Quantum Imaging:
New Methods and Applications

Robert W. Boyd

The Institute of Optics and
Department of Physics and Astronomy
University of Rochester, Rochester, NY 14627
http://www.optics.rochester.edu

Research in Quantum Imaging

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

Can we "beat" the Rayleigh criterion?

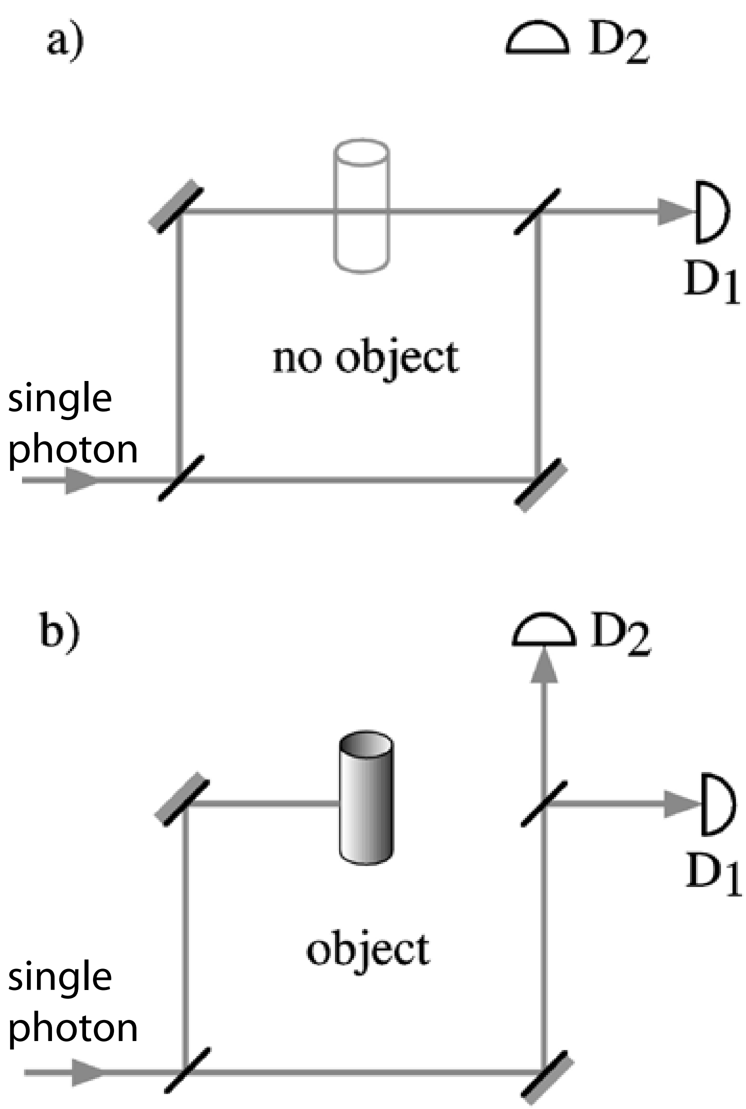
What are the implications of “interaction free” and “ghost” imaging

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

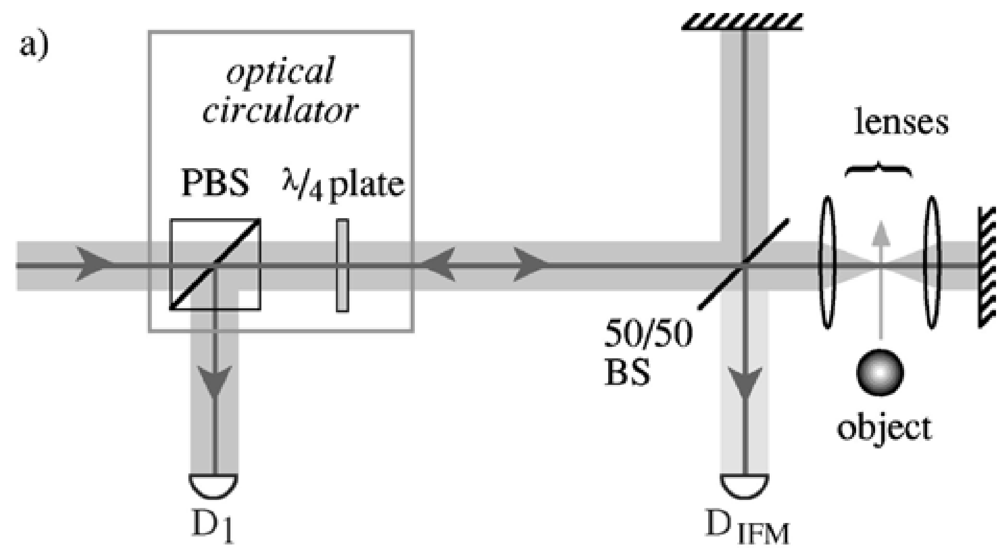
Ghost and Interaction-Free Imaging

Stealth Imaging

Quantum Imaging by Interaction-Free Measurement

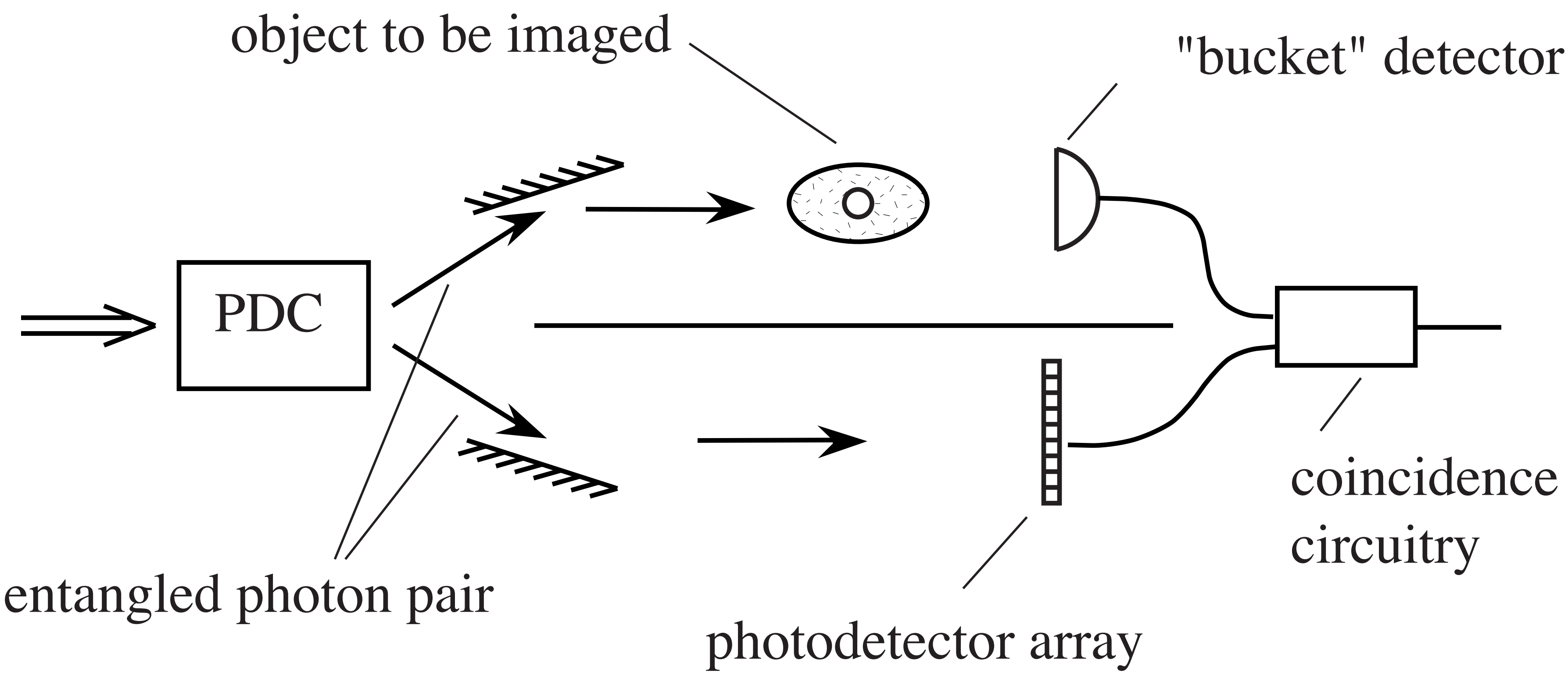


imaging setup



A. Elitzur and L. Vaidman, Foundations of Physics, 23 987 (1993).
Kwiat, Weinfurter, Herzog, Zeilinger, and Kasevich, Phys. Rev. Lett. 74 4763 1995
White, Mitchell, Nairz, and Kwiat, Phys. Rev. A58, 605 (1998).

