# 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

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# Quantum Lithography

Robert Boyd, Sean Bentley*, Hye-Jeong Chang, Heedeuk Shin,
Malcolm O'Sullivan-Hale and Kam Wai Chan

Institute of Optics, University of Rochester, Rochester, NY
*Department of Physics, Adelphi University, Garden City, NY

Girish Agarwal

Department of Physics, Oklahoma State University, Stillwater, OK

Hugo Cable, Jonathan Dowling

Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA

Presented at SPIE, August 14th, 2006

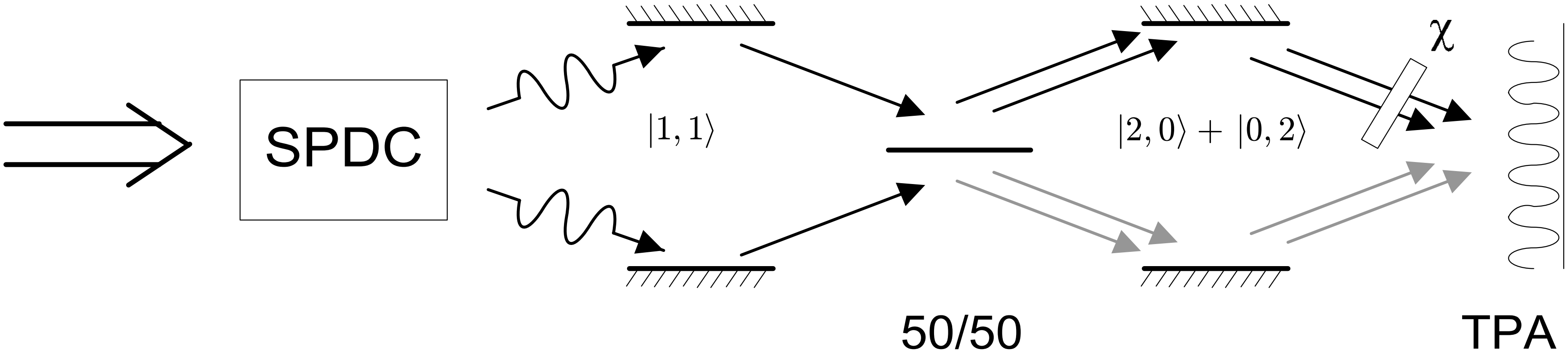
# Demonstration of Sub-Rayleigh Lithography Using a Multi-Photon Absorber

Heedeuk Shin, Hye Jeong Chang*, Malcolm N. O'Sullivan-Hale,
Sean Bentley# , and Robert W. Boyd

The Institute of Optics, University of Rochester, Rochester, NY 14627, USA
* The Korean Intellectual Property Office, DaeJeon 302-791, Korea
# Department of Physics, Adelphi University, Garden City, NY

Presented at OSA annual meeting, October 11th, 2006

# Original Quantum Lithography Proposal



- Entangled photons produced in SPDC can increase resolution of an interferometric lithography system by factor of 2 (Boto et al., 2000)

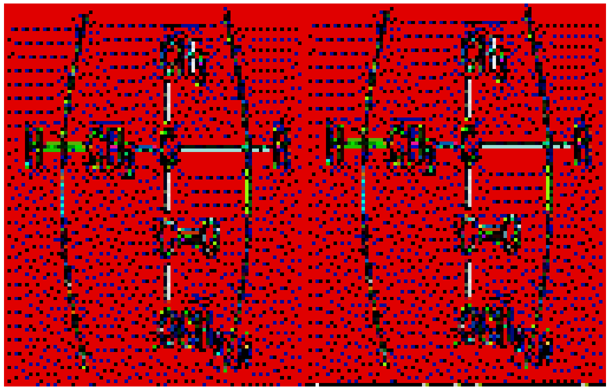
- *N*-fold enhancement possible when *N* photons are entangled

Boto et al., PRL **85**, 2733 (2000)

# Experimental Challenges

- What quantum state of light to use?
  - Need *strong* enough light to excite two-photon absorption
  - Need *weak* enough light so that the statistics are those of individual photon pairs

- Develop a multi-photon absorber
  - *N*th harmonic generation/coincidence circuitry
  - Polymethylmethacrylate (PMMA)
    - Multi-photon absorber at visible wavelengths
    - e-beam resist



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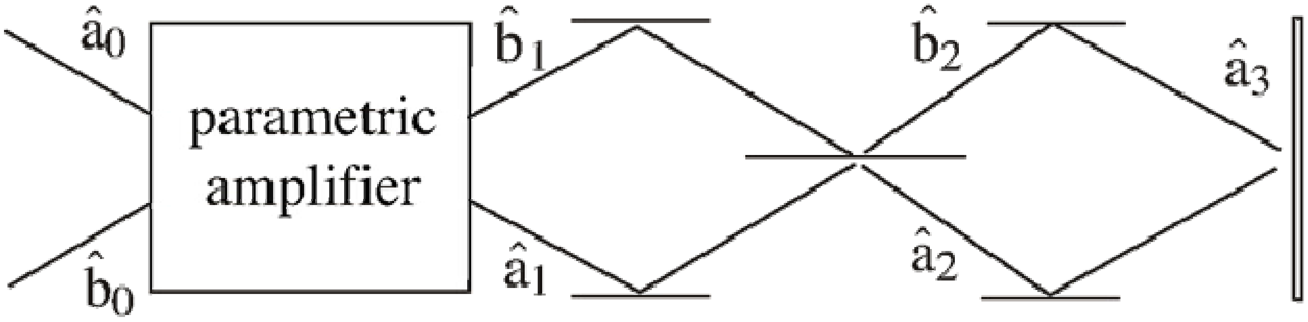
# Quantum Lithography with an OPA

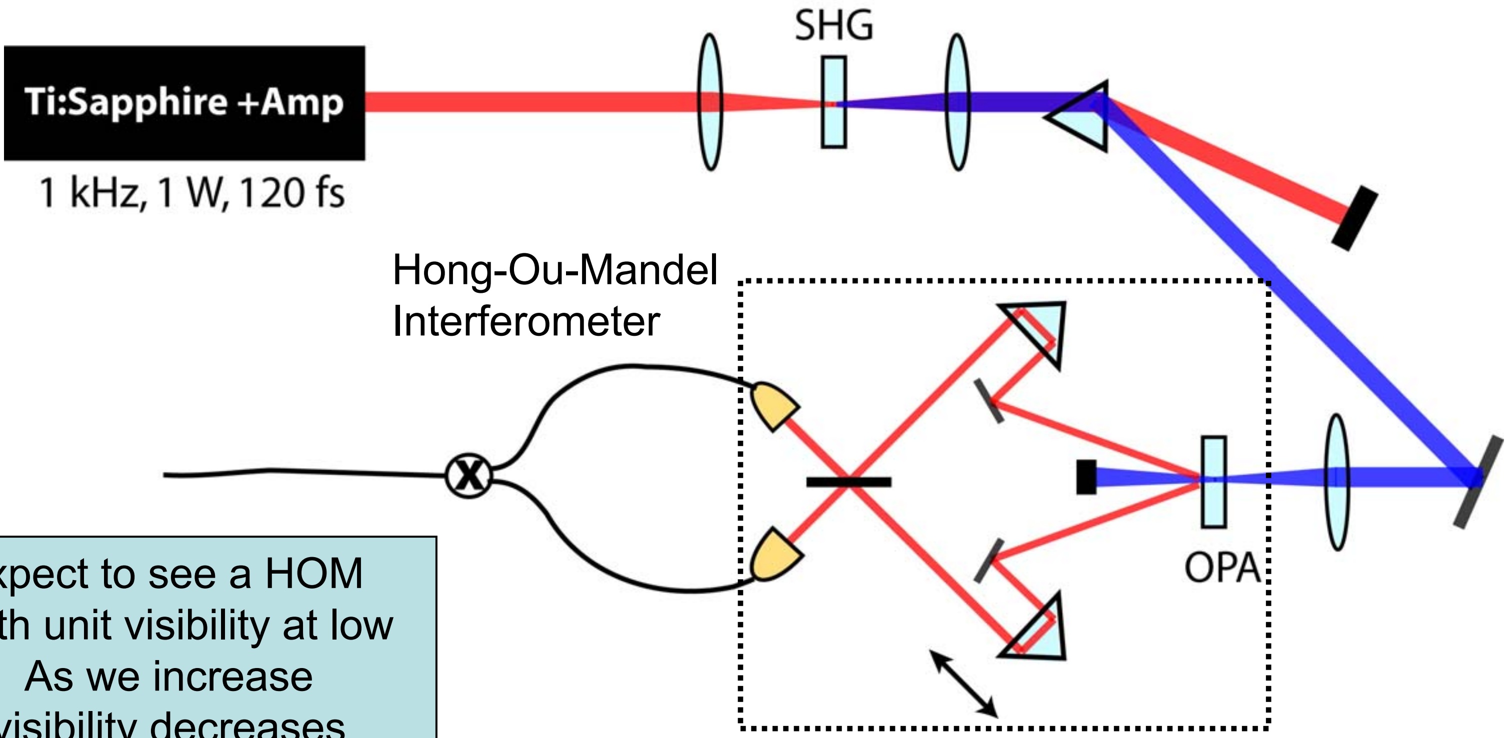
- Replace parametric down-converter with high gain optical parametric amplifier (OPA)
  - Can be very intense
  - Possesses strong quantum features



Agarwal, Boyd, Nagasko, Bentley, PRL **86**, 1389 (2001)

# Experimental Setup

Experiment to realize *NOON* (*N*=2) state for quantum lithography



We expect to see a HOM dip with unit visibility at low gains. As we increase gain, visibility decreases but does not vanish.

