Quantum Imaging:
New Methods and Applications

Welcome and Introduction

Robert W. Boyd
University of Rochester

MURI Kickoff Meeting, Rochester NY, June 9-10, 2005.

MURI in Quantum Imaging: Kick-Off Meeting Agenda

Thursday, June 9, 2005

11:00 am	Registration desk opens
12:00 pm	Buffet lunch (informal discussion over lunch)
1:00 pm	Introductions and Welcome
	Dean Paul Slattery, Research and Graduate Studies
	Dr. Wayne H. Knox, Director and Professor, The Institute of Optics
	Dr. Peter Reynolds, ARO
	Dr. Robert Boyd, University of Rochester
1:45 pm	Dr. Jeffrey Shapiro, MIT
2:30 pm	Dr. Bahaa Saleh, Dr. Alexander Sergienko, Dr. Malvin Teich, Boston University
3:15 pm	short break
3:30 pm	Dr. Morton Rubin, Dr. Yanua Shih, University of Maryland, Baltimore County
4:15 pm	Dr. Jonathan Dowling, Louisiana State University
5:00 pm	Discussion
6:00 pm	Social Hour, Hawthorne's Restaurant, 3500 East Avenue, Rochester (385-4959)
7:00 pm	Dinner, Hawthorne's Restaurant, 3500 East Avenue, Rochester (385-4959)

Friday. June 10, 2005

8:30 am	Continental Breakfast: coffee, juices, assorted pastries
9:00 am	Dr. Geraldo Barbosa, Dr. Prem Kumar, Northwestern University
9:45 am	Dr. Robert Boyd, Dr. John Howell, University of Rochester
10:30 am	Break
11:00 am	Panel Discussion/Government Input, chaired by Drs. Reynolds and Boyd
12:00 pm	Lunch (box lunch so those on a tight schedule can take it with them)

Research in Quantum Imaging

Can the images be formed with higher resolution or better sensitivity through use of quantum states of light?

Can we “beat” the Rayleigh criterion?

Quantum states of light: For instance, squeezed light or entangled beams of light.

Founders: Barbosa, Fabre, Klyshko, Kolobov, Kumar, Lugiato, Saleh, Sergienko, Shih, Teich.

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Announcements

1. I need a copy of all presentations to post on team website.

2. Need to discuss timing/format/location of annual review meetings.

3. Please be thinking about topics for tomorrow's panel discussion.

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Founders: Barbosa, Fabre, Klyshko, Kolobov, Kumar, Lugiato, Saleh, Sergienko; Shih, Teich.

Quantum Imaging MURI Team

Robert Boyd, John Howell, UR
Sasha Sergienko, Bahaa Saleh, Mal Teich, BU
Jon Dowling, LSU
Jeff Shapiro, MIT
Geraldo Barbosa, Prem Kumar, NWU
Yanhua Shih, Fow-Sen Choa, Mortin Rubin, UMBC

International Collaborators

- Claude Fabre, University of Paris
- Mikhail Kolobov, University of Lille
- Luigi Lugiato, Alessandra Gatti, Como
- Hans Bachor, Australian National University

Quantum Imaging Research Plan

Quantum Imaging Systems

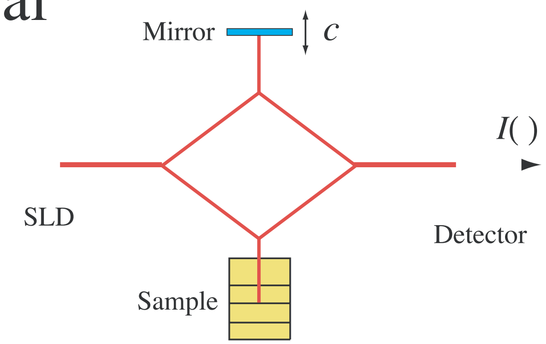
- Quantum Optical Coherence Tomography (QOCT).
- Quantum Coincidence (or Ghost) Imaging.
- Quantum Laser Radar.
- Quantum Lithography.

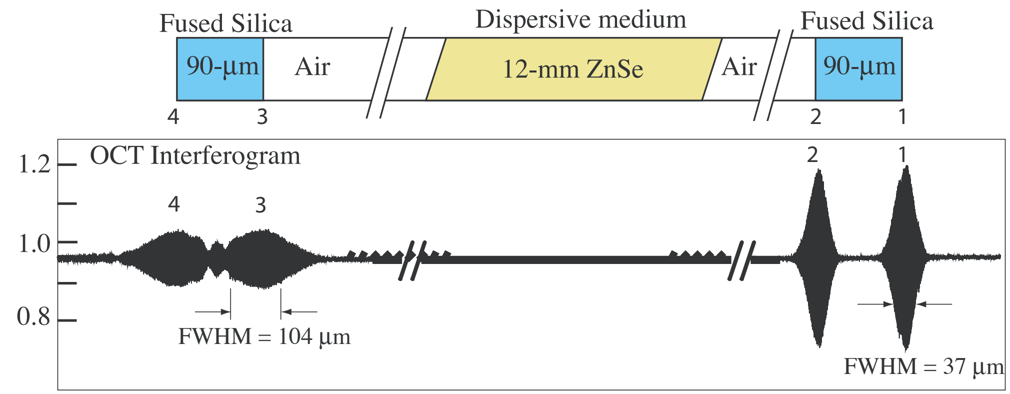
Quantum Imaging Technologies

- Intense Sources of Entangled Photons
  - Parametric Downconversion in Periodically Poled Waveguides.
  - Quantum Entangled Sources based on Third-Order Interactions.
  - Entanglement Utilizing Complex Pump Mode Patterns.
- High-Order Entanglement.
- Pixel Entanglement and Secure Transmission of Images.
- Unified Theoretical Framework for Classical and Quantum Imaging.

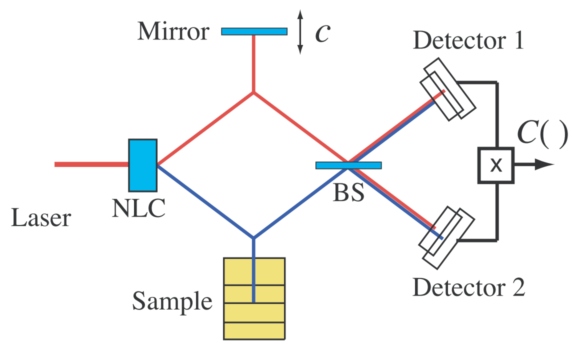
Quantum Optical Coherence Tomography

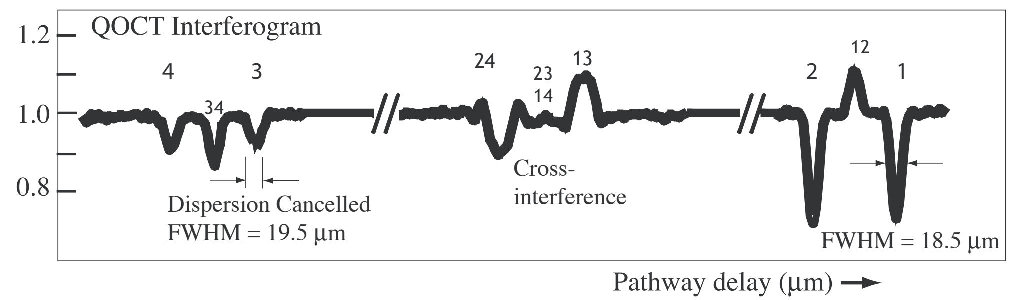
Classical





Quantum



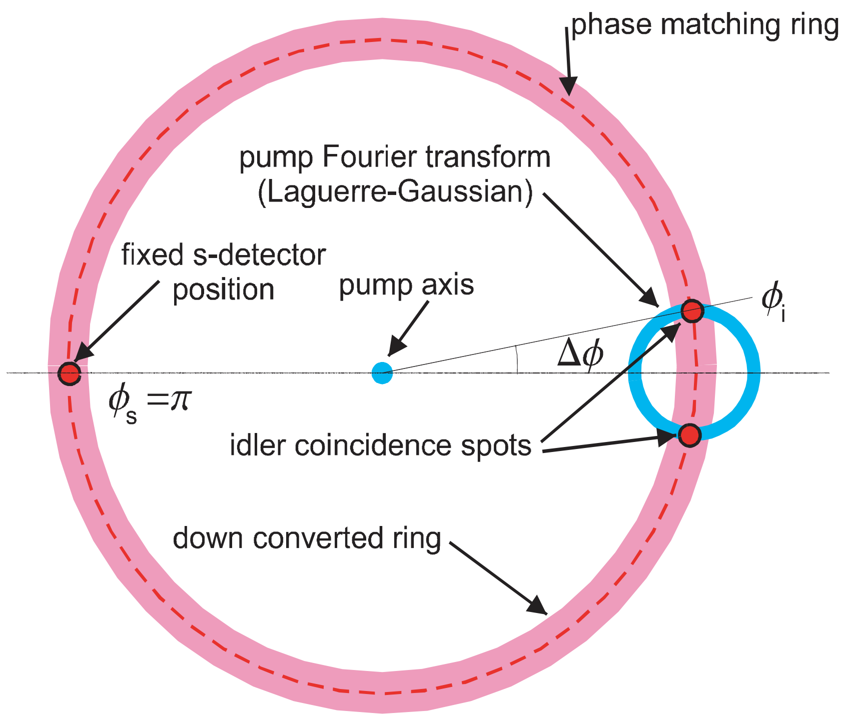


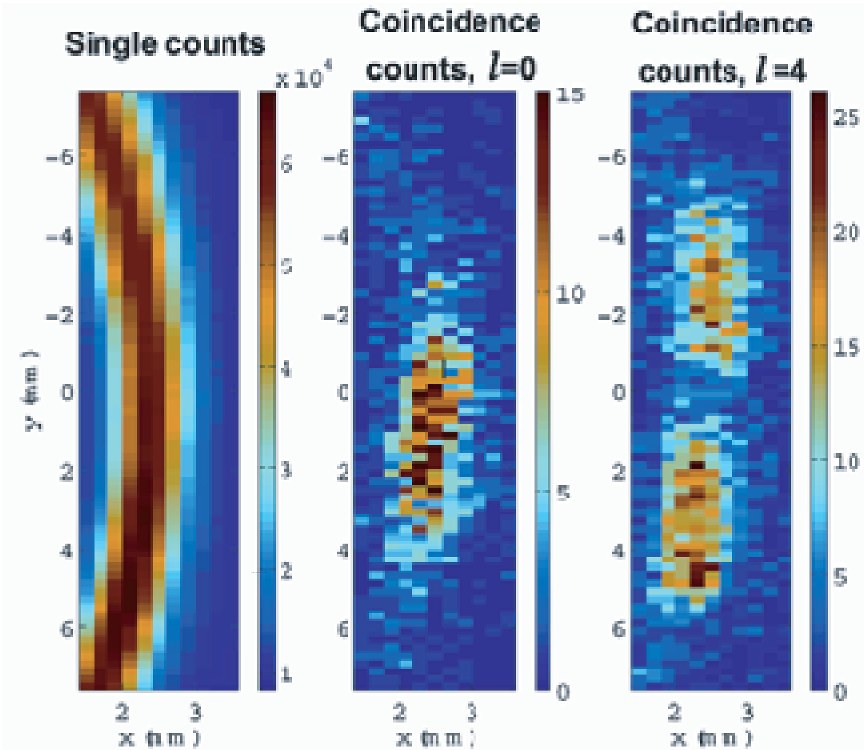
Quantum OCT offers three advantages over classical:

- Factor-of-two better spatial resolution
- Dispersion cancellation
- Cross-interference provides additional information

