Quantum Imaging, Structured Light Fields, and Materials and Structures for Quantum Sensing

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Presented at the DTRA Quantum Sensing Initiative Workshop, Lorton, VA, November 30 through December 1, 2016.

Quantum Sensing

In this talk I present some ideas for research directions in the field of Quantum Sensing

Quantum Imaging

- Two-color ghost imaging
- Interaction-free ghost imaging
- Imaging with photon-added states
- Imaging with “undetected photons”

Structured Light Fields for Quantum Information

- Dense coding of information using orbital angular momentum of light
- Secure Communication transmitting more than one bit per photon
- Mobius structures of light

Materials for Quantum Information

- Epsilon-near-zero materials
- Single-photon sources
- Chip-scale photonic devices for quantum information

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Quantum Imaging

- Goal of quantum imaging is to produce "better" images using quantum methods
  - image with a smaller number of photons
  - achieve better spatial resolution
  - achieve better signal-to-noise ratio
- Alternatively, quantum imaging exploits the quantum properties of the transverse structure of light fields

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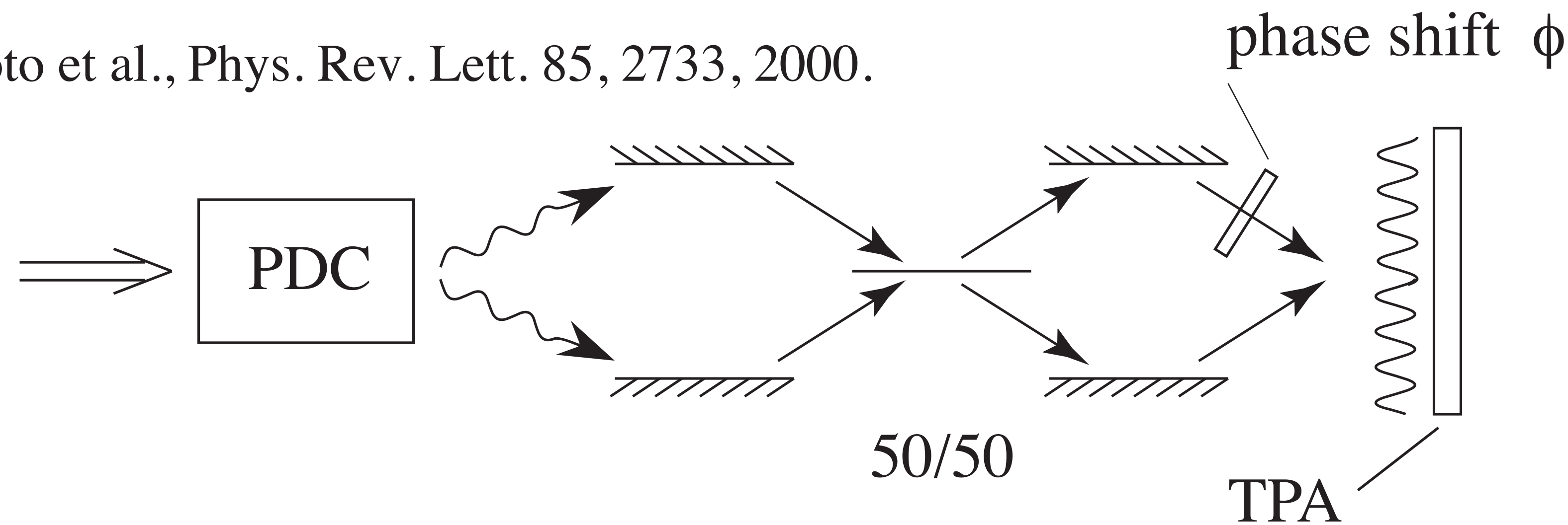
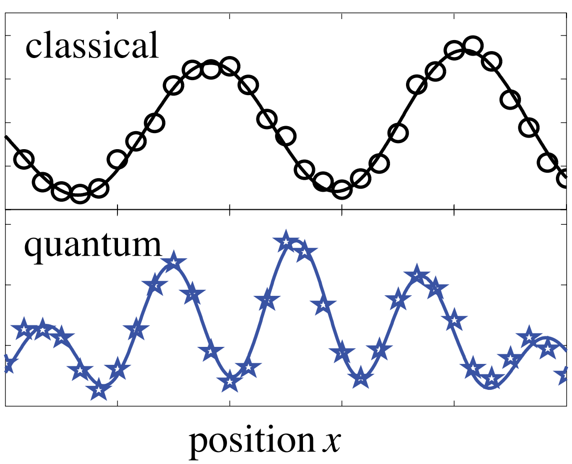
Quantum Lithography: Concept of Jonathan Dowling

- 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

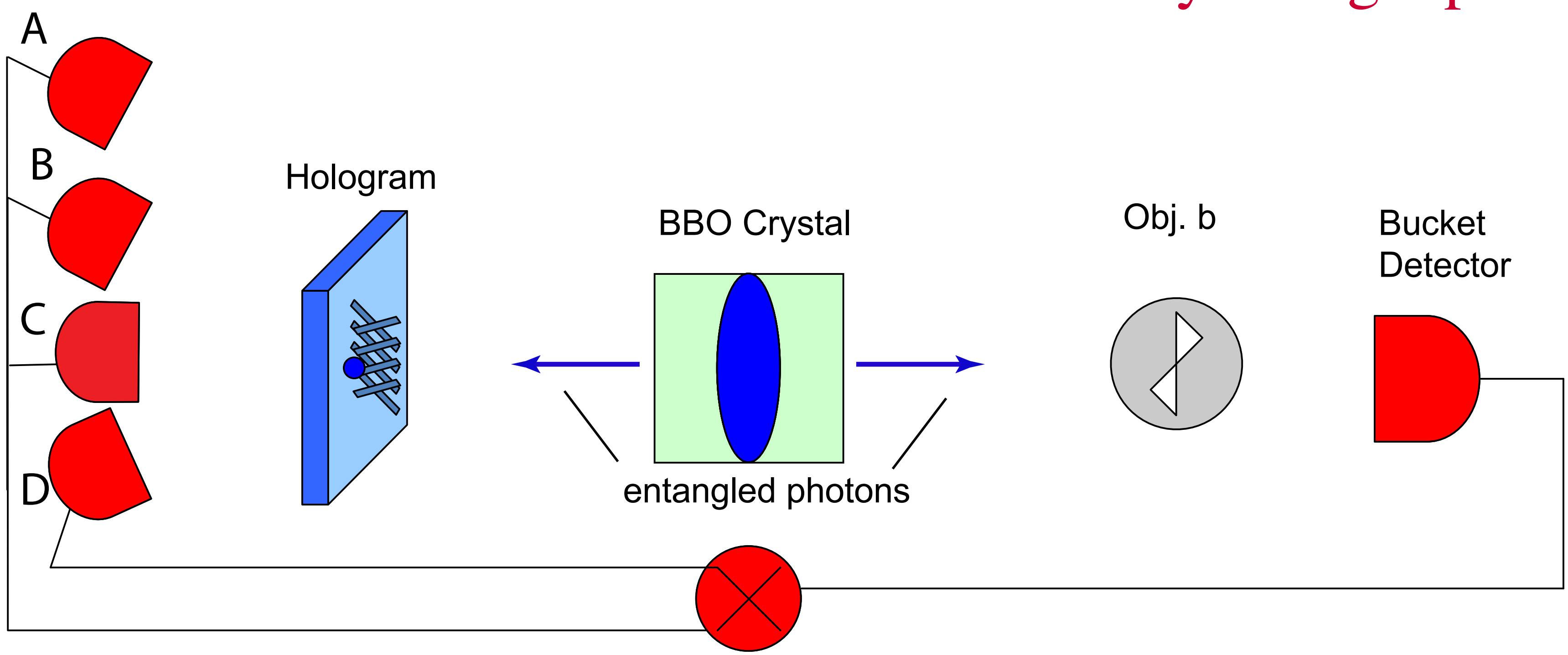


Quantum spatial superresolution by optical centroid measurements, Shin, Chan, Chang, and Boyd, Phys. Rev. Lett. 107, 083603 (2011).

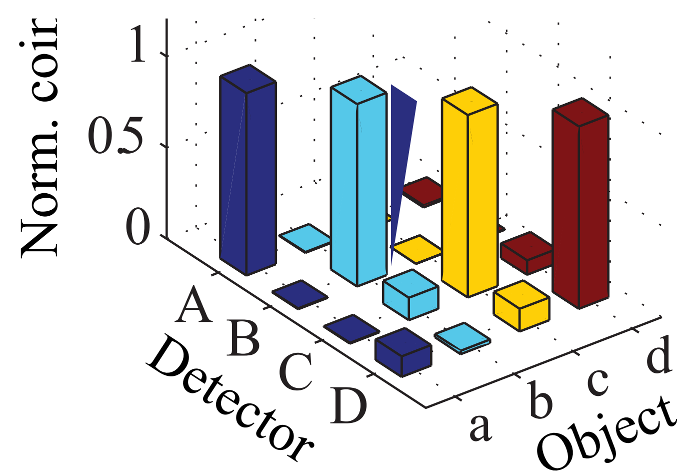
See also, Quantum Lithography: Status of the Field, R.W. Boyd and J.P. Dowling, Quantum Information Processing, 11:891–901 (2012).

Single-Photon Coincidence Imaging

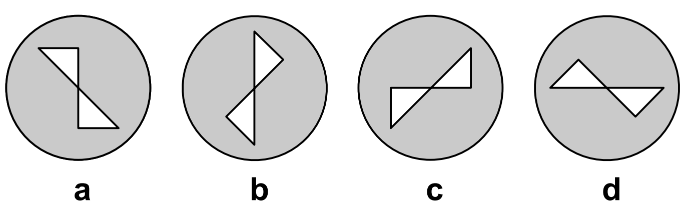
How much information can be carried by a single photon?



coincidence count rate

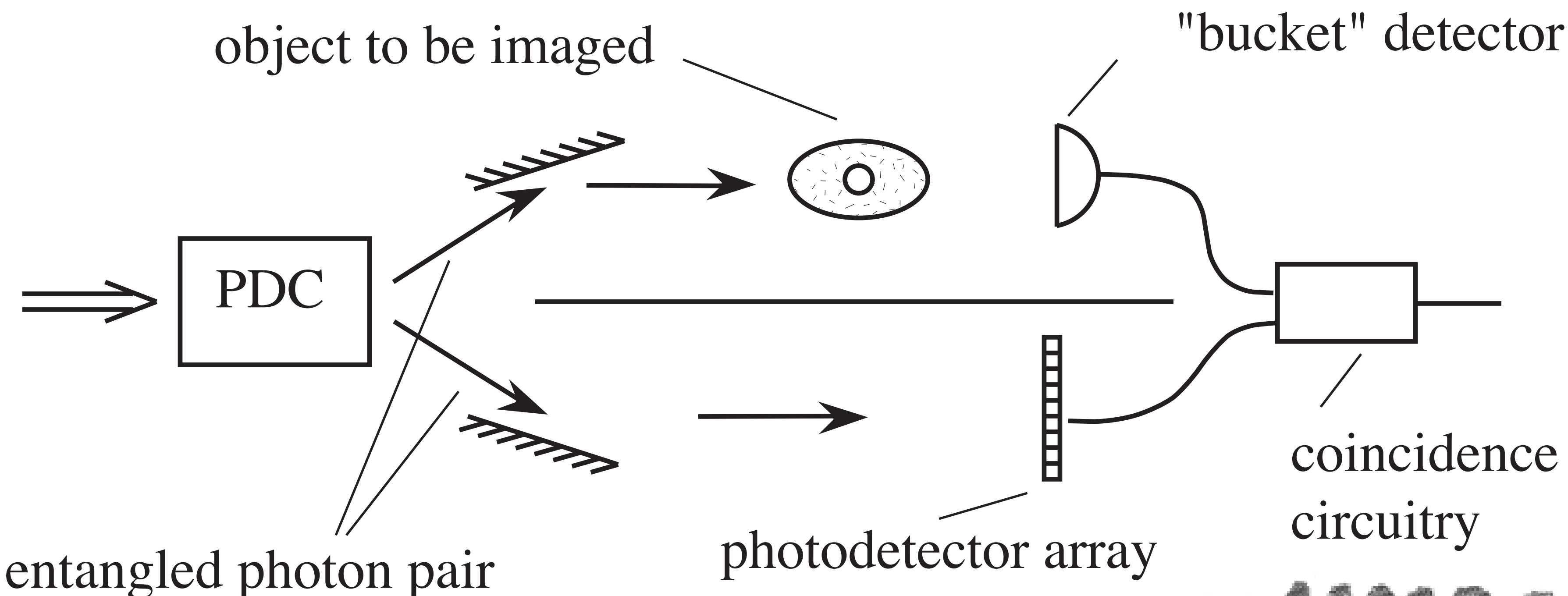


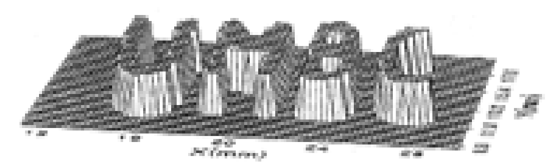
We discriminate among four orthogonal images using single-photon interrogation in a coincidence imaging configuration.