**Problem:** Scattering from pump laser saturates detection with APDs → Need to shield beam path.

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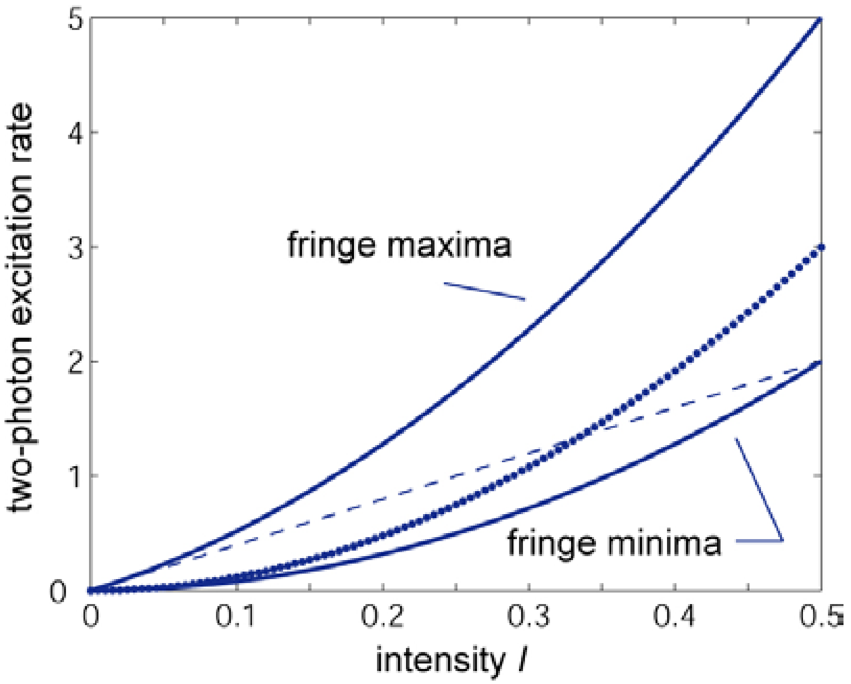
# Two-Photon Excitation Rate



- For light from an OPA, both linear and quadratic dependence are present.

- Cross-over point:

$$I = \frac{1}{3} \text{ photons/mode}$$

$$G = 0.55$$

For cases of practical interest, the rate scales quadratically with $I$.

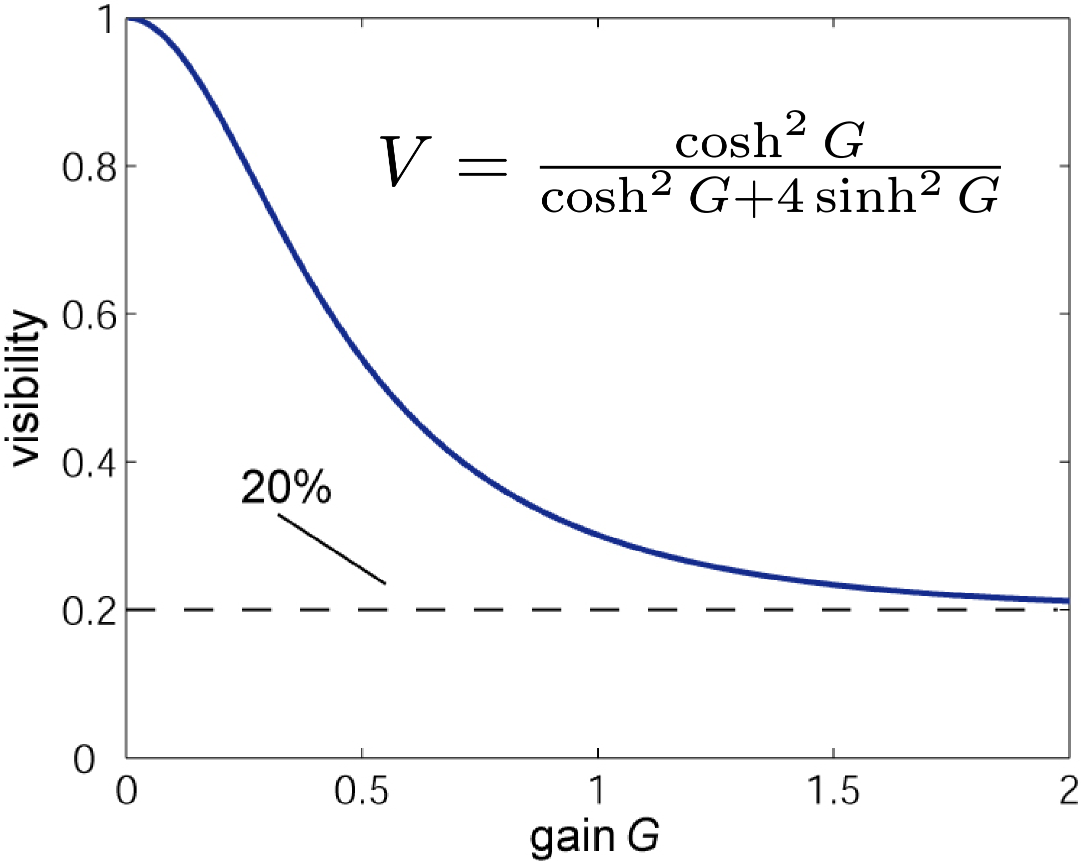
Accepted for publication in JOSA B

# Visibility using an OPA and TPA

## Visibility versus Gain

$$V = \frac{R^{(2)}_{max} - R^{(2)}_{min}}{R^{(2)}_{max} + R^{(2)}_{min}}$$

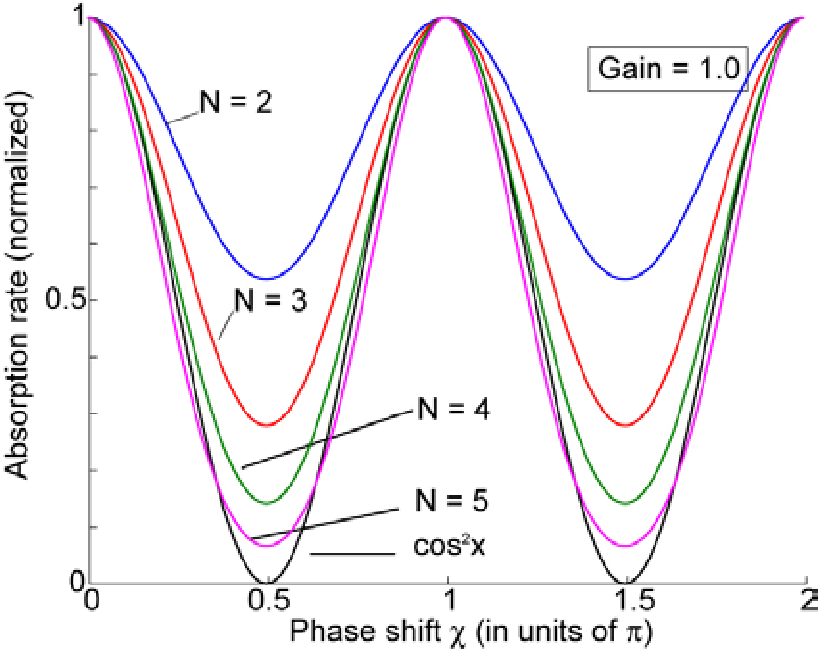
Visibility never falls below 20%

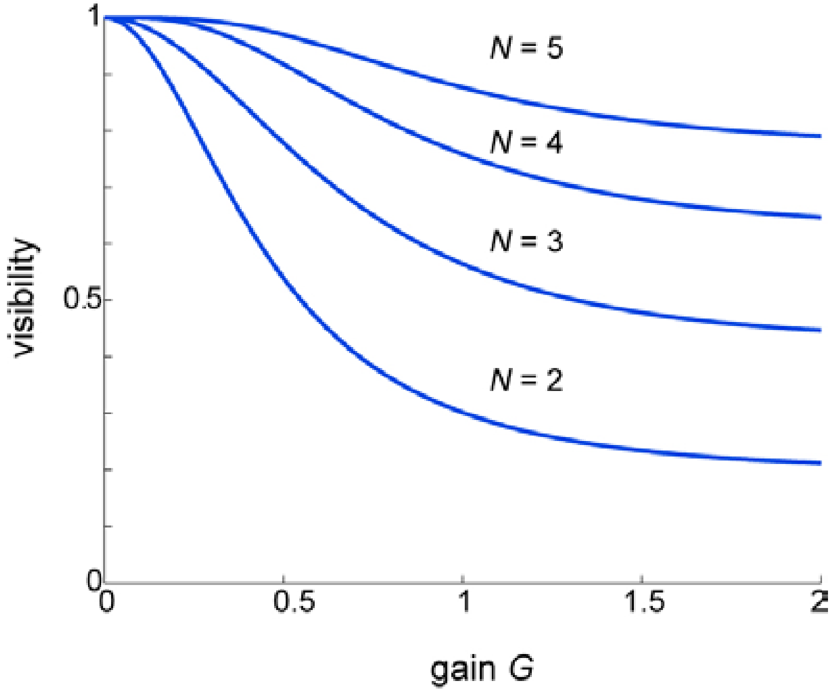


$$V = \frac{\cosh^2 G}{\cosh^2 G + 4\sinh^2 G}$$

# Effect of an *N*-Photon Absorber

(But still for a two-photon entangled state)





- As *N* increases the visibility improves, but there is no improvement in resolution.

