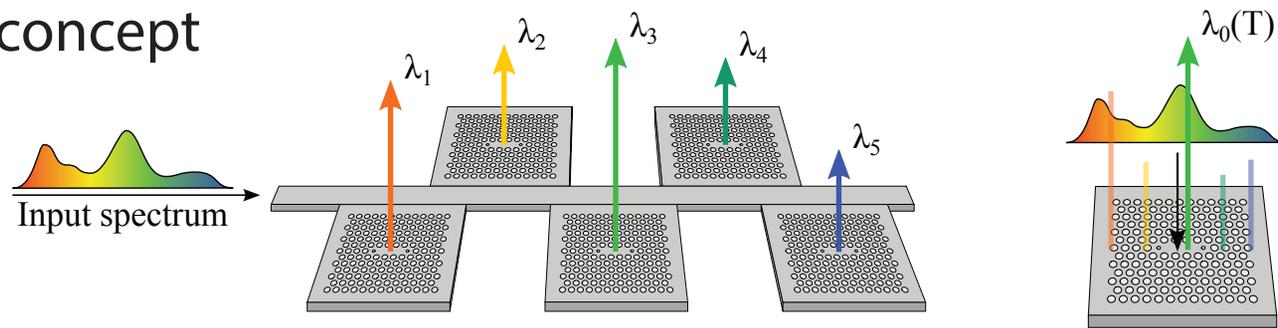
Challenge: Fabricate a chip-scale spectrometer that can discriminate acetylene (H_2C_2) from hydrogen cyanide (HCN)?



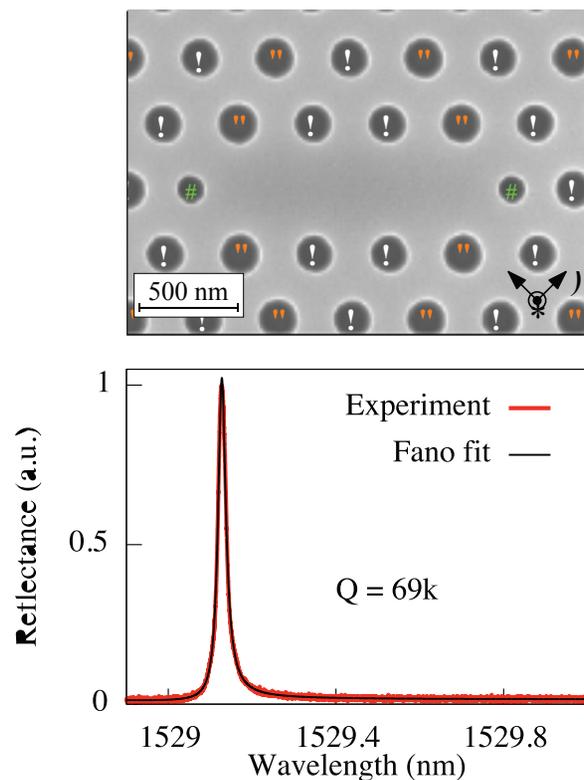
(data from our own lab)

