Outline of Presentation

Part I. Tutorial Introduction to Nonlinear Optics

Part II. Recent Research in Quantum Nonlinear Optics uOttawa | University of Glasgow | UNIVERSITY of ROCHESTER

Weak Values and Direct Measurement of the Quantum Wavefunction

Robert W. Boyd

University of Ottawa

University of Rochester

University of Glasgow

Collaborators:

University of Ottawa: Jonathan Leach,* Jeff Z. Salvail, Megan Agnew, Allan S. Johnson, Eliot Bolduc, Filippo M. Miatto

University of Rochester: Mehul Malik, Mohammad Mirhosseini, Omar Magana, Zhimin Shi,** Andrew Jordan, and Justin Dressel

University of Glasgow: Martin P. J. Lavery, Miles J. Padgett,

*Currently at Heriot-Watt University   **Currently at the University of South Florida

How the Result of a Measurement of a Component of the Spin of a Spin-$\frac{1}{2}$ Particle Can Turn Out to be 100

Yakir Aharonov, David Z. Albert, and Lev Vaidman
Physics Department, University of South Carolina, Columbia, South Carolina 29208, and School of Physics and Astronomy, Tel-Aviv University, Ramat Aviv 69978, Israel
(Received 30 June 1987)

We have found that the usual measuring procedure for preselected and postselected ensembles of quantum systems gives unusual results. Under some natural conditions of weakness of the measurement, its result consistently defines a new kind of value for a quantum variable, which we call the weak value. A description of the measurement of the weak value of a component of a spin for an ensemble of preselected and postselected spin-$\frac{1}{2}$ particles is presented.

PACS numbers: 03.65.Bz

standard expectation value: $< A >=< \Psi|\hat{A}|\Psi >$

weak value: $A_w \equiv \langle \psi_f | A | \psi_{\text{in}} \rangle / \langle \psi_f | \psi_{\text{in}} \rangle.$

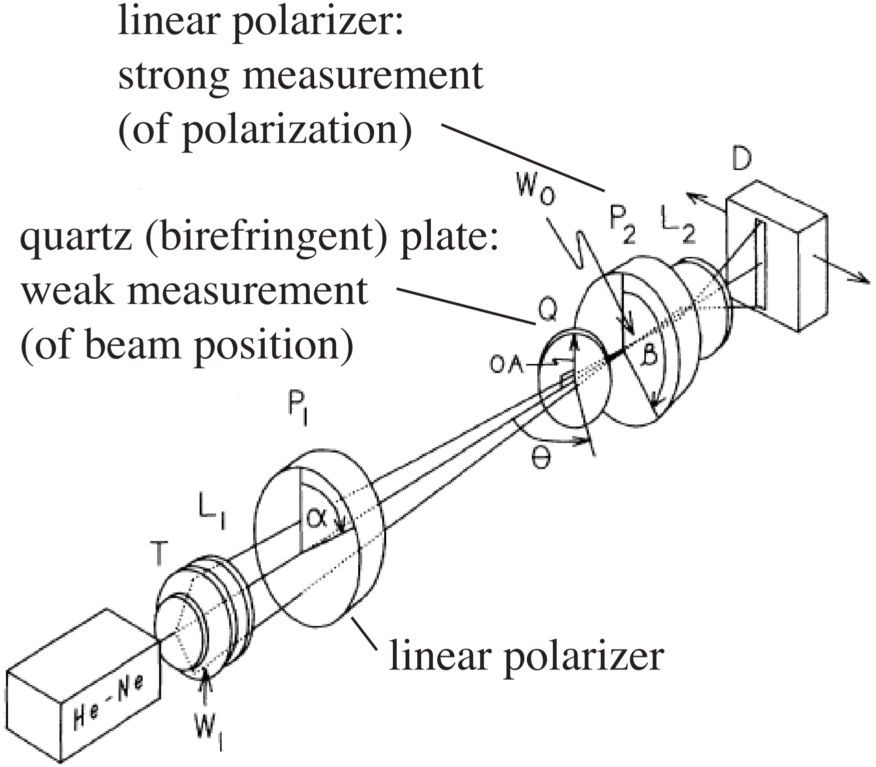
Why are weak values important?

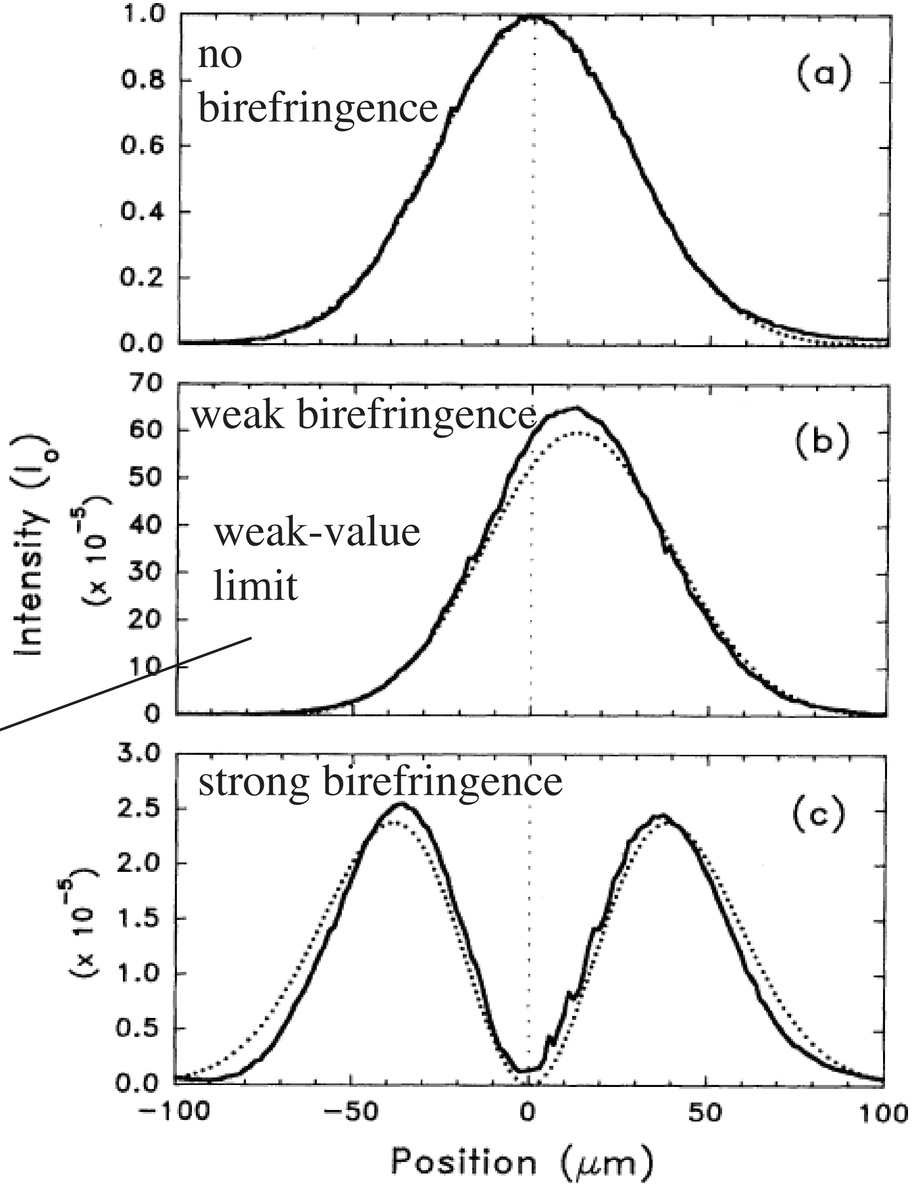
can lead to amplification of small signals

can lead to direct measurement of the quantum wavefunction

Realization of a Measurement of a "Weak Value"

N. W. M. Ritchie, J. G. Story, and Randall G. Hulet
Department of Physics and Rice Quantum Institute, Rice University, Houston, Texas 77251-1892
(Received 7 December 1990)





Birefringence separates polarized beams by 0.64 μm, but gaussian in (b) is displaced by 12 μm.

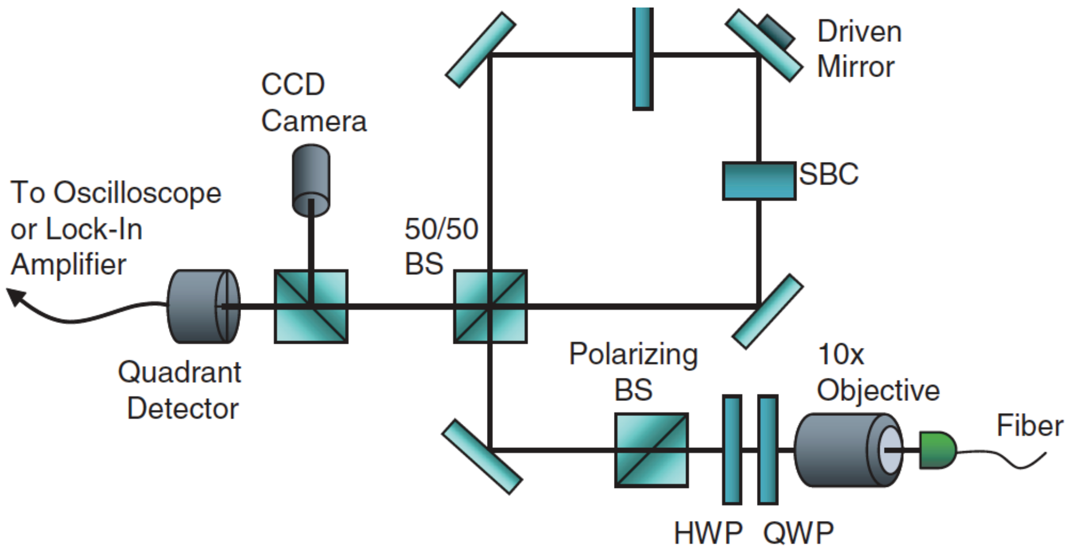
PRL 1991

Selected for a Viewpoint in *Physics*
PRL **102,** 173601 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Ultrasensitive Beam Deflection Measurement via Interferometric Weak Value Amplification

P. Ben Dixon, David J. Starling, Andrew N. Jordan, and John C. Howell
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA
(Received 12 January 2009; published 27 April 2009)

We report on the use of an interferometric weak value technique to amplify very small transverse deflections of an optical beam. By entangling the beam's transverse degrees of freedom with the which-path states of a Sagnac interferometer, it is possible to realize an optical amplifier for polarization independent deflections. The theory for the interferometric weak value amplification method is presented along with the experimental results, which are in good agreement. Of particular interest, we measured the angular deflection of a mirror down to 400 ± 200 frad and the linear travel of a piezo actuator down to 14 ± 7 fm.



Direct Measurement of the Quantum Wavefunction

The wavefunction of quantum mechanics is notoriously difficult to measure

Measurement at any one position causes the entire wavefunction to "collapse"

(The problem is related to the Heisenberg Uncertainty Relation; if you measure position you cannot also know momentum.)

Historically, the wavefunction has been measured only indirectly and inefficiently, using "quantum state tomography."

Recent work has demonstrated how to measure the wavefunction directly.

The idea is to perform a "weak measurement" on one variable (which thus only minimally disturbs the system), followed by a "strong measurement."

J. Lundeen et al., Nature 474, 188 (2011)
J. Z. Salvail et al., Nature Photonics, 10.1038 (2013)

LETTER

doi:10.1038/nature10120

Direct measurement of the quantum wavefunction

Jeff S. Lundeen[1], Brandon Sutherland[1], Aabid Patel[1], Corey Stewart[1] & Charles Bamber[1]

$$\langle A\rangle_{\mathrm{W}} = \frac{\langle c|A|\Psi\rangle}{\langle c|\Psi\rangle}$$

Returning to our example of a single particle, consider the weak measurement of position ($A = \pi_x = |x\rangle\langle x|$) followed by a strong measurement of momentum giving $P = p$. In this case, the weak value is:

$$\langle\pi_x\rangle_{\mathrm{W}} = \frac{\langle p|x\rangle\,\langle x|\Psi\rangle}{\langle p|\Psi\rangle} \tag{2}$$

$$= \frac{e^{ipx/\hbar}\,\Psi(x)}{\Phi(p)} \tag{3}$$

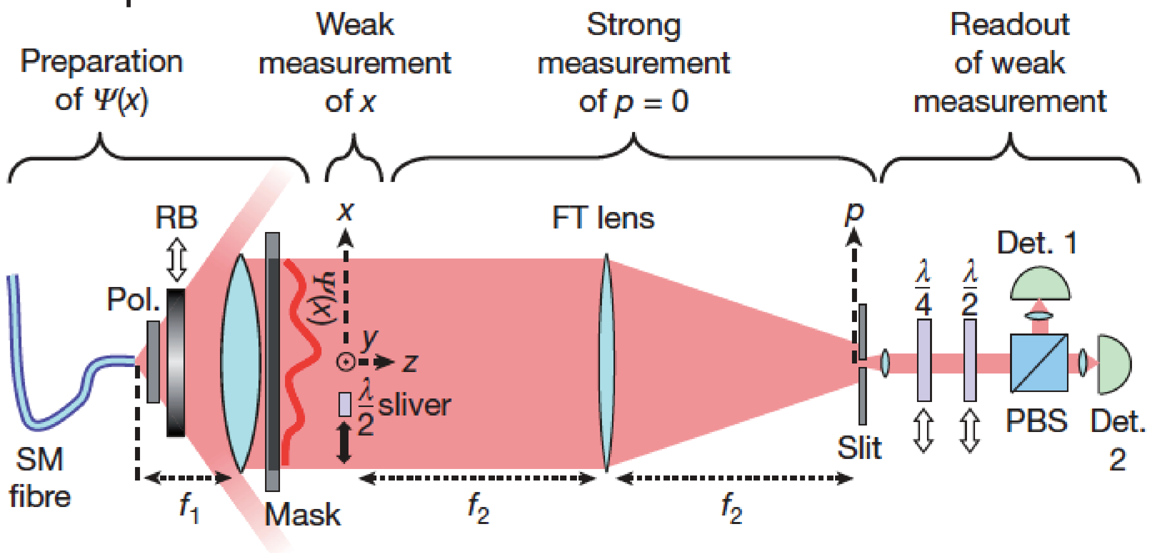
In the case $p = 0$, this simplifies to

$$\langle\pi_x\rangle_{\mathrm{W}} = k\Psi(x) \tag{4}$$

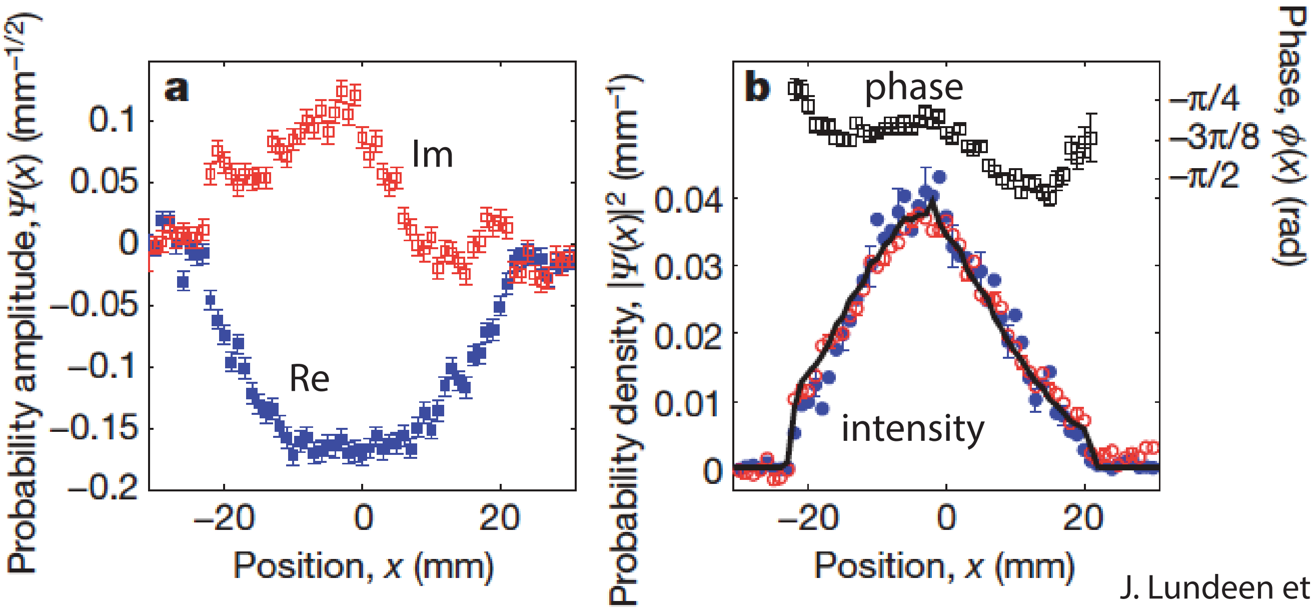
where $k = 1/\Phi(0)$ is a constant (which can be eliminated later by normalizing the wavefunction). The average result of the weak mea-

Direct Measurement of the Photon "Wavefunction"

Measurement setup



Typical results



J. Lundeen et al., Nature 474, 188 (2011)

Wavefunction of the Photon?

Many people feel it is inaccurate to speak of the "wavefunction" of the photon.

I personally try to avoid the term wavefunction of the photon. A photon is an excitation of a mode of the field. I prefer to distinguish the photon from the mode in which it lives.

Lundeen et al. use the term "wavefunction of the photon," but comment that it is sometimes called the "spatial mode of the photon."

See also Iwo Bialynicki-Birula, The Photon Wave Function, Coherence and Quantum Optics VII, Eds. J. H. Eberly, L. Mandel, and E. Wolf Plenum, NY 1996, p. 313

Work of My Own Group

1. We have made a direct measurement of the state of polarization of the photon. This is thus the first direct measurement of a qubit.

2. We have measured the statevector of a state imbedded in a 27-dimensional OAM Hilbert space. One expects direct measurement to be increasingly useful with increasing size of the Hilbert space.