Nasr, Saleh, Sergienko, and Teich, PRL 91 083601 (2003)

Nonlocal Quantum Spatial Correlations Induced by Pump Beams Carrying Orbital Angular Momentum





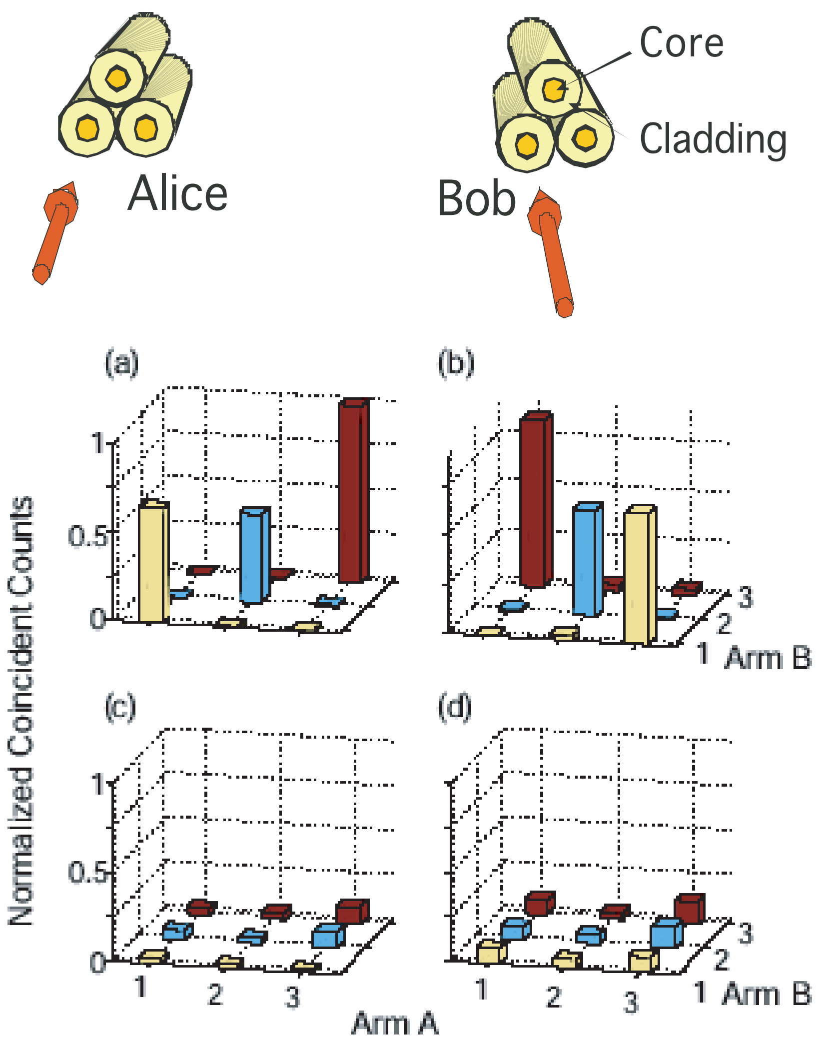
- Image information encoded on pump beam leads to quantum correlations in the down-converted photons.
- Demonstrates entanglement of orbital angular momentum.

Altman, Kumar, Barbosa, et al., PRL 94 123601 (2005).

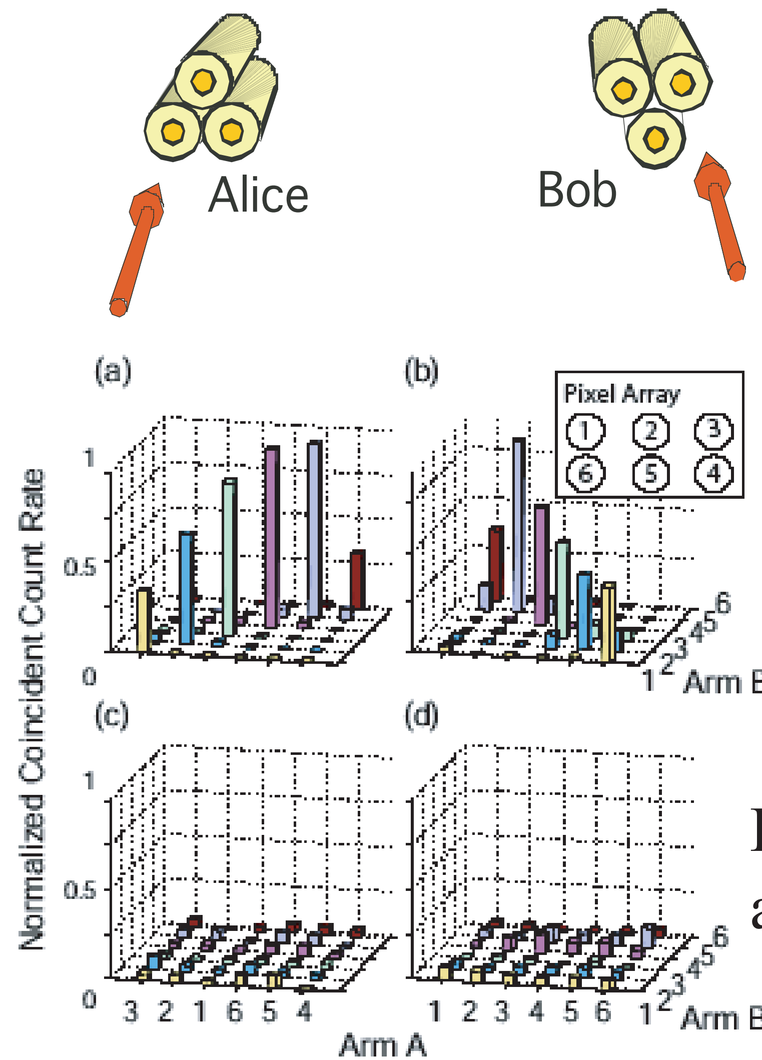
Pixel Entanglement: Entanglement in a Very Large Hilbert Space

Pixel entanglement: highly correlated, discretized, continuous variable entanglement in two non-commuting bases (x and p).

Position Correlation



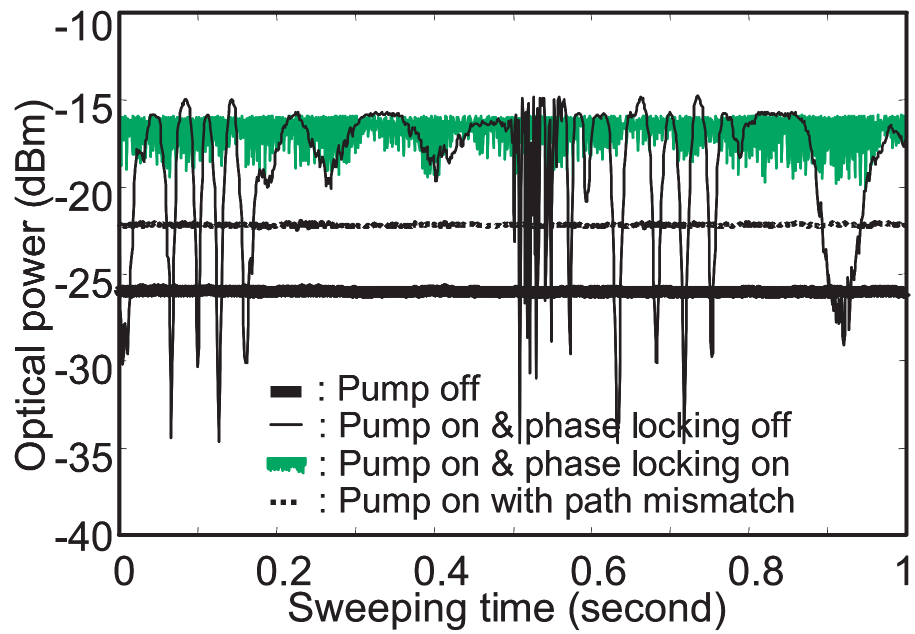
Momentum Correlation



Howell and Boyd

Quantum Laser Radar

Primary goal is to use noiseless preamplification (phase sensitive amplification) to increase senstivity of laser radar.



Kumar and Shapiro

Quantum Imaging: New Methods and Applications

Individual Research Project

Robert W. Boyd
University of Rochester

ResearchThemes:

- Implementation of quantum lithography
- Applications of ghost imaging (joint with J. Howell)
- Entanglement in high-dimensional spaces (joint w/ Howell)
- New sources of entangled photons

Research in Quantum Lithography

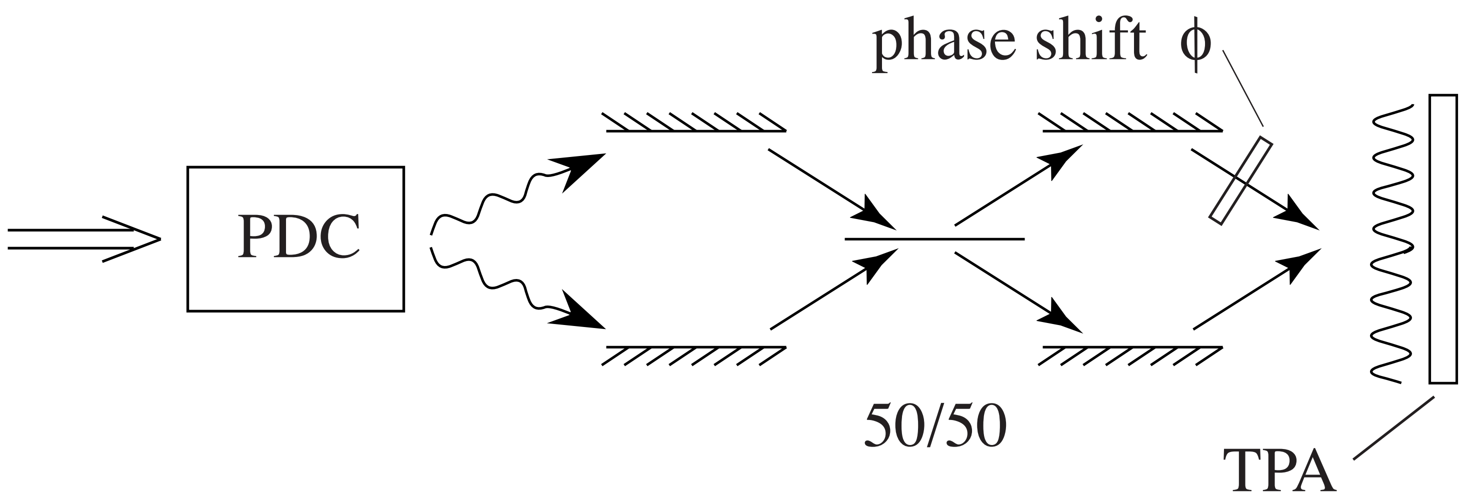
Sean J. Bentley, Robert W. Boyd, Hye Jeong Chang,
Anand Jha, Malcolm N. O'Sullivan-Hale, Heedeuk Shin

University of Rochester

(in close collaboration with Jon Dowling and group, LSU)

Quantum Lithography

- Entangled photons can be used to form interference pattern with detail finer than the Rayleigh limit
- Process "in reverse" performs sub-Rayleigh microscopy

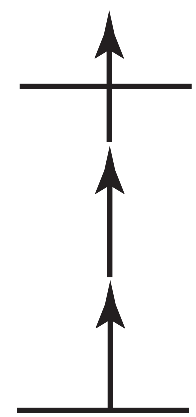


Boto et al., Phys. Rev. Lett. 85, 2733, 2000.

