Progress in Quantum Lithography and Ghost Imaging

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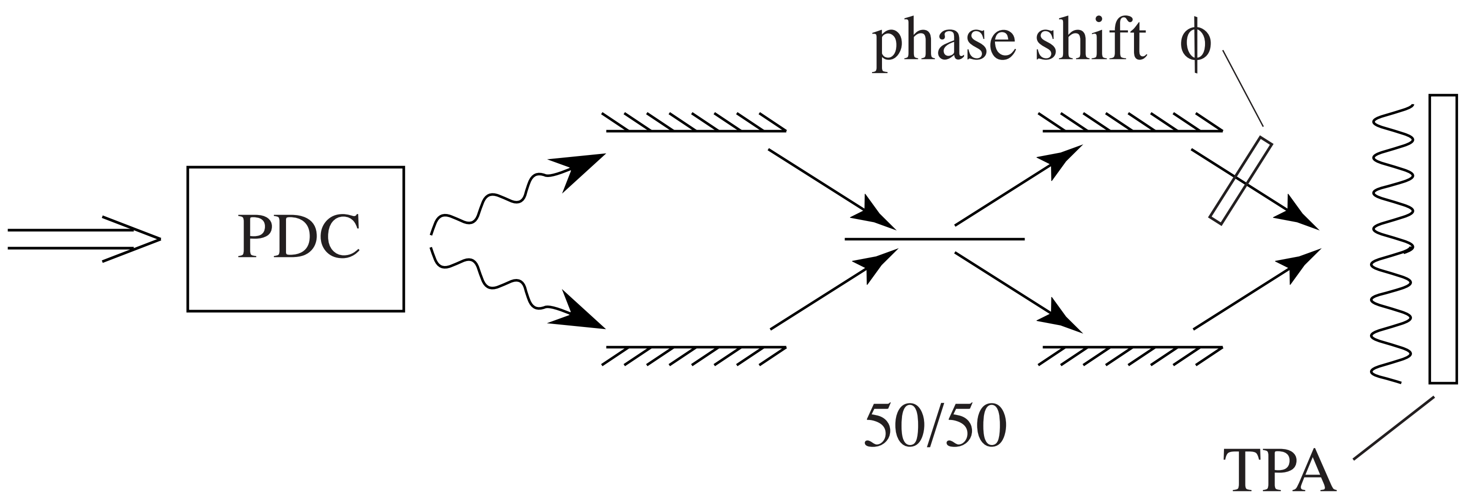
Quantum Lithography

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

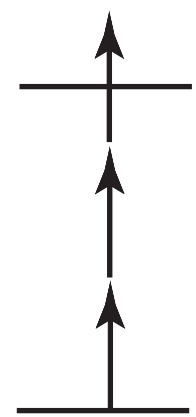


Boto et al., Phys. Rev. Lett. 85, 2733, 2000.

("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

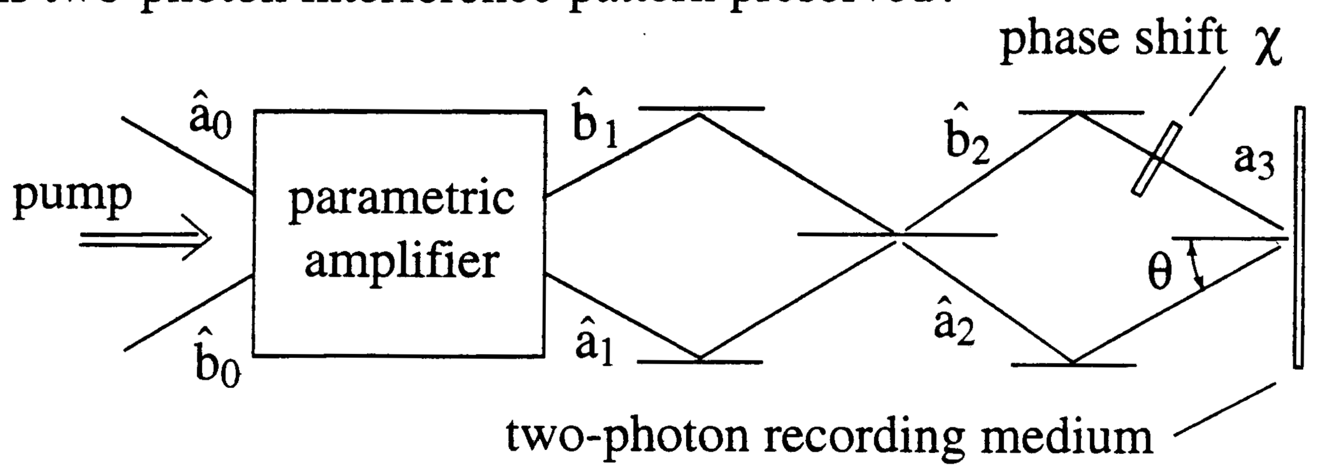


TPA in PMMA breaks chemical bond, modifying optical properties. Problem: self healing

