Super-Resolution by Nonlinear Optical Lithography

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Outline

- Resolution Issues in Lithography
- Review of Previous Proposals
- Classical Multi-Photon Lithography
- Experimental Results
- Conclusions and Future Work

Lithography & the Rayleigh Limit

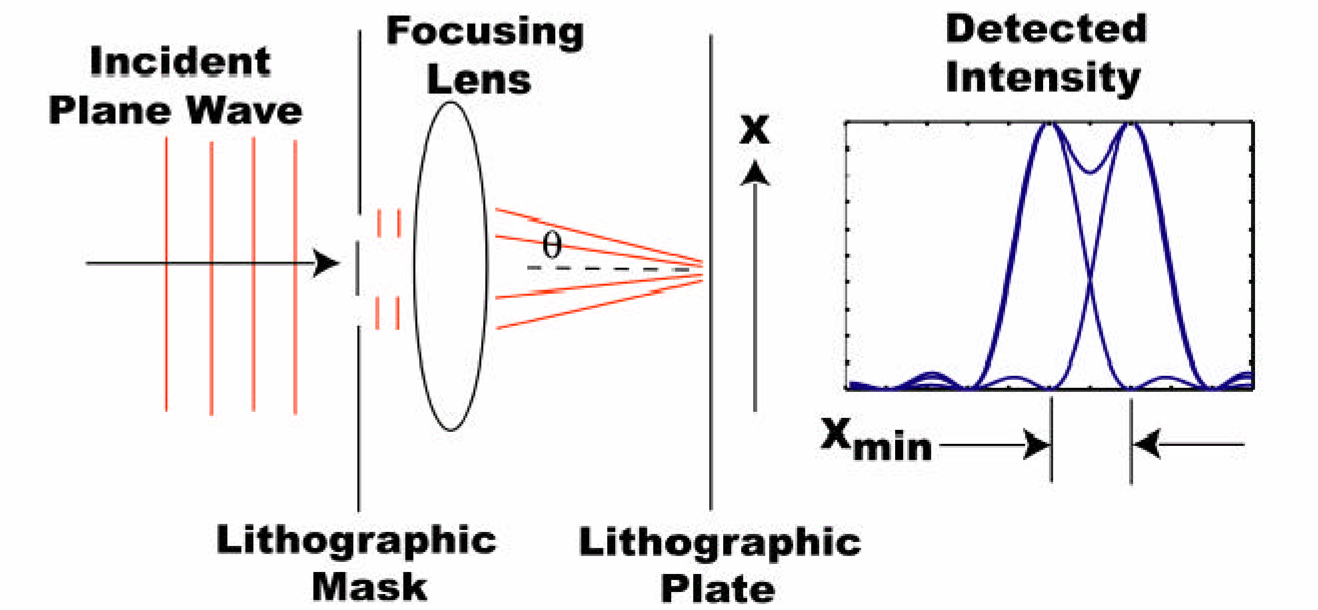
In common lithographic terminology, the Rayleigh limit is generalized to:

$$X_{min} = \lambda k_1 / NA$$

where k_1 is a parameter measuring degree of imaging (0.5 for original Rayleigh peak-to-valley with rectangular aperture). Number of writeable elements on a surface increases quadratically with decreasing *Xmin*, so important to minimize. Here will assume wavelength and numerical aperture fixed, and focus on methods to minimize k_1.

Mask Lithography

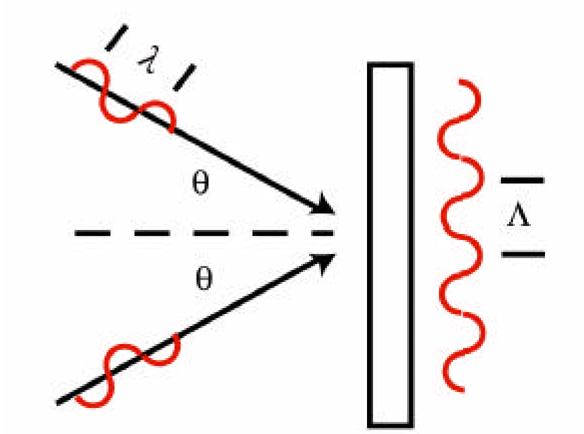
Traditional Optical Mask Lithography is Limited By Diffraction



Numerical Aperture: *NA* = sin(q)
Minimum Resolvable Feature Size Based on Diffraction is *Xmin* = l/*NA*
(Rayleigh Limit)