Accepted for publication in JOSA B

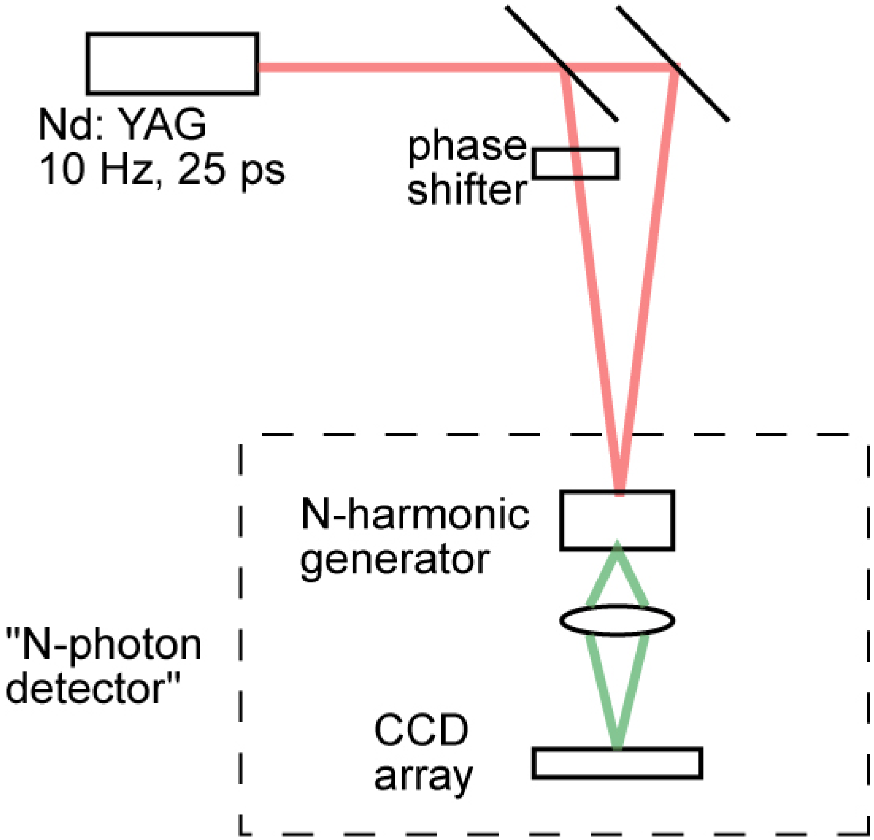
# Summary of OPA Results

- For most cases, two-photon excitation rate scales as $I^2$.
- OPA + TPA produces fringes with visibility greater than 20%
- OPA + *N*-photon absorber produces fringes with even greater visibility (but with no greater resolution)

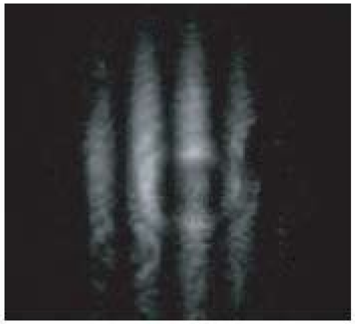
# Classically Simulated Quantum Lithography

## Proof-of-Principle Experiment

Bentley and Boyd, Opt. Exp. **12,** 5735 (2004)

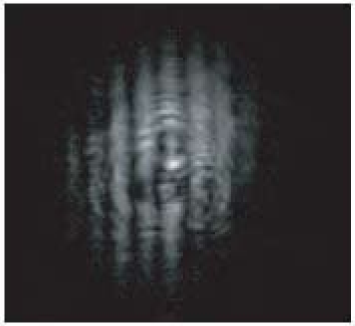


One-photon detector



Two-photon detector and one laser pulse

Two-photon detector and two pulses with phase shift



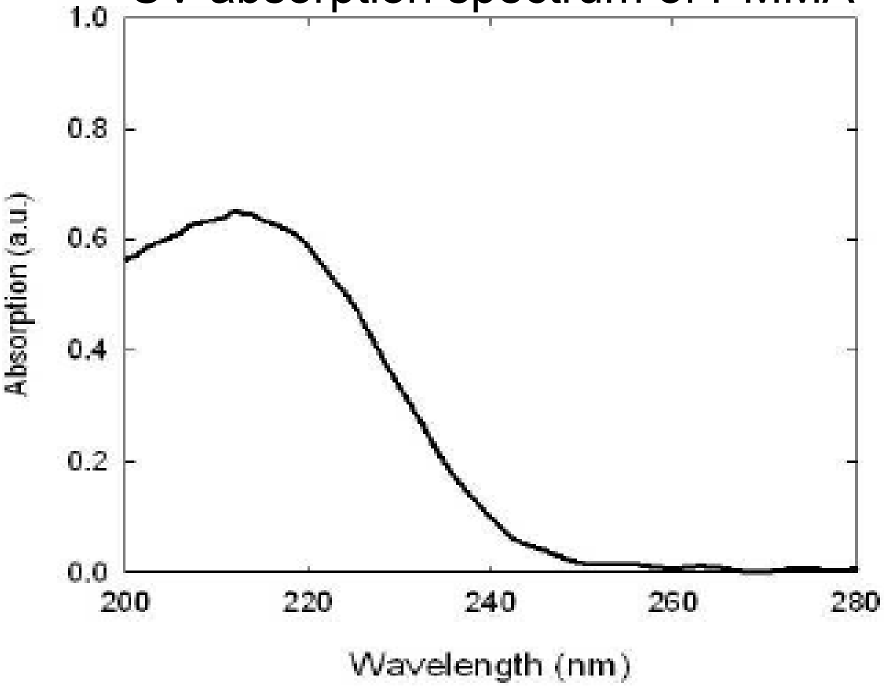
- Use classically simulated quantum lithography to develop an *N*-photon recording material

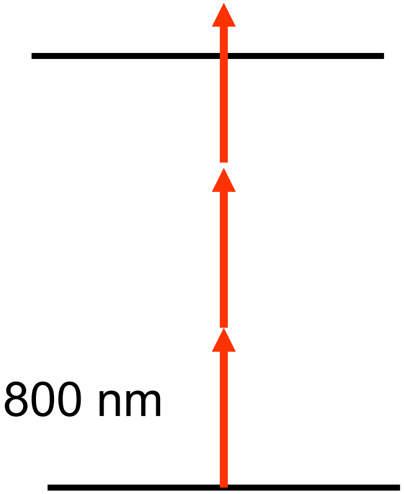
# PMMA

- Polymethylmethacrylate (PMMA) is a positive photo-resist that is transparent in the visible region.

- 3PA @ 800 nm can break chemical bonds, and the affected regions can be removed in the development process.

UV absorption spectrum of PMMA





PMMA is 3-photon absorber @ 800 nm.

*Problem*: Self-healing means multiple bonds must be broken.

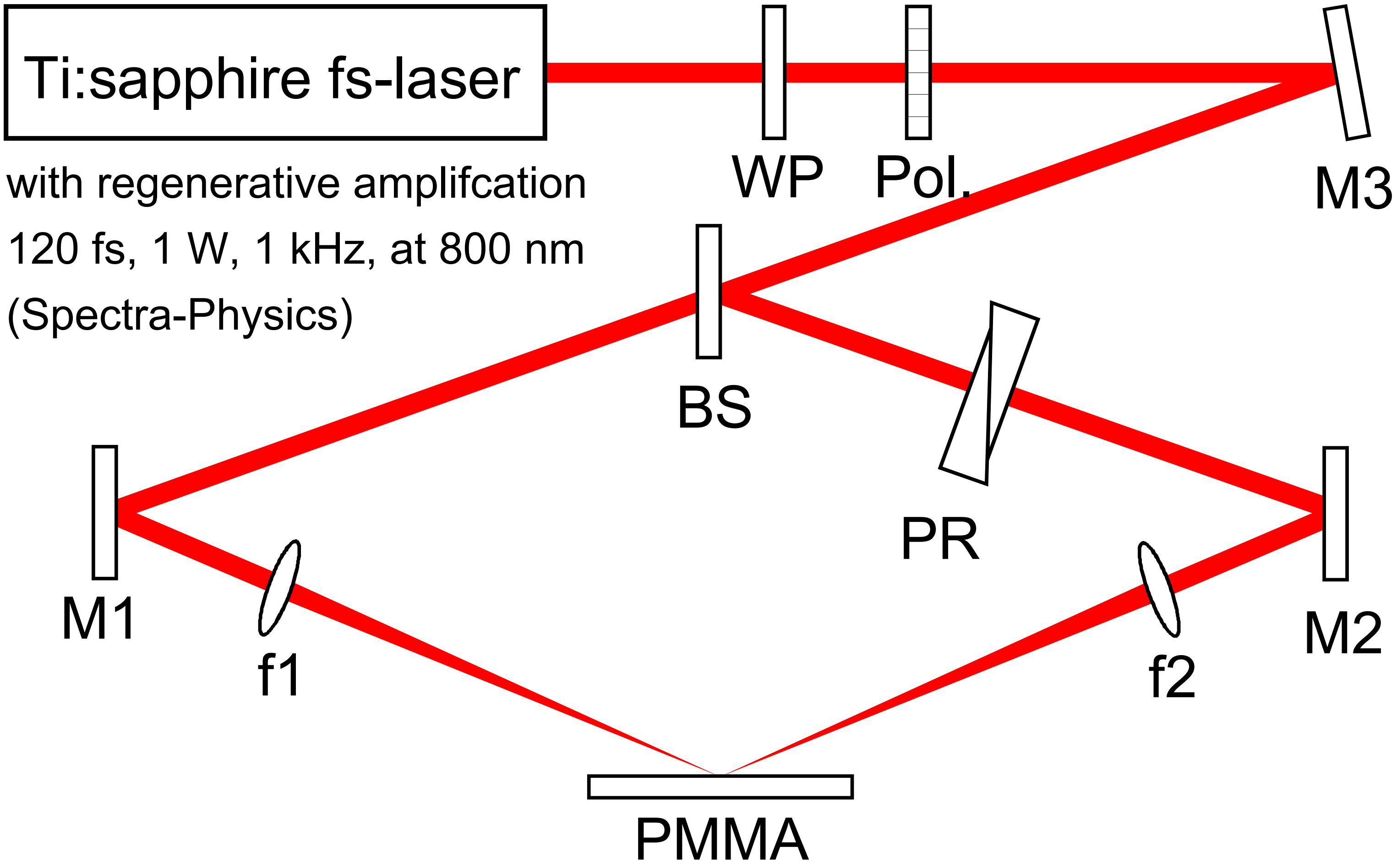
# PMMA Preparation

- Sample
  - PMMA (120,000 MW) + Toluene Solution (20% solids by weight)
  - PMMA is spin-coated on a glass substrate
    - spin-coated @ 1000 rpm, 20 sec
    - dried for 3 min
    - repeated 3 times