("al." includes Jon Dowling)

Quantum Lithography: Easier Said Than Done

- Need an *N*-photon recording material
  For proof-of-principle studies, can use
    *N*th-Harmonic generator, correlation circuitry,
    N-photon photodetector
  For actual implementation, use ????
    Maybe best bet is UV lithographic material excited in the visible or a broad bandgap material such as PMMA excited by multiphoton absorption

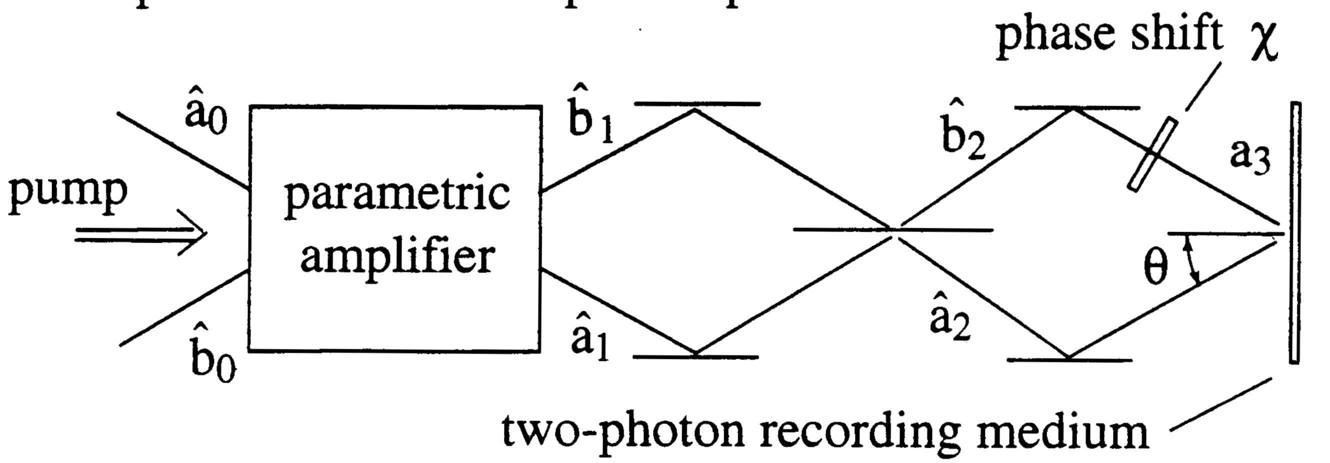


TPA in PMMA breaks chemical bond, modifying optical properties. Problem: self healing

- Need an intense source of individual biphotons
  (Inconsistency?)
  Maybe a high-gain OPA provides the best tradeoff between high intensity and required quantum statistics

Use of High-Gain Parametric Amplifier

Is two-photon interference pattern preserved?



- Transfer equations of OPA

$$\hat{a}_1 = U\hat{a}_0 + V\hat{b}_0^\dagger, \quad \hat{b}_1 = U\hat{b}_0 + V\hat{a}_0^\dagger$$

where

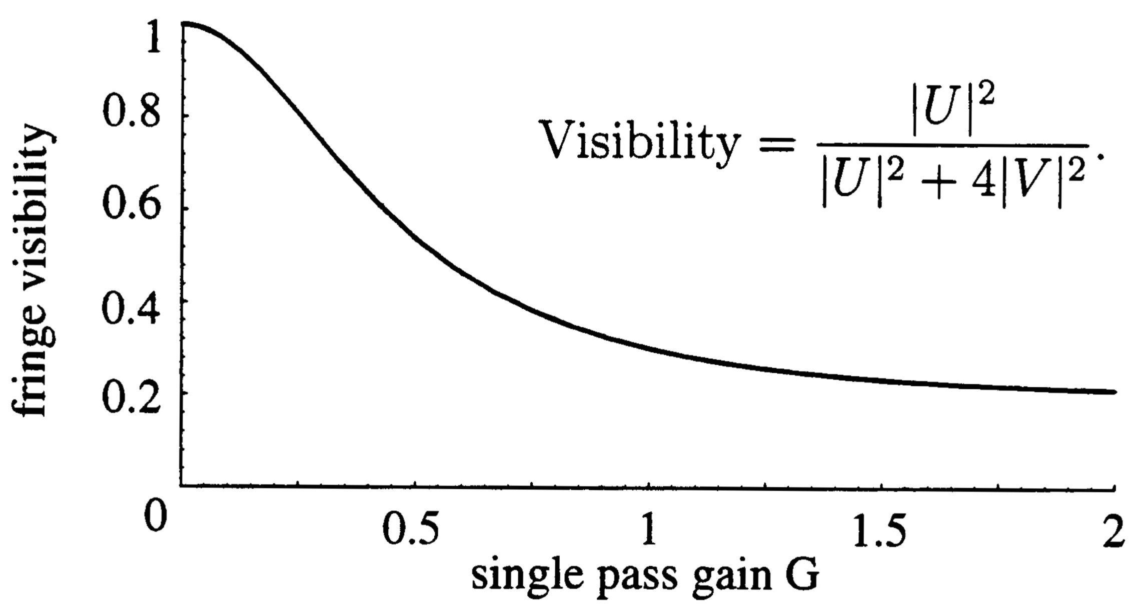
$$U = \cosh G \qquad V = -\, i \exp(i\varphi) \sinh G$$

- Field at recording medium

$$\hat{a}_3 = \frac{1}{\sqrt{2}} \left[(-\, e^{i\chi} + i)(U\hat{a}_0 + V\hat{b}_0^\dagger) + (ie^{i\chi} - 1)(U\hat{b}_0 + V\hat{a}_0^\dagger) \right]$$

- Two-photon absorption probablility

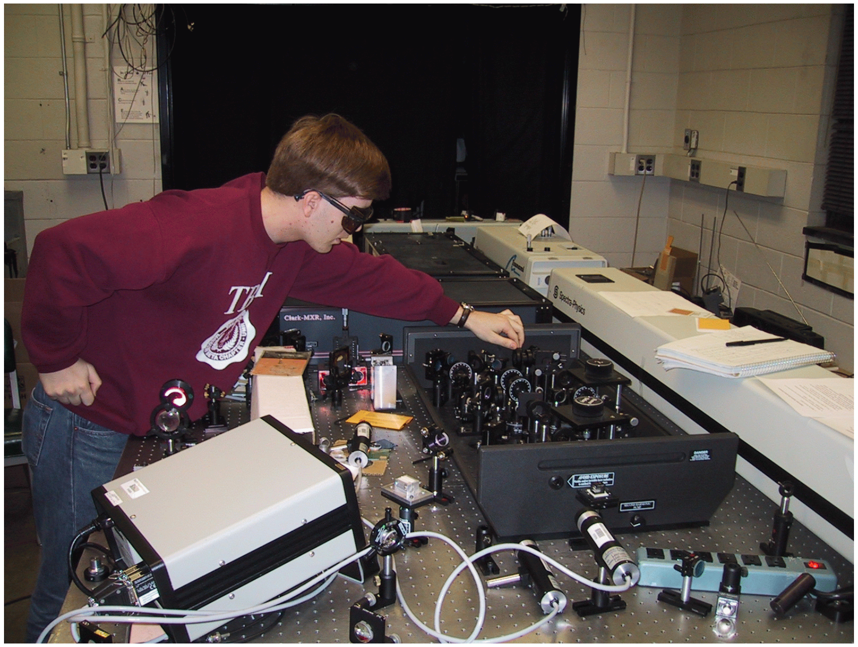
$$\langle 0, 0 | \hat{a}_3^\dagger \hat{a}_3^\dagger \hat{a}_3 \hat{a}_3 | 0, 0 \rangle = 4|V|^2 \left[|U|^2 \cos^2 \chi + 2|V|^2 \right]$$

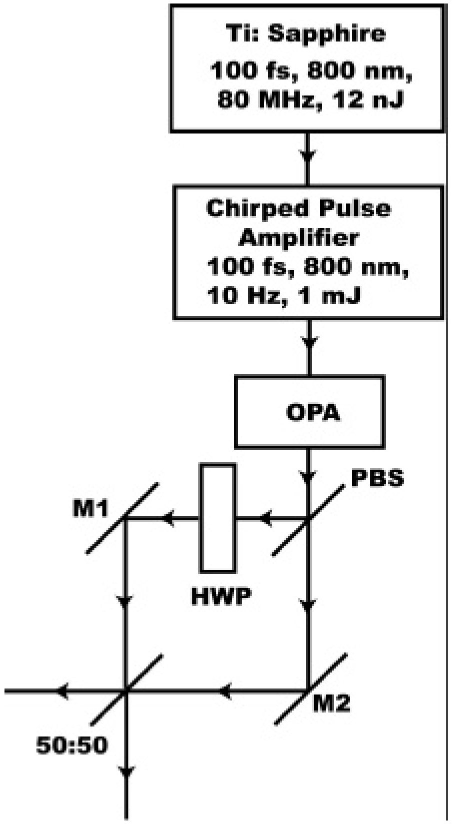


(Phys. Rev. Lett. 86, 1389, 2001)