Ghost (Coincidence) Imaging

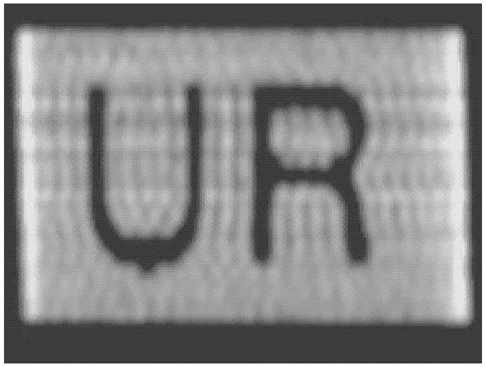


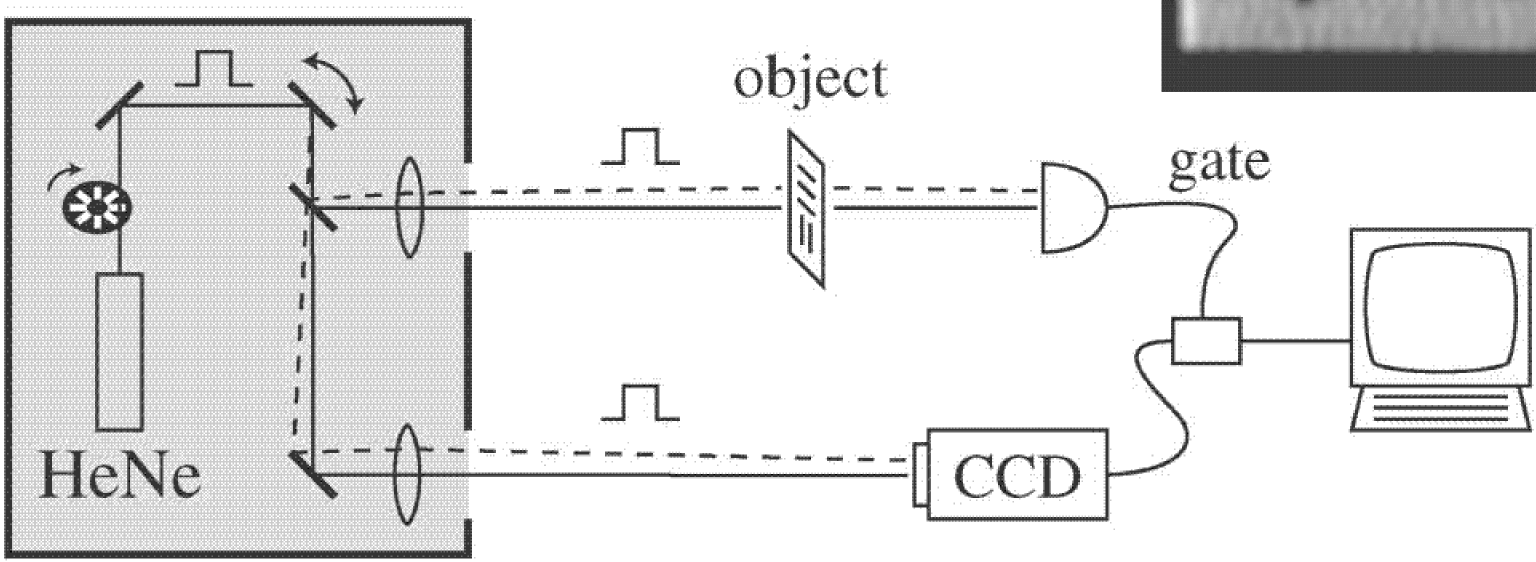
- Obvious applicability to remote sensing!
- Is this a purely quantum mechanical process?

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

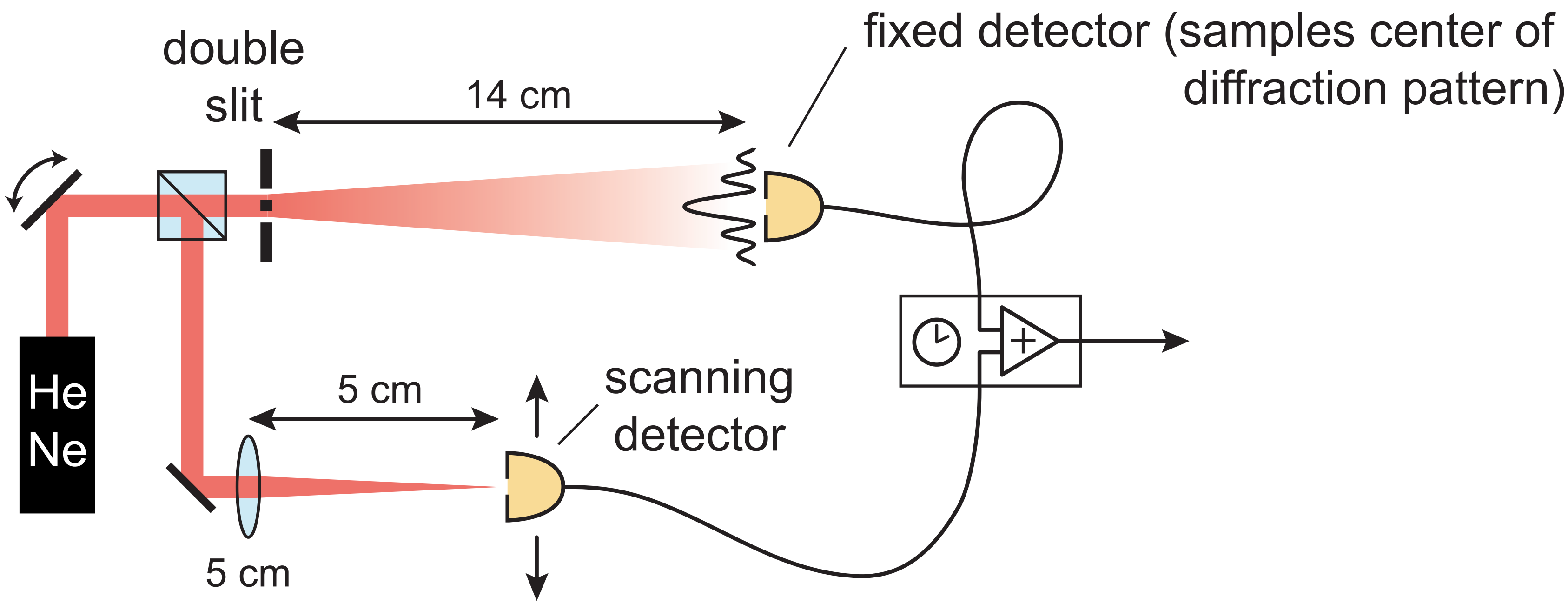
We have performed coincidence imaging with a demonstrably classical source.



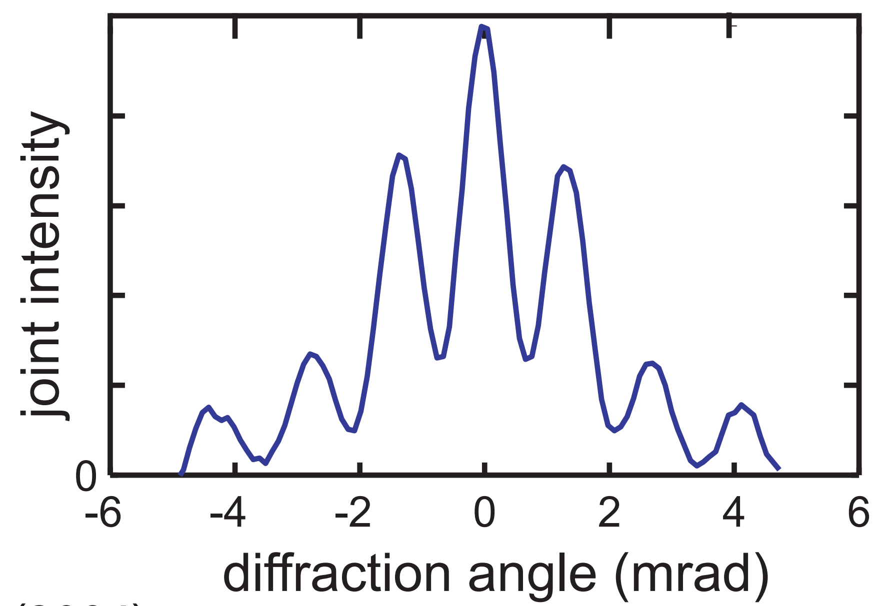


Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601 (2002).