- 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

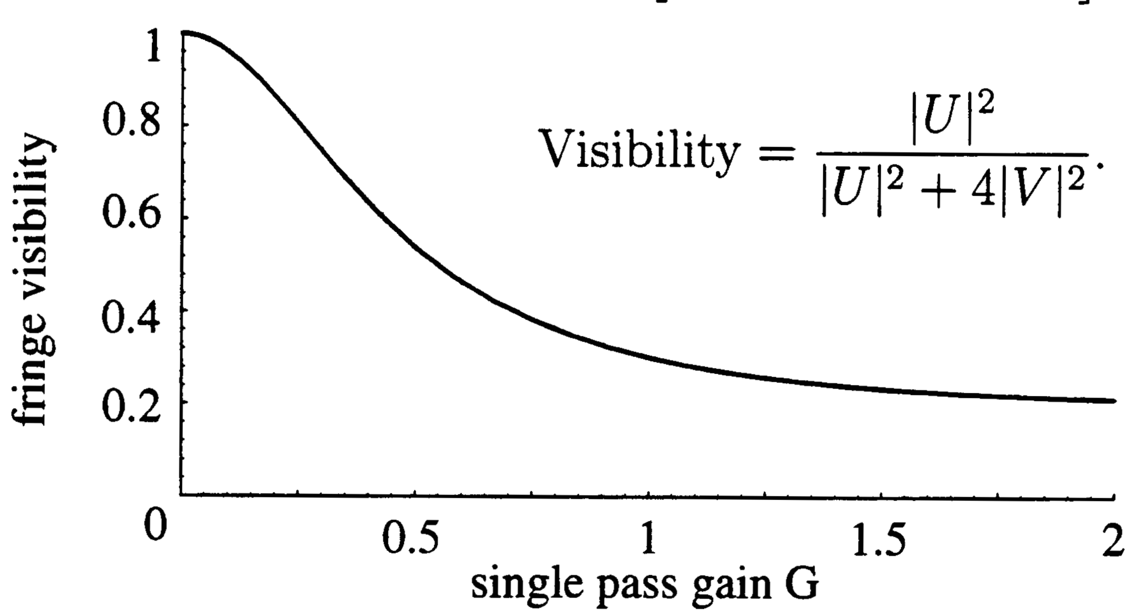
$$U = \cosh G \qquad V = -\, i\exp(i\varphi)\sinh G$$

- 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

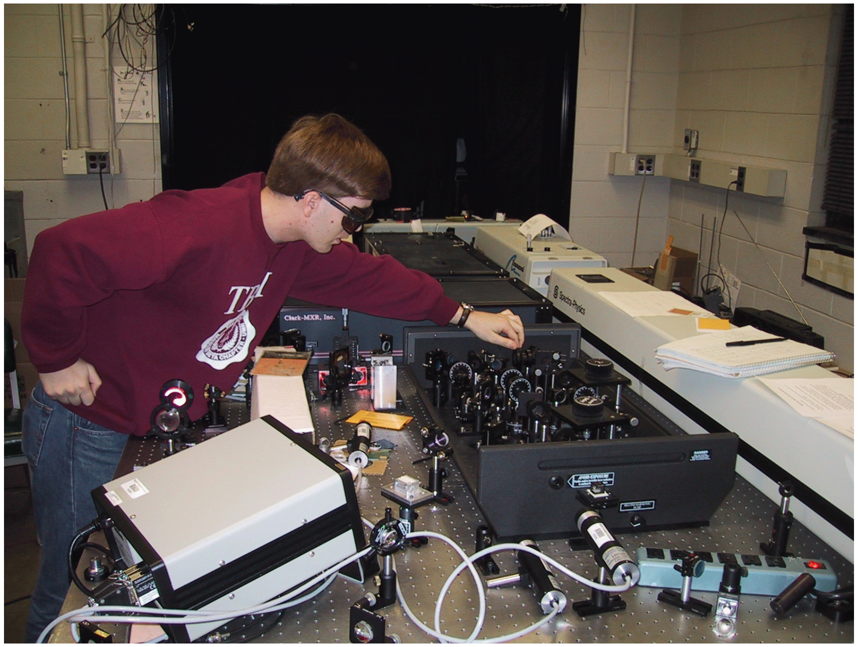
$$\langle 0,0|\hat{a}_3^\dagger\hat{a}_3^\dagger\hat{a}_3\hat{a}_3|0,0\rangle = 4|V|^2\left[|U|^2\cos^2\chi + 2|V|^2\right]$$

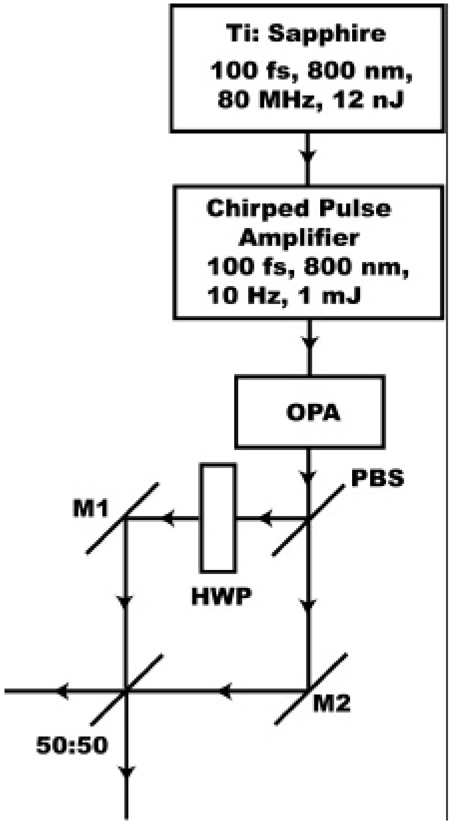


(Phys. Rev. Lett. 86, 1389, 2001)

