Research in Quantum Photonics

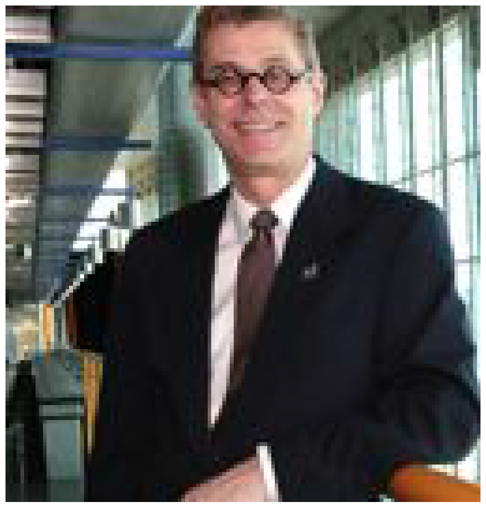
Robert Boyd
Canada Excellence Research Chair in Quantum Nonlinear Optics
University of Ottawa

Our research interests include:

- Nanophotonics
- Plasmonics
- Photonic crystals
- Photonic device
- Applications of slow and fast light
- Quantum nonlinear optics
- Optical methods for quantum information
- Biophotonics
- Nonlinear optics of atomic vapors
- Optical chirality and structure surfaces

Presented at the 5th Annual Meeting of the Canada Excellence Research Chairs, April 13-14 2015, University of Waterloo

University of Ottawa Nonlinear Photonics Program - Senior Staff



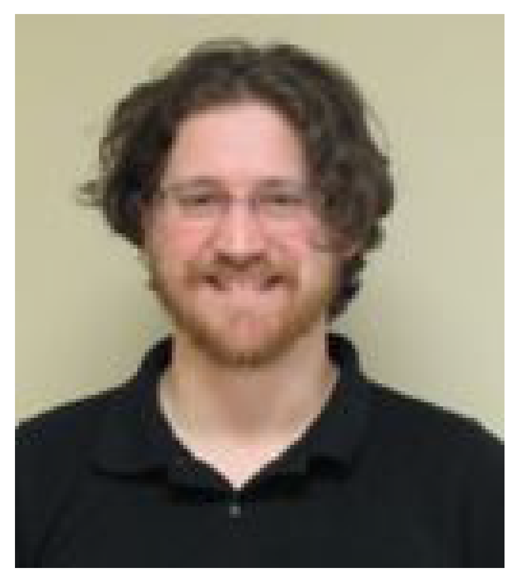
Robert Boyd
CERC

Ksenia Dolgaleva
Asst. Prof.

Jeff Lundeen
Asst. Prof.

Ebrahim Karimi
Asst. Prof.

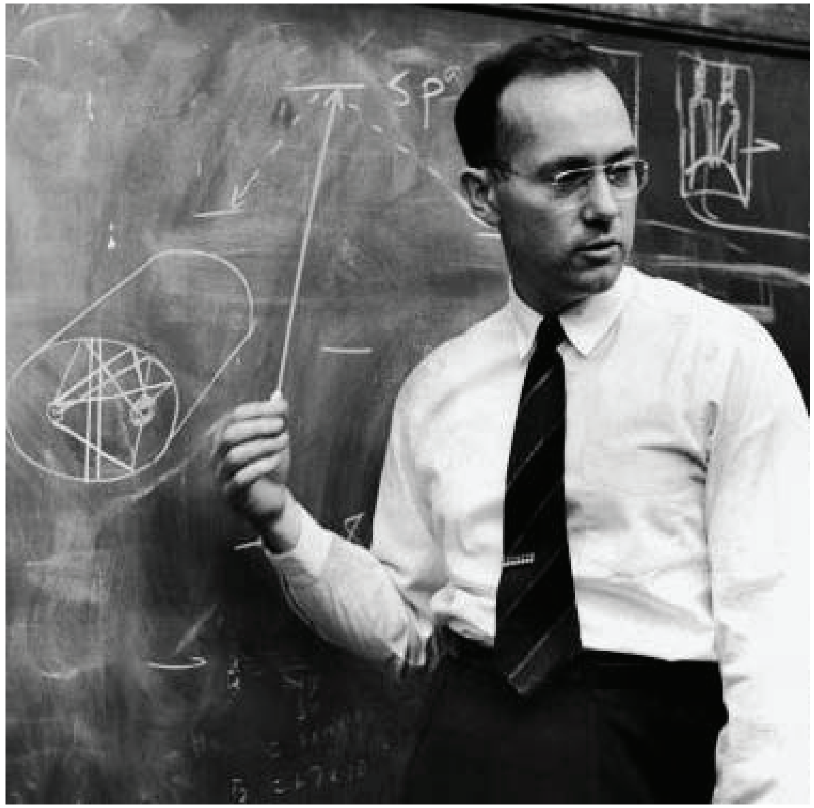
Gerd Leuchs
Adjunct Prof.



Jeremy Upham
Staff Scientist

Charles H. Townes

July 28, 1915 to January 27, 2015



- Inventor of the maser and laser
- Nobel Prize, 1964
- Advisor to three US presidents
- Teacher, mentor, and friend

Nature 519, 292 (2015).

Research in Quantum Nonlinear Optics

Three research updates:

1. Observation of polarization Möbius structures of light

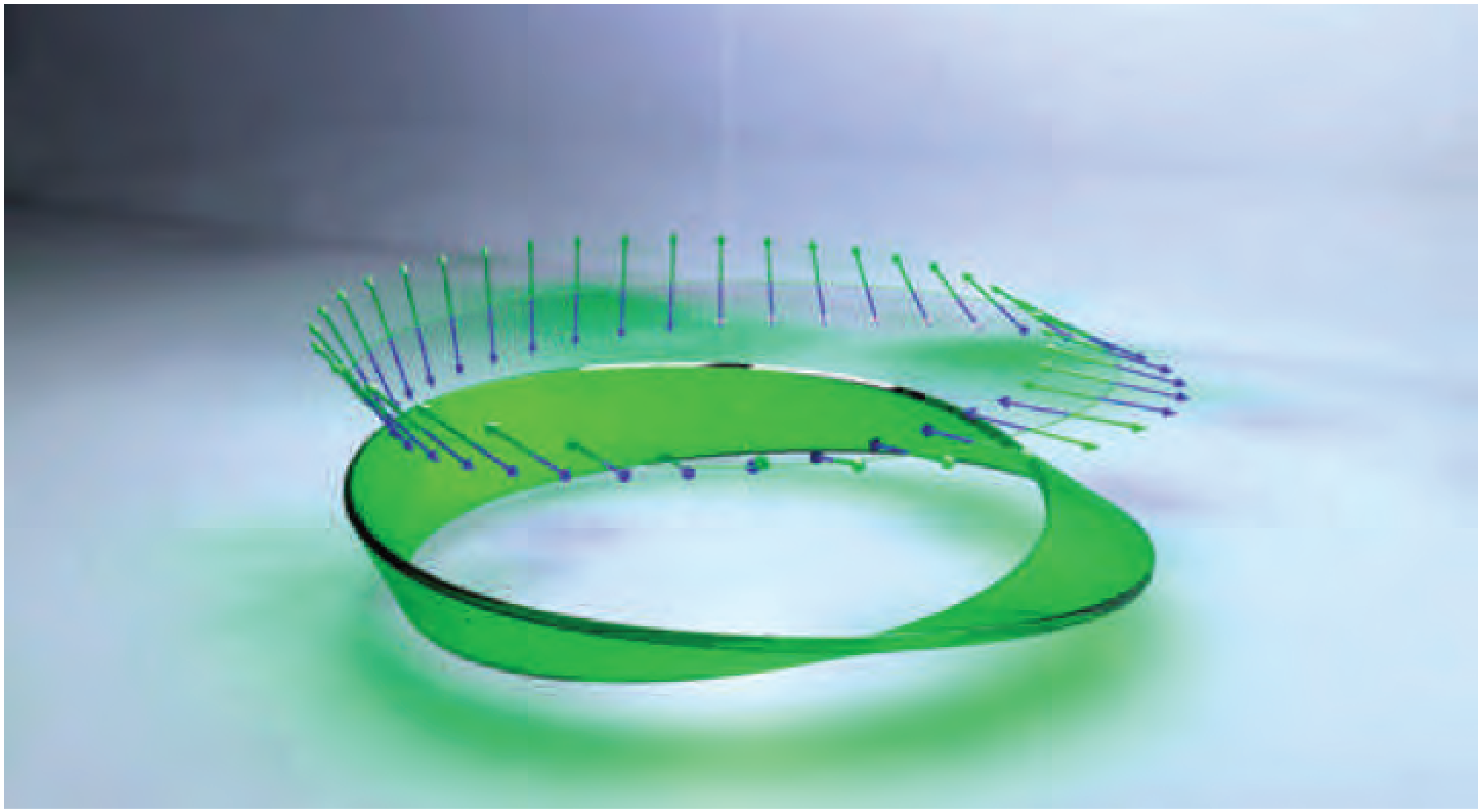
2. Fresnel drag effects enhanced by "slow light"