    → 1-μm-thick film

- Development
  - Developer: 10 sec in 1:1 methyl isobutyl ketone (MIBK) to isopropyl alcohol
  - Rinse:  10 sec in DI water
  - Air blow dried

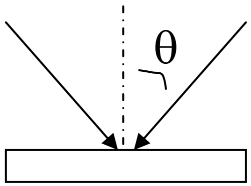
# Experimental Setup



with regenerative amplifcation
120 fs, 1 W, 1 kHz, at 800 nm
(Spectra-Physics)

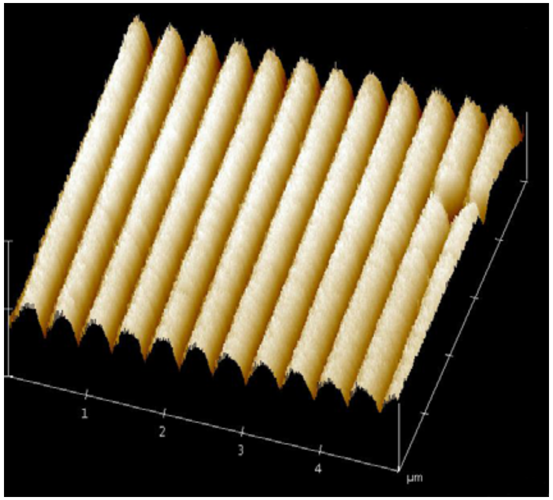
WP: half-wave plate; Pol.: polarizer; M1,M2,M3: mirrors; BS: beamsplitter; f1,f2: lenses; PR: phase retarder (Babinet-Soleil compensator)

# Fringes on PMMA



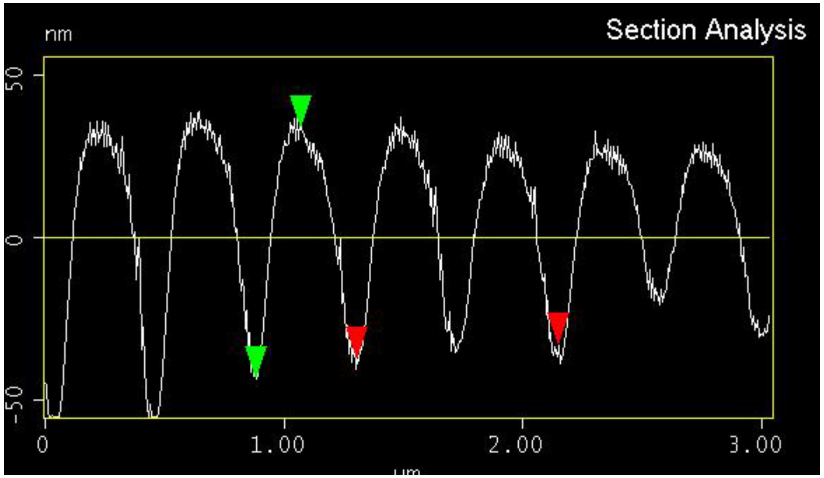
| | |
|---|---|
| Recording wavelength: | 800 nm |
| Pulse energy: | 130 μJ/beam |
| Pulse duration: | 120 fs |
| Recording Angle θ: | 70° |

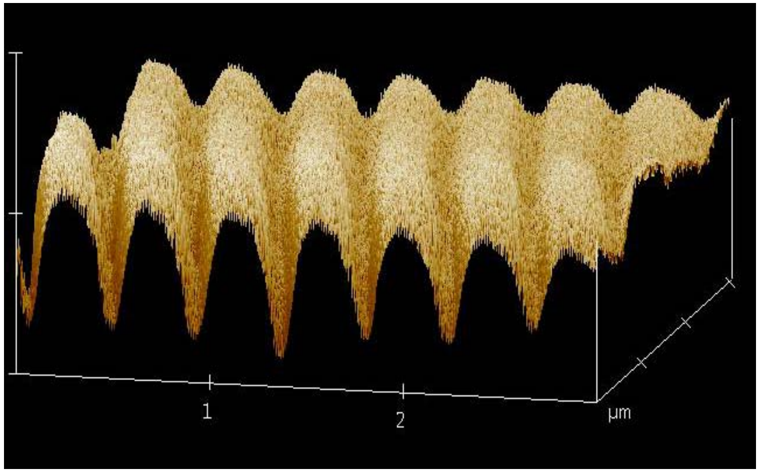
**Period: 425 nm**



AFM images of PMMA surface

## Surface Cross-Section





SPIE: Aug. 14th, 2006

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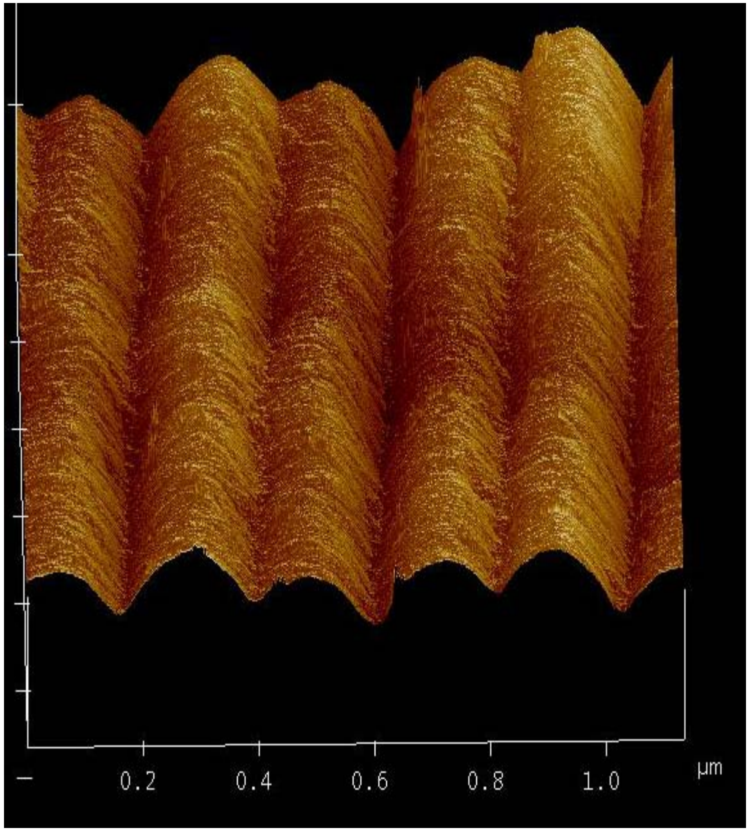
# Sub-Rayleigh Fringes on PMMA

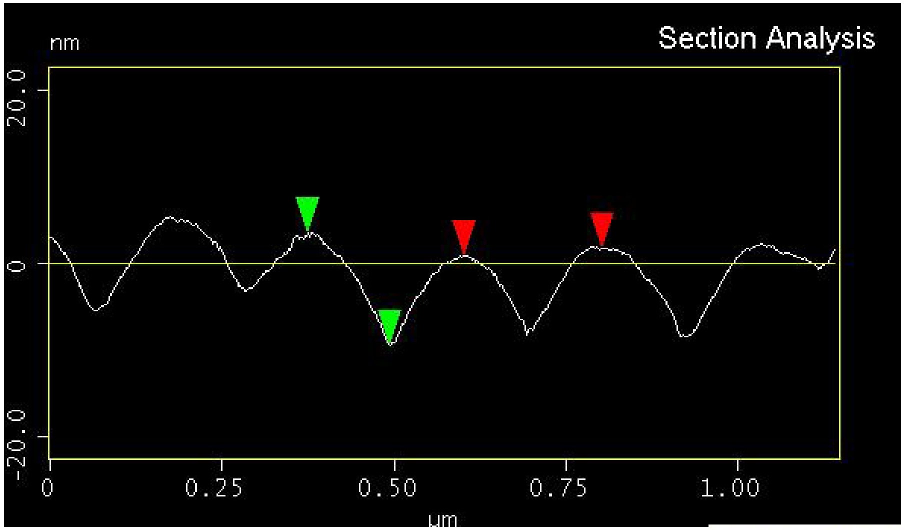


AFM image of PMMA surface

**Two pulses with π phase-shift**

| | |
|---|---|
| Recording wavelength: | 800 nm |
| Pulse energy: | 90 μJ/beam |
| Pulse duration: | 120 fs |
| Recording Angle θ: | 70° |