QUANTUM LITHOGRAPHY RESEARCH

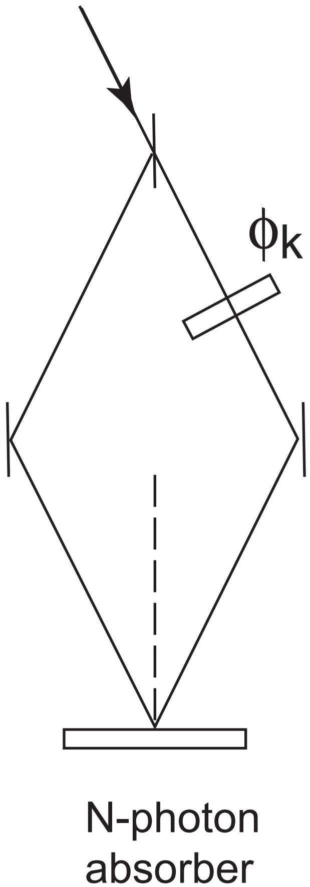
Experimental Layout

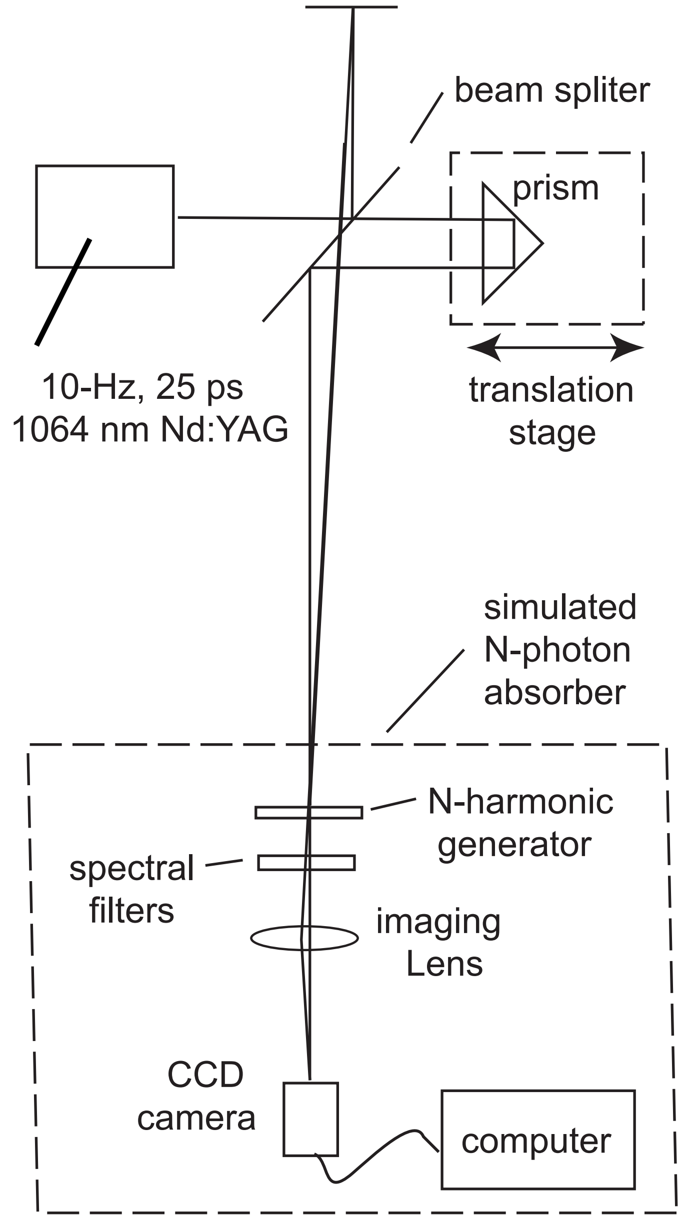




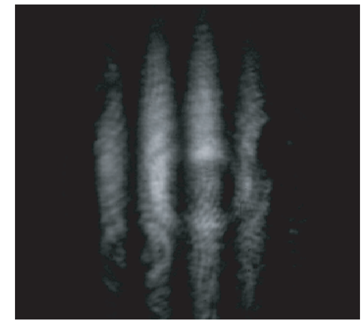
Non-Quantum Quantum Lithography

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

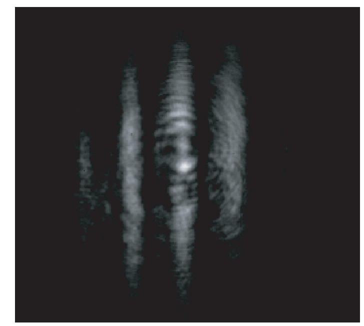




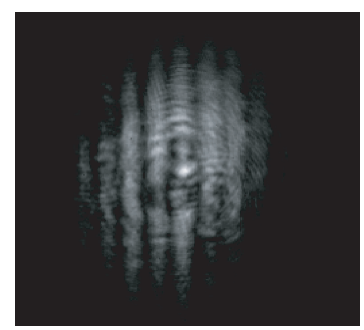
N=1, M=1



N=2, M=1