3. High-capacity QKD with more than one bit per photon

Observation of Optical Polarization Möbius Strips

Thomas Bauer, Peter Banzer, Ebrahim Karimi, Sergej Orlov, Andrea Rubano,
Lorenzo Marrucci, Enrico Santamato, Robert W Boyd and Gerd Leuchs

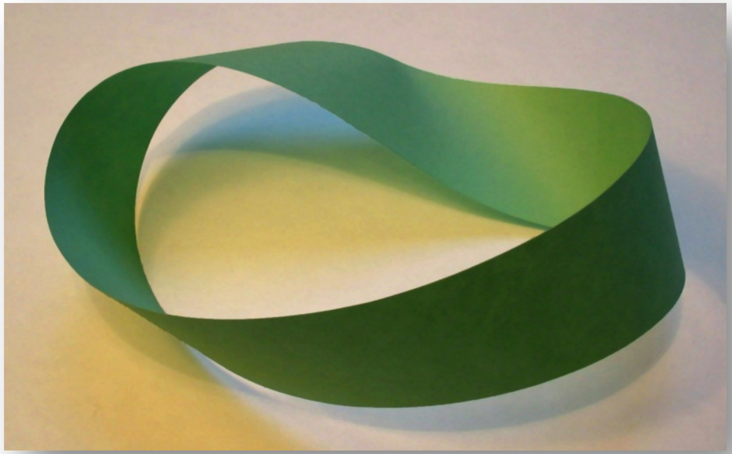
Science, 347, 964 (2015)



Mobius 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.

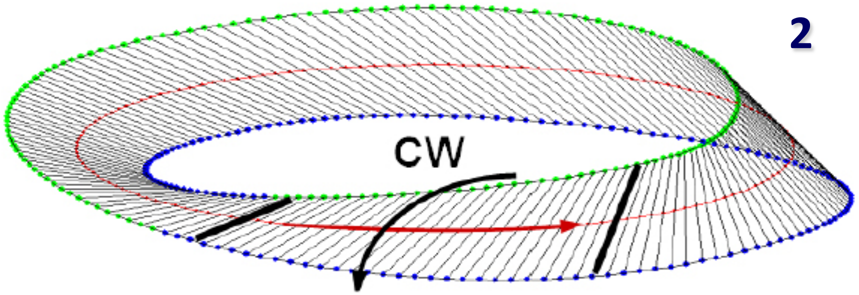
Optical Möbius Strips – When Light Turns One-Sided and Single-Edged

An 'ordinary' Möbius strip



1

A polarization Möbius strip
(introduced by Isaac Freund)



2

Isaac Freund discovered, described, and investiated these unusal objects

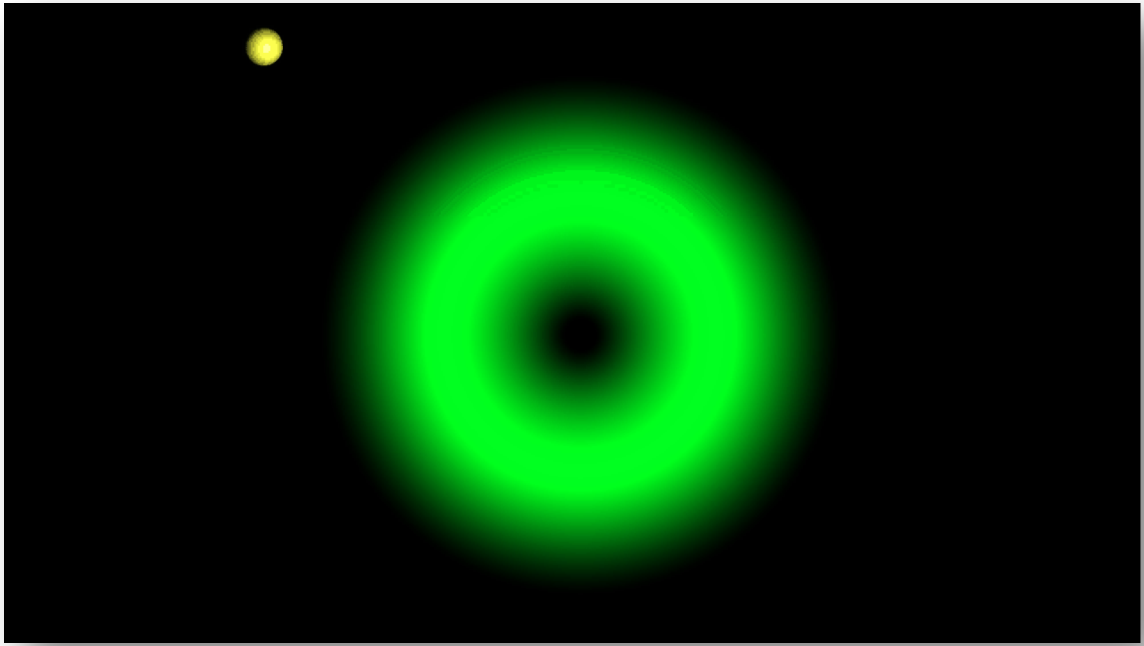
- **Optical Möbius strips can be found in light fields**
- **One has to look at a very special field distribution in a very special way**
- **By doing so, one can observe optical Möbius strips in the field structure**

[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)

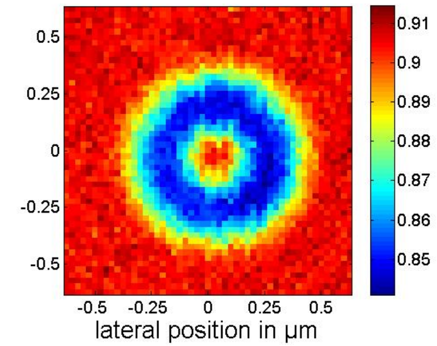
Full vectorial beam measurement on the nanoscale