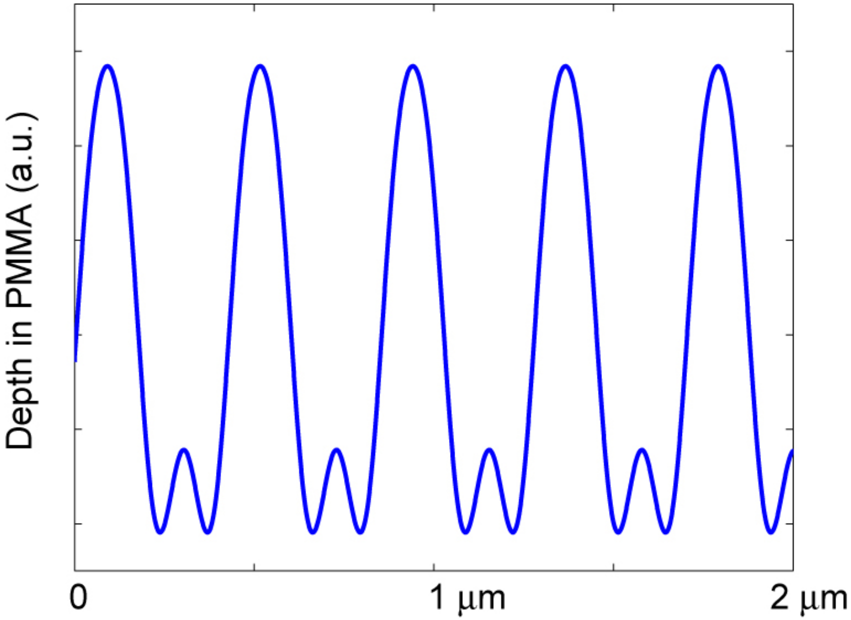
**Period: 213 nm**

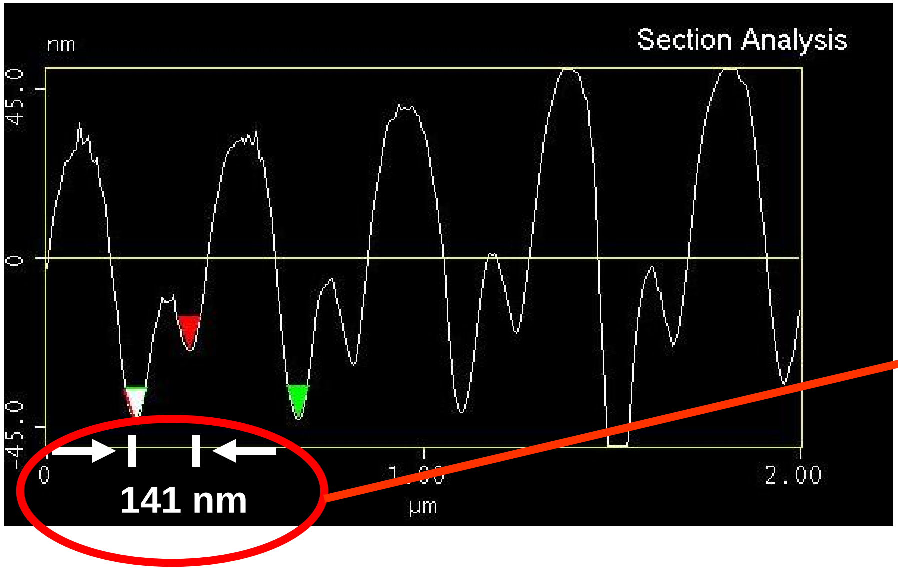


# Further Enhancement?

PMMA is 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!

# Importance of PMMA Result

- Demonstrates sub-Rayleigh resolution on a real material using the phase-shifted grating method.

- Shows that PMMA is an *N*-photon absorber with adequate resolution for use in true quantum lithography.

- But we are looking into other materials that can provide greater sensitivity.

# Non-sinusoidal Patterns

- In principle, Fourier’s Theorem can be applied to generate arbitrary patterns.
  - Can only remove material
  - Visibility???

- Alternatively, we can generalize method…

$$E_{N,M} = \sum_{k=1}^{M} I_k^N$$

where

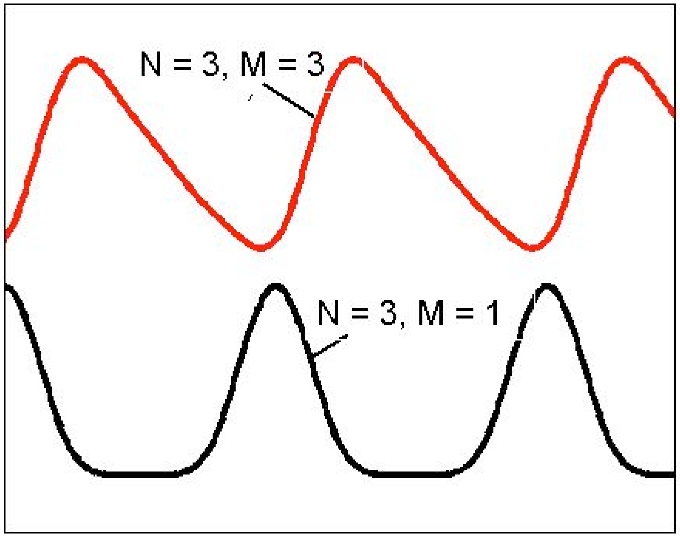
$$I = \left|1 + A_k e^{i\chi} e^{i2\pi k/M}\right|^2$$

New term: Allow different amplitudes on each shot

# Non-Sinusoidal Patterns - Theory

- Different field amplitudes on each shot can generate more general non-sinusoidal patterns.

$$I = \sum_{m=1}^{M} A_m [1 + \cos(Kx + \Delta_m)]^N$$



For example, if N = 3 , M = 3

$A_1 = 1$ $\quad\Delta_1 = 0$

$A_2 = 0.75$ $\quad\Delta_2 = \pi/2$

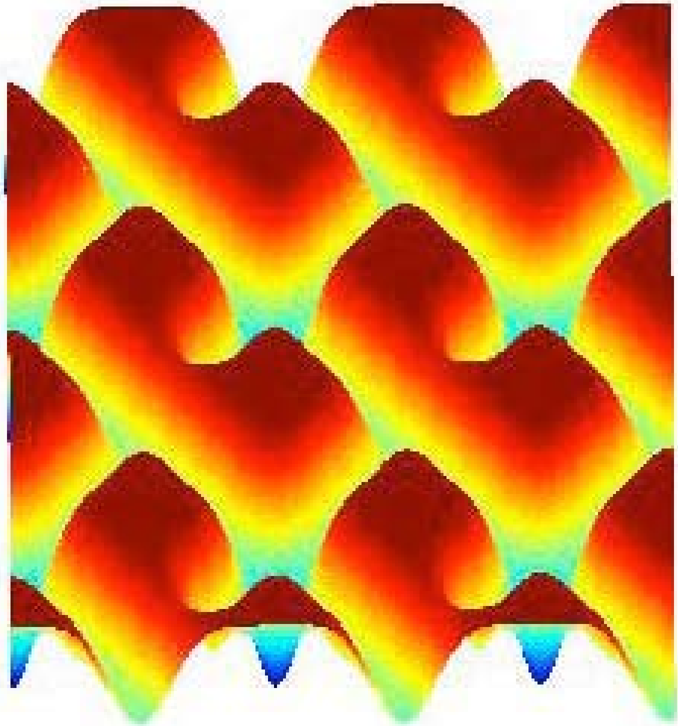
$A_3 = 0.4$ $\quad\Delta_3 = \pi$

# Two-Dimensional Patterns - Theory

- Method can be extended into two dimensions using four recording beams.

$$Pattern = thickness - \sum_{mx,my=1}^{M} A_{mx}[1+\cos(Kx+\Delta_{mx})]^{N} A_{my}[1+\cos(Ky+\Delta_{my})]^{N}$$

For example,
$N$=8, $M$=14



With S. Bentley, Adelphi University

# Conclusions

- PMMA is a suitable multi-photon absorbing material for use in quantum lithography
- Demonstrated sub-Rayleigh ($\lambda/4$) resolution using NL lithography

## Ongoing research

- Construct an intense light source based on high-gain optical parametric amplification
- Demonstrate quantum lithography

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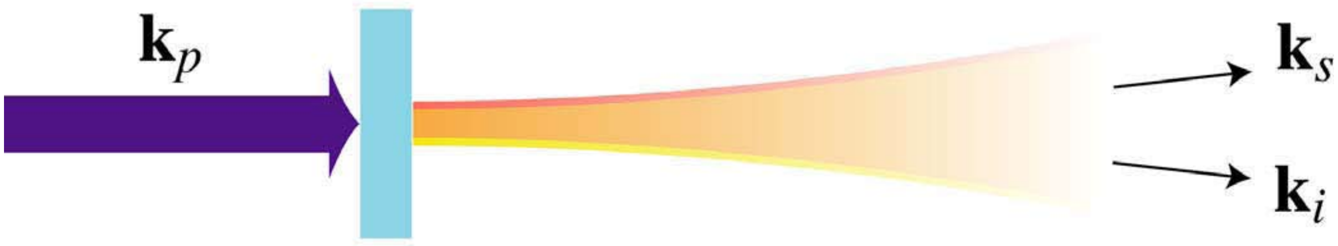
# Entanglement Propagation in Photon Pairs created by SPDC