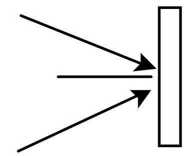


N=2, M=2



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

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

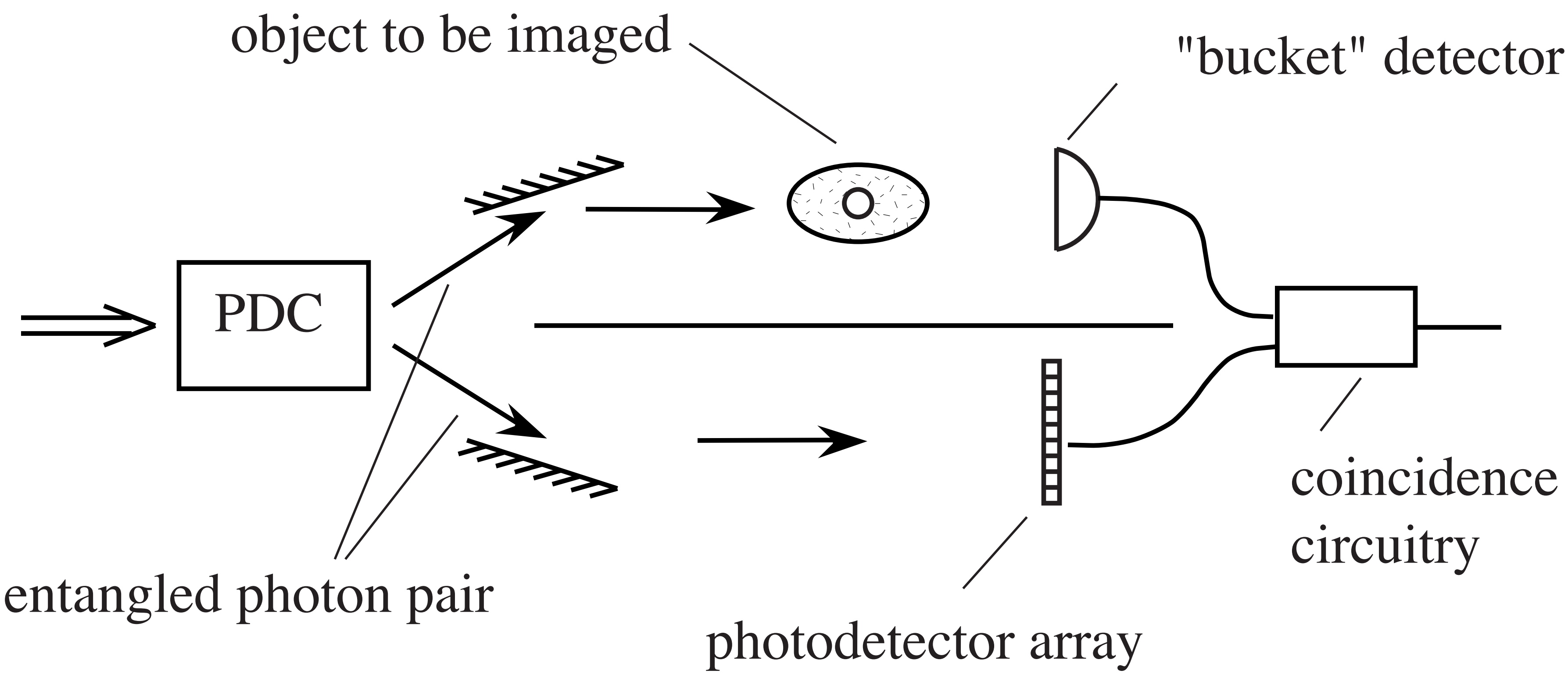
where k = 2(/c) sin

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.

Ghost (Coincidence) Imaging



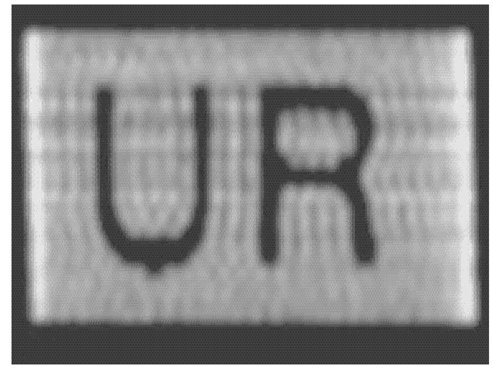
Obvious applicability to remote sensing!