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

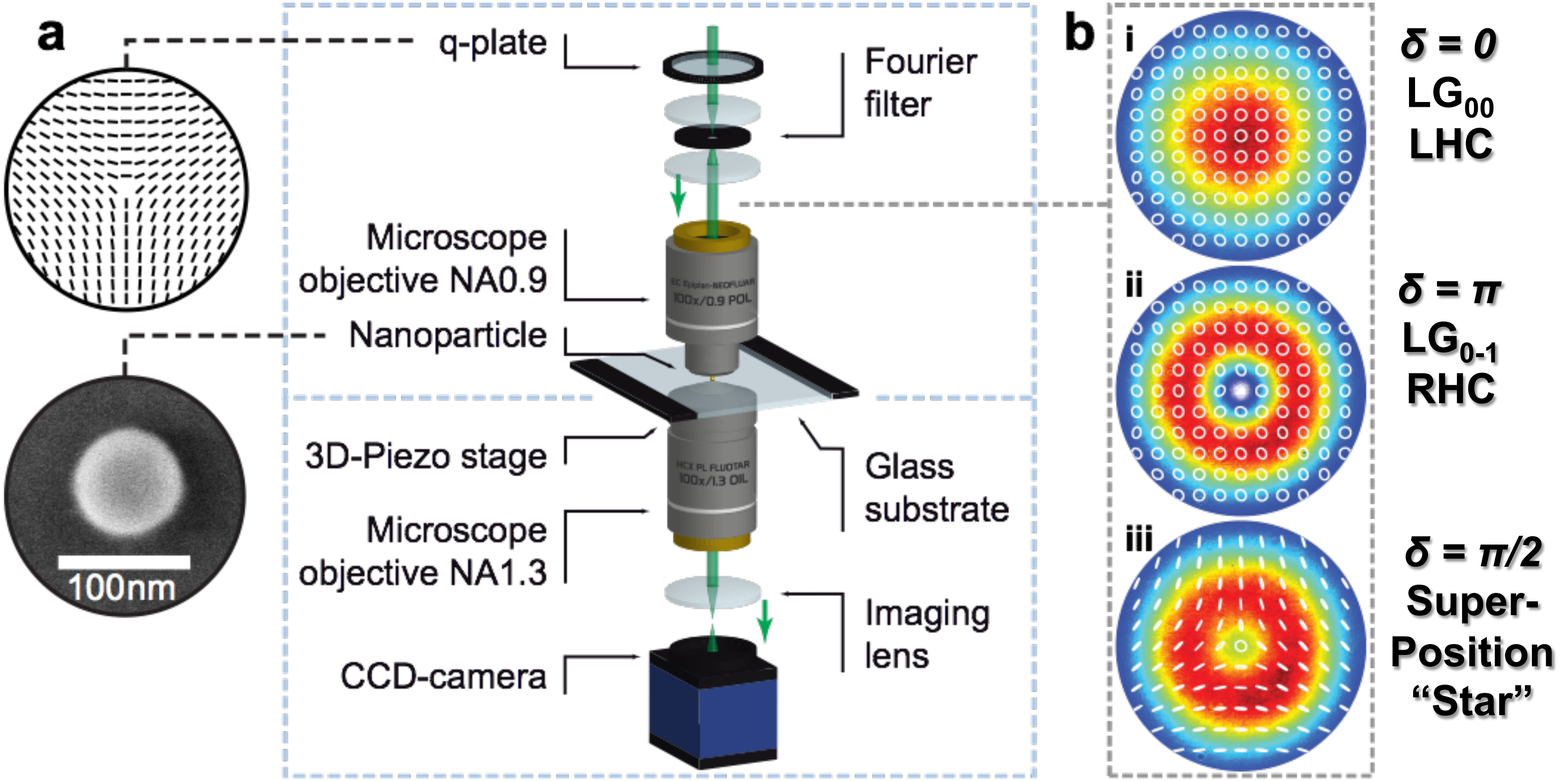


measured intensity
(can also measure
polarization and phase)



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).

Observing a Polarization Möbius Strip



Crucial: tight focusing enhances the Möbius effect, which depends on the z component of the field

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

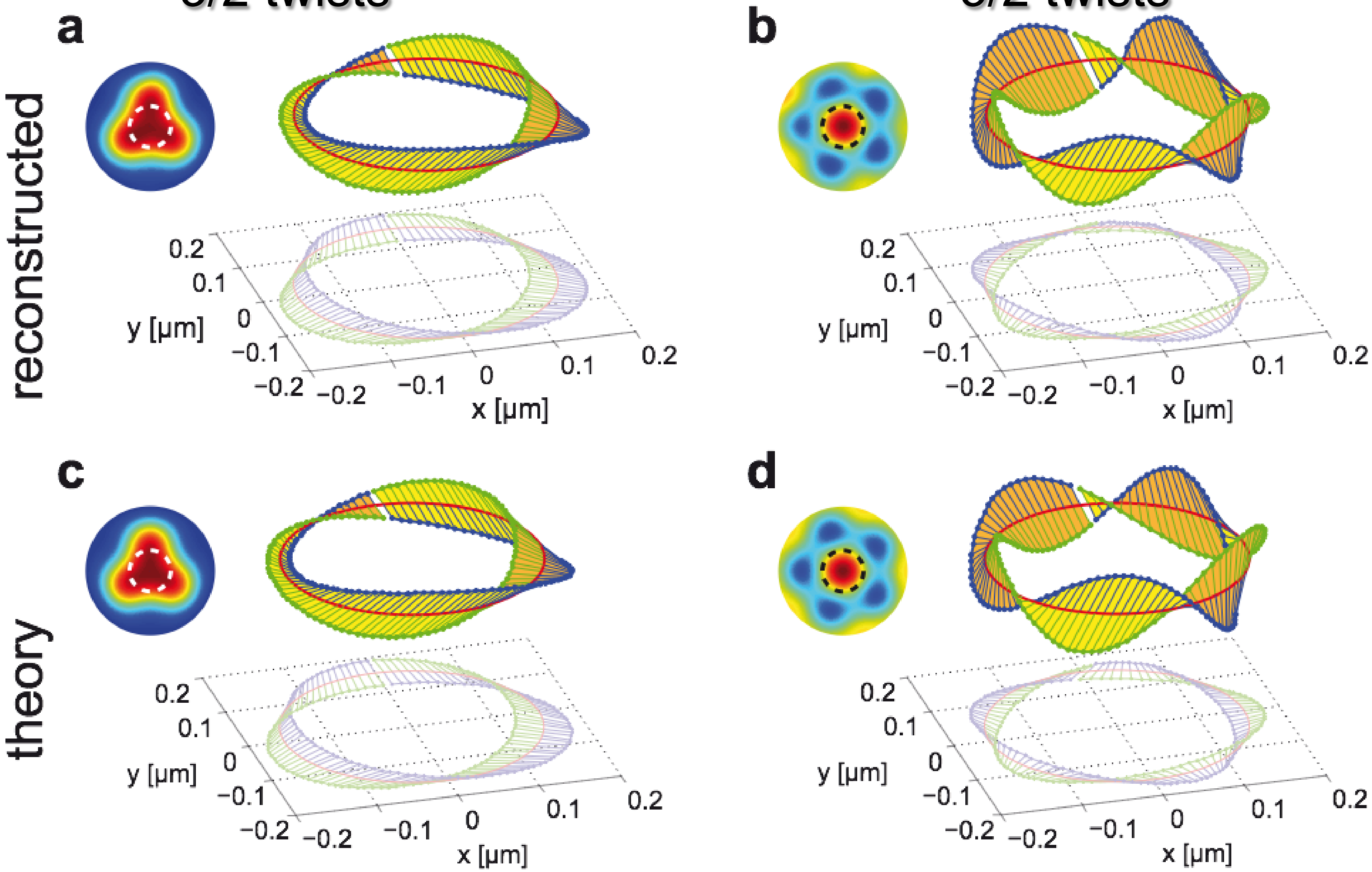
Observation of Polarization Möbius Strips

q =-1/2
3/2 twists

q = -3/2
5/2 twists

- Measured

- Theory



We find |q|+1
half twists

Bauer, Banzer, Karimi, Orlovas, Rubano, Marucci, Santamato, Boyd, Leuchs, Science (2015).

Research in Quantum Nonlinear Optics

Three research updates:

1. Observation of polarization Möbius structures of light
2. Fresnel drag effects enhanced by "slow light"
3. High-capacity QKD with more than one bit per photon

Optical Forces and Fresnel Drag in Atomic Vapor "Slow-Light" Media

Akbar Safari,[1] Israel De Leon,[1] Mohammad Mirhosseini,[2] Omar S. Magana-Loaiza,[2] and Robert W. Boyd[1,2,3]

1. Department of Physics, University of Ottawa
2. Institute of Optics, University of Rochester
3. School of Physics and Astronomy, University of Glasgow

Why Care about Optical Forces?

- Optical levitation
- Optical tweezers
- Optomechanical systems
- But can we ***control*** optical forces?

  - Yes! Photon momentum and optical forces depend on both refractive index and group index of optical materials.

