EUV
An NSF Engineering Research Center

Colorado State University

Center for Functional Nanomaterials
Brookhaven National Laboratory

THE UNIVERSITY of WISCONSIN MADISON

Coherent EUV lithography with Capillary Discharge Laser

Lukasz Urbanski, Apr 6 2012

EUV
An NSF Engineering Research Center

Colorado State University

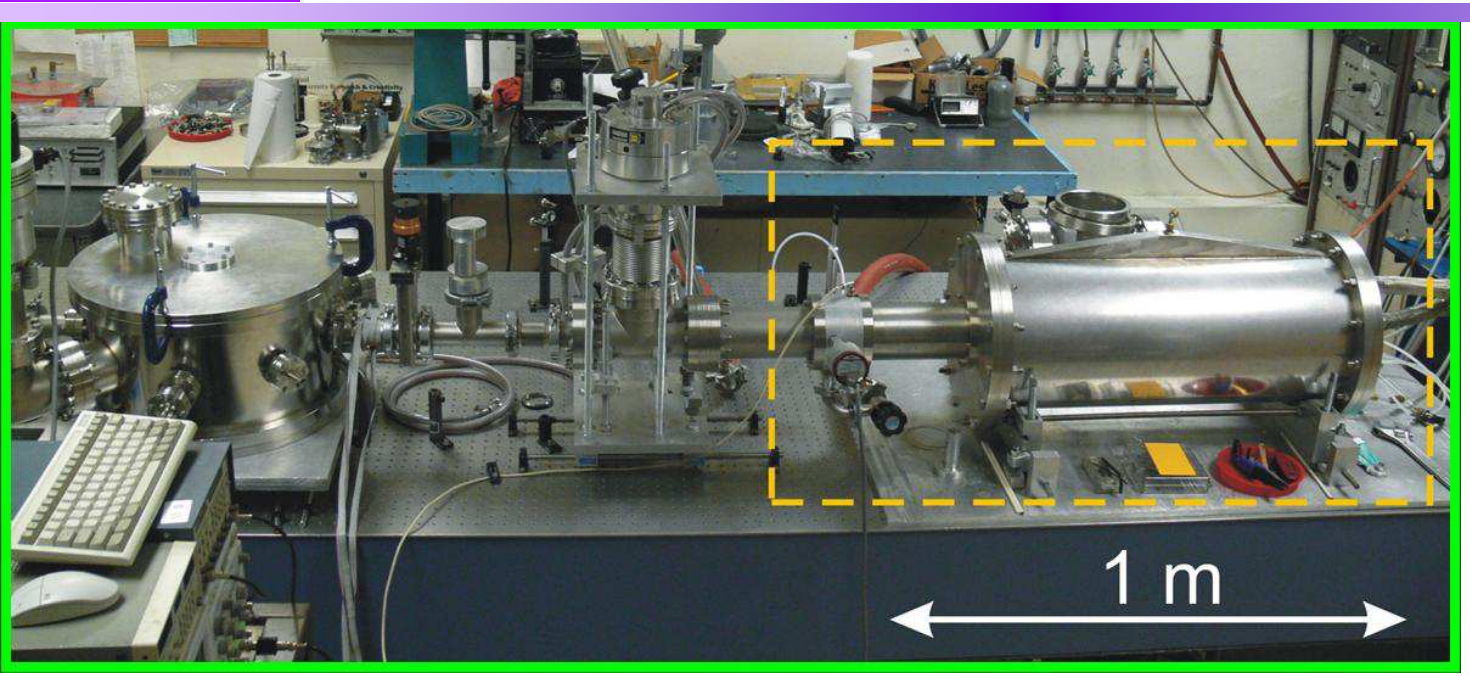
Center for Functional Nanomaterials
Brookhaven National Laboratory

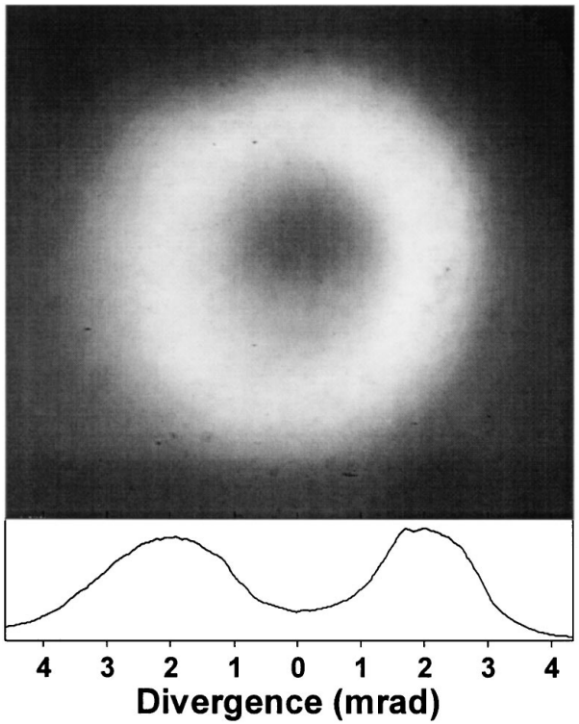
THE UNIVERSITY of WISCONSIN MADISON

Outline

- Introduction
  - Laser description
  - Lithography schemes in the past
- Work done so far
  1. Holographic projection lithography
  2. Generalized Talbot Imaging lithography
  3. De-magnified Generalized Talbot Imaging lithography
  4. Defect Tolerance in Generalized Talbot Imaging
- My TO DO list
- Summary

Intro: Capillary discharge EUV Laser





J.J. Rocca, V.N. Shlyaptsev, F.G. Tomasel, O.D. Cortazar, D. Hartshorn, and J.L.A. Chilla, "Demonstration of a Discharge Pumped Table-Top Soft-X-Ray Laser", Physical Review Letters **73**, 2192, (1994)

Parameters of the Capillary discharge laser @ 46.9 nm

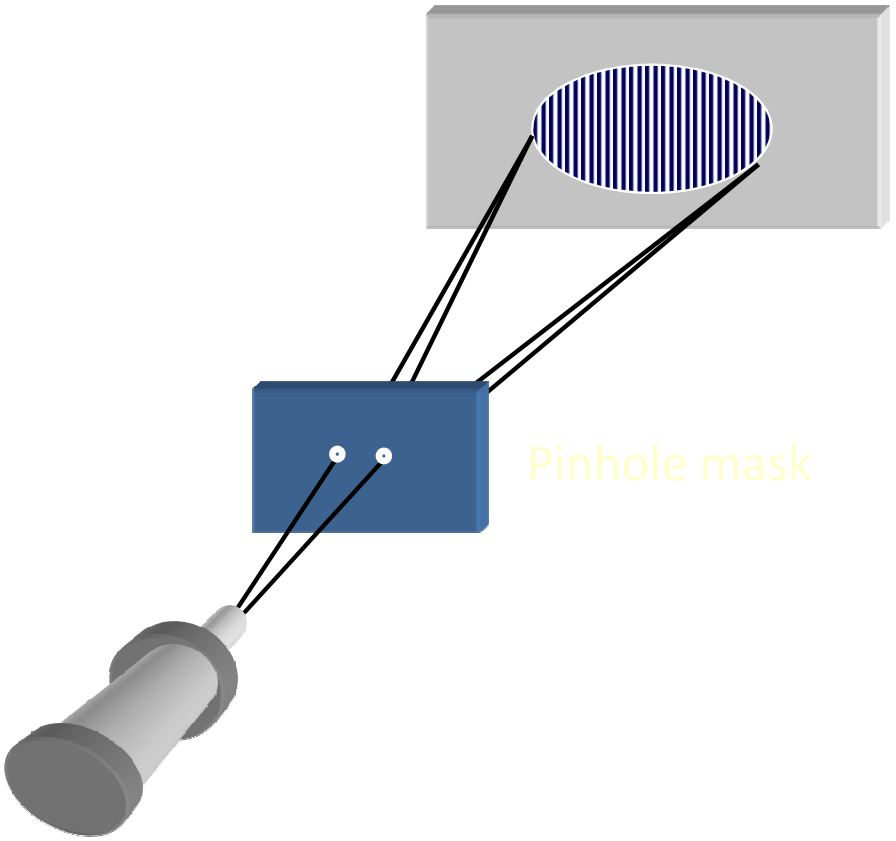
- Spectral bandwidth: $\Delta\lambda/\lambda = 3.5\ 10^{-5}$
- Power: miliwatts range
- Energy: typ. 0.1mJ-0.8mJ

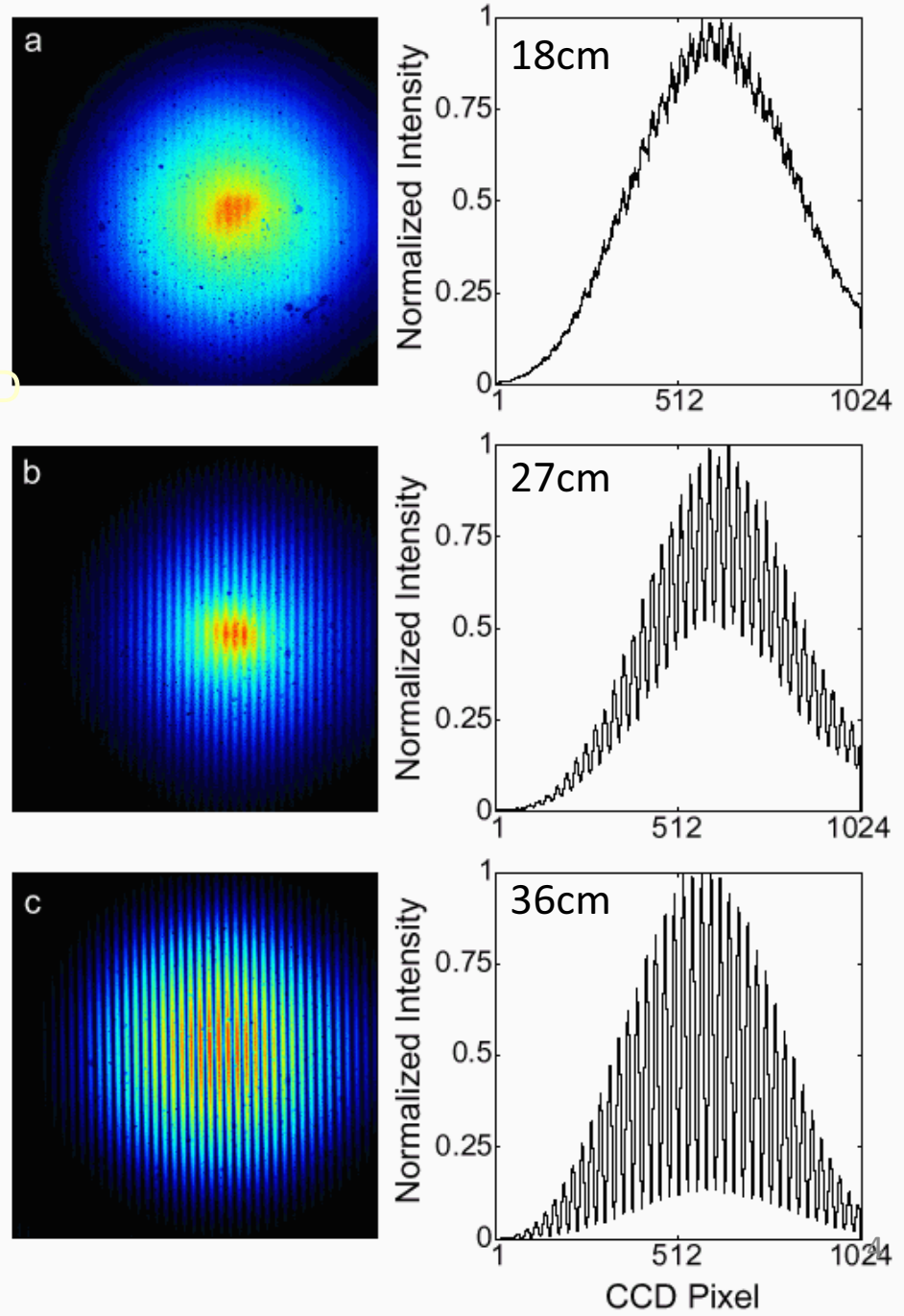
B.R. Benware, C.D. Macchietto, C.H. Moreno and J.J. Rocca, "Demonstration of a High Average Power Tabletop Soft X-Ray Laser," Phys. Rev. Lett. 81, 5804 (1998).