Ghost Diffraction with a Classically Correlated Source



Even diffraction effects are observable with classical coincidence imaging.



Bennink, Bentley, Boyd, and Howell, PRL 92 033601 (2004)

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

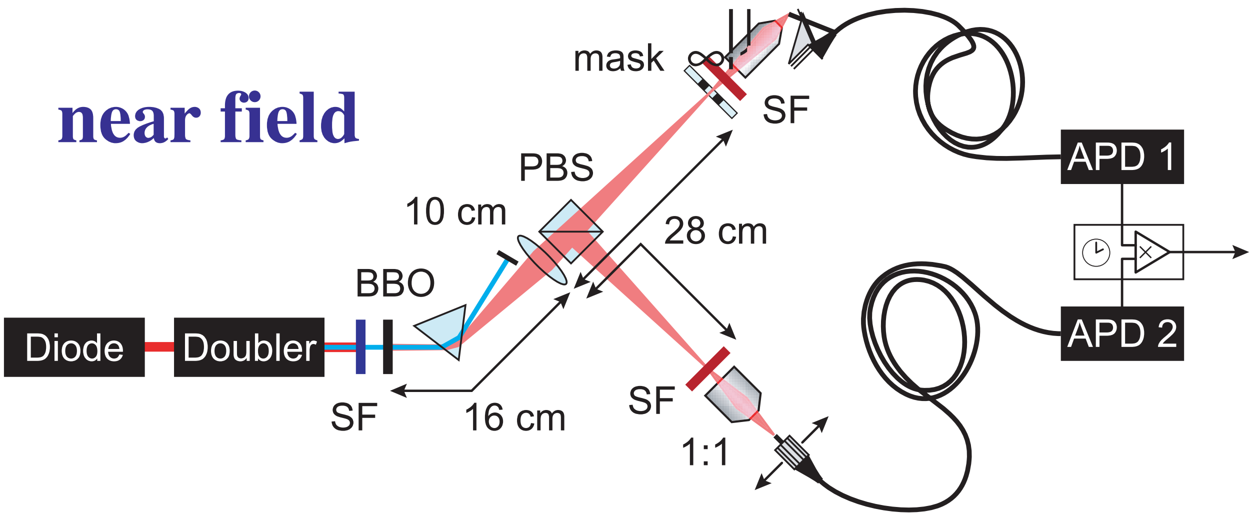
(Received 11 October 2002; published 3 April 2003)

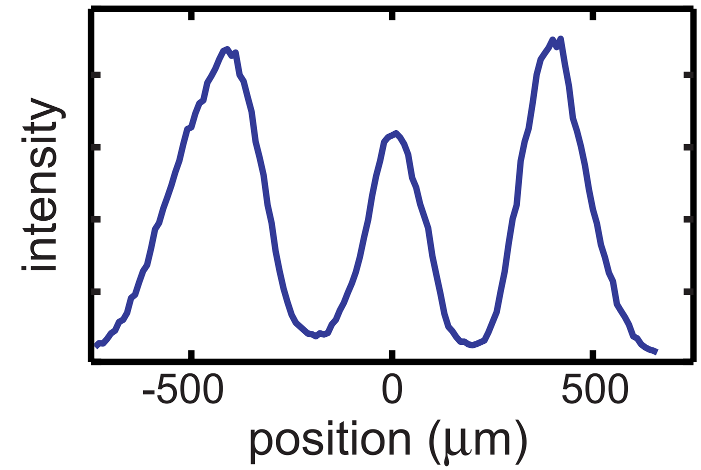
We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain.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

