Advances in Quantum Nonlinear Optics

Robert W. Boyd

Department of Physics and
Max-Planck Centre for Extreme and Quantum Photonics
University of Ottwa

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

Department of Physics and Astronomy
University of Glasgow

Presented at Photonics North, Québec City, May 24, 2016.

Advances in Quantum Nonlinear Optics

1. Secure optical communication with multiple bits per photon

2. New nonlinear optical material for quantum information processing

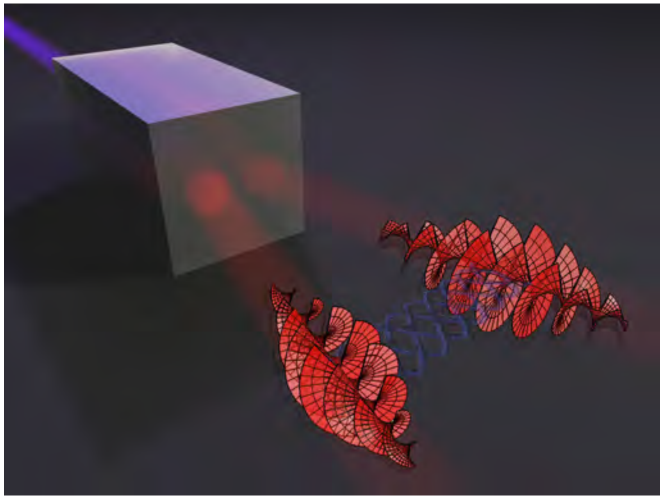
3. The promise of ghost imaging

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

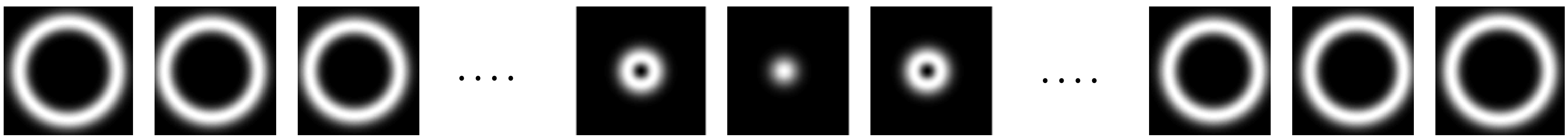
We are constructing a QKD system in which each photon carries many bits of information

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

As a diagnostic, we need to be able to measure the statevector of OAM states

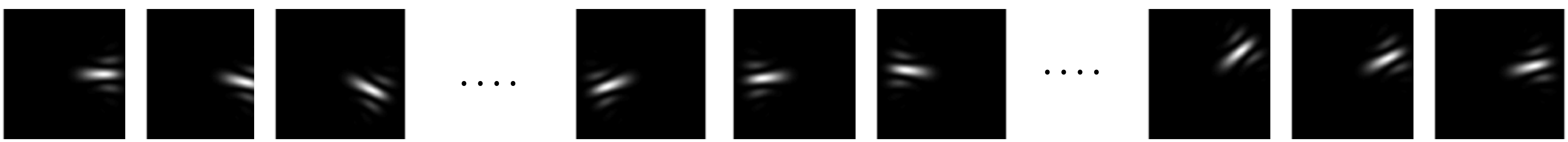
Single Photon States

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



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

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

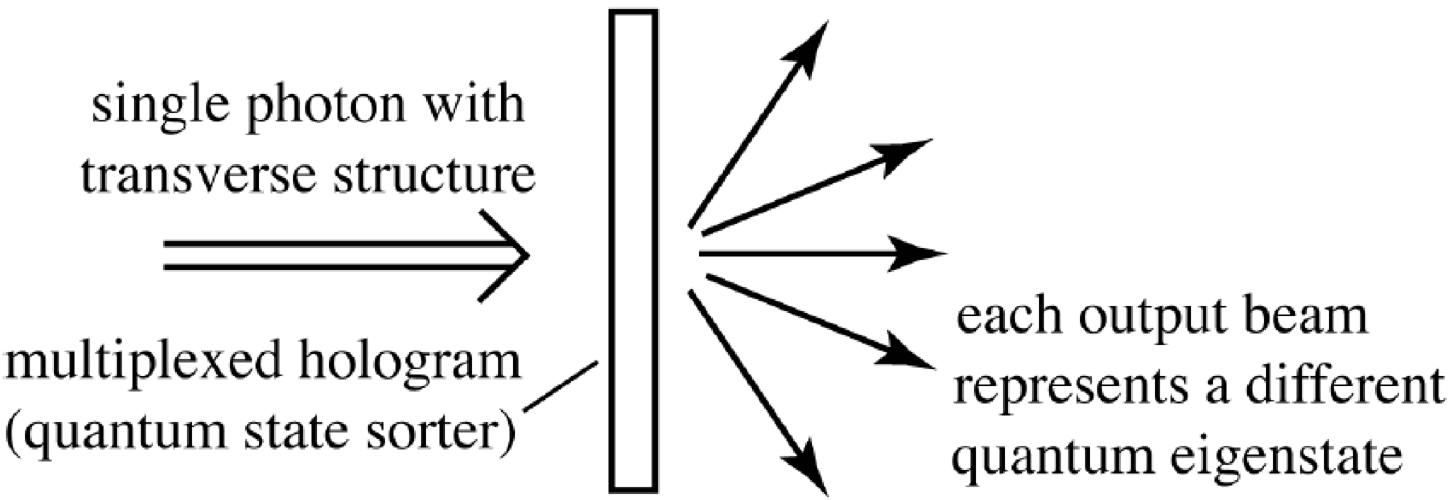


0 1 2 12 13 14 25 26 27

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

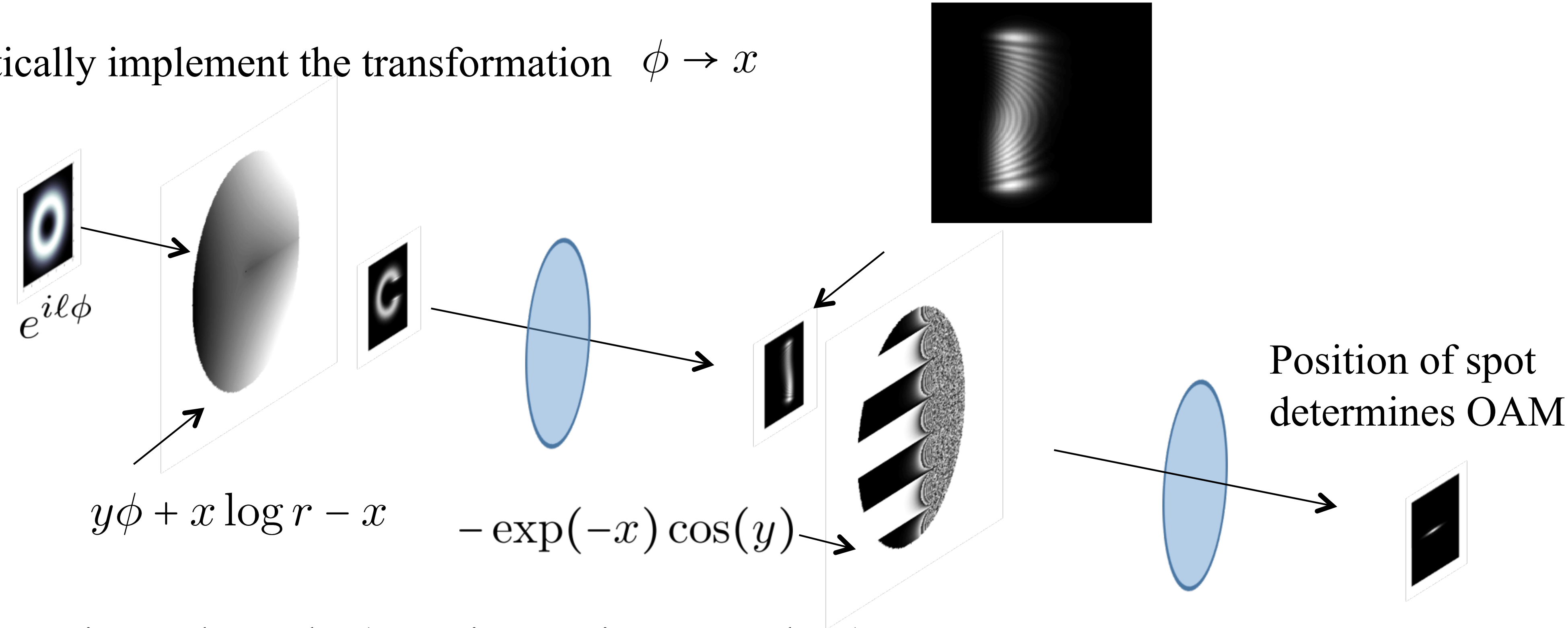
Mode Sorting

A mode sorter

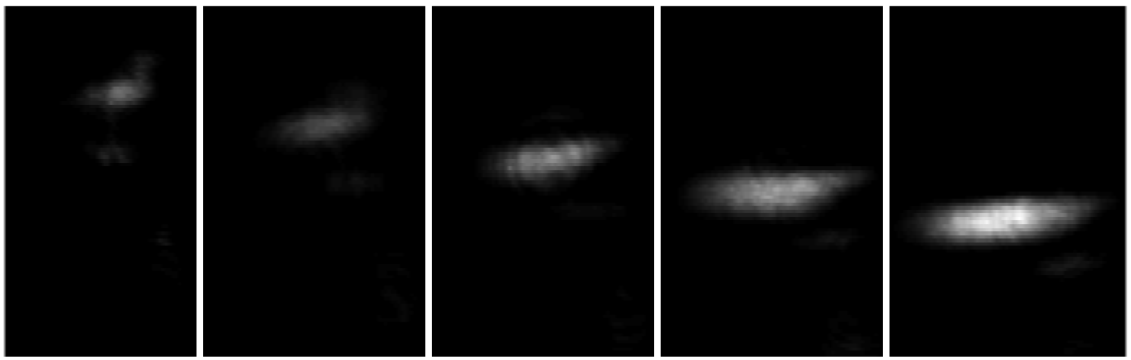


Sorting OAM using Phase Unwrapping

Optically implement the transformation $\phi \rightarrow x$



Experimental Results (CCD images in output plane)



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

-Can also sort angular position states.