Interferometric Lithography

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



Rmin **= L/2 = l/4sinq**

Minimum Resolvable Feature At Grazing Incidence is *Rmin* = l/4

(Modified Rayleigh Limit For Classical Lithography)

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

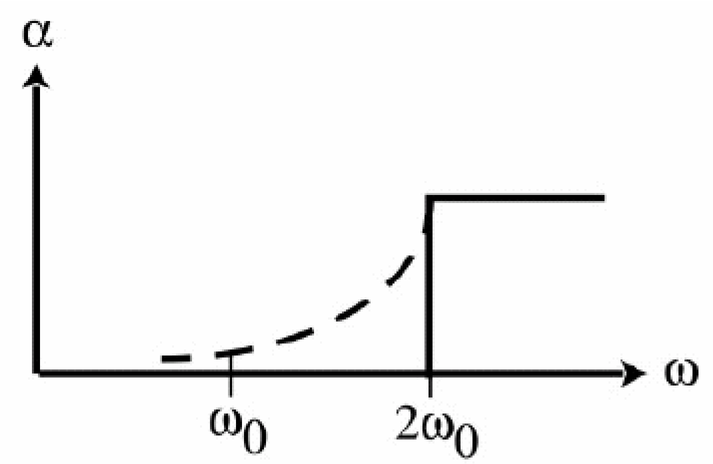
Previous Proposals for Increased Resolution

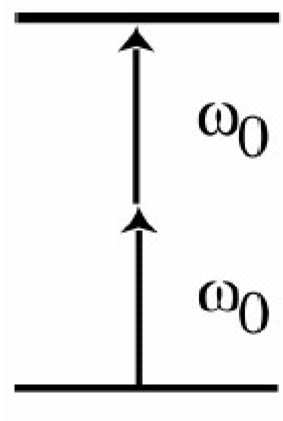
Both classical (eg, E. Yablonovitch and R.B. Vrijen, Opt. Eng. 38, 334 (1999)) and quantum (eg, A.N. Boto, P. Kok, D.S. Abrams, S.L. Braunstein, C.P. Williams, and J.P. Dowling, Phys. Rev. Lett. 85, 2773 (2000)) optical techniques have been proposed, relying on multi-photon absorption.

Previous Proposals for Increased Resolution

- Essentially all existing proposals are interferometric techniques
- Quantum techniques have disadvantage of low deposition rate
- Classical techniques have disadvantage of low feature visibility
- Quantum theory proposed for arbitrary resolution improvement, but beyond 2x experimental technique not yet realized
- Classical techniques only proposed for 2x improvement