  - The "slow light" community knows how to manipulate the group velocity of light.

What is the Momentum of a Photon?

In vacuum: $p = (\hbar\omega/c)$

Abraham form (for matter)

$\mathbf{P} = \mathbf{E} \times \mathbf{H}/c^2$ (EM momentum density)

$p = (\hbar\omega/c)(1/n_g)$ (photon momentum)

It is the kinetic (as in mv) momentum

Minkowski form (for matter)

$\mathbf{P} = \mathbf{D} \times \mathbf{B}$ (EM momentum density)

$p = (\hbar\omega/c)(n^2/n_g)$ or $p = (\hbar\omega/c)\, n$ photon momentum

It is the canonical momentum (as in $h/\lambda_{deBroglie}$)

If we can control the photon momentum, can we control optical forces?

See, e.g., Barnett, PRL (2010), Milonni and Boyd, AOP (2010).

rev 1/28/2014

Controlling the Velocity of Light

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

– Light can be made to go:

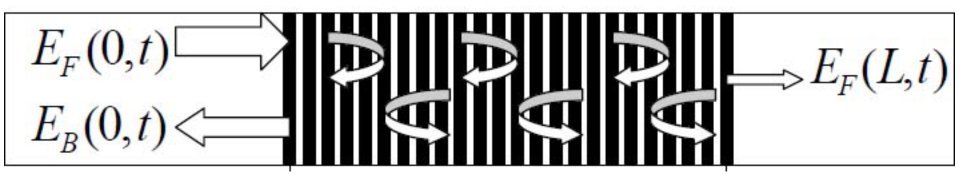
slow: $v_g << c$ (as much as 10^6 times slower!)

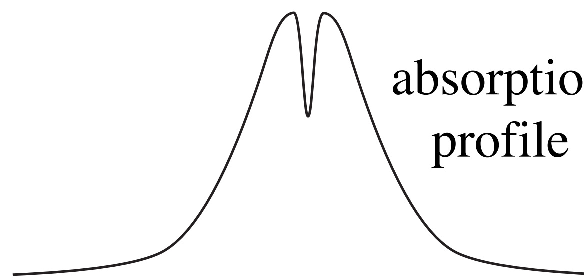
fast: $v_g > c$

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





absorption profile

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

Photon Drag Effects with Slow Light

We would like to use the dependence of the photon momentum on the group index as a means to control optical forces.

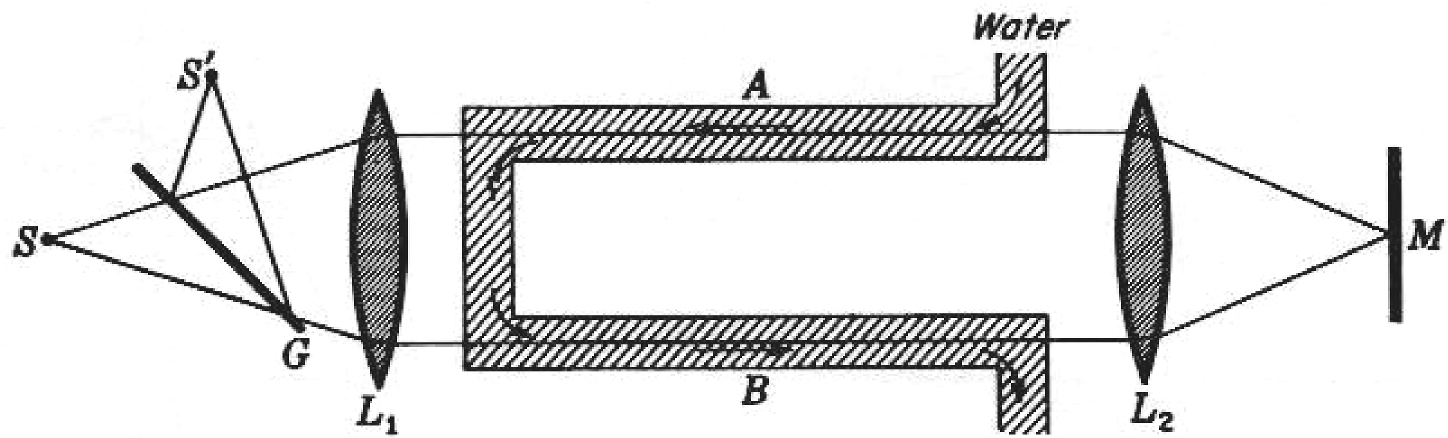
As a first step down this pathway, we are studying how to control photon drag effects using slow light.

Velocity of (Slow) Light in Moving Matter: Photon 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.



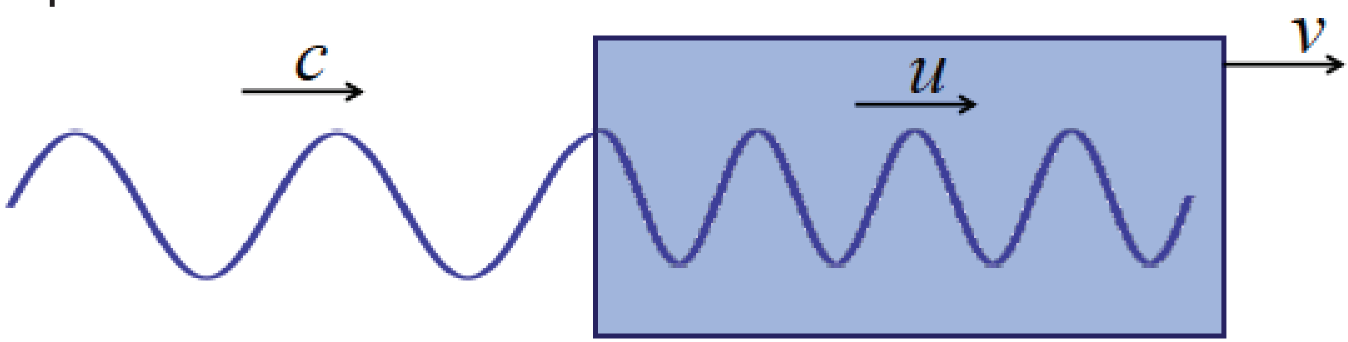
Modern theory: relativistic addition of velocities

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

Fresnel “drag” coefficient

Fresnel Drag Effect in Nondispersive and Dispersive Media

- Nondispersive medium



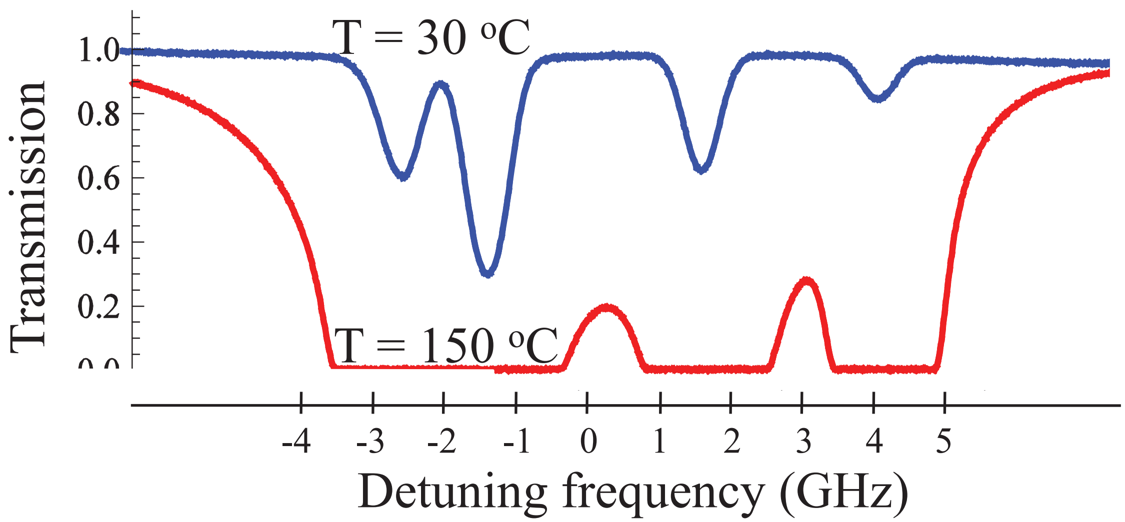
$$u = \frac{c/n \pm v}{1 + v/nc} \simeq \frac{c}{n} \pm v\left(1 - \frac{1}{n^2}\right)$$