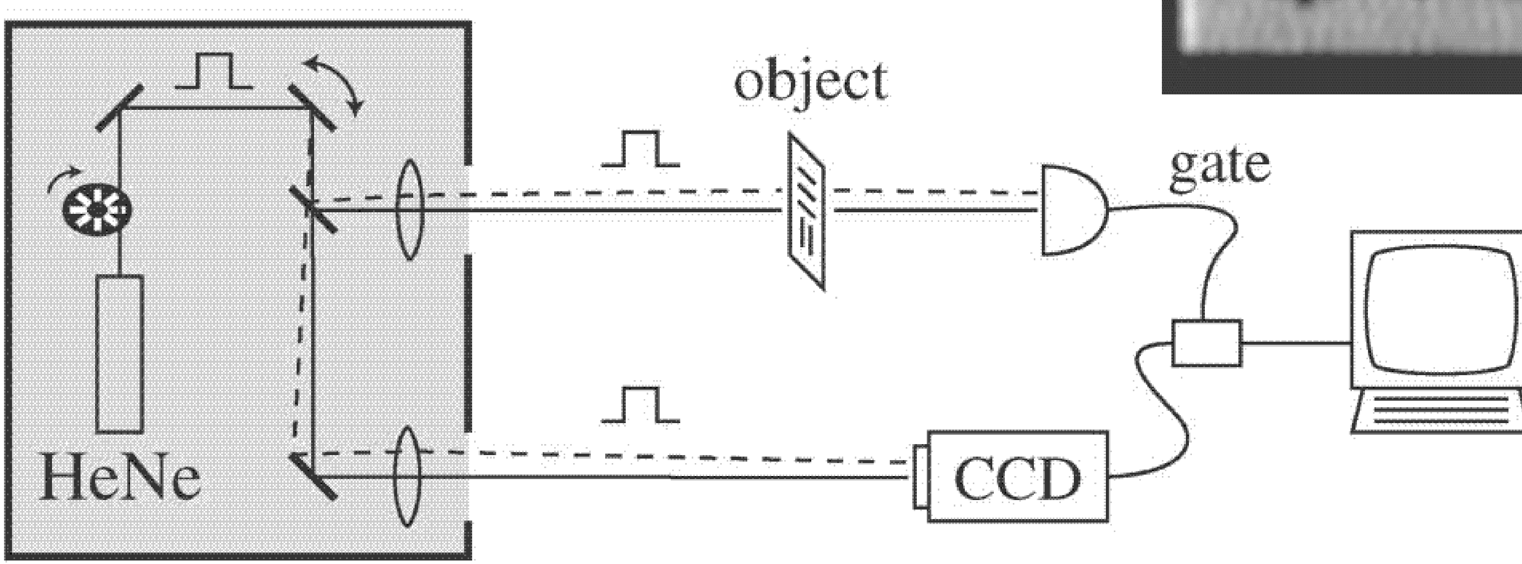
- Is this a purely quantum mechanical process?

  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).

Classical Coincidence Imaging

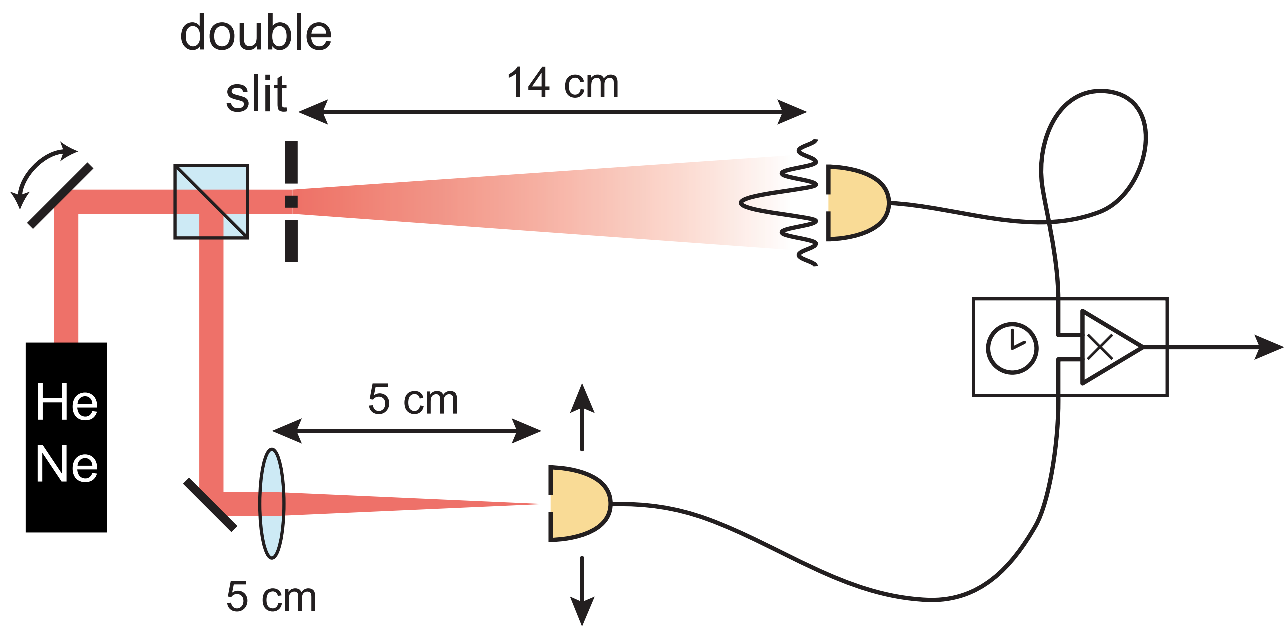
We have performed coincidence imaging with a demonstrably classical source.



