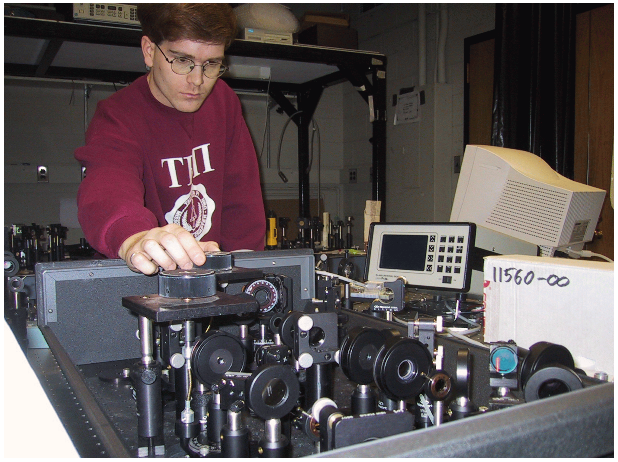
QUANTUM ENTANGLEMENT FOR OPTICAL LITHOGRAPHY AND MICROSCOPY BEYOND THE RAYLEIGH LIMIT



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May 8, 2001

OUTLINE

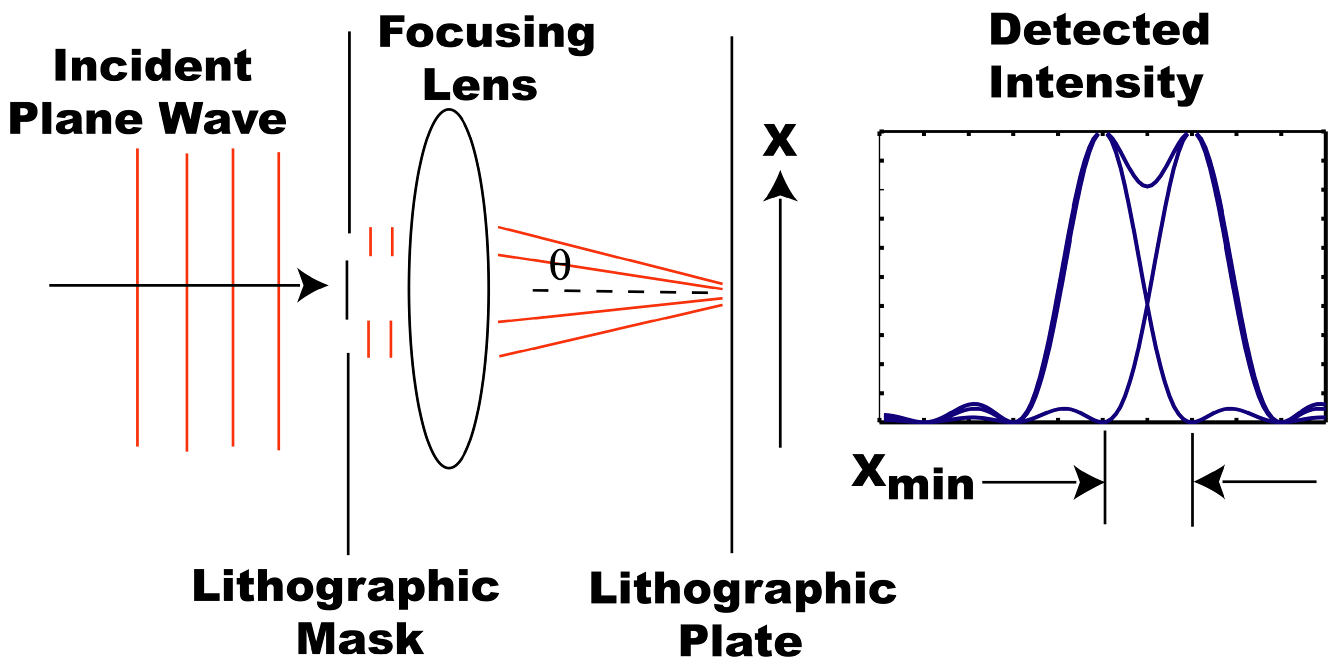
- **The Rayleigh Limit and Optical Lithography**
    - < **Introduction of the Problem**
    - < **Classical Method to Increase Resolution**
    - < **Quantum Method to Increase Resolution**