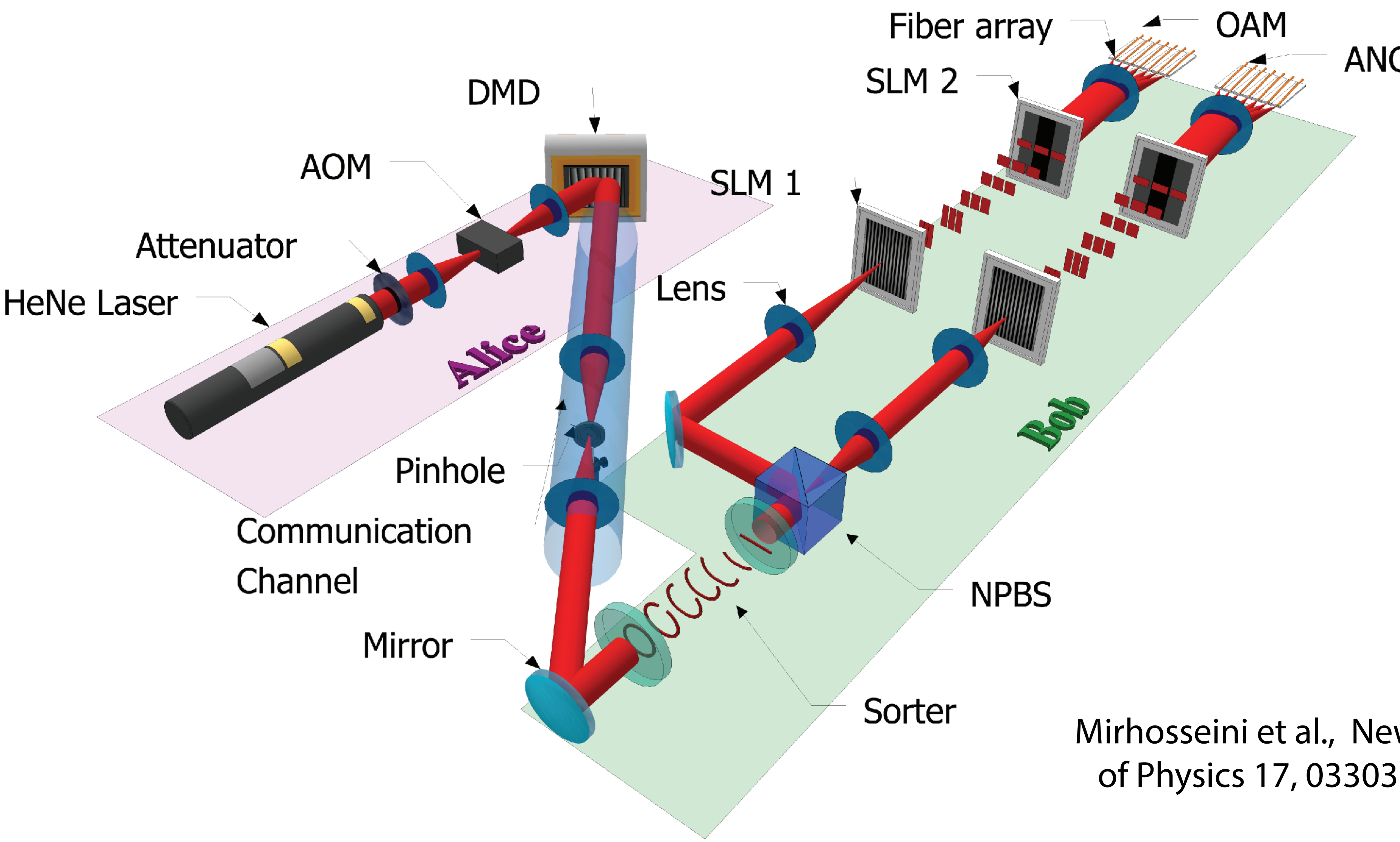
-Limited by the overlap of neighboring states.

University of Rochester

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

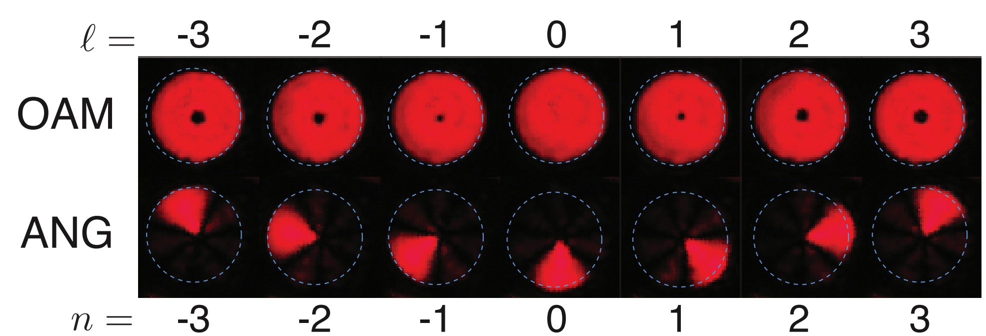
Nonlinear Optics Group

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

0631336021320454444456141026645
545050363603025261643215524164
230146602513401613222451551026

Bob

063033601132021444456141026645
545022353603025261643215524164
230146602515403613422451551026

Error Correction

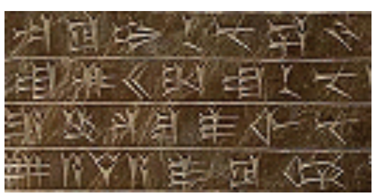
0000 0100 0111 0100 0101 0001 1100 0010 1100 1001 0010 0100 1101 0001 0000
0001 0011 0100 0000 0100 0010 0001 0001 0011 0000 0101 0010 0111 1000 0101
1101 0011 0001 1001 1011 0101 0000 0100 0111 0100 0011 0110 0101 0000 1101
0101 0010 1111 1010 1111 0010 1000