Two-Photon Absorption

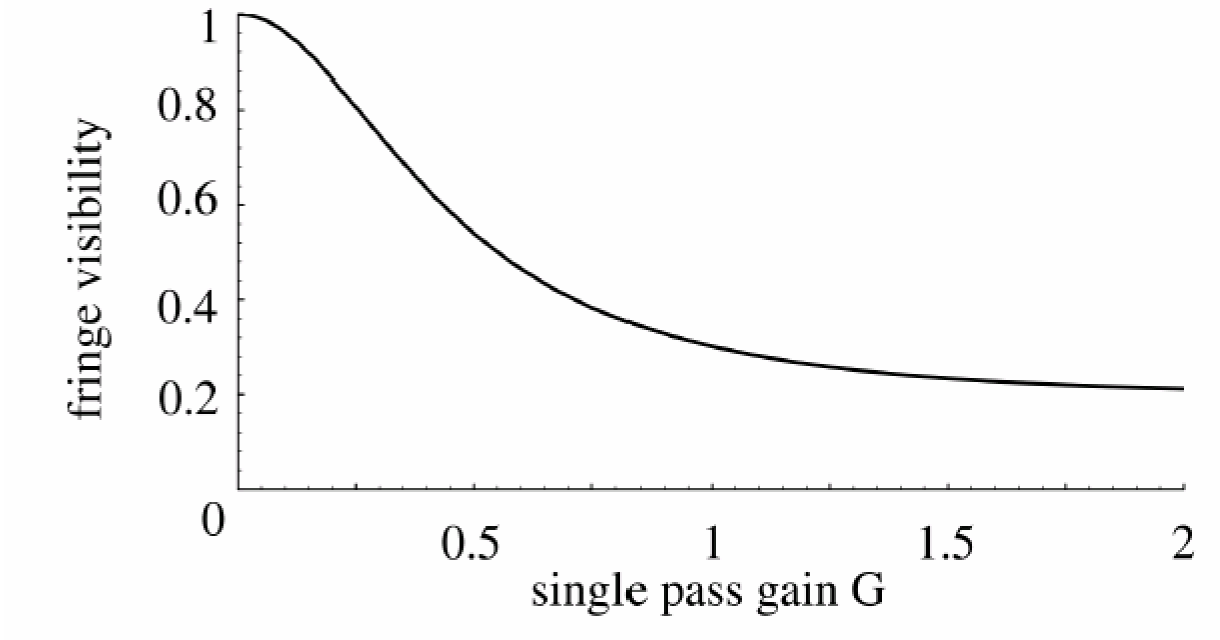




Two-photon absorption generally requires high intensities since the absorption cross-section scales with the intensity squared rather than linearly in the intensity as is the case for linear absorption.

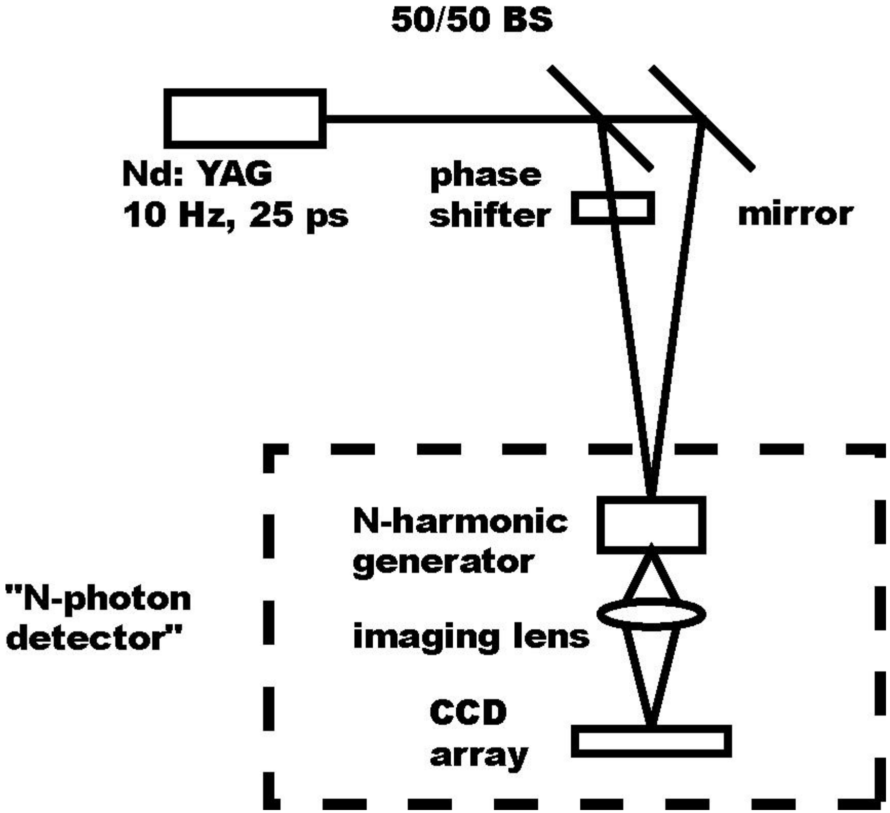
High-Gain Quantum Lithography Theory

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



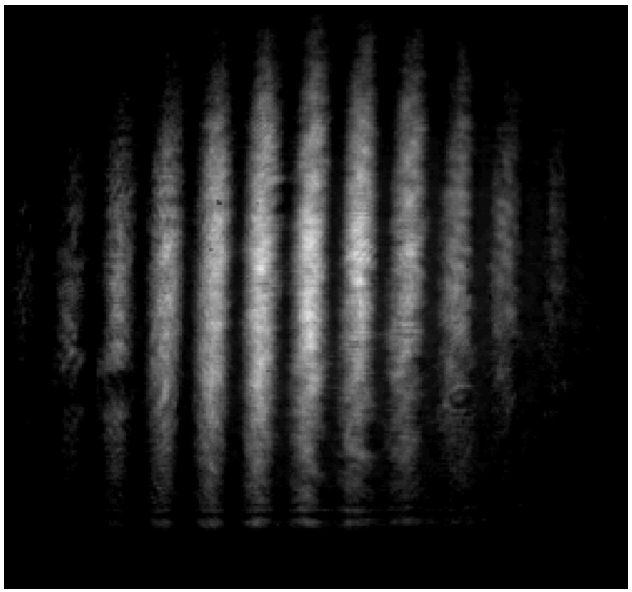
G.S. Agarwal, R.W. Boyd, E.M. Nagasako, and S.J. Bentley, Phys. Rev. Lett. 86, 1389 (2001).