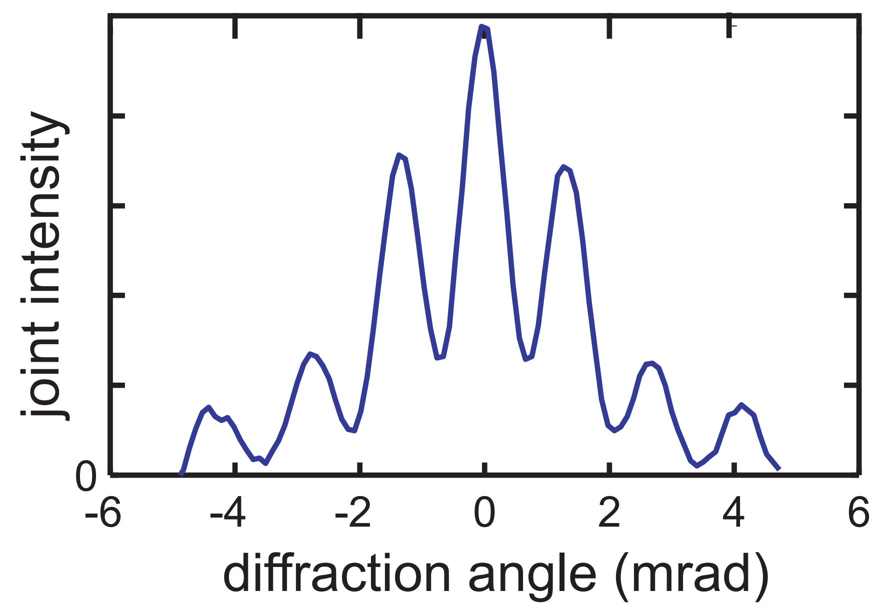


Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601 (2002).

Ghost Diffraction with a Classically Correlated Source



Even diffraction effects are observable with classical coincidence imaging.



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

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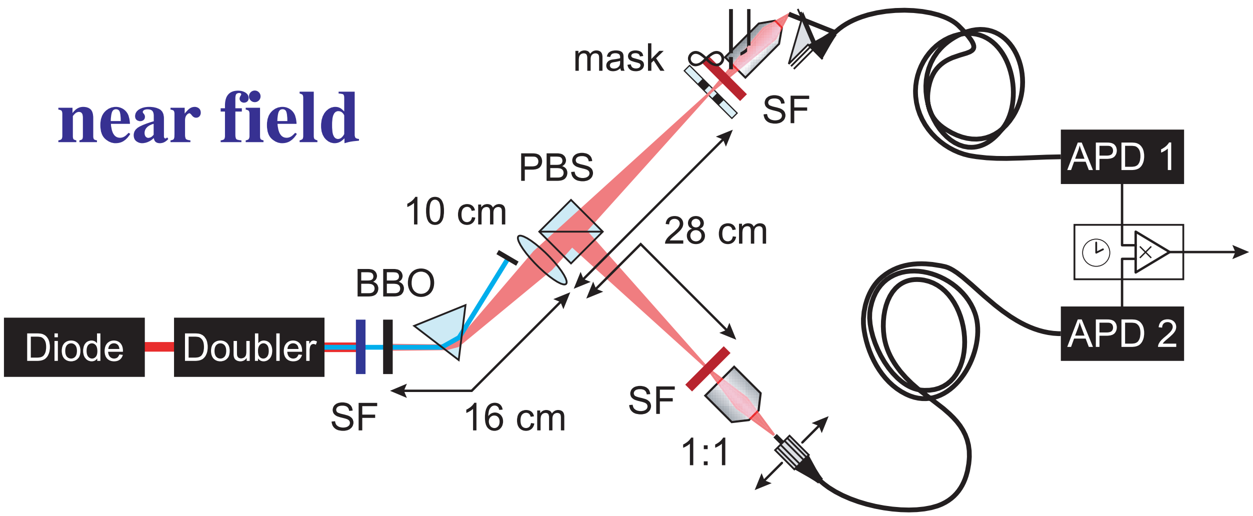
(Received 11 October 2002; published 3 April 2003)

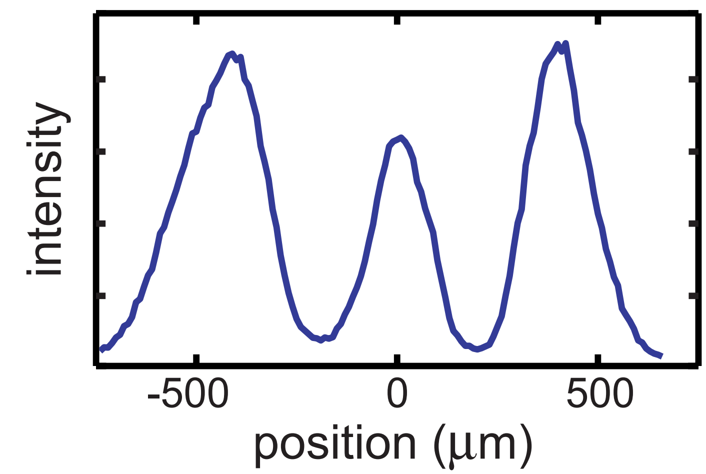
We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain.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