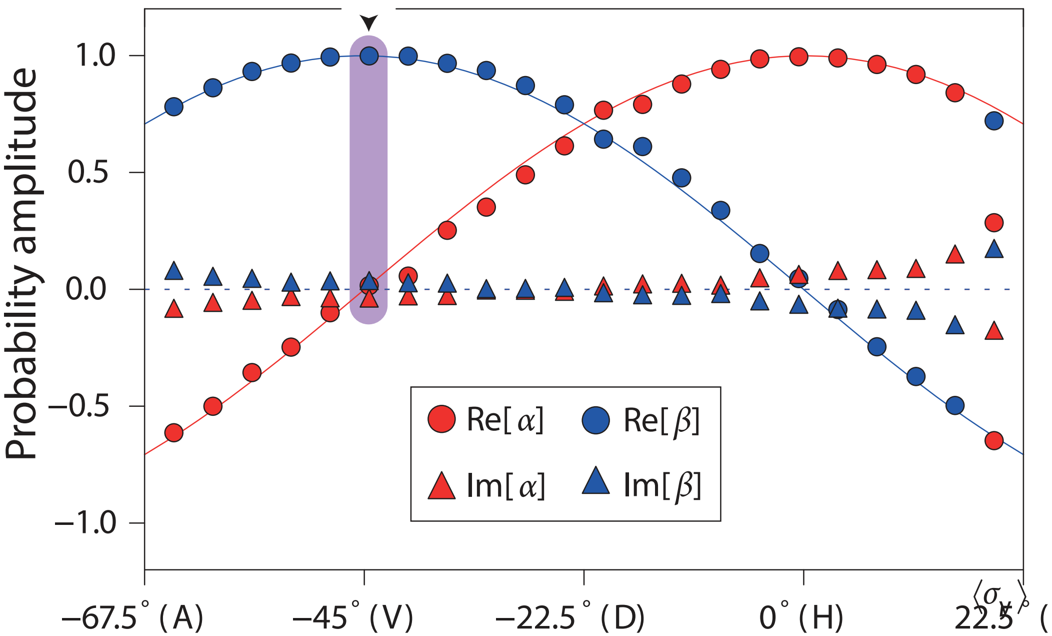
nature photonics | ARTICLES
PUBLISHED ONLINE: 3 MARCH 2013 | DOI: 10.1038/NPHOTON.2013.24

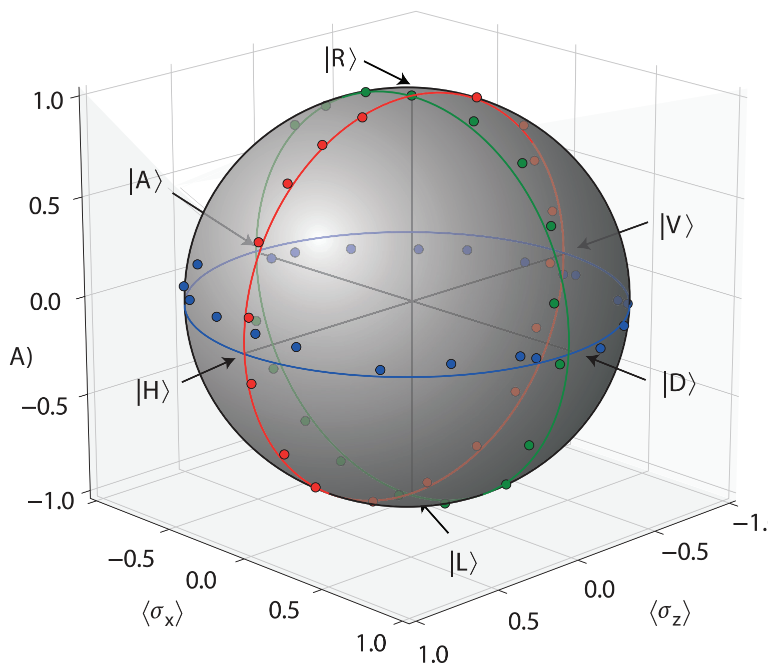
Full characterization of polarization states of light via direct measurement

Jeff Z. Salvail[1]*, Megan Agnew[1], Allan S. Johnson[1], Eliot Bolduc[1], Jonathan Leach[1] and Robert W. Boyd[1,2]

$$|\psi\rangle = \alpha|H\rangle + \beta|V\rangle.$$

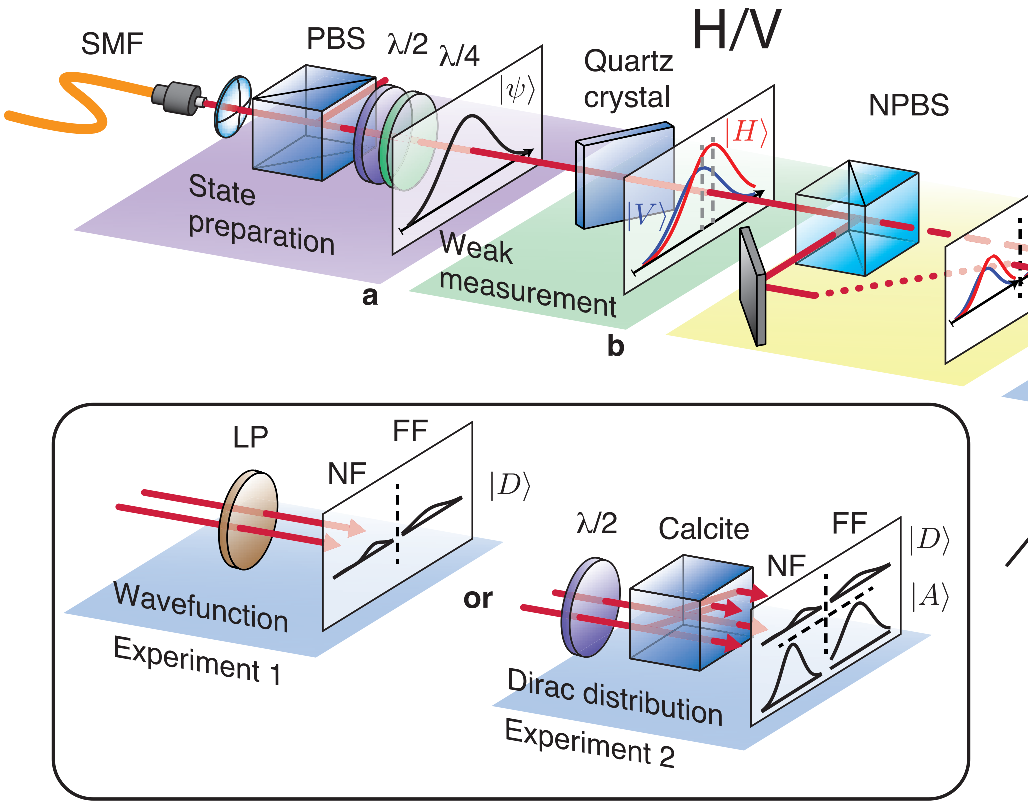
points on Poincaré sphere

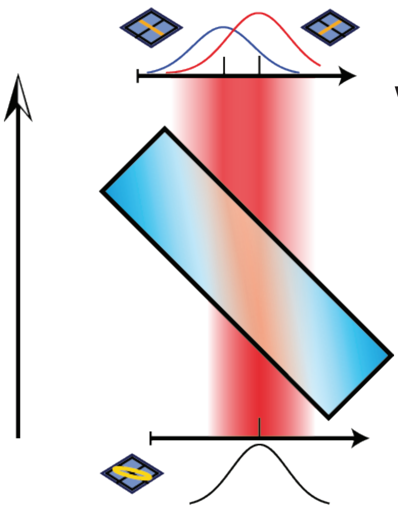




Half-wave plate angle (input polarization state)

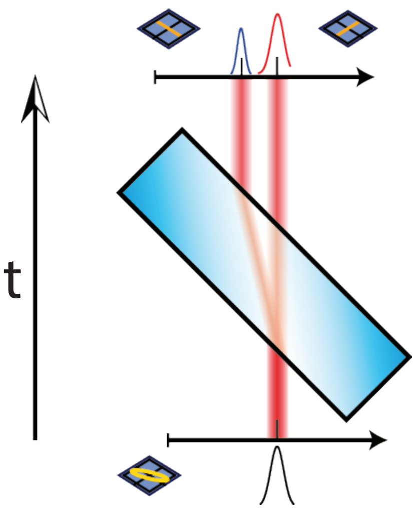
Experimental Setup





weak measurement

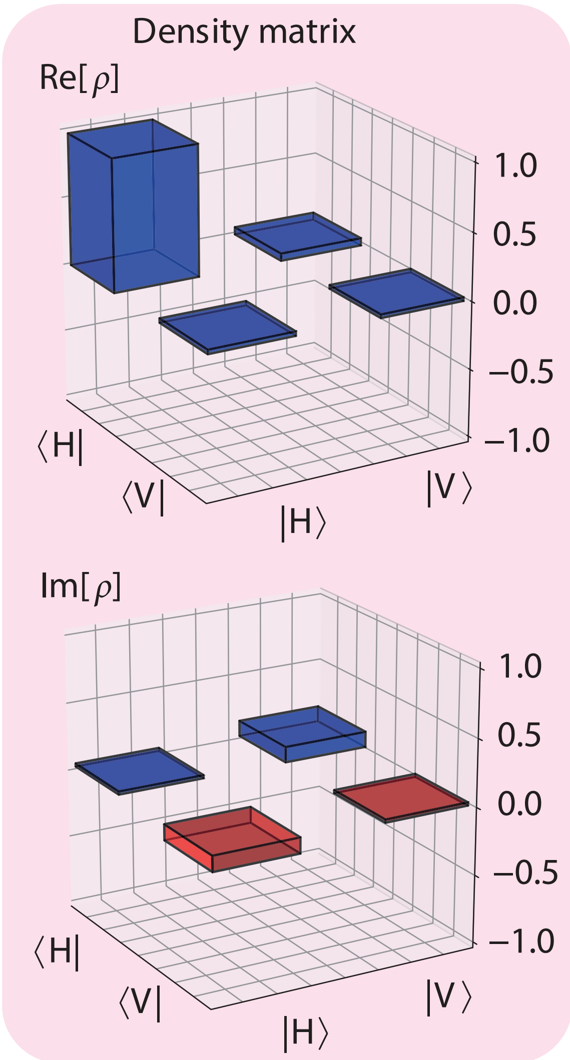
strong measurement



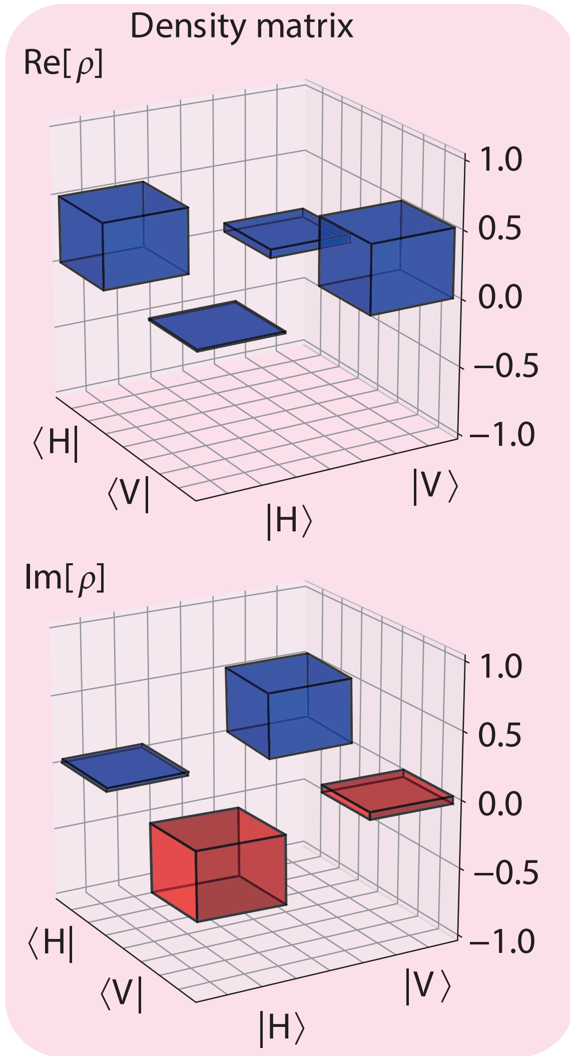
Direct Measurement of the Full Density Matrix

Meaurement provides enough information to determine density matrix*

Horizontal polarization



Left-hand-circular polarization



* J.S. Lundeen & C. Bamber, Phys. Rev. Lett. 108, 070402 (2012).

News Accounts of Our Work

physicsworld.com

First weak measurements made on optical polarization states

Mar 11, 2013 4 comments

Physicists in Canada and the US claim to be the first to make a direct measurement of the polarization quantum state of light – a feat that at first glance appears to defy Heisenberg's uncertainty principle. The technique, which relies on a process known as weak measurement, could help in fundamental studies on quantum mechanics or in the development of quantum computing.

NATIONAL POST

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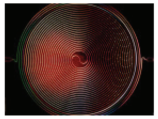
JEFF SALVAIL

Canadian researchers take a sneak peek at Schrödinger's Cat and a step toward a quantum computer



In an Ottawa lab, scientists have succeeded in side-stepping an obstacle of Heisenberg's Uncertainty Principle, a strange law of the quantum world

Lawrence Krauss: The Large Hadron Collider helps science do a quantum leap

Neil Turok: Furthering our understanding of the universe

Freezing antimatter could allow scientists to study the strangest stuff in existence: Canadian researcher

SCIENCE RECORDER

BIOLOGY GEOLOGY SPACE PHYSICS CHEMISTRY HEALTH PA

Scientists discover a way around Heisenberg's Uncertainty Principle

A new technique for quantum mechanics.

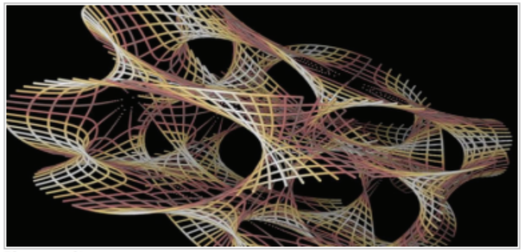


Photo credit:

Science Recorder | Mark Petillo | **Monday, March 04, 2013**

It could be big news of the world of quantum physics. According to a pair of scientists from the University of Rochester and the University of Ottawa, there may be a way around Heisenberg's famous Uncertainty Principle. According to a report published this week in *Nature Photonics*, a recently developed technique that allows scientists to directly measure the polarization states of light could be the key… **To continue reading, subscribe to *Science Recorder* today.**

Work of My Own Group

1. We have made a direct measurement of the state of polarization of the photon. This is thus the first direct measurement of a qubit.

2. We have measured the statevector of a state imbedded in a 27-dimensional OAM Hilbert space. One expects direct measurement to be increasingly useful with increasing size of the Hilbert space.

Malik, Mirhosseini, Lavery, Leach, Padgett, Boyd, in review

High Dimensional QKD Protocol

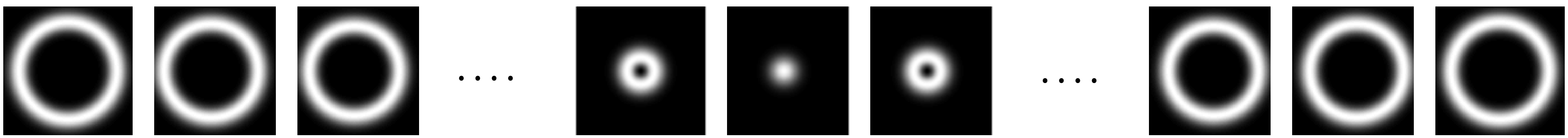
We are constructing a QKD system in which each photon carries many bits of information

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

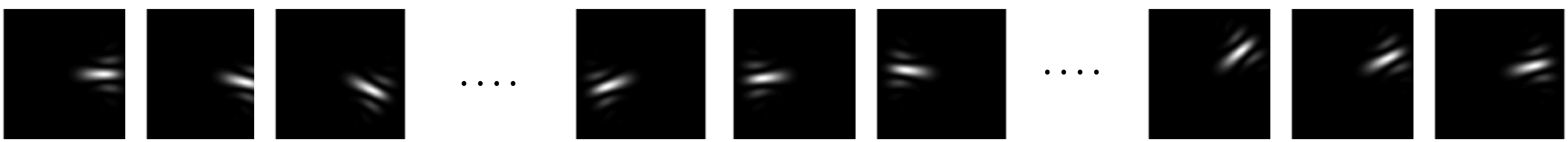
<u>Single Photon States</u>

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



0 1 2 12 13 14 25 26 27

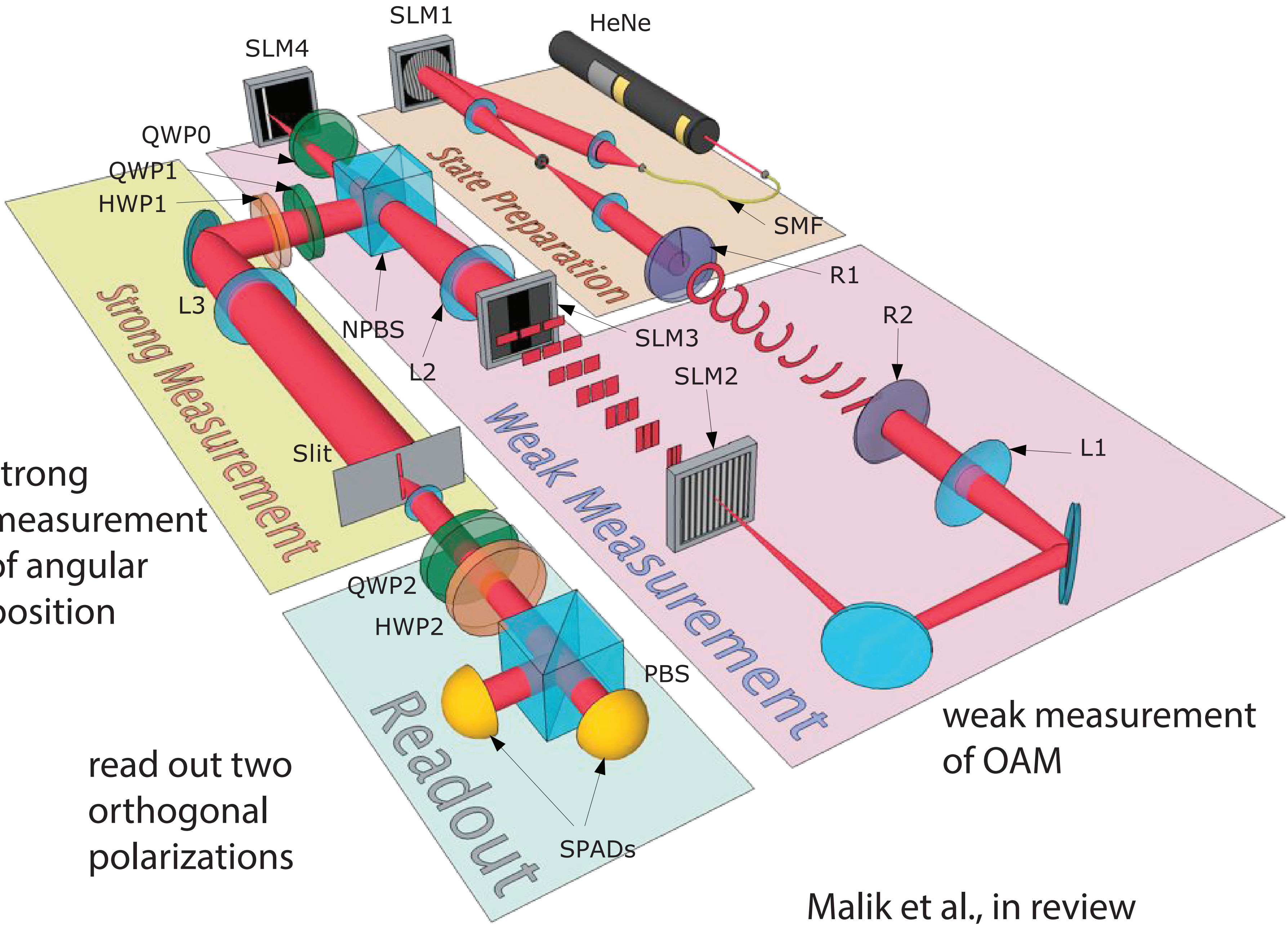
"Angular" Basis (mutually unbiased with respect to LG)