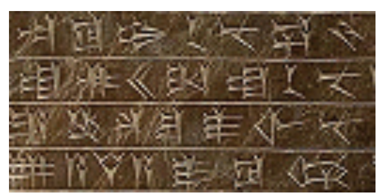
Privacy Amplification

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

Alice Encrypts

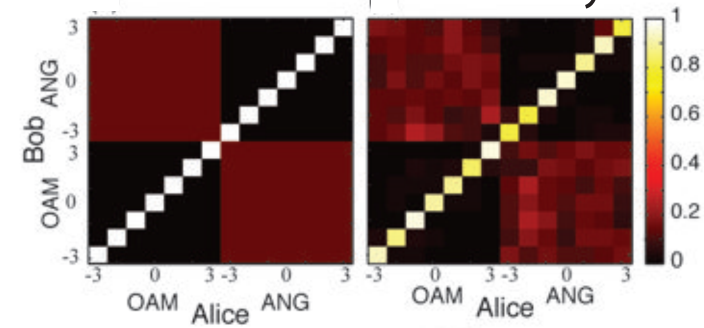
Bob Decrypts

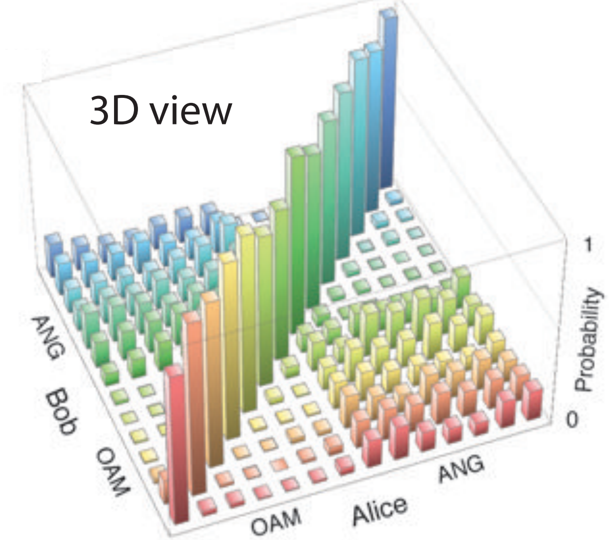




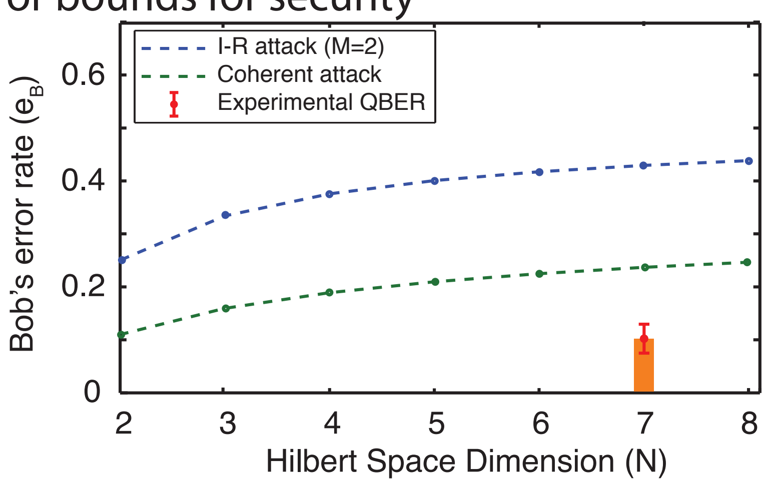
cross-talk matrices

ideal laboratory





- error bounds for security



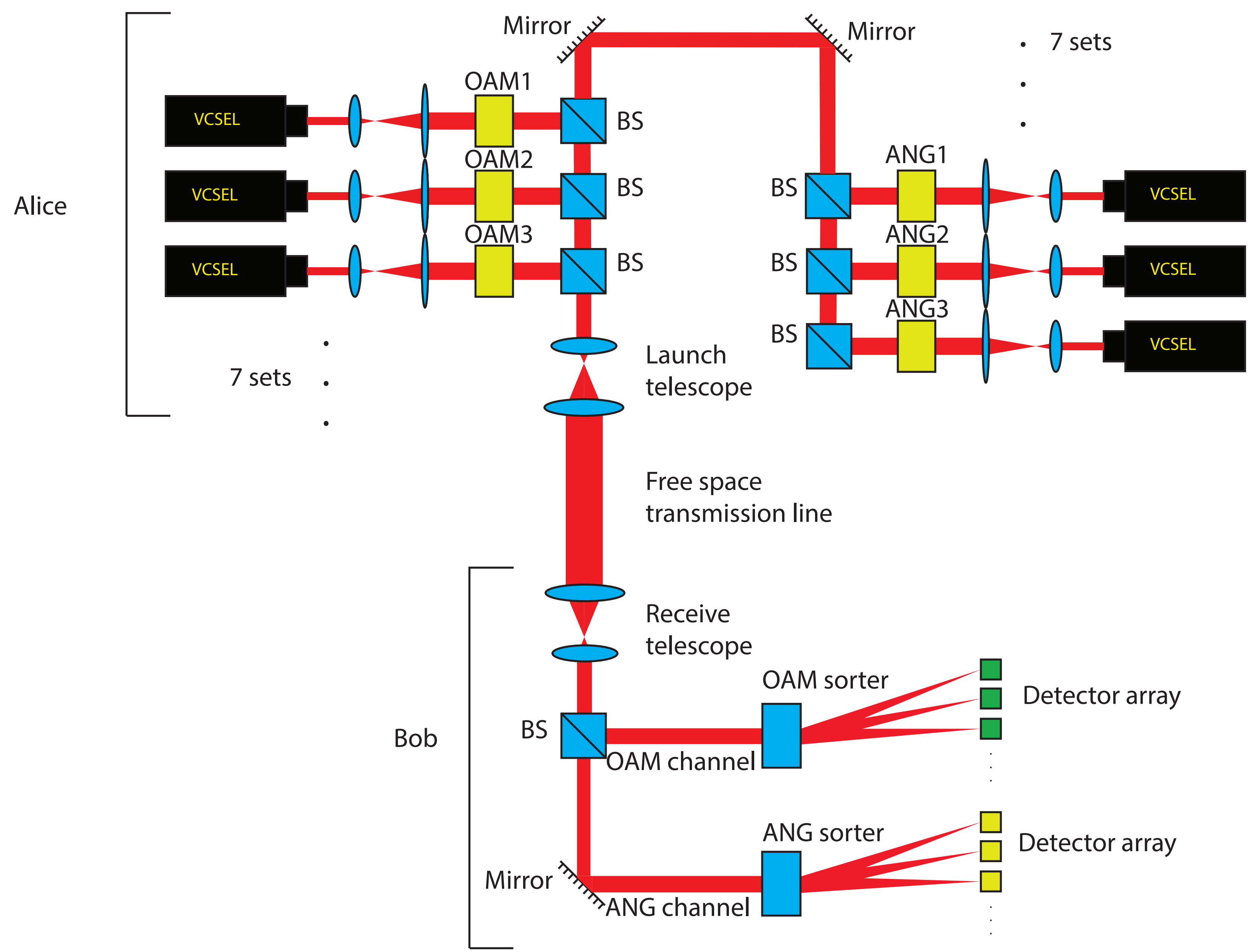
We use a 7-letter alphabet, and achieve a channel capacity of 2.1 bits per sifted photon.

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.



Advances in Quantum Nonlinear Optics

1. Secure optical communication with multiple bits per photon

2. New nonlinear optical material for quantum information processing

3. The promise of ghost imaging

2. New Nonlinear Optical Material for Quantum Information Processing

- We want all-optical switches that work at the single-photon level

- We need photonic materials with a much larger NLO response

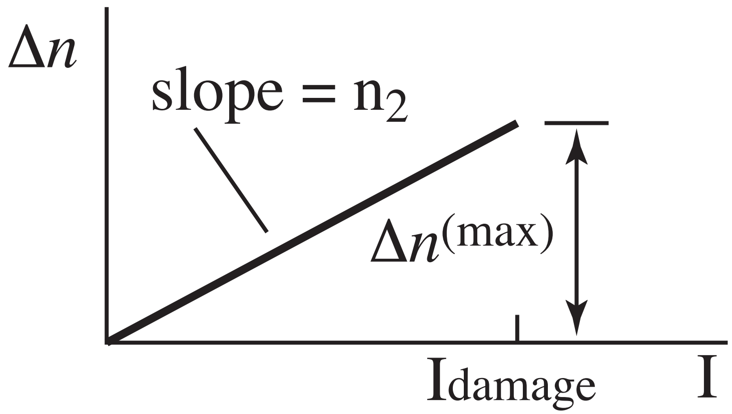
- I report a new NLO material with an n_2 value 100 times larger than any previously reported results (but with background absorption).

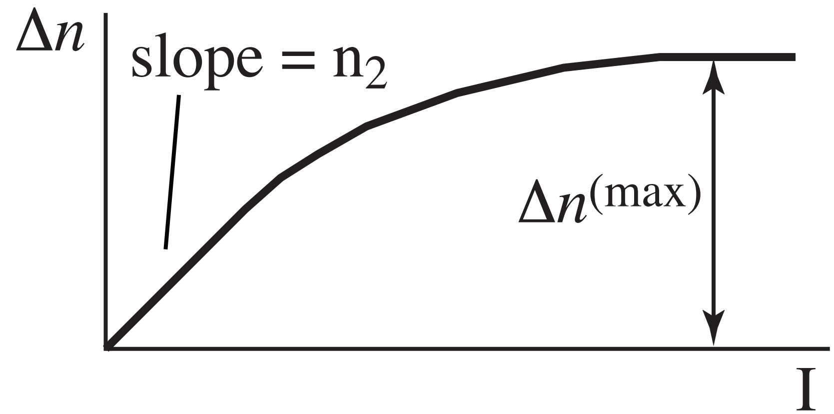
(First release: M. Z. Alam et al., Science 10.1126/science.aae0330 2016.)

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 $\Delta n^{(max)} = 3 \times 10^{-4}$)

Nonlinear Optical Properties of Indium Tin Oxide (ITO)

ITO is a degenerate semiconductor (so highly doped as to be metal-like).

It has a very large density of free electrons, and a bulk plasma frequency corresponding to a wavelength of approximately 1.24 μm.

Recall the Drude formula

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

Note that $\mathrm{Re}\,\epsilon = 0$ for $\omega = \omega_p/\sqrt{\epsilon_\infty} \equiv \omega_0$.

The region near ω_0 is known as the epsilon-near-zero (ENZ) region.

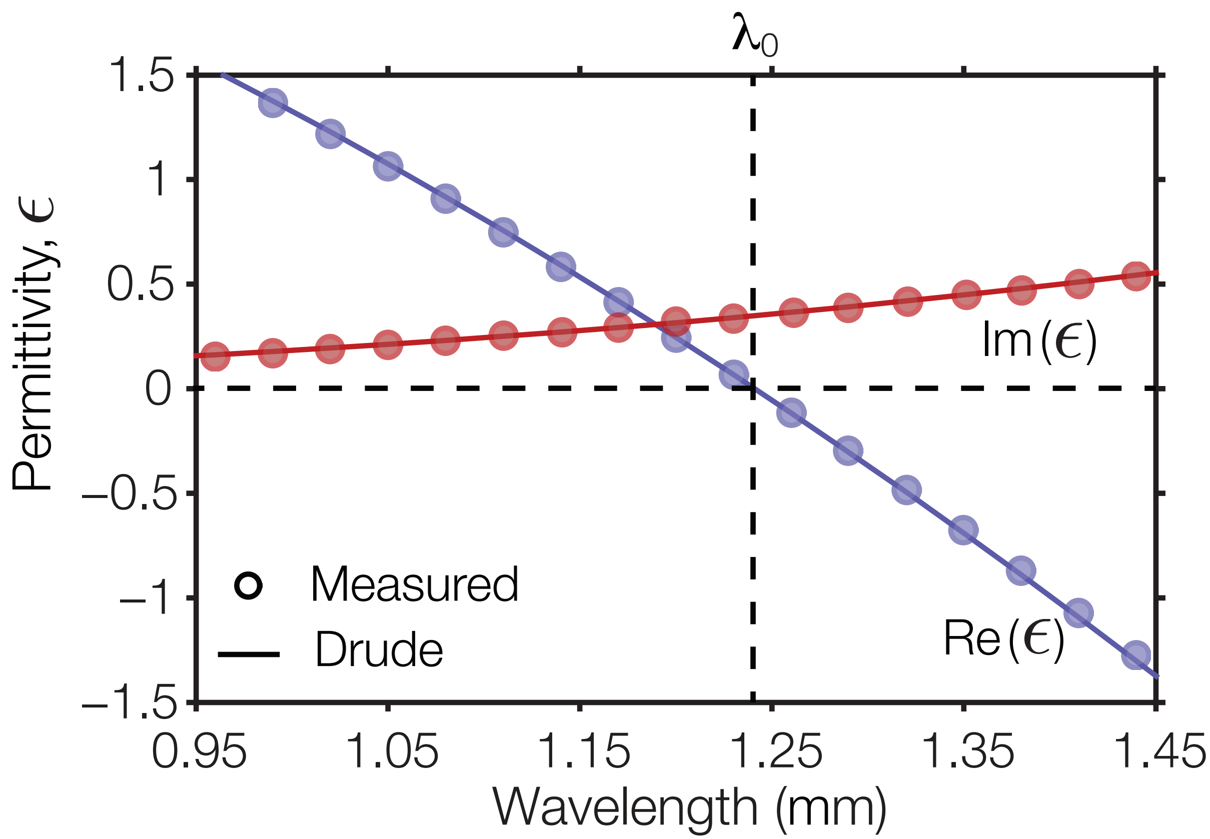
There has been great recent interest in studies of ENZ phenomena:

H. Suchowski, K. O'Brien, Z. J. Wong, A. Salandrino, X. Yin, and X. Zhang, Science 342, 1223 (2013).
C. Argyropoulos, P.-Y. Chen, G. D'Aguanno, N. Engheta, and A. Alu, Phys. Rev. B 85, 045129 (2012).
S. Campione, D. de Ceglia, M. A. Vincenti, M. Scalora, and F. Capolino, Phys. Rev. B 87, 035120 (2013).
A. Ciattoni, C. Rizza, and E. Palange, Phys. Rev. A 81,043839 (2010).

The Epsilon-Near-Zero (ENZ) region of Indium Tin Oxide (ITO)

Measured real and imaginary parts of the dielectric permittivity.

Commercial ITO sample, 310 nm thick on a glass substrate



Drude fit

$\epsilon_\infty = 3.77$

$\gamma = 0.0468\ \omega_p$

$\omega_p/2\pi = 473$ THz

Note that $\mathrm{Re}(\epsilon)$ vanishes at 1.24 mm, but that the loss-part $\mathrm{Im}(\epsilon)$ is non-zero.

Implications of ENZ Behavior for Nonlinear Optics

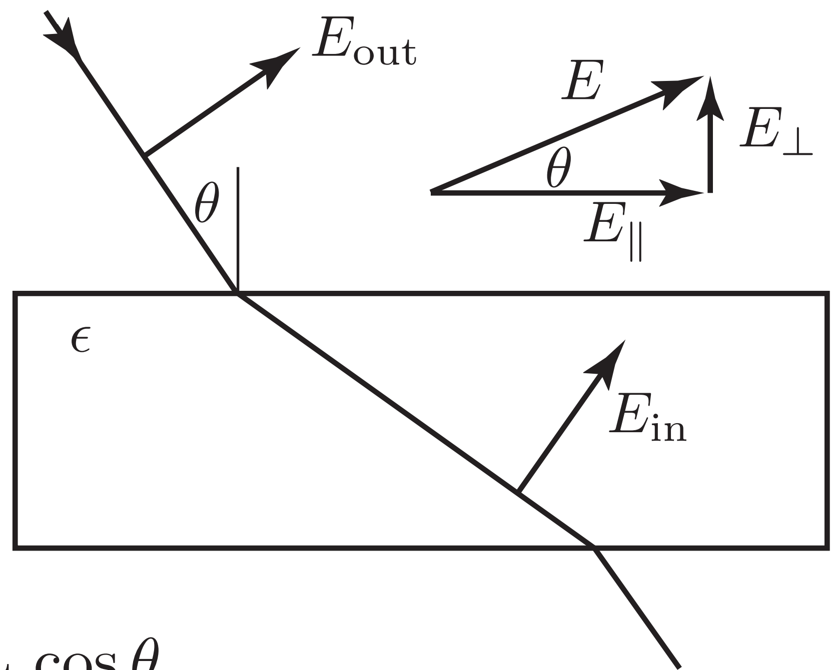
Here is the intuition for why the ENZ conditions are of interest in NLO

Recall the standard relation between n_2 and $\chi^{(3)}$

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

Note that for ENZ conditions the denominator becomes very small, leading to a very large value of n_2

The NLO Response Is Even Larger at Oblique Incidence



Standard boundary conditions show that:

$$E_{\rm in,\parallel} = E_{\rm out,\parallel} = E_{\rm out}\cos\theta$$

$$D_{\rm in,\perp} = D_{\rm out,\perp} \quad \Rightarrow \quad E_{\rm in,\perp} = E_{\rm out,\perp}/\epsilon = E_{\rm out}\cos\theta/\epsilon$$

Thus the total field inside of the medium is given by

$$E_{\rm in} = E_{\rm out}\sqrt{\cos^2\theta + \frac{\sin^2\theta}{\epsilon}}$$

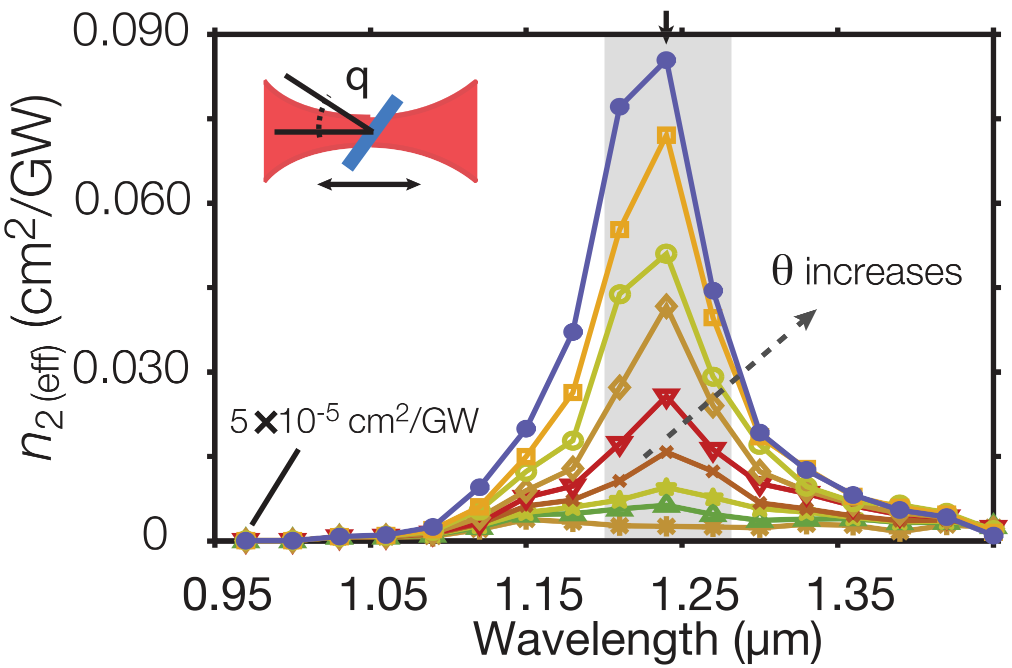
Note that, for $\epsilon < 1$, $E_{\rm in}$ exceeds $E_{\rm out}$ for $\theta \neq 0$.

Note also that, for $\epsilon < 1$, $E_{\rm in}$ increases as θ increases.