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

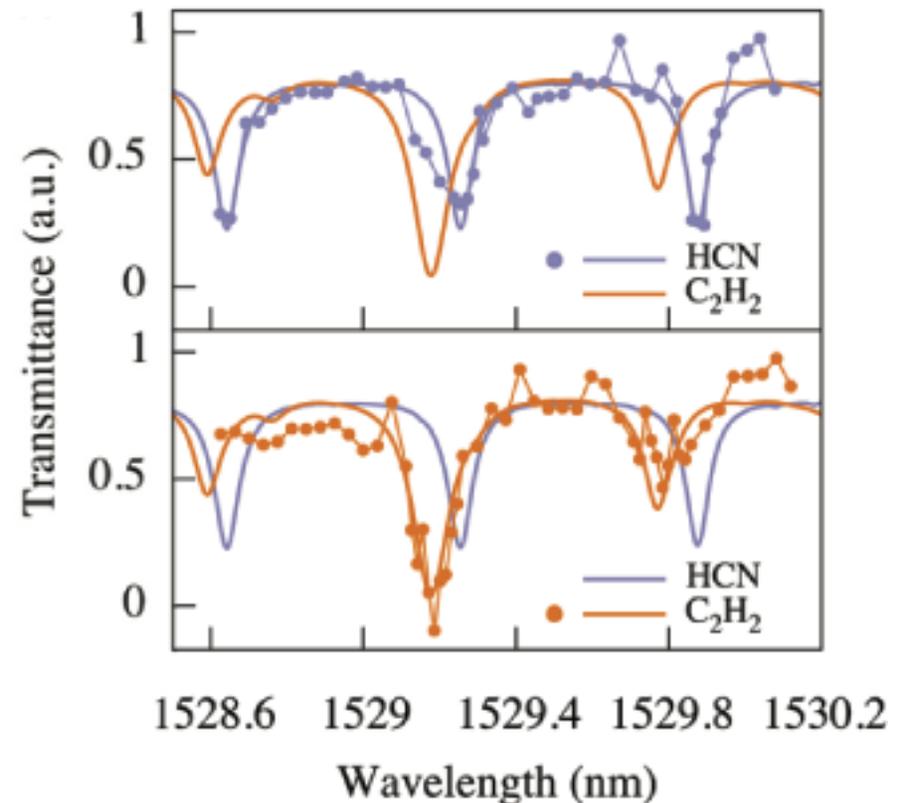
- The concept



- Cavity design



- Spectroscopy results

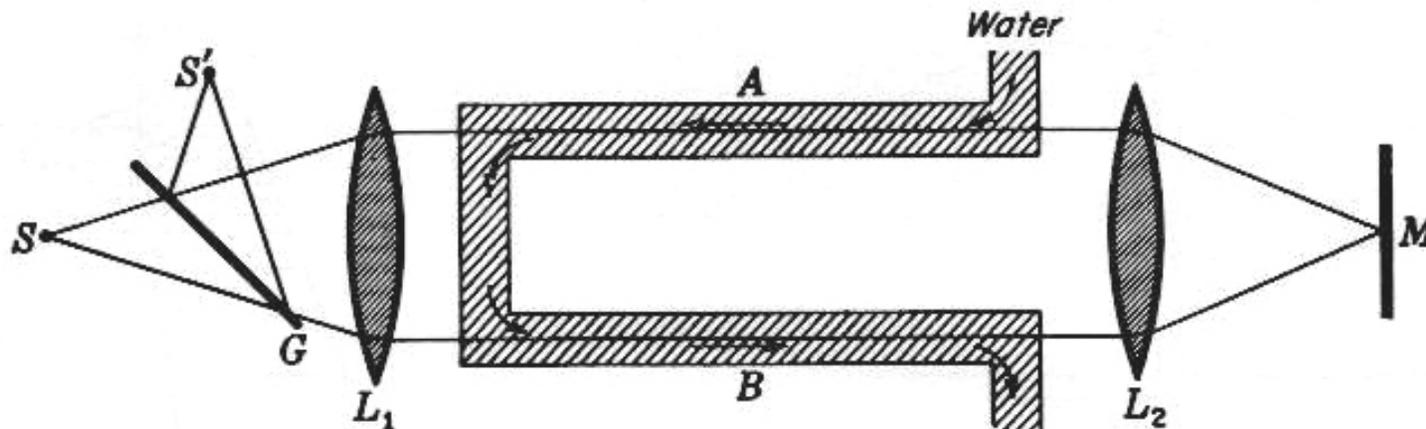


The Velocity of Light in Moving Matter: Fresnel Drag (or Ether Drag) Effects

- Fizeau (1859): Longitudinal photon drag:

Velocity of light in flowing water.

$V = 700 \text{ cm/sec}$; $L = 150 \text{ cm}$; displacement of 0.5 fringe.



- Modern theory: relativistic addition of velocities

$$v = \frac{c/n + V}{1 + (V/c)(1/n)} \approx \frac{c}{n} + V \left(1 - \frac{1}{n^2} \right) \quad \text{— Fresnel “drag” coefficient}$$

- But what about slow-light media?

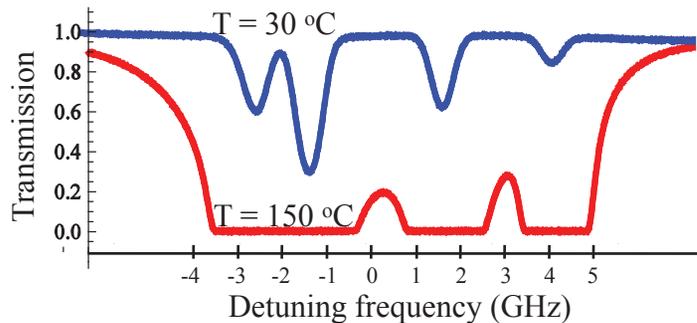
Fresnel Drag in a Highly Dispersive Medium

Light Drag in a Slow Light Medium (Lorentz)

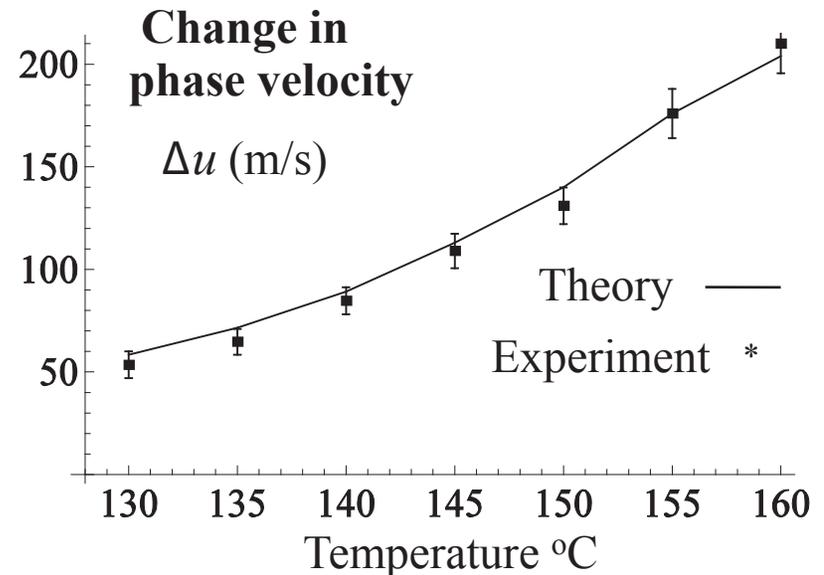
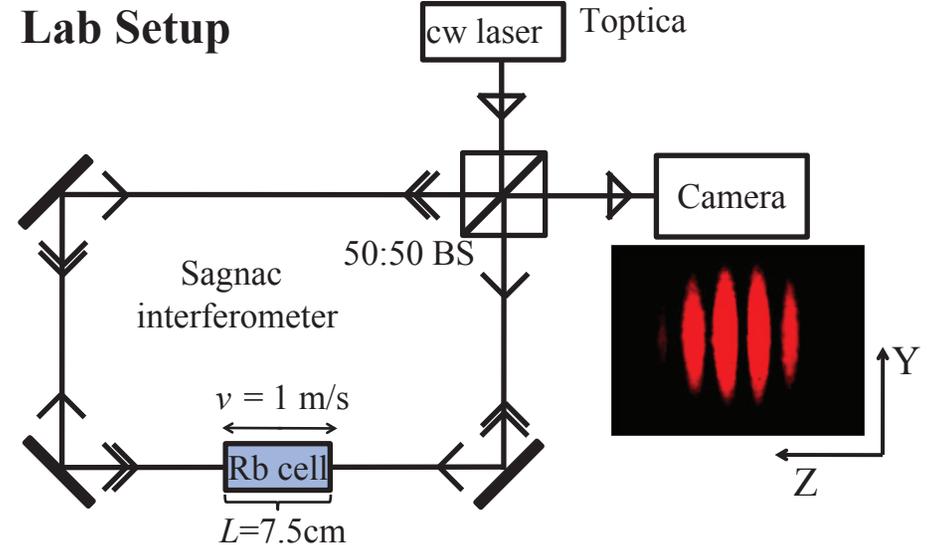
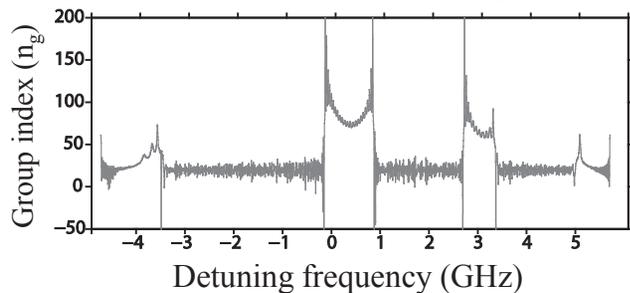
$$u \approx \frac{c}{n} \pm v \left(1 - \frac{1}{n^2} + \frac{n_g - n}{n^2} \right)$$