Essentially full spatial coherence is achieved increasing the capillary length

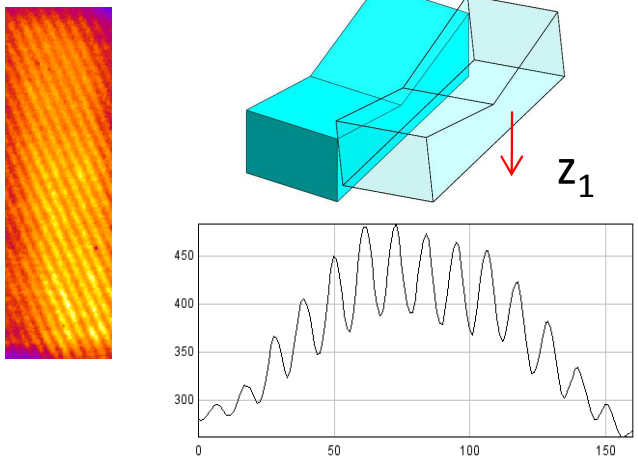
Characterization of spatial coherence:

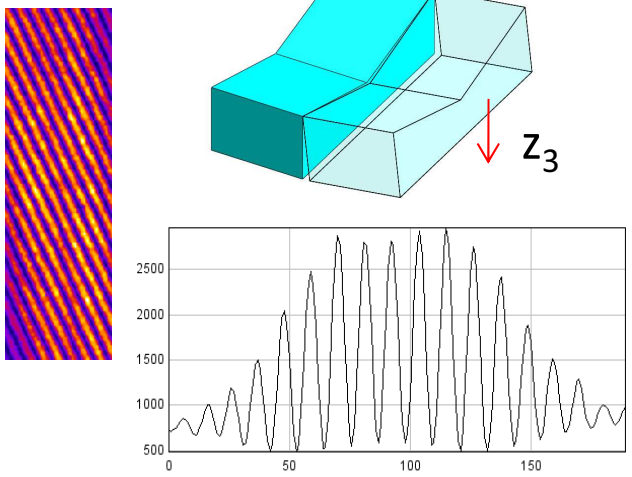
Young's interferometer

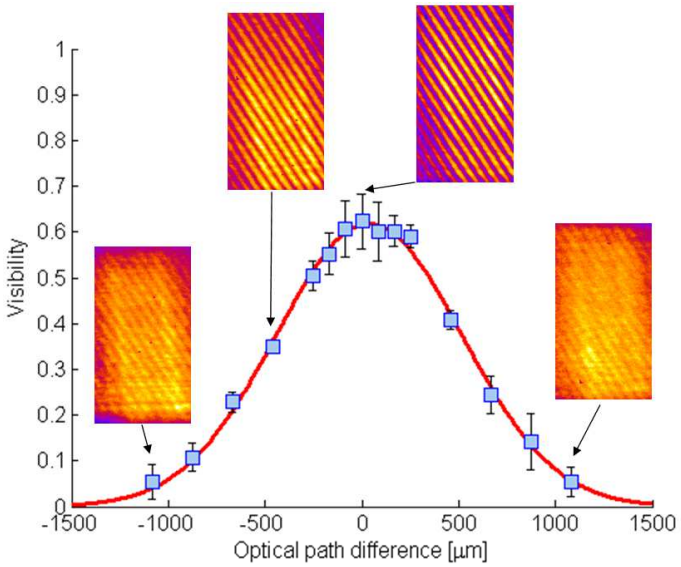




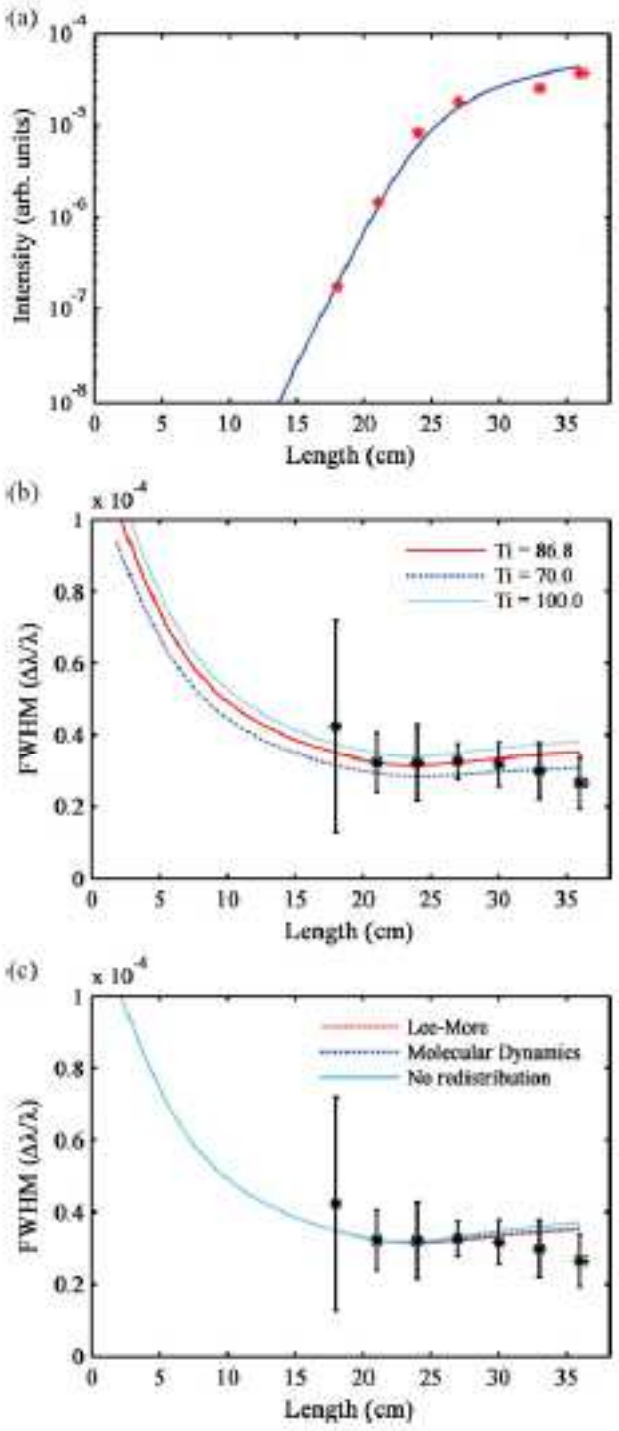
Source: Y Liu, et.al. *Phys. Rev. A,* 63, 3, 2001







$$\Delta\lambda/\lambda = 3.5\times10^{-5}$$



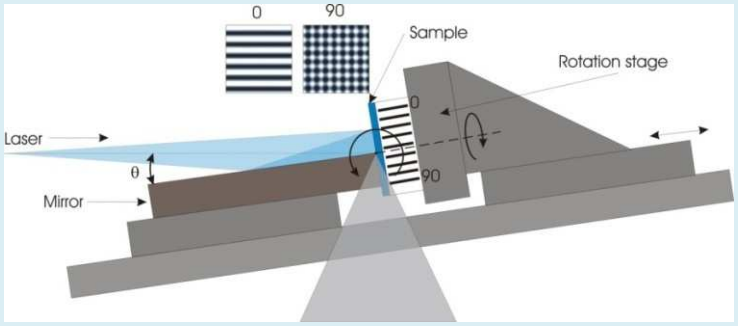
Source: Urbanski, L. et.al. *Phys. Rev. A,* 2012, *85*, 033837