Malcolm O'Sullivan-Hale, Kam Wai Chan, and Robert W. Boyd

Institute of Optics, University of Rochester, Rochester, NY

Presented at OSA Annual Meeting, October 10th, 2006

# Motivation



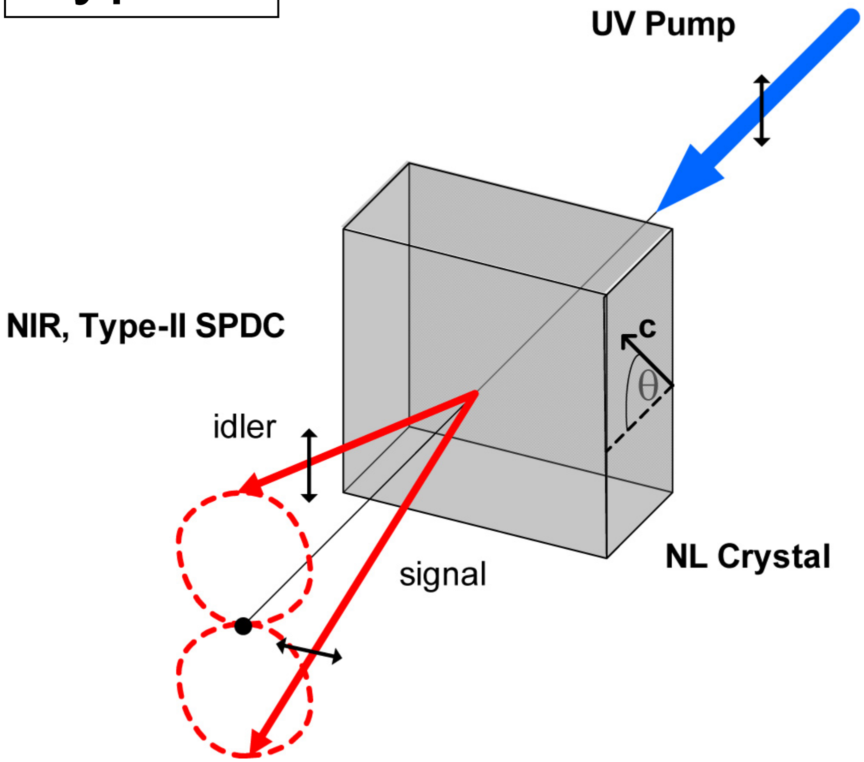
Entangled position and momentum spaces in SPDC involve high dimensional Hilbert spaces.

Questions:

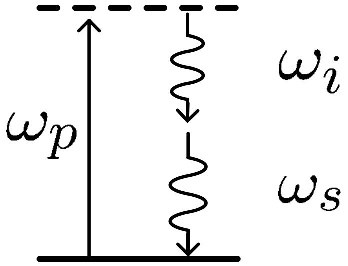
- Effects of free-space propagation on the spatial correlations between photons?
- Implications about the entanglement present in the system?
- How rapidly do these correlations degrade as a consequence of loss or propagation through turbulence?

# Spontaneous Parametric Down-Conversion

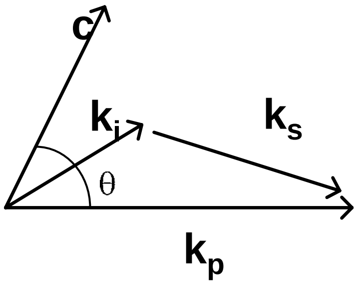
Type-II



$$\omega_p = \omega_s + \omega_i$$



$$\mathbf{k}_\mathbf{p}^{(e)} = \mathbf{k}_\mathbf{s}^{(o)} + \mathbf{k}_\mathbf{i}^{(e)}$$



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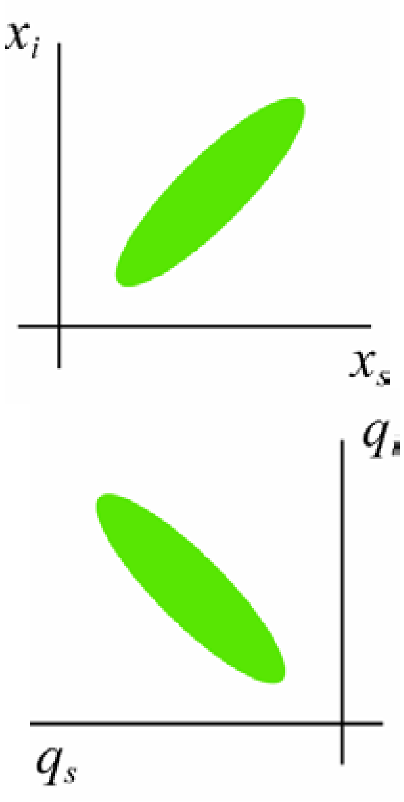
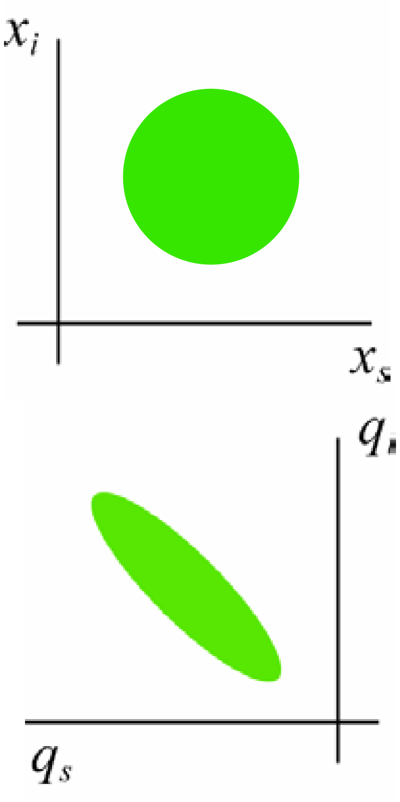
# Propagation of Correlations

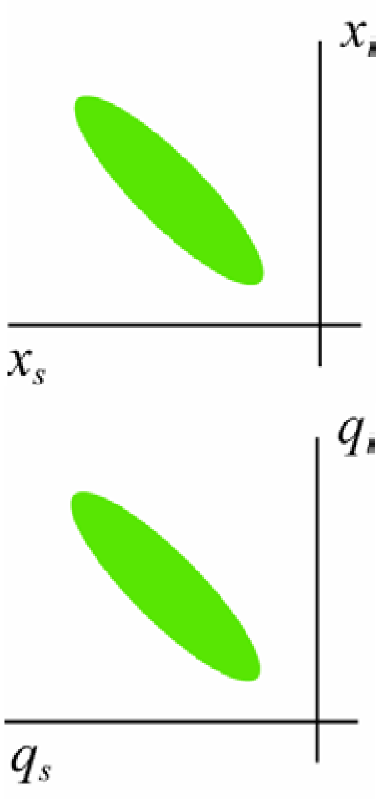
Near-field



Intermediate-field

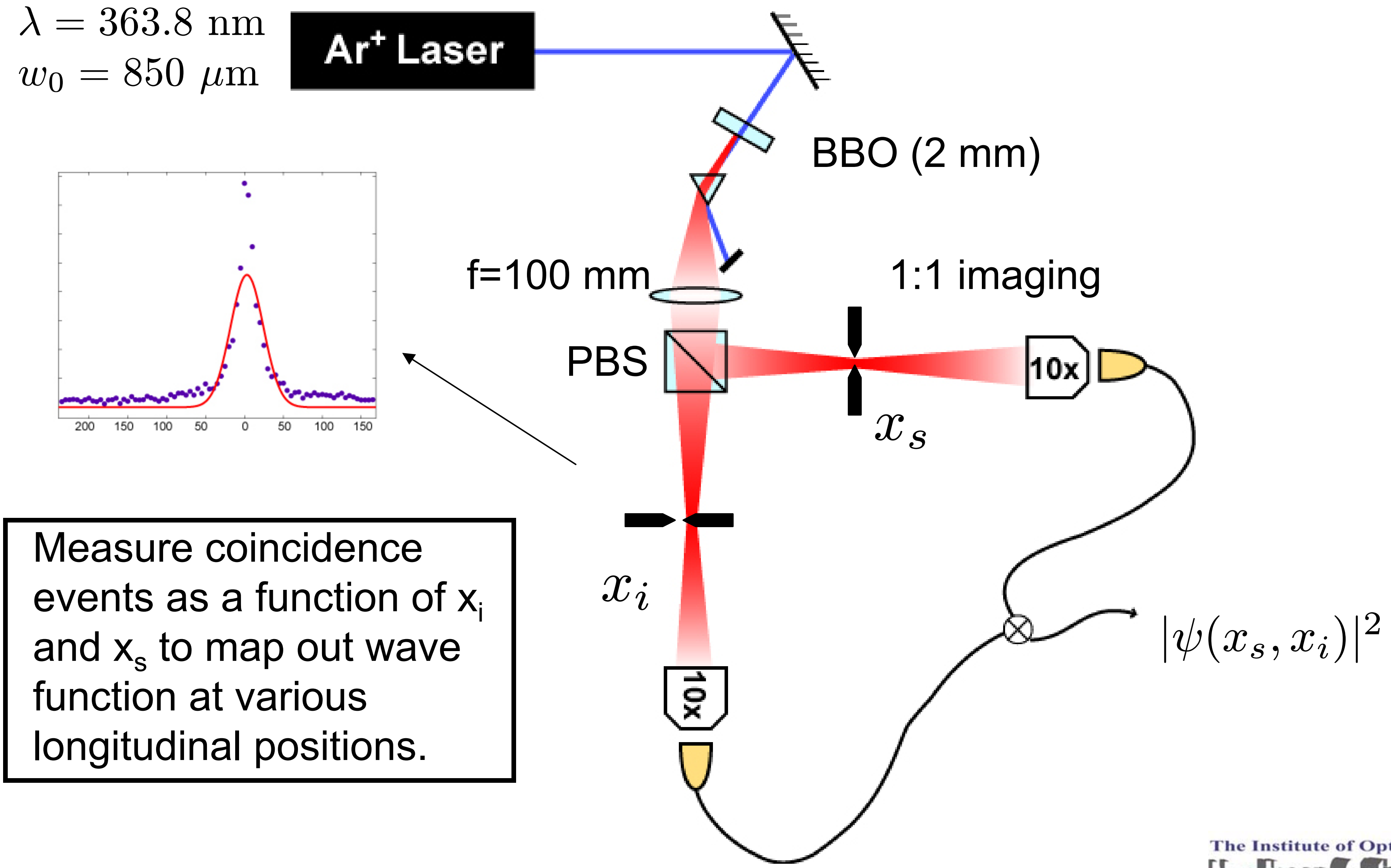


Far-field



Question: What is going on in the intermediate zone? Is entanglement "lost"?