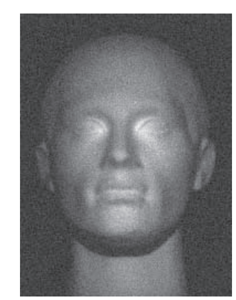
Malik, Shin, O'Sullivan. Zerom, and Boyd, Phys. Rev. Lett. 104, 163602 (2010).

Ghost (Coincidence) Imaging





- Obvious applicability to remote sensing!
  (imaging under adverse situations, bio, two-color, etc.)
- Is this a purely quantum mechanical process? (No)
- Can Brown-Twiss intensity correlations lead to ghost imaging? (Yes)



Padgett Group

Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).
Bennink, Bentley, Boyd, and Howell, PRL 92 033601 (2004)
Gatti, Brambilla, and Lugiato, PRL 90 133603 (2003)
Gatti, Brambilla, Bache, and Lugiato, PRL 93 093602 (2003)

Is Ghost Imaging a Quantum Phenomenon?

VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

A. Gatti, E. Brambilla, and L. A. Lugiato

INFM, Dipartimento di Scienze CC.FF.MM., Università dellíInsubria, Via Valleggio 11, 22100 Como, Italy

(Received 11 October 2002; published 3 April 2003)

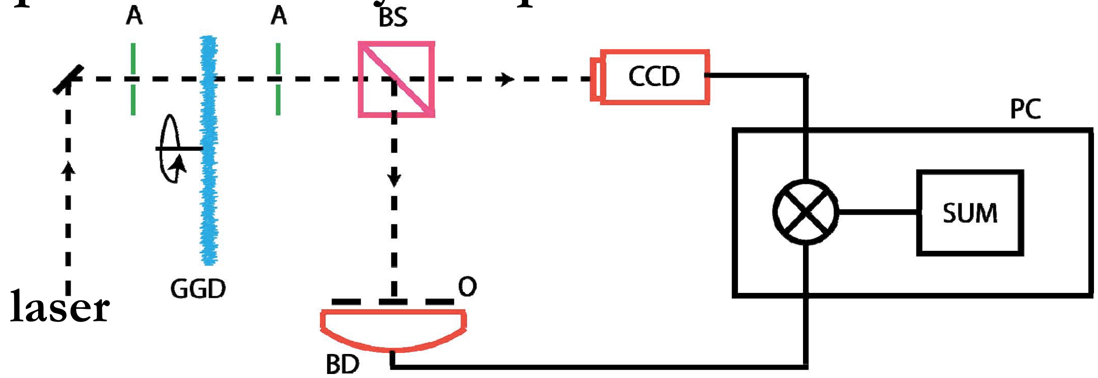
We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

Experimental verification by Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

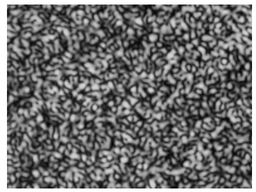
Thermal Ghost Imaging

Instead of using entangled photons, one can perform ghost imaging using the (HBT) correlations of thermal (or quasithermal) light.*

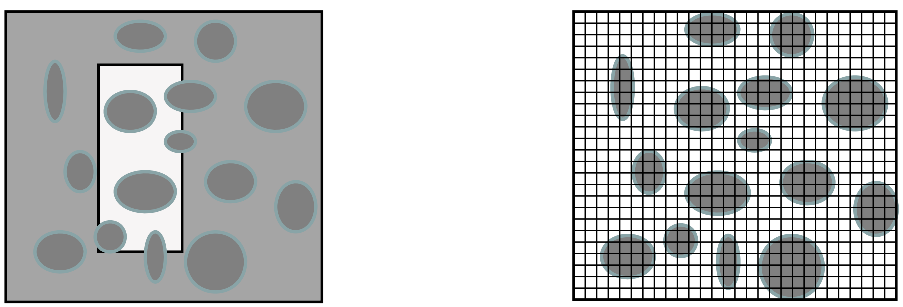
- Typical laboratory setup



identical speckle patterns in each arm



- How does this work? (Consider the image of a slit.)



Object arm, bucket detector   Reference arm, CCD

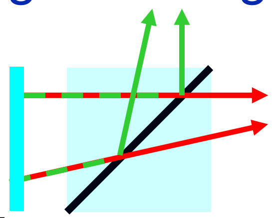
Calculate (total transmitted power) x (intensity at each pixel) and average over many speckle patterns.

* A. Gatti, E. Brambilla, M. Bache, and L. A. Lugiato, Phys. Rev. Lett. 93, 093602 (2004).

Two-Color Ghost Imaging

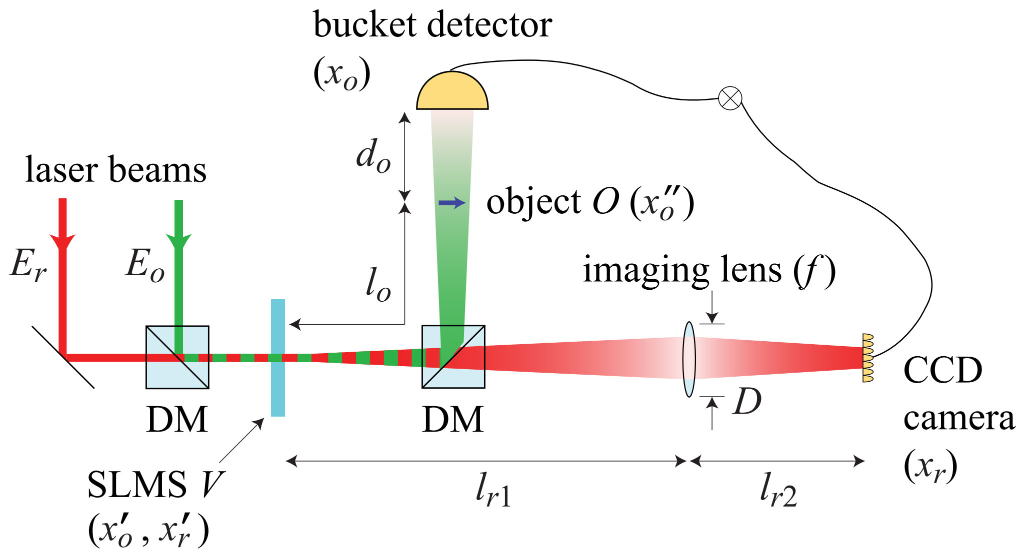
New possibilities afforded by using different colors in object and reference arms

Thermal ghost imaging

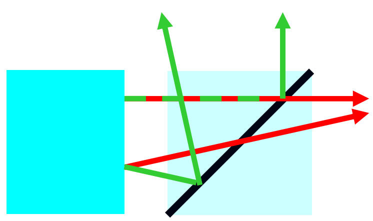


SLM

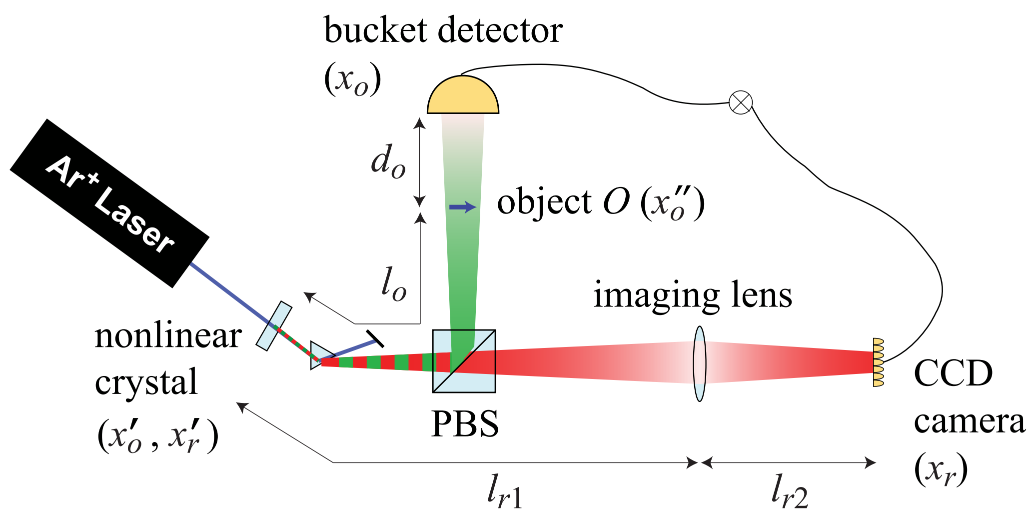
But no obvious way to make identical speckle patterns at two wavelengths