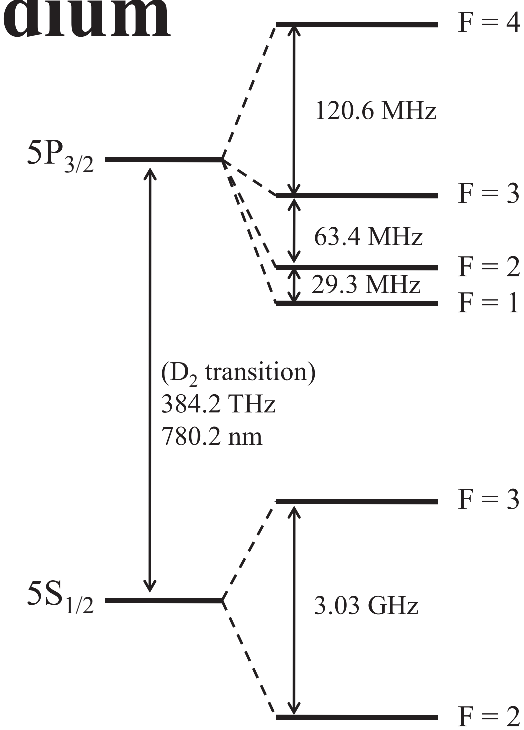
- Dispersive medium

$$u \simeq \frac{c}{n} \pm v\left(1 - \frac{1}{n^2} + \frac{n_g - n}{n^2}\right) \quad \text{where} \quad n_g \equiv n + \omega\frac{dn}{d\omega}$$

We Use Rubidium as Our Slow Light Medium

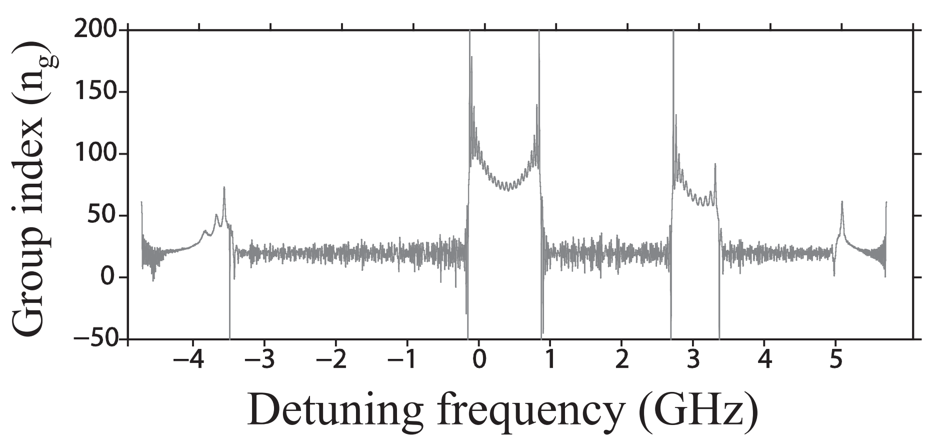
- Transmission spectrum of Rb around D_2 transition:



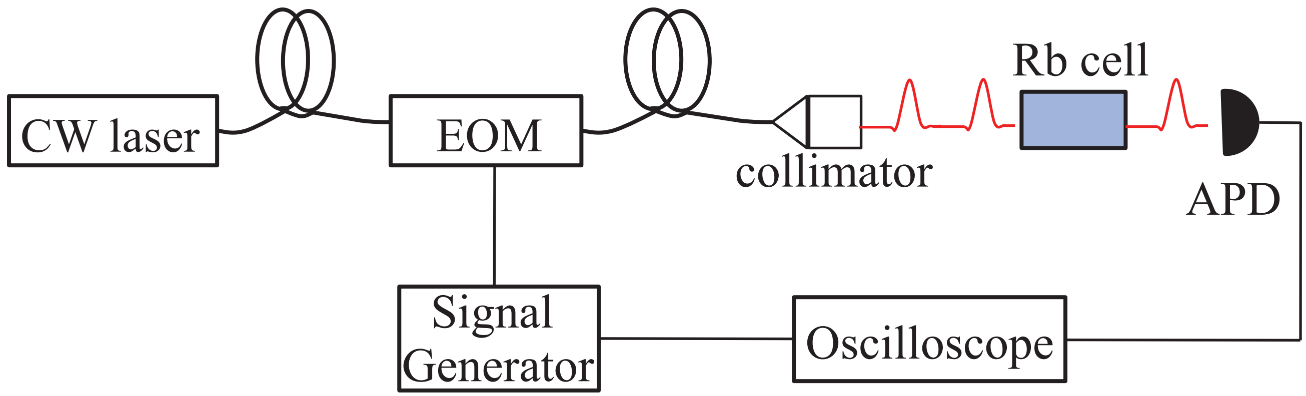


- There is large dispersion where rapid changes in transmission are observed

- Group index of Rb around D_2 transition line at T=130 °C:



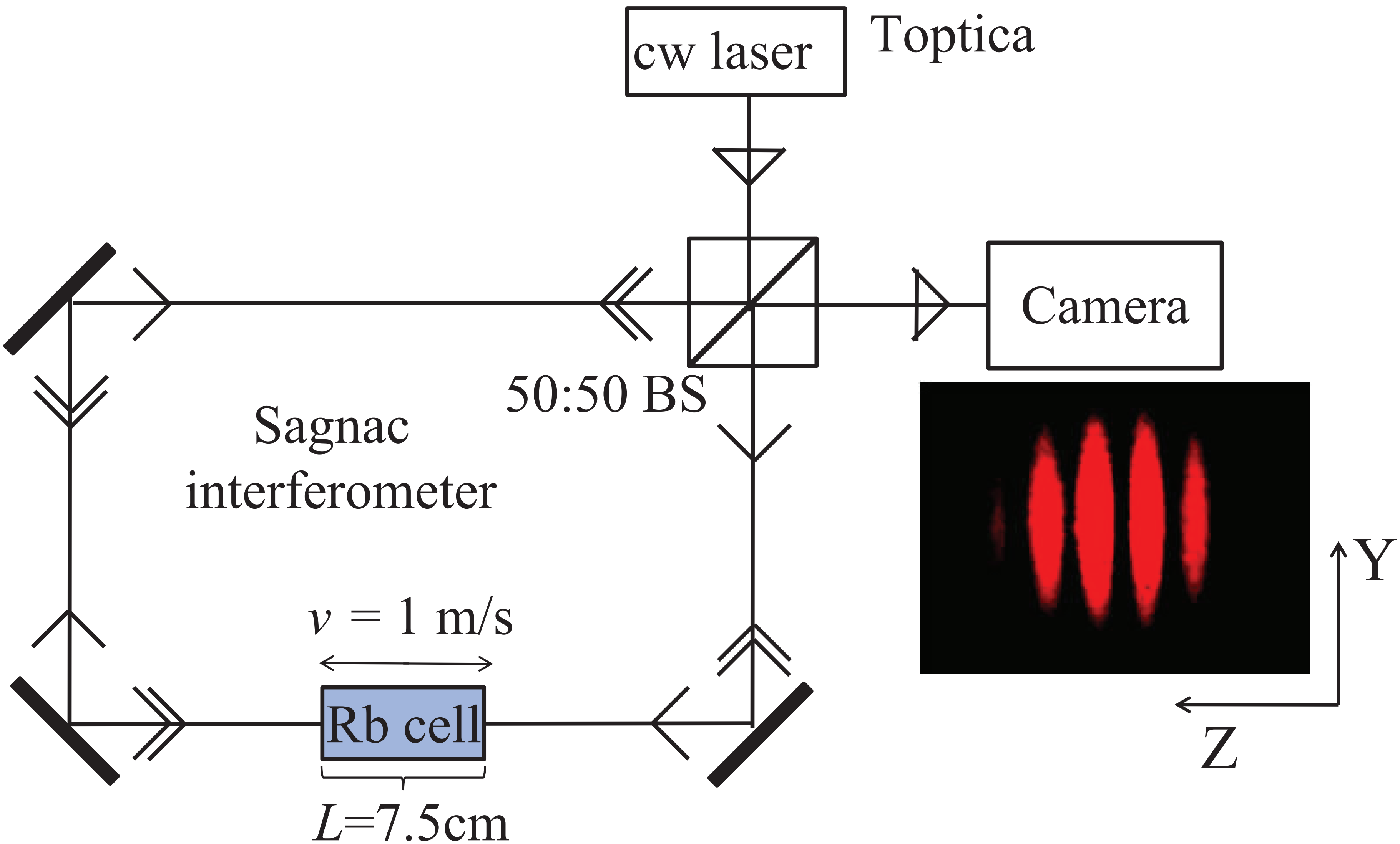
Direct Measurement of the Group Index of Rubidium