0 1 2 12 13 14 25 26 27

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

Direct Measurement of a High-Dimensional OAM State



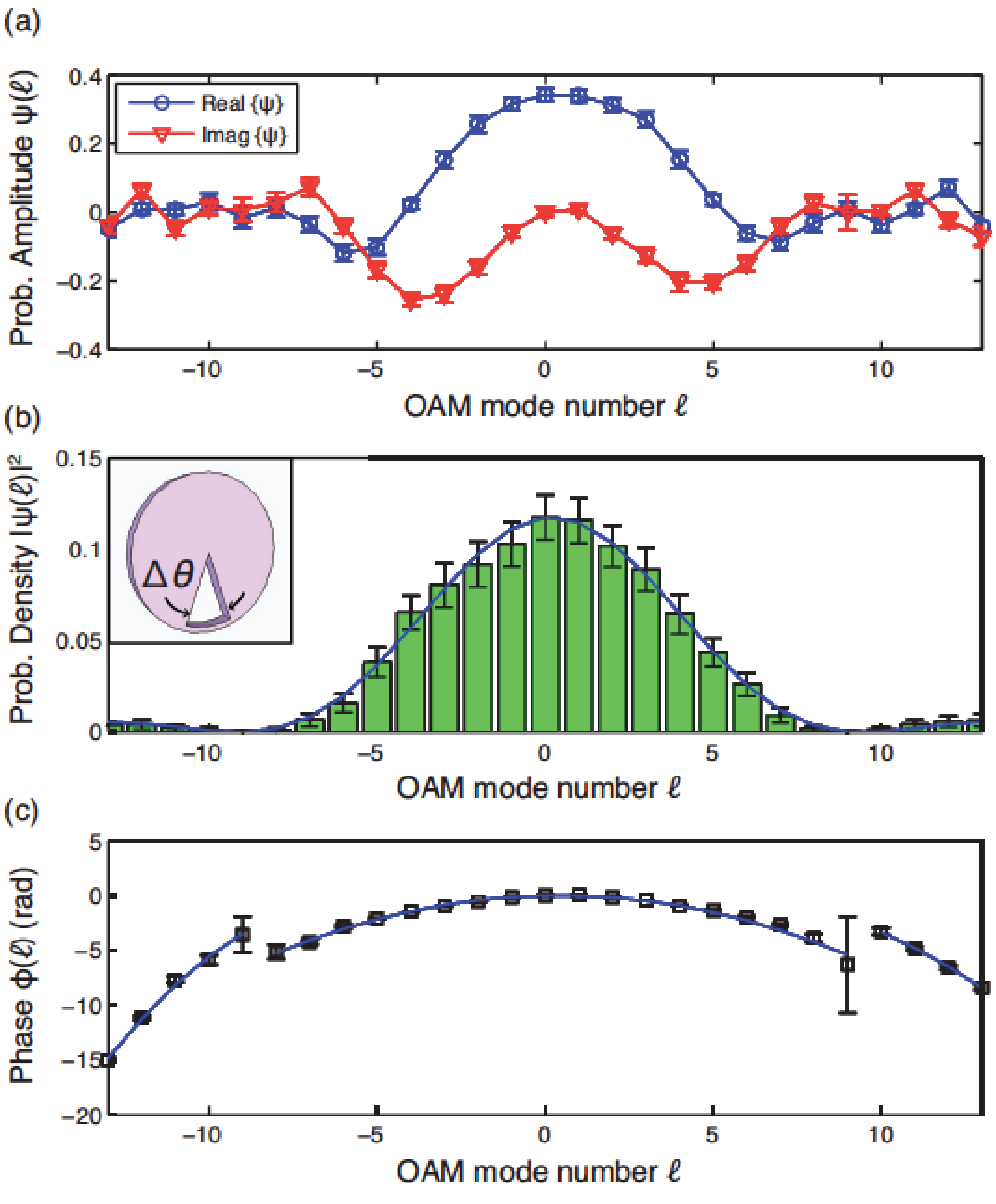
strong measurement of angular position

weak measurement of OAM

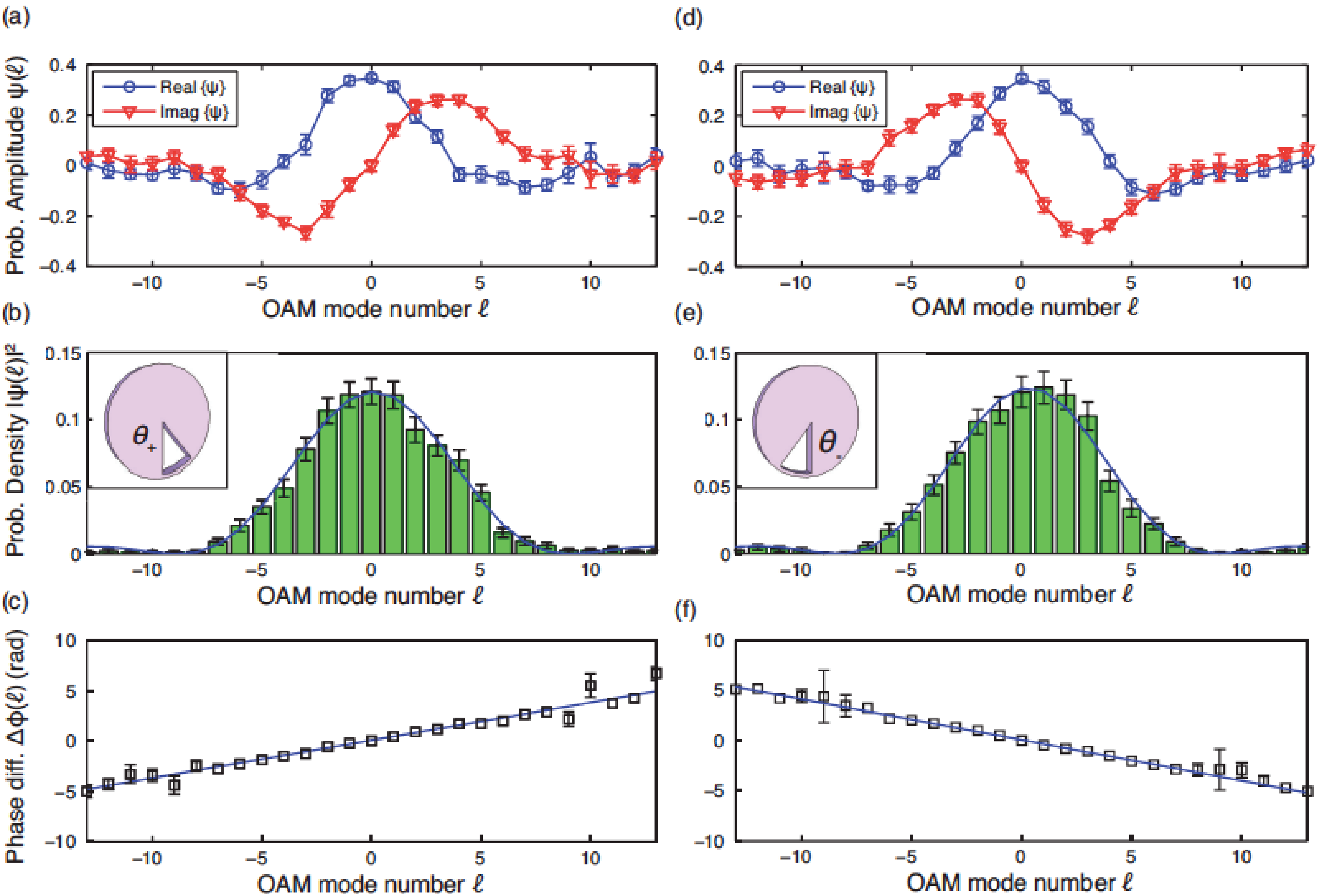
read out two orthogonal polarizations

Malik et al., in review

Results: Direct Measurement of a High-Dimensional OAM State



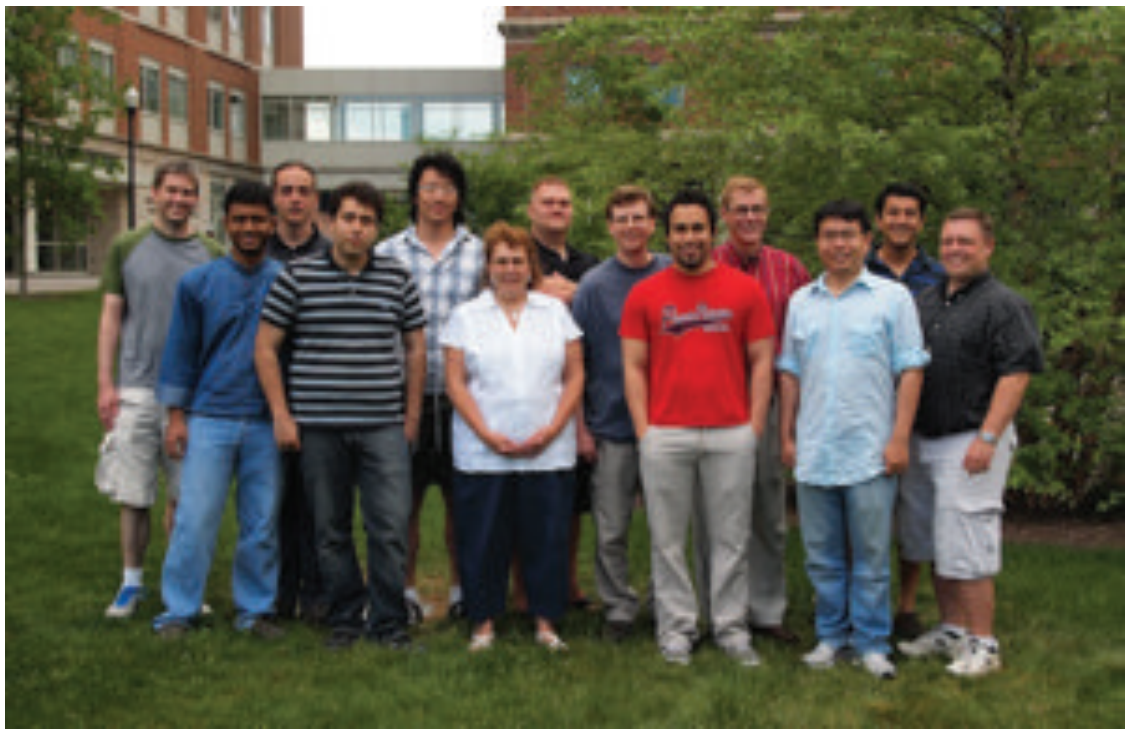
Direct Measurement Procedure Properly Measures Phase



Summary

Weak values and weak measurements offer important opportunities in quantum optics, including the ability to “amplify” weak signals and the ability to perform direct measurements of the quantum state vector.

Thanks To My Research Groups



Rochester

Ottawa

Quantum Photonics

(Encompassing nanophotonics and quantum nonlinear optics)

Robert Boyd

Canada Excellence Research Chair in Quantum Nonlinear Optics

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

University of Ottawa Nonlinear Photonics Programme - Senior Staff

Robert Boyd
CERC

Ksenia Dolgaleva
Asst. Prof.

Jeff Lundeen
Asst. Prof.

????

Gerd Leuchs
Adjunct Prof.

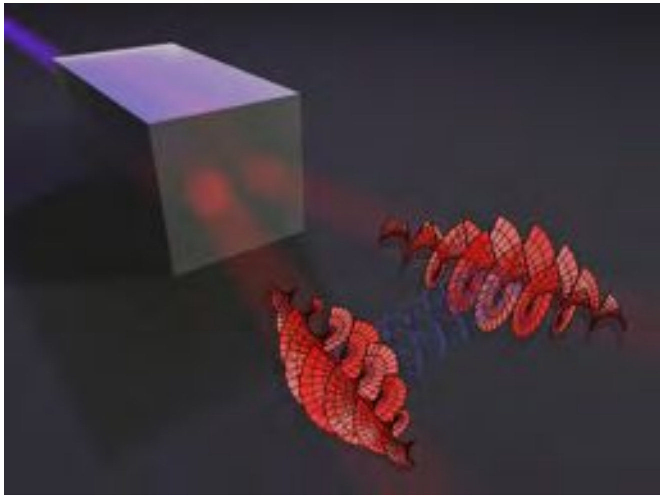
Jeremy Upham
Staff Scientist

Our Quantum Information Program

A Quantum Key Distribution (QKD) System Utilizing Orbital Angular Momentum (OAM) States of Light to Carry Many Bits of Information per Photon.

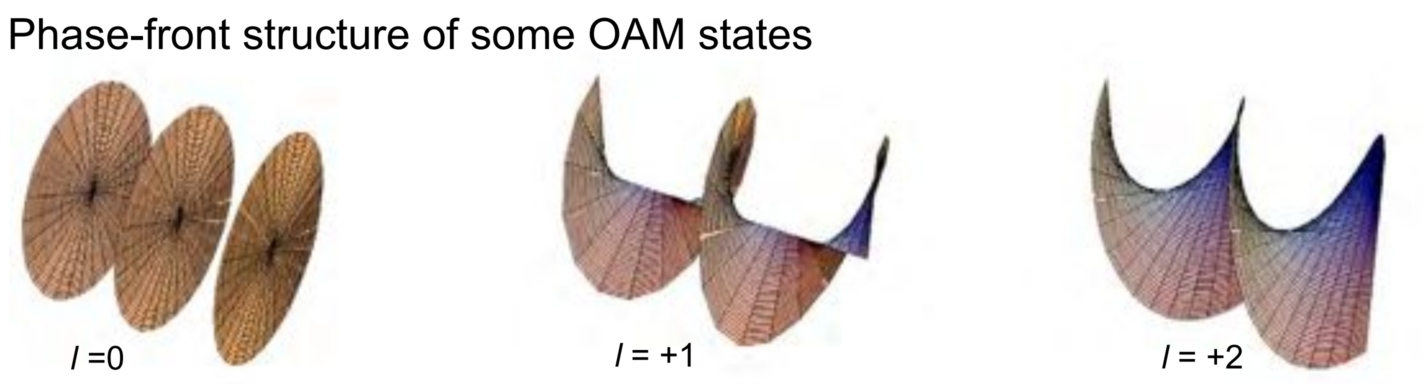
Role of Light Beams Carrying OAM in Quantum Information Science

- Brief overview of orbital angular momentum (OAM) of light
- Use of OAM states for high capacity quantum key distribution (QKD)
  - Can we build a QKD system that carries many bits per photon?
  - In traditional telecom, one uses many photons per bit!
- If time permits, description of some related work



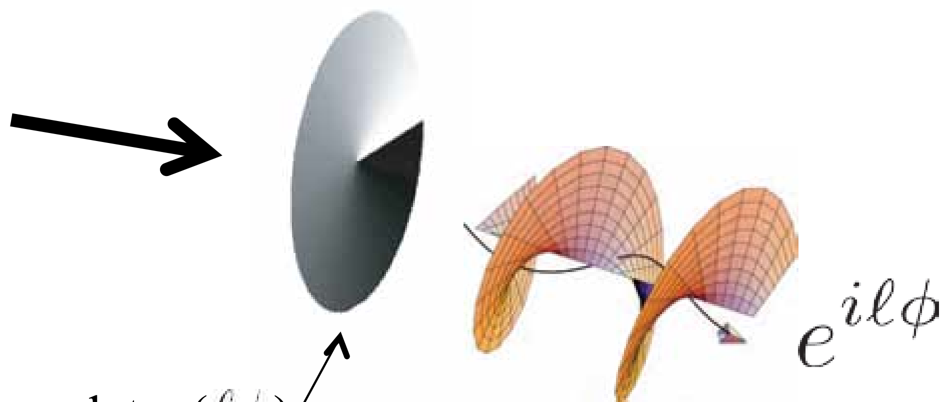
What Are the OAM States of Light?

- Light can carry spin angular momentum (SAM) by means of its circular polarization.
- Light can also carry orbital angular momentum (OAM) by means of the phase winding of the optical wavefront.
- A well-known example are the Laguerre-Gauss modes. These modes contain a phase factor of $\exp(il\phi)$ and carry angular momentum of $l\hbar$ per photon. (Here ϕ is the azimuthal coordinate.)



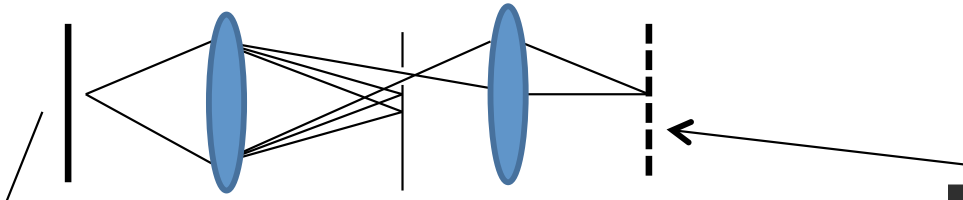
How to create a beam carrying orbital angular momentum?

Pass beam through a spiral phase plate

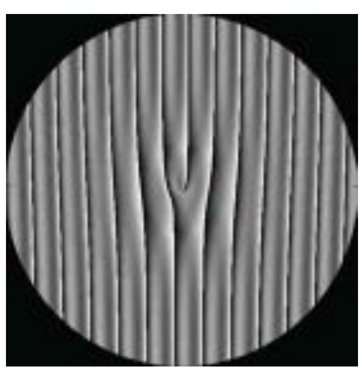


Spiral phase plate ($\ell\phi$)

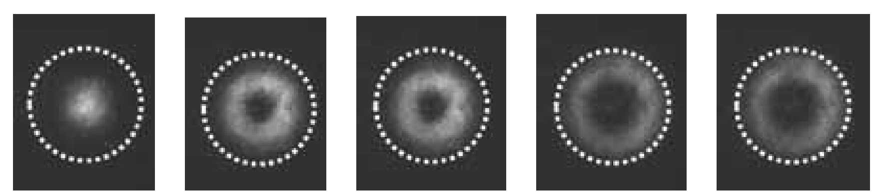
Use a spatial light modulator acting as a computer generated hologram
(more versatile)



LG



Laguerre-Gauss



E. Bolduc, N. Bent, E. Santamato, E. Karimi, and R. W. Boyd, Optics Letters 38, 3546 (2013).

OAM States and Quantum Key Distribution

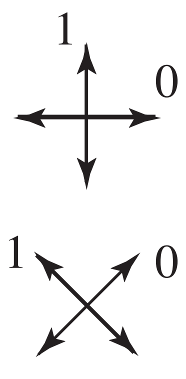
- The most widely studied protocol is that of Bennett and Brassard (1984), known as the BB84 protocol. It makes use of measurements performed on a single photon, but in more than one set of bases.
- Our work involves an extension of the BB84 protocol by making use of the OAM states of light. One motivation is to increase the data transfer rate by impressing more than one bit per photon.
- Let us begin by reviewing the BB84 protocol.

The BB84 QKD Protocol – Polarized Light Implementation

Alice sends an individual photon in one of two polarization bases, chosen at random

x-y basis

diagonal-anti-diagonal basis

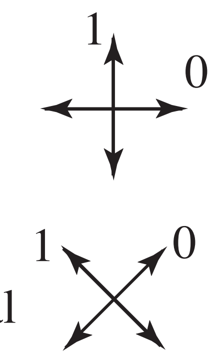


transmission

Bob receives in one of two polarization bases, which he choses at random

x-y basis

diagonal-anti-diagonal basis

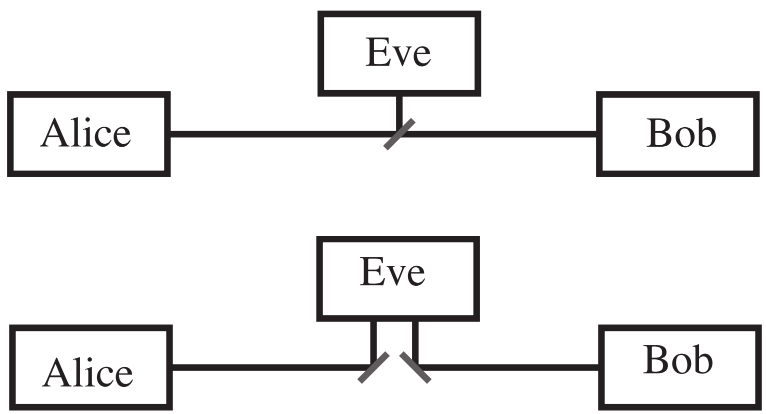


After sending the entire string of numbers that constitutes the key, Alice and Bob openly divulge the basis that they used for each measurement. If they chose different bases, they discard the result of that measurement. (The remaining data is known as sifted data.)

Why Is This Protocol Secure?

- Suppose that an eavesdropper (Eve) intercepts the transmission. Since only one photon was transmitted, Bob will know that the message was intercepted, because he does not receive Alice's photon.

- To avoid divulging her presence in such an obvious manner, Eve can resend the photon after she intercepts it. But Eve has no guarantee that she will be sending the photon in the same basis as that used by Alice. And if she choses wrong, Alice and Bob will realize that there is a problem.