- **What Do We Propose?**
    - < **Increased signal intensities**
    - < **True resolution doubling**
    - < **Extension to optical microscopy**

- **Conclusions and Future Work**

OPTICAL LITHOGRAPHY AND THE RAYLEIGH LIMIT

Traditional Optical Mask Lithography is Limited By Diffraction



Numerical Aperture: *NA* = sin(2)
Minimum Resolvable Feature Size Based on Diffraction is X_{min} = 8 / 2*NA*
(Rayleigh Limit)

OPTICAL LITHOGRAPHY AND THE RAYLEIGH LIMIT

In common lithographic terminology, the Rayleigh limit is generalized to:

$$X_{min} = 8\, k_1 \,/\, NA$$

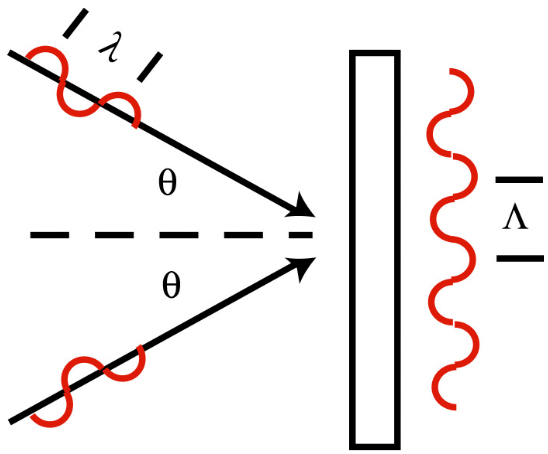
where k_1 is a parameter measuring degree of imaging (0.5 for original Rayleigh).

Number of writeable elements on a surface increases quadratically with decreasing X_{min}, so important to minimize.

Here will assume wavelength and numerical aperture fixed, and focus on methods to minimize k_1.

OPTICAL LITHOGRAPHY AND THE RAYLEIGH LIMIT

Classical Interferometric Lithography (CIL) is Limited by the Fringe Spacing



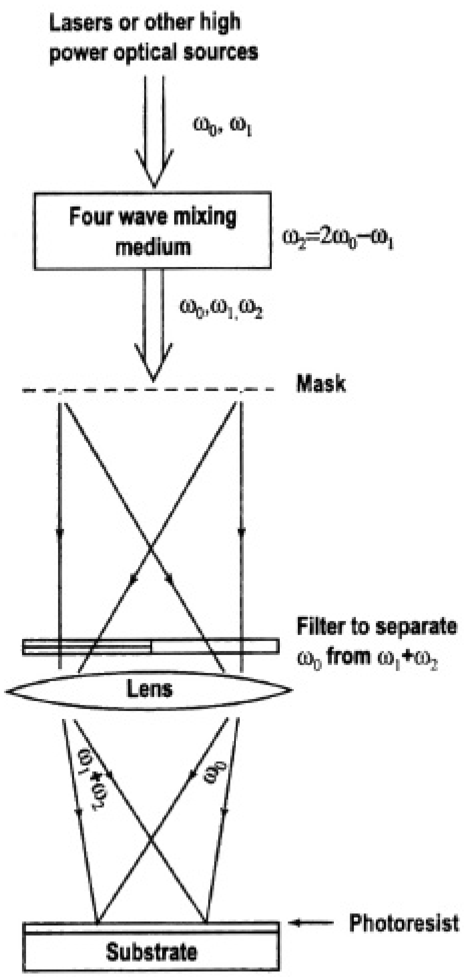
R_{min} = 7/2 = 8/4sin2

Minimum Resolvable Feature At Grazing Incidence is R_{min} = 8/4
(Modified Rayleigh Limit For Classical Lithography)

S.R.J. Brueck, et al., Microelectron. Eng. 42, 145 (1998).