# Experimental Set-up



Measure coincidence events as a function of $x_i$ and $x_s$ to map out wave function at various longitudinal positions.

OSA: Oct. 10th, 2006

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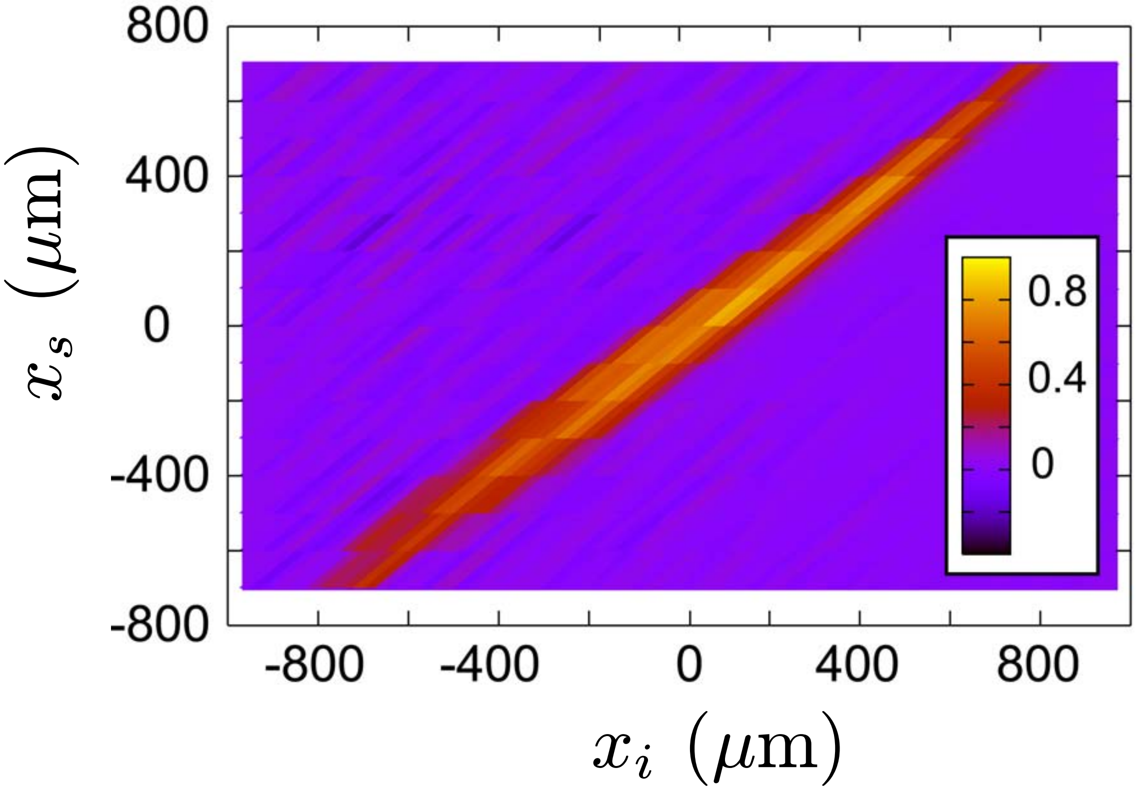
# Near-field Correlations

Normalized Coincidence Rates



- Slits/knife edge placed in the imaged plane of the crystal.
- Strongly correlated photon positions.
- $R_x = 9.61$

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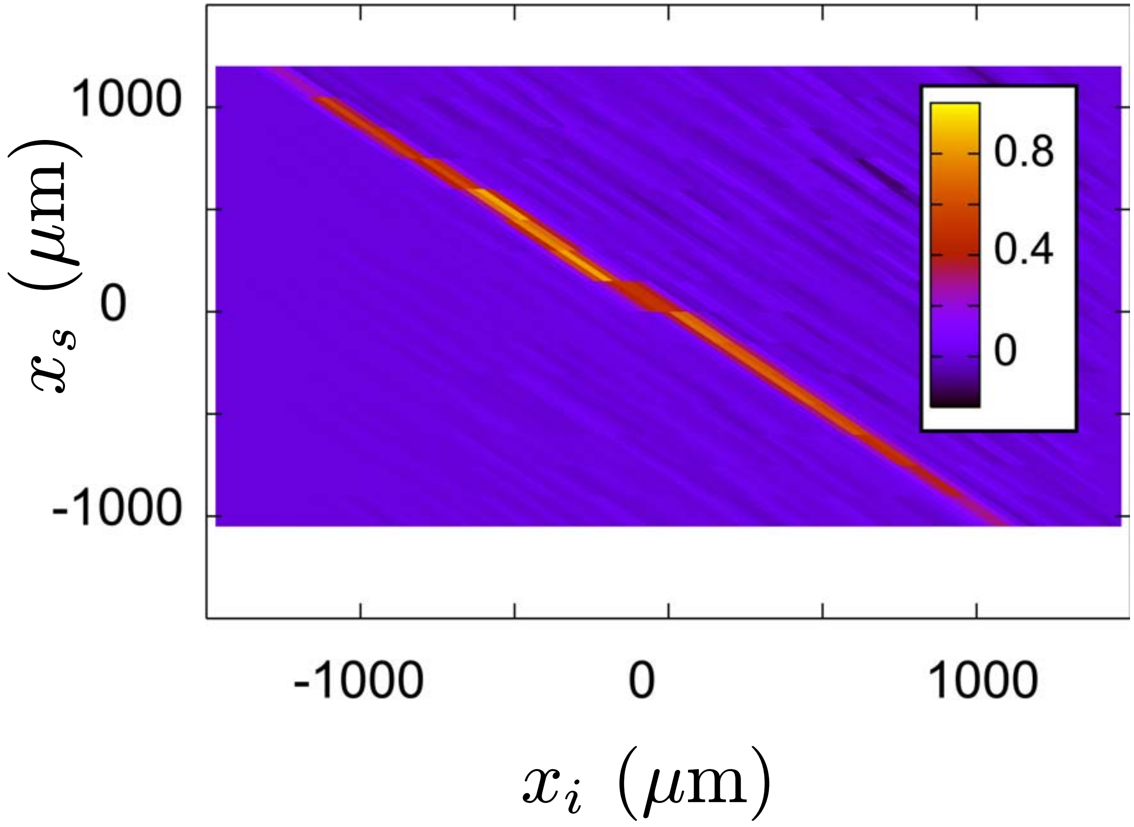
# Far-field Correlations

Normalized Coincidence Rates



- Slits/knife edge placed in the focal plane of the lens.
- Strongly anti-correlated photon positions.
- $R_x = 28.52$

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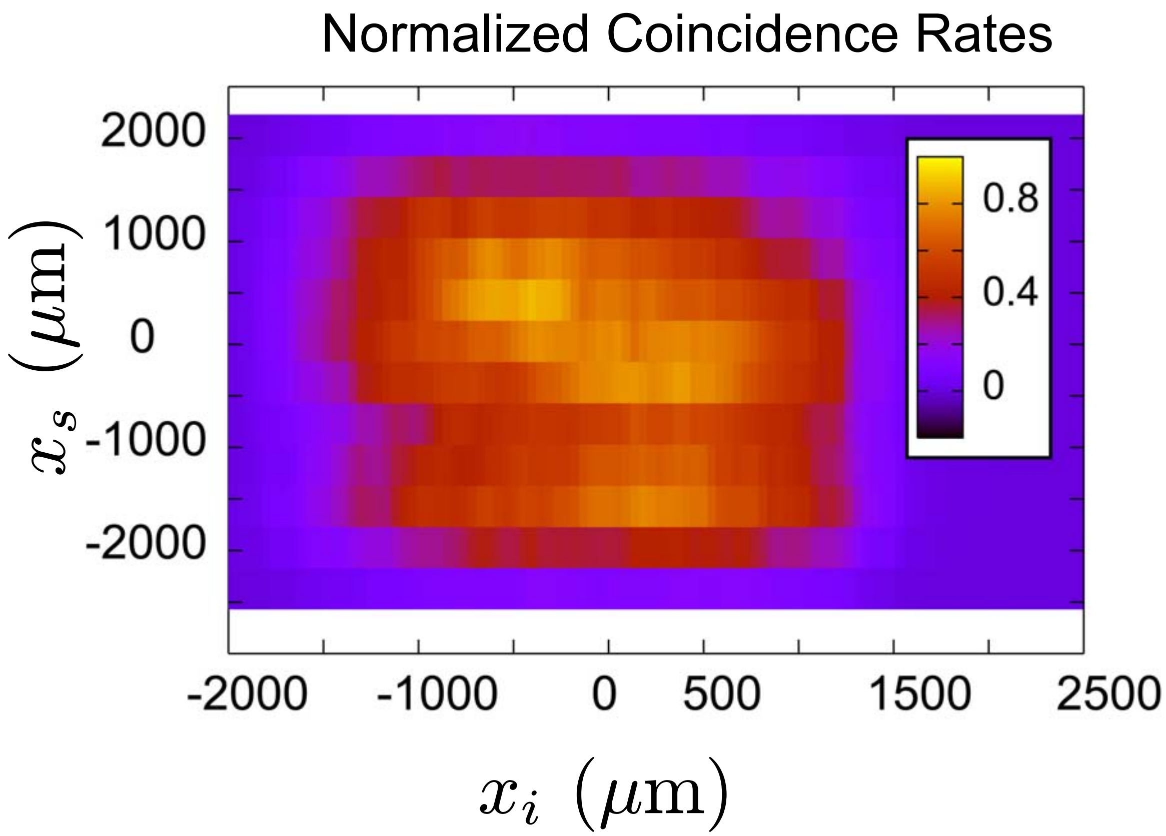
# The Intermediate Zone?