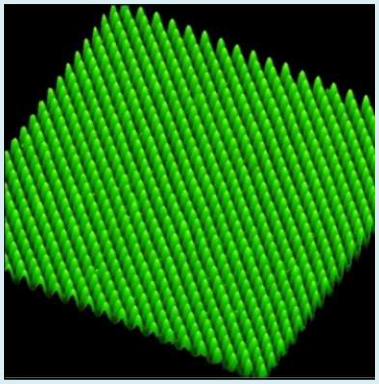
EUV

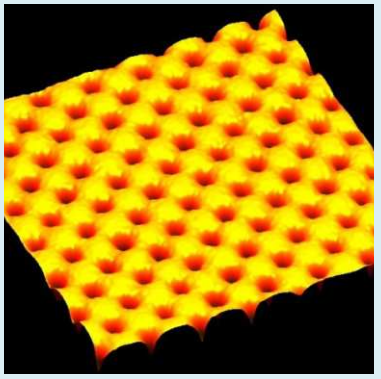
An NSF Engineering Research Center

Nanoscale coherent lithography with table top EUV lasers

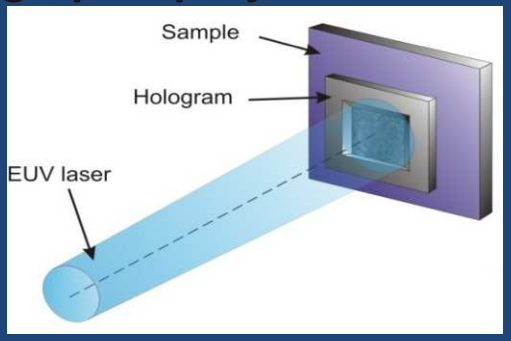
Interferometric lithography

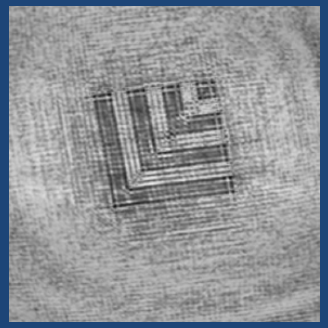


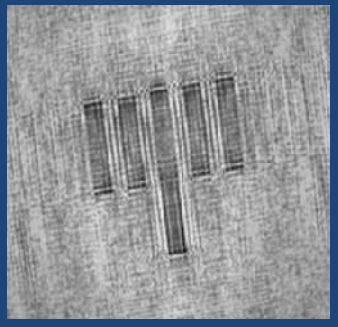




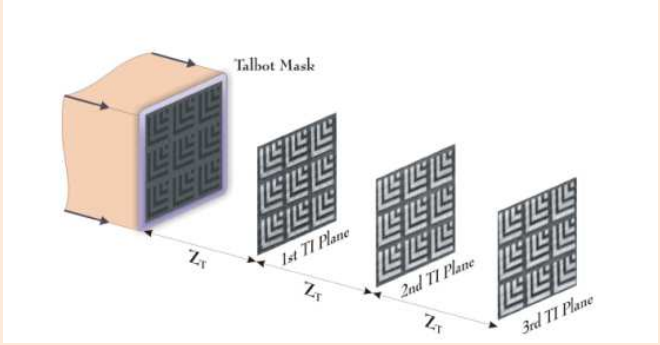
Holographic projection lithography

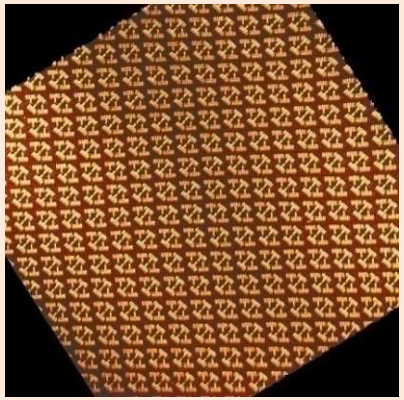


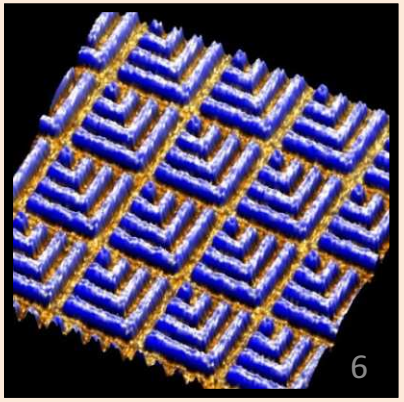




Generalized Talbot Imaging lithography







EUV
An NSF Engineering Research Center

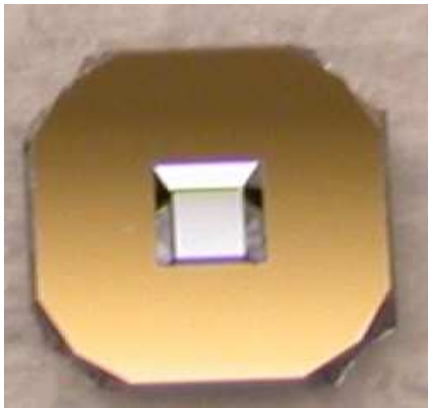
Colorado State University

Center for Functional Nanomaterials
Brookhaven National Laboratory

THE UNIVERSITY of WISCONSIN MADISON

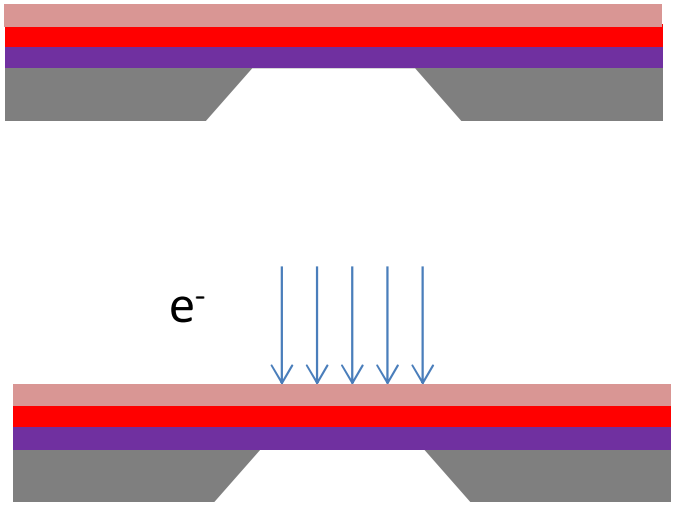
Work done so far

Mask Fabrication: Preparation



1

2



3

4

5

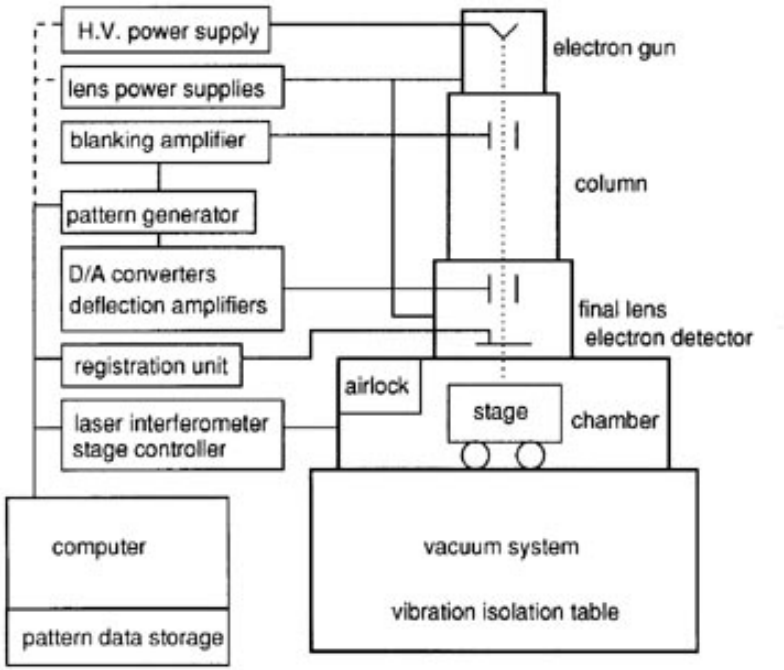
1. Silicon Nitride Membrane
2. Spin Coating w. Resist & ESPACER
3. E-beam lithography
4. Developing
5. Diffractive Mask

EUV
An NSF Engineering Research Center

Colorado State University

Center for Functional Nanomaterials
Brookhaven National Laboratory

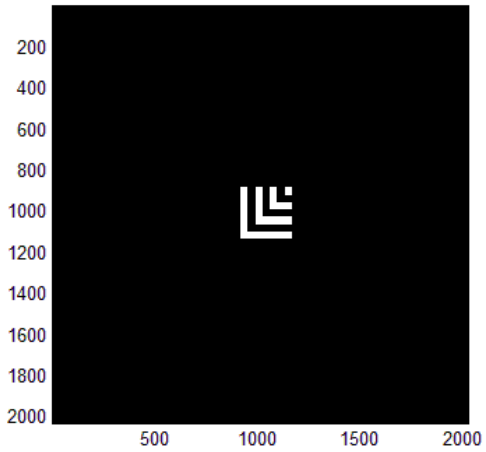
Mask Fabrication EBL



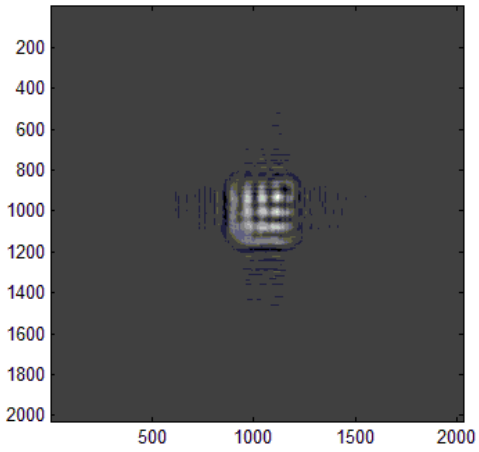
http://www.cnf.cornell.edu/image/spiefig1.jpg

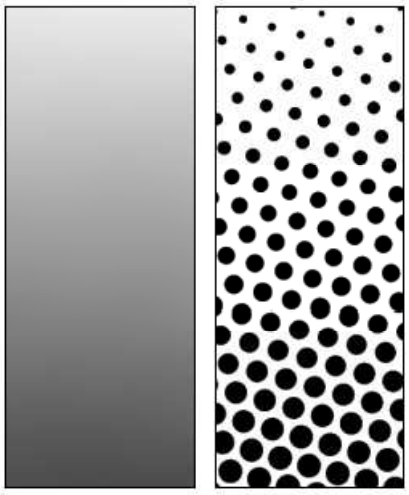
1. Holographic projection lithography

Binary object

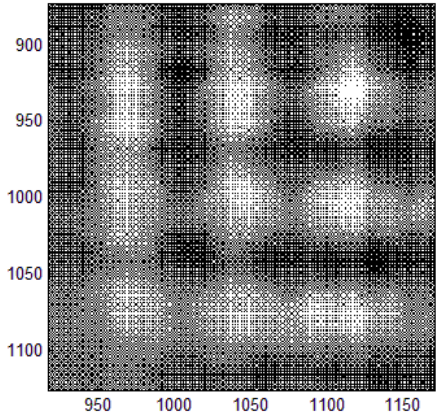


Fresnel propagation
(cont. tone hologram)