OPTICAL LITHOGRAPHY AND THE RAYLEIGH LIMIT

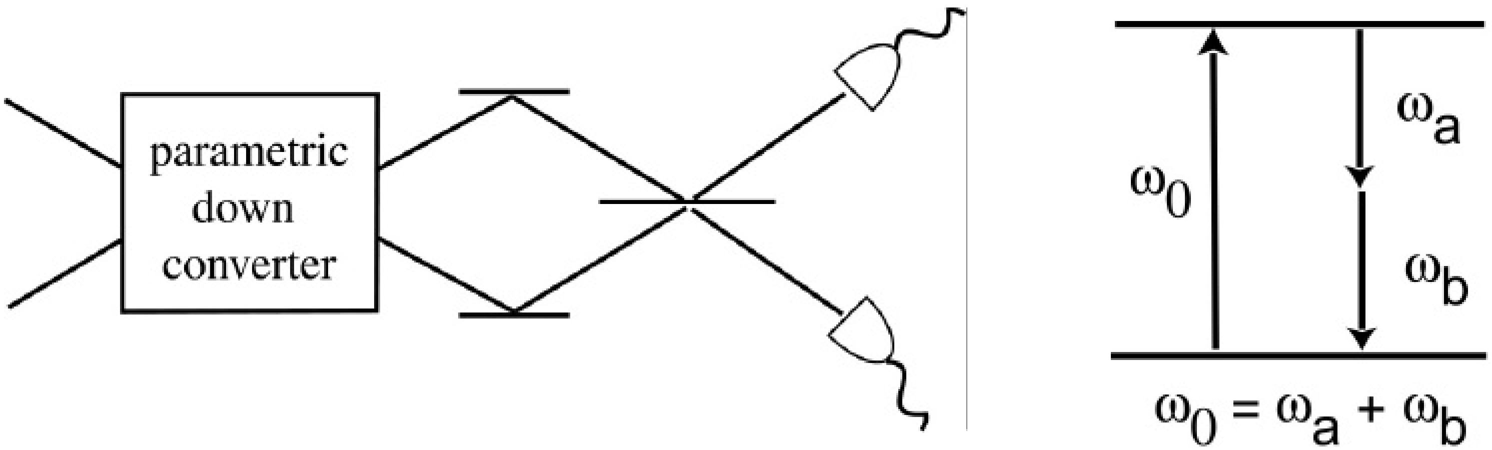
A complicated classical nonlinear optical scheme for achieving twice the CIL modified Rayleigh limit resolution has been proposed.



E. Yablonovitch and R.B. Vrijen, Opt. Eng. 38, 334 (1999).

THEORETICAL BACKGROUND

Hong-Ou-Mandel Interferometer (HOMI)

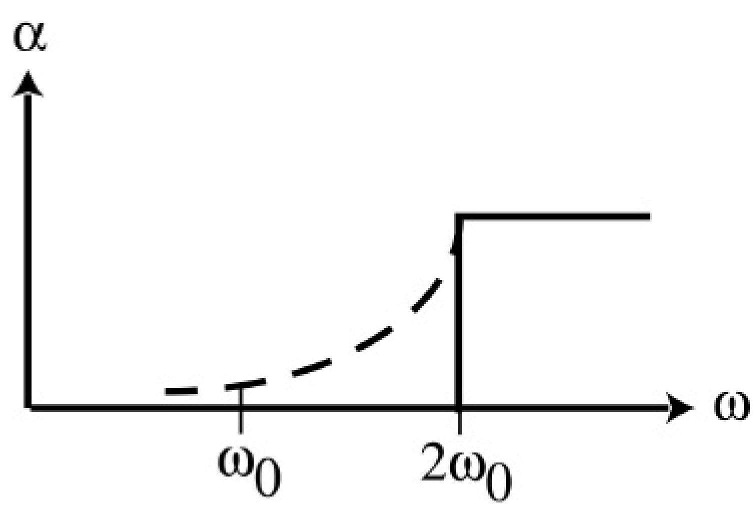


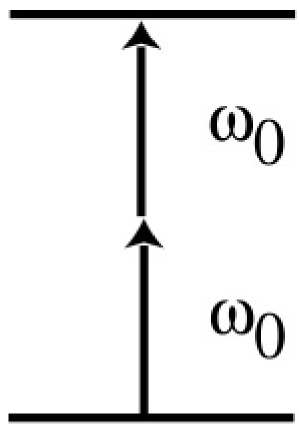
Schematic of a Hong-Ou-Mandel interferometer, with parametric down converter as source of the two one-photon states. With equal path lengths and a 50/50 beamsplitter, no coincidences will be observed by the photodetectors.

C.K. Hong, Z.Y. Ou, and L. Mandel, Phys. Rev. Lett. 59, 2044 (1987).