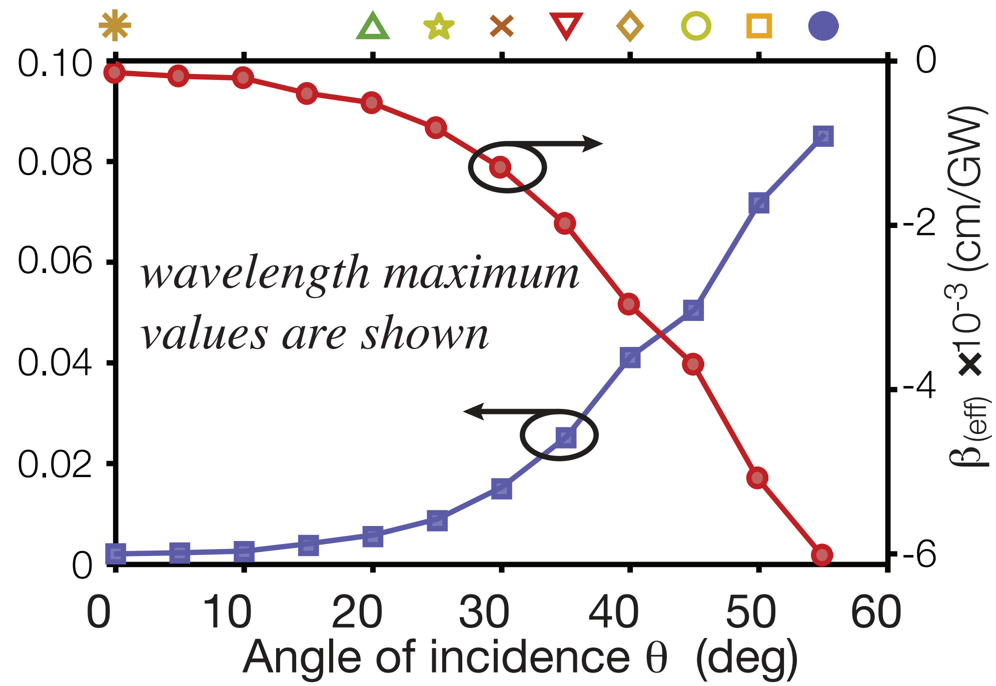
Huge Nonlinear Optical Response of ITO

Z-scan measurements for various angles of incidence

Wavelength dependence of n_2

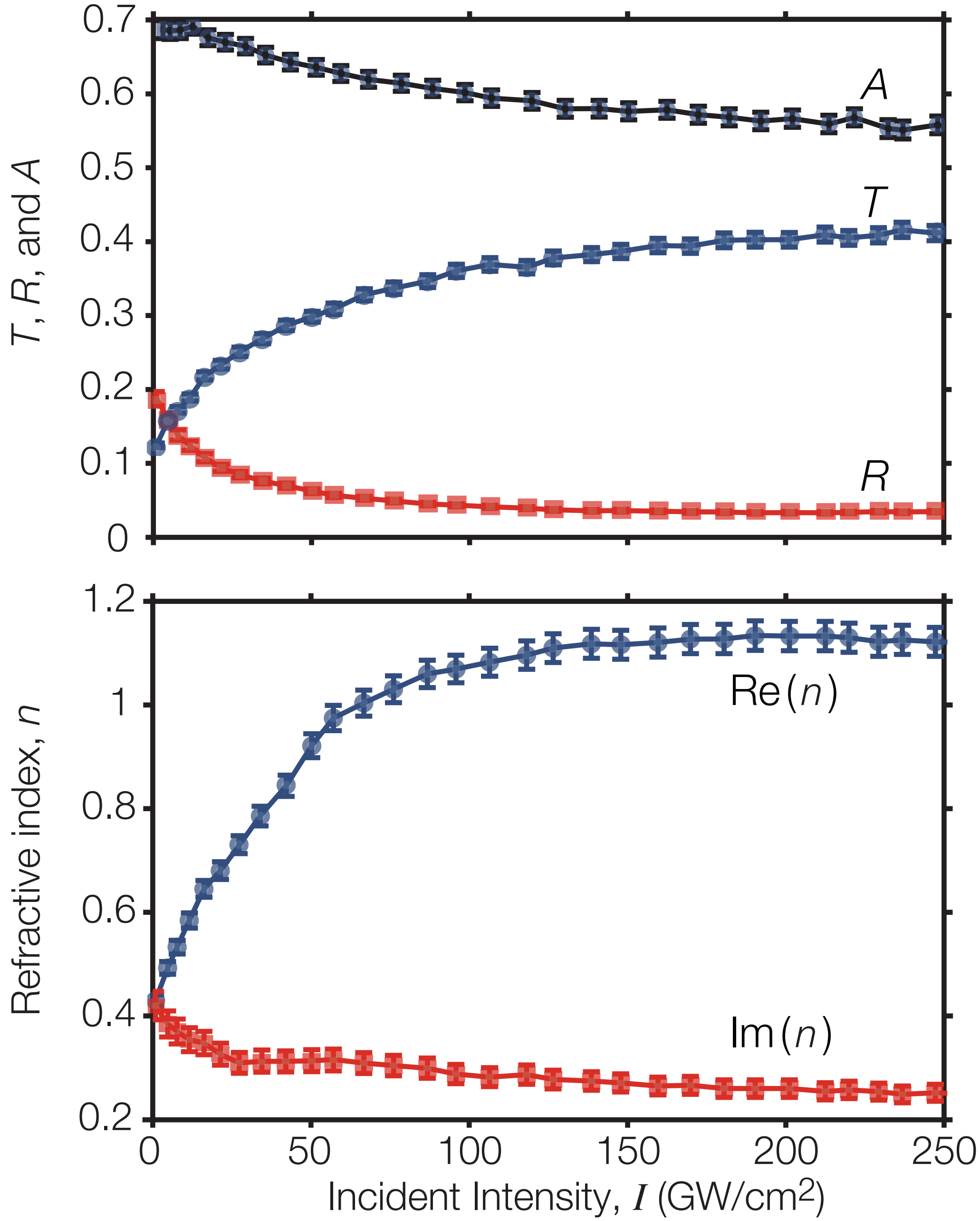


Variation with incidence angle



- Note that n2 is positive (self focusing) and β is negative (saturable absorption).
- Both n_2 and nonlinear absorption increase with angle of incidence
- n_2 shows a maximum value of 0.11 cm^2/GW = 1.1 x 10^{-10} cm^2/W at 1.25 µm and 60 deg.

Beyond the $\chi^{(3)}$ limit



The nonlinear change in refractive index is so large as to change the transmission, absorption, and reflection!

Note that transmission is increased at high intensity.

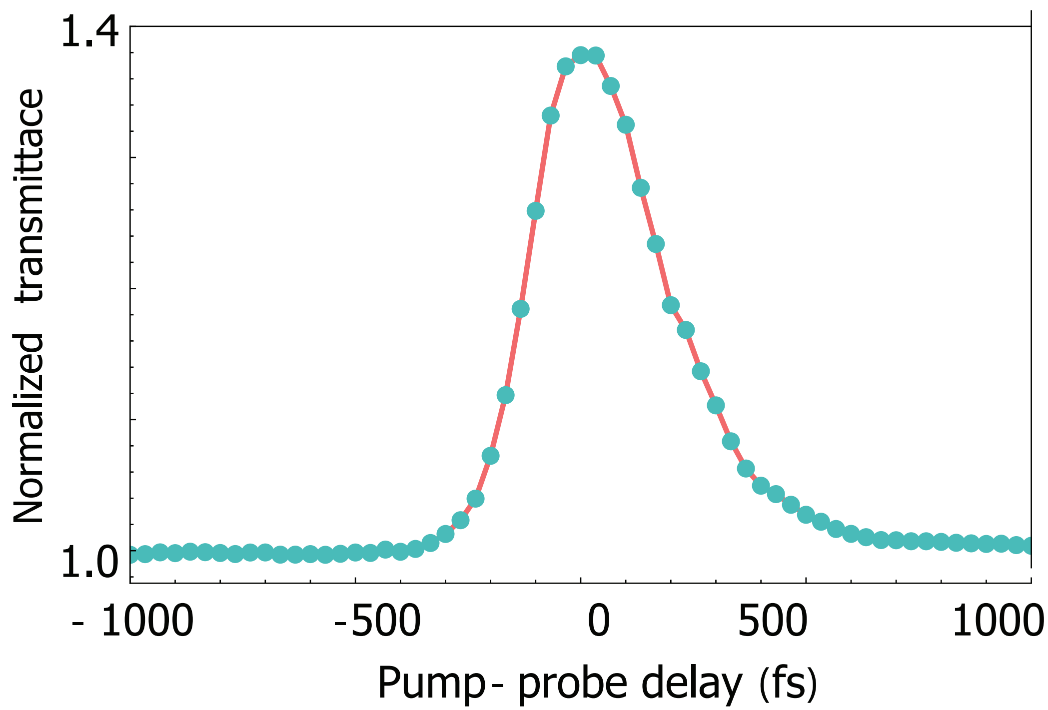
Here is the refractive index extracted from the above data.

Note that the total nonlinear change in refractive index is $\Delta n = 0.8$.

The absorption decreases at high intensity, allowing a predicted NL phase shift of 0.5 radians.

Measurement of Response Time of ITO

- We have performed a pump-probe measurement of the response time. Both pump and probe are 100 fs pulses at 1.2 μm.
- Data shows a rise time of no longer than 200 fs and a recover time of of 360 fs.
- Results suggest a hot-electron origin of the nonlinear response
- ITO will support switching speeds as large as 1.5 THz



Implications of the Large NLO Response of ITO

Indium Tin Oxide at its ENZ wavelength displays enormously strong NLO properties:

n_2 is 3.4 x 10^5 times that of fused silica
Nonlinear change in refractive index as large as 0.8

Note that the usual "power-series" description of NLO is not adequate for describing this material. (We can have fun reformulating the laws of NLO!)

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

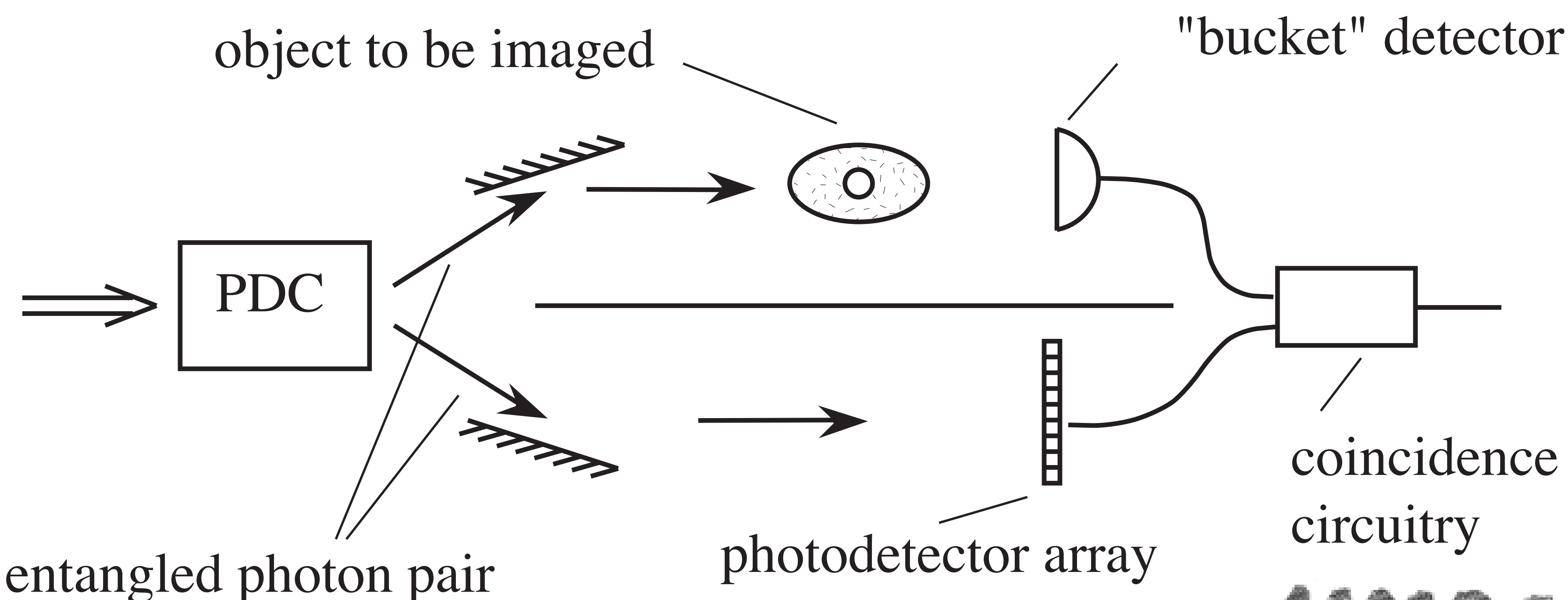
Advances in Quantum Nonlinear Optics

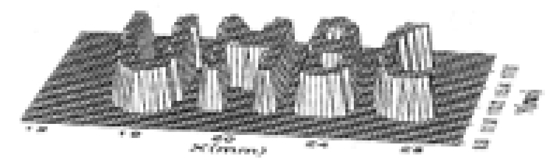
1. Secure optical communication with multiple bits per photon