We Use Rubidium as Our Slow Light Medium

- Transmission spectrum of Rb around D₂ transition:



- Group index of Rb around D₂ line at T=130



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

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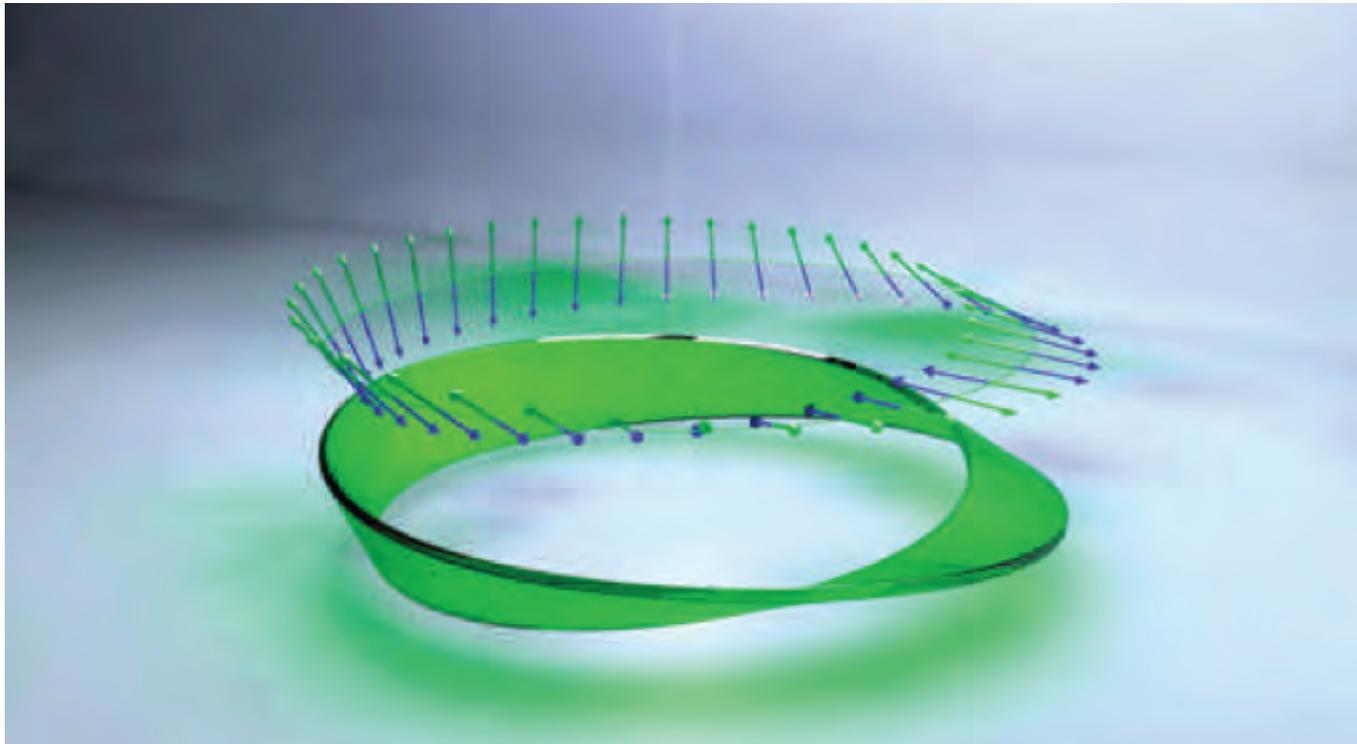
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Observation of Optical Polarization Möbius Strips

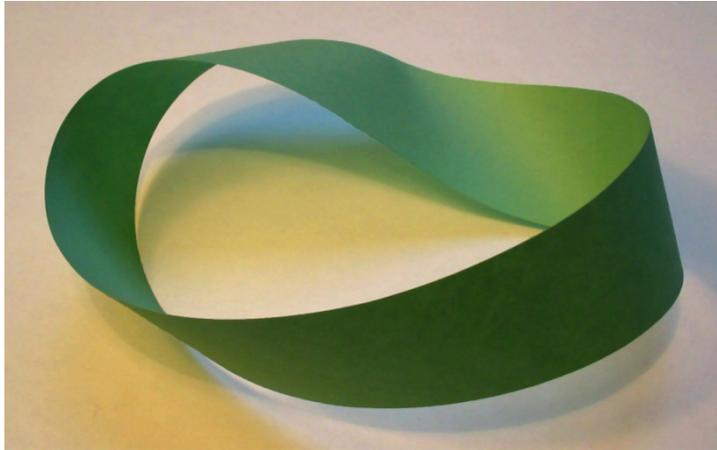
- Möbius strips are familiar geometrical structures, but their occurrence in nature is extremely rare.
- We generate such structures in the nanoscale in tightly focused vector light beams and confirm experimentally their Möbius topology.