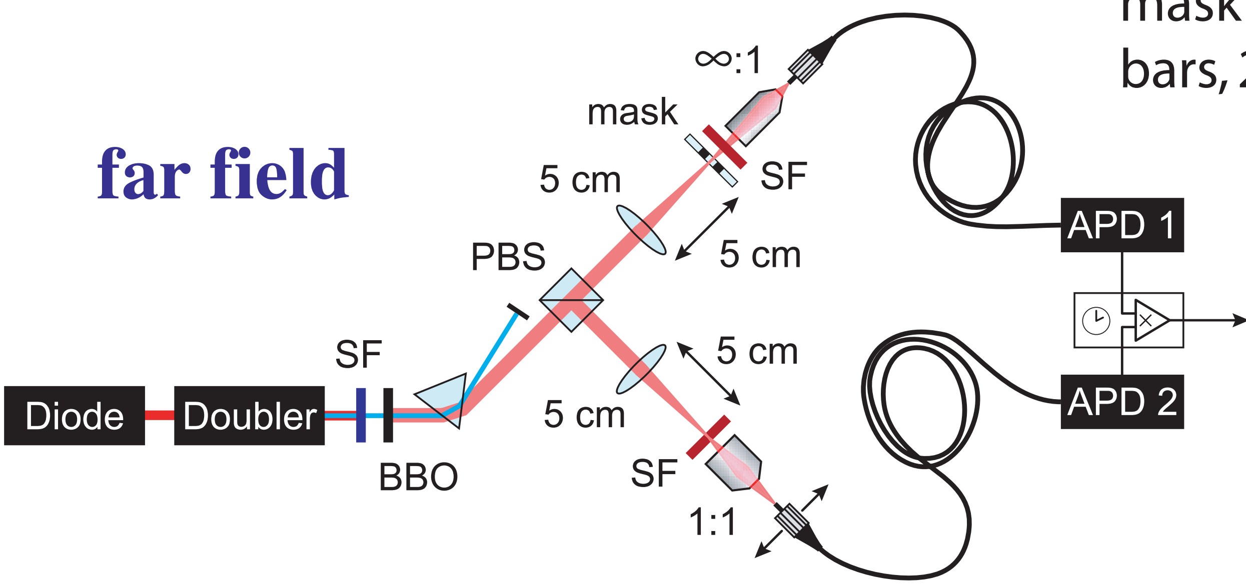
near field

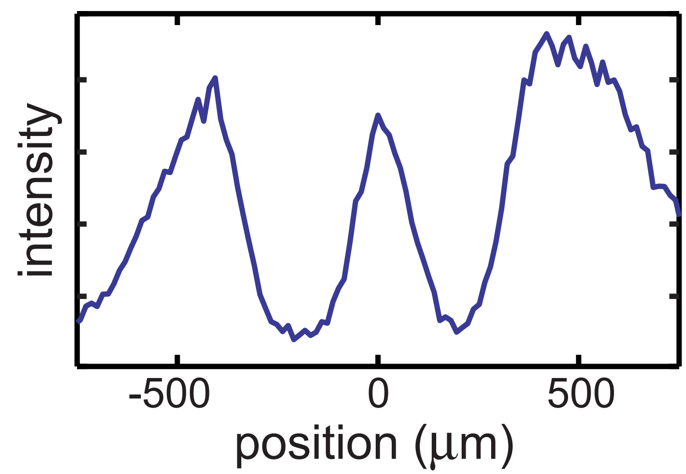




mask (object) is two opaque bars, 200 µm wide

far field

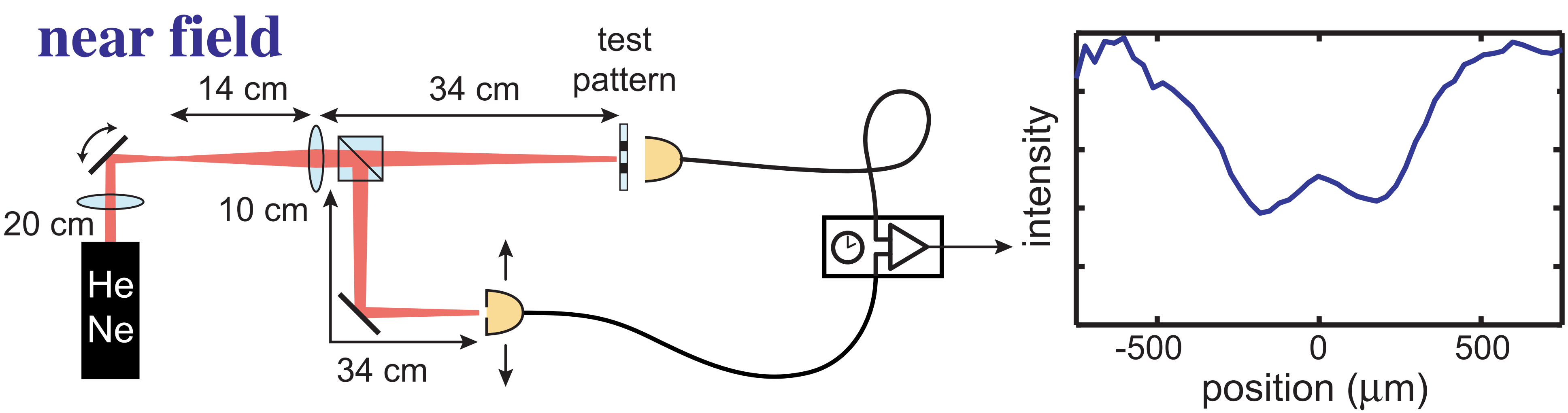


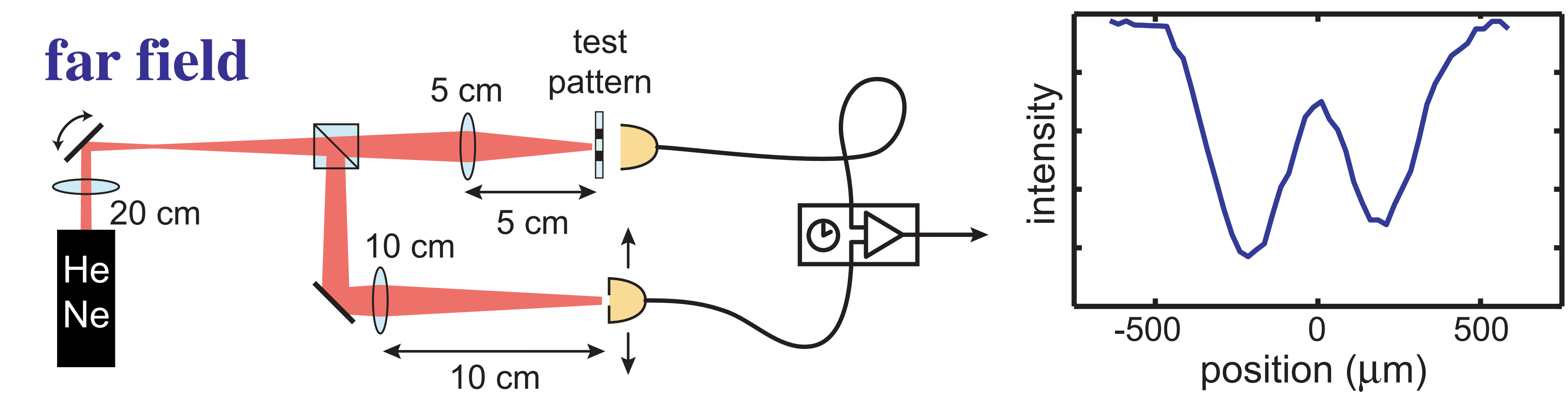


Good imaging observed in both the near and far fields!

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.

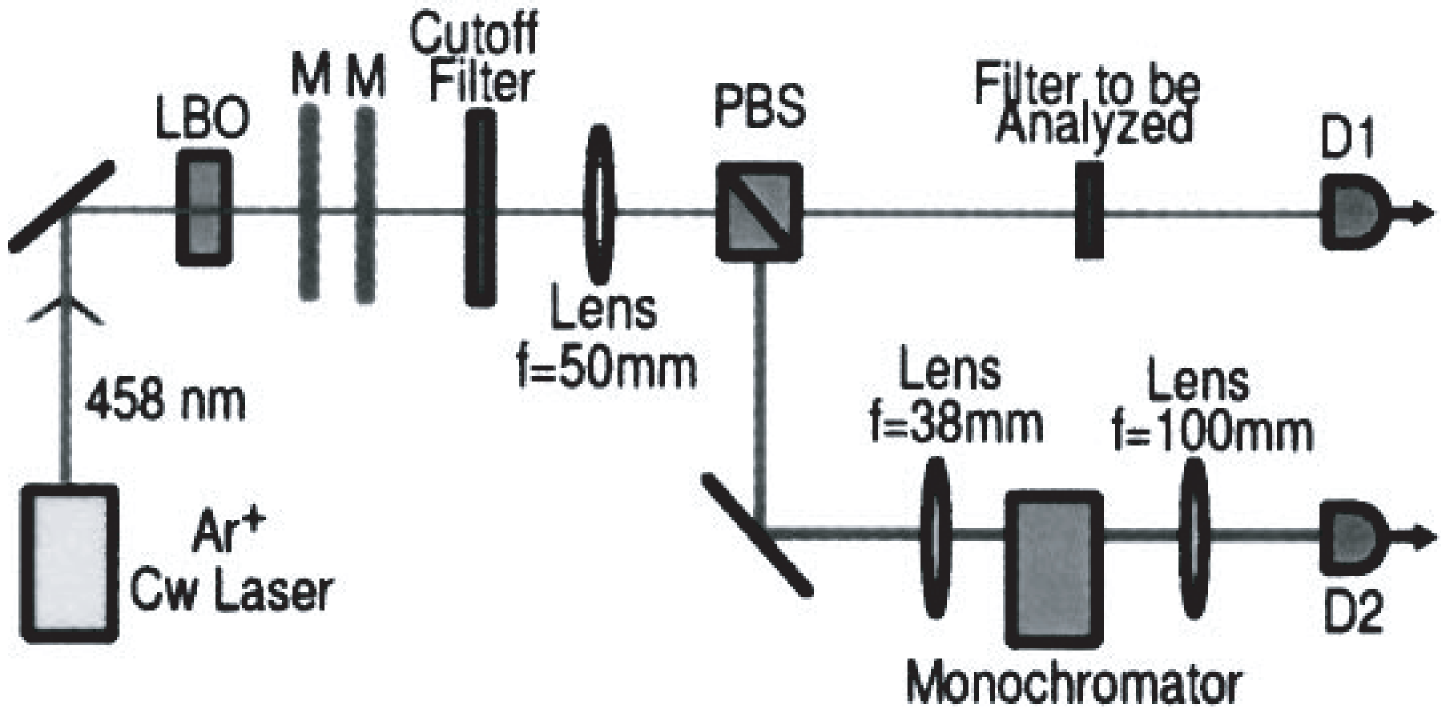
Is Entanglement Really Needed for Ghost Imaging with an Arbitrary Object Location?

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 presented by Como and UMBC groups

But the contrast of the images formed in this manner is limited to 1/2 or 1/N (depending on the circumstances) 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.

See also the related work of Bellini et al., Phys. Rev. Lett. 90 043602 (2003).