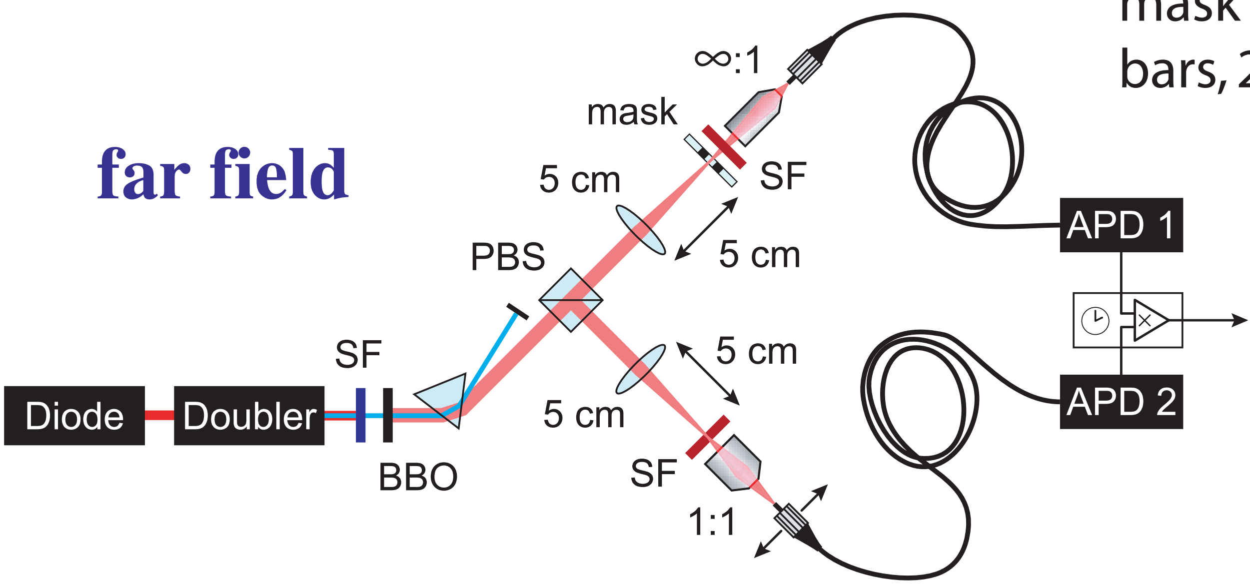
near field

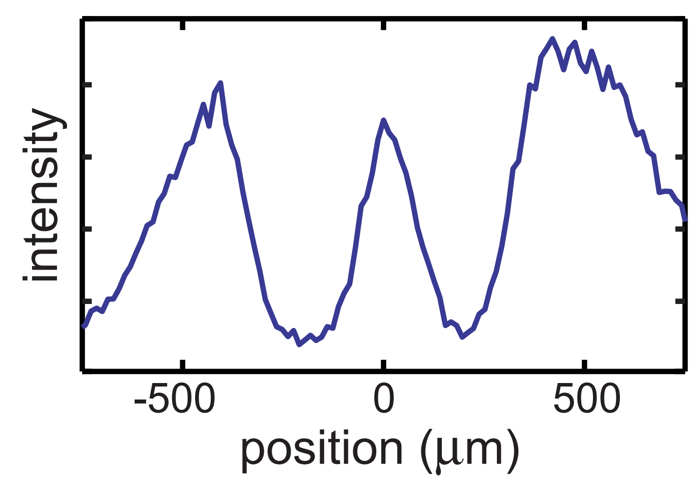




mask (object) is two opaque bars, 200 μm wide

far field

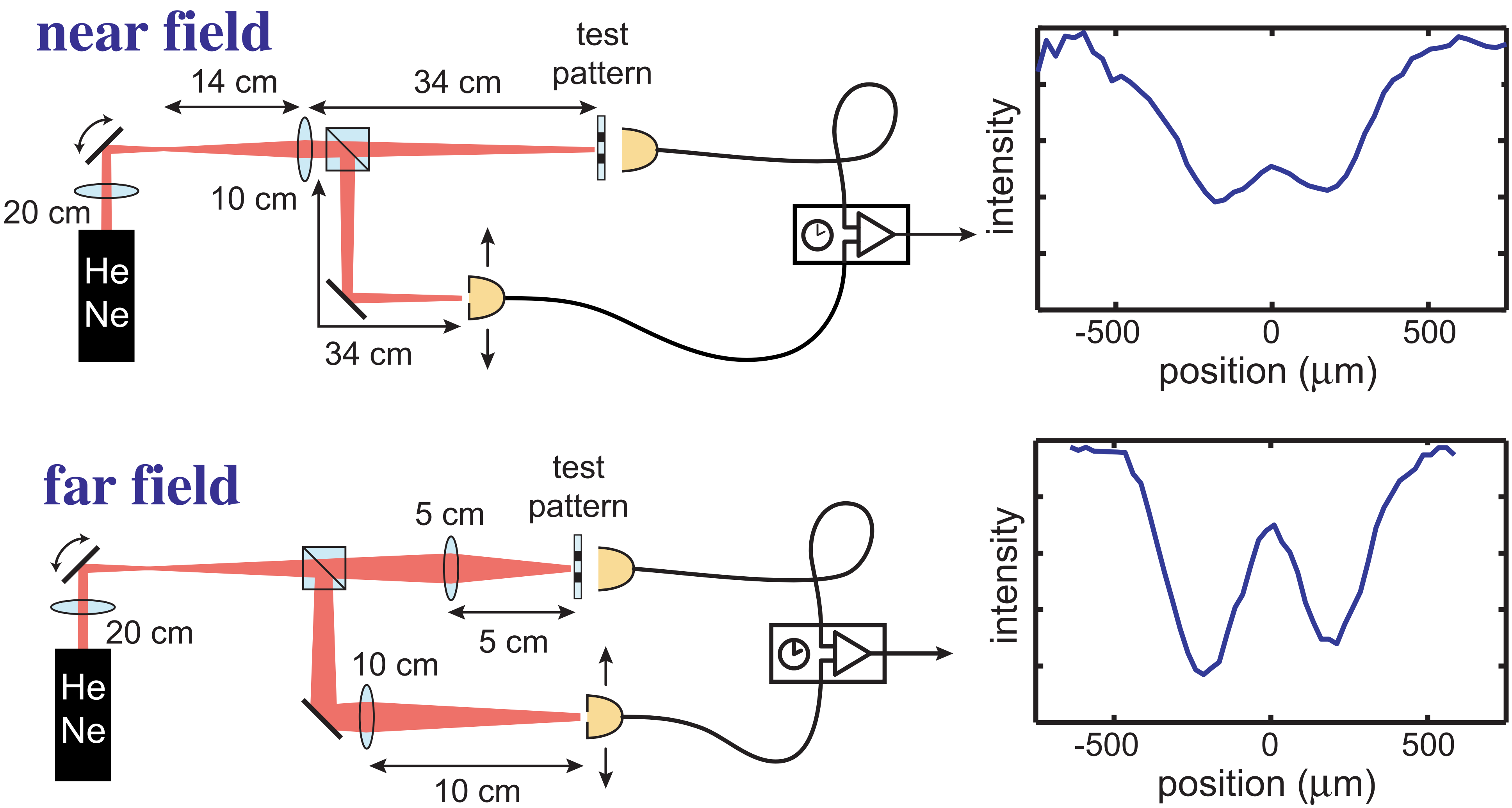




Good imaging observed in both the near and far fields!