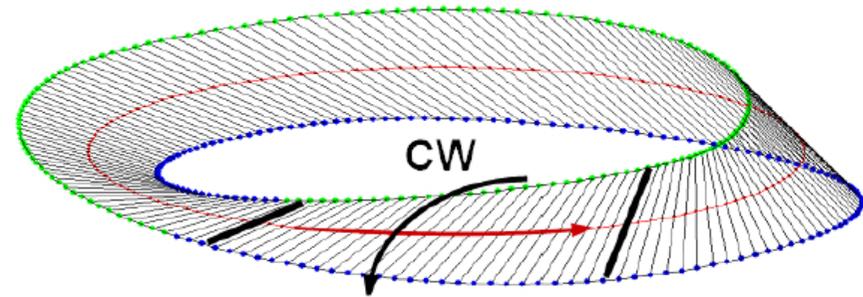
Bauer, Banzer, Karimi, Orlov, Rubano, Marrucci, Santamato, Boyd and Leuchs, Science, 347, 964 (2015)

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)

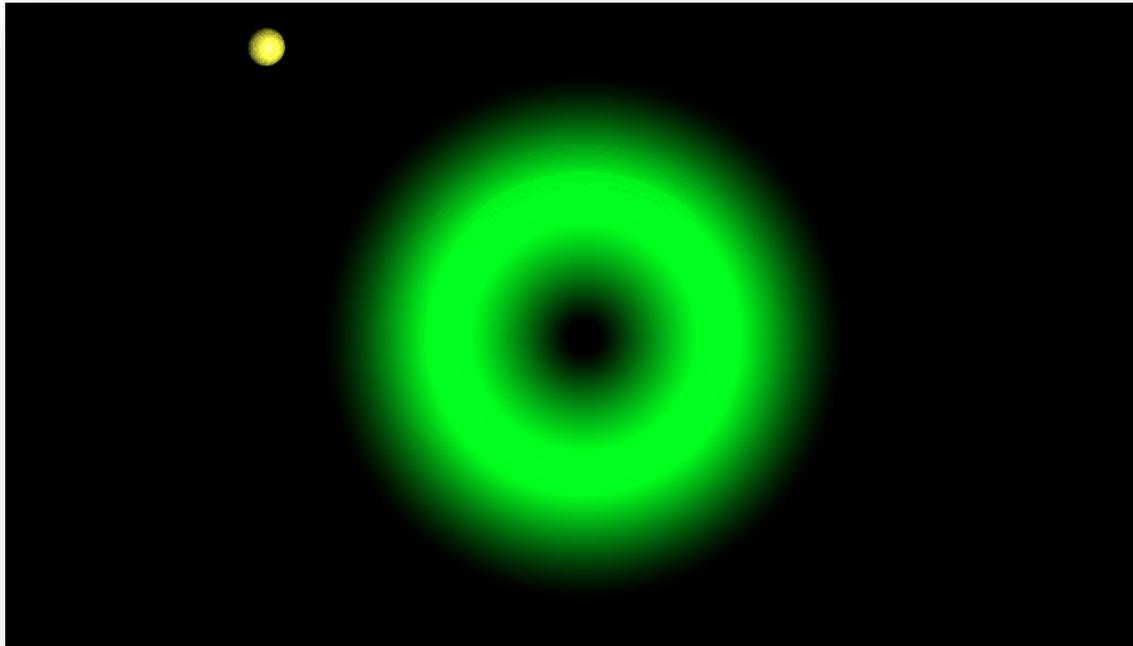
Isaac Freund, *Opt. Lett.* 35, 148-150 (2010)

Isaac Freund, *Opt. Commun.* 284, 3816-3845 (2011)

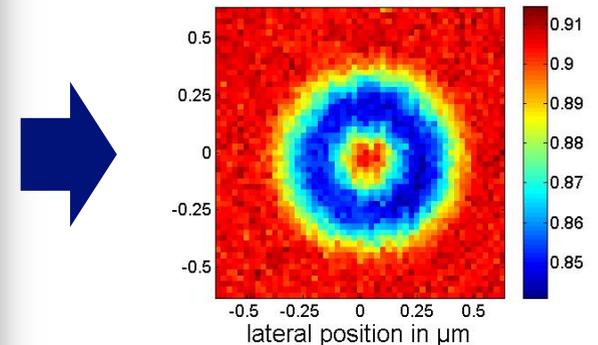
Full vectorial beam measurement on the nanoscale

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



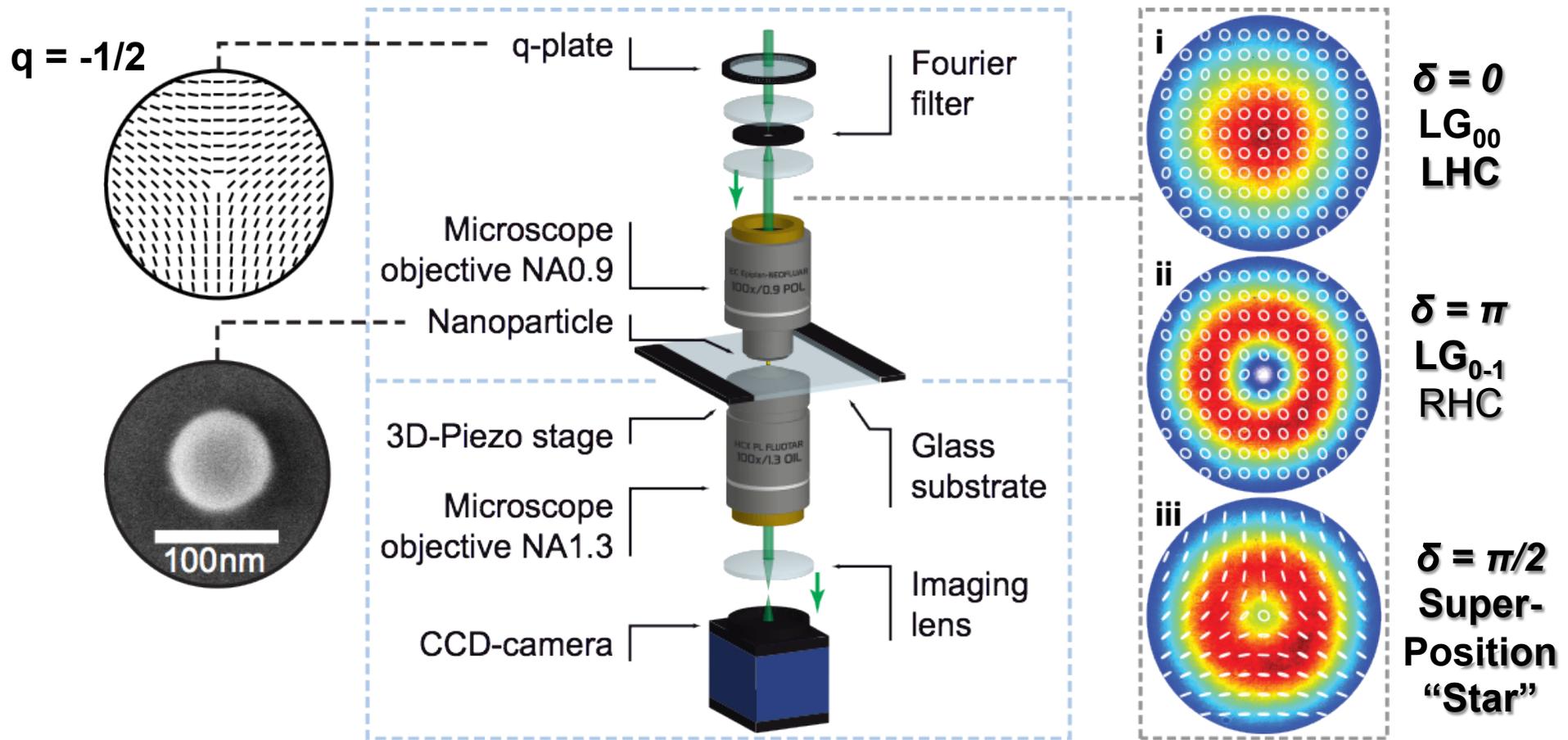
measured intensity
(can also measure
polarization and phase)