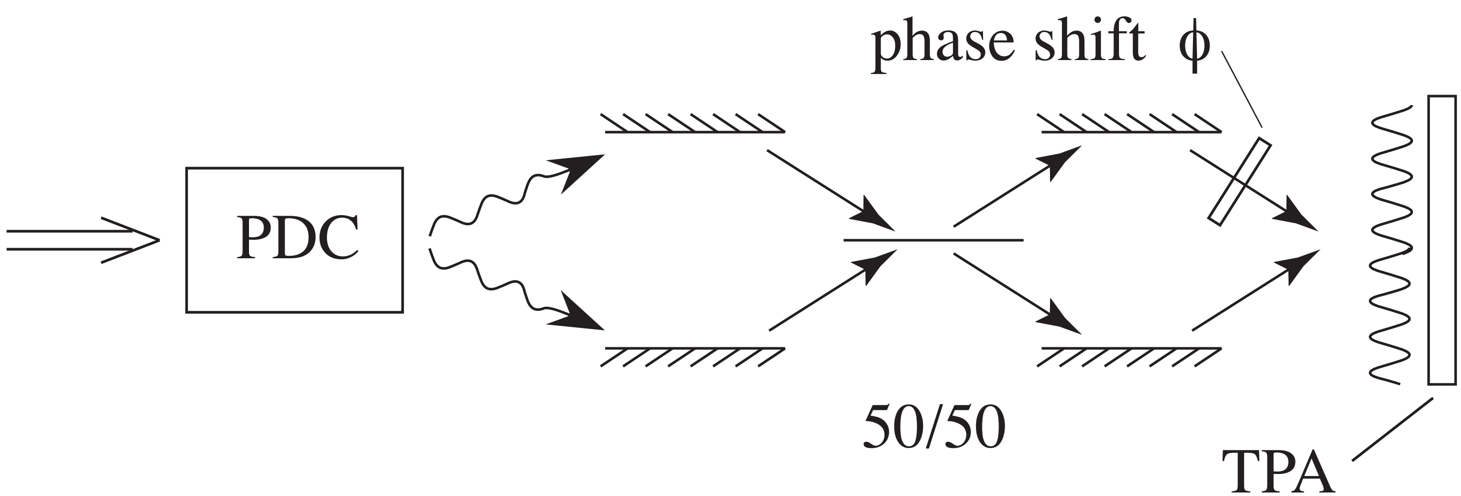
Progress in Quantum Lithography

Robert W. Boyd, Sean J. Bentley,
Hye Jeong Chang, and Malcolm N. O'Sullivan-Hale

Institute of Optics, University of Rochester,
Rochester NY,USA

Quantum Lithography

- Entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit
- Process "in reverse" performs sub-Rayleigh microscopy, etc.
- Resolution $\approx \lambda / 2N$, where N = number of entangled photons



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

("al." includes Jon Dowling)

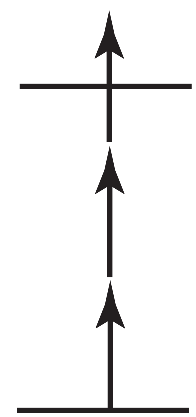
Quantum Lithography: Easier Said Than Done

- 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.



3PA in PMMA breaks chemical bond, modifying optical properties.

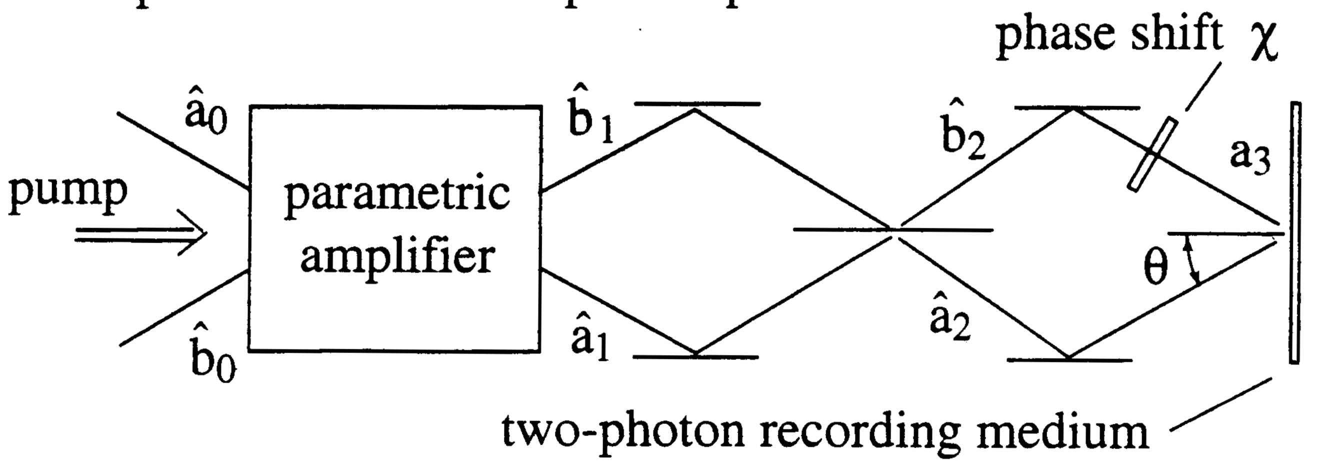
Problem: self healing

- 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

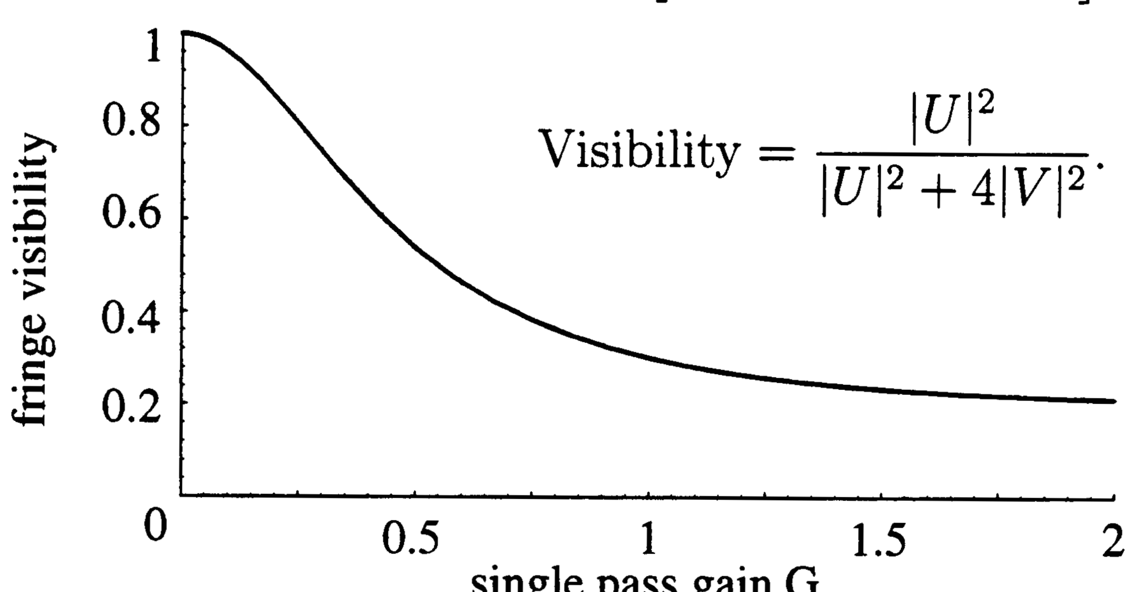
$$U = \cosh G \qquad V = -\,i\exp(i\varphi)\sinh G$$

- 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

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

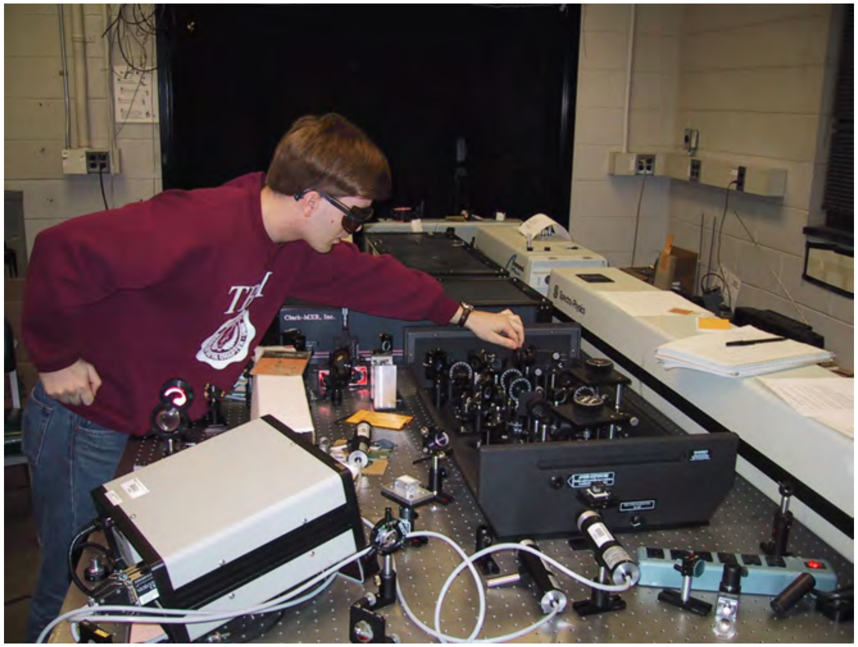


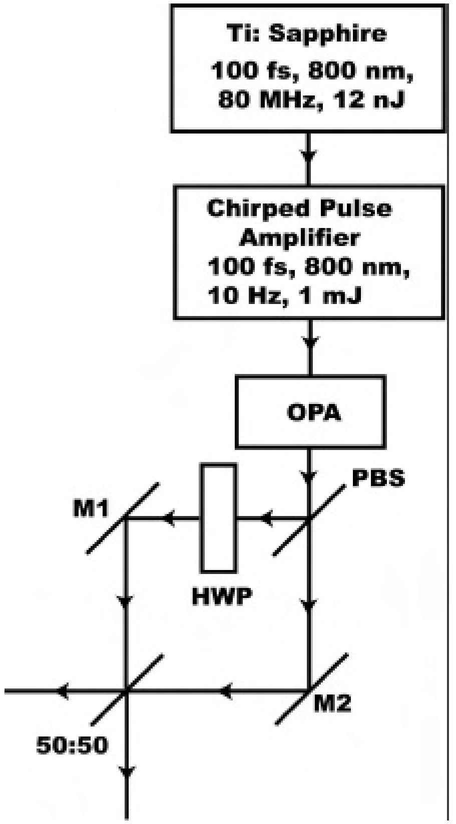
$$\text{Visibility} = \frac{|U|^2}{|U|^2 + 4|V|^2}.$$