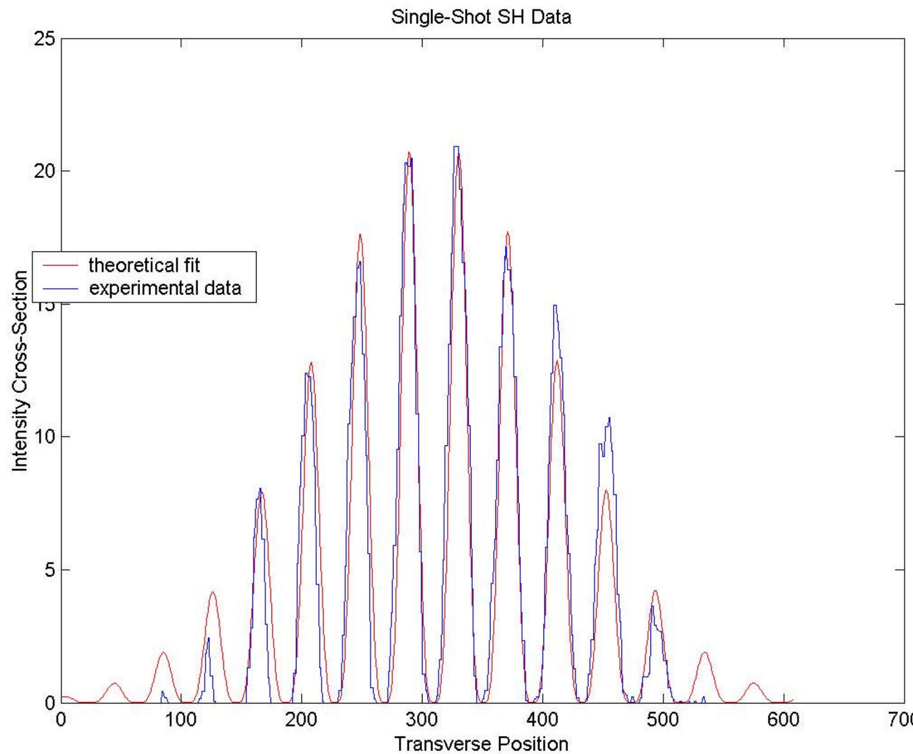
Interferometric Experimental Schematic



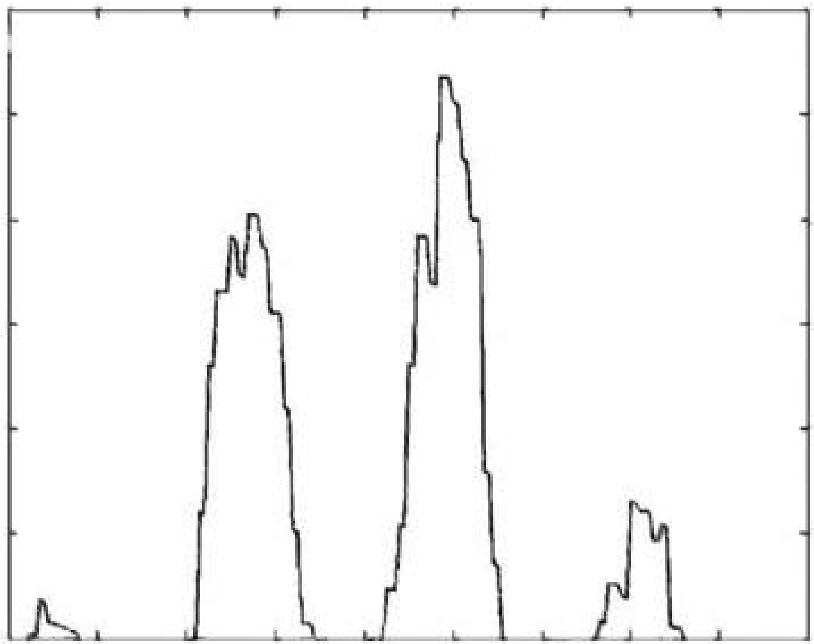
Write pattern with N-shots varying phase by 2p/N for each successive shot.