QKD System Carrying Many Bits Per Photon

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

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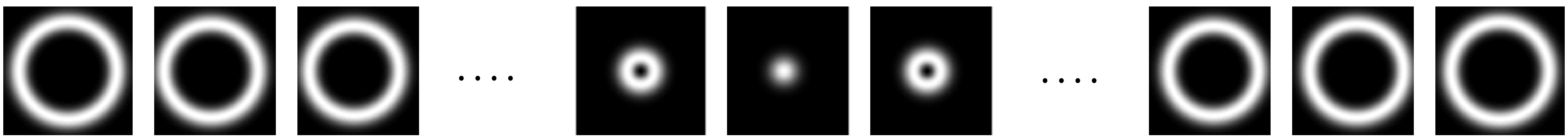
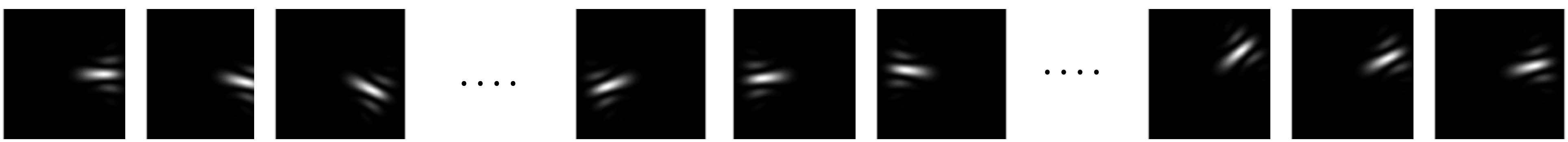


0 1 2 .... 12 13 14 .... 25 26 27

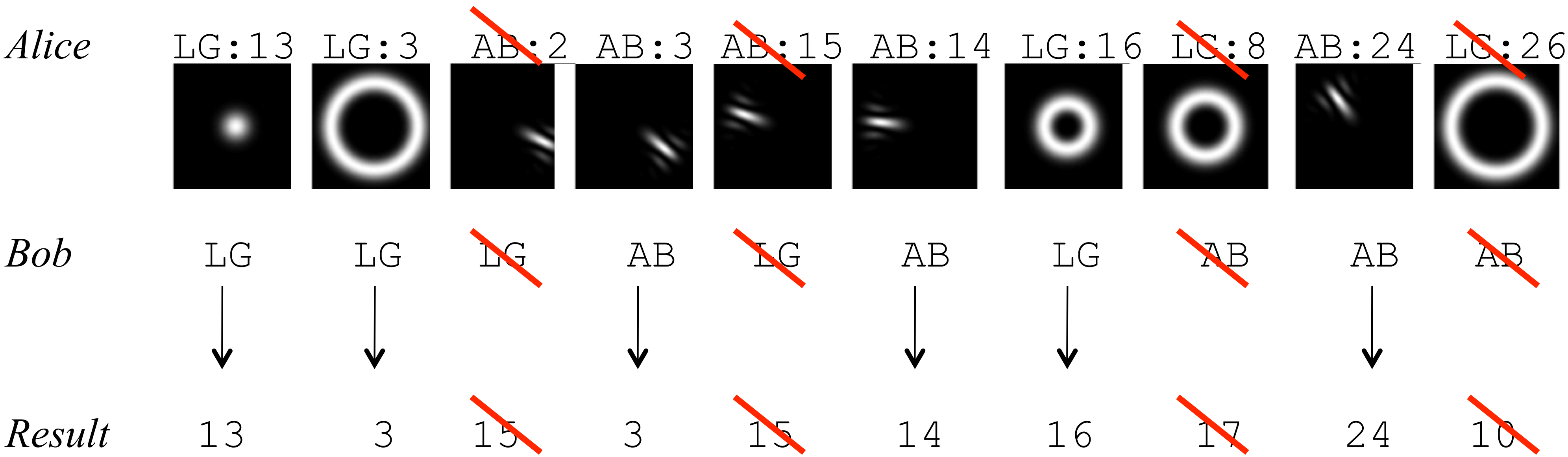
"Angular" Basis (mutually unbiased with respect to LG)



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

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

Protocol



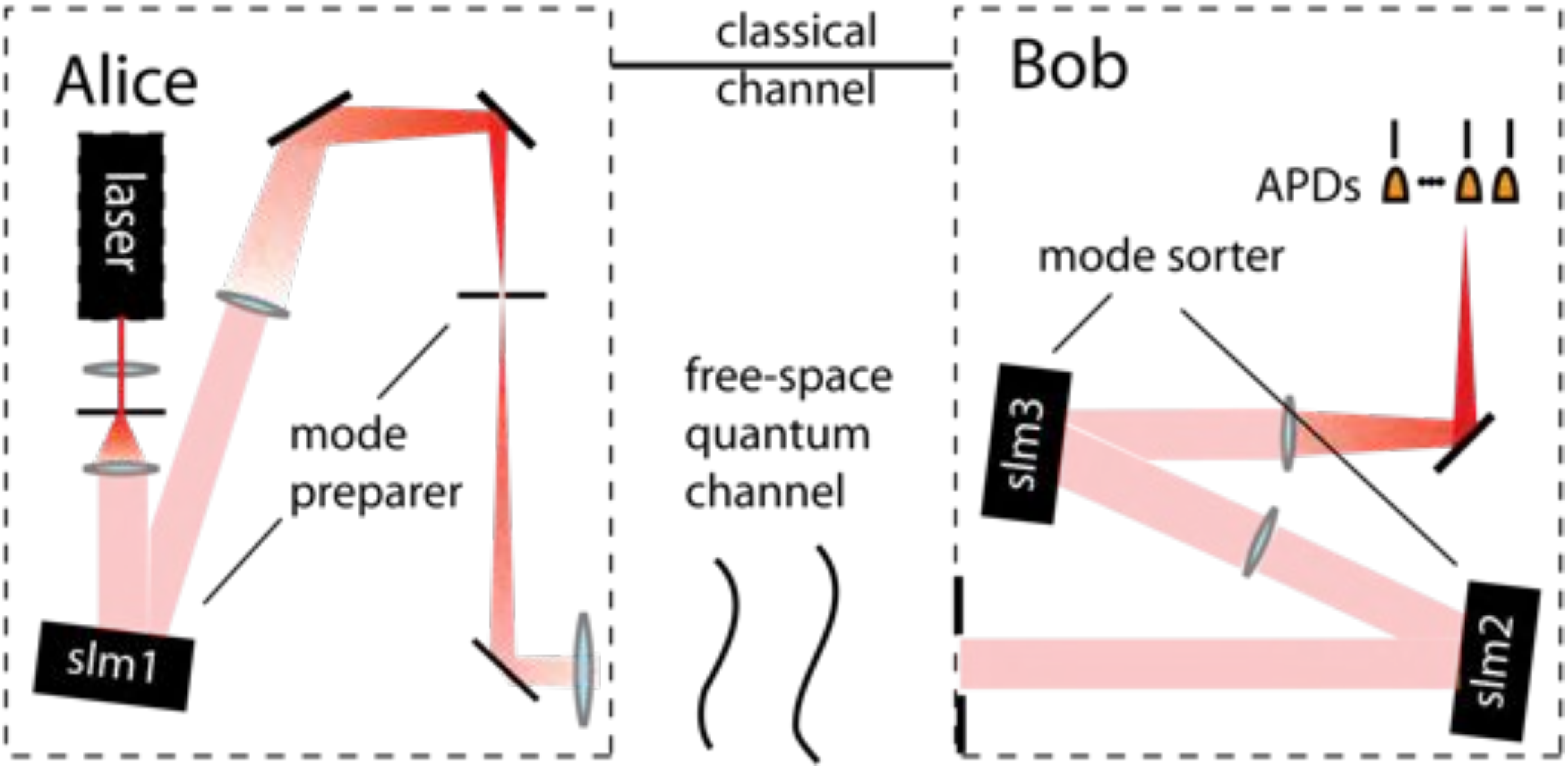
Sifted Key 13 3 3 14 16 24 … ← in principle contains no errors unless eavesdropper is present.

In any real system, Bob's key will have errors due to system imperfections.

1. Error Correction (Cascade Protocol)
2. Privacy Amplification

Under many conditions, these protocols can be successfully implemented if Alice/Bob share more bits of information than Alice and Eve.

Spatially-Based QKD System



<u>Source</u>

Weak Coherent Light

Heralded Single Photon

<u>Protocol</u>

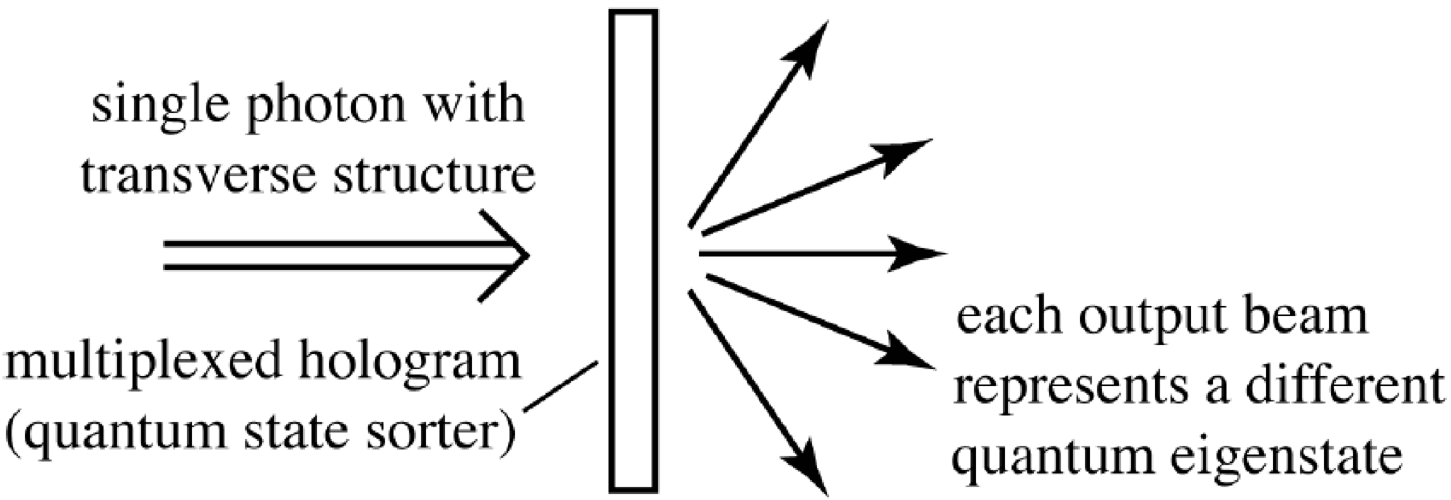
Modified BB84 as discussed

<u>Challenges</u>

1. State Preparation
2. State Detection
3. Turbulence

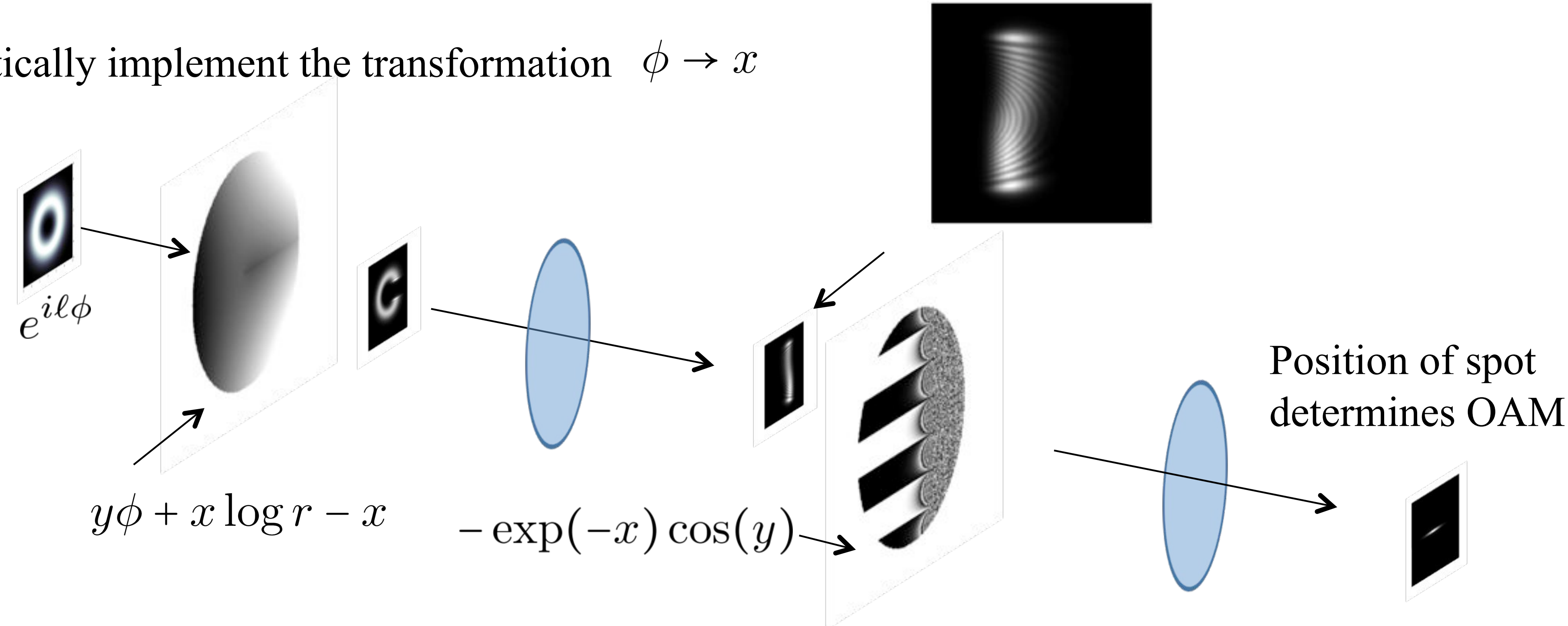
Mode Sorting

A mode sorter

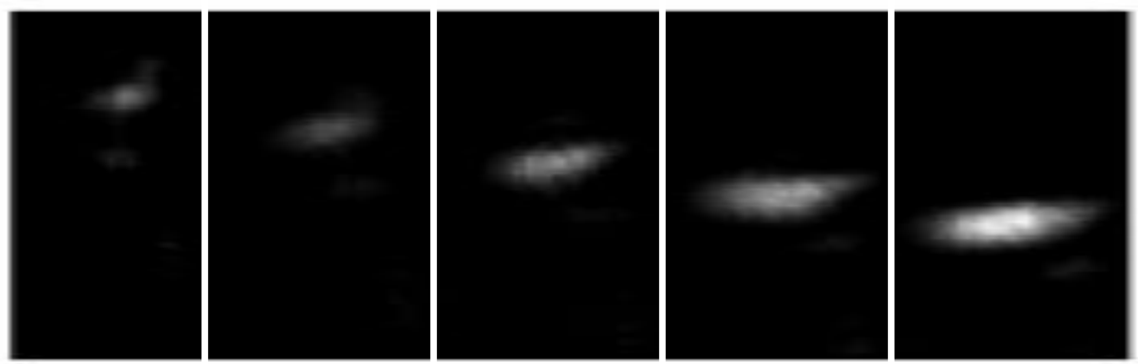


Sorting OAM using Phase Unwrapping

Optically implement the transformation $\phi \to x$



Experimental Results (CCD images in output plane)



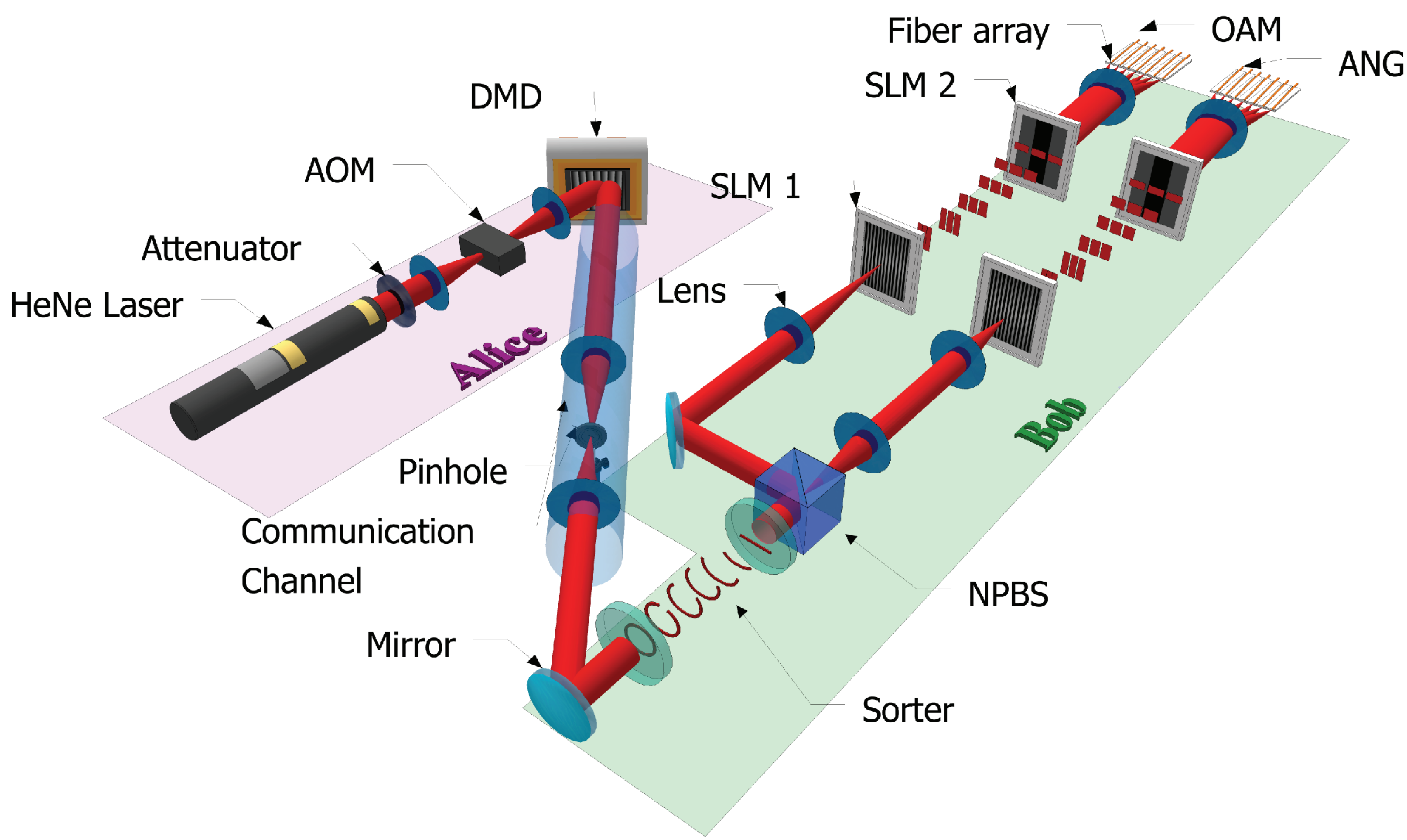
$\ell = 1$ $\ell = 2$ $\ell = 3$ $\ell = 4$ $\ell = 5$

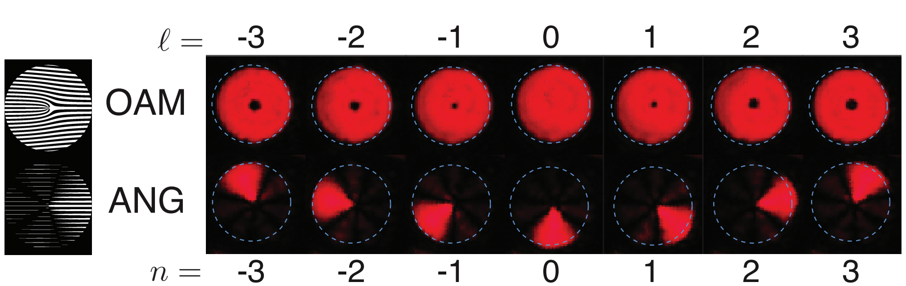
-Can also sort angular position states.

-Limited by the overlap of neighboring states.