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

QUANTUM LITHOGRAPHY RESEARCH

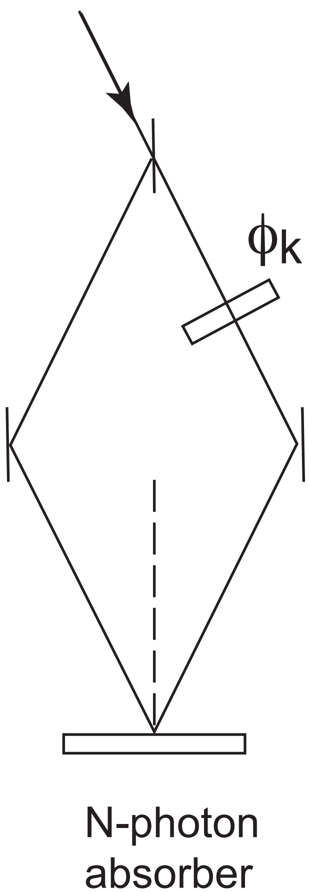
Experimental Layout

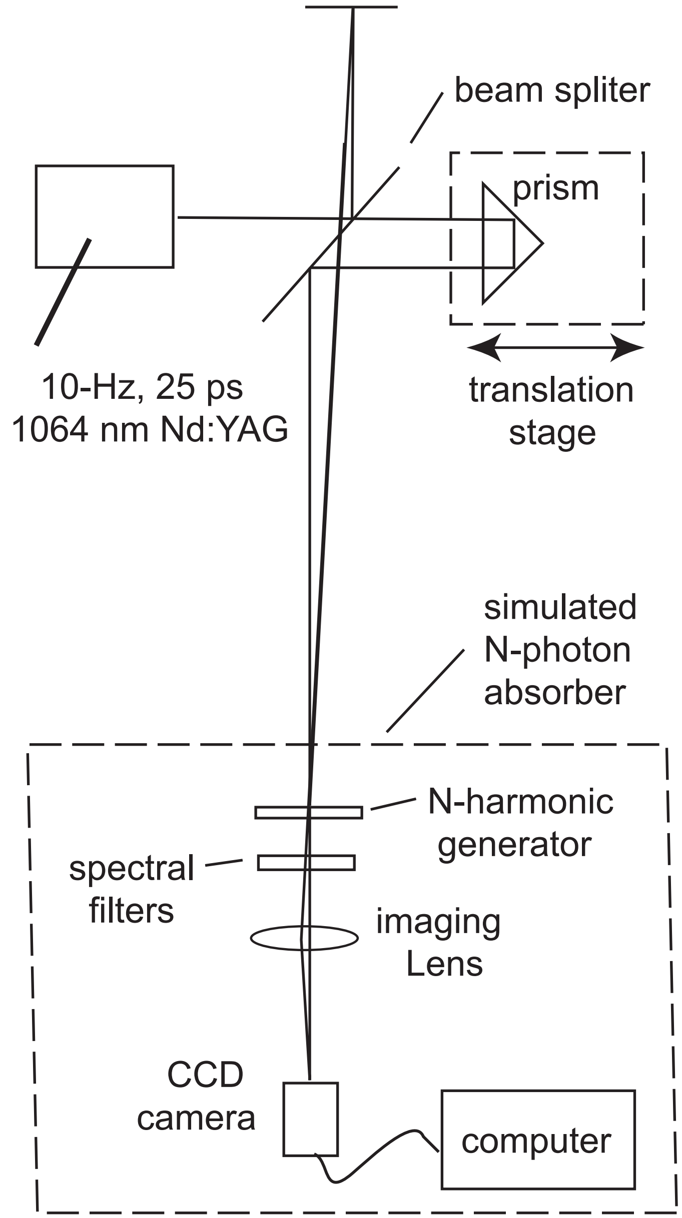




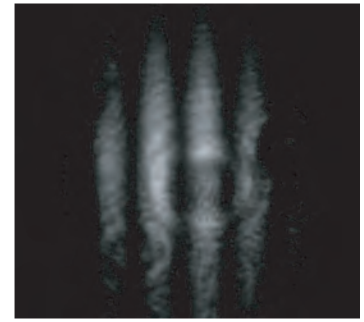
Classically Simulated (Non-Quantum) Quantum Lithography

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

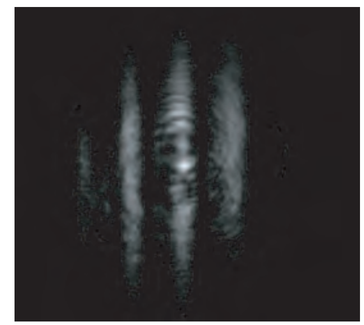




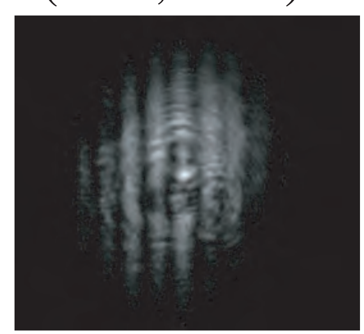
One-photon absorber (N=1, M=1)



Two-photon absorber (N=2, M=1)

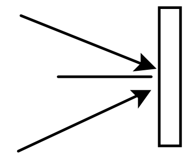


Two-photon absorber two exposures (N=2, M=2)



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

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

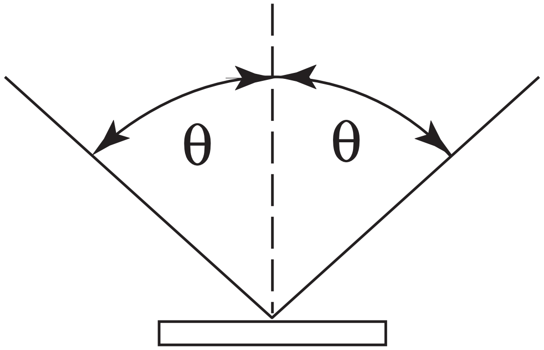
$$= 3/2 + 2 \cos kx + (1/2) \cos 2kx$$

- Two-photon absorbing medium, entangled photons

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

where k = 2(/c) sin

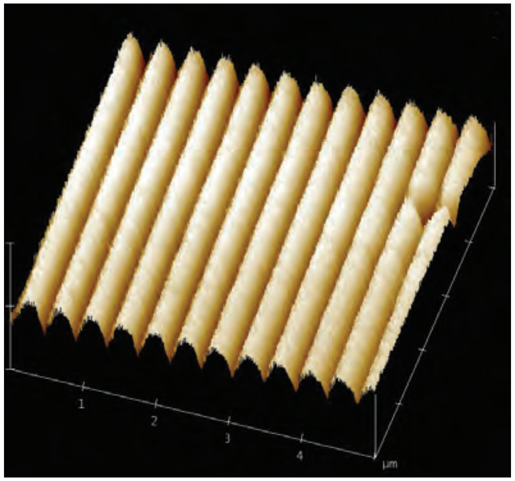
Demonstration of Fringes Written into PMMA