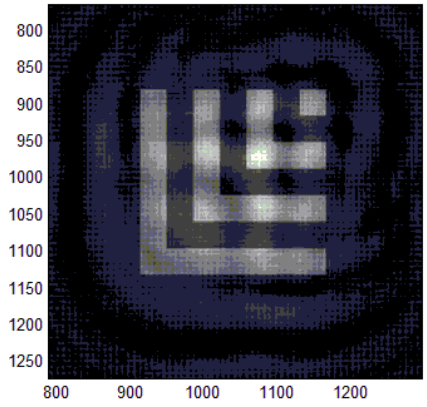




Half-toning

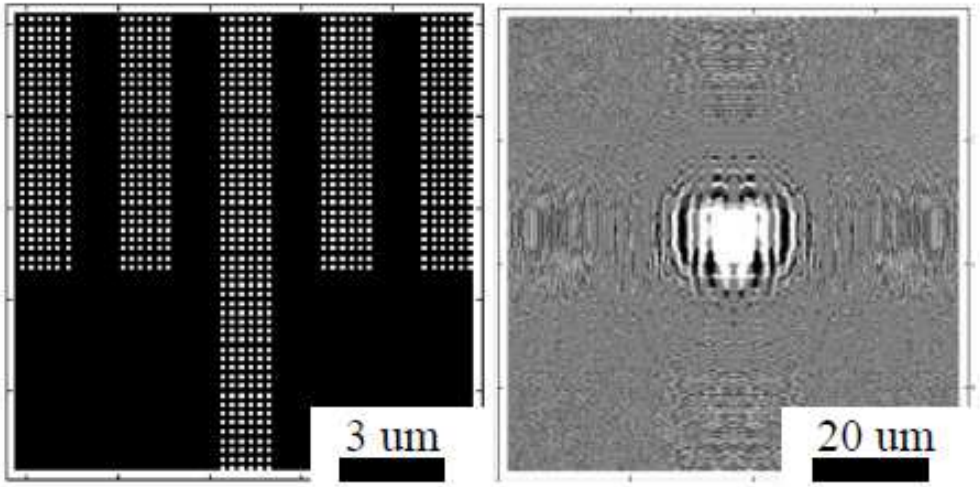


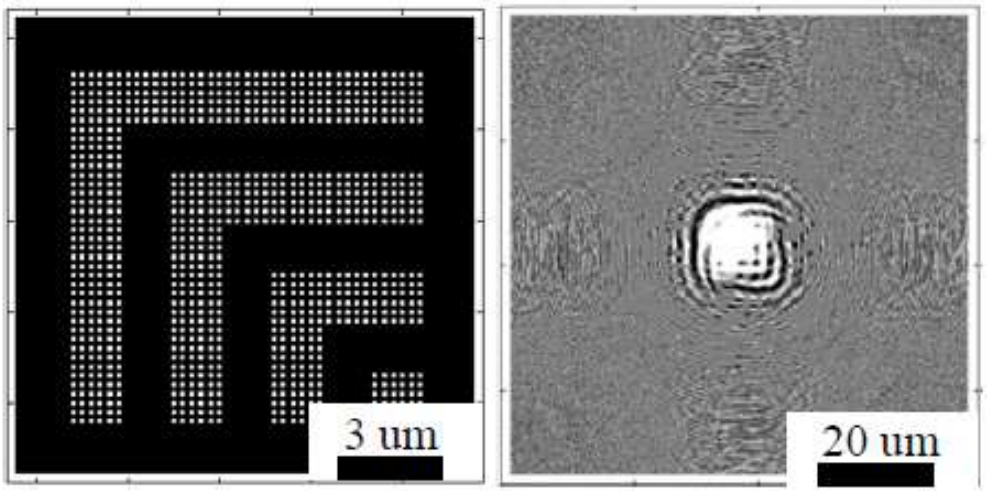
Binary
hologram



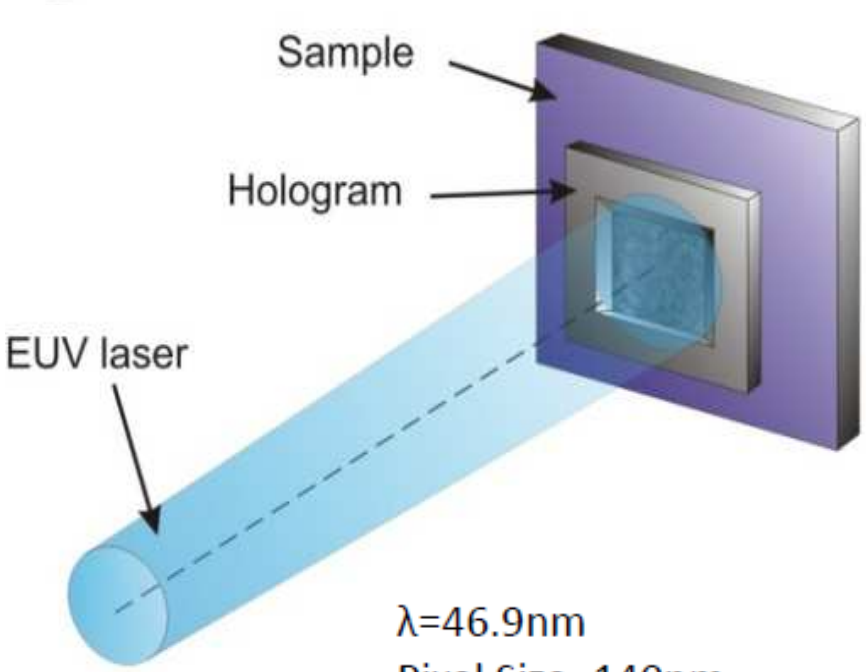
Reconstruction

Holographic projection lithography





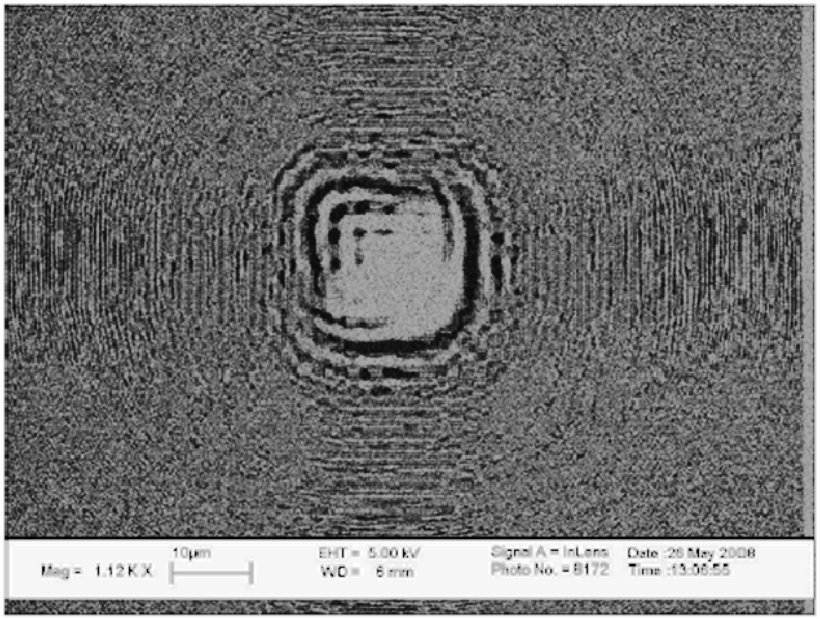
Binary objects and corresponding binary CGHs

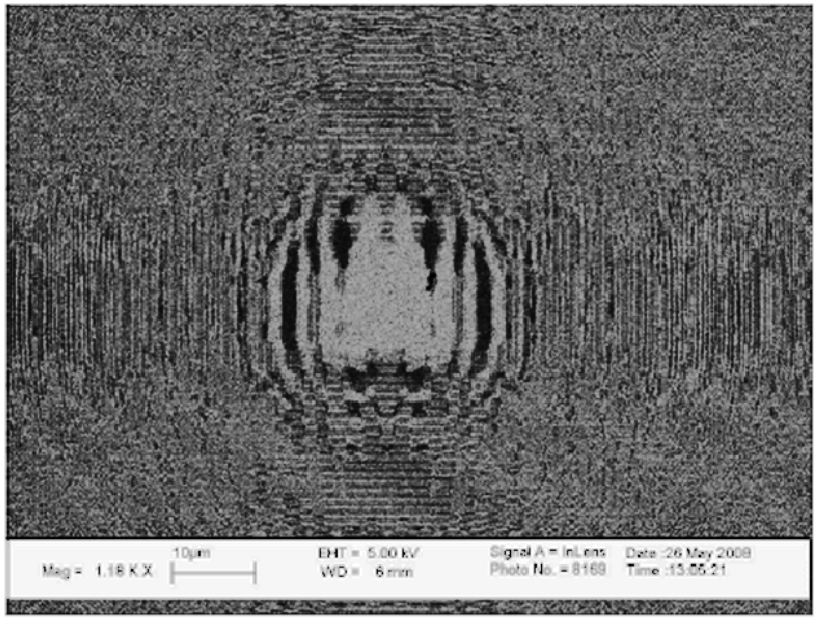


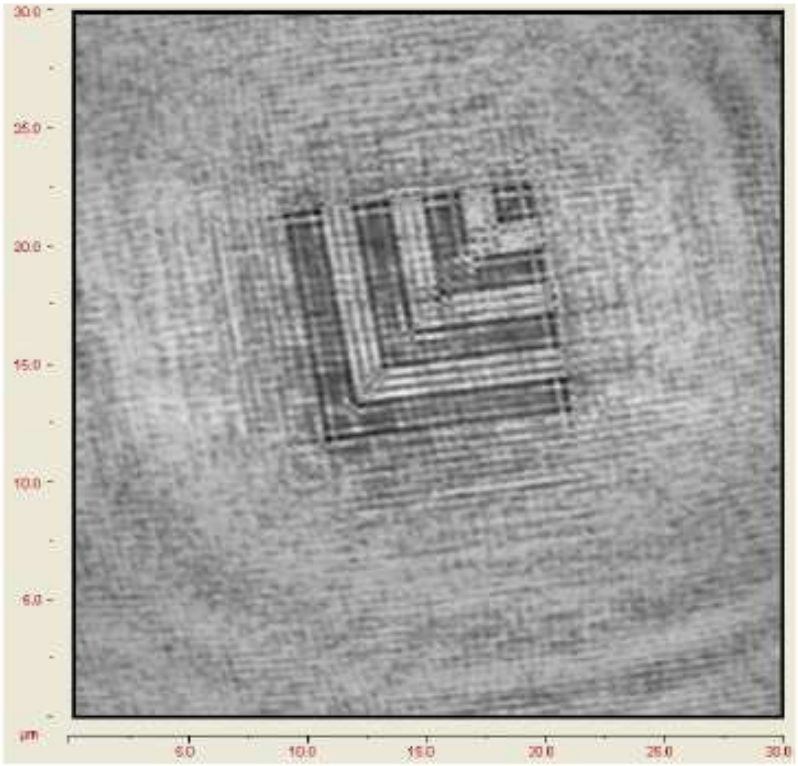
λ=46.9nm
Pixel Size=140nm
Z=500μm
Field=102.9μm
NA=0.102
DOF=4.5μm