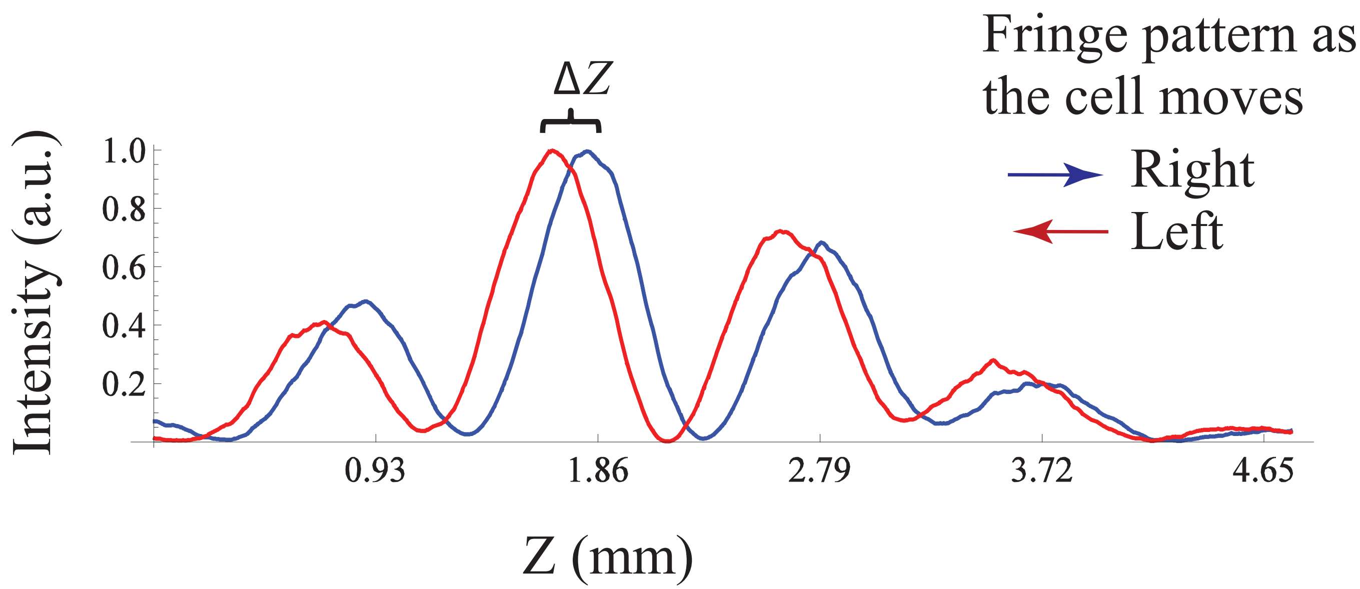
Variation of n_g with temperature of the Rb cell:

T	130	135	140	145	150	155	160
n_g	59.4	72.6	90.2	114	141	177	205

Our Experimental Setup

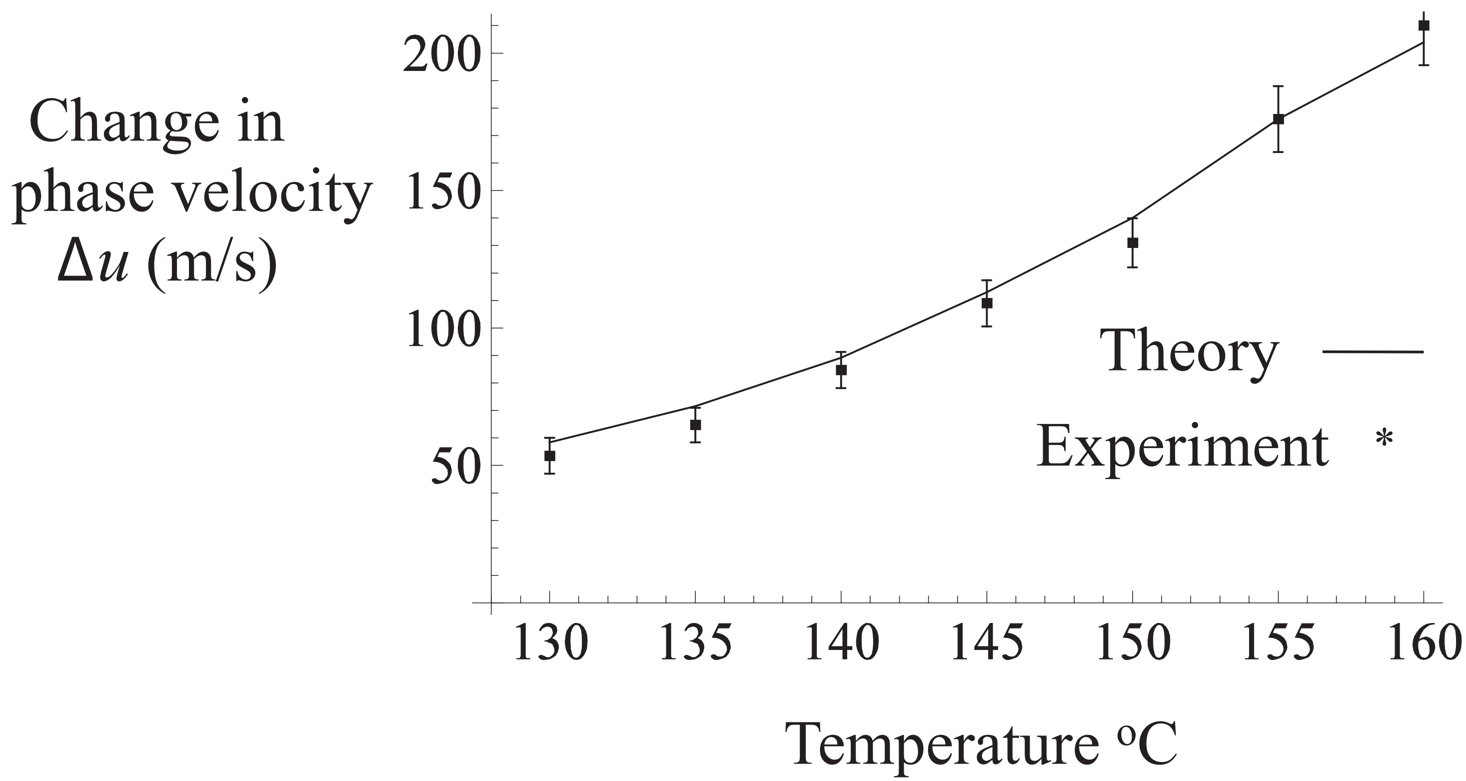


The Fringe Pattern Shifts According to Velocity of the Rubidium Cell



Velocity of cell is (+/-) 1 m/s.

Light Dragging Experimental Results



Recall that the rubidium cell was moving at only 1 m/s.

Conclusions

- A maximum drag speed of 205 m/s was measured in a highly dispersive medium (hot Rb vapor).