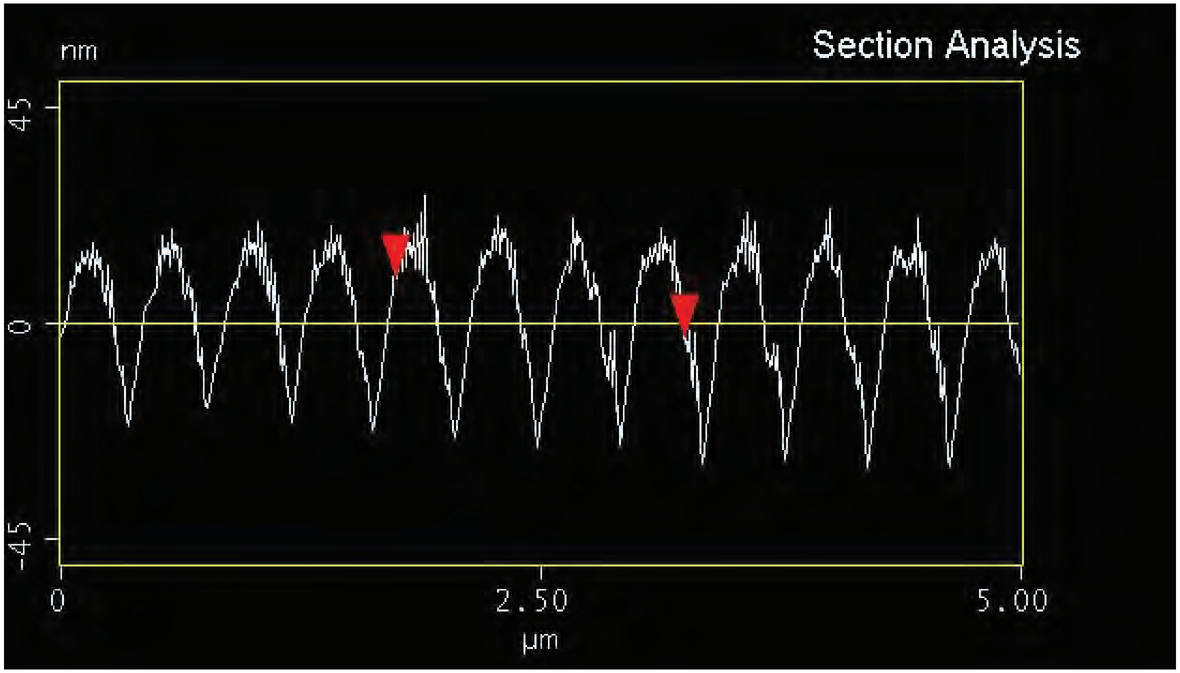
N-photon absorber
(N = 3 ?)

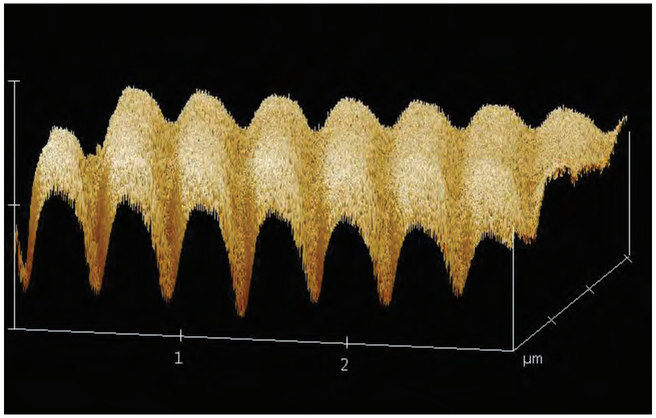
θ = 70 degrees
write wavelength = 800 nm
pulse energy = 130 μJ per beam
pulse duration = 120 fs
period = λ / (2 sin θ) = 425 nm

PMMA on glass substrate
develop for 10 sec in MBIK
rinse 30 sec in deionized water



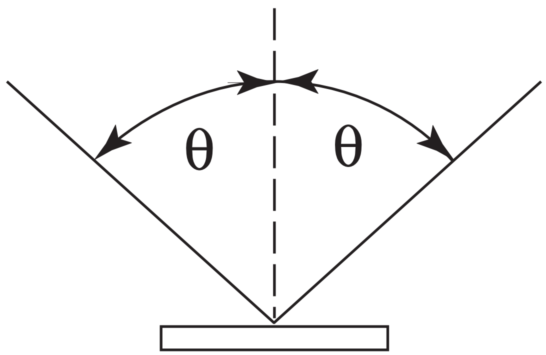
AFM



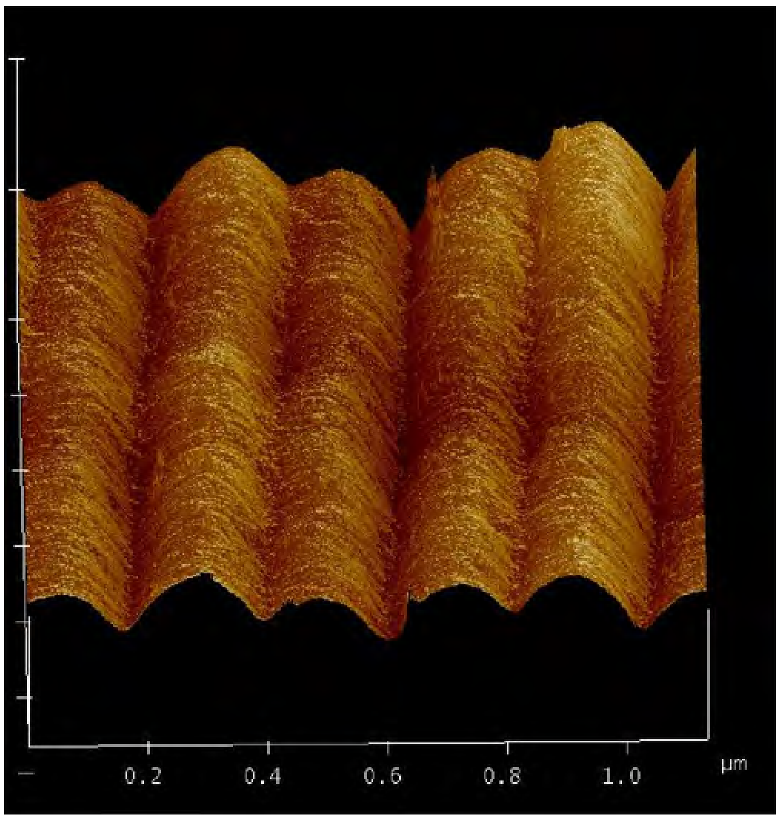


PMMA is a standard lithographic material

Demonstration of Sub-Rayleigh Fringes (Period = $\lambda/4$)

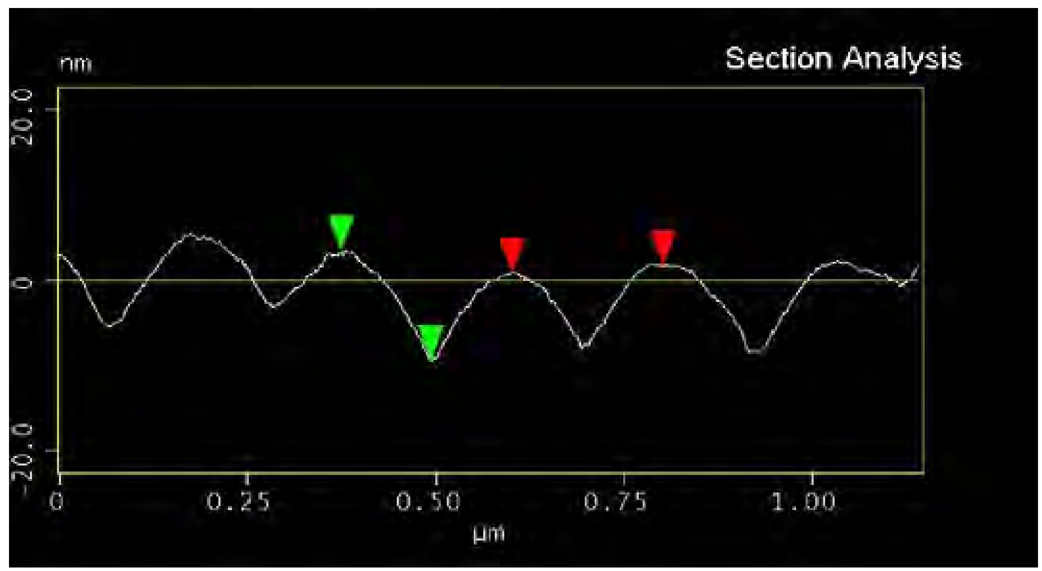


N-photon absorber



θ = 70 degrees
two pulses with 180 deg phase shift
write wavelength = 800 nm
pulse energy = 90 μJ per beam
fundamental period = λ / (2 sin θ) = 425 nm
period of written grating = 212 nm