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

Laboratory Setup





Laboratory Results - OAM-Based QKD

Alice	Bob
063133602132045444456141026645 545050363603025261643215524164 230146602513401613222451551026	063033601132021444456141026645 545022353603025261643215524164 230146602515403613422451551026

Error Correction

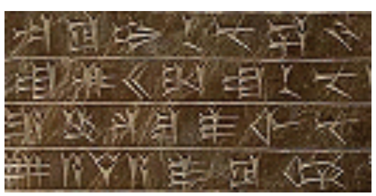
0000 0100 0111 0100 0101 0001 1100 0010 1100 1001 0010 0100 1101 0001 0000
0001 0011 0100 0000 0100 0010 0001 0001 0011 0000 0101 0010 0111 1000 0101
1101 0011 0001 1001 1011 0101 0000 0100 0111 0100 0011 0110 0101 0000 1101
0101 0010 1111 1010 1111 0010 1000

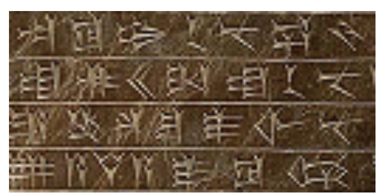
Privacy Amplification

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

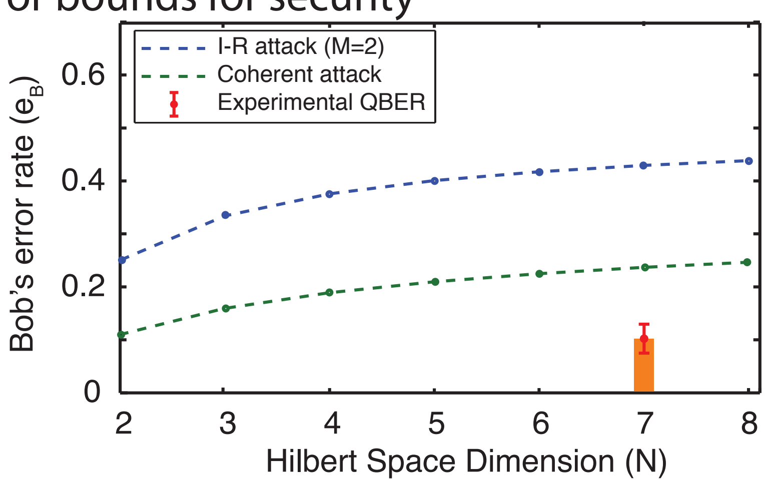
Alice Encrypts

Bob Decrypts

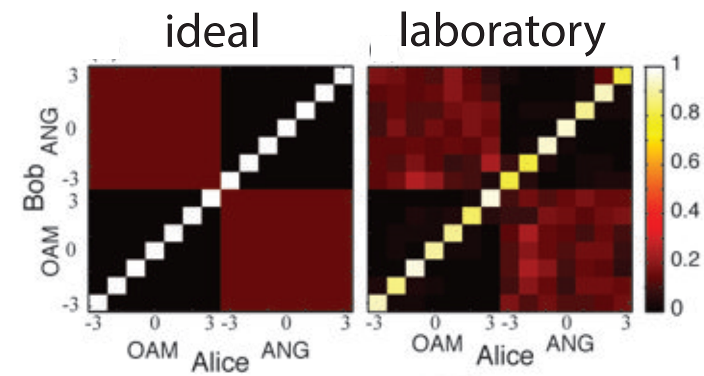


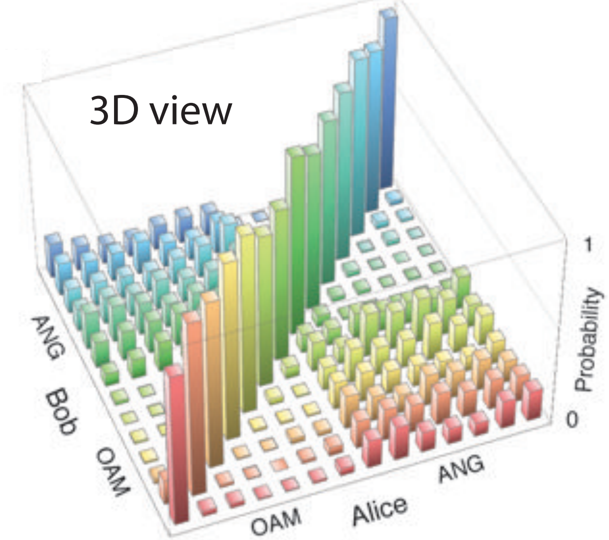


- error bounds for security



cross-talk matrices





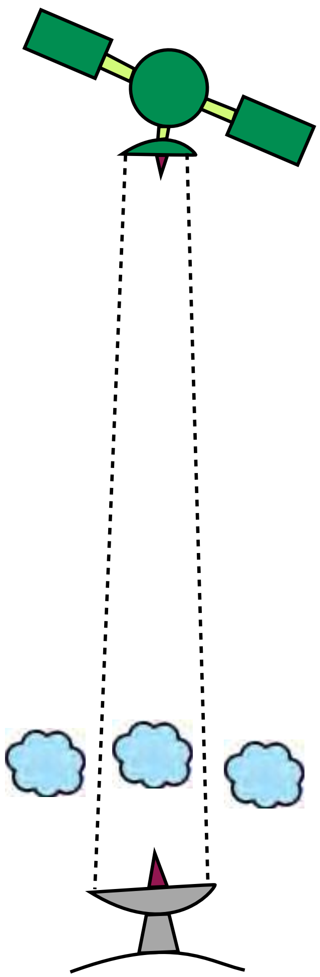
We use a 7-letter alphabet, and achieve a channel capacity of 2.1 bits per sifted photon.

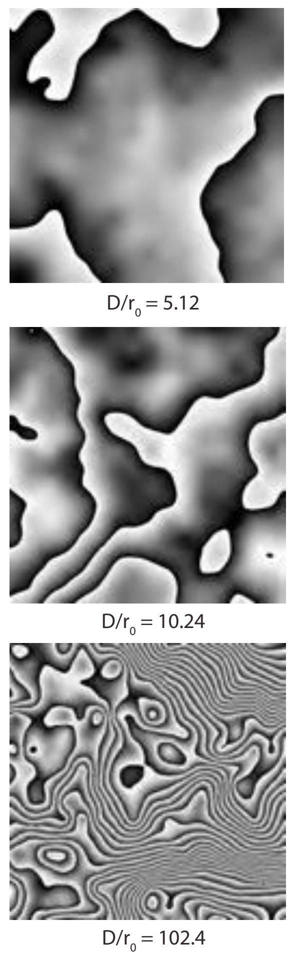
We do not reach the full 2.8 bits per photon for a variety of reasons, including dark counts in our detectors and cross-talk among channels resulting from imperfections in our sorter.

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

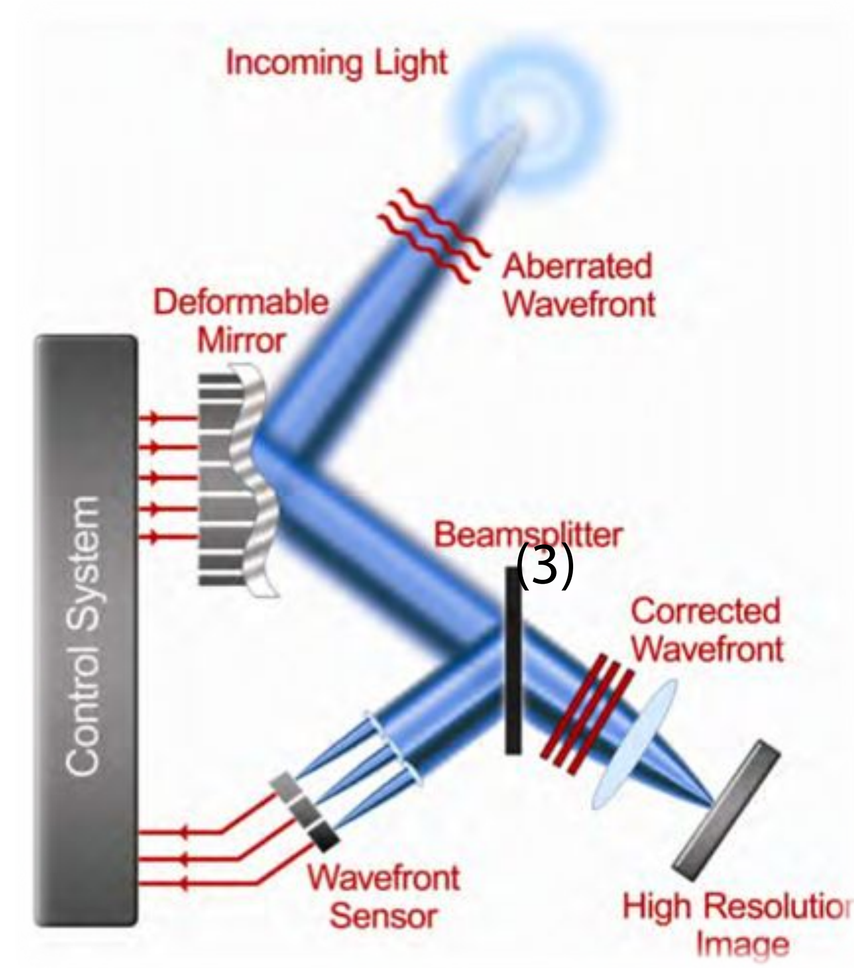
Turbulence and Adaptive Optics

Atmospheric Turbulence Model





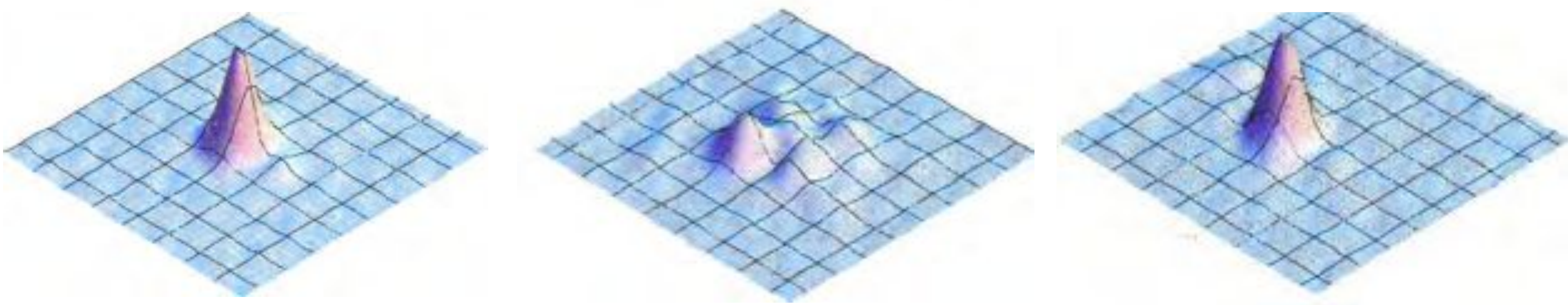
Our Adaptive Optics System



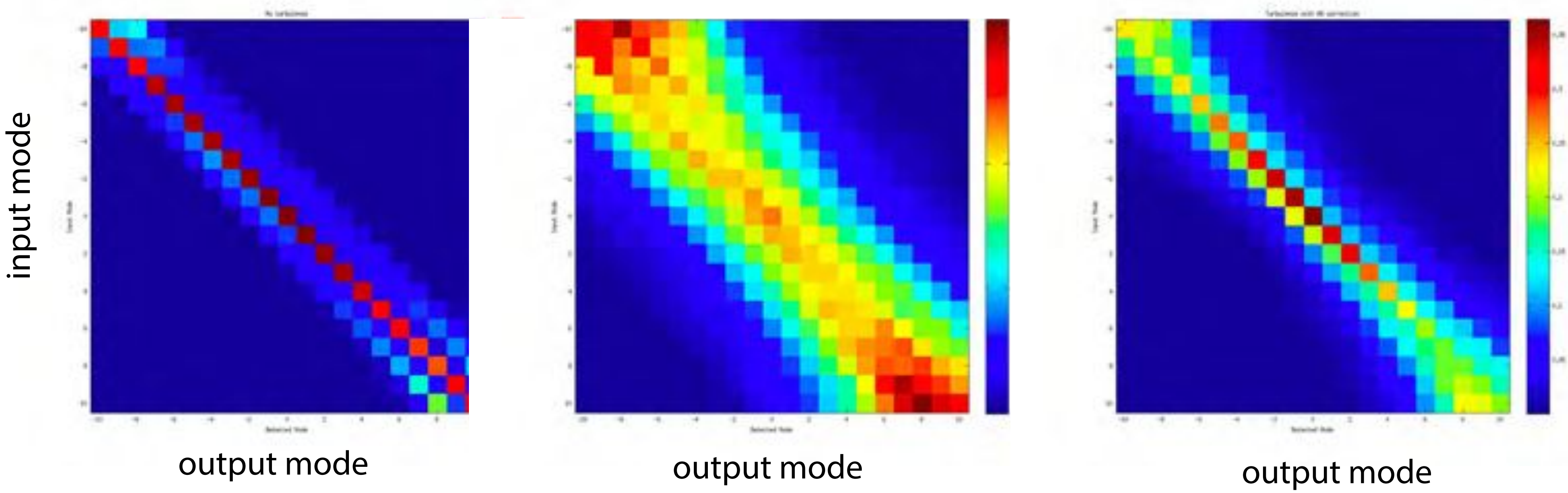
Improved QKD Performance Using Adaptive Optics

Before turbulence | After turbulence | After adaptive optics correction

- focal plane distribution

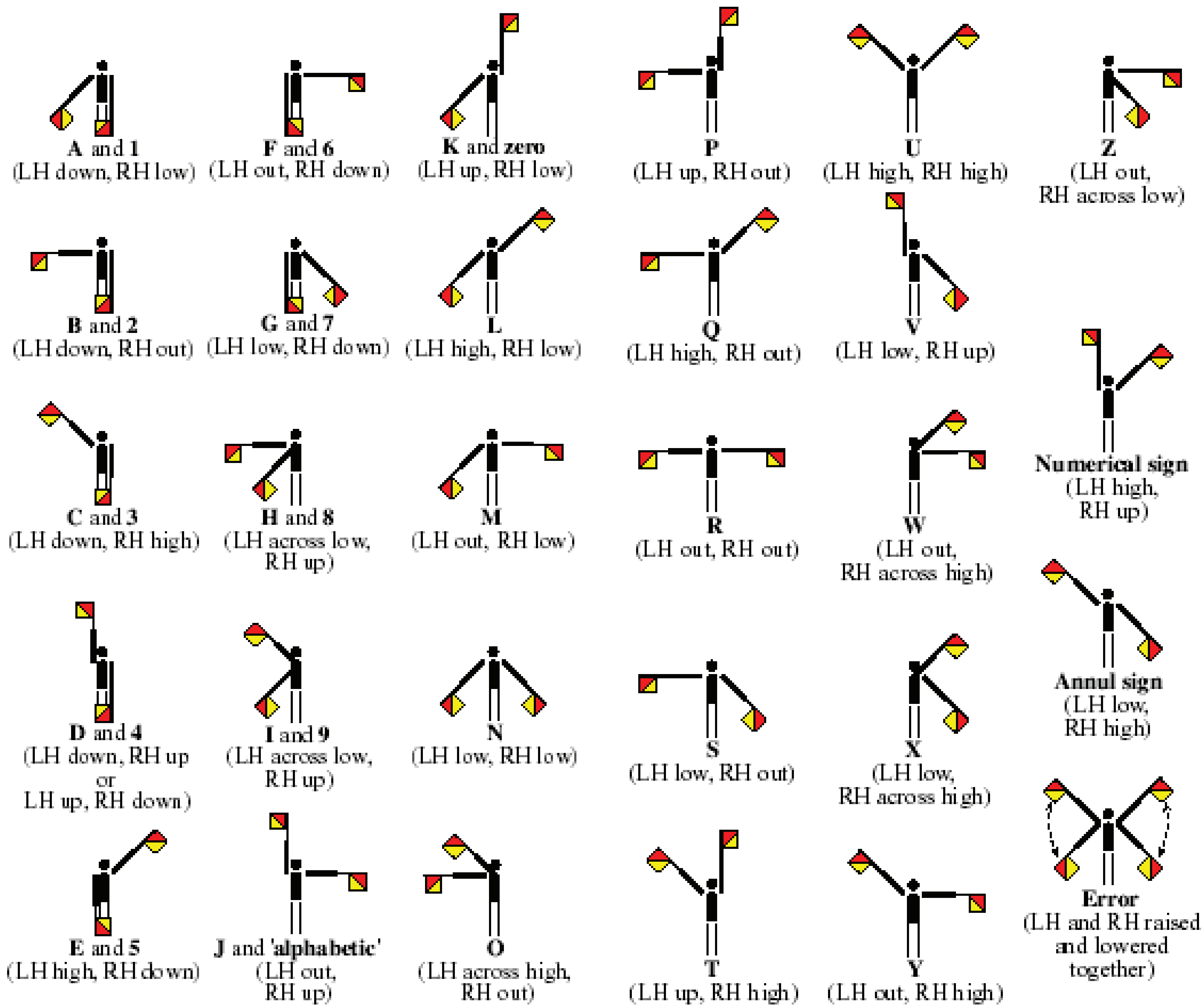


- OAM cross talk



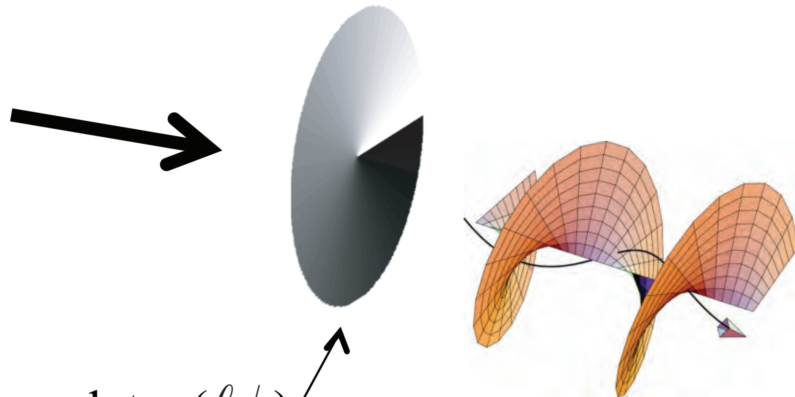
Malik et al., Optics Express 20, 13195 (2012); Rodenburg, et al., Optics Letters 17 3735 (2012).

Free-Space Optical Telecommunication based on Transverse Field Structures



How to create a beam carrying orbital angular momentum?

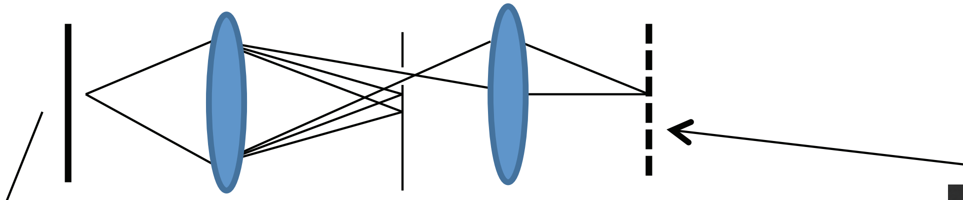
Pass beam through a spiral phase plate



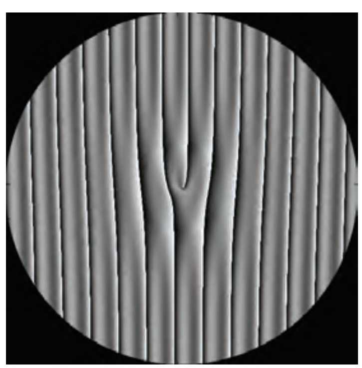
$e^{i\ell\phi}$

Spiral phase plate $(\ell\phi)$

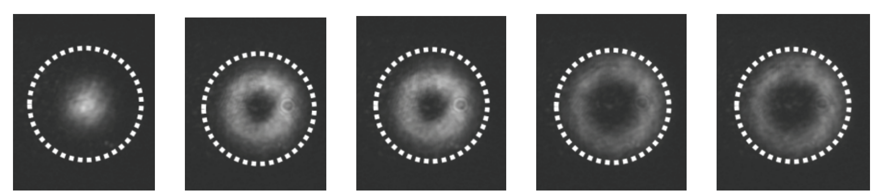
Use a spatial light modulator acting as a computer generated hologram (more versatile)



LG



Laguerre-Gauss



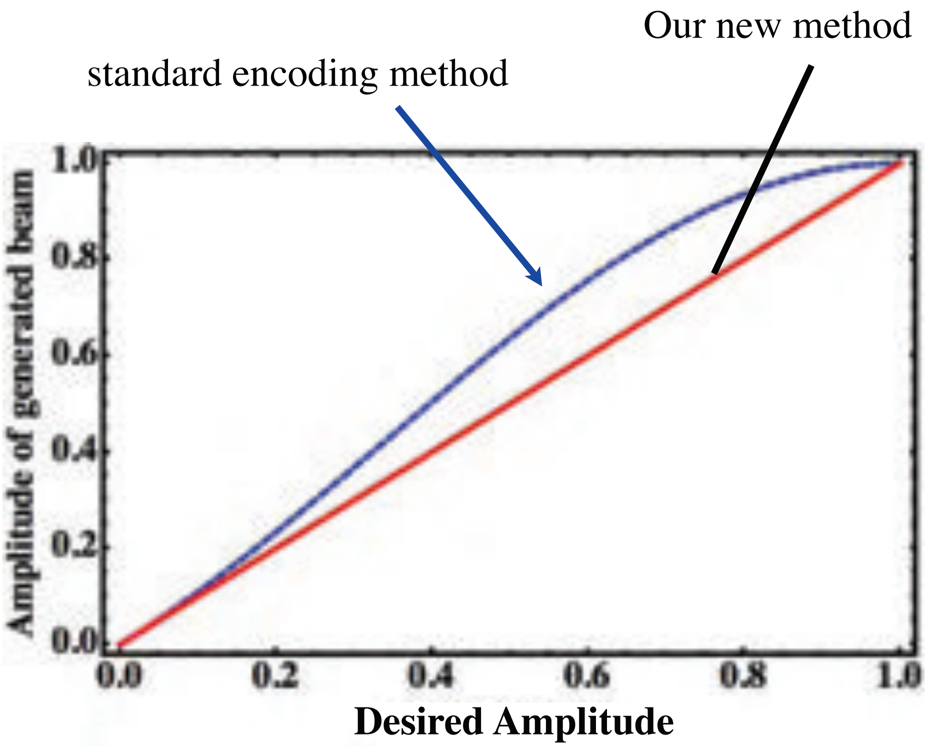
Exact solution to simultaneous intensity and phase masking with a single phase-only hologram, E. Bolduc, N. Bent, E. Santamato, E. Karimi, and R. W. Boyd, Optics Letters 38, 3546 (2013).