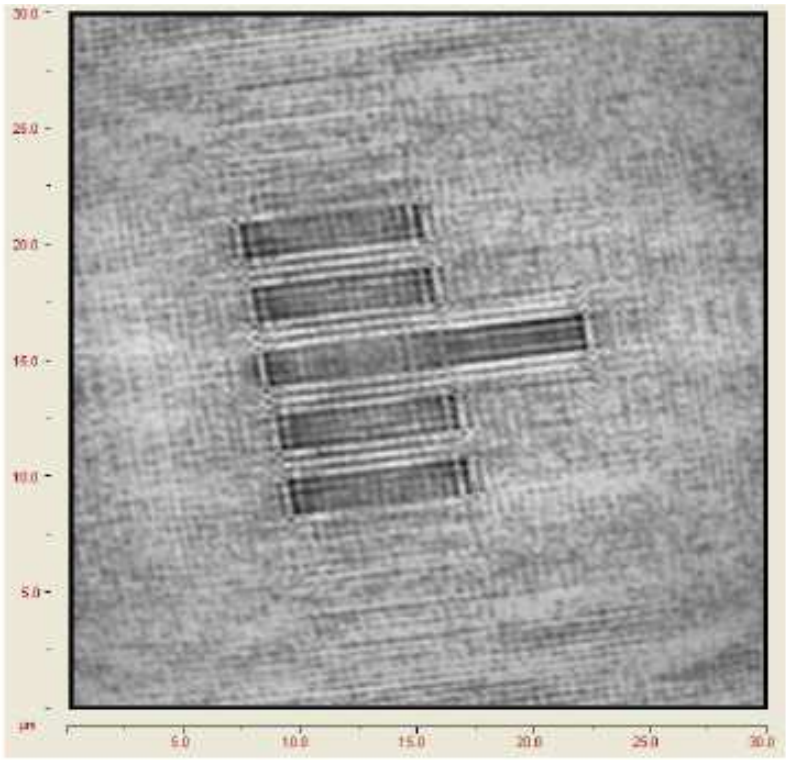
Illumination scheme

Holographic projection lithography



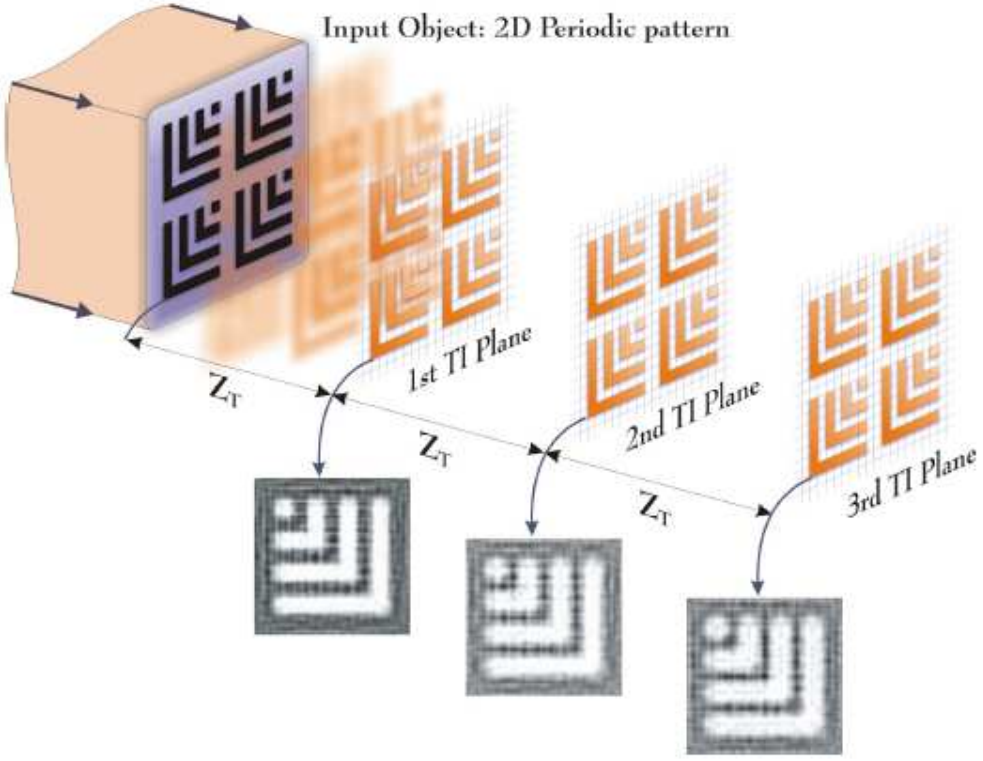


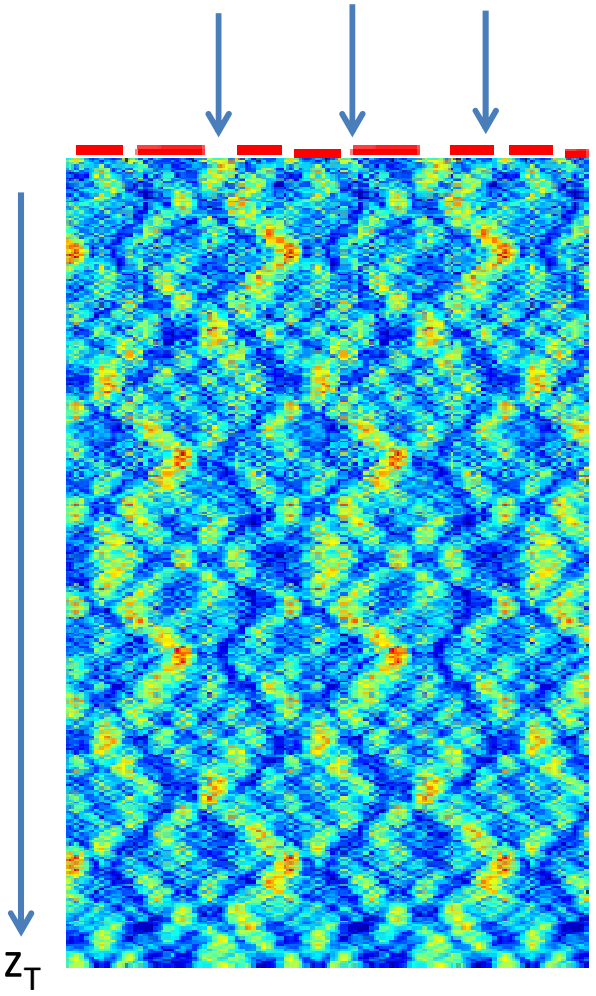




2. Generalized Talbot Imaging lithography

$$z_T = \frac{2a^2}{\lambda}$$

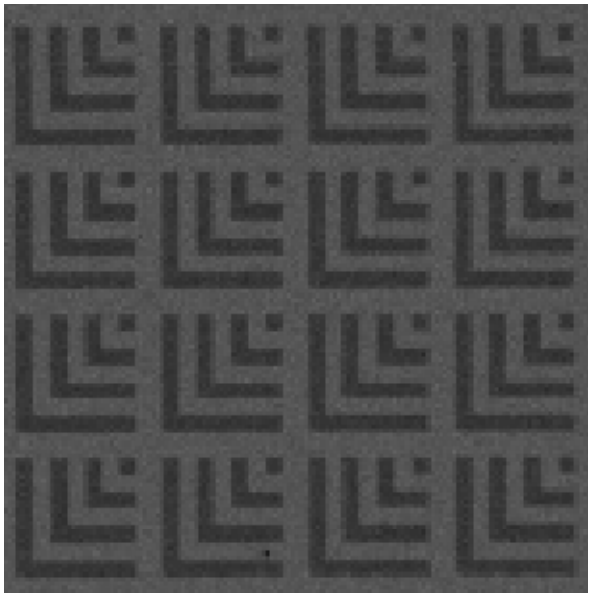




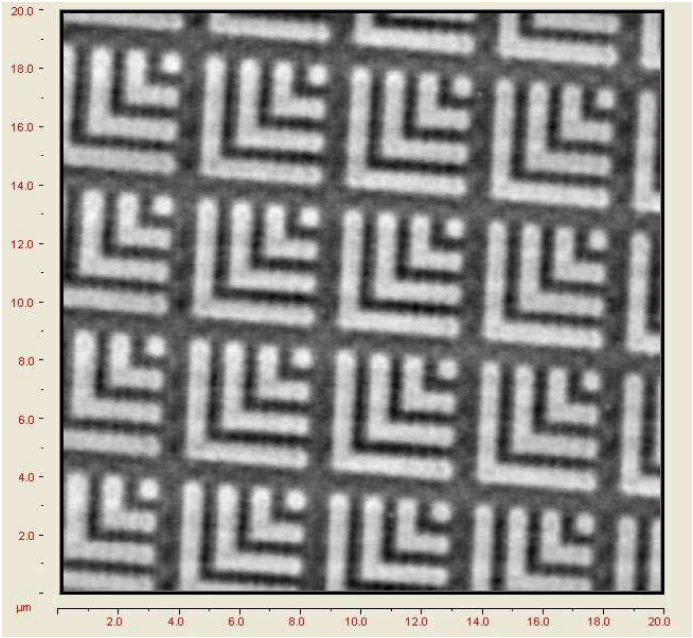
- H. F. Talbot 1836 "Facts relating to optical science" *No. IV, Philos. Mag. 9*
- Lord Rayleigh 1881 "On copying diffraction gratings and on some phenomenon connected therewith" *Philos. Mag. 11*