Quantum ghost imaging



SPDC



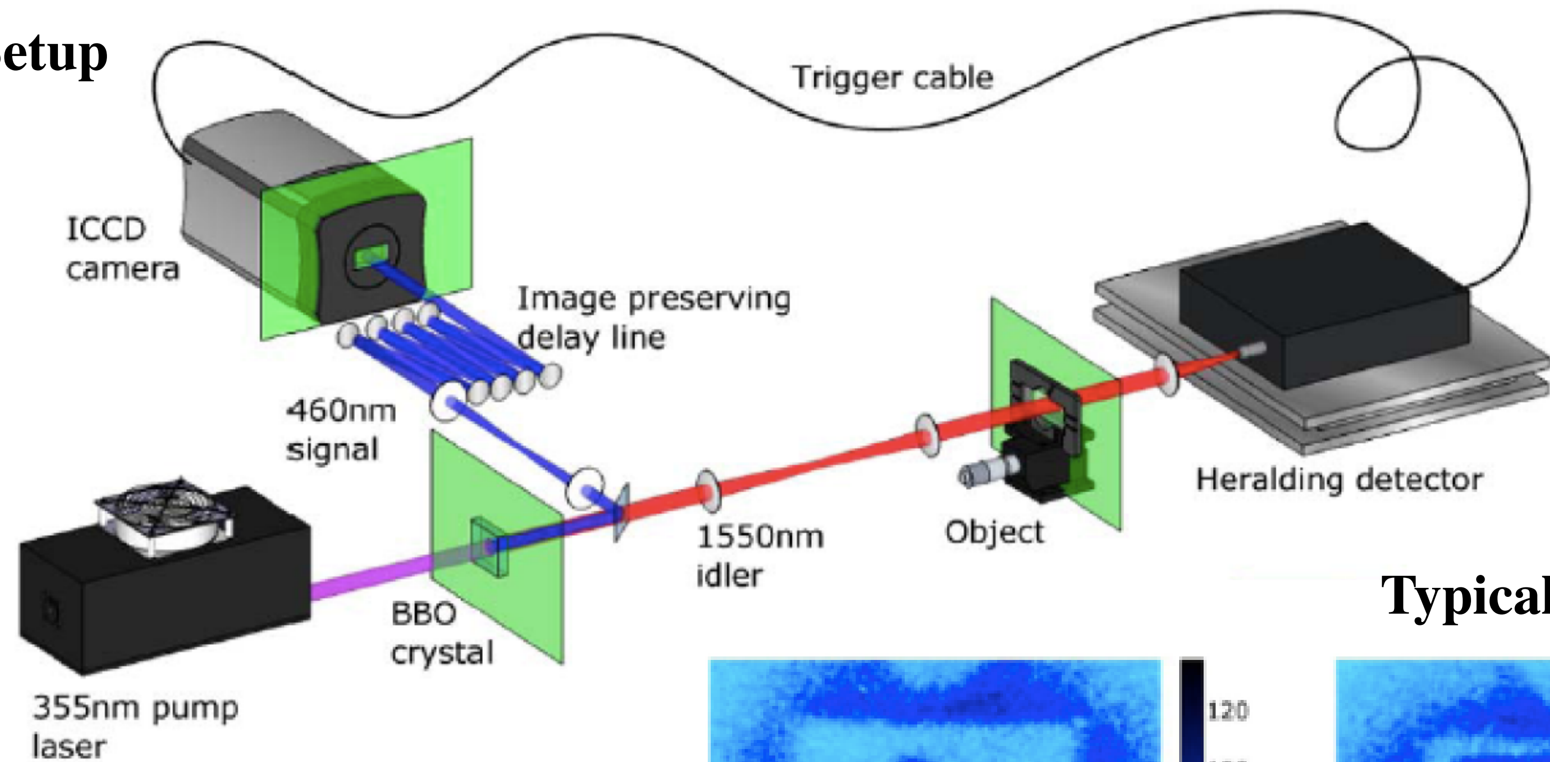
Spatial resolution depends on wavelength used to illuminate object.

Two-Color Ghost Imaging, K.W.C. Chan, M.N. O'Sullivan, and R.W. Boyd, Phys. Rev. A 79, 033808 (2009).

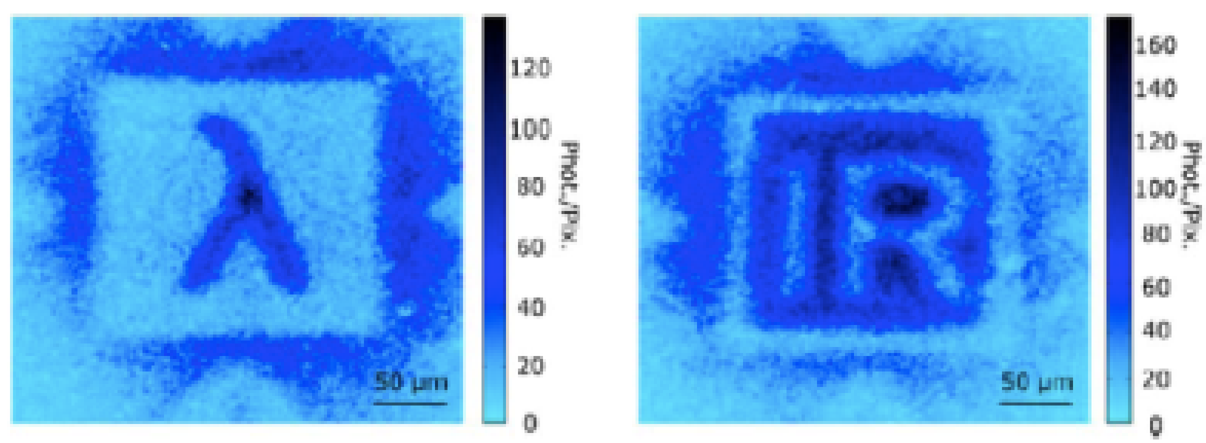
Wavelength-Shifted (Two-Color) Ghost Microscopy

- Pump at 355 nm produces signal at 460 nm and idler at 1550 nm
- Object is illuminated at 1550 nm, but image is formed (in coincidence) at 460 nm
- Wavelength ratio of 3.4 is the largest yet reported.

Setup

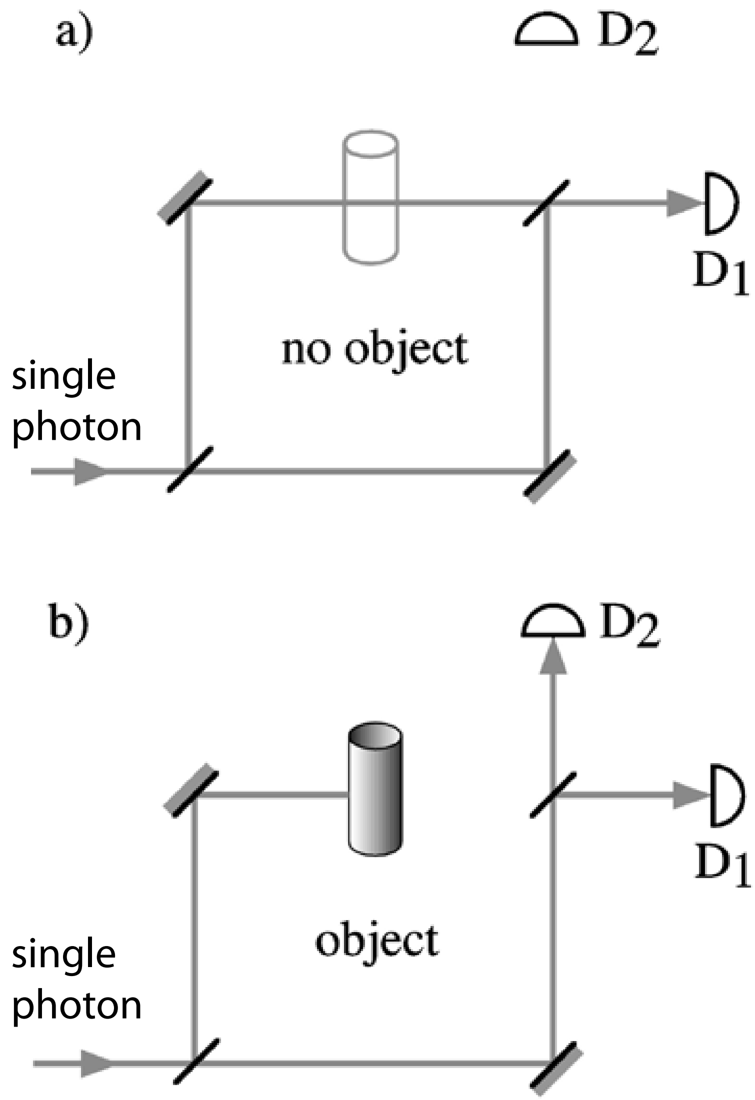


Typical images

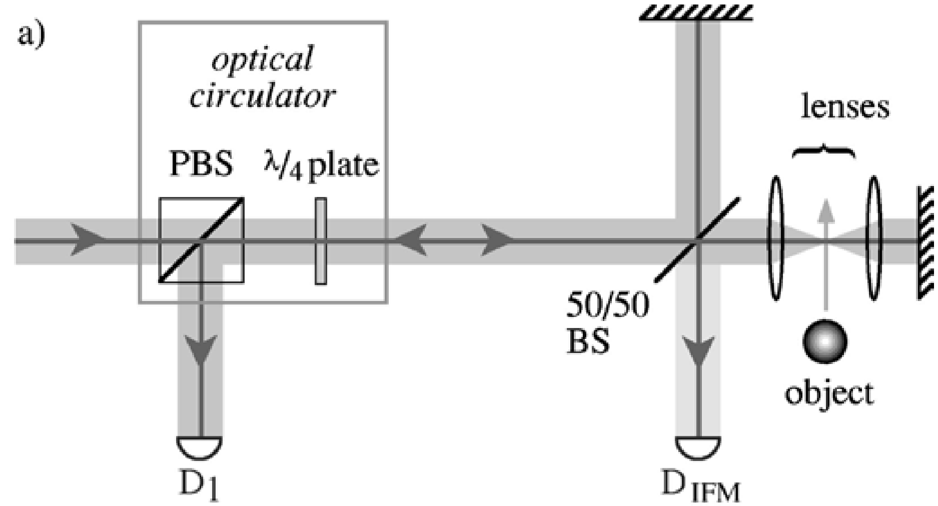


Photon-sparse microscopy: visible light imaging using infrared illumination, R.S. Aspden, N. R. Gemmell, P.A. Morris, D.S. Tasca, L. Mertens, M.G. Tanner, R. A. Kirkwood, A. Ruggeri, A. Tosi, R. W. Boyd, G.S. Buller, R.H. Hadfield, and M.J. Padgett, Optica 2, 1049 (2015).

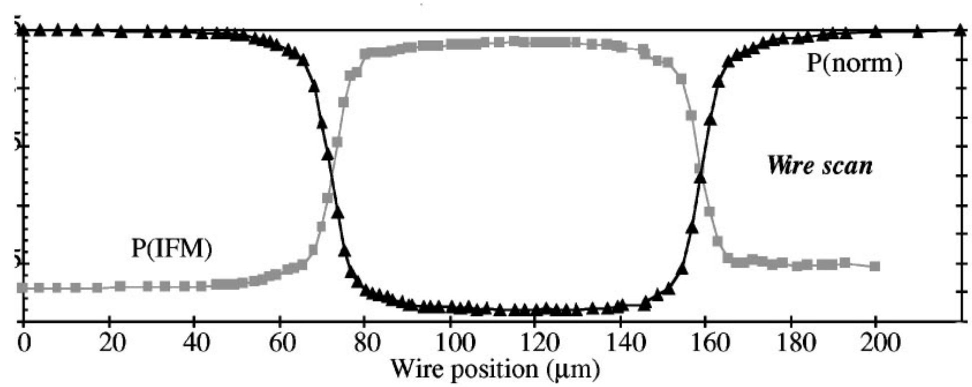
Quantum Imaging by Interaction-Free Measurement