QUANTUM LITHOGRAPHY RESEARCH

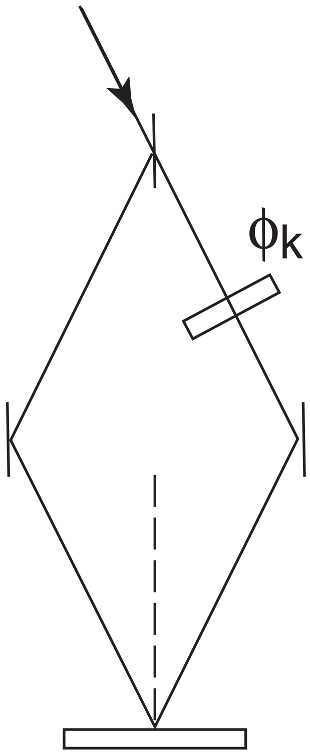
Experimental Layout

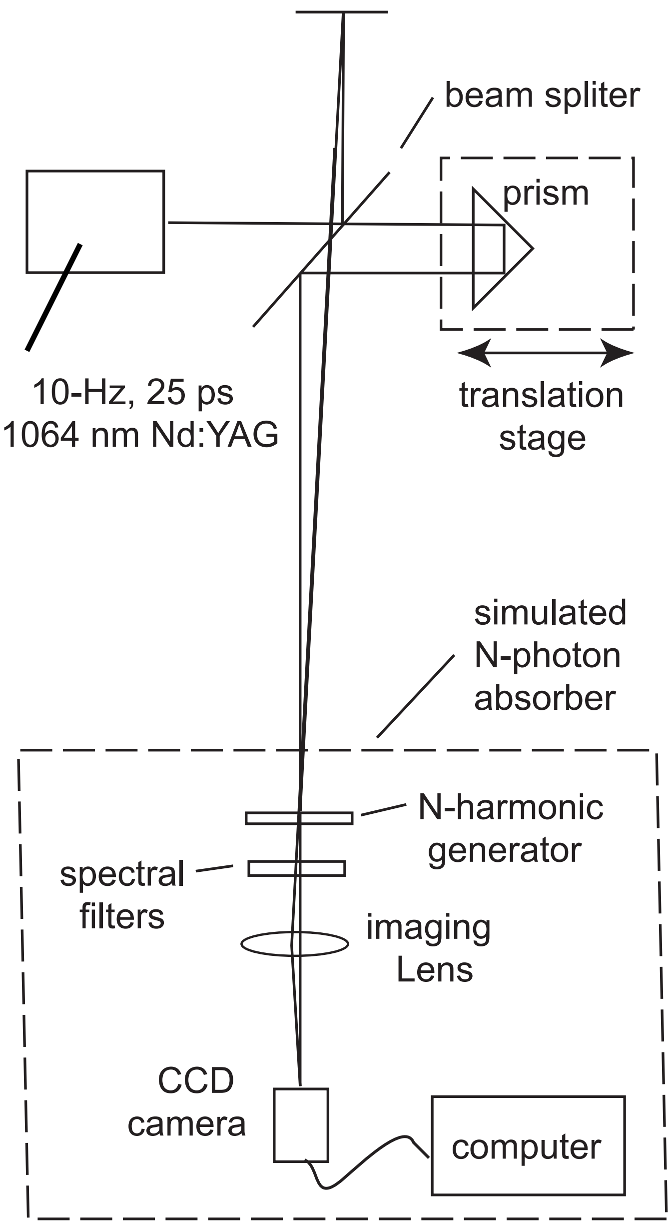




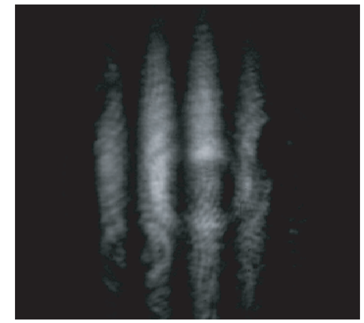
Non-Quantum Quantum Lithography

Concept: average M shots with the phase of shot k given by $2\pi k/M$

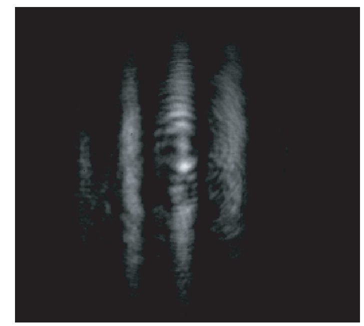




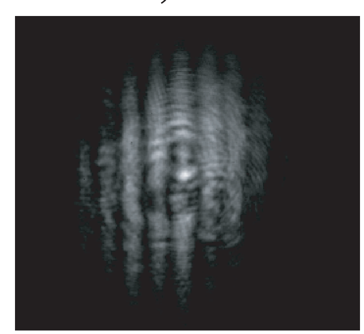
N=1, M=1



N=2, M=1

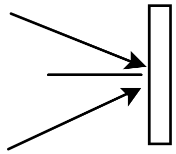


N=2, M=2



S. J. Bentley and R.W. Boyd, Optics Express, 12, 5735 (2004).

Spatial Resolution of Various Systems



- Linear optical medium

$$E = 1 + \cos kx$$

- Two-photon absorbing medium, classical light

$$E = (1 + \cos kx)^2 = 1 + 2 \cos kx + \cos^2 kx$$

$$= 3/2 + 2 \cos kx + (1/2) \cos 2kx$$

- Two-photon absorbing medium, entangled photons

$$E = 1 + \cos 2kx$$

where k = 2(/c) sin

Demonstration of Sub-Rayleigh Fringes Written into PMMA

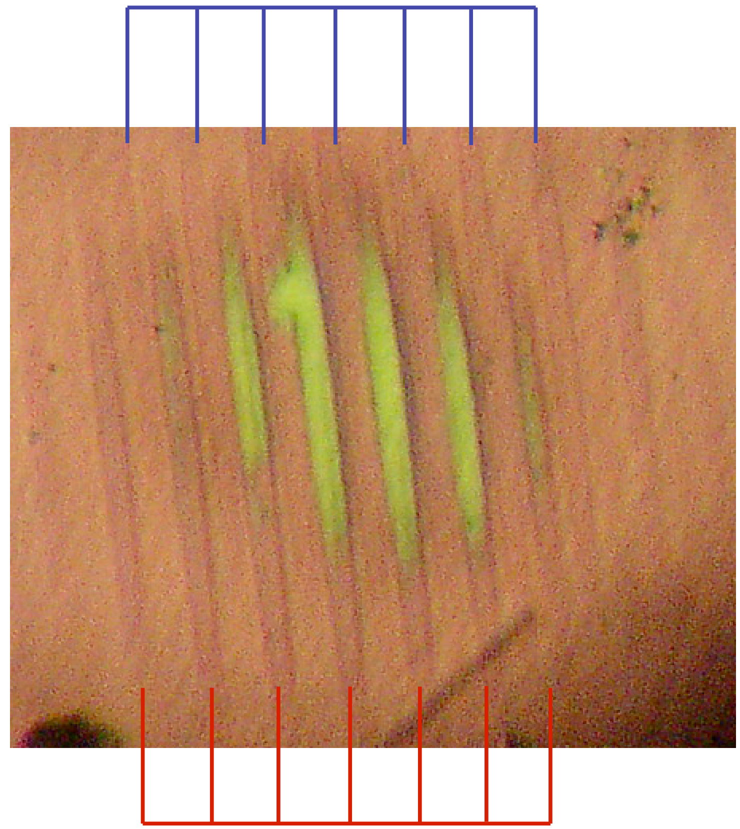
PMMA is a standard lithographic material

Fringes written by multiphoton excitation (N = 3 or 4)

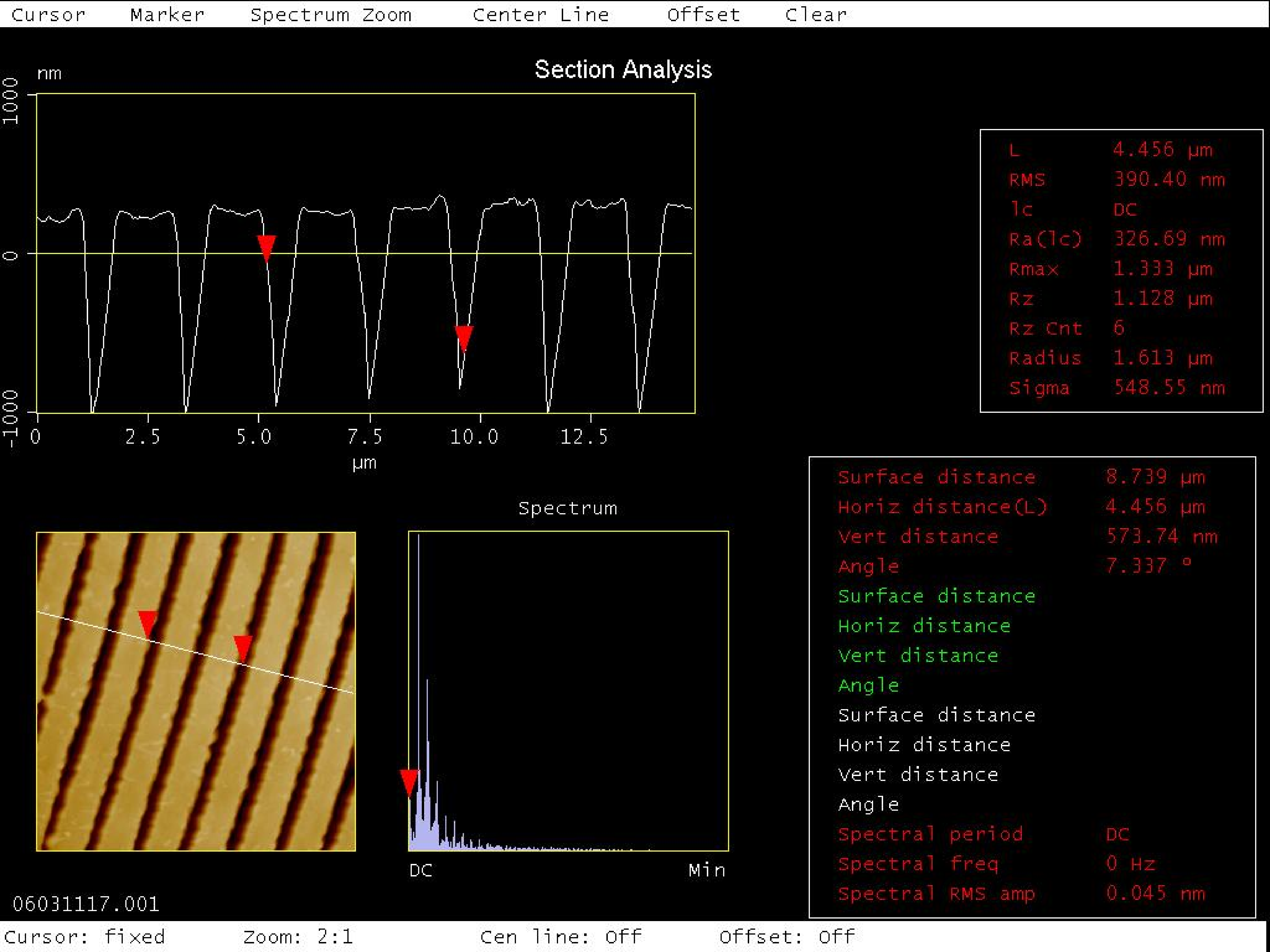
Very preliminary result

Optical microscope image

First Shot



Second shot : Phase shifted image


Cursor
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nm
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L 4.456 µm
RMS 390.40 nm
lc DC
Ra(lc) 326.69 nm
Rmax 1.333 µm
Rz 1.128 µm
Rz Cnt 6
Radius 1.613 µm
Sigma 548.55 nm
Spectrum
DC
Min
Surface distance 8.739 µm
Horiz distance(L) 4.456 µm
Vert distance 573.74 nm
Angle 7.337 °
Surface distance
Horiz distance
Vert distance
Angle
Surface distance
Horiz distance
Vert distance
Angle
Spectral period DC
Spectral freq 0 Hz
Spectral RMS amp 0.045 nm
06031117.001
Cursor: fixed
Zoom: 2:1
Cen line: Off
Offset: Off

Quantum Lithography Prospects

Quantum lithography (as initially proposed by Dowling) has a good chance of becoming a reality.

Classically simulated quantum lithography may be a realistic alternative approach, and one that is much more readily implemented.