Previous results

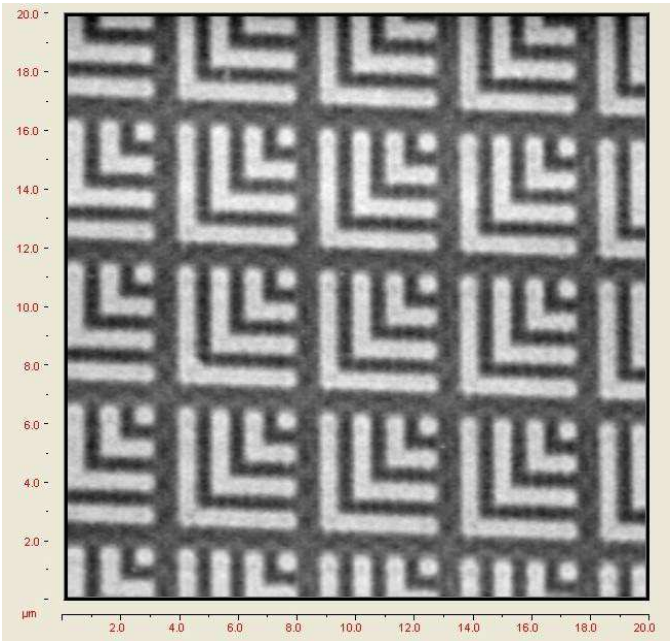
Talbot Mask



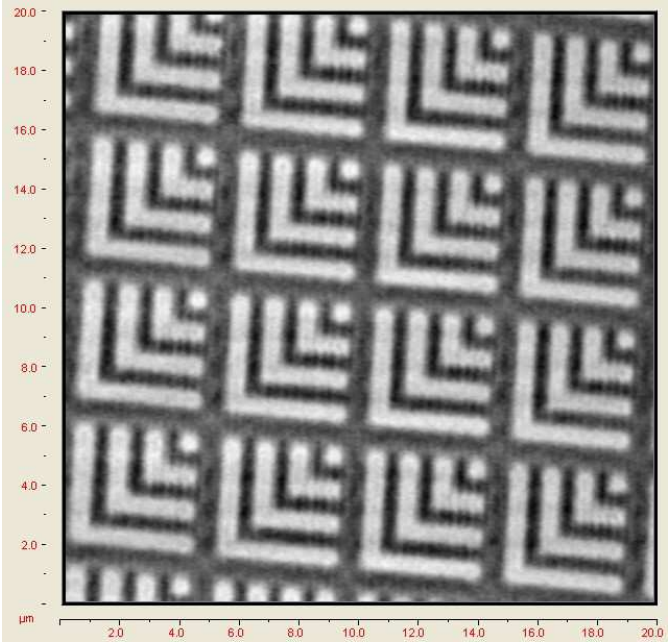
1st Talbot Plane



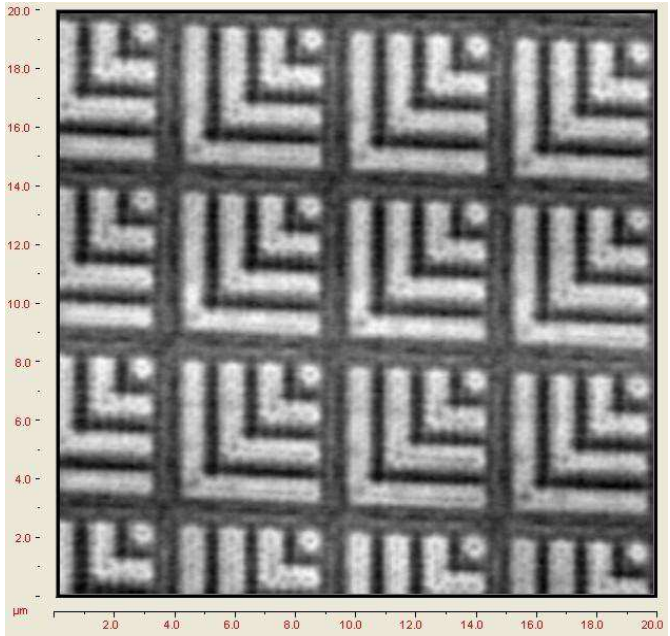
2nd Talbot Plane



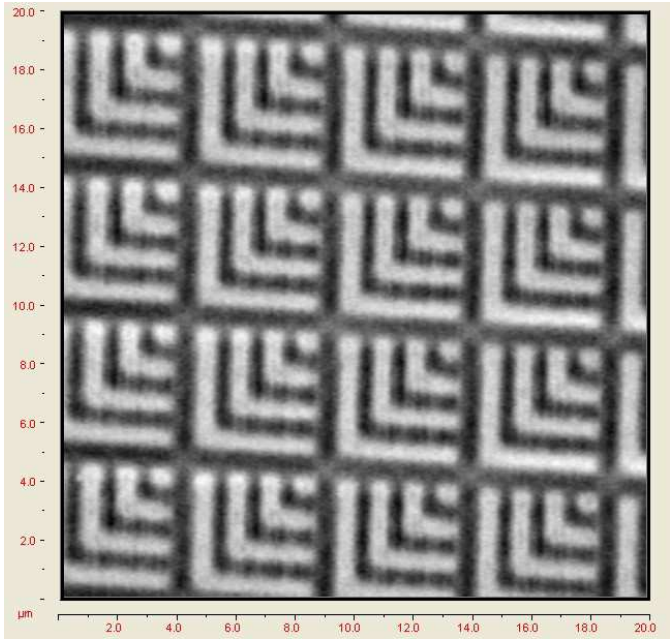
3rd Talbot Plane



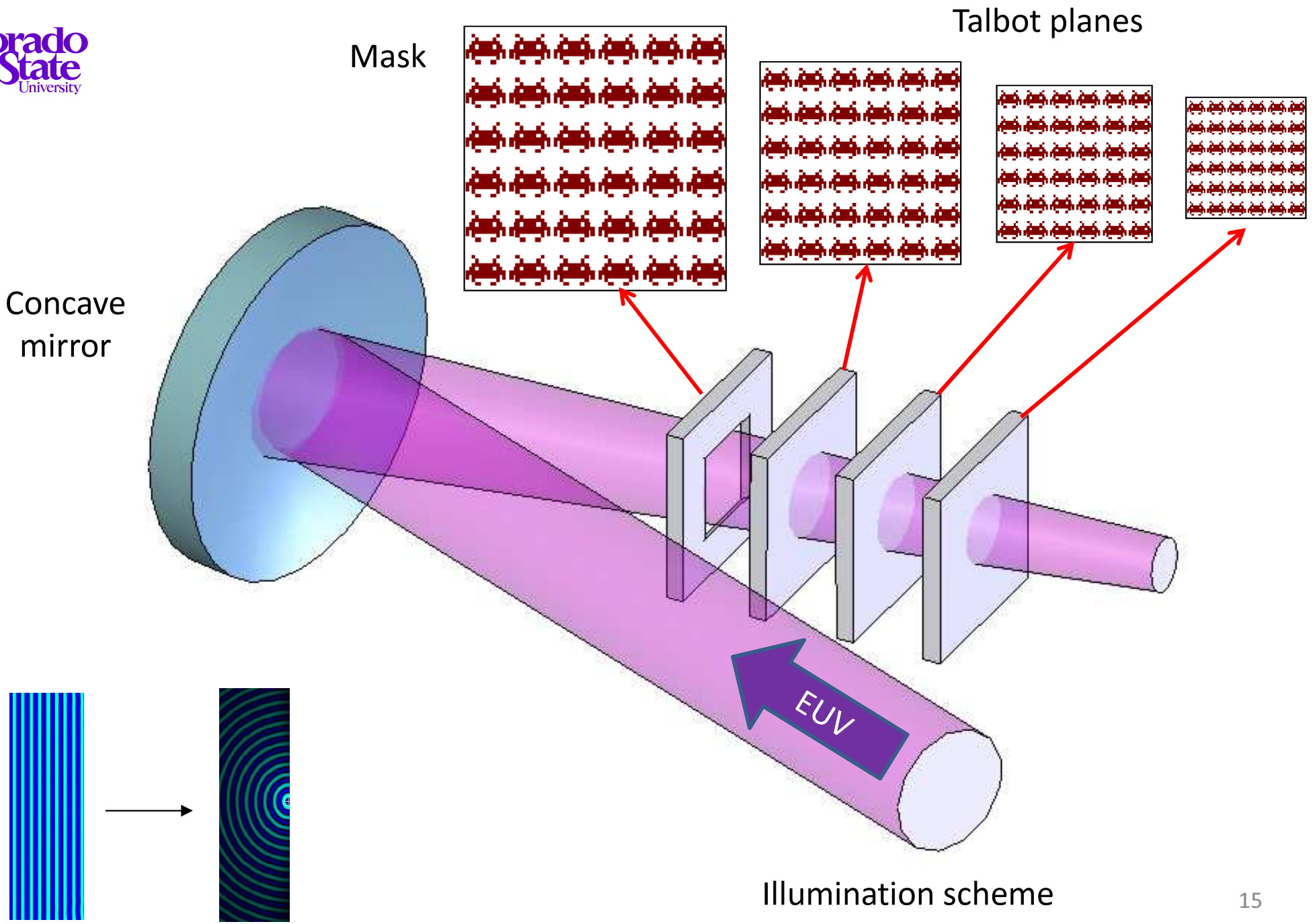
4th Talbot Plane



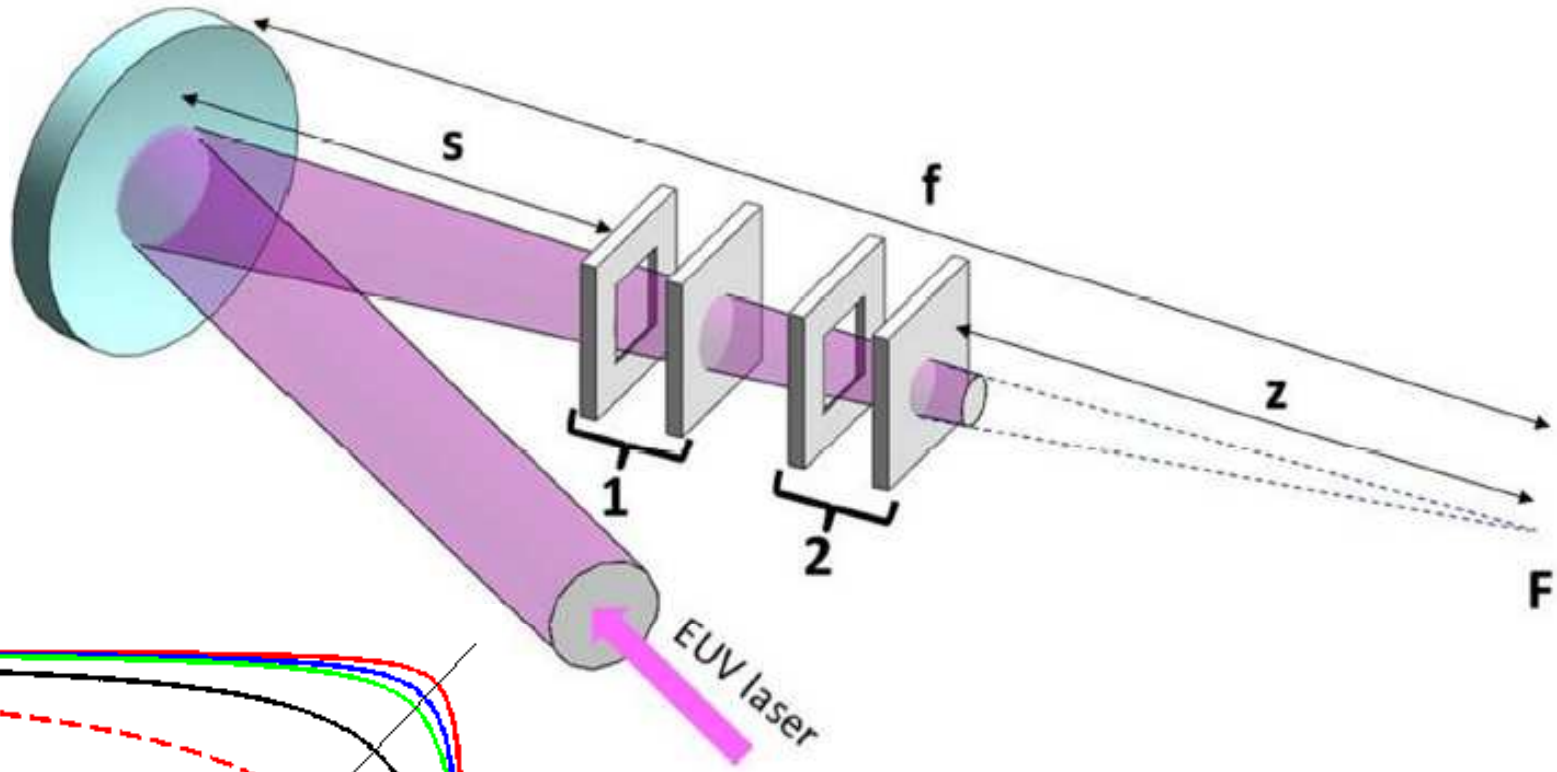
5th Talbot Plane

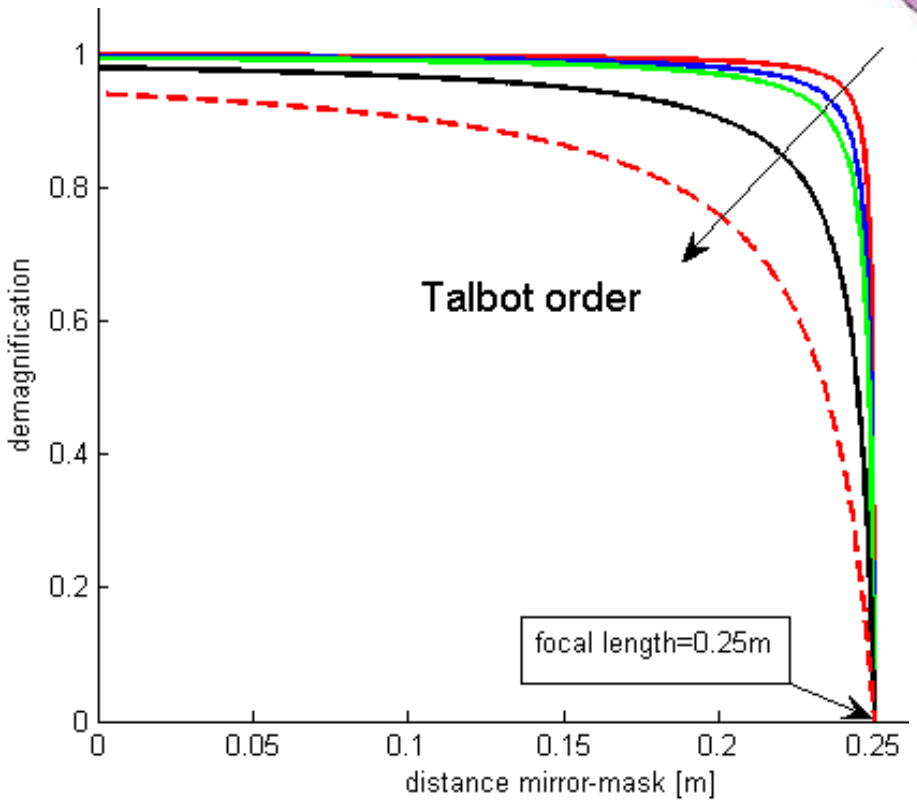


3. De-magnified Talbot Imaging



De-magnified Talbot Imaging: Schematic

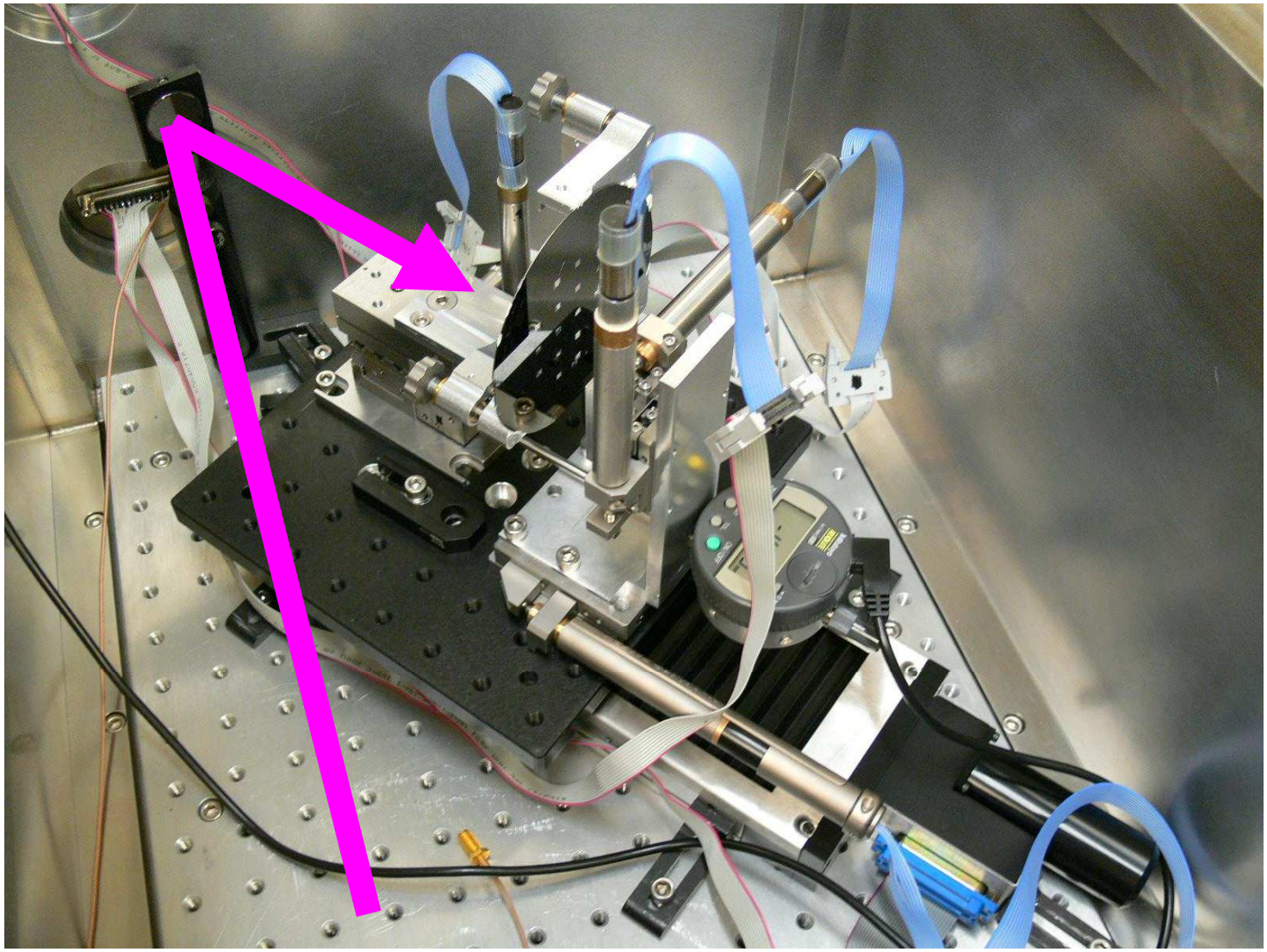




$$p' = p\left[\frac{z}{(f-s)}\right]$$

$$z_T = \frac{2np^2(f-s)}{2np^2 + \lambda(f-s)}$$

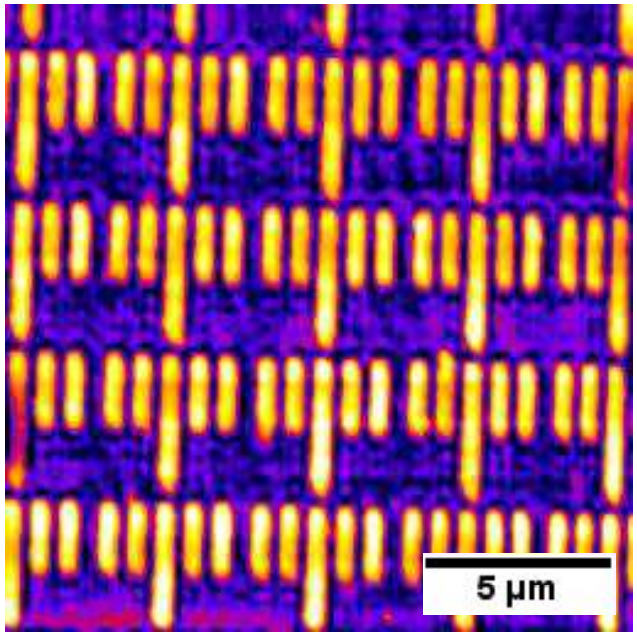
De-magnified Talbot Imaging: Experimental setup