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).

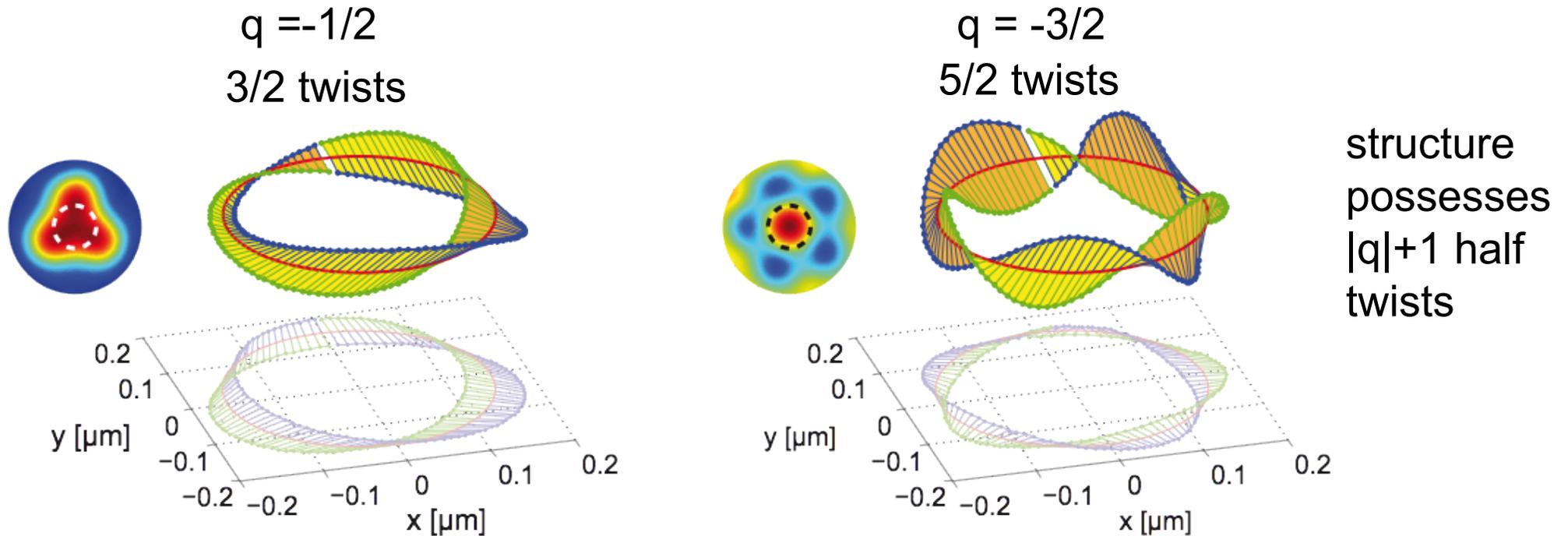
Lab Setup to Observe a Polarization Möbius Strip



- 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



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.

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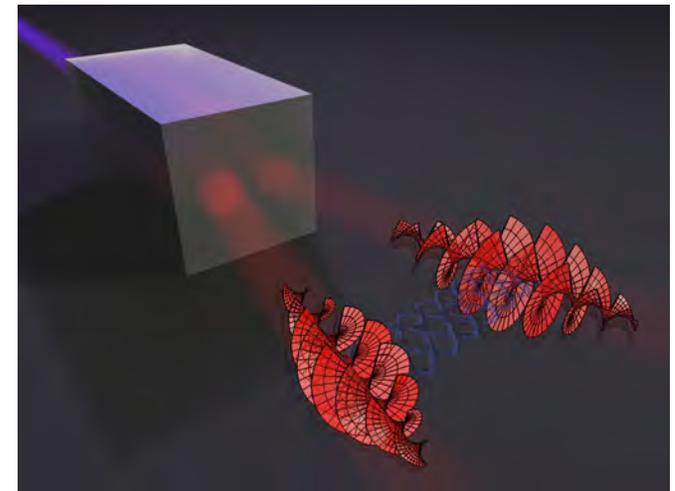
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Use of Quantum States for Secure Optical Communication