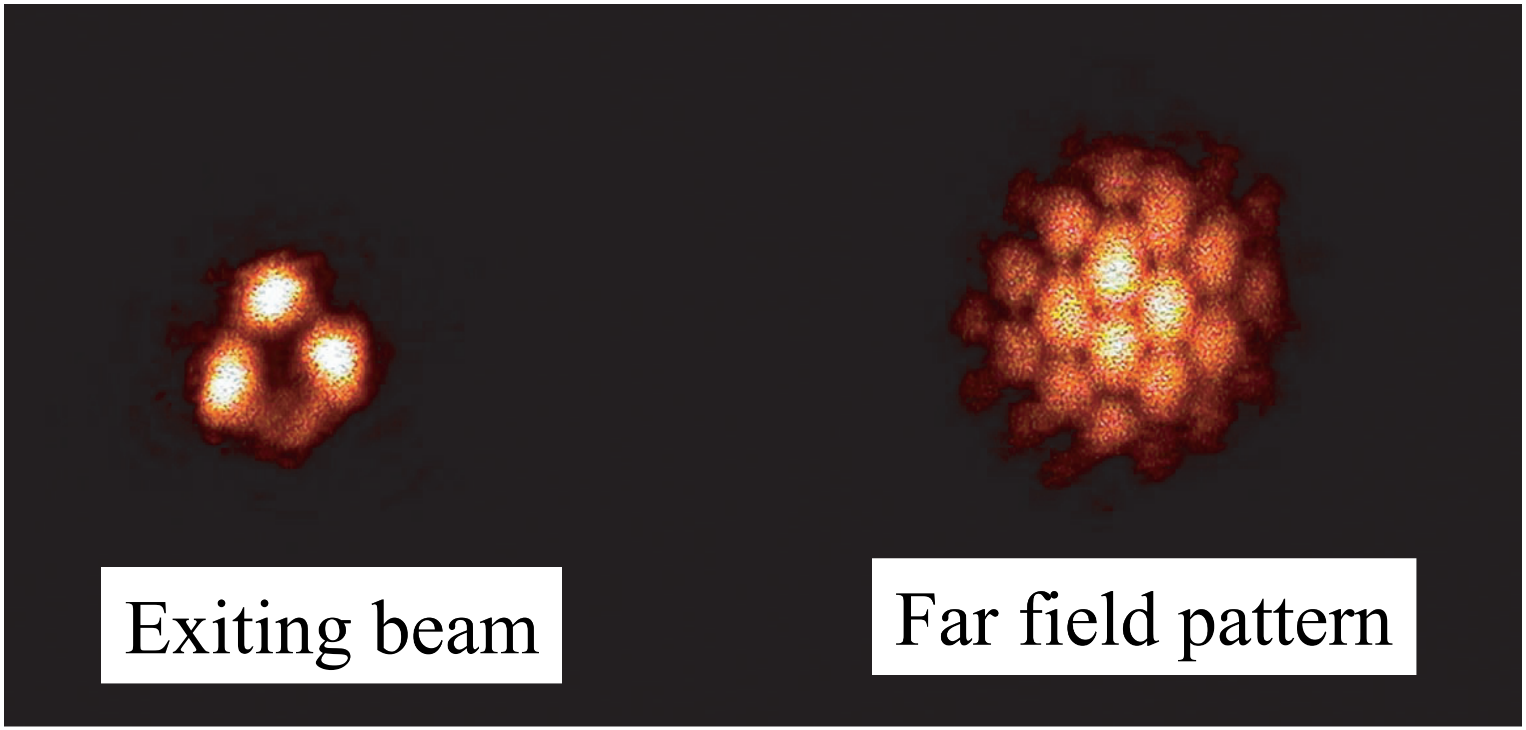
New Sources of Entangled Photons and other Quantum States of Light

Robert W. Boyd, Ksenia Dolgaleva, Anand Zha,
Malcolm N. O'Sullivan-Hale, Petros Zerom,

University of Rochester

Honey Comb Pattern Formation

Output from Na cell with single gaussian input beam



Quantum features?

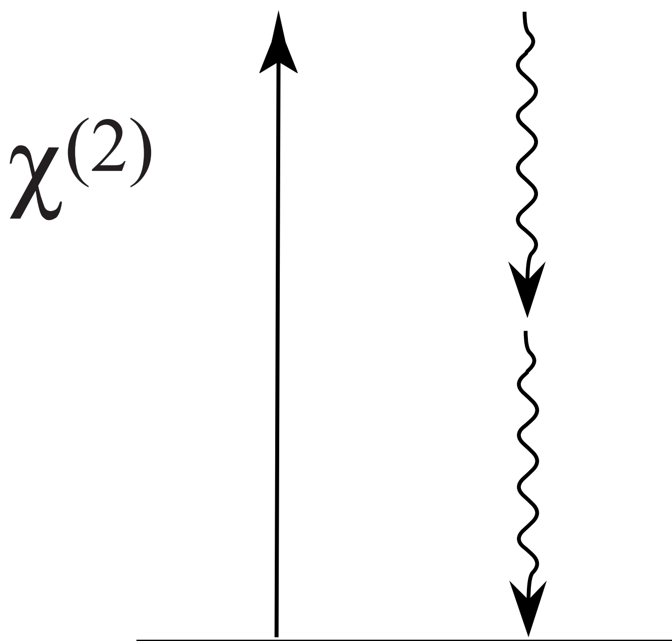
Input power 150 mW
Input beam diameter 0.22 mm
$\lambda = 588.995$ nm

Sodium vapor cell T = 220° C

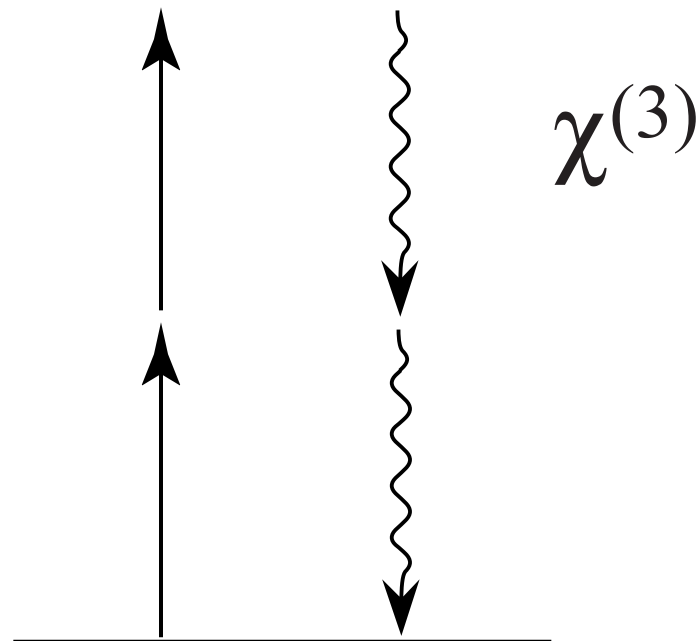
Bennink et al., PRL 88, 113901 2002.

Implications of Spontaneous Pattern Formation

Two Routes to Entanglement:

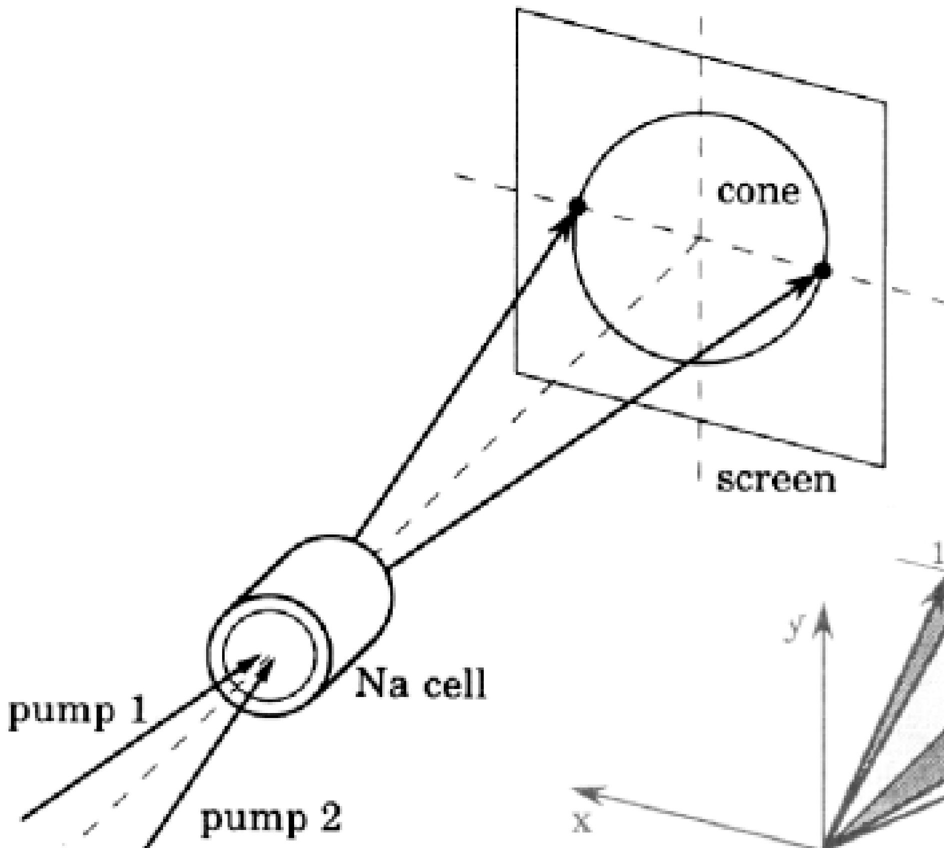


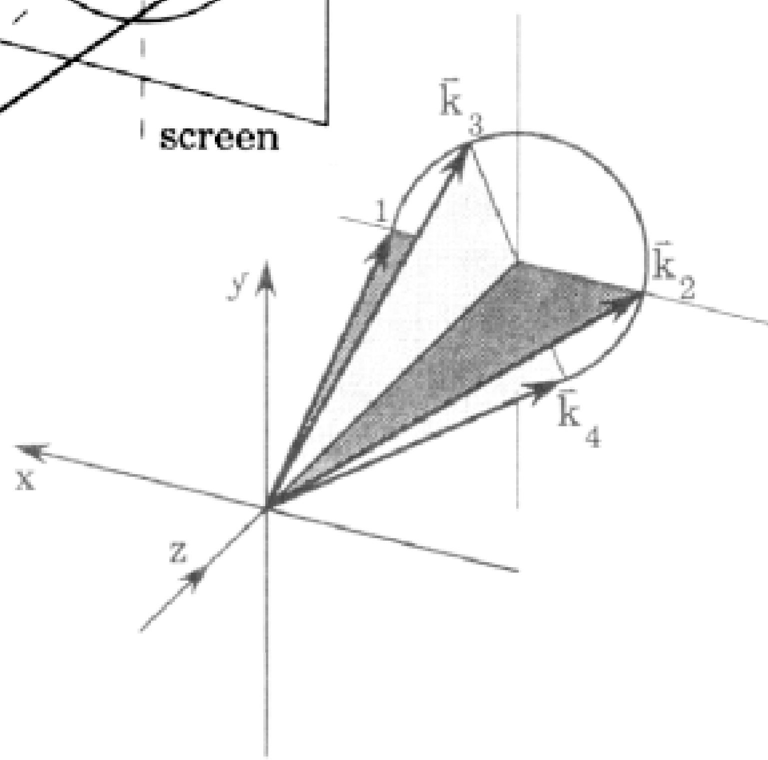
parametric downconversion

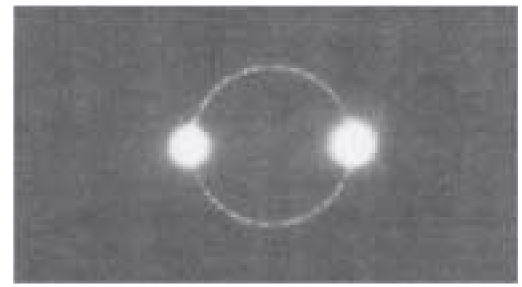


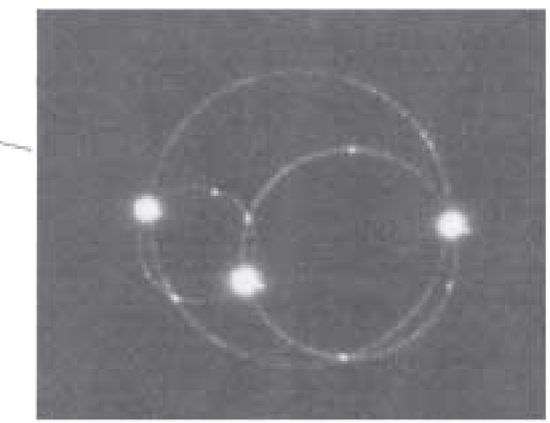
four-wave mixing

Generation of Quantum States of Light by Two-Beam Excited Conical Emission





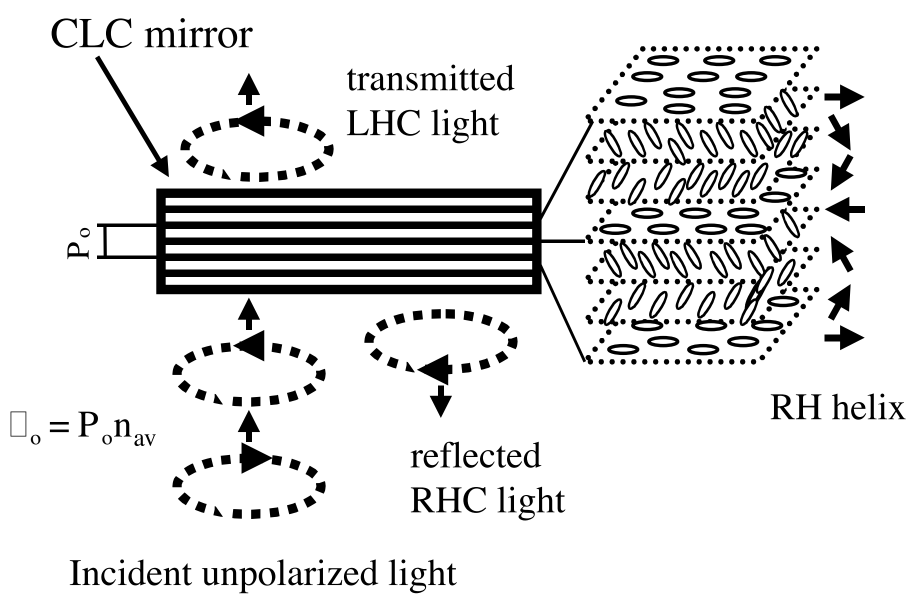




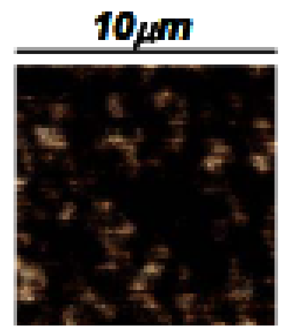
Kauranen et al, Opt. Lett. 16, 943, 1991; Kauranen and Boyd, Phys. Rev. A, 47, 4297, 1993.

Source of Polarized, Single-Photons on Demand

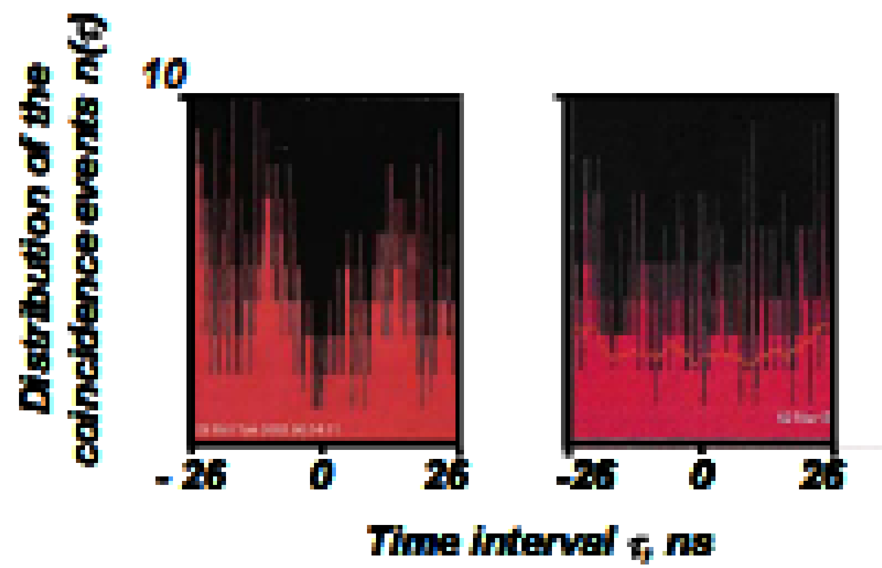
- Useful for secure communication by quantum cryptgraphy
- Embed isolated dye molecules in chiral nematic liquid crystal
- Host acts as self-assembled photonic bandgap material
- Host composition helps prevent dye from bleaching
- Fluorescence shows strong antibunching



Experimental procedure. Terrylene dye molecules are doped into a polymer cholesteric iquid crystal host.



Confocal fluorescence micrograph



Brown Twiss intensity correlations

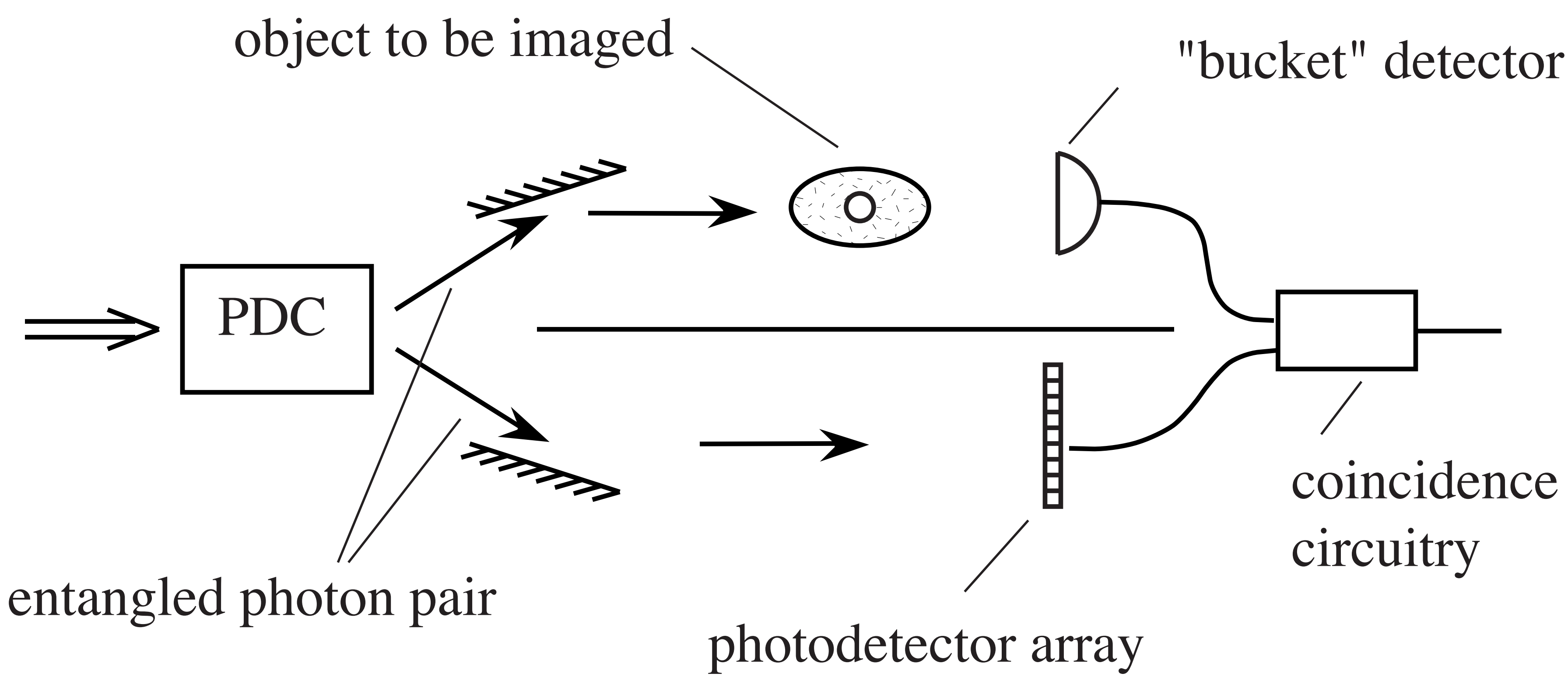
S. Lukishova, A. Schmid, C. Stroud, RWB

Research in Ghost Imaging and Pixel Entanglement

Robert Boyd, John Howell, Irfan Ali Khan,
Malcolm N. O'Sullivan-Hale

University of Rochester

Ghost (Coincidence) Imaging

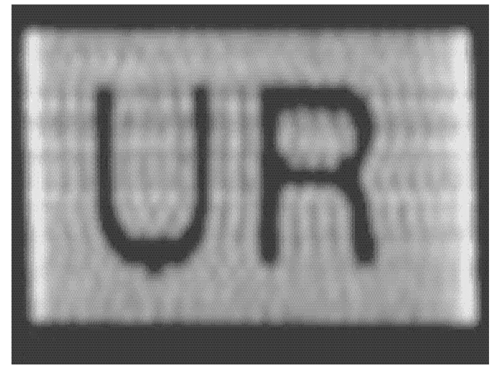


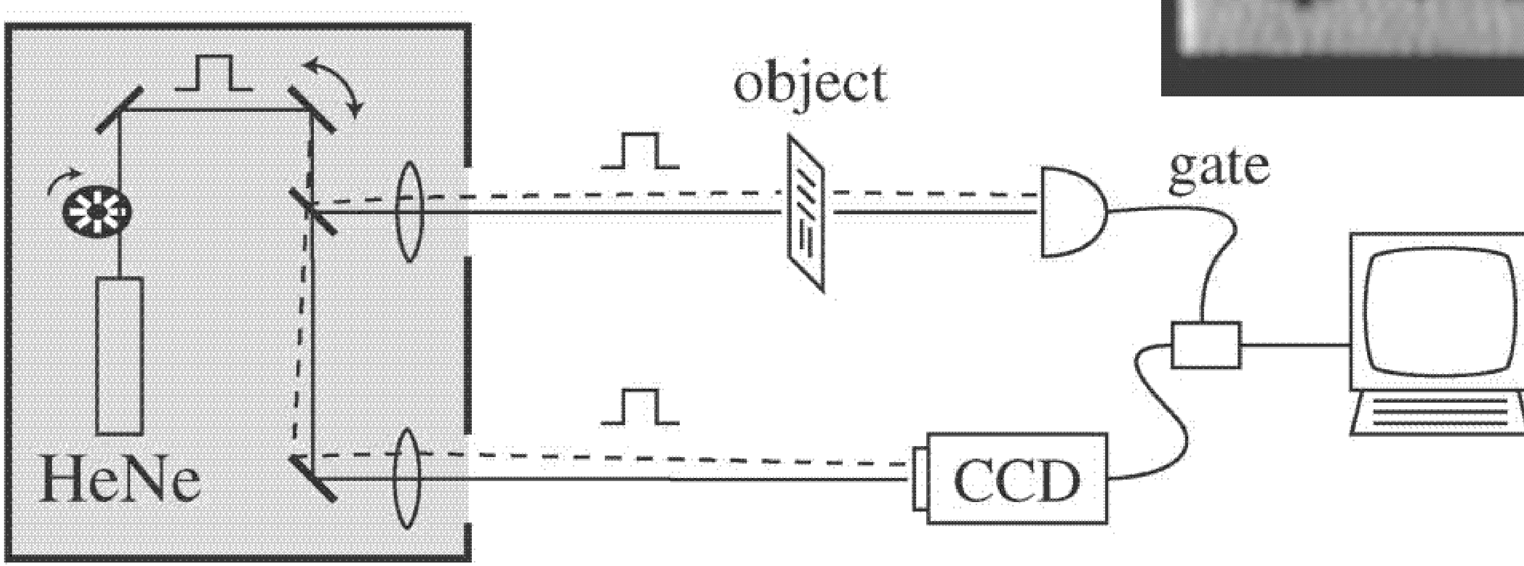
- Obvious applicability to remote sensing!
- Is this a purely quantum mechanical process?

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)

Classical Coincidence Imaging

We have performed coincidence imaging with a demonstrably classical source.





Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601 (2002).