imaging setup

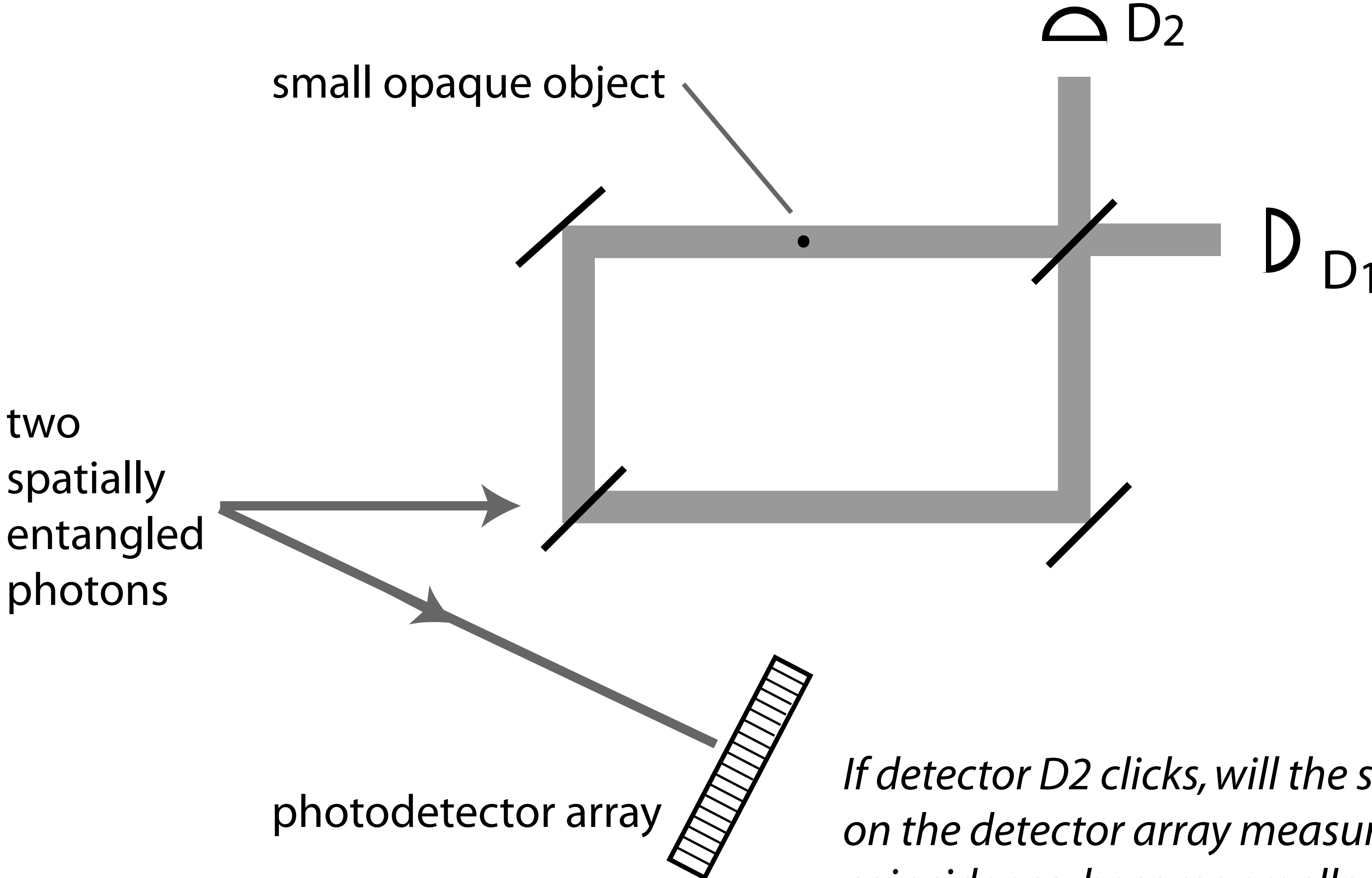


results



M. Renninger, Z. Phys. 15S, 417 (1960).
R. H. Dicke, Am. J. Phys. 49, 925 (1981).
A. Elitzur and L. Vaidman, Found. Phys. 23, 987 (1993).
L. Vaidman, Quant. Opt. 6, 119 (1994).
P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, Phys. Rev. Lett. 74, 4763 (1995)
A. G. White, J. R. Mitchell, O. Nairz, and P. G. Kwiat, Phys. Rev. A 58, 605 (1998).

Interaction-Free Measurements and Entangled Photons



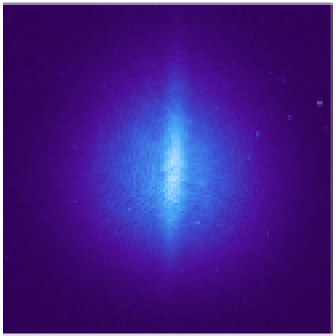
If detector D2 clicks, will the spot size on the detector array measured in coincidence become smaller?

- Does an interaction-free measurement constitute a “real” measurement?
- Does it lead to the collapse of the wavefunction of its entangled partner?
- More precisely, does the entire two-photon wavefunction collapse?

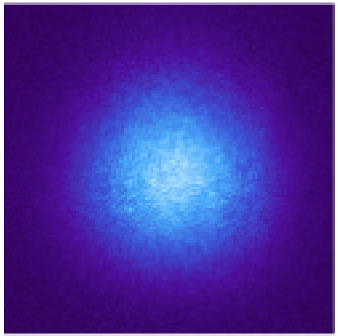
Experimental Results

Interaction-free ghost image of a straight wire

coincidence counts



singles counts



- Note that the interaction-free ghost image is about five times narrower than full spot size on the ICCD camera

- This result shows that interaction-free measurements lead to wavefunction collapse, just like standard measurements.

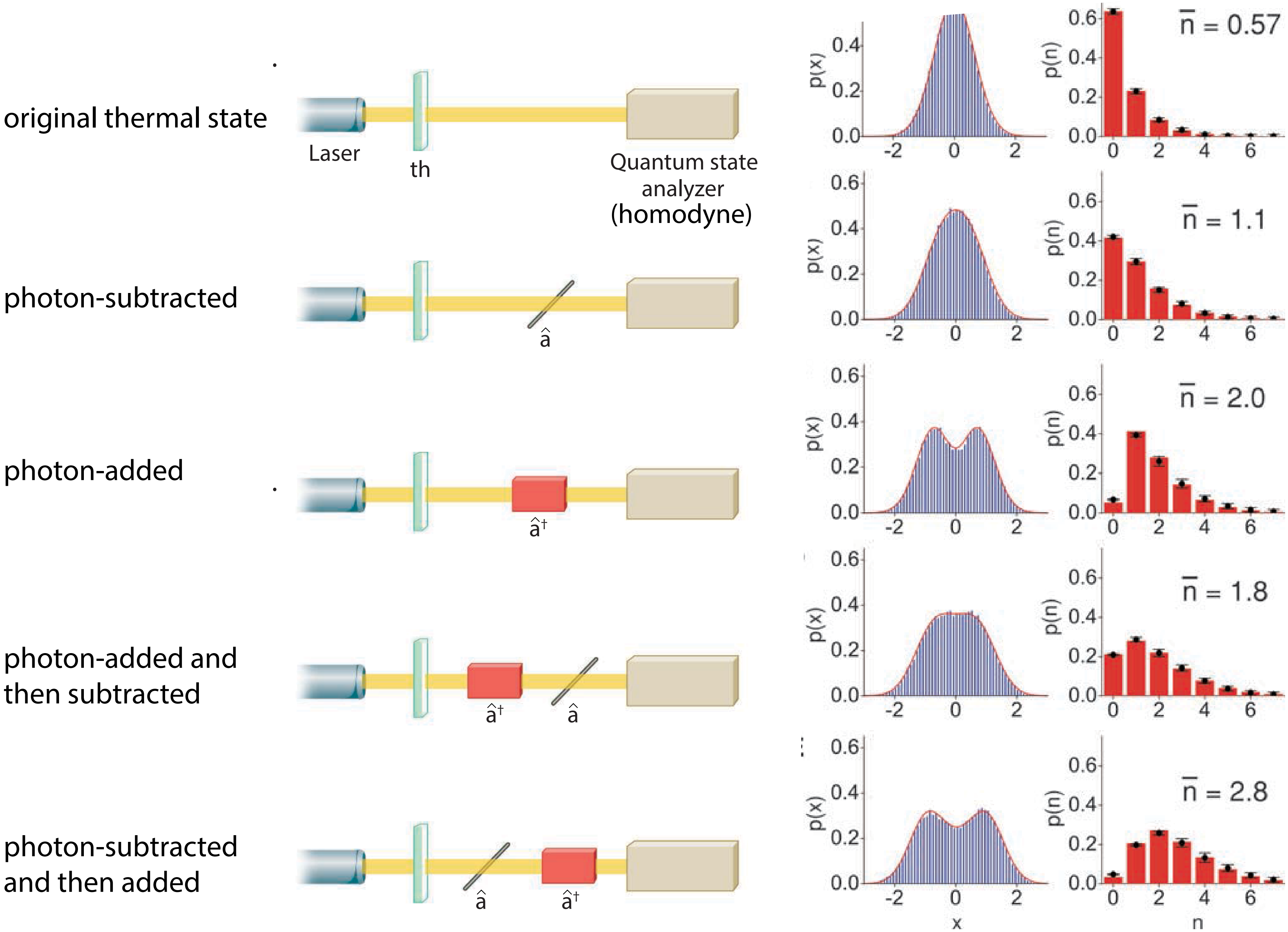
With Frédéric Bouchard, Harjaspreet Mand, and Ebrahim Karimi,

Is interaction-free imaging useful?

Interaction-free imaging allows us to see what something looks like *in the dark*!

Could be extremely useful for biophysics. What does the retina look like when light does not hit it?

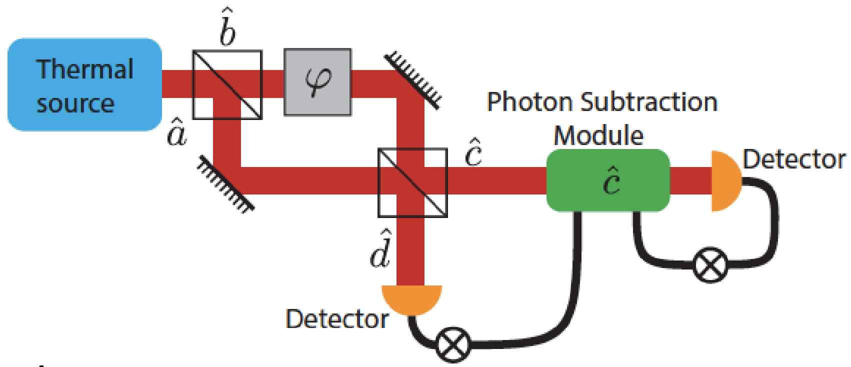
Photon-Added and Photon-Subtracted States



Note!

V. Parigi, A. Zavatta, M. Kim, M. Bellini, Science 317,1890 (2007).

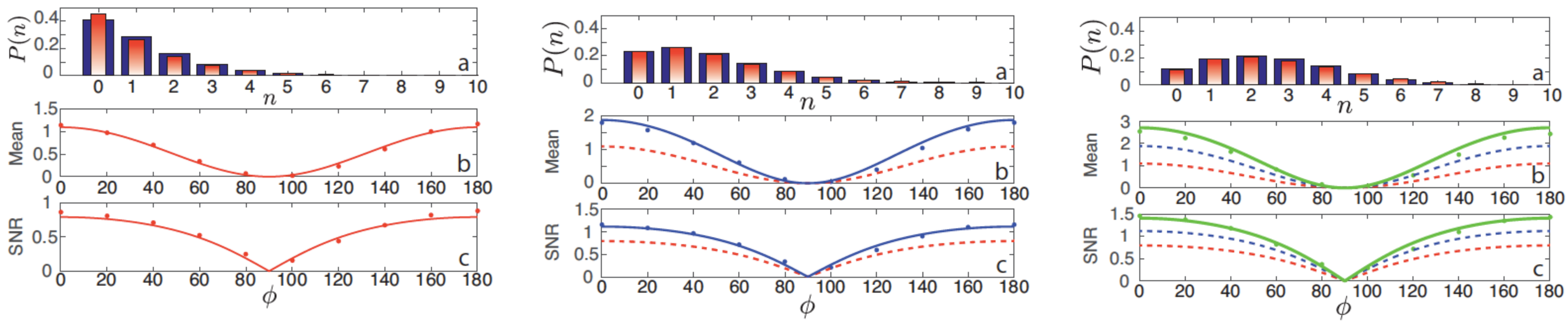
Enhanced Interferometry with Photon-Subtracted Thermal Light



Can we measure the phase ϕ more accurately by using photon-subtracted states?