- 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

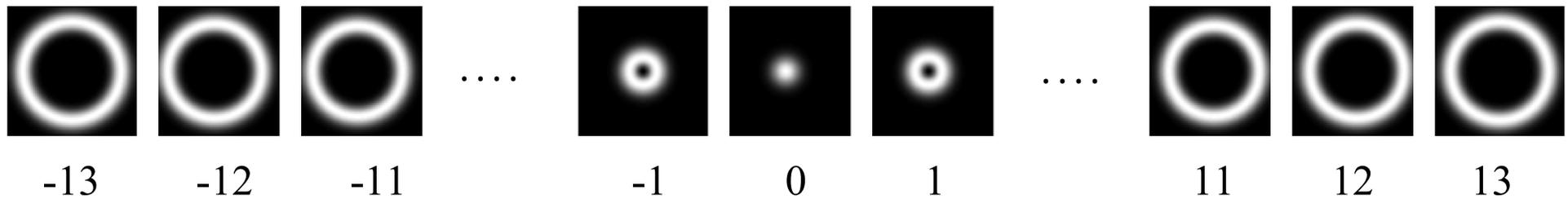
We are constructing a QKD system in which each photon carries many bits of information

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

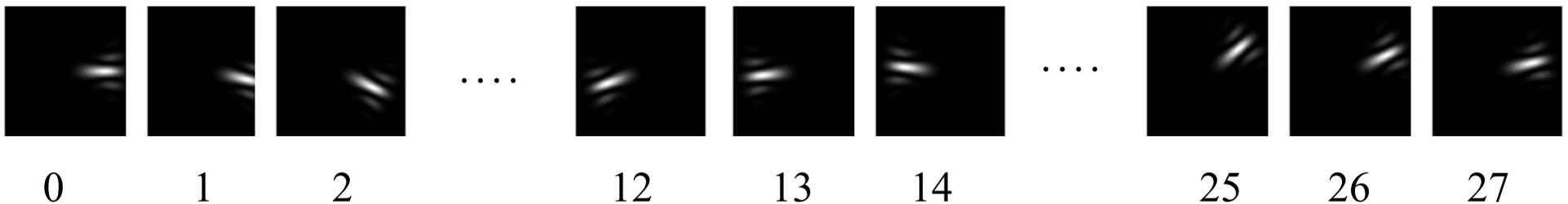
We also need a second basis composed of linear combinations of these states

Single Photon States

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

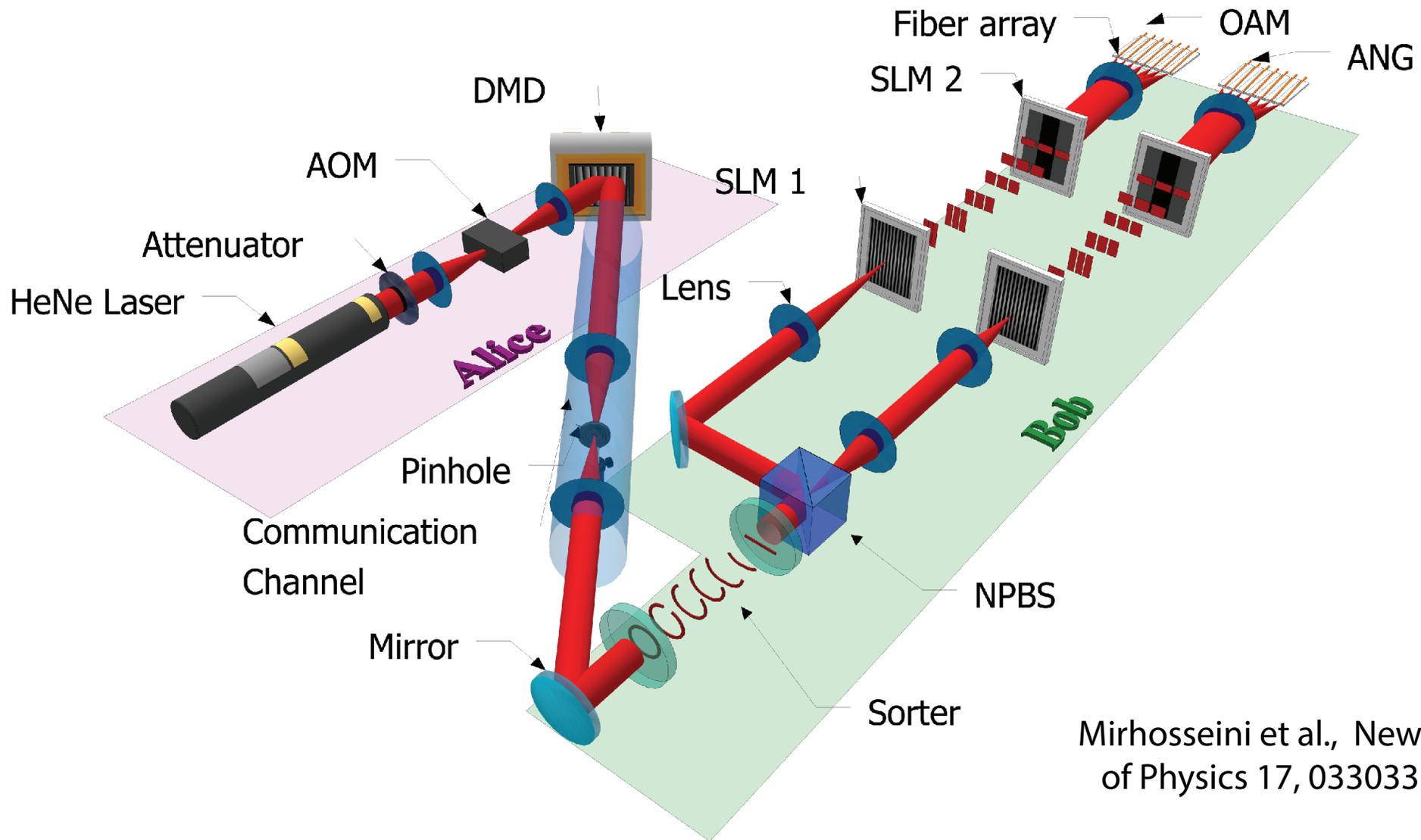


“Angular” Basis (mutually unbiased with respect to LG)