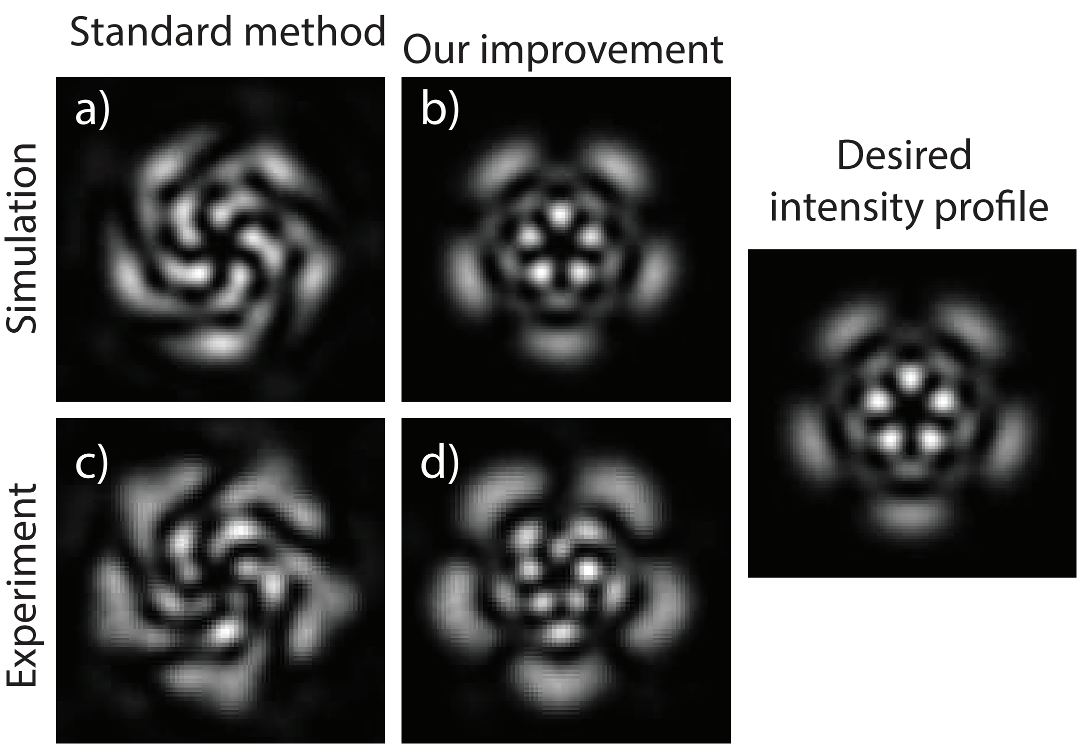
Exact Solution to Simultaneous Intensity and Phase Masking with a Single Phase-Only Hologram

We believe that previously workers used good but only approximate algorithms to encode holograms onto SLMs.

We have found an encoding algorithm that is mathematically exact.

We are currently investigating the conditions under which the use of the approximate encoding method could lead to significant errors.

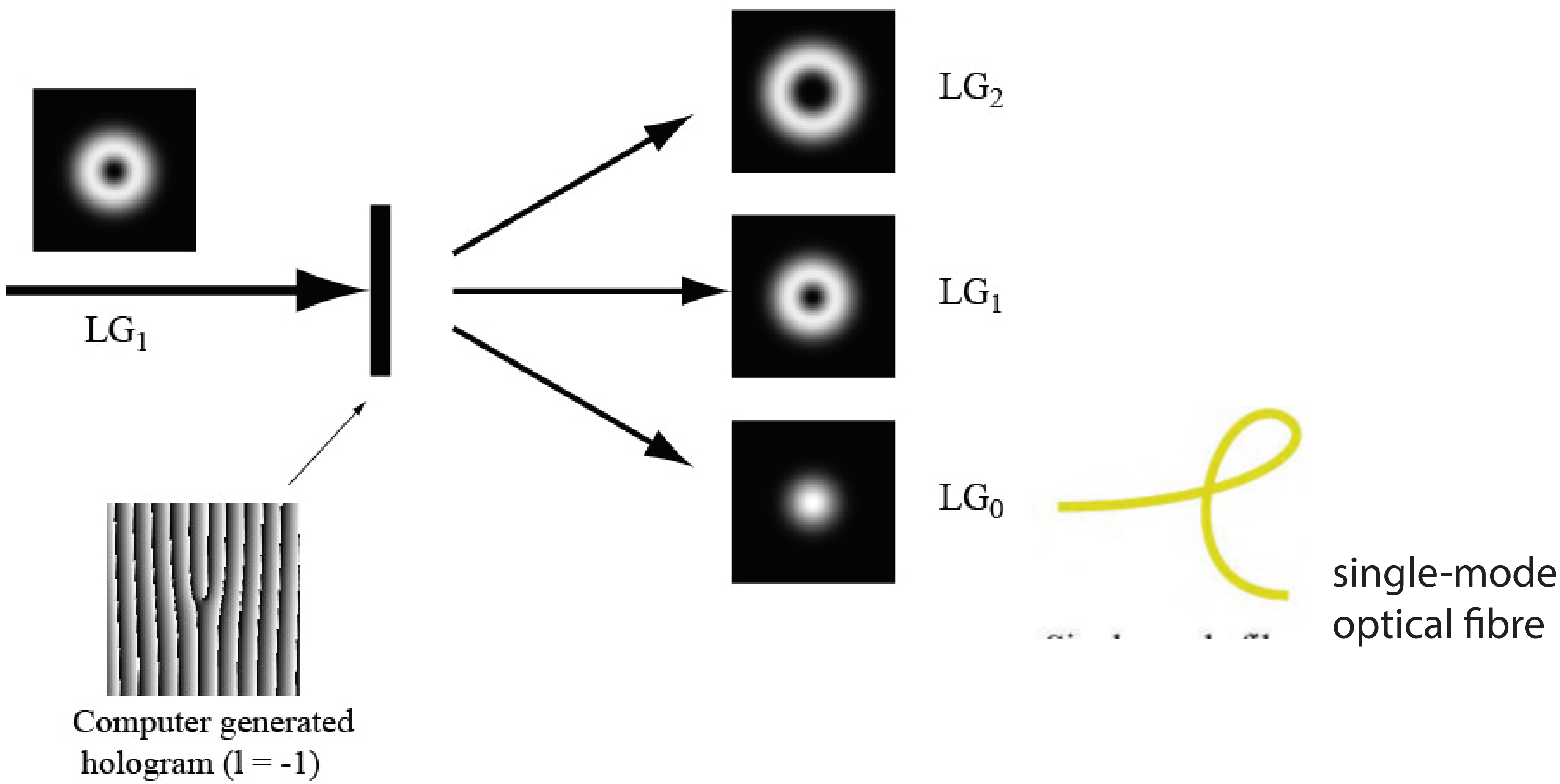




E. Bolduc, N. Bent, E. Santamato, E. Karimi, and R. W. Boyd, Optics Letters 38, 3546 (2013).

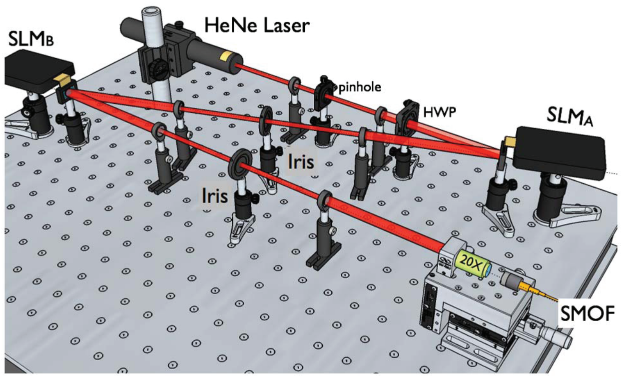
How to Measure the OAM Azimuthal Quantum Number of a Laguerre-Gauss Beam

Standard Method – Projective Measurement



Seems almost too good to be true

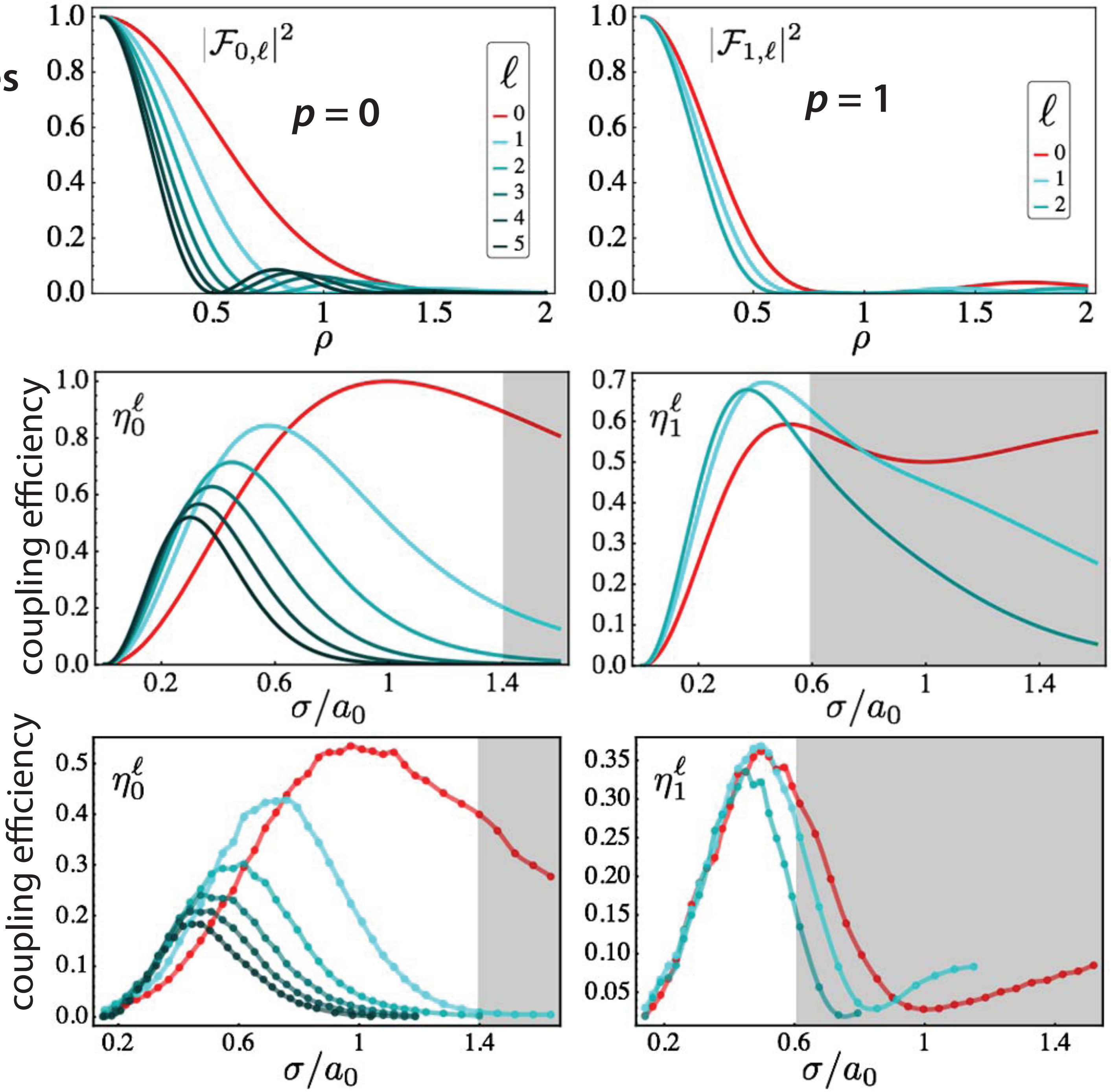
We Have Quantified the Level of Inaccuracy Resulting from this Procedure



mode profiles

theory

experiment



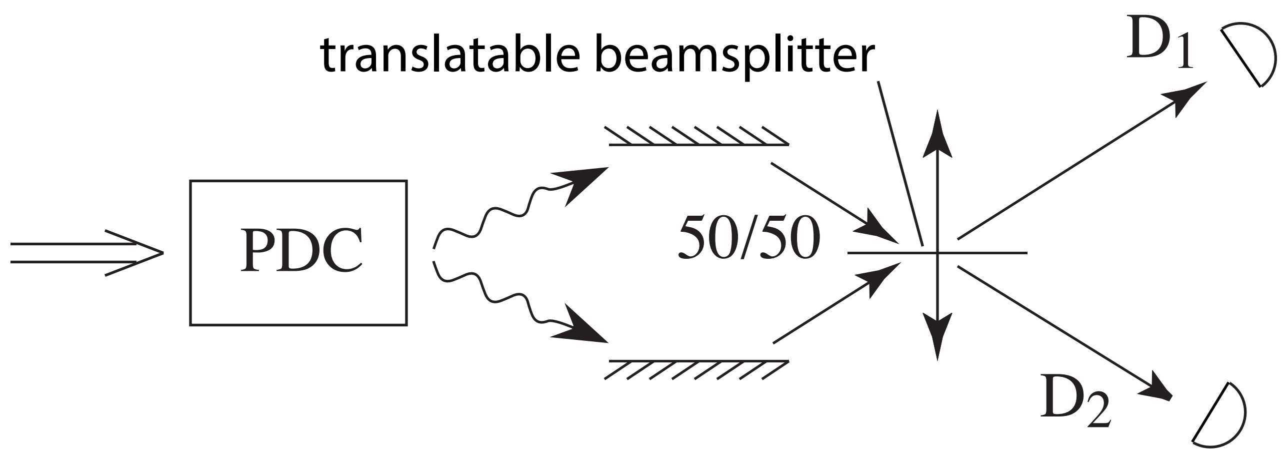
σ is the beam waist radius of the SMOF Gaussian mode.

$a_0 = (\sqrt{2}\lambda f)/(\pi w_0)$

Conclusion: coupling efficiency depends on mode indices, properties of fibre, and on degree of focussing

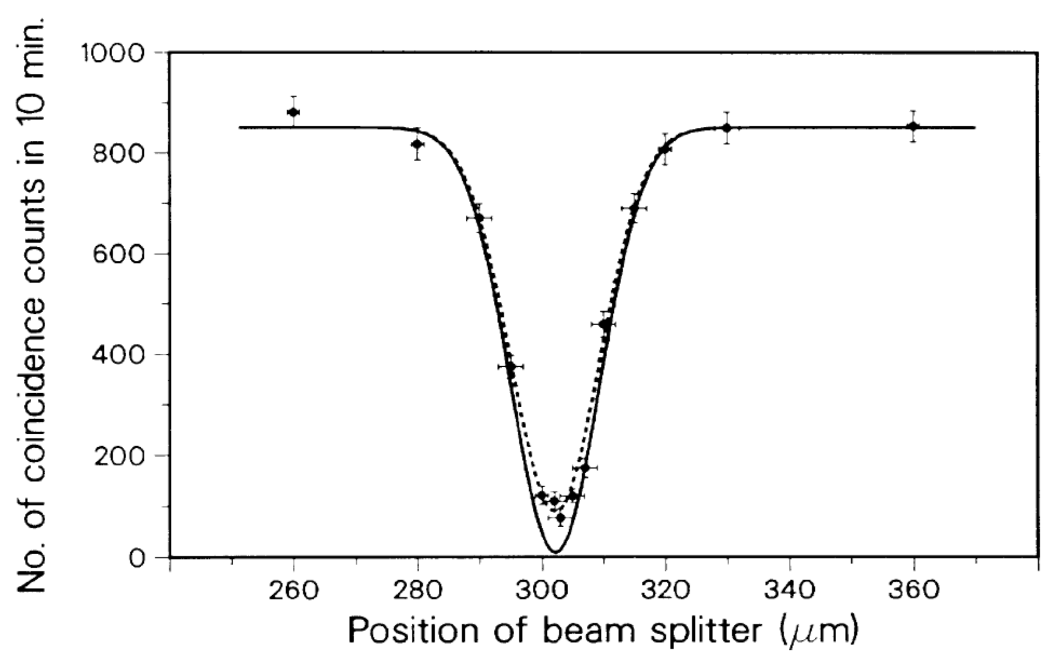
Qassim et al., J. Opt. Soc. Am. B 31, A20 (2014)