2. New nonlinear optical material for quantum information processing

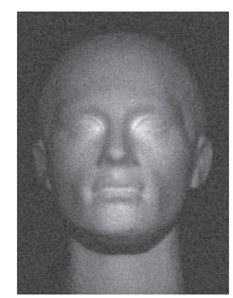
3. The promise of ghost imaging

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

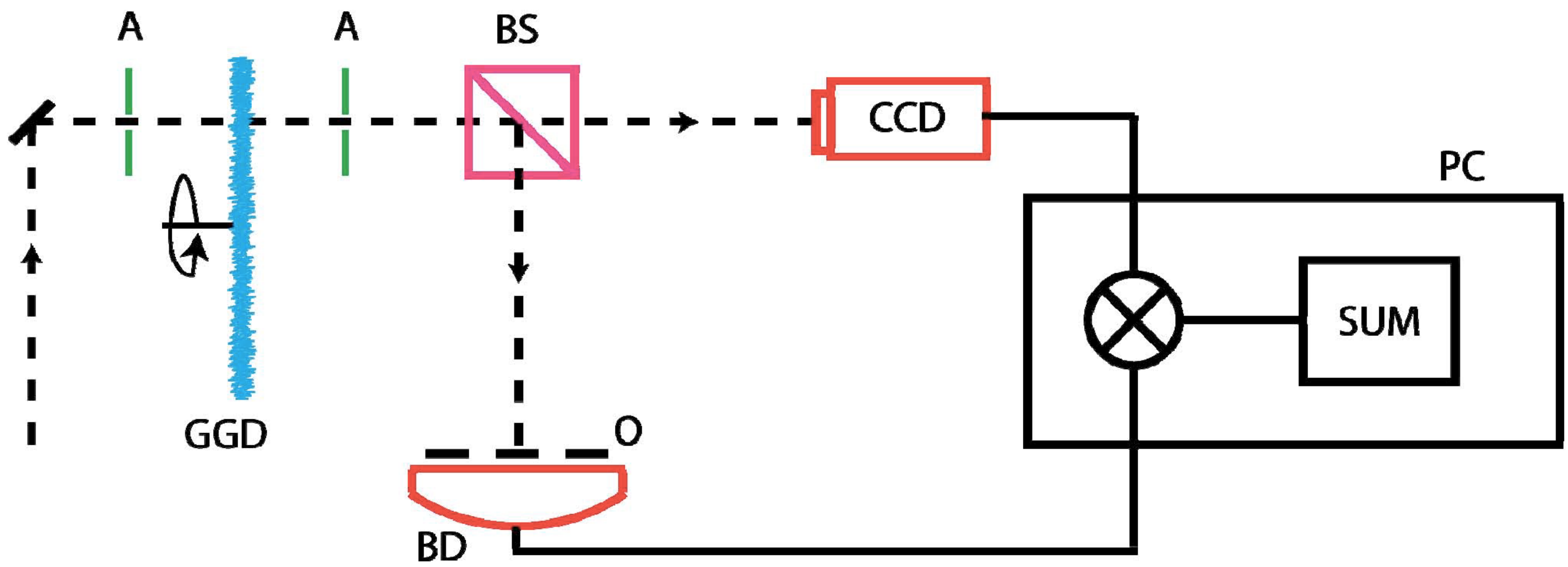
(Received 11 October 2002; published 3 April 2003)

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.

DOI: 10.1103/PhysRevLett.90.133603 PACS numbers: 42.50.Dv, 03.65.Ud

Experiment: Bennink, Bentley, Boyd, and Howell, Phys. Rev. Lett., 92, 033601, 2004.

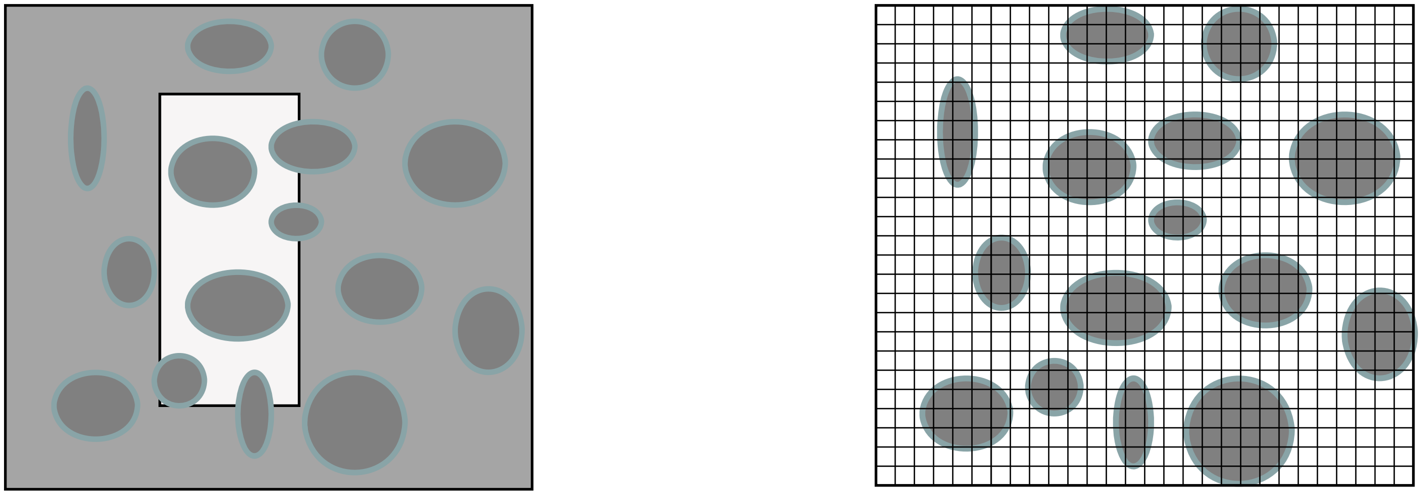
How does thermal ghost imaging work?



- Ground glass disk (GGD) and beam splitter (BS) create two identical speckle patterns
- Many speckles are blocked by the opaque part of object (O), but some are transmitted, and their intensities are summed by bucket detector (BD)
- CCD camera measures intensity distribution of speckle pattern
- Each speckle pattern is multiplied by the output of the BD
- Results are averaged over a large number of frames.

Origin of Thermal Ghost Imaging

Create identical speckle patterns in each arm.



object arm
(bucket detector)

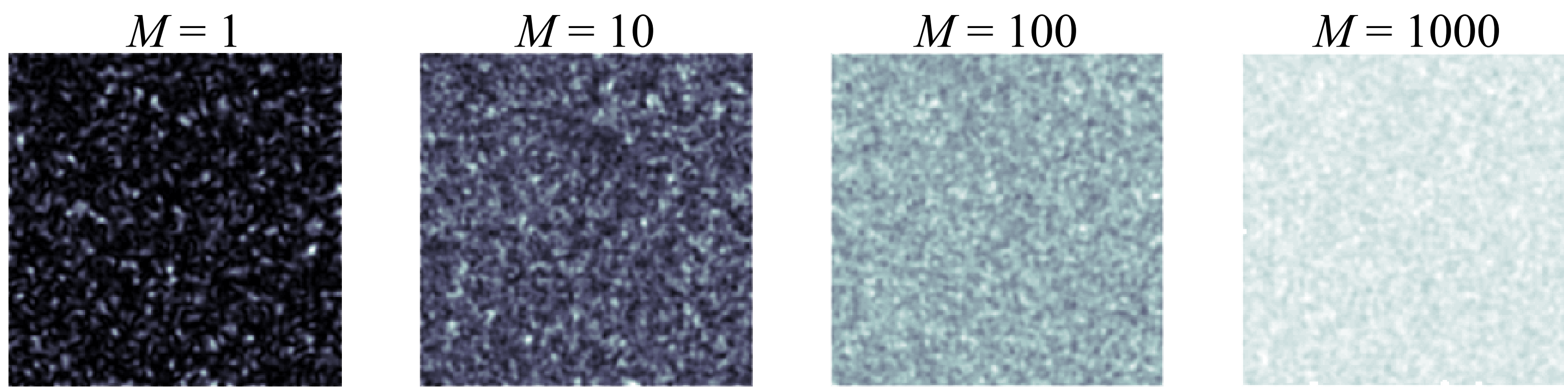
reference arm
(pixelated imaging detector)