Further Development

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

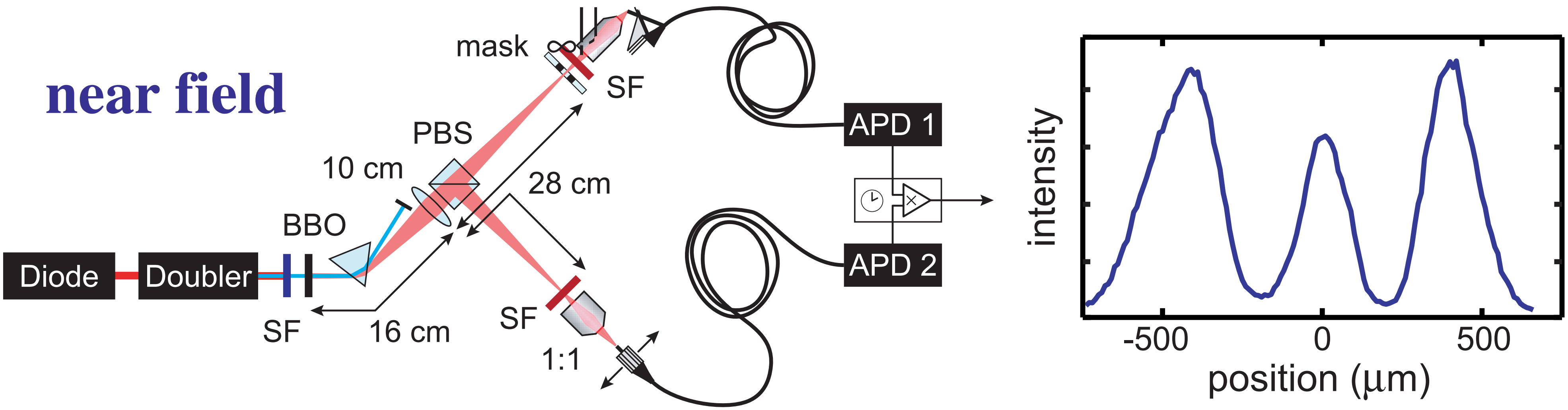
INFM, Dipartimento di Scienze CC.FF.MM., Università dellíInsubria, Via Valleggio 11, 22100 Como, Italy

(Received 11 October 2002; published 3 April 2003)

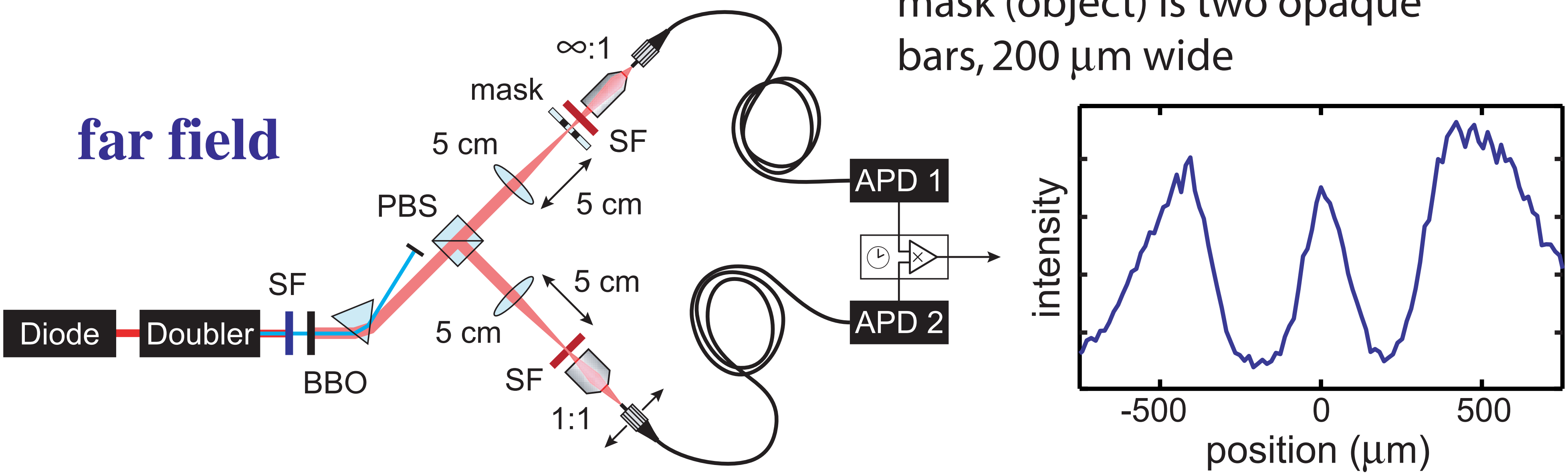
We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. 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

Near- and Far-Field Imaging Using Quantum Entanglement



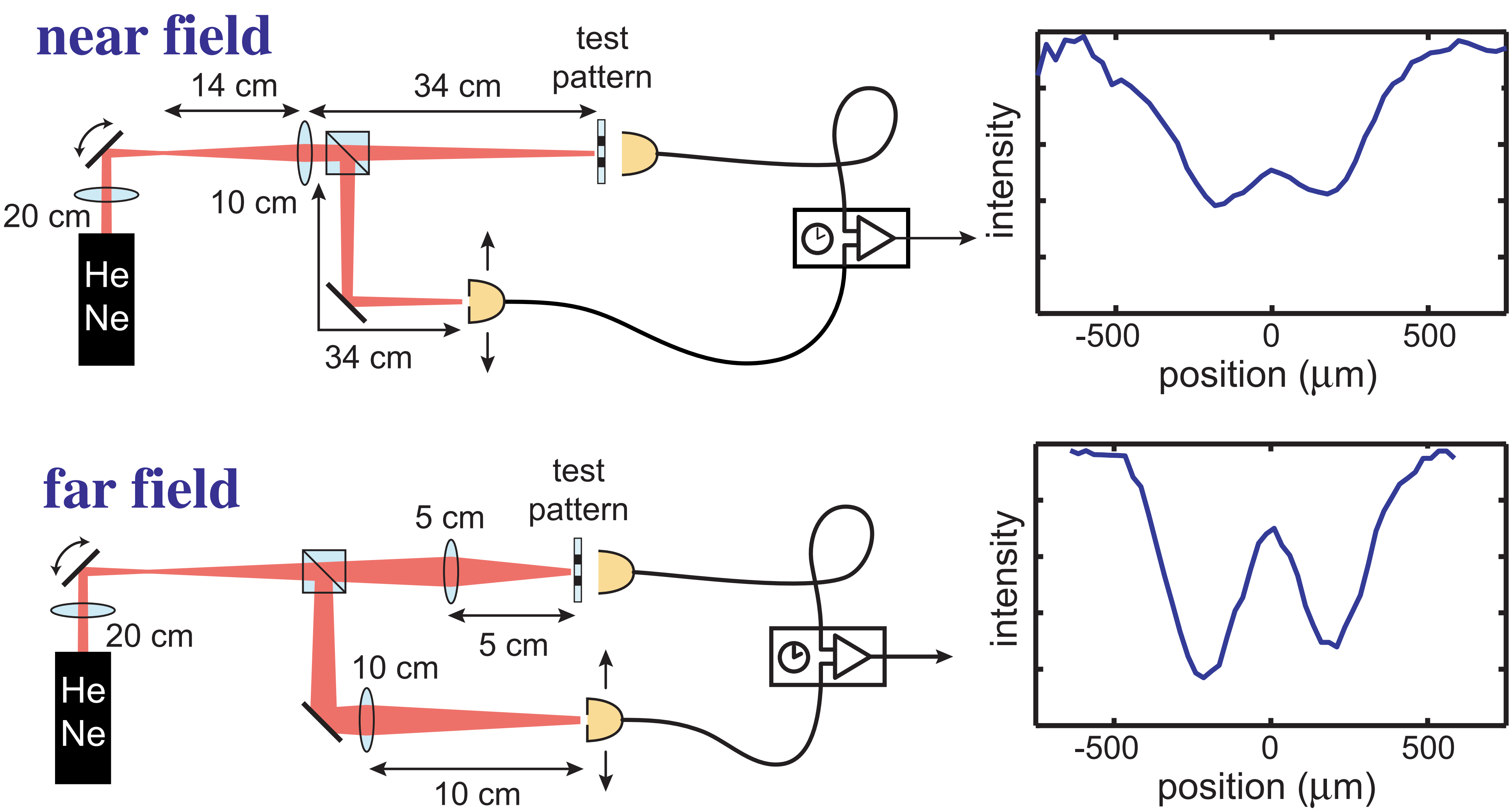
mask (object) is two opaque bars, 200 μm wide



Good imaging observed in both the near and far fields!

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

Near- and Far-Field Imaging With a Classical Source



- Good imaging can be obtained only in near field **or** far field.
- Detailed analysis shows that in the quantum case the space-bandwidth exceeded the classical limit by a factor of ten.

Uncertainty Product: Classical Versus Quantum

- The image resolution can be quantified by the width of the point spread function.
- For images obtained with our classical source, we find that the uncertainty product is given by

$$(\Delta x_2)_{x_1}{}^2 \, (\Delta k_2)_{k_1}{}^2 = 2.2 \pm 0.2$$

which in agreement with theory is larger than unity.

- For images obtained with entangled photons, we find that the uncertainty product is given by

$$(\Delta x_2)_{x_1}{}^2 \, (\Delta k_2)_{k_1}{}^2 = 0.01 \pm 0.03$$

which is 100 times smaller than the limiting value of unity.

- Thus, nonclassical behavior has been observed.

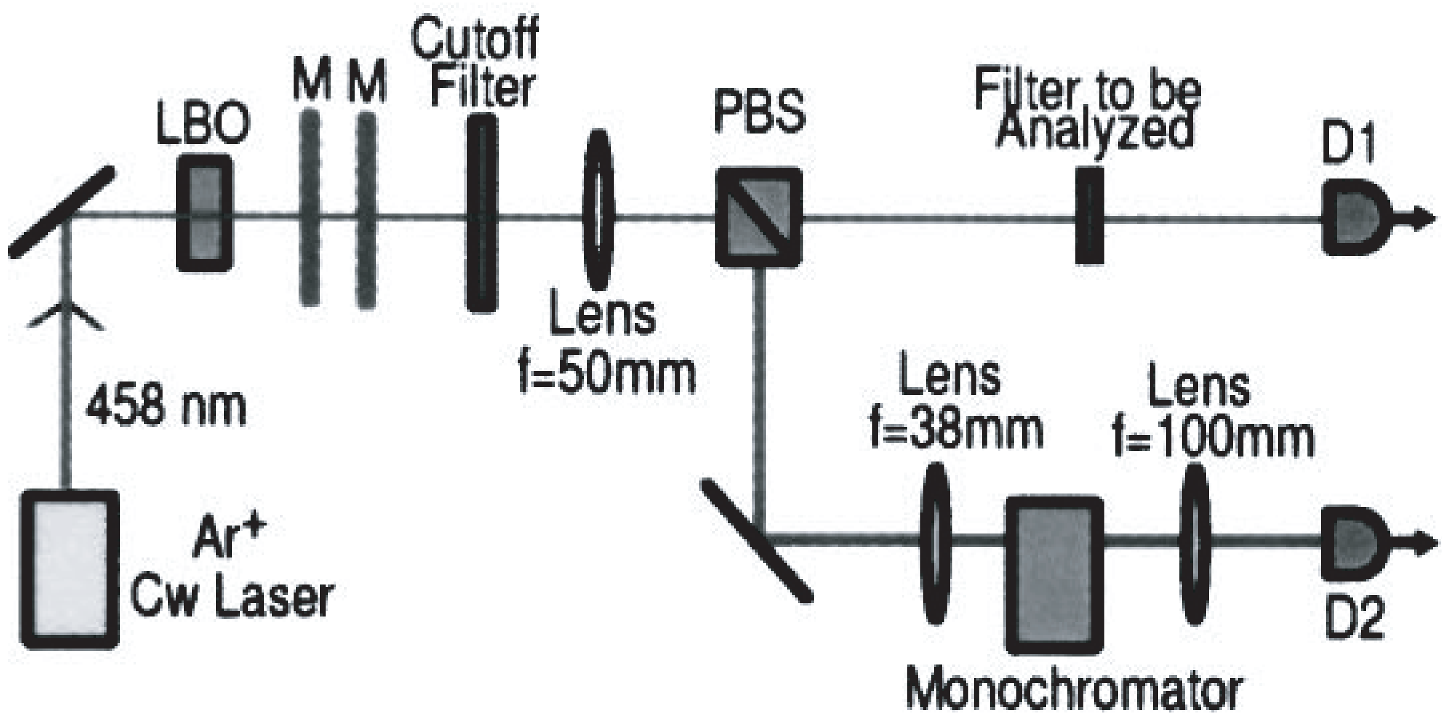
Is Entanglement Really Needed for Ghost Imaging with an Arbitrary Object Location?