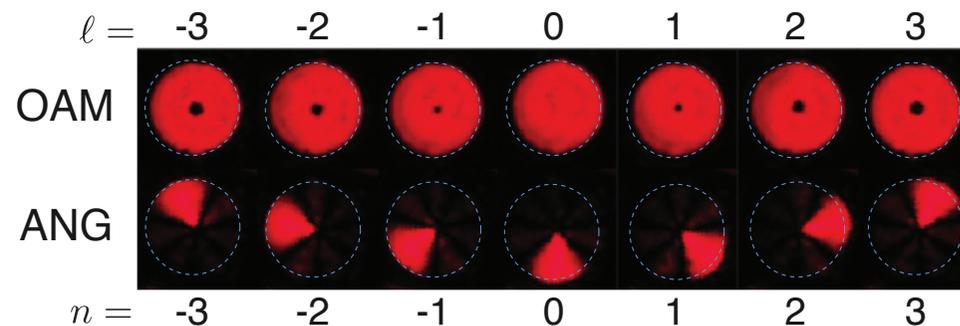
$$\Psi_{AB}^N = \frac{1}{\sqrt{27}} \sum_{l=-13}^{13} \text{LG}_{l,0} \exp(i2\pi Nl/27)$$

Our Laboratory Setup

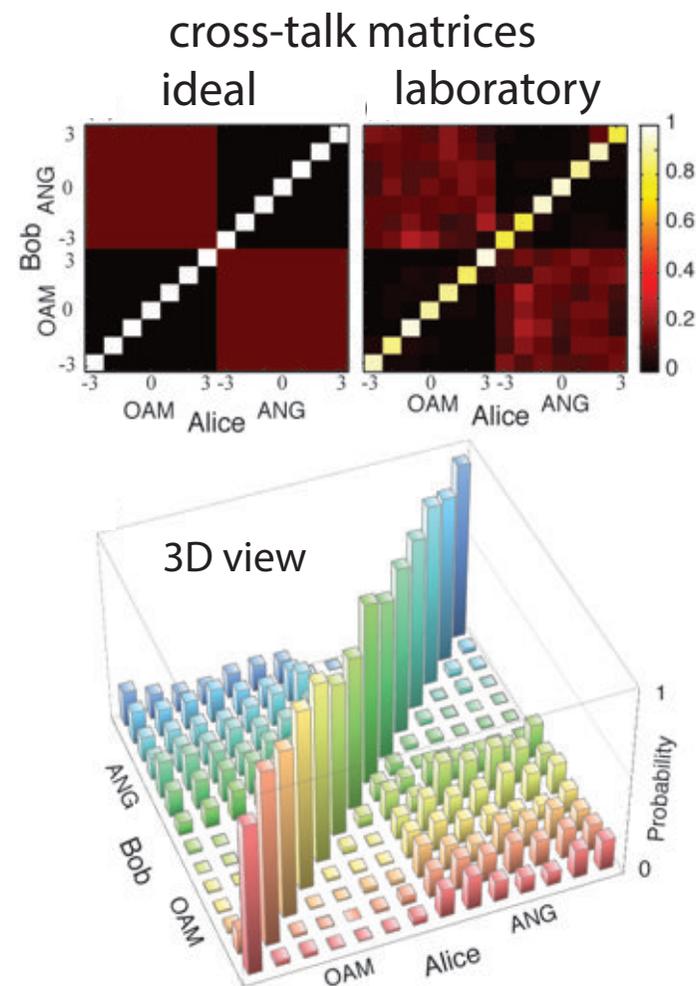
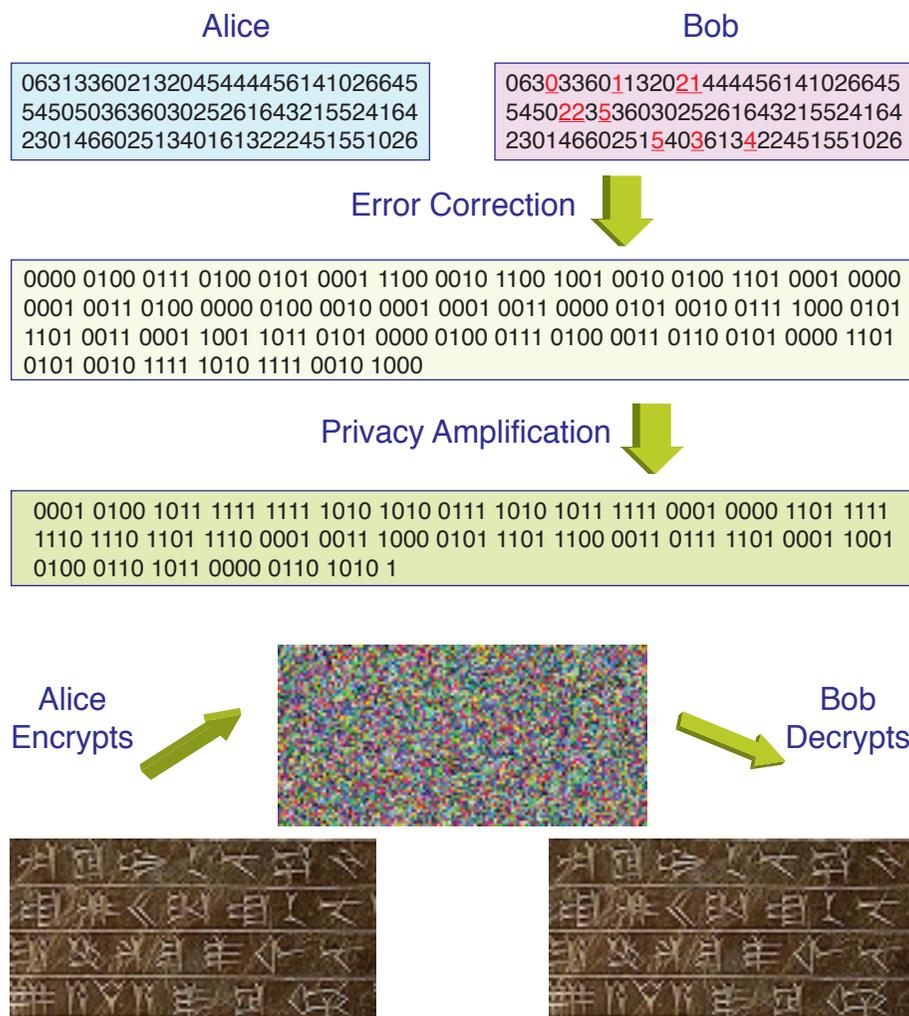


Mirhosseini et al., New Journal of Physics 17, 033033 (2015).