THEORETICAL BACKGROUND

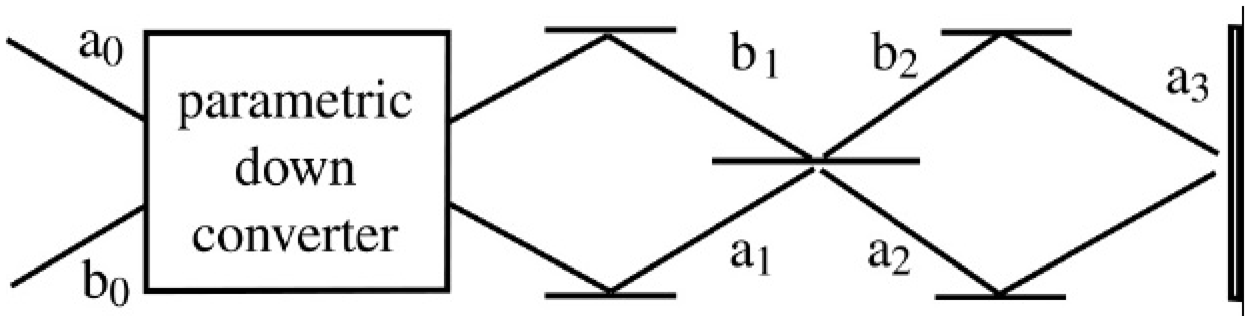
Two-Photon Absorption





Two-Photon Absorption generally requires high intensities since the absorption cross-section scales with the intensity squared rather than linearly in the intensity as is the case for linear absorption.

INITIAL QUANTUM LITHOGRAPHY PROPOSAL

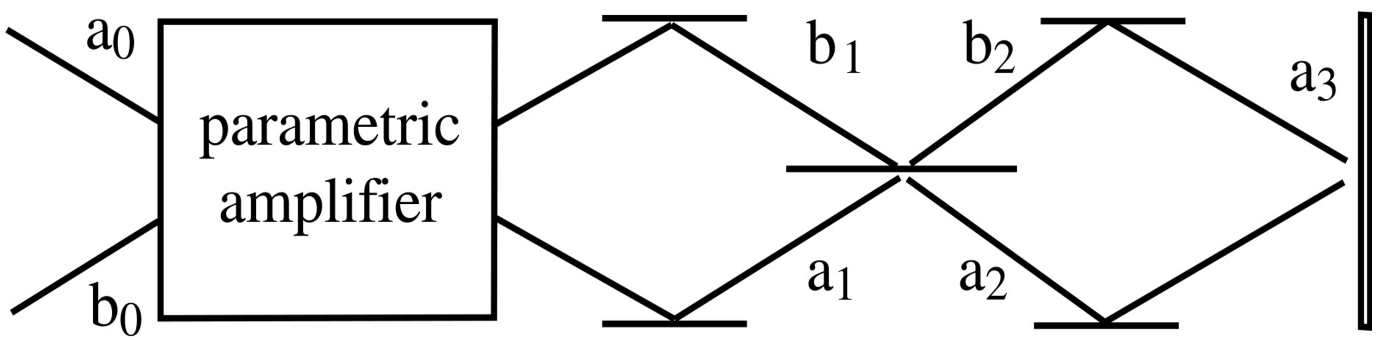


Recombine output beams from HOMI pumped by PDC onto a two-photon responsive lithographic plate. This gives a resolution twice that of the CIL modified Rayleigh limit.

In theory, can use N-photon generation and N-photon plates to beat the Rayleigh limit by a factor of N, but the experimental details would quickly become complex for N > 2.

A.N. Boto, P. Kok, D.S. Abrams, S.L. Braunstein, C.P. Williams, and J.P. Dowling, Phys. Rev. Lett. 85, 2773 (2000).