Nonlinear Interferometric Lithography Data

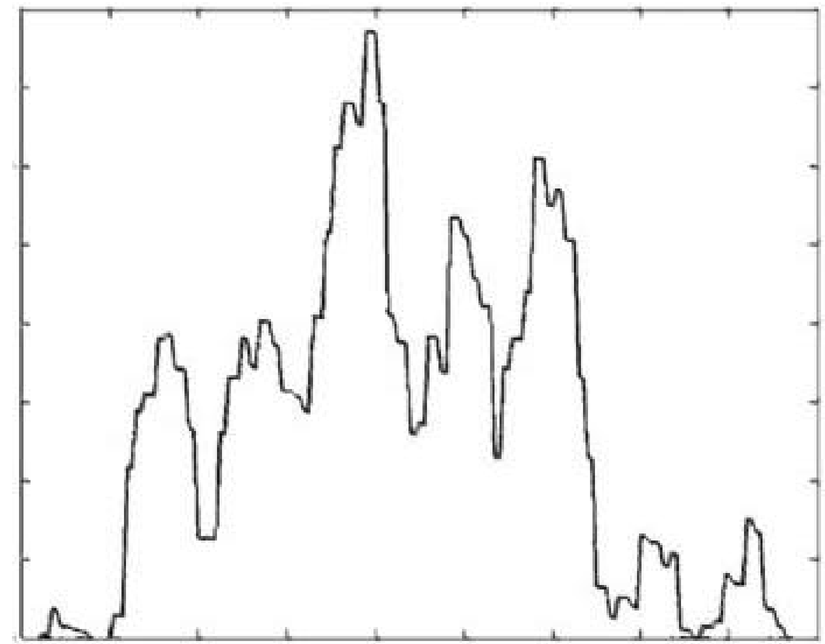




Nonlinear Interferometric Lithography Data



Single-Shot Interference Intensity Cross-Section



Summed, p-Phased Interference Intensity Cross-Section

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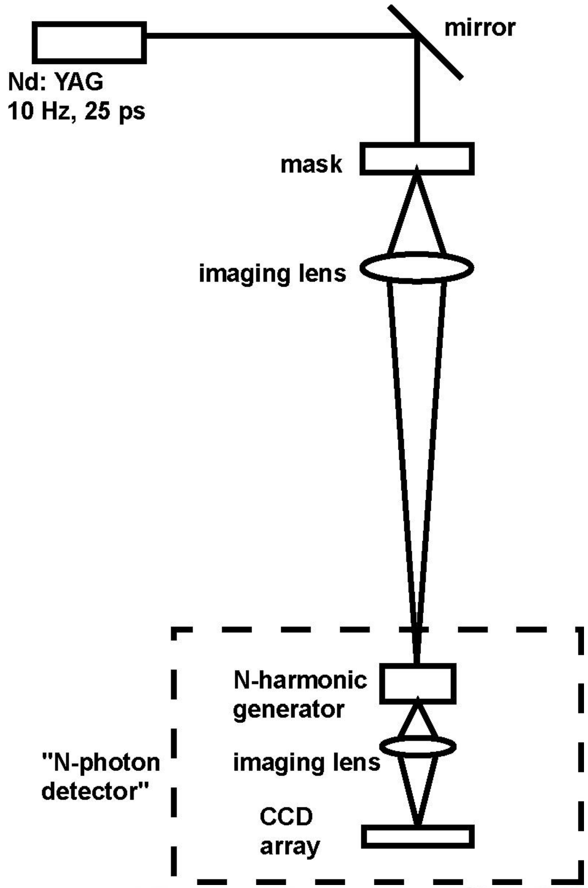
Mask Experimental Schematic