- Results

without photon subtraction | with one-photon subtraction | with two-photon subtraction



- We find that the signal-to-noise ratio (SNR) is increased through use of photon-subtracted states!

- However, in the present setup, photon-subtraction occurs probabilistically and only a small fraction of the time

- Is there a means to obtain photon-addition and photon-subtraction deterministically?

- Can we use this method to perform quantum imaging with improved SNR?

Rochester, Boeing, LSU, Lehman collaboration

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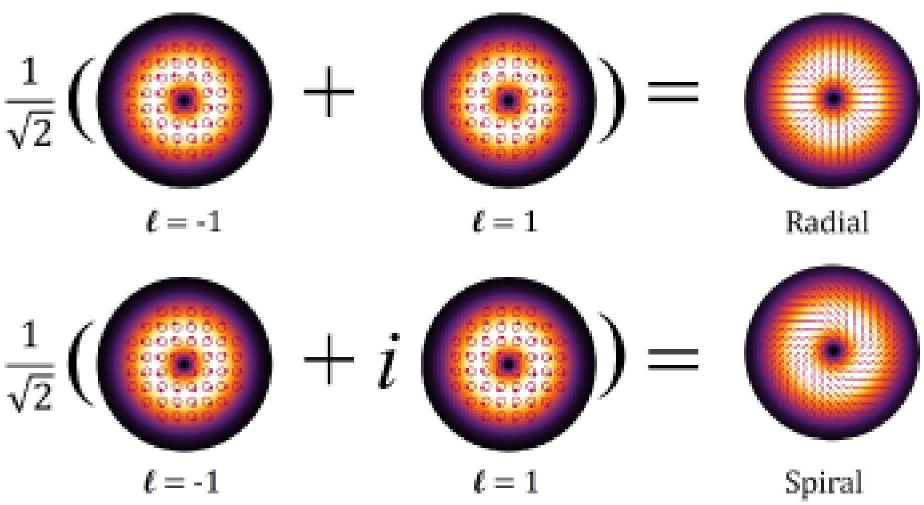
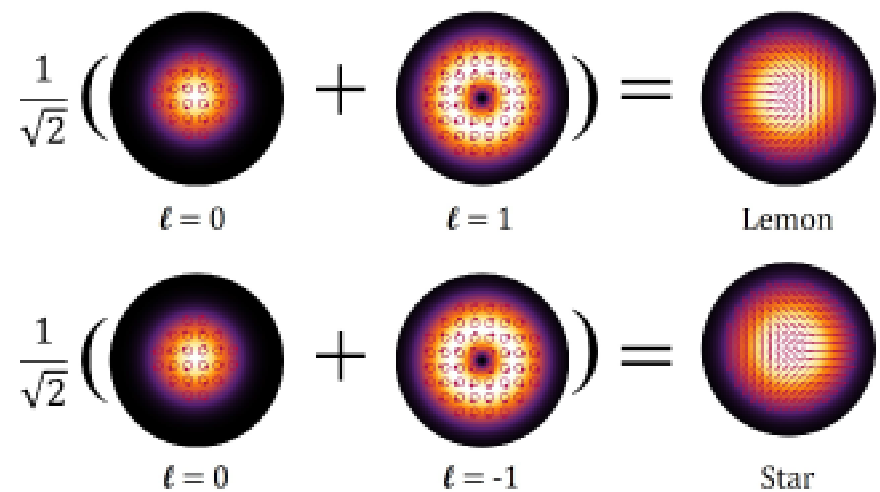
Structured Light Beams

- One can use the transverse degree of freedom of the light field to encode information.
- Not all light waves are infinite plane waves!
- Even a single photon in such a structured field can carry many bits of information
- Example: Space-Varying Polarized Light Beams

Vector Vortex Beams



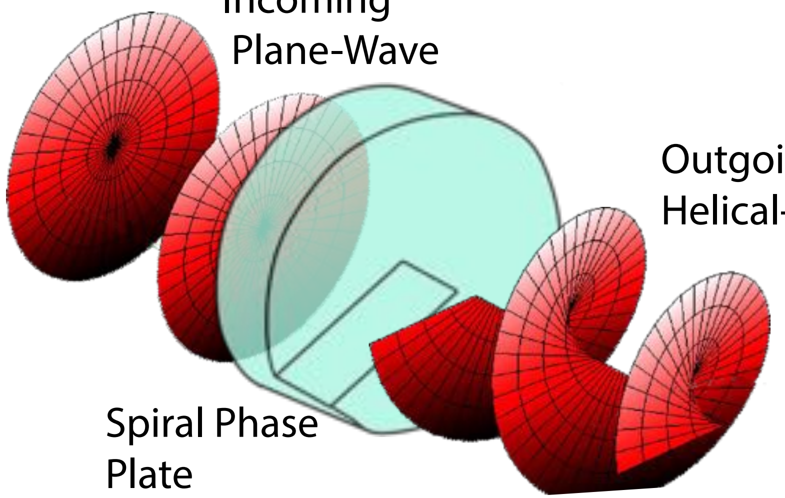
Poincaré Beams



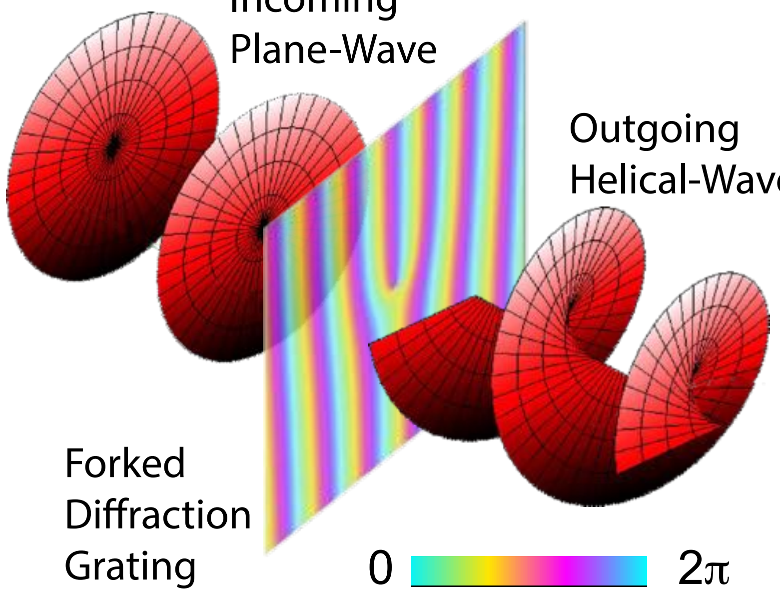
Laroque et al, PRL 2016 (in press)

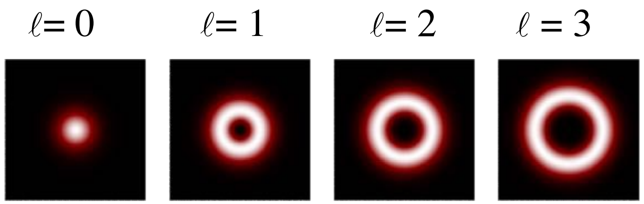
How to create a beam carrying orbital angular momentum?

- Pass beam through a spiral phase plate



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





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).

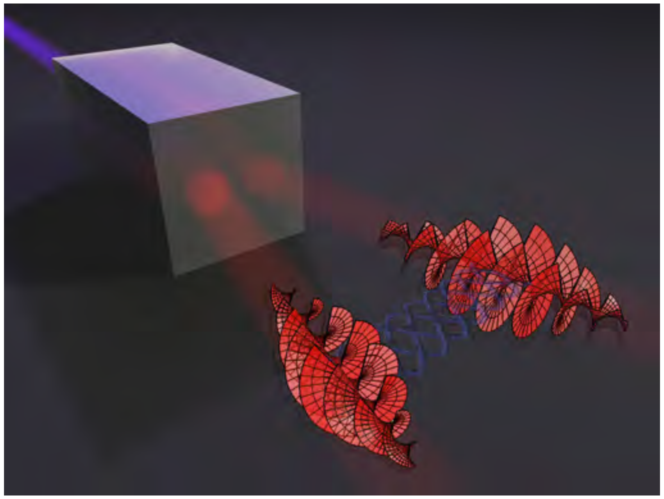
Use of Quantum States for Secure Optical Communication

- 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.

Key collaborators: Karimi, Leuchs, Padgett, Willner.



QKD System Carrying Many Bits Per Photon

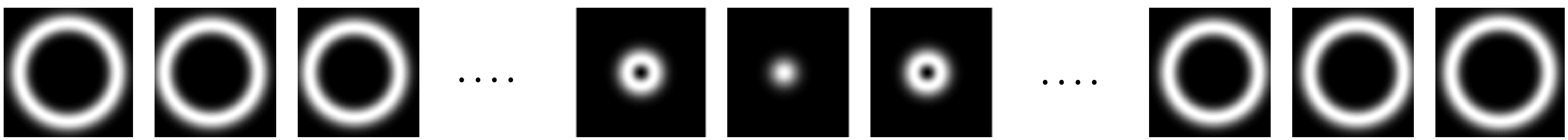
We are constructing a QKD system in which each photon carries many bits of information