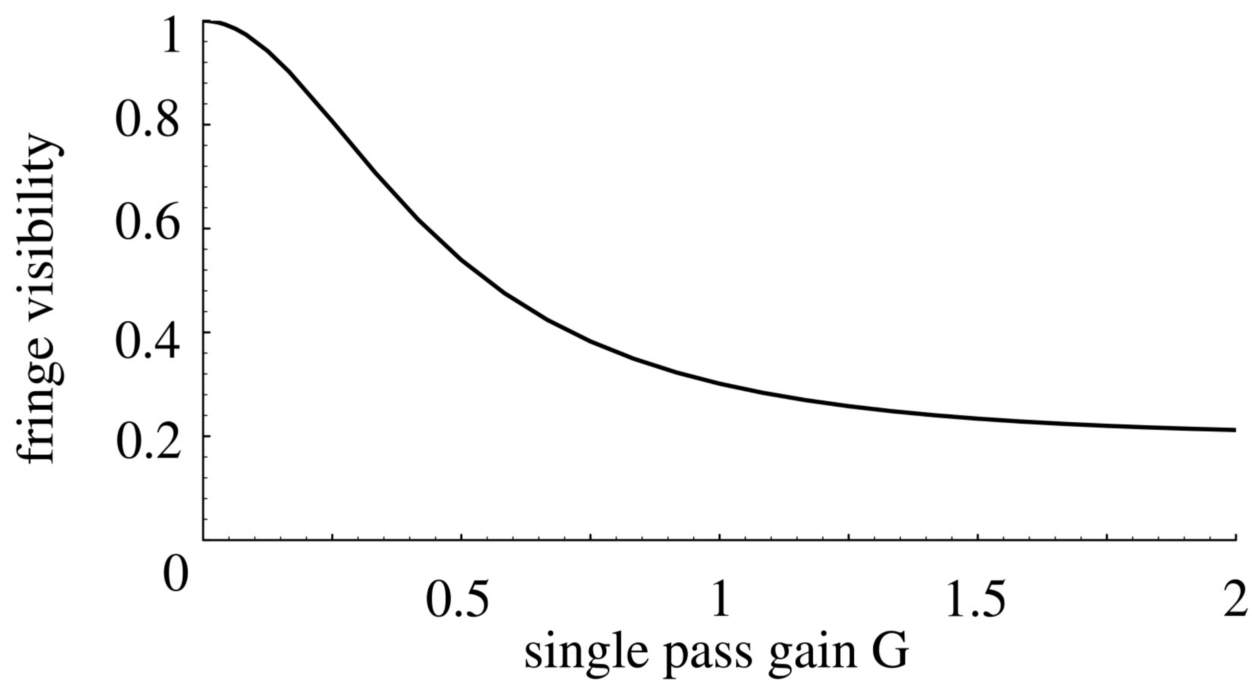
QUANTUM LITHOGRAPHY PROPOSAL



“Replace” parametric down converter (PDC) with optical parametric amplifier (OPA)–essentially the same device, but now pumped harder to generate sufficient energy levels to be recorded by two-photon responsive lithographic plate at a_3.

QUANTUM LITHOGRAPHY PROPOSAL

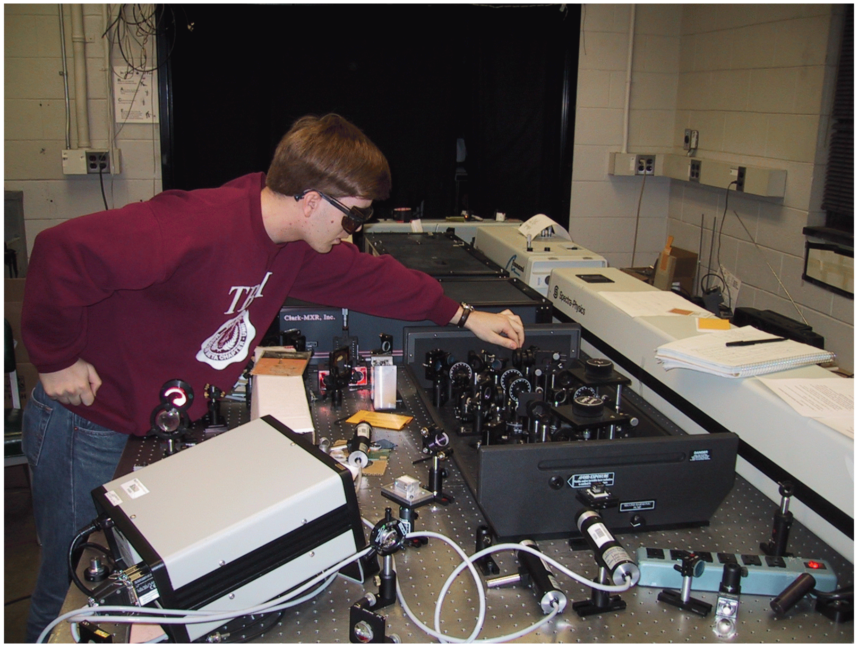
As the gain is increased (the pump is turned up) for the amplifier, the fringe visibility does decrease, but never below 20%.