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.

Summary

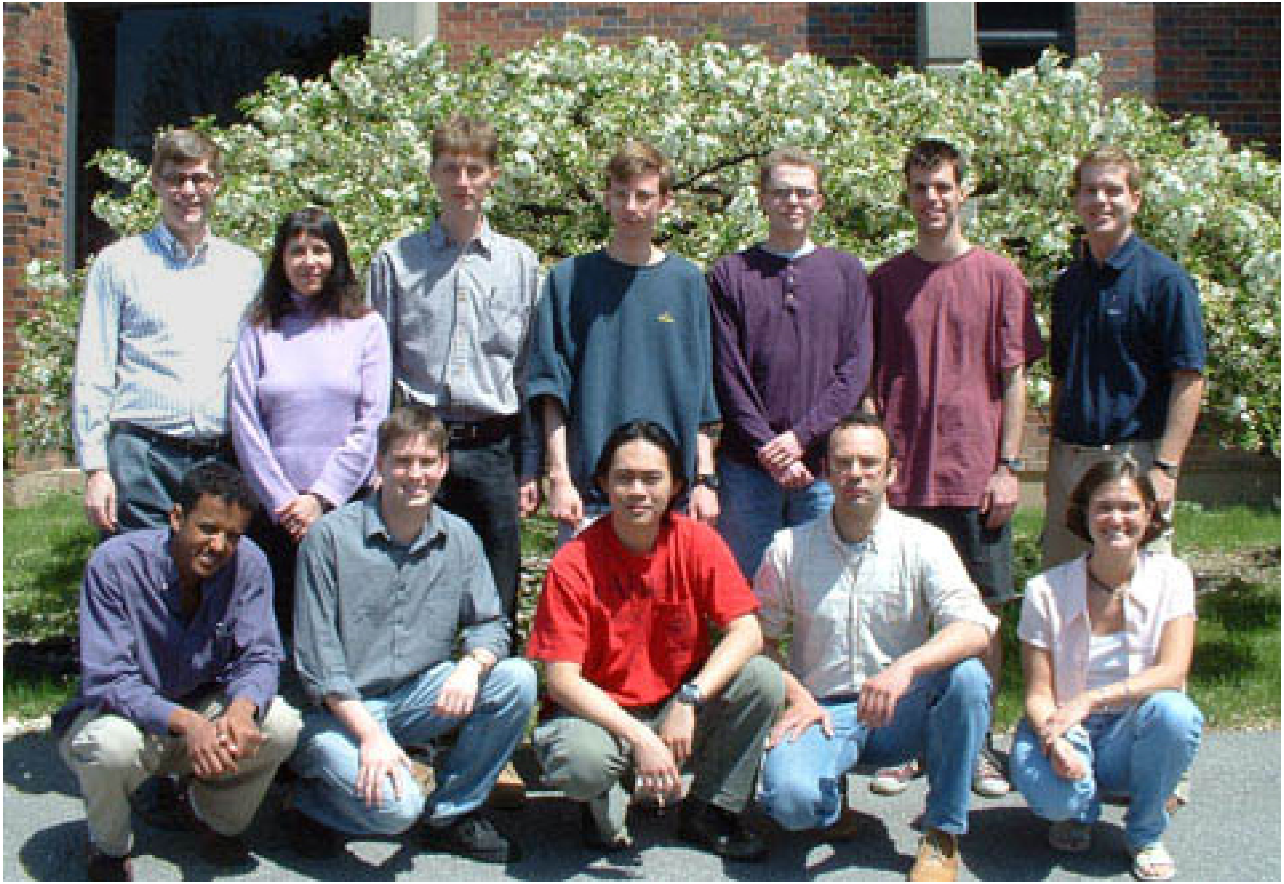
Quantum lithography has a good chance of becoming a reality.

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