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

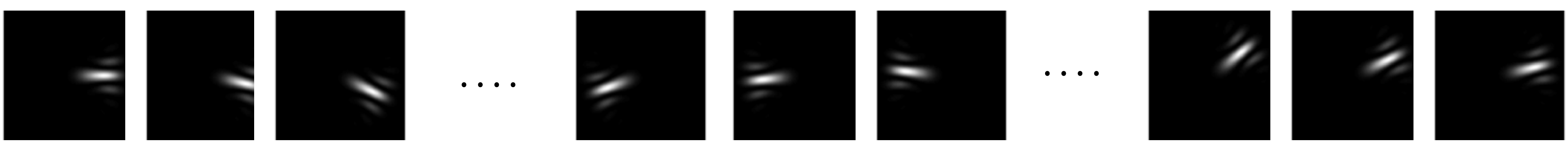
<u>Single Photon States</u>

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



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

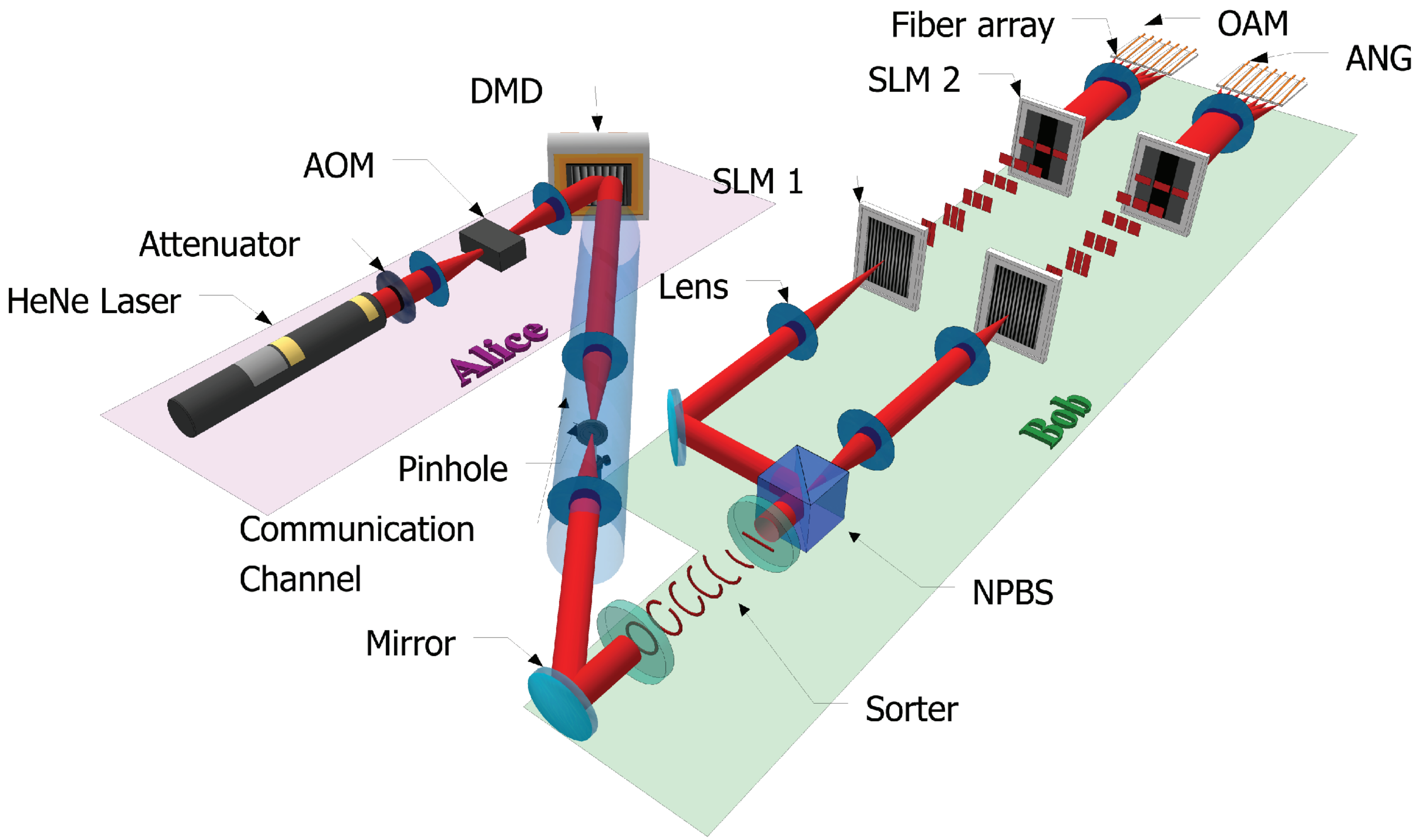
"Angular" Basis (mutually unbiased with respect to LG)

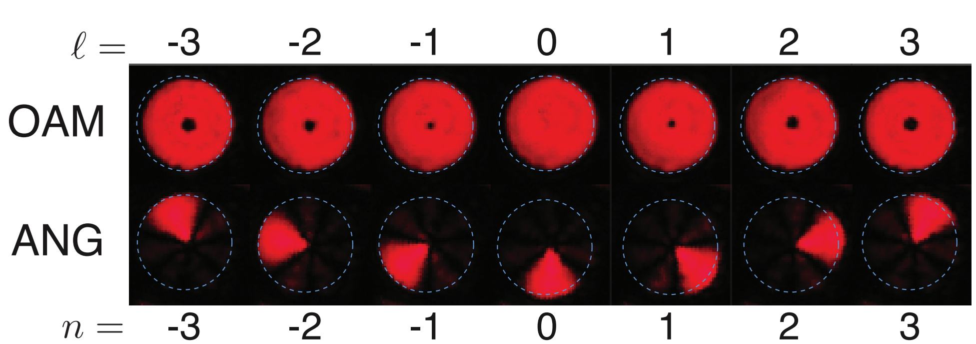


0 1 2 12 13 14 25 26 27

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

Laboratory Demonstration of OAM-Based Secure Communication





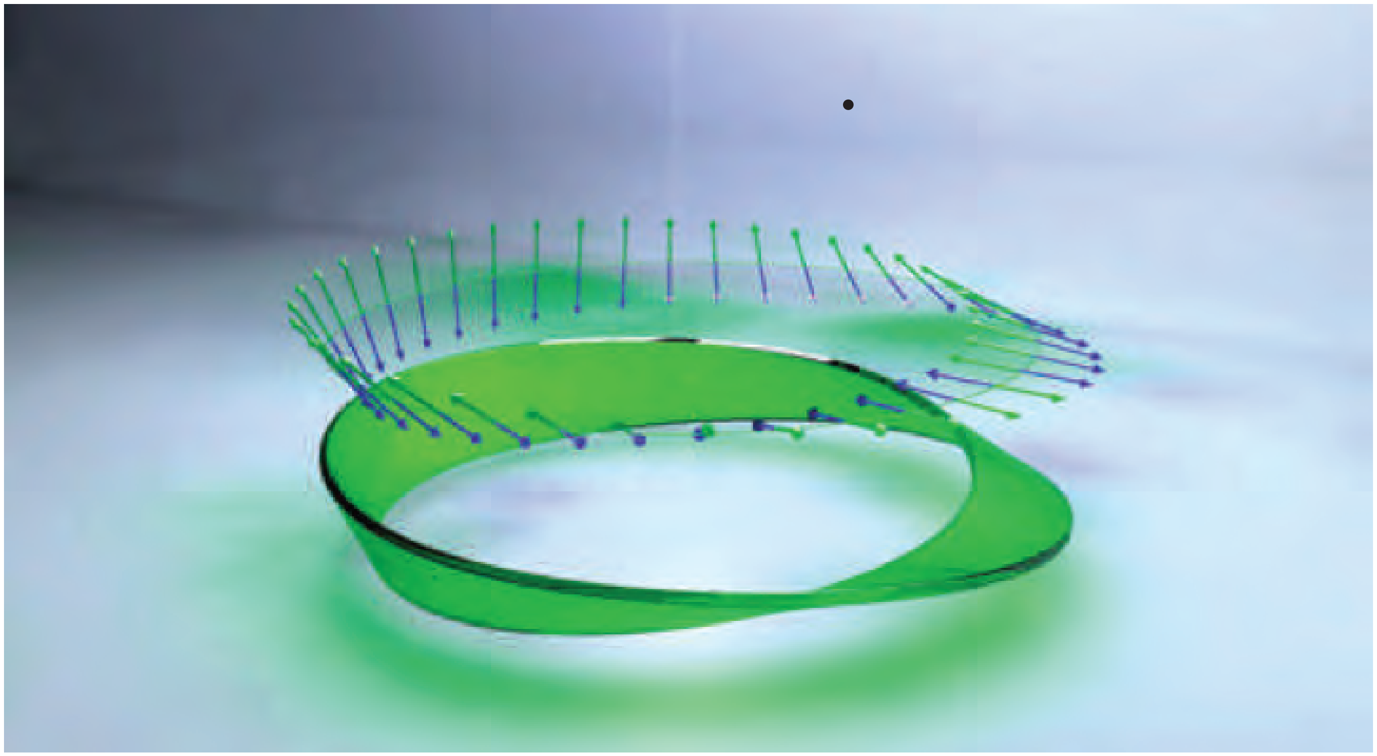
We use a seven-dimensional state space.

We transfer 2.1 bits per detected photon

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

Observation of Optical Polarization Möbius Strips

- Möbius strips are familiar geometrical structures, but their occurrence in nature is extremely rare.
- We generate and characterize Möbius structures on the nanoscale in tighly focused vector beams.



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

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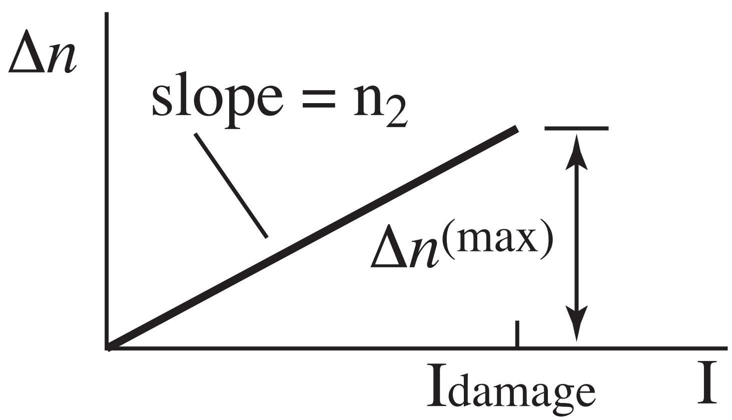
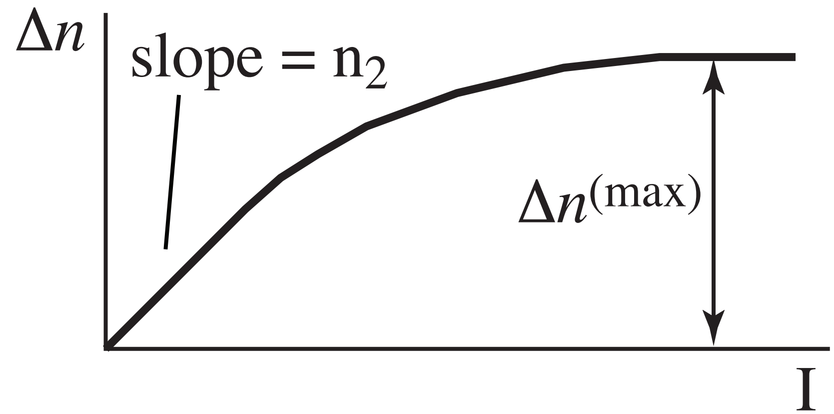
What Makes a Good (Kerr-Effect) Nonlinear Optical Material?

Want n_2 large ($\Delta n = n_2 I$). We also want $\Delta n^{(max)}$ large.

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





We report a material for which both n_2 and $\Delta n^{(max)}$ are extremely large!
(M. Z. Alam et al., Science 10.1126/science.aae0330 2016.)

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

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

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

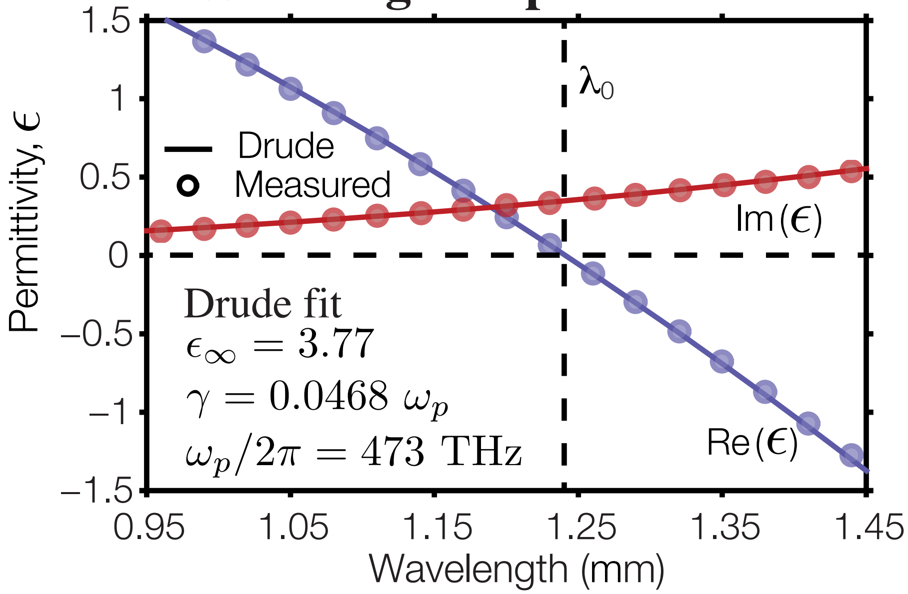
Indium Tin Oxide (ITO) displays enormously strong NLO properties:

- 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

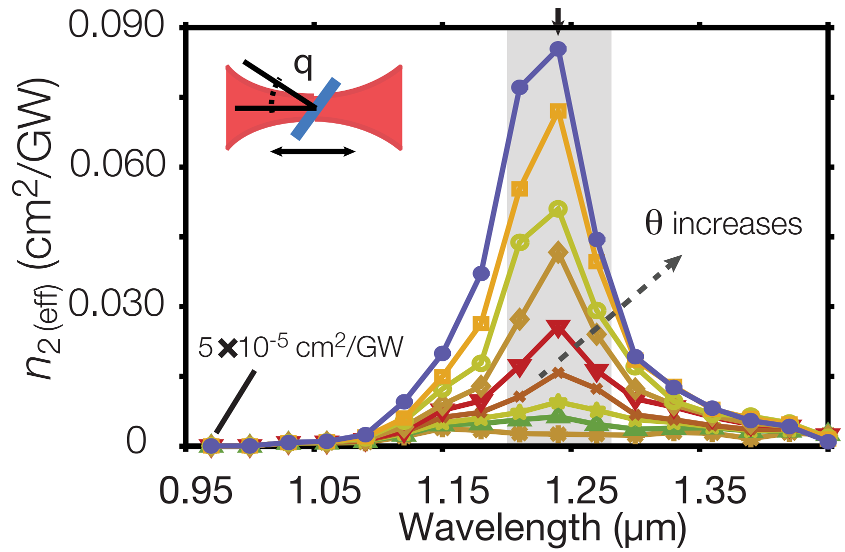
$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

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

Wavelength dependence of ε



Wavelength dependence of n_2



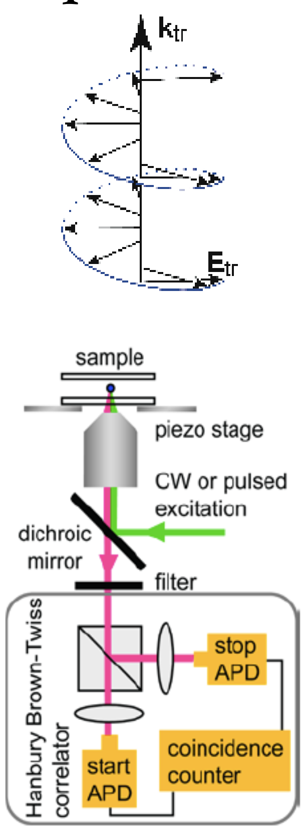
Some possible new effects

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

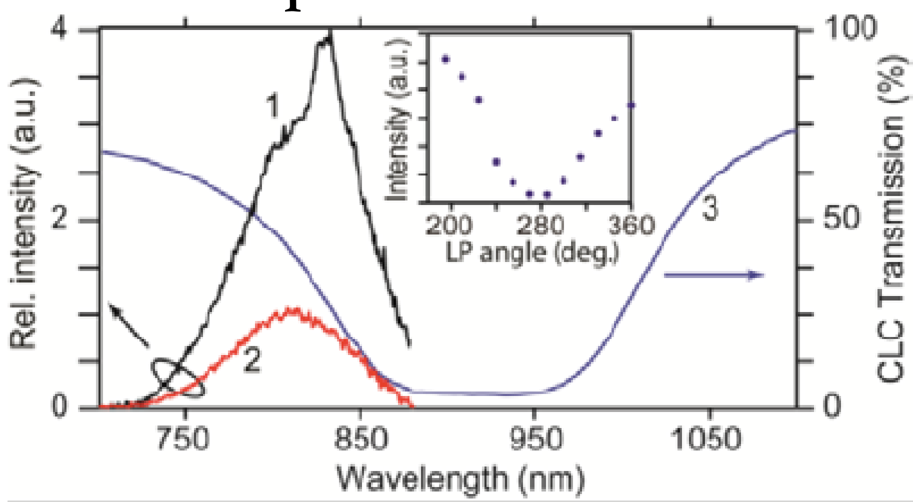
M. Z.Alam, I. De Leon, and R.W. Boyd, Science 352, 795 (201

Single-Photon Sources

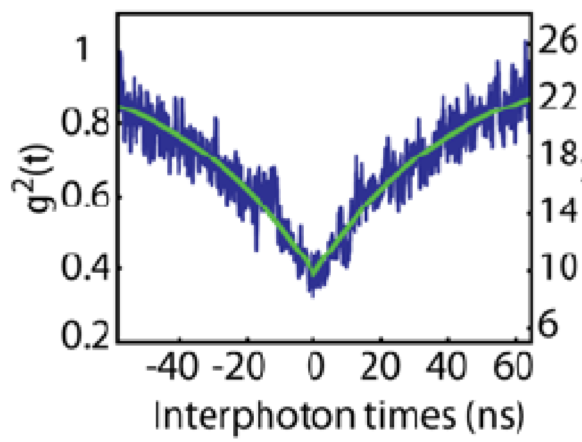
- Many protocols in quantum information require a single-photon source
- An example is the BB84 protocol of quantum key distribution
  - If by accident two photons were sent, one could be stolen by an eavesdropper
  - Even in a weak coherent state, there is a nonvanishing probability of two or more photons being sent
- Circularly polarized fluorescence and antibunching from a nanocrystal quantum dot doped into a glassy cholesteric liquid crystal microcavity



spectrum



anti-bunching

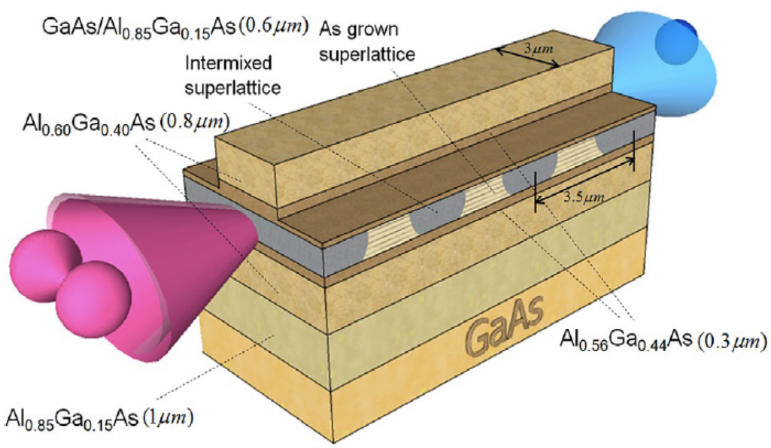


Lukishova et al., Journal of Physics: Conference Series 594 (2015) 012005

On-Chip Photonic Devices for Quantum Technologies

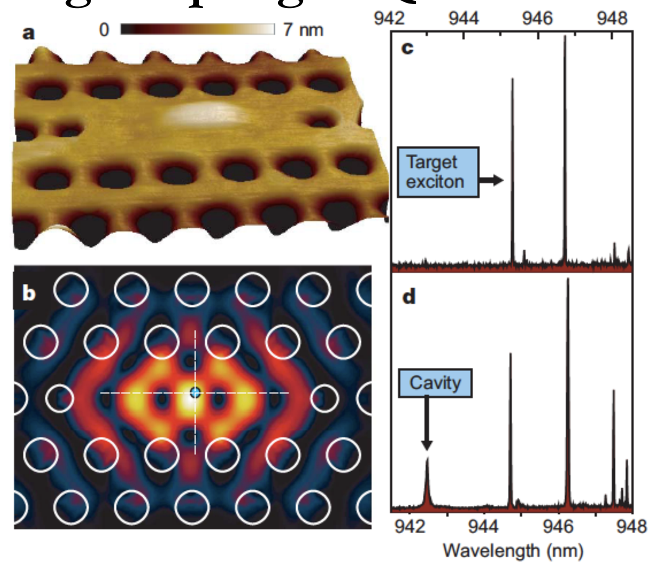
- To make quantum technolgies practical, we need to develop networks of quantum devices on a single chip

- Source of correlated photons



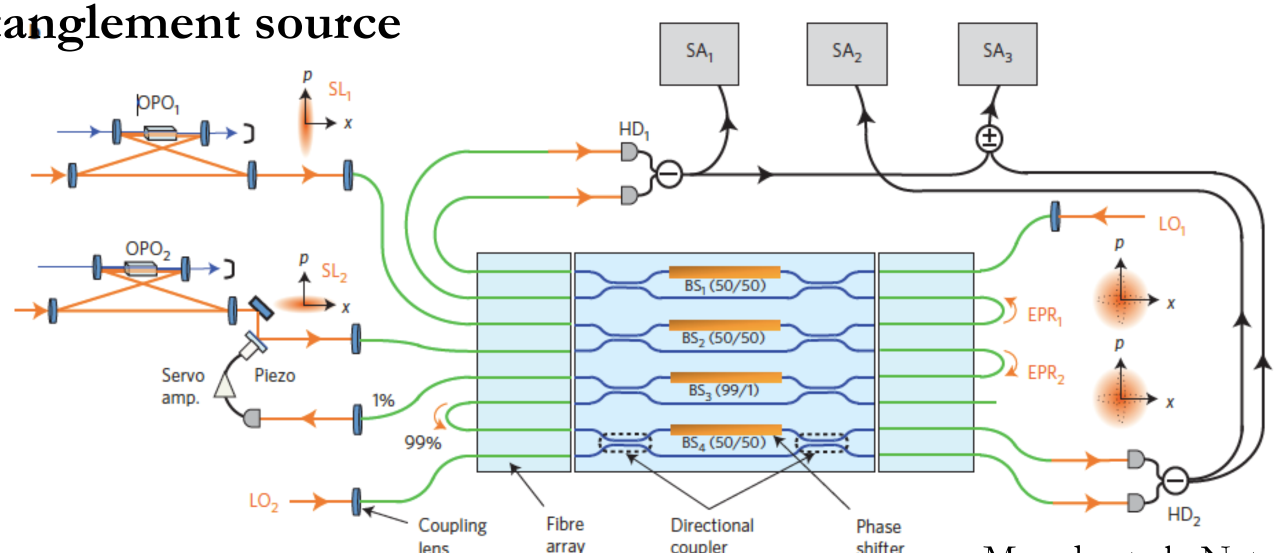
Sarrafi et al., Appl. Phys. Lett. 103, 251115 (2013).

- Strong coupling of QD to PhC resonator



Hennessy et al., Nature 445, 896 (2007)

- Entanglement source

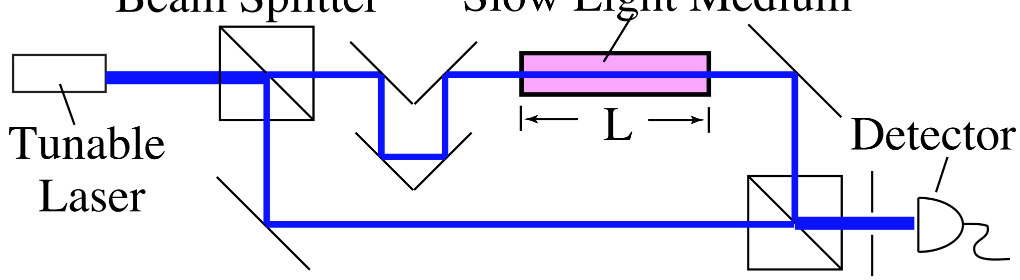


Masada et al., Nature Photonics 9, 316 (2015).