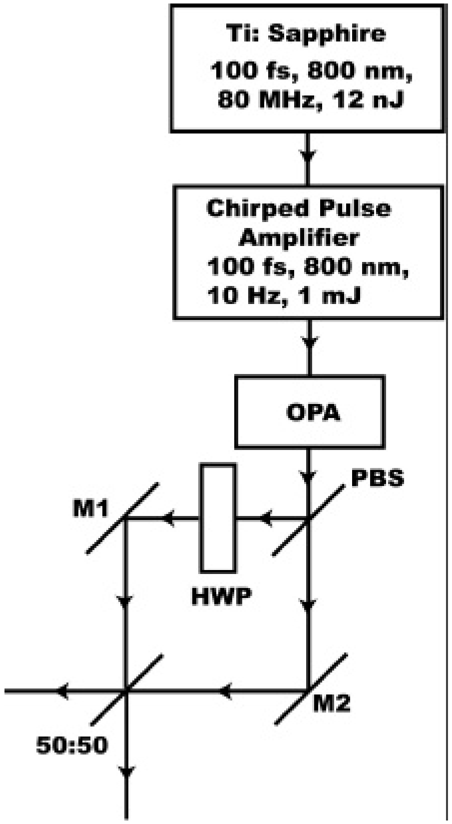


G.S. Agarwal, R.W. Boyd, E.M. Nagasako, and S.J. Bentley, Phys. Rev. Lett. 86, 1389 (2001).

QUANTUM LITHOGRAPHY PROPOSAL

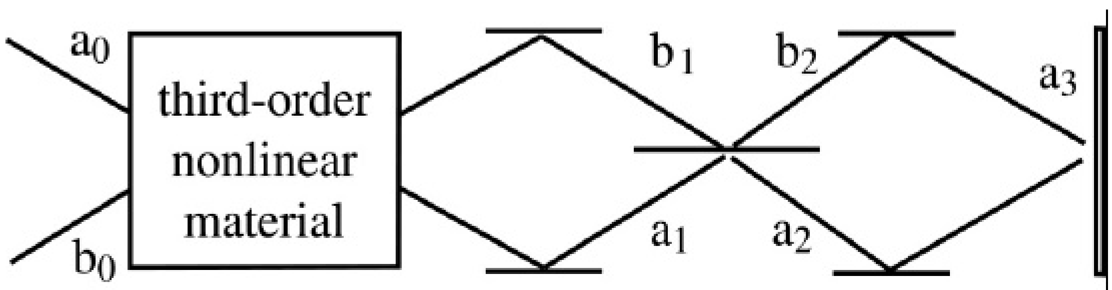
Experimental Layout

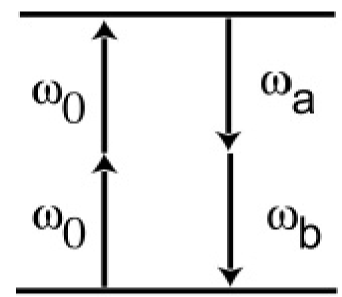




QUANTUM LITHOGRAPHY PROPOSAL

Parametric amplifiers take a photon at 8 and generate two photons at 28. Thus you are losing one factor of two to gain another. A good alternative would be a third-order effect which takes two photons at 8 and generates two new (entangled) photons at 8.





$$2\omega_0 = \omega_a + \omega_b$$

True resolution doubling using near-forward four-wave mixing (NFFWM).

QUANTUM MICROSCOPY

With quantum lithography, can write features smaller than classically possible.

Using similar methods in "reverse," would like to create a quantum microscope to view features smaller than classically possible.

FUTURE WORK

- Complete experimental verification of these proposals.
- Investigate ways of improving, expanding, and simplifying the techniques.
- Explore the possibilities of other applications for similar techniques.
- Study related areas in the field of quantum imaging.

SUMMARY AND CONCLUSIONS

< Showed quantum techniques for improving resolution may be extended to higher intensity regimes.

< Propose using a high-gain, third-order nonlinear process to experimentally verify practical true resolution doubling.

< Propose extending technique to optical microscopy.