- This effect is at least two orders of magnitude larger than that observed to date.

- Much larger dispersion can be achieved in Rb atoms using electromagnetically induced transparency (n_g as high as 10^7).

This project is the PhD thesis topic of one of my graduate students, Akbar Safari. Please note the correct spelling of Akbar.

Note Carefully: Akbar, not Ackbar

Akbar Safari

Admiral Ackbar

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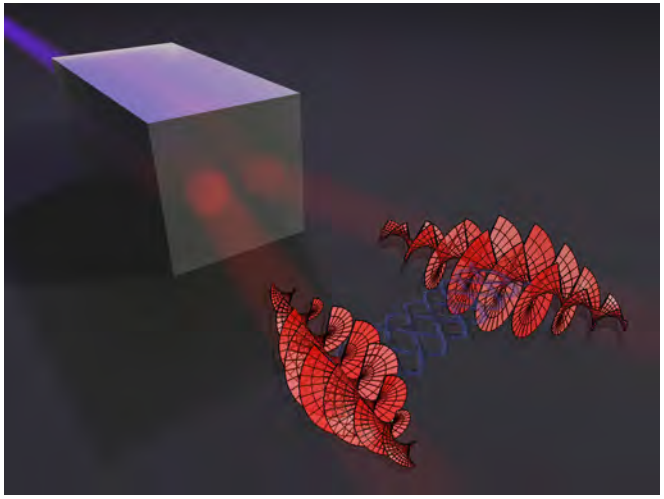
3. High-capacity QKD with more than one bit per photon

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.



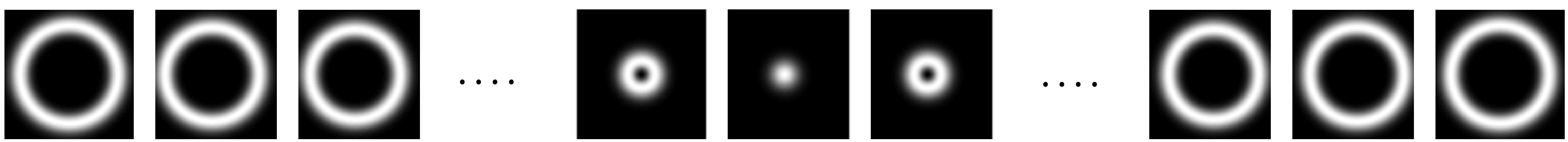
High Capacity QKD Protocol

We are developing a free-space quantum key distribution system that can carry many bits per photon (think about it!).

We encode either in the Laguerre-Gauss modes or in their linear superpositions (or in other transverse modes).

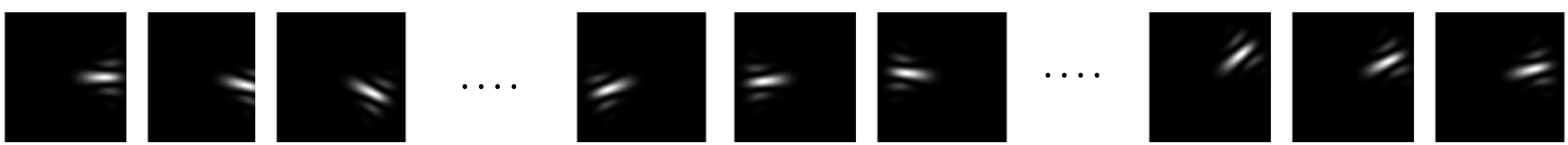
We are developing means to mitigate the influence of atmospheric turbulence

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



0 1 2 12 13 14 25 26 27

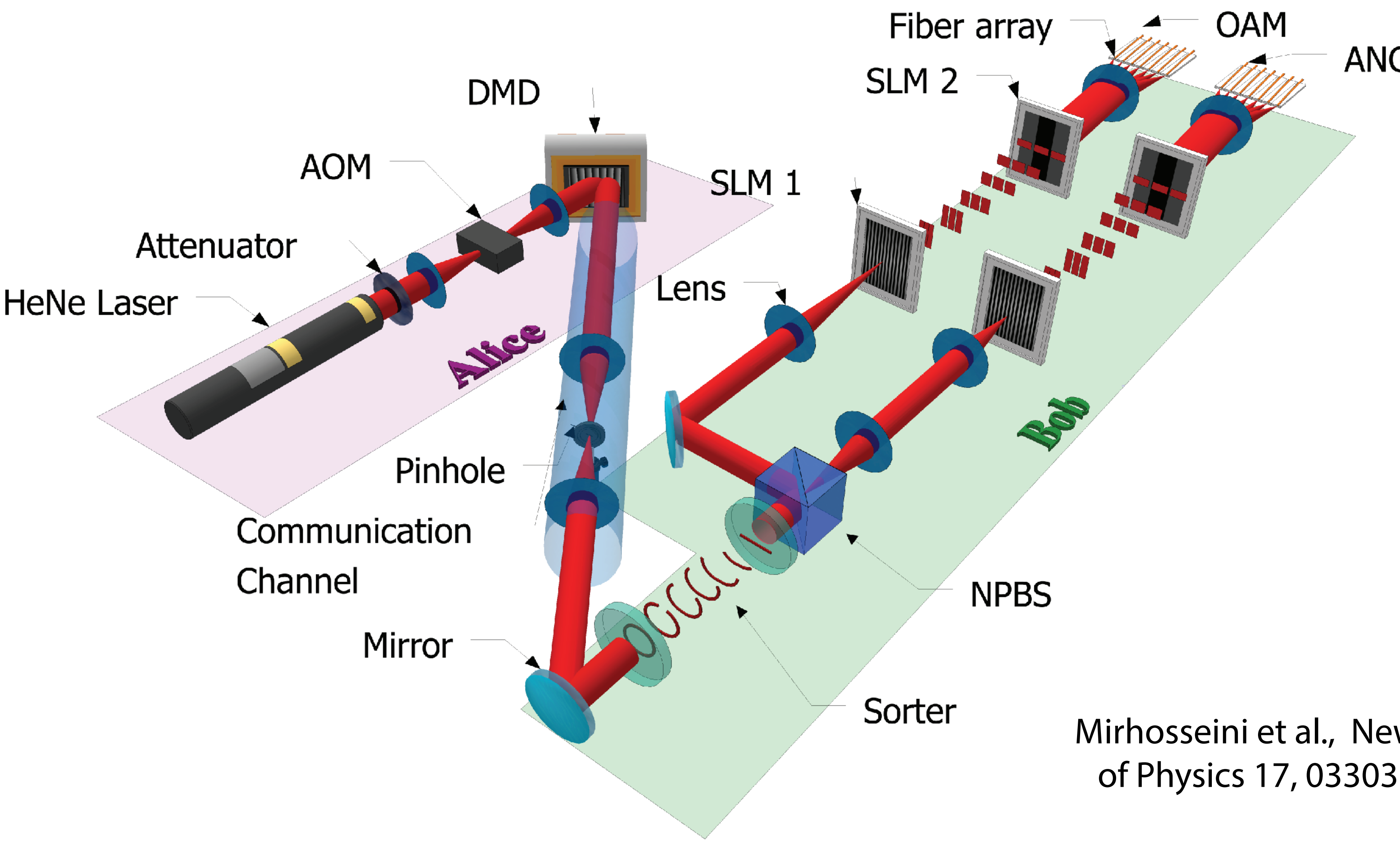
"Angular" Basis (mutually unbiased with respect to LG)