The Hong-Ou-Mandel Effect



- measure coincidences between D1 and D2

- coincidence rate drop to zero when the photons are indistinguishable

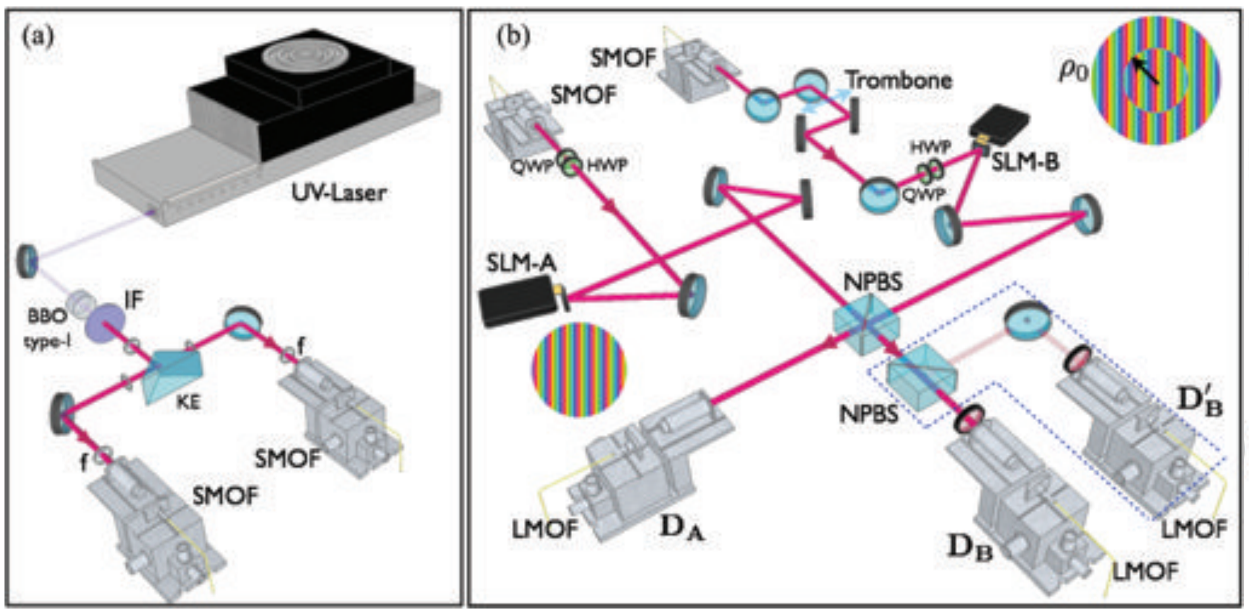


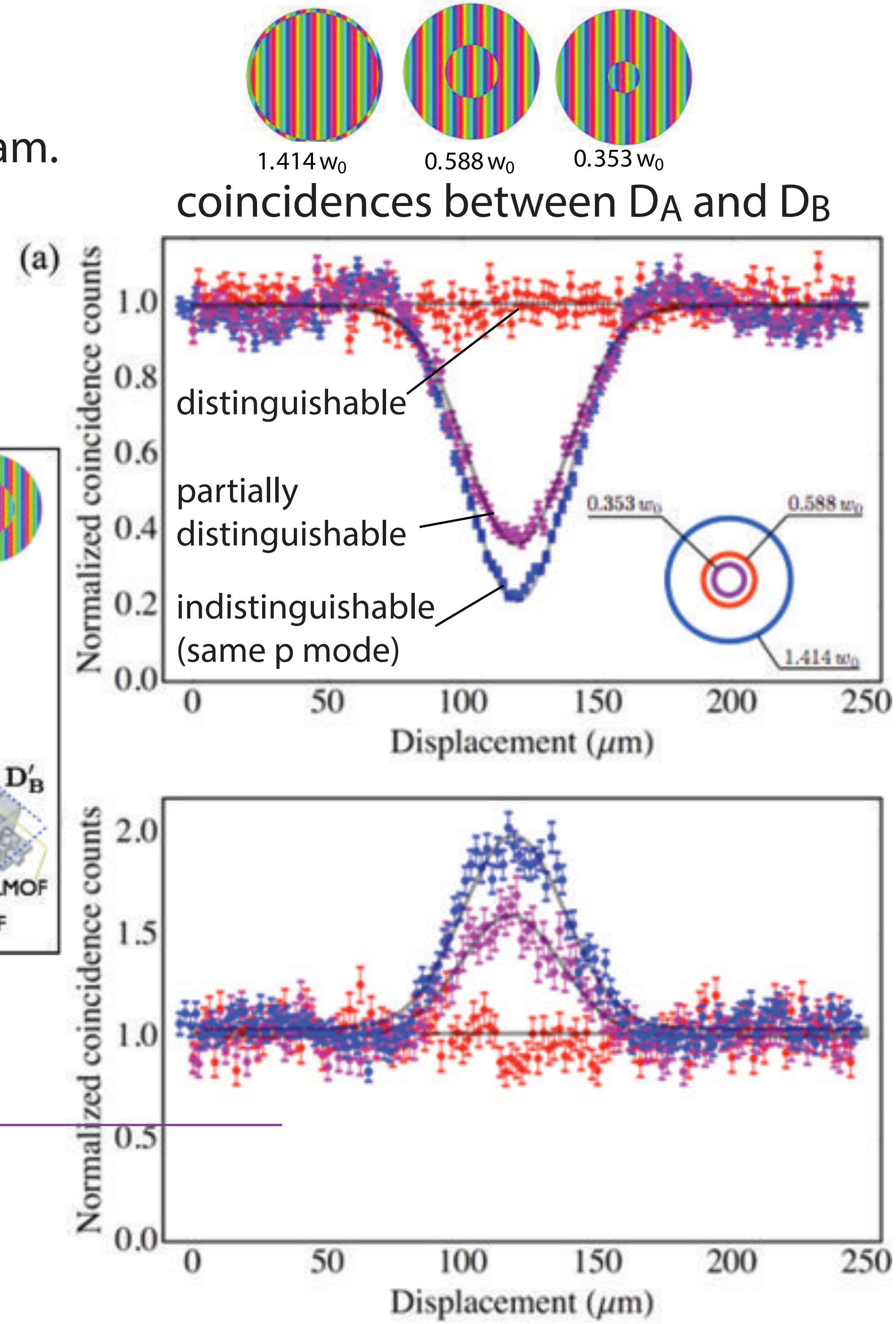
•Hong, Ou, Mandel, PRL, 1987

Hong-Ou-Mandel Effect and and LG Beams

- We can control the degree of distinguishability through the radial degree of freedom of a LG beam.
- Note that the radius is a continuous variable; azimuthal index is a discrete variable.

Experimental setup





- coincidences between D_B and $D_{B'}$
- measurement of coalescence

Karimi et al. PHYSICAL REVIEW A 89, 013829 (2014)

How to Fit a Square Peg into a Round Hole
(Really, how to couple an elliptical beam into an optical fiber.)

nature COMMUNICATIONS

ARTICLE

Received 12 Jul 2013 | Accepted 16 Oct 2013 | Published 12 Nov 2013

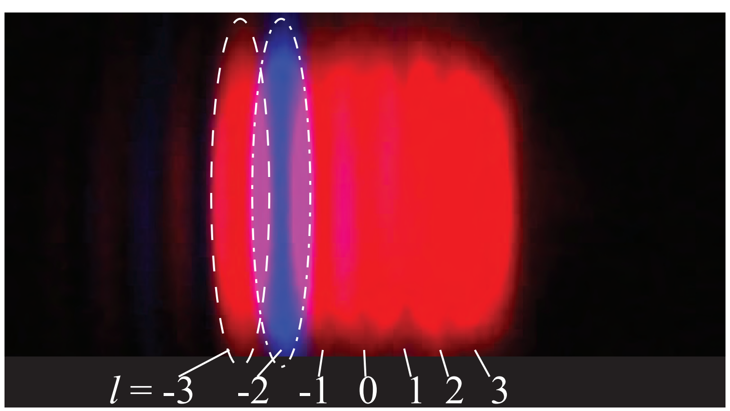
DOI: 10.1038/ncomms3781

Efficient separation of the orbital angular momentum eigenstates of light

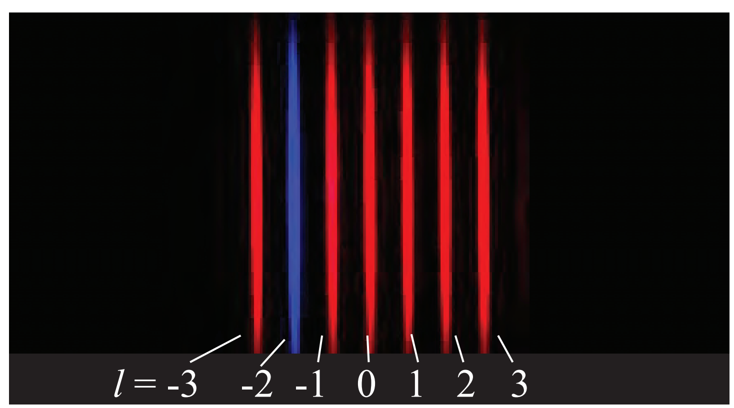
Mohammad Mirhosseini[1], Mehul Malik[1,2], Zhimin Shi[1,3] & Robert W. Boyd[1,4]

- Output of Glasgow sorter is elliptical, and ellipticity made worse by a 1D fanout.
- Solution: use a 2-D fanout, implemented on an SLM at present

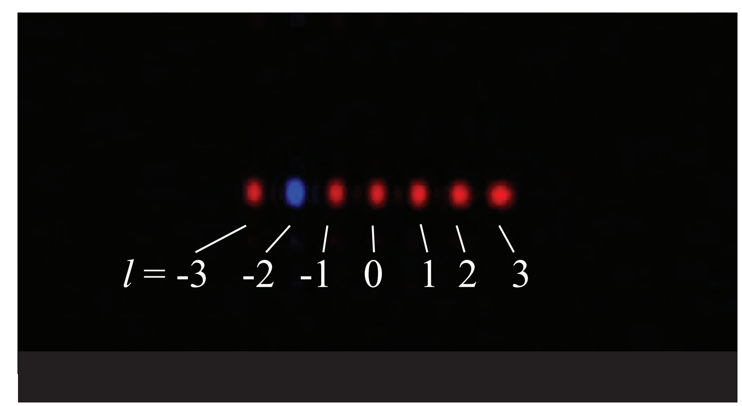
Output of sorter



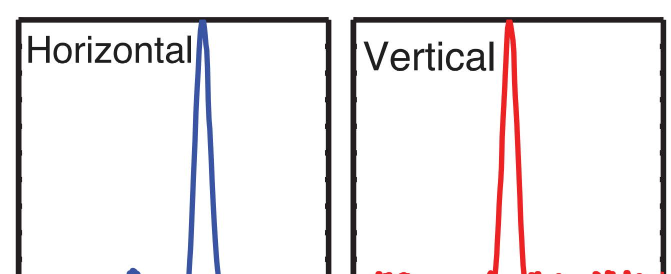
Output after 7X fanout



Output after 3 by 9 fanout



output nearly round



Experimental separation efficiency > 92%

Our Program in Nanophotonics

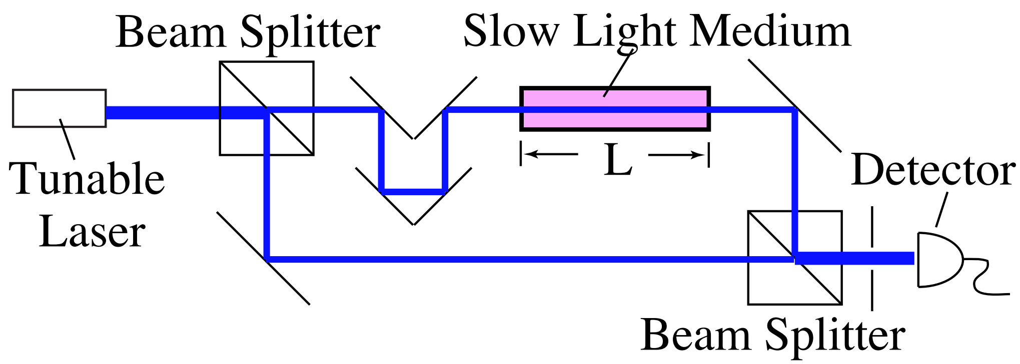
Nanofabrication Goal: Chip-Scale Slow Light Spectrometer

- 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:

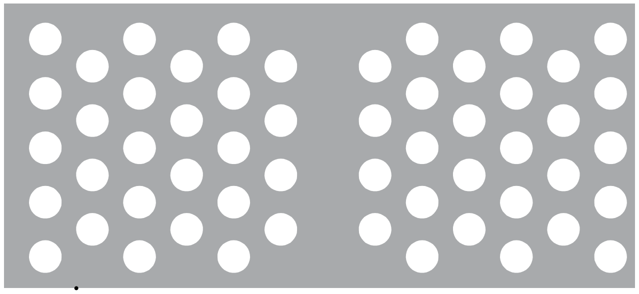


Simple analysis

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

- 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.



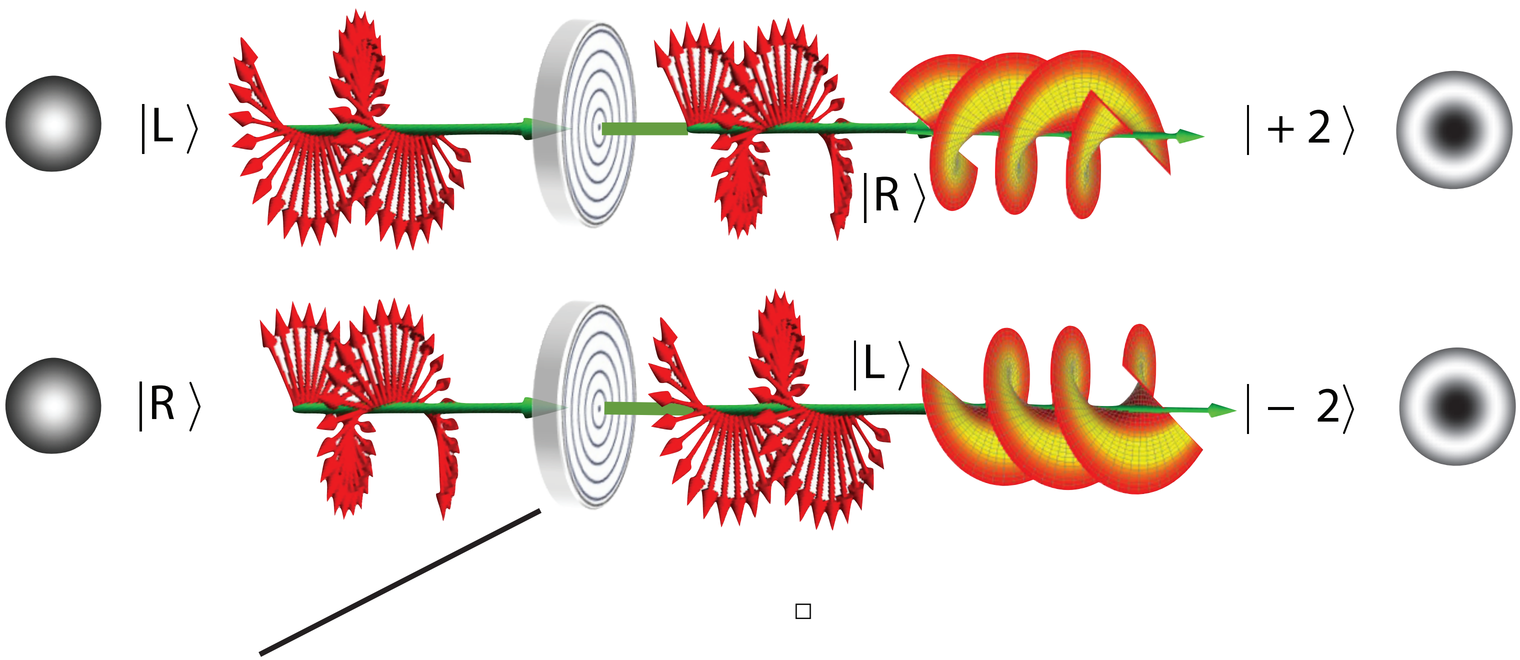
Shi, Boyd, Gauthier, and Dudley, Opt. Lett. 32, 915 (2007)
Shi, Boyd, Camacho, Vudyasetu, and Howell, PRL. 99, 240801 (2007)
Shi and Boyd, J. Opt. Soc. Am. B 25, C136 (2008).

See also the group of Shahriar on fast-light and interferometry

Photonic Q-Plates

Spin angular momentum can be transferred to OAM through use of a Q-plate

Ability to change basis of encoding useful for quantum information processing

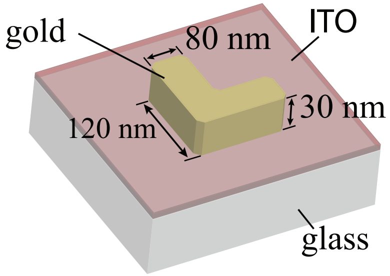


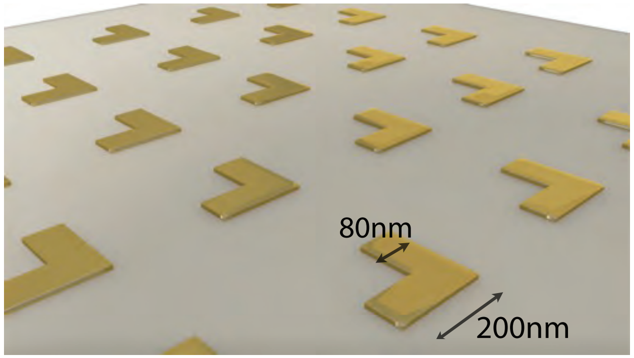
Q-plate. Usually a carefully constructed liquid-crystal cell

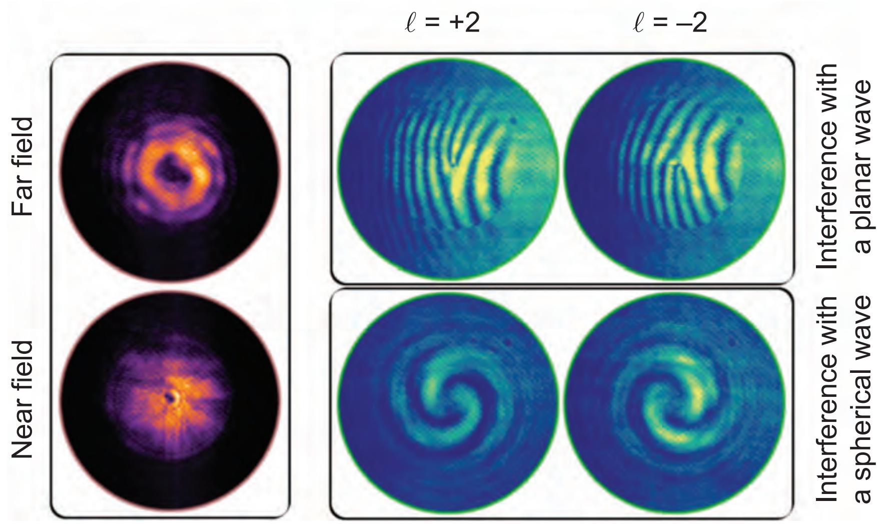
Marrucci et al., PRL 96 , 163905 (2006)
Karimi et al.,APL 98 , 231124 (2009)

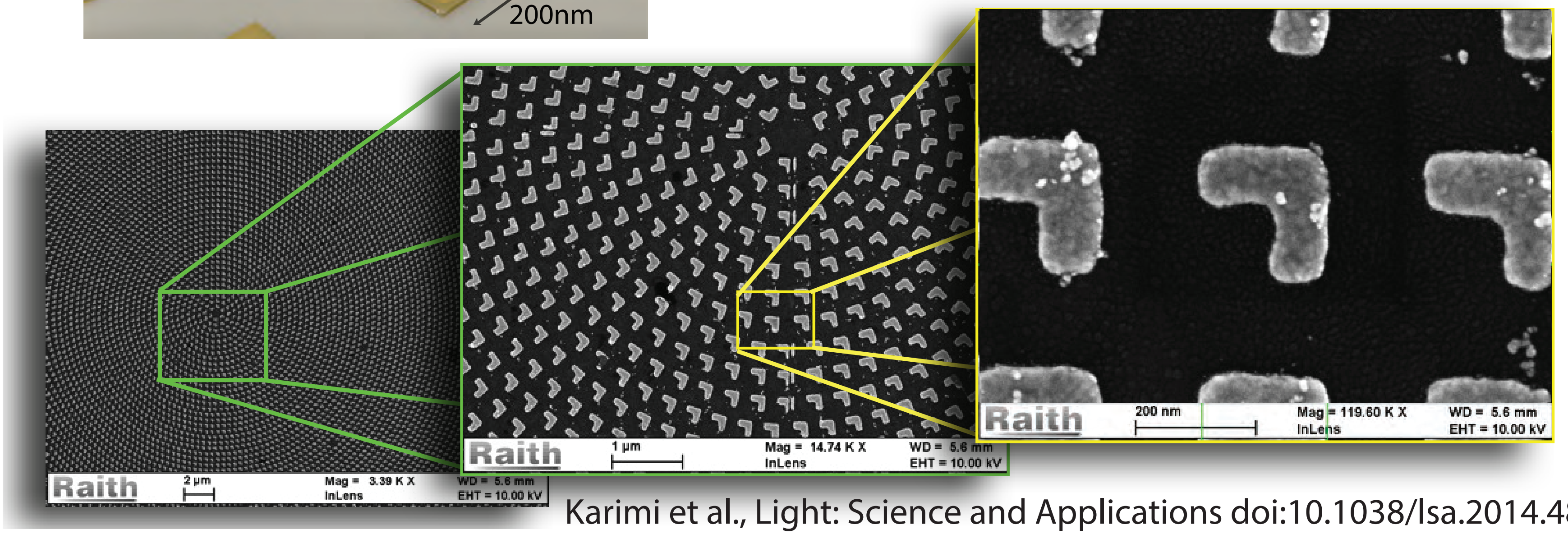
Fabrication of a Nano-Scale q-Plate

- A q-plate is a device that converts spin angular momentum into orbital angular momentum.
- It functions as a quantum interface.
- Fabricated device is only 30-nm thick and thus suitable for use in integrated quantum circuits.