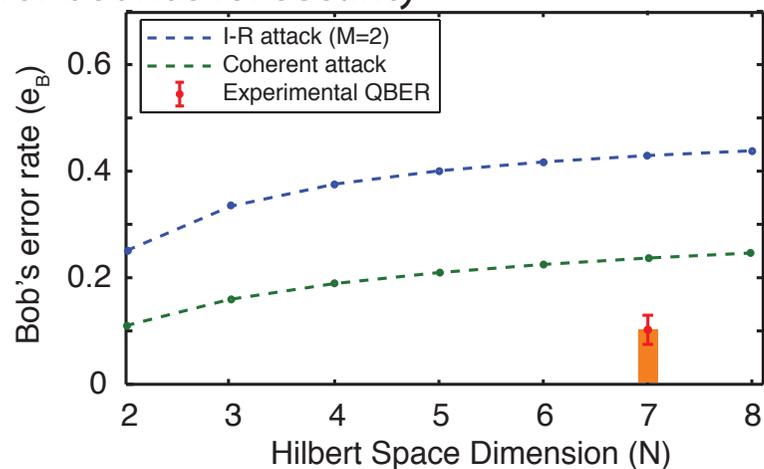
We use a seven-dimensional state space.



Laboratory Results - OAM-Based QKD



- 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

The image shows a Google search interface for the name "robert boyd". The search bar contains the text "robert boyd" and a magnifying glass icon. The top navigation bar includes the Google logo, the search bar, and user account information for "Robert". Below the search bar, there are tabs for "Web", "Images", "Books", "News", "Shopping", "More", and "Search tools". The search results show "About 63,300,000 results (0.26 seconds)".

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Robert W. Boyd

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Born: 1948, Buffalo, NY
Education: University of California, Berkeley
Doctoral advisor: Charles H. Townes
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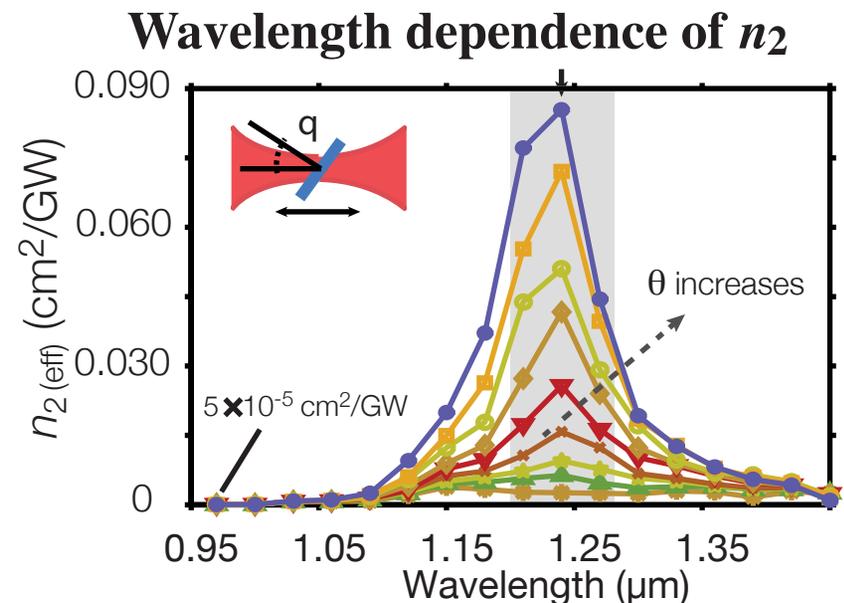
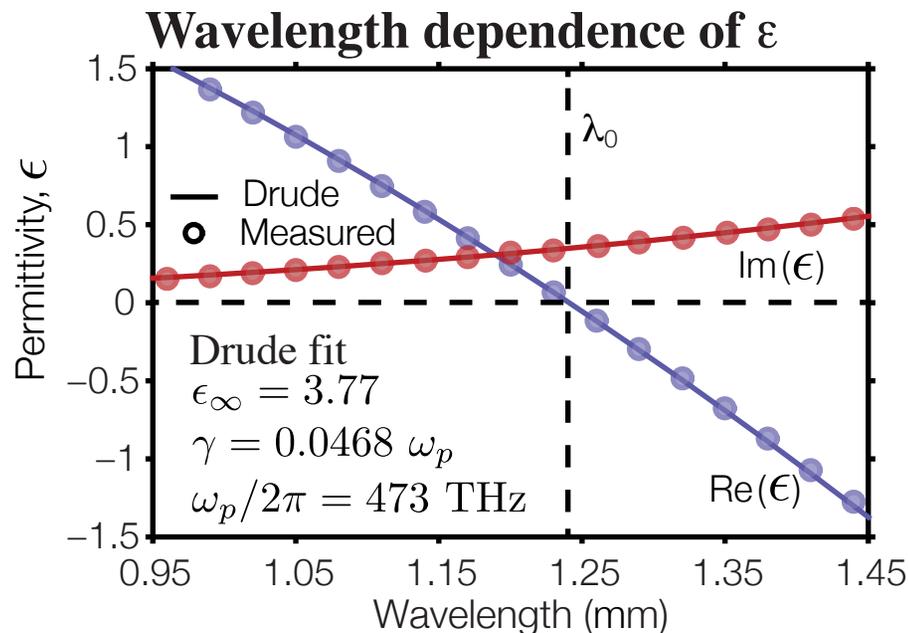
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Huge Nonlinear Optical Response of ITO near its Epsilon-Near-Zero Wavelength

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

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

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



Some possible new effects

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