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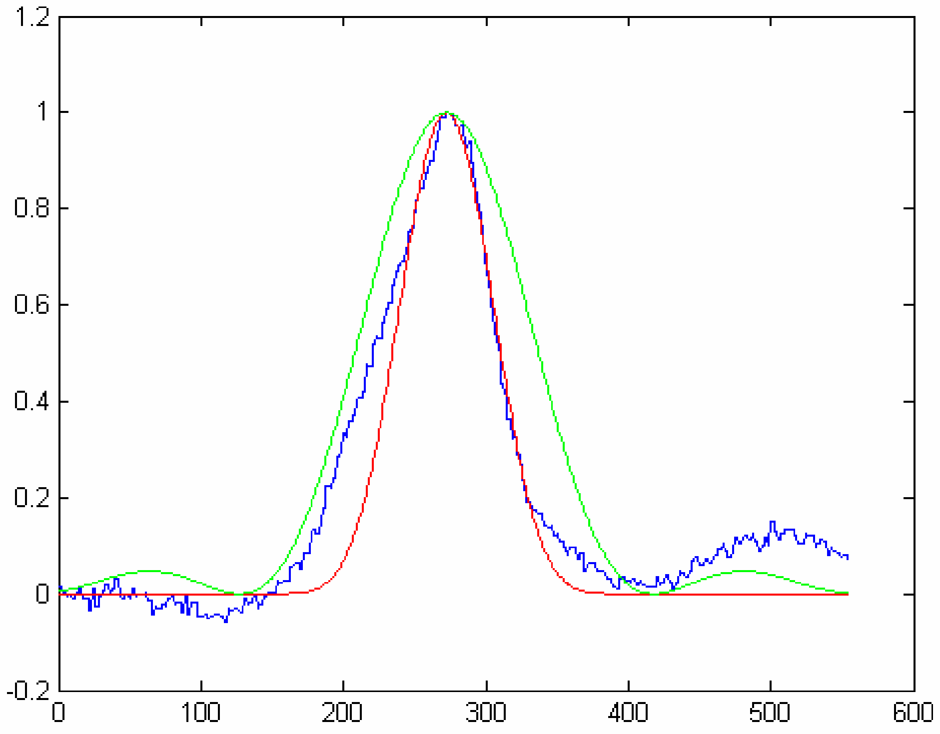
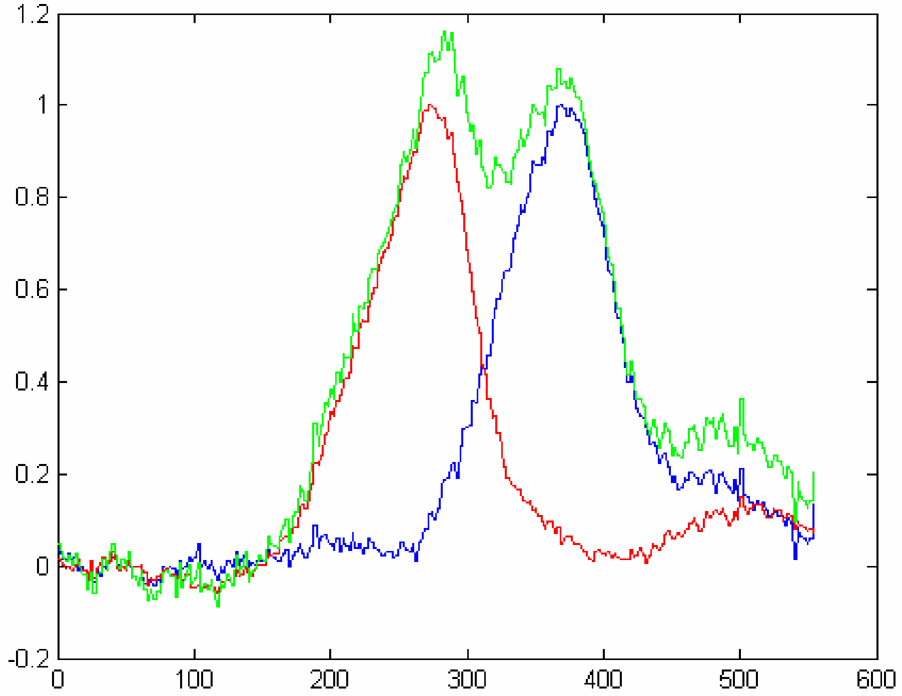
Nonlinear Mask Lithography Data



Blue: Data
Red: Sinc^6 (desired)
Green: Sinc^2

Single-Shot Mask Pattern Showing Near-Desired Shape

Nonlinear Mask Lithography Data



Blue: Pulse 1
Red: Pulse 2 (shifted 991 μm)
Green: Sum

For 1-Photon case, need shift of ~1716 μm for same visibility

Two-Shot Mask Data Showing ~x3$^{0.5}$ Improved Resolution

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Conclusions

- **Proposed techniques for improving resolution by arbitrary amount**
- **Demonstrated mask technique for 2- and 3-photon cases with no loss of visibility!**
- **Demonstrated interferometric technique for 2-photon case**
- **Technique is in principal simple to extend to any level**
- **Limitations are visibility (interferometric only) and available substrate materials**

Future Work

- Demonstrate the technique to further levels of improvement
- Find practical substrate materials to go from proof-of-principal to "real" lithography
- Search for methods to improve visibility possible in interferometric case
- Write patterns using interferometric techniques

Acknowledgments

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