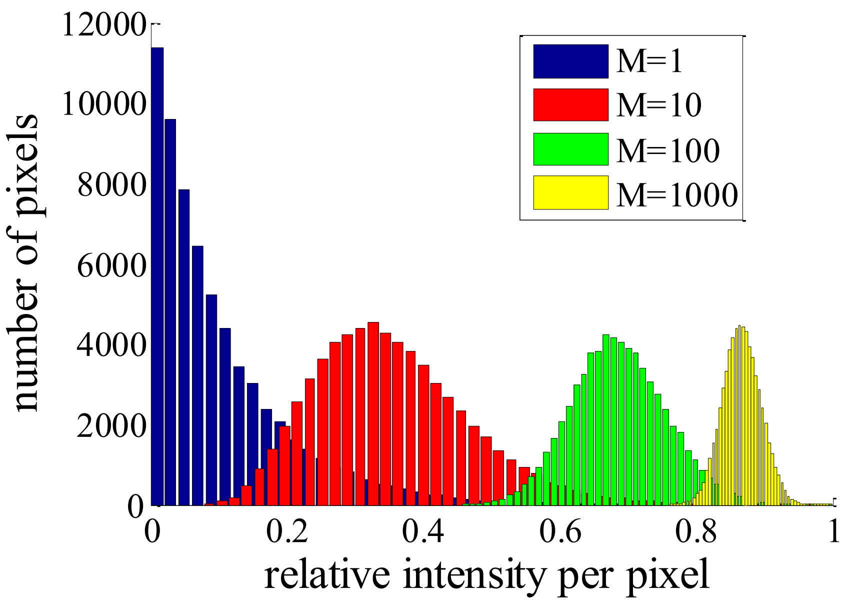
$g_1(x,y)$ = (total transmitted power) x (intensity at each point x,y)

Average over many speckle patterns

Can one Perform Thermal Ghost Imaging With Natural Thermal Light Sources?

- No current detector can time-resolve the rapidly changing speckle pattern of a natural light source.
- Detector sees intensity time-averged averaged speckles; contrast is reduced





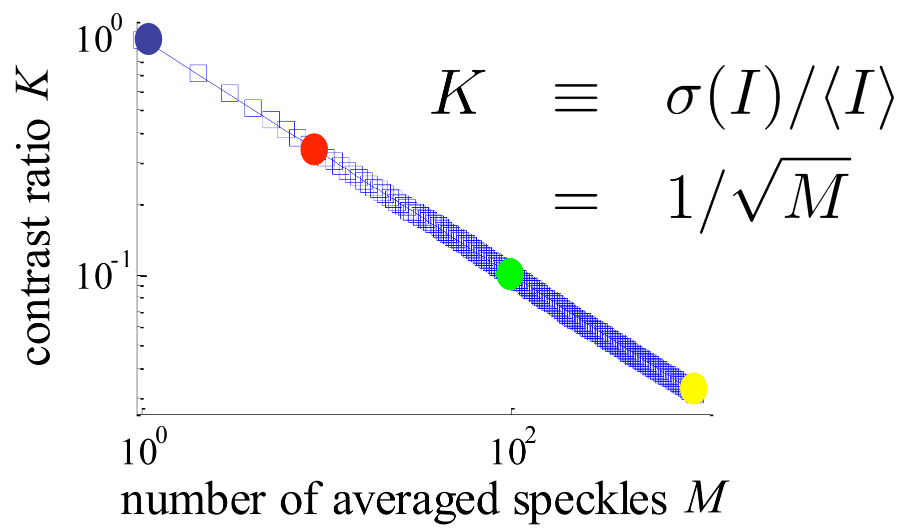
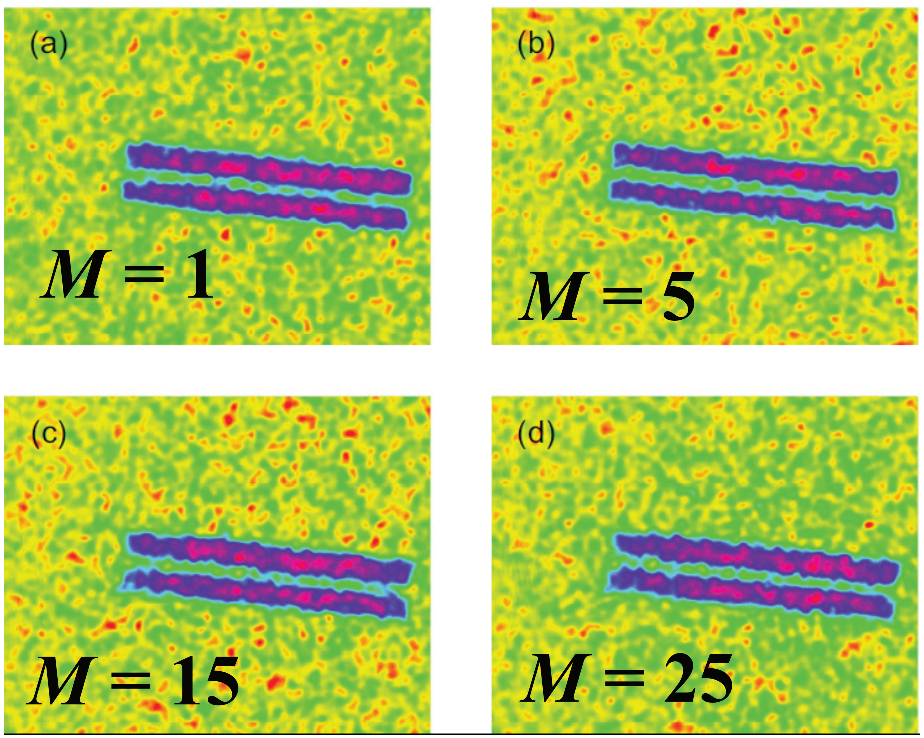
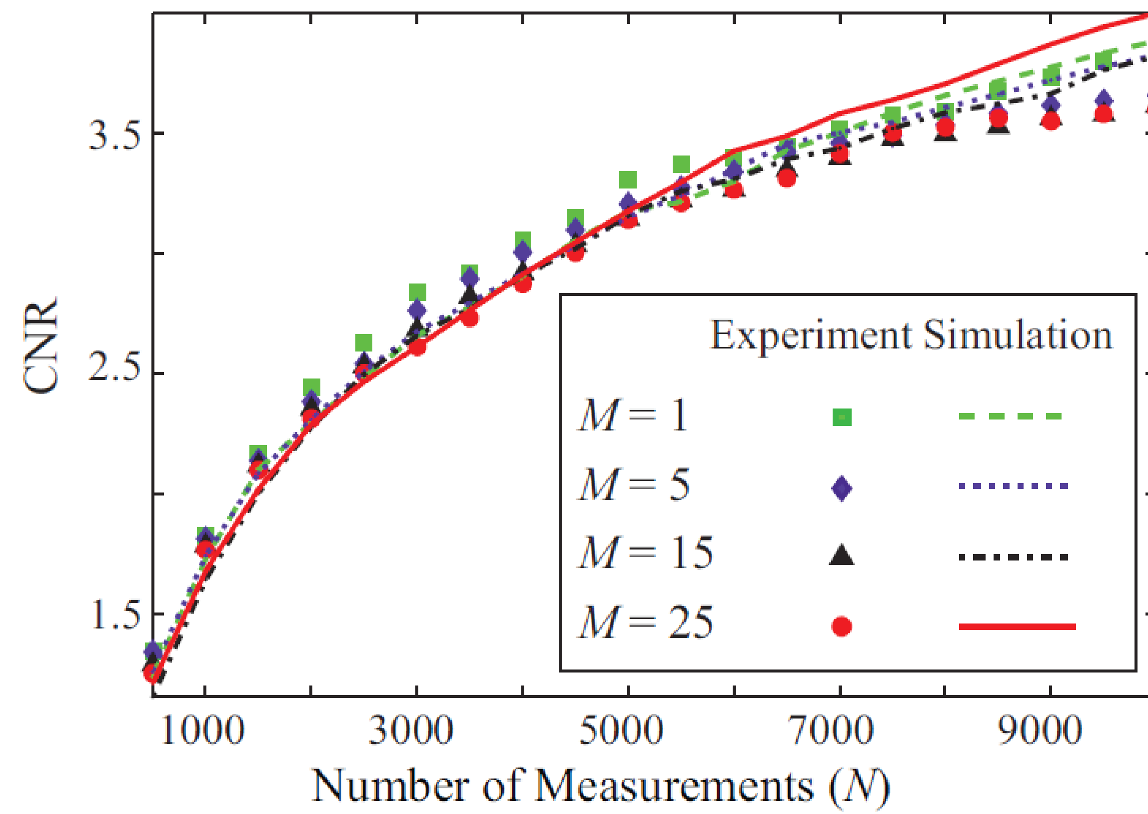


Image Quality is not Degraded through Use of Slow Detectors!