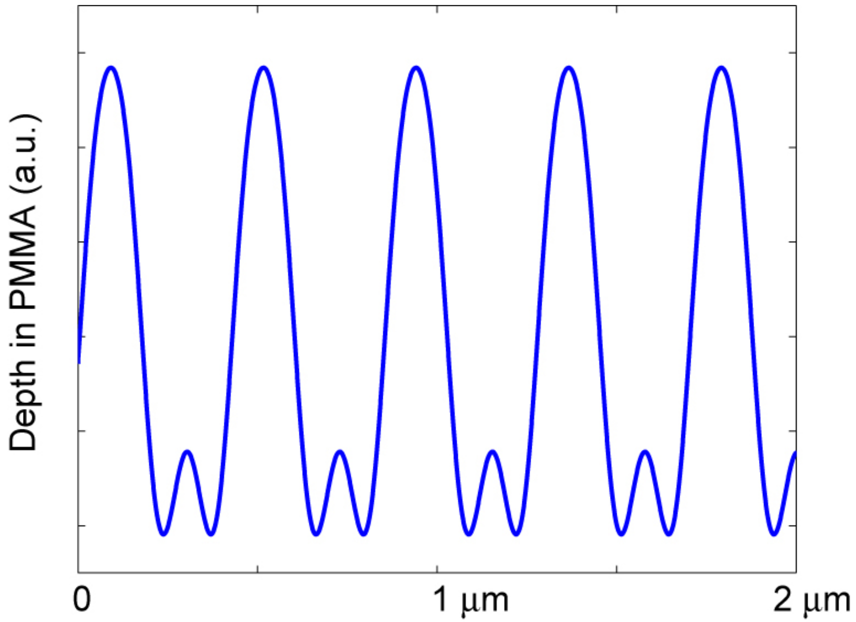
PMMA on glass substrate
develop for 10 sec in MBIK
rinse 30 sec in deionized water

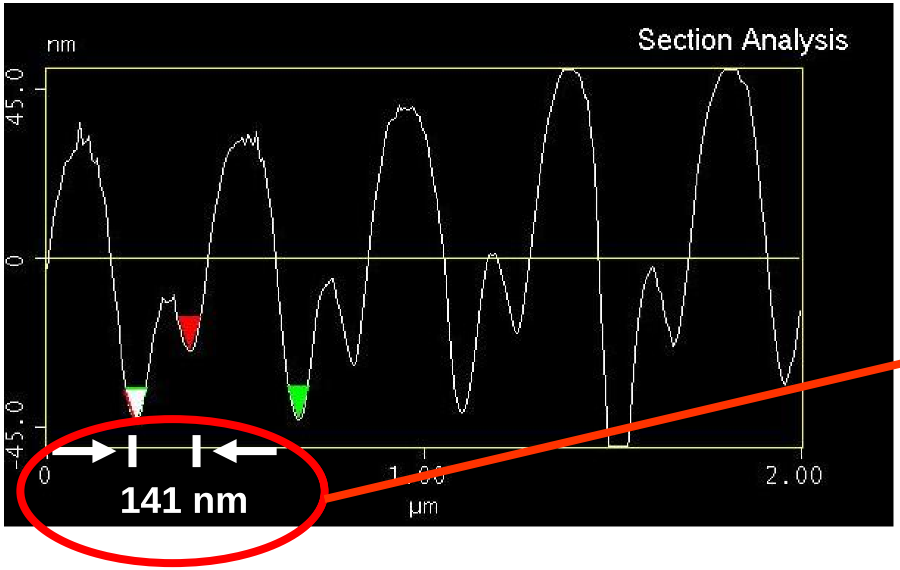


Further Enhancement?

PMMA is at least a 3PA @ 800 nm, so further enhancement should be possible.

- Illuminate with two pulses with a $2\pi/3$ phase-shift.





1/6 the recording wavelength!

The Institute of Optics
Nonlinear Optics
University of Rochester

Significance of PMMA Grating Results

- Provides an actual demonstration of sub-Rayleigh resolution by the phase-shifted grating method
- Demonstrates an N-photon absorber with adequate resolution to be of use in true quantum lithography

Summary

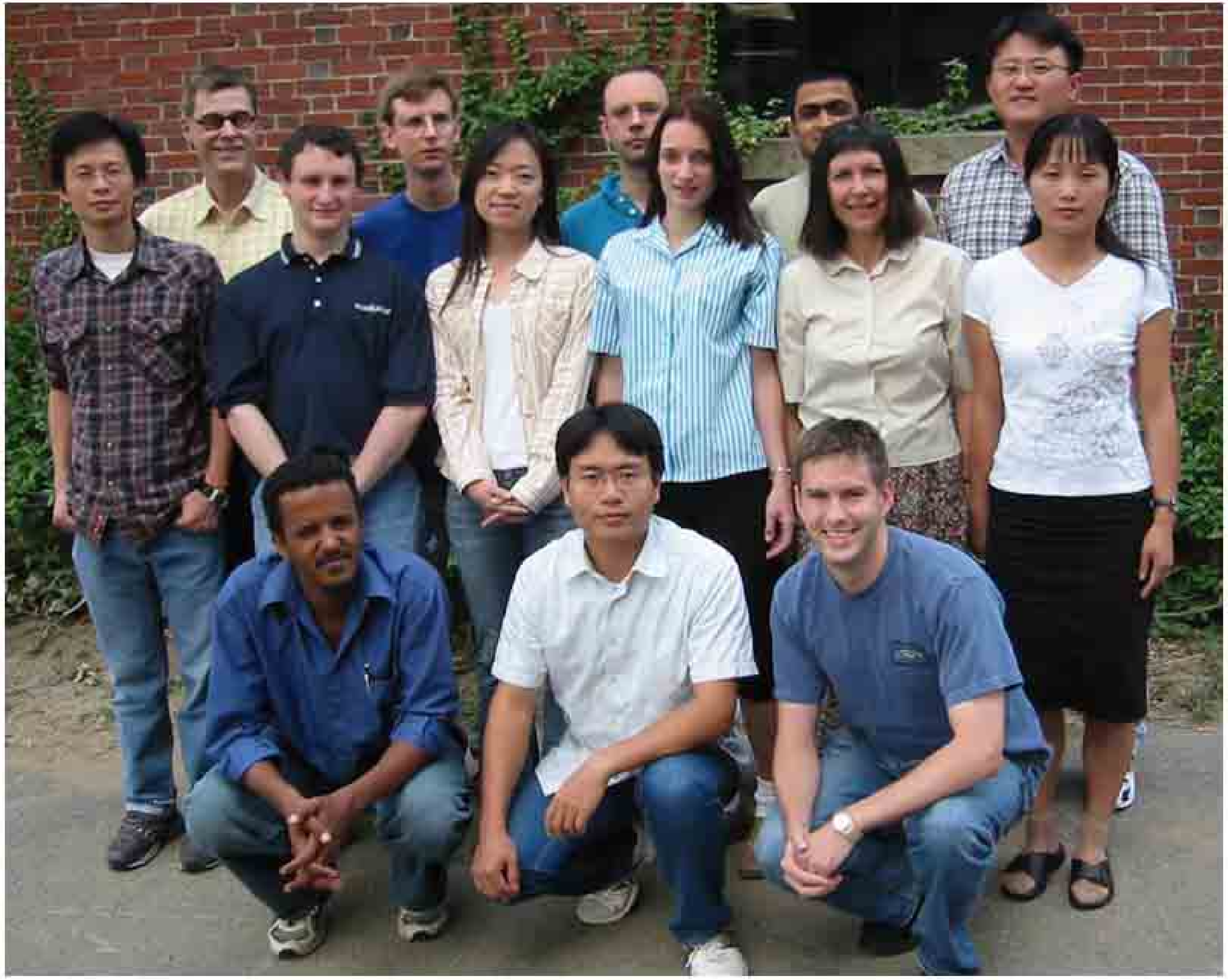
Quantum lithography has a good chance of becoming a reality.

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!

Physics is all about asking the right questions

Just ask

Evelyn **Hu**

Watt Webb (or James **Watt**)

Michael **Ware**

Wen I Wang

Kam **Wai** Chan

Not to mention

Lene **Hau**