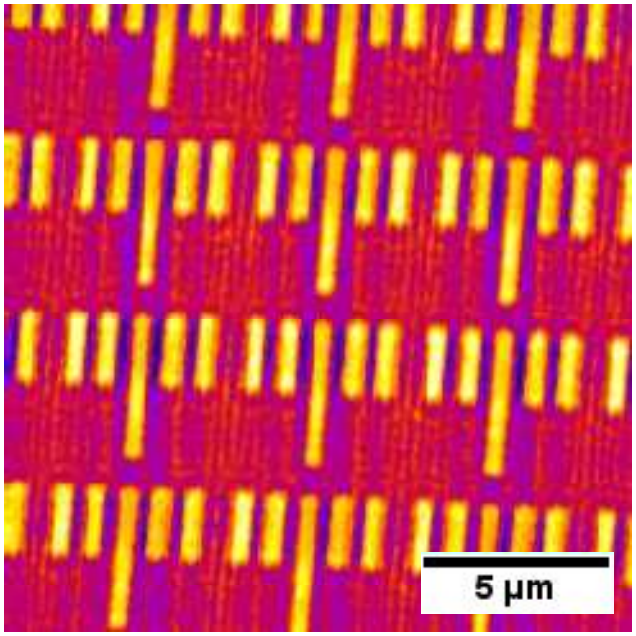


EUV Laser

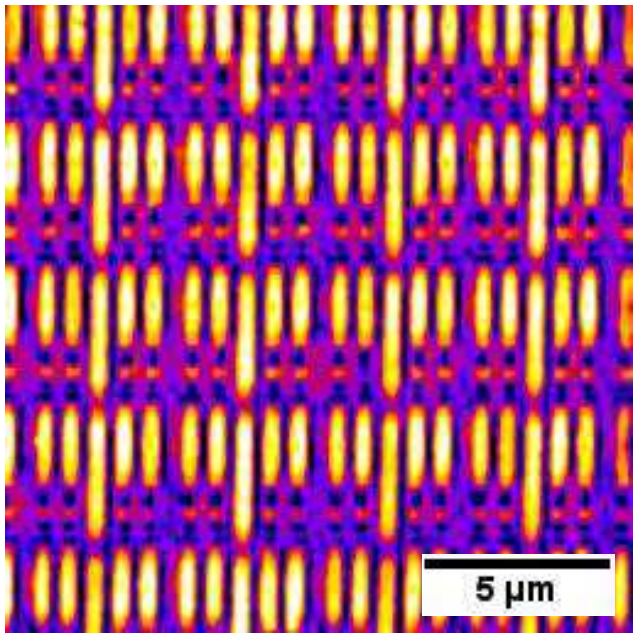
De-magnified Talbot Imaging: Results

p'/p = 0.98

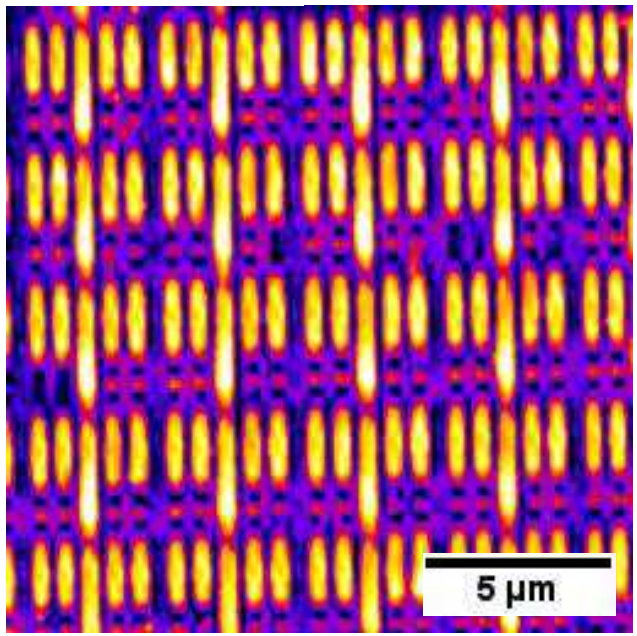




p'/p = 0.887

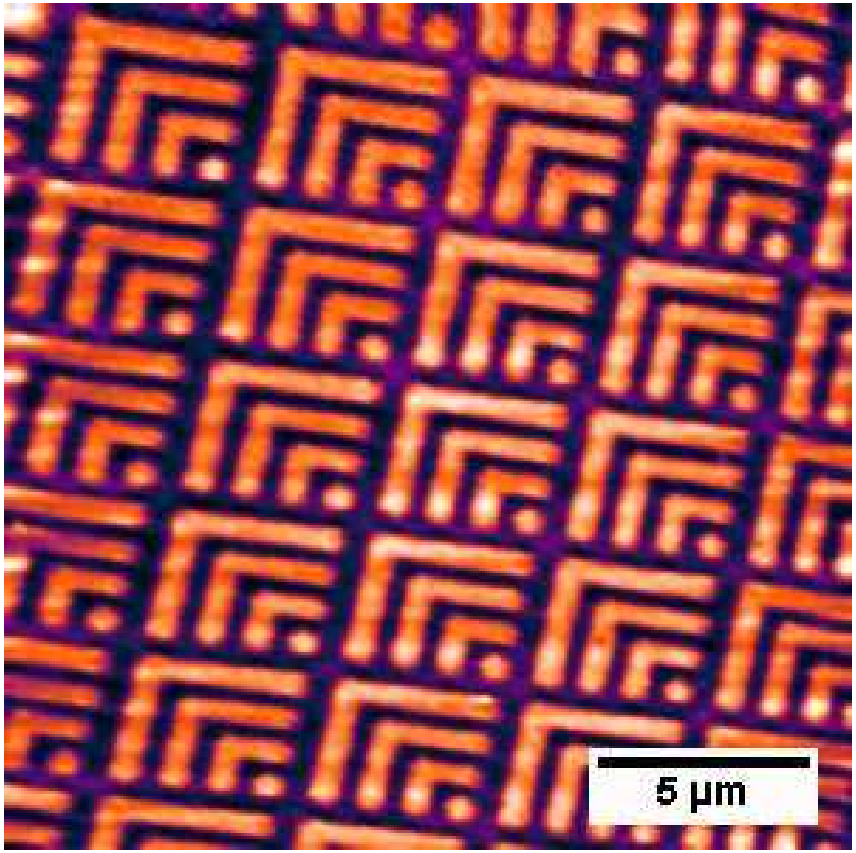


p'/p = 0.867

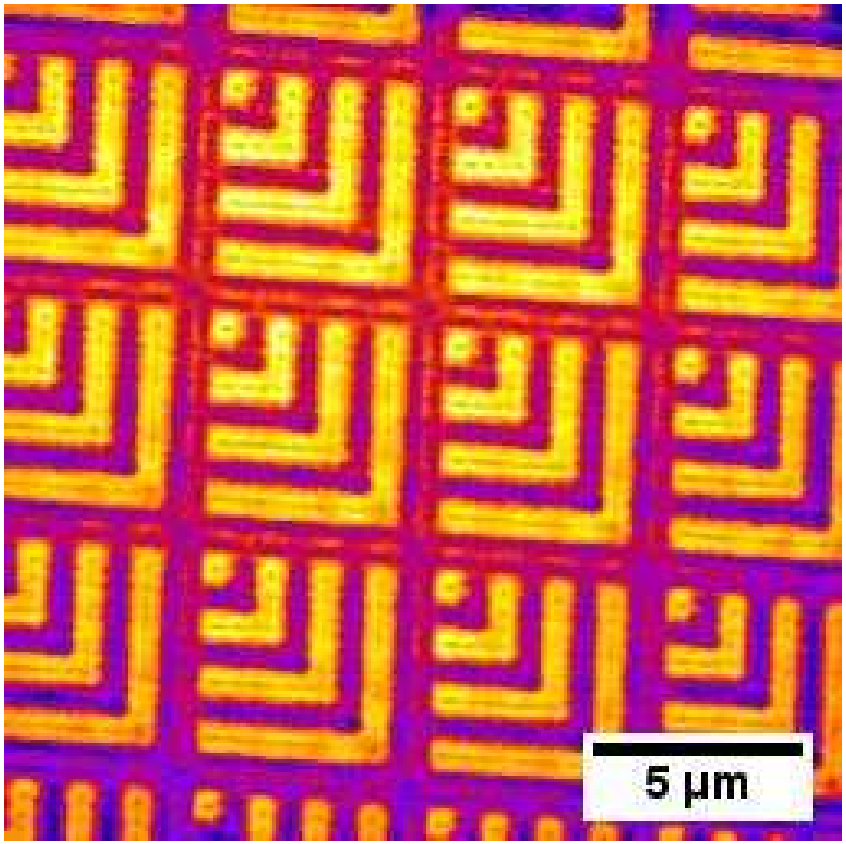


De-magnified Talbot Imaging: Results cont.