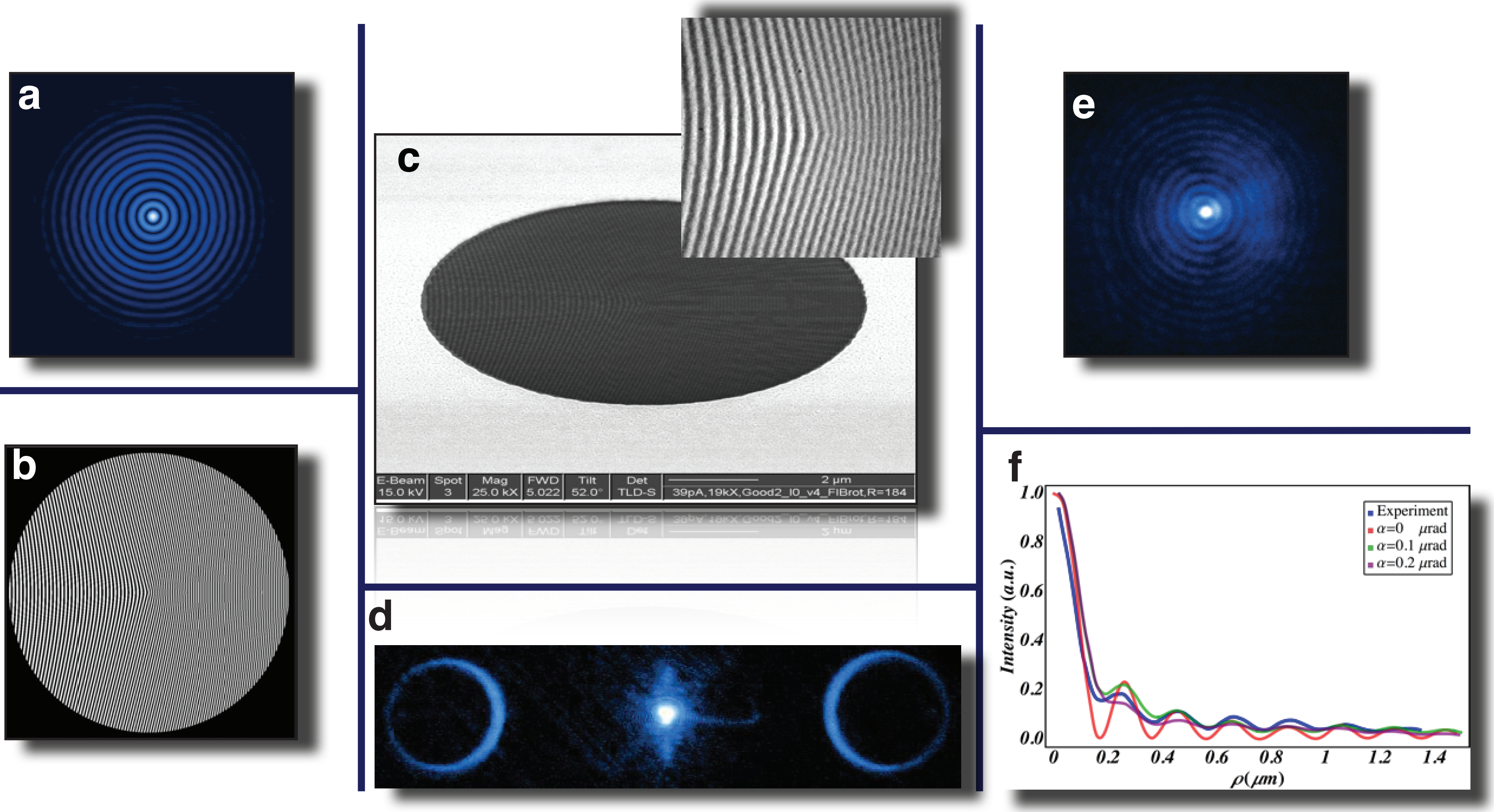


Karimi et al., Light: Science and Applications doi:10.1038/lsa.2014.48 (2014)

Demonstration of an Electron Bessel Beam

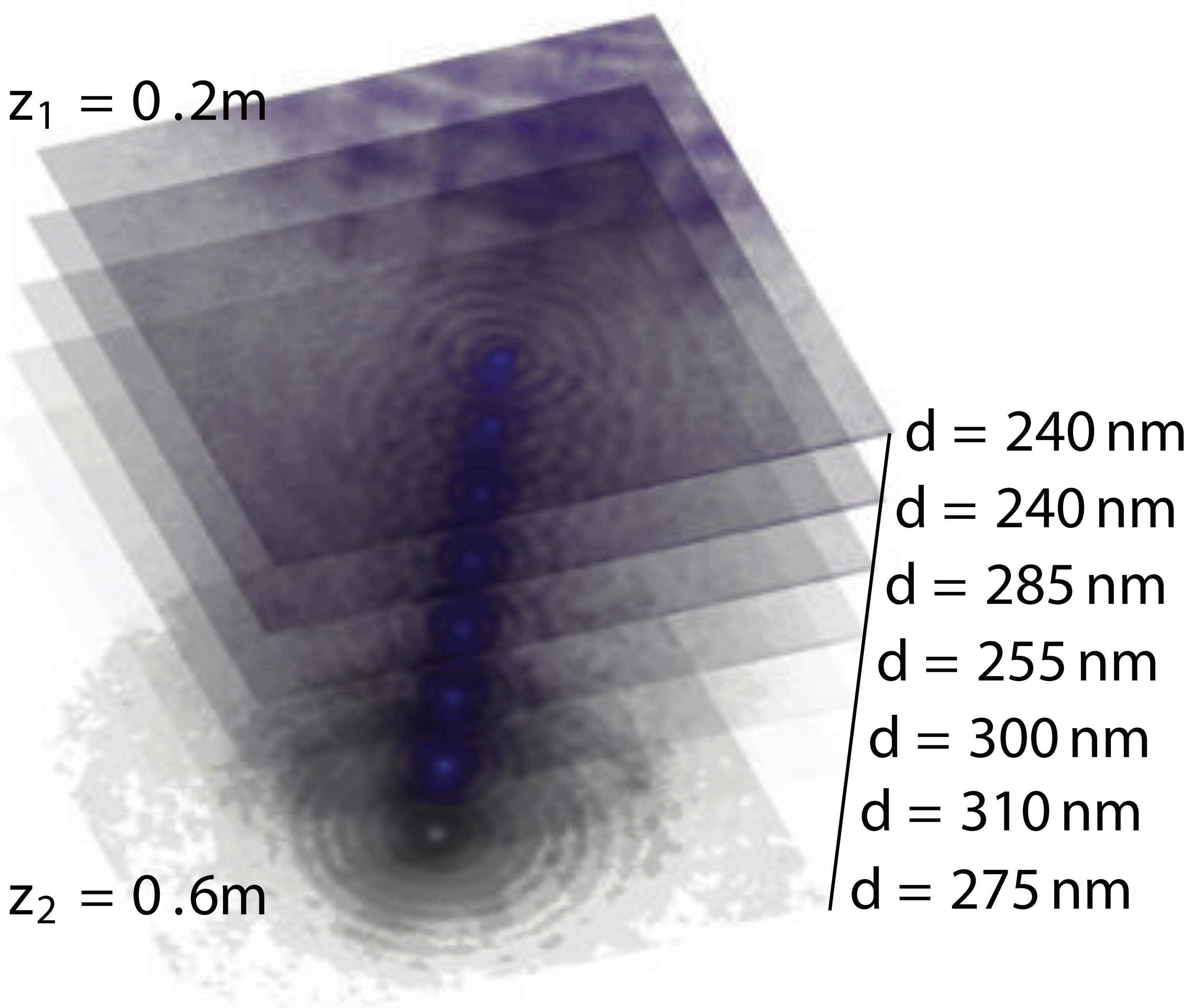
- Huge implications for electron microscopy!

Theoretical modeling | Hologram for electrons | Lab results

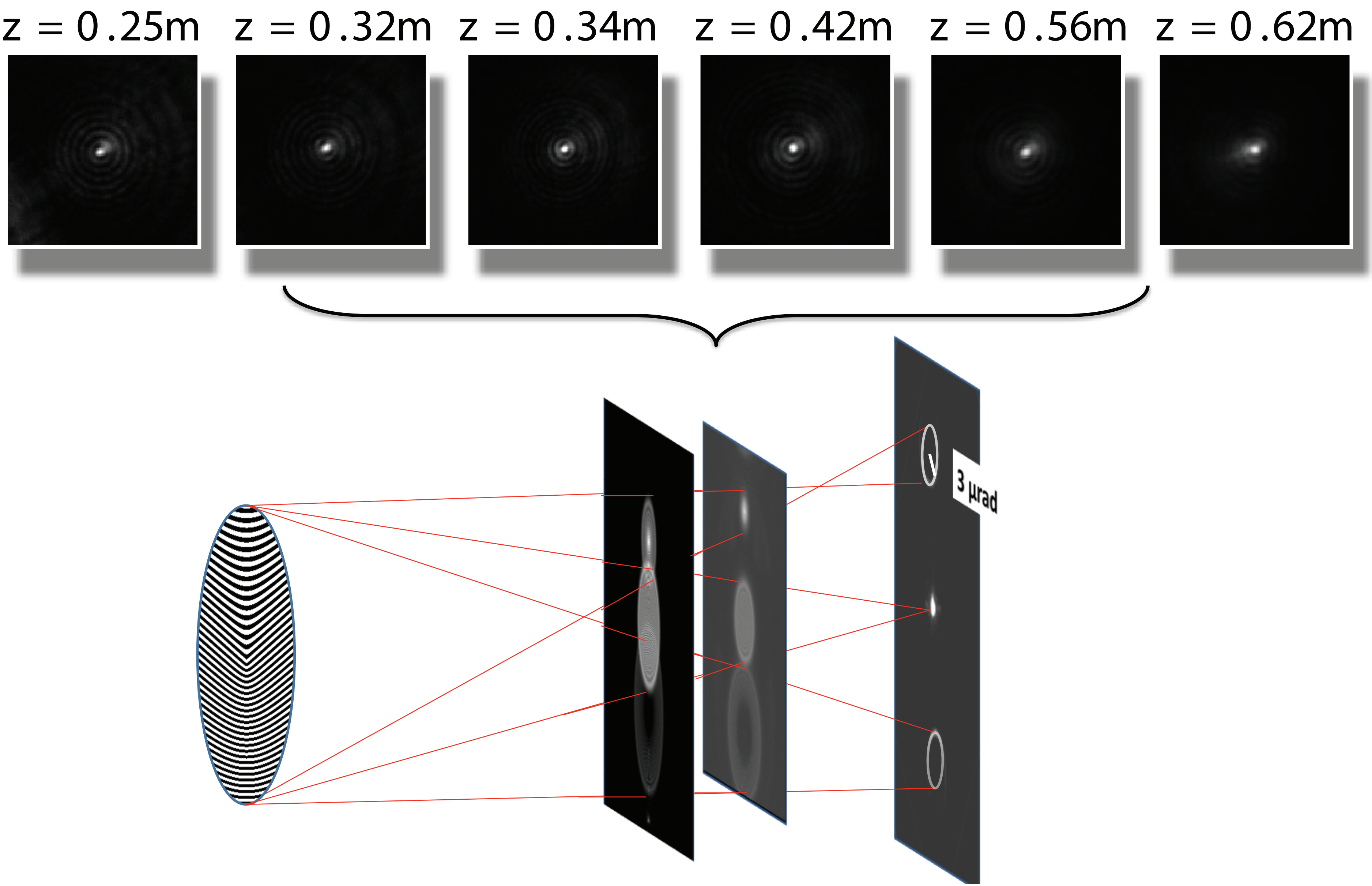


Karimi et al. (especially the Italians)

Propagates 0.8 Metres Without Diffractive Spreading!

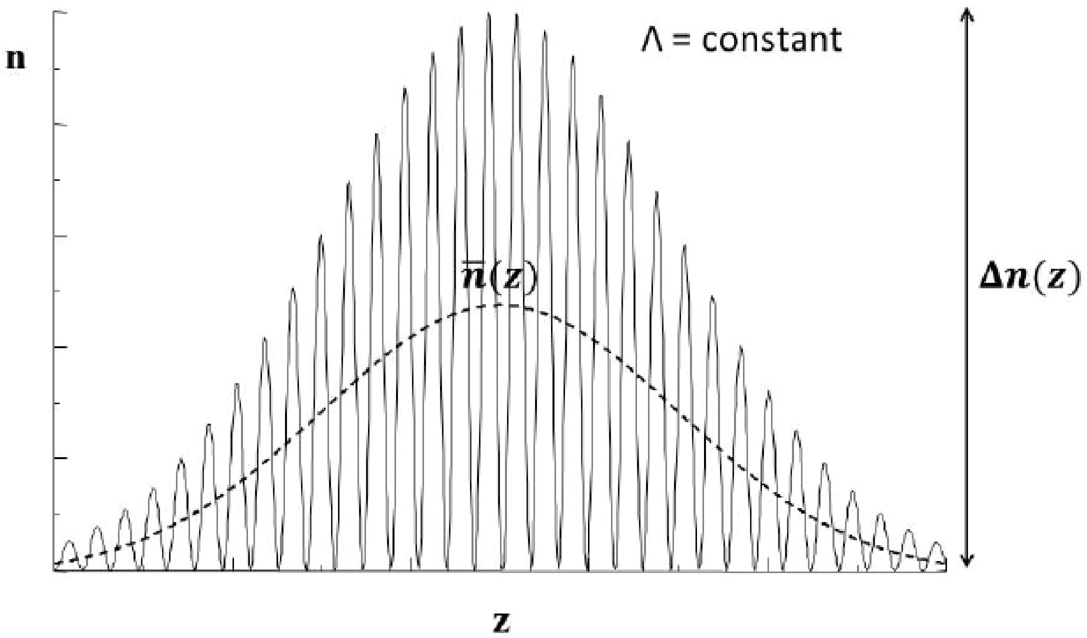


The Geometry

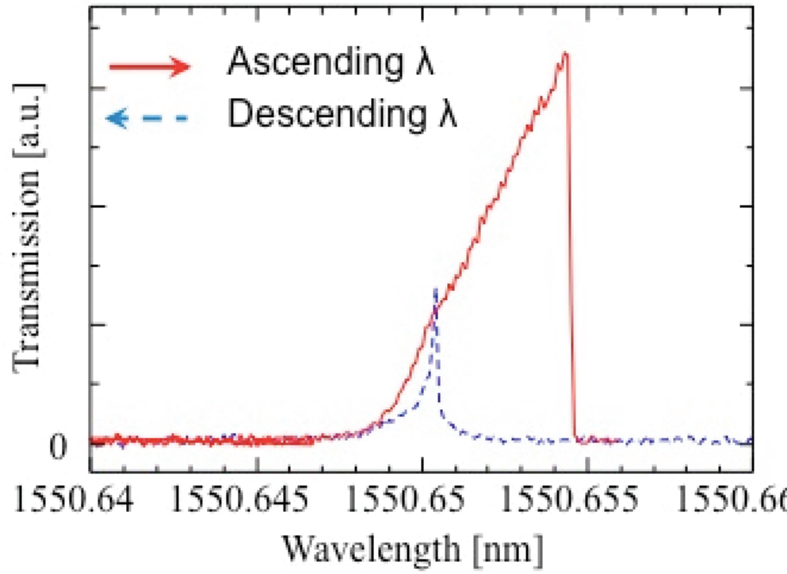


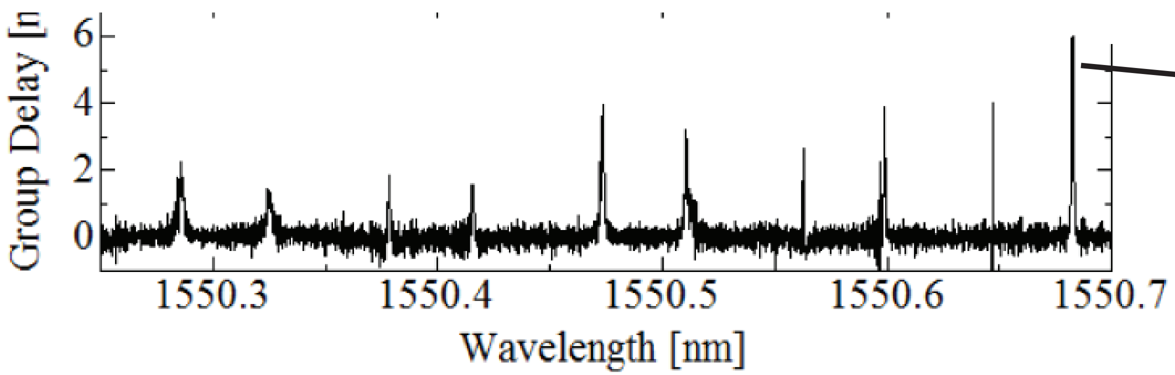
Improved Slow-Light Fiber Bragg Grating (FBG) Structure

Much larger slow-down factors possible with a Gaussian-profile grating



Observation of (thermal) optical bistability at mW power levels





group index approximately 140

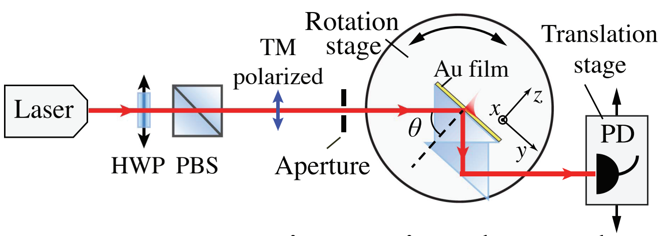
H. Wen, M. Terrel, S. Fan and M. Digonnet, IEEE Sensors J. 12, 156-163 (2012).

J. Upham, I. De Leon, D. Grobnic, E. Ma, M.-C. N. Dicaire, S.A. Schulz, S. Murugkar, and R.W. Boyd, Optics Letters 39, 849-852 (2014).

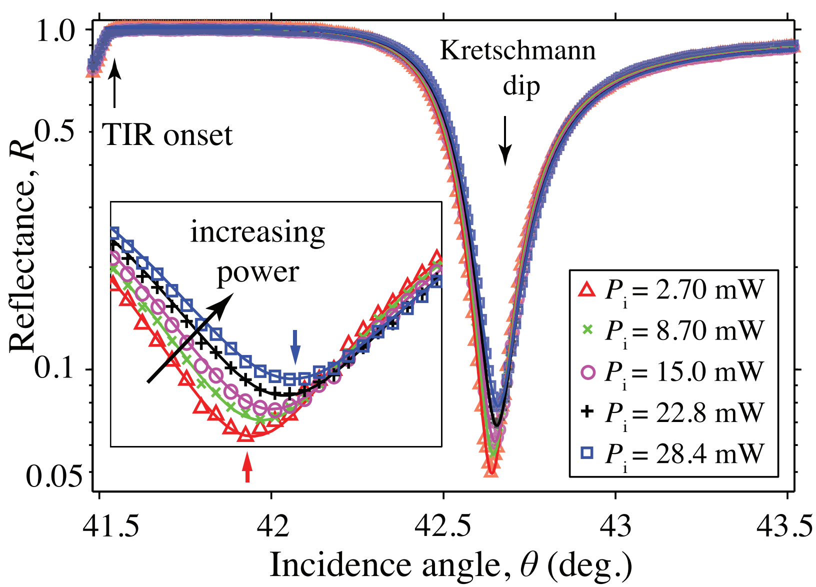
NLO in Plasmonics (Photonics Using Metals)

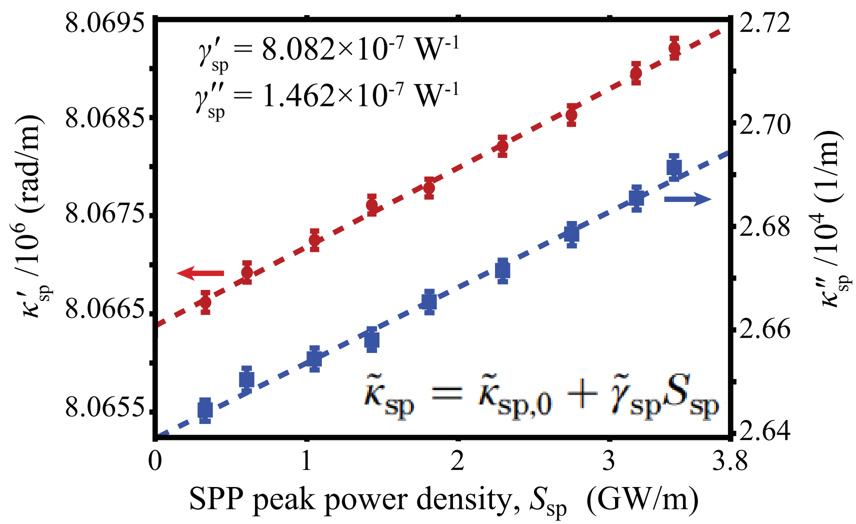
Is there an intrinsic nonlinear reponse to surface plasmon polaritons (SPPs)?

- A nonlinar response would be useful for photonics applications
- Metals are highly nonlinear (n_2 is10^6 times that of silica)
- High (sub-wavelength) field confinement in an SPP
- But SPPs tend to show high loss



Measure intensity dependence of the Kretschmann angle





$$\tilde{\chi}^{(3)}_{\mathrm{Au}} = (4.67 + i3.03) \times 10^{-19}\ \mathrm{m}^2/\mathrm{V}^2$$

power varies from 2 to 18 mW;
intensity varies from 2 to 22 GW/cm
laser wavelength is 796.5 nm
laser pulse duration is 100 fs

I. De Leon, Z. Shi, A. Liapis and R.W.Boyd, Optics Letters 39, 2274 (2014)

Thank you for your attention!