- M = number of speckle patterns averaged together
- 10,000 measurements with four different values of M
- All images qualitatively similar



- Contrast-to-noise ratio increases with mumber of measurements, and does not decrease with M



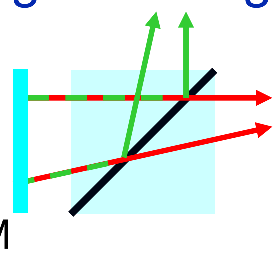
- Results suggest that ghost imaging can be performed with natural light sources

Thermal ghost imaging with averaged speckle patterns, P. Zerom, Z. Shi, M.N. O'Sullivan, K.W.C. Chan, M.Krogstad, J.H. Shapiro, and R.W. Boyd, Phys. Rev. A 86, 063817 (2012)

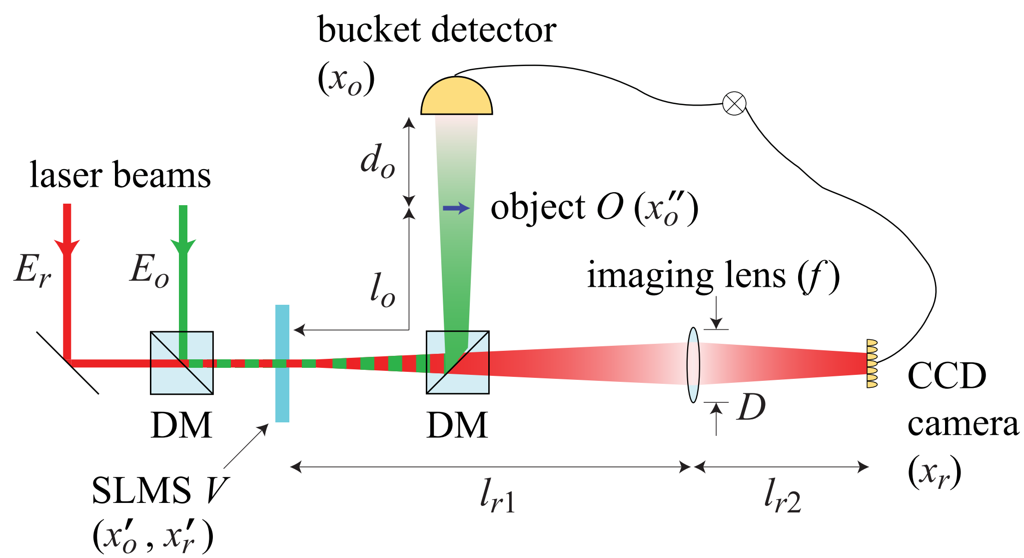
Two-Color Ghost Imaging

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

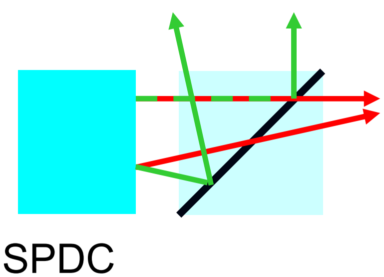
Thermal ghost imaging

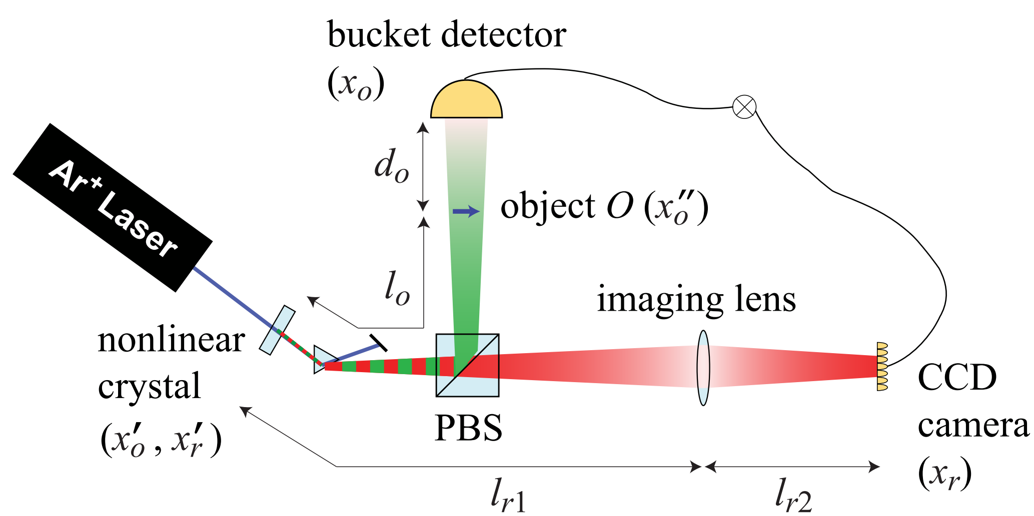


But no obvious way to make identical speckle patterns at two wavelengths



Quantum ghost imaging





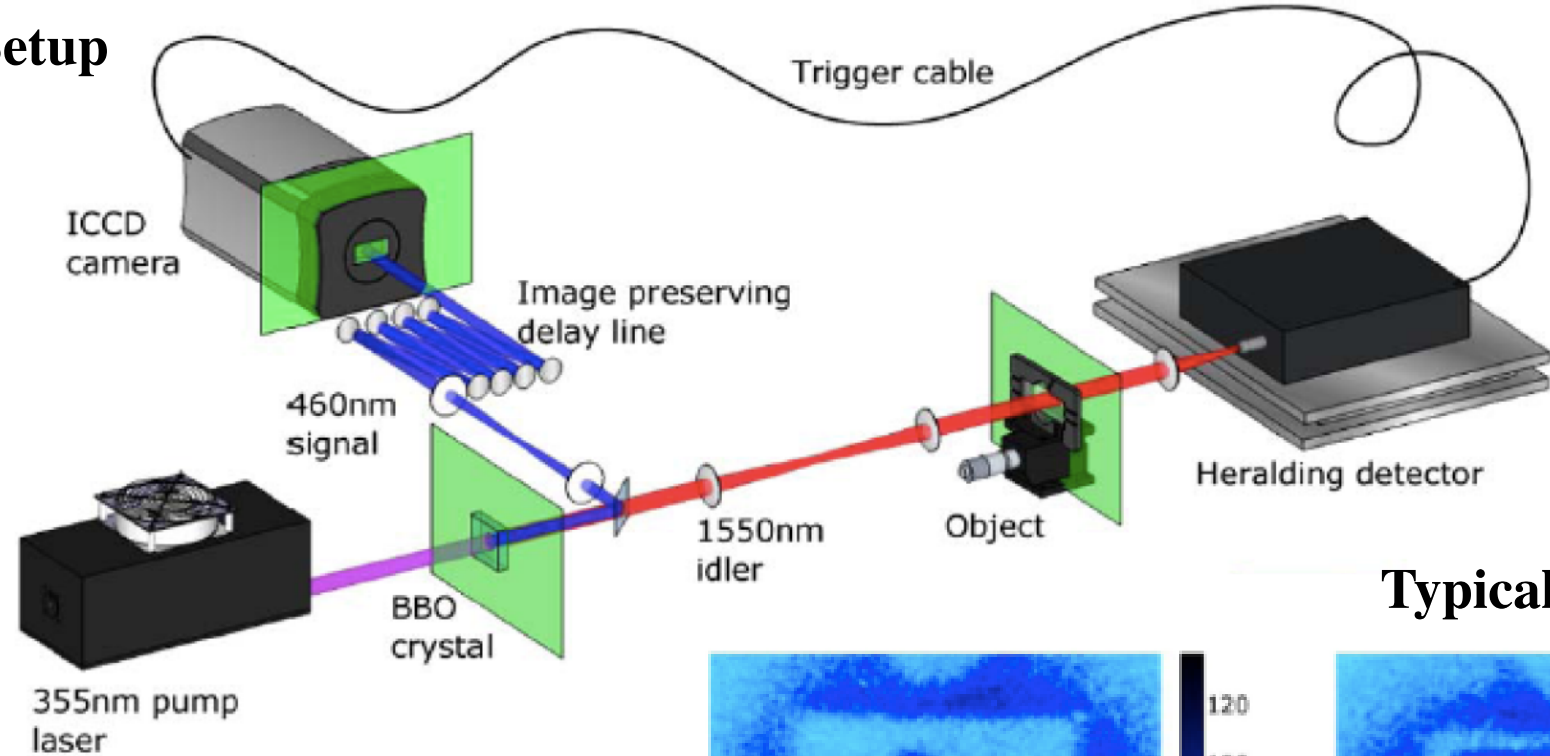
Spatial resolution depends on wavelength used to illuminate object.

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

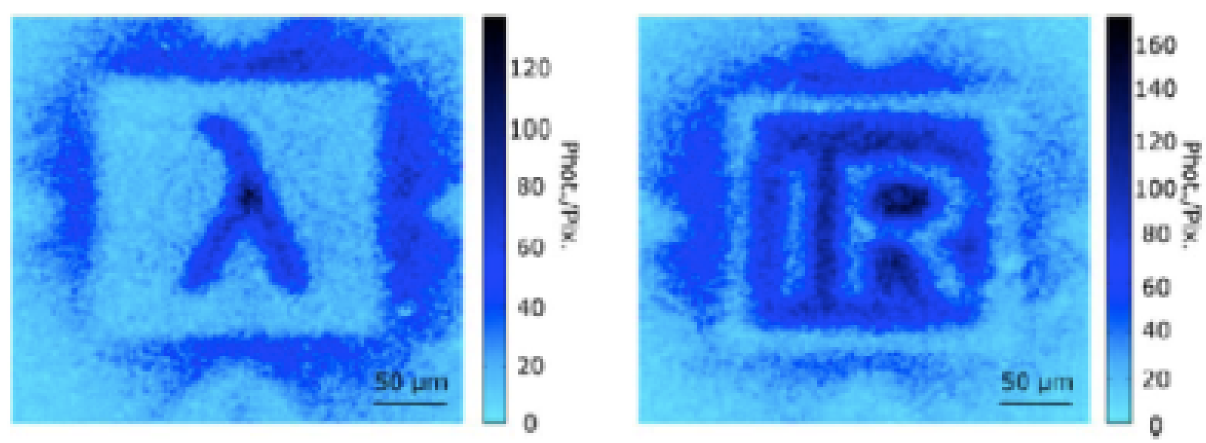
Wavelength-Shifted (Two-Color Ghost) Microscopy

- 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).

Summary

1. Secure optical communication with multiple bits per photon

2. New nonlinear optical material for quantum information processing

3. The promise of ghost imaging

Boyd Name Origin

(Road outside Glasgow)

Why We Shouldn’t Always Trust Google