Gatti et al. (PRA and PRL, 2004) argue that thermal sources can mimic the quantum correlations produced by parametric down conversion. (Related to Brown-Twiss effect.)

Experimental confirmation of ghost imaging with thermal sources given in arxiv manuscripts (from UMBC and Como groups).

But the contrast of the images formed in this manner is limited to 1/N, where N is the total number of pixels in the image.

Remote (Ghost) Spectroscopy

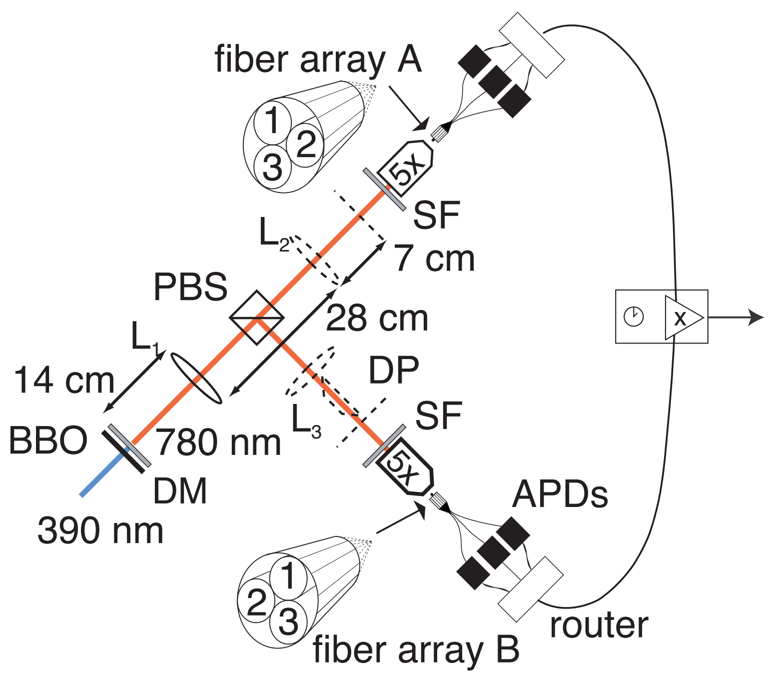


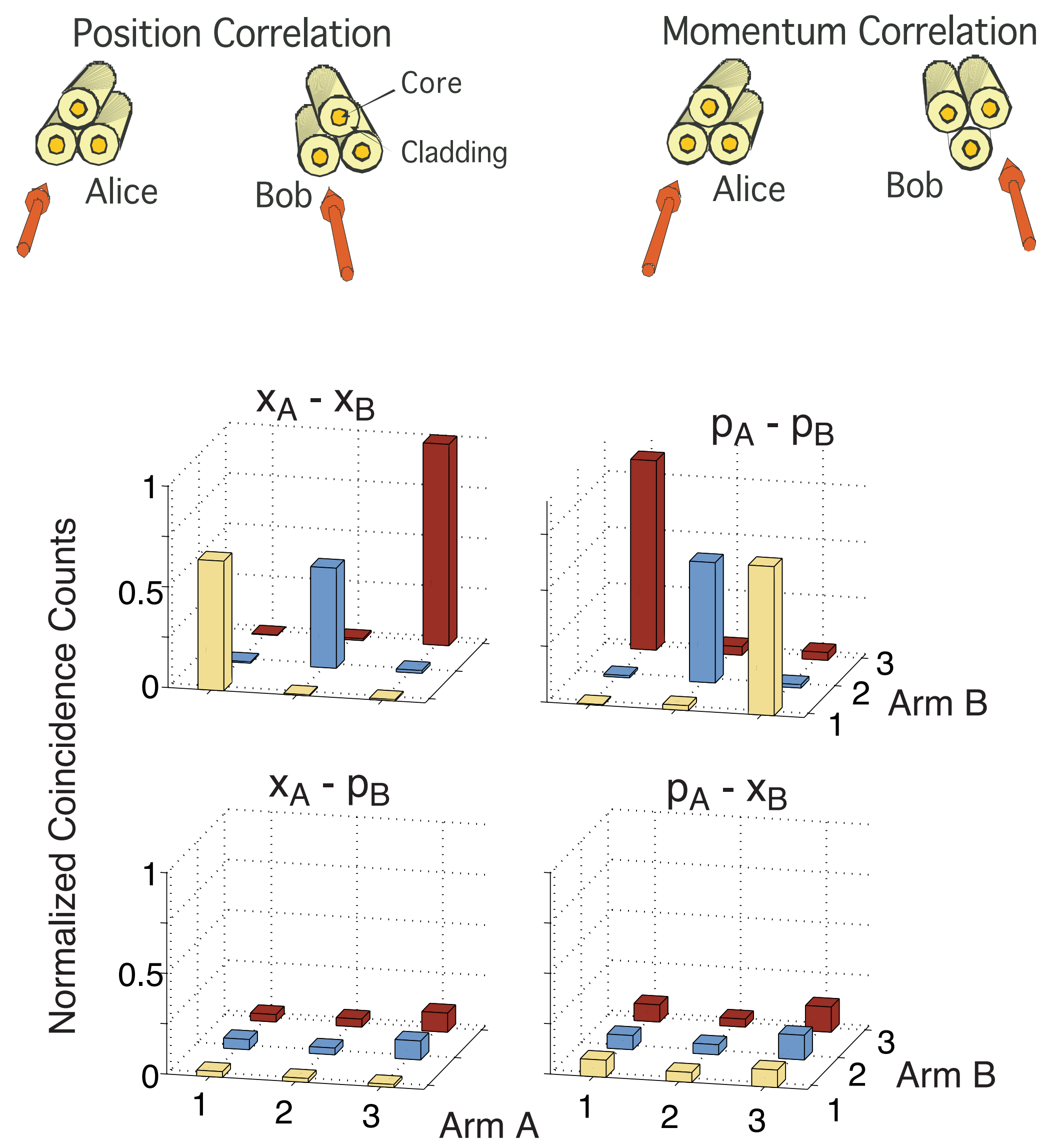
Can this idea be implemented with thermal light?

Scarcelli, Valencia, Compers, and Shih, APL 83 5560 2003.

Pixel Entanglement: Entanglement In A Very Large Hilbert Space

Quantum pixel: discrete average of a non-commuting, continuous variable (e.g., x or p).





Possible application: generalization of cryptographic protocols to qudits of higher dimension.

O'Sullivan-Hale, Khan, Boyd, and Howell, PRL 2005

Summary

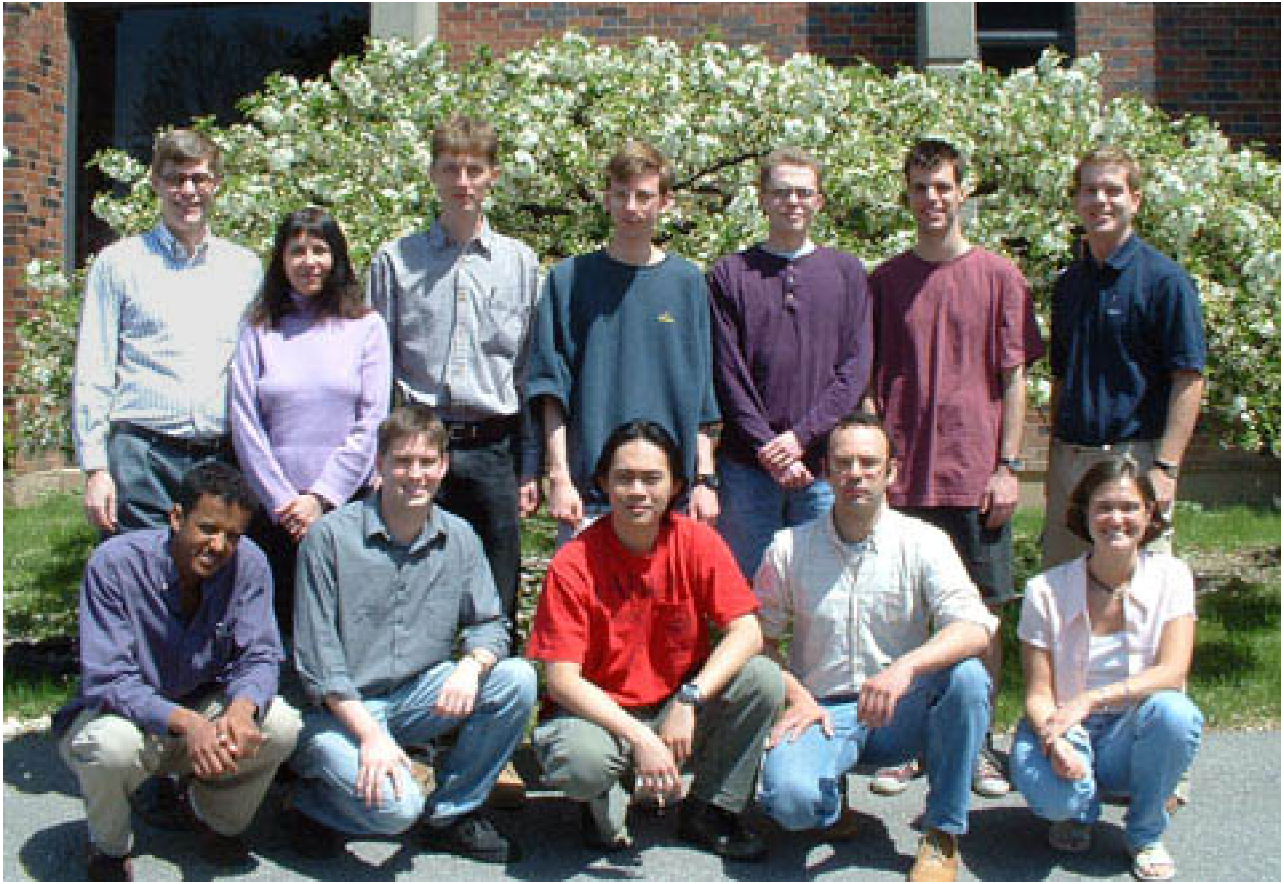
Quantum lithography has a good chance of becoming a reality.

The quantum vs. classical nature of ghost imaging is more subtle than most of us had appreciated.

Many of our cherished "quantum effects" can be mimicked classically.

There is still work to be done in the context of quantum imaging to delineate the quantum/classical frontier.

Special Thanks to my Students and Research Associates



Thank you for your attention!

Our results are posted on the web at:

http://www.optics.rochester.edu/~boyd

Research in Quantum Imaging

Quantum Imaging or Quantum Imogene?

Sid Caesar and
Imogene Coca in 1953