Related Project: 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:

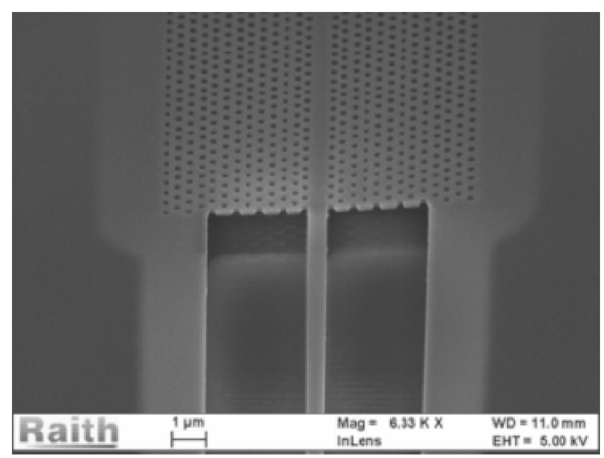


Simple analysis

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

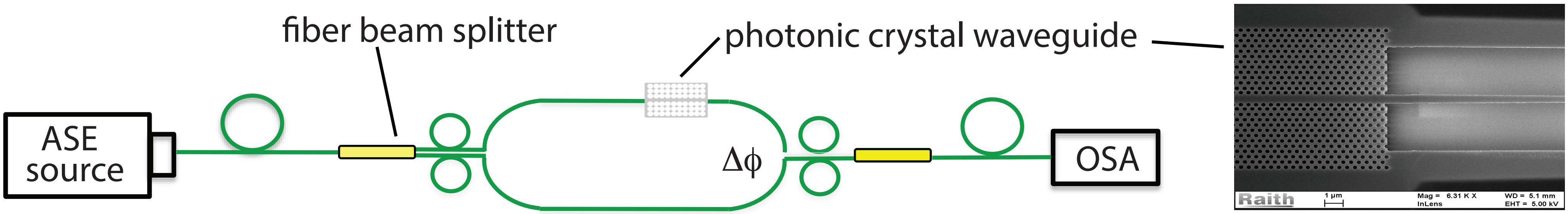
- We use line-defect waveguides in photonic crystals as our slow light mechanism

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

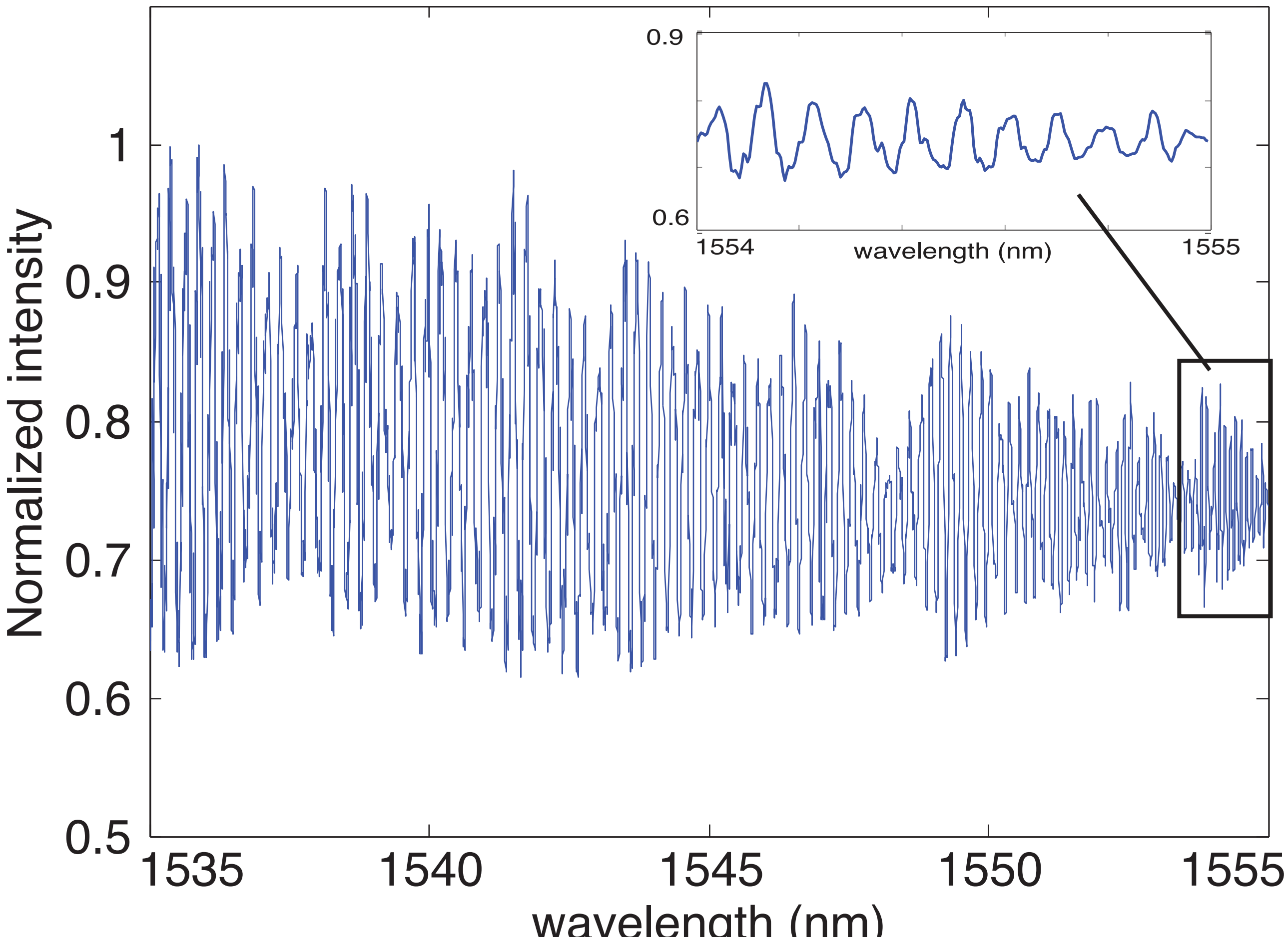


Shi, Boyd, Gauthier, and Dudley, Opt. Lett. 32, 915 (2007)
Shi, Boyd, Camacho, Vudyasetu, and Howell, PRL. 99, 240801 (2007)
Shi and Boyd, J. Opt. Soc. Am. B 25, C136 (2008).

Laboratory Characterization of the Slow-Light Mach-Zehnder Interferometer



- Interference fringes

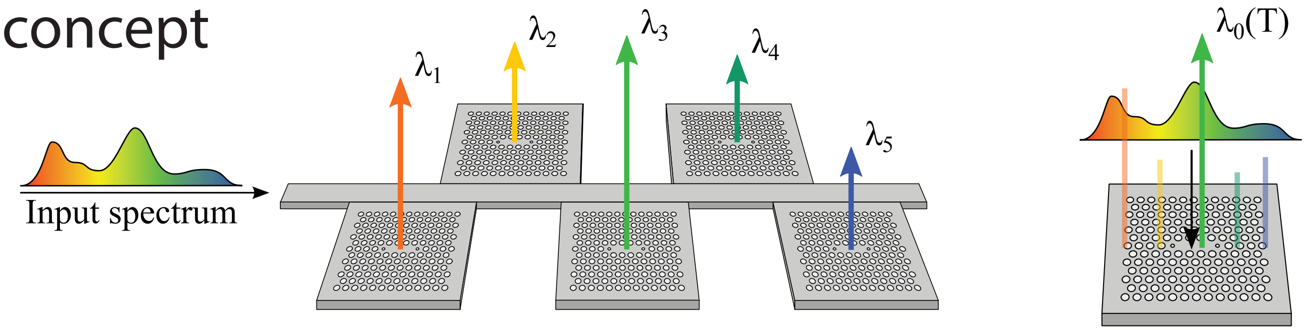


- Resolution (quarter wave) is 17 pm or 2.1 GHz or 0.071 cm^{-1}
- (Slow-light waveguide is only 1 mm long!)

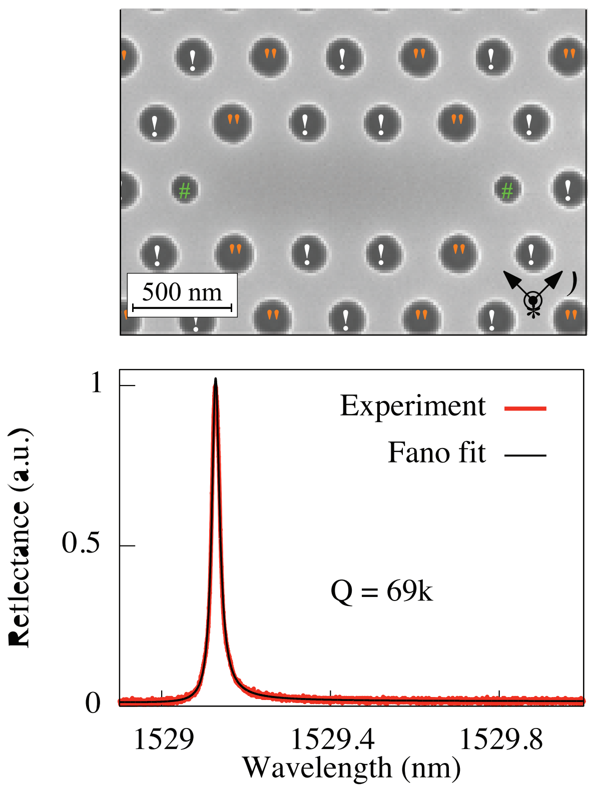
Magaña-Loaiza, Gao, Schulz, Awan, Upham, Dolgaleva, and Boyd, in review.

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

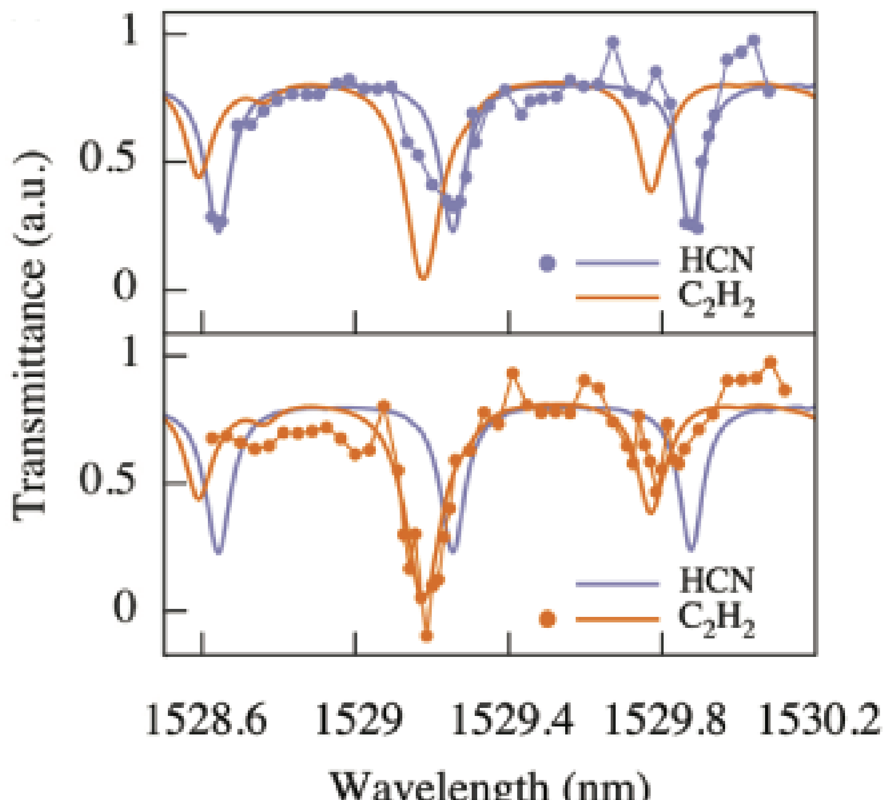
- The concept



- Cavity design



- Spectroscopy results



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

Quantum Sensing

In this talk I present some ideas for research directions in the field of Quantum Sensing

Quantum Imaging
- Two-color ghost imaging
- Interaction-free ghost imaging
- Imaging with photon-added states
- Imaging with “undetected photons”

Structured Light Fields for Quantum Information
- Dense coding of information using orbital angular momentum of light
- Secure Communication transmitting more than one bit per photon
- Mobius structures of light

Materials for Quantum Information
- Epsilon-near-zero materials
- Single-photon sources
- Chip-scale photonic devices for quantum information