- Slits moved behind image plane
  (12 cm behind image plane or
  14.5 cm after crystal).
- Little residual spatial correlations.
- $R_x = 1.19$

# Migration of Entanglement to Phase

- At a particular propagation distance $z_0$ the amplitude-squared wave function will become separable, although the wave function itself is entangled, i.e.

$$|\psi(x_s, x_i)|^2 = f(x_s)g(x_i)$$

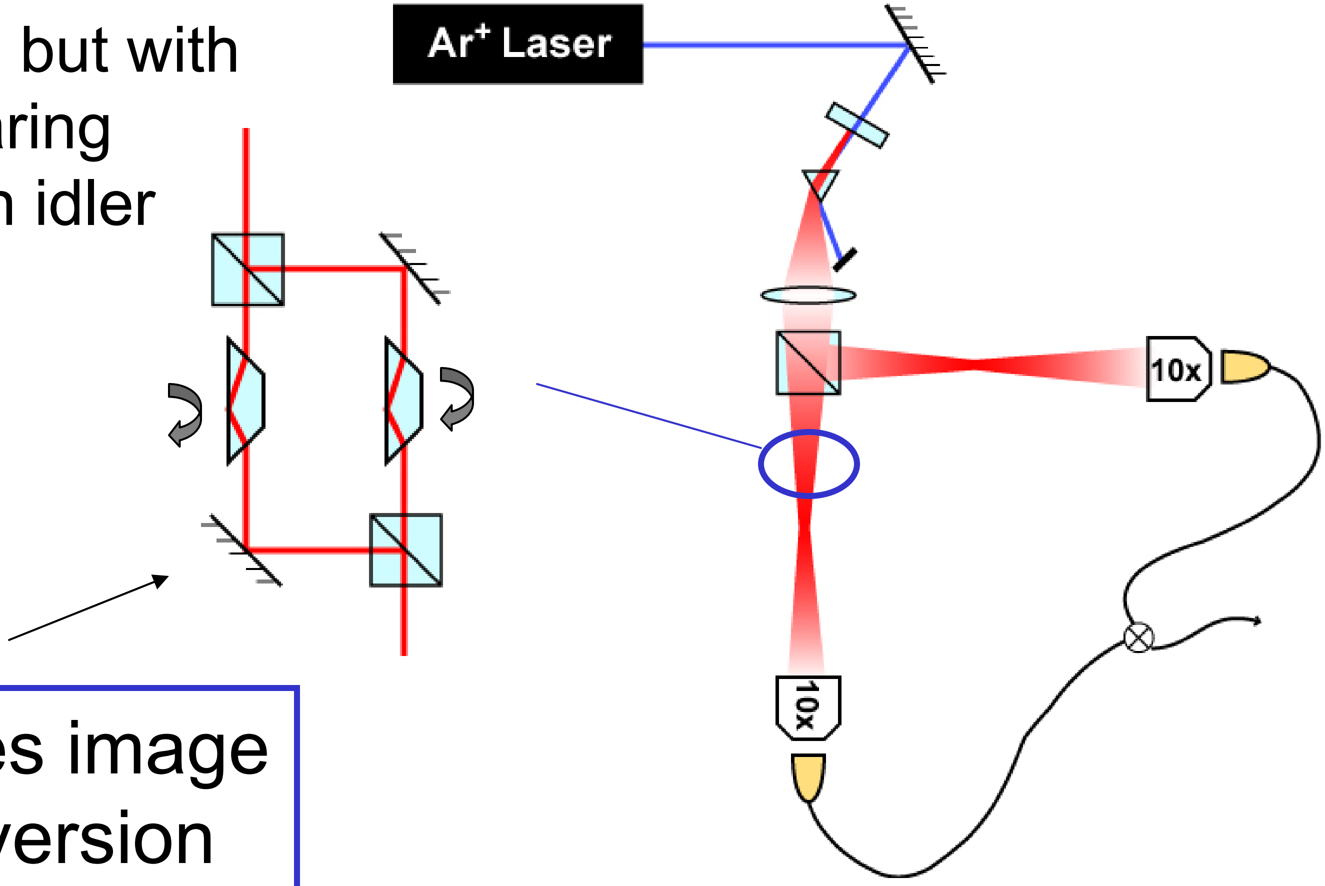
$$\psi(x_s, x_i) = \sqrt{f(x_s)g(x_i)}e^{i\phi(x_s,x_i)}$$

- The entanglement has migrated to phase. We need interferometric methods to get information about the entanglement.

$$|\psi(x_s, x_i) + \psi(x_s, -x_i)|^2$$

# Experiment to Detect Phase Entanglement

Same as before, but with a rotational shearing interferometer in idler arm.



Superimposes image with rotated version of itself

$$|\psi(x_s, x_i) + \psi(x_s, -x_i)|^2$$

# Conclusions

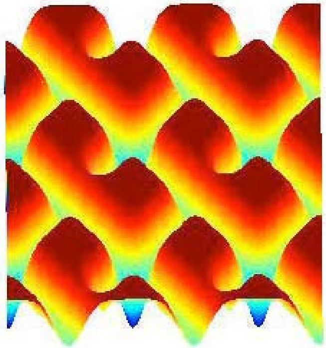
- We have experimentally investigated the propagation of spatial correlations in SPDC.
- The apparent disappearance of entanglement can be explained by the migration of entanglement from intensity to the phase of the wave function.
- Rotational shearing interferometers should enable us to recover the entanglement information in the intermediate zones.

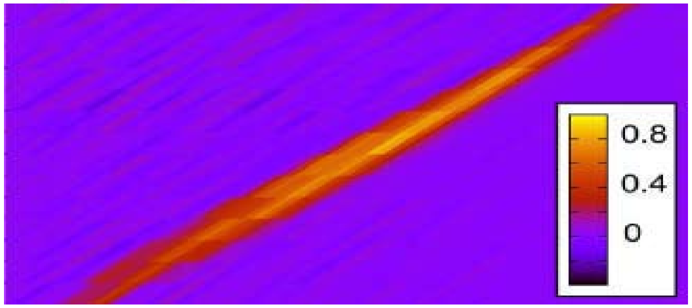
# Quantum Imaging: New Methods and Applications

# Quantum Lithography and Large Entanglement

## Objectives

- Develop sub-Rayleigh photo-lithography
- Develop related imaging modalities
- Exploit entanglement in large Hilbert spaces for imaging applications
- Develop means of minimizing the loss of quantum coherence due to propagation





## Approach

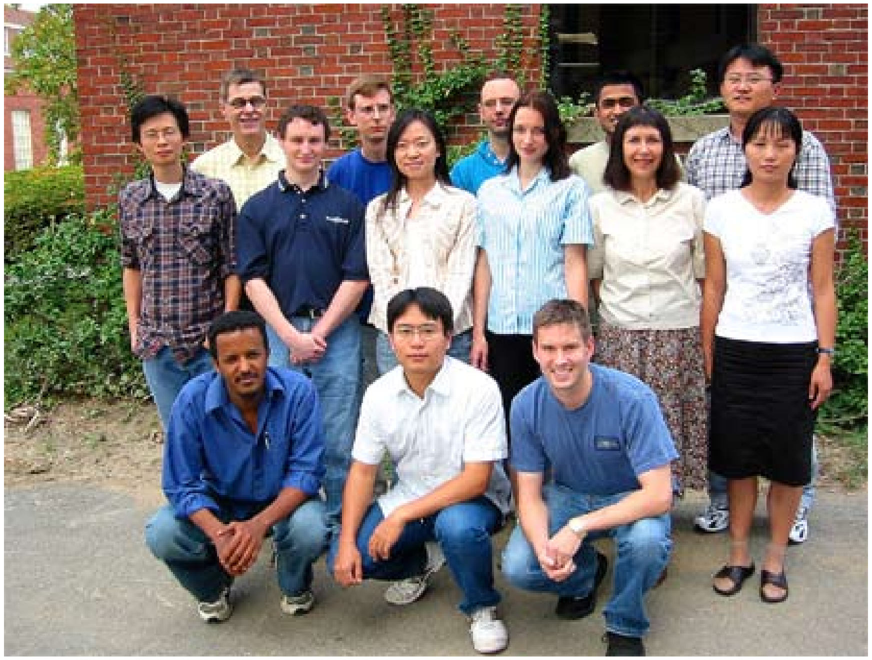
- Develop sensitive multiphoton lithographic materials
- Make use of high-gain OPA as source of light for quantum lithography
- Exploit continuous-variable entanglement to produce high-dimensional entanglement
- Develop imaging protocols based on high-dimensional entanglement

## Accomplishments

- Established PMMA as a suitable lithographic material
- Demonstrated ability to write λ/6 features
- Developed protocol for writing non-sinusoidal features
- Performed study of properties of OPA as a source for quantum lithography
- Performed measurements of modification of entanglement upon propagation

R W Boyd, University of Rochester

# Acknowledgements



Supported by
- the US Army Research Office through a MURI grant