0 1 2 12 13 14 25 26 27

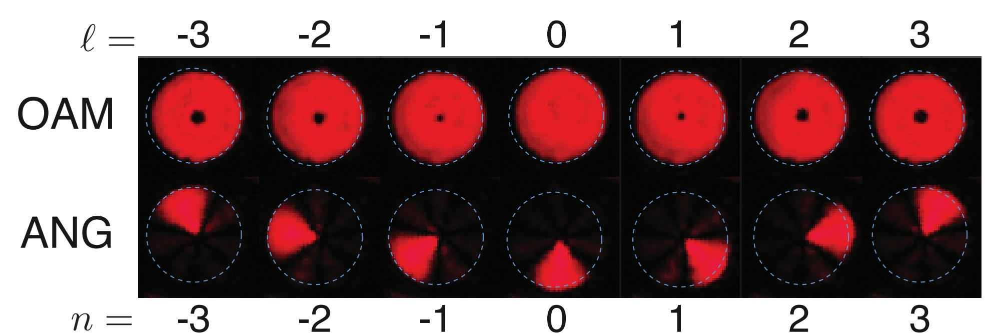
$$\Psi_{\mathrm{AB}}^{N} = \frac{1}{\sqrt{27}} \sum_{l=-13}^{13} \mathrm{LG}_{l,0} \exp\left(i 2\pi N l / 27\right)$$

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

063133602132045444456141026645
545050363603025261643215524164
230146602513401613222451551026

Bob

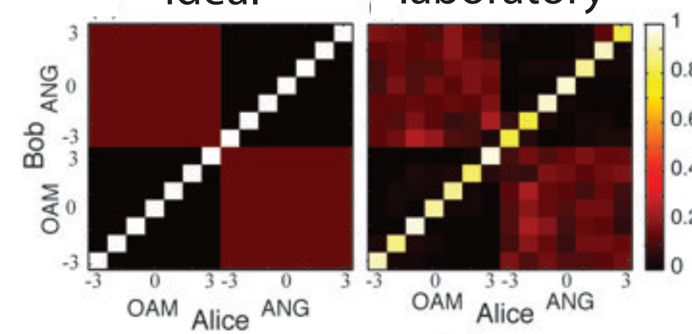
063033601132021444456141026645
545022353603025261643215524164
230146602515403613422451551026

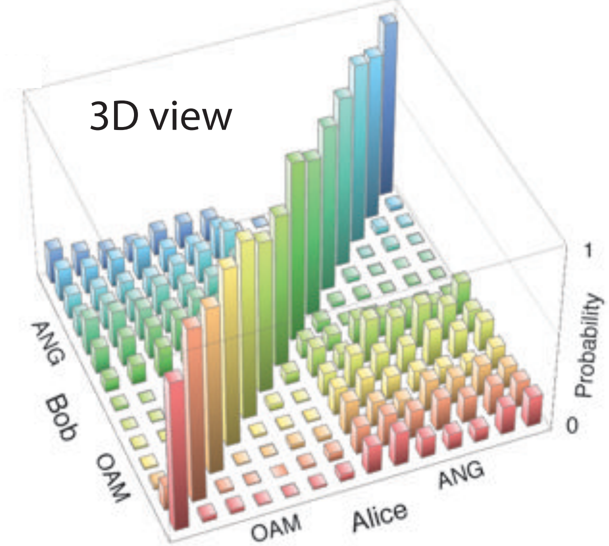
Error Correction

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

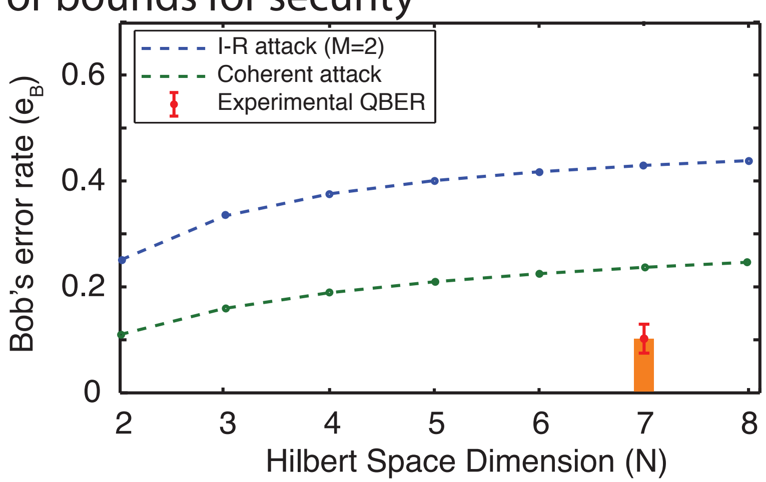
Privacy Amplification

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





- error bounds for security



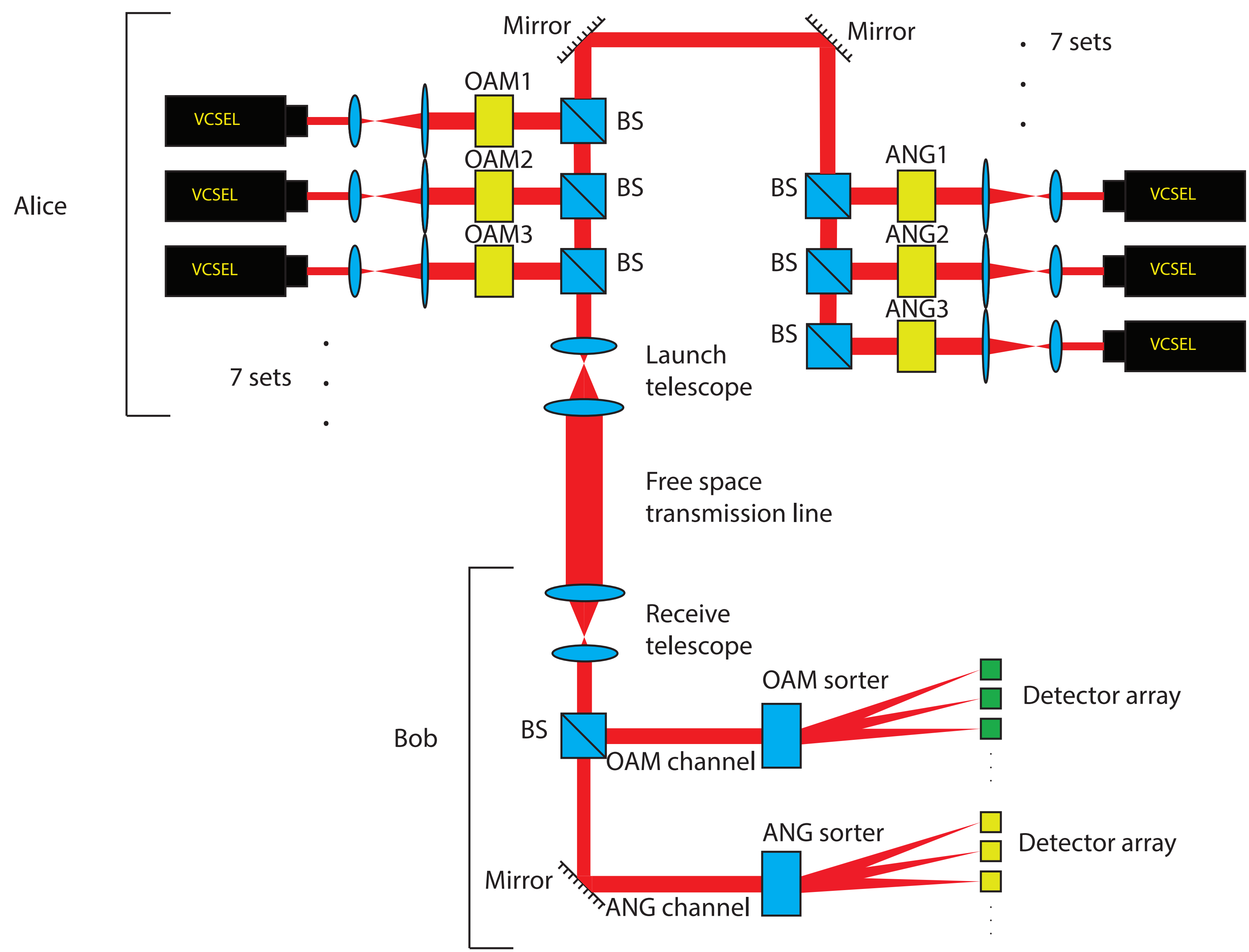
We use a 7-letter alphabet, and achieve a channel capacity of 2.1 bits per sifted photon.

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.



Thank you for your attention!