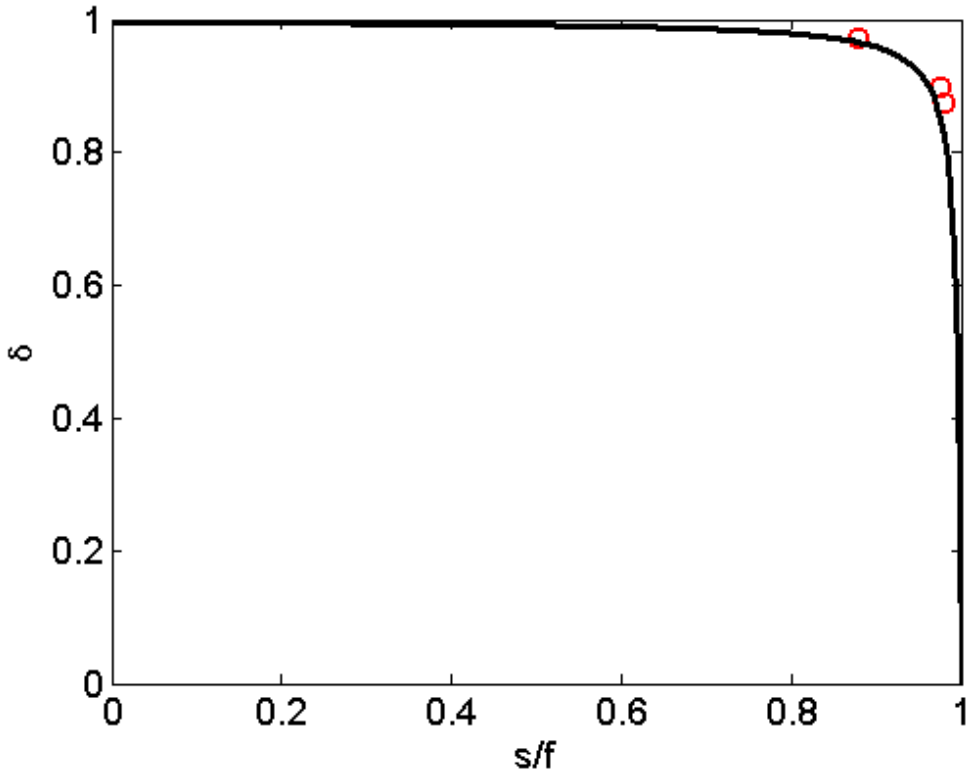
Reconstruction with de- magnification



Reconstruction without de-magnification



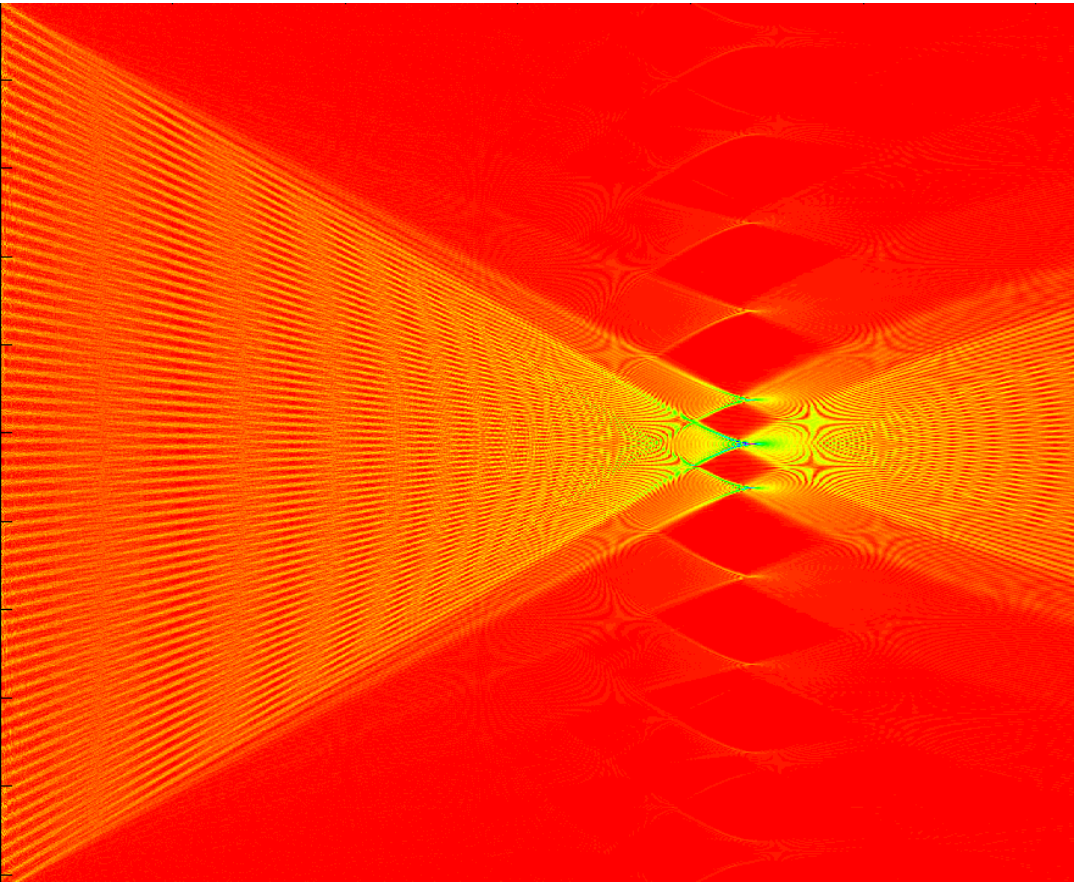
De-magnified GTI: Summary

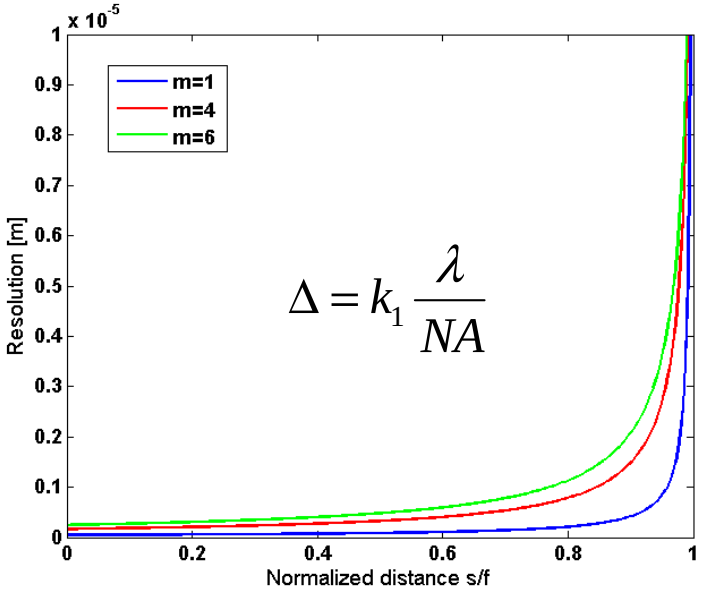


Calculated de-mag.	Measured de-mag.
0.96	0.980
0.86	0.887
0.82	0.865

Comparison between measured and calculated values of de-magnification

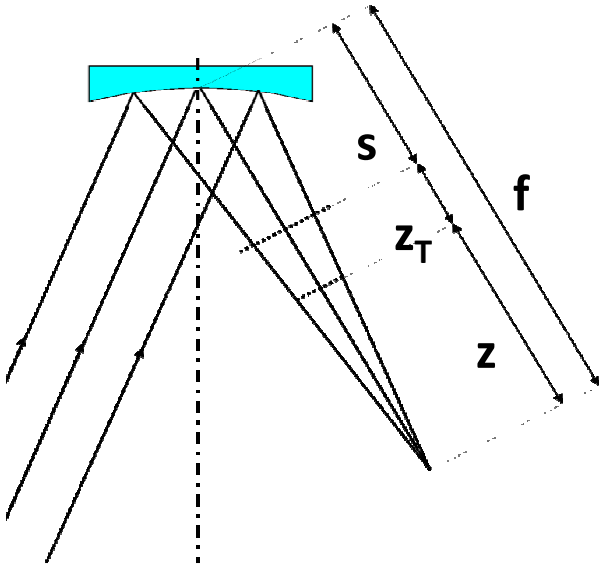
De-magnified GTI: Limitation to de-magnification





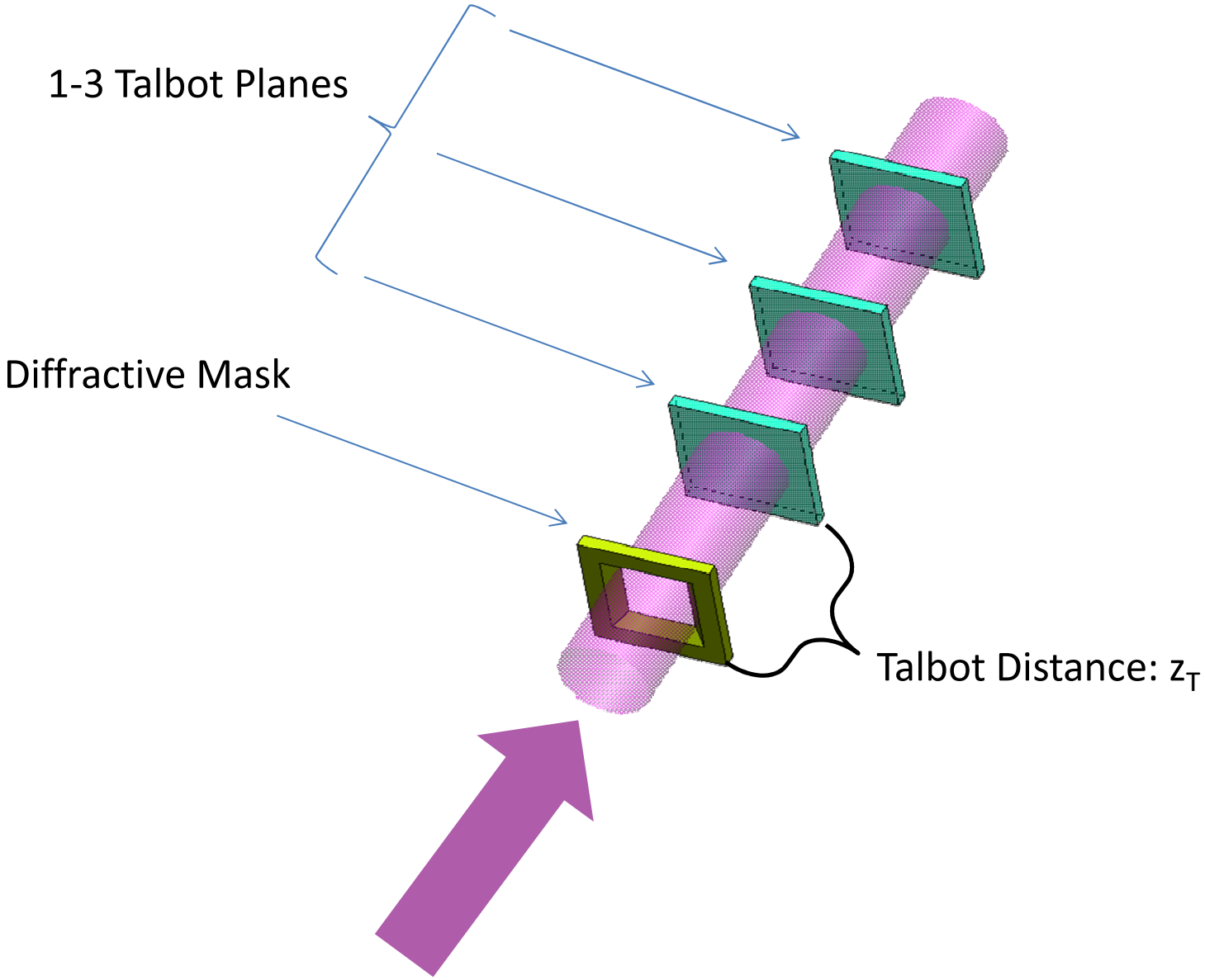
$$\Delta = k_1 \frac{\lambda}{NA}$$

$$NA = \left[\sqrt{1 + \left(\frac{2(f-s)p^2 mf}{(2p^2 m + \lambda(f-s))(f-d-s)W} \right)^2} \right]^{-1}$$

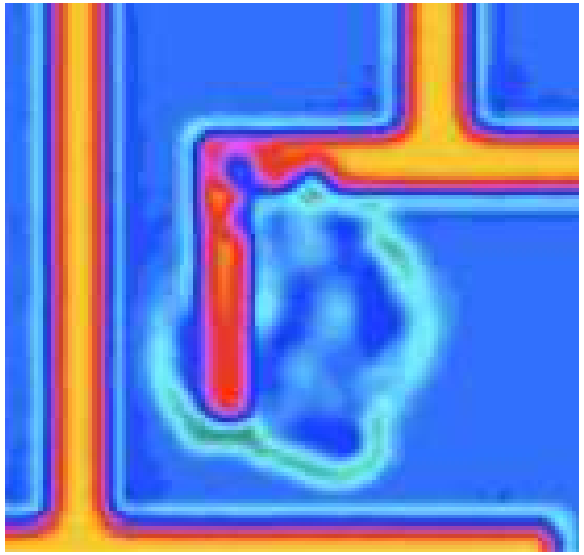


Urbanski, L.; Marconi, M. C.; Isoyan, A.; Stein, A.; Menoni, C. S. & Rocca, J. J. „Analysis of a scheme for de-magnified Talbot lithography" *JVST B: Microelectronics and Nanometer Structures, AVS,* **2011**, *29*, 06F504

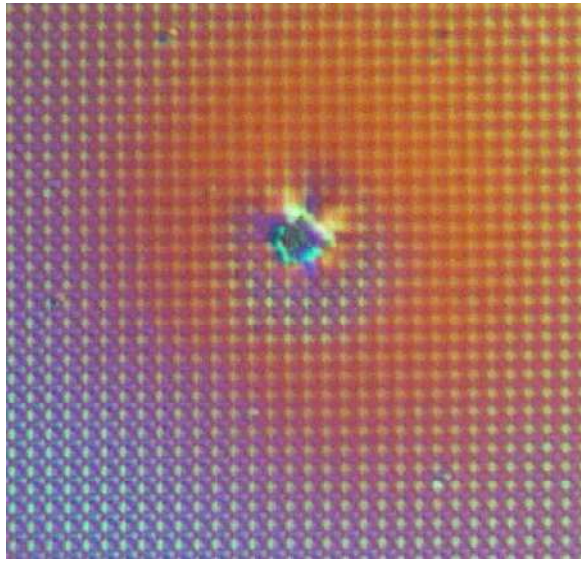
4. Generalized Talbot Imaging: Defect Tolerance

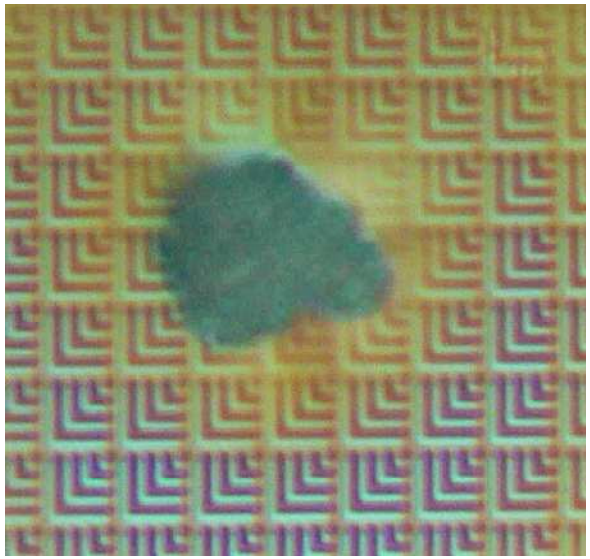


Typical Defects in a Mask



http://www.als.lbl.gov/als/science/sci_archive/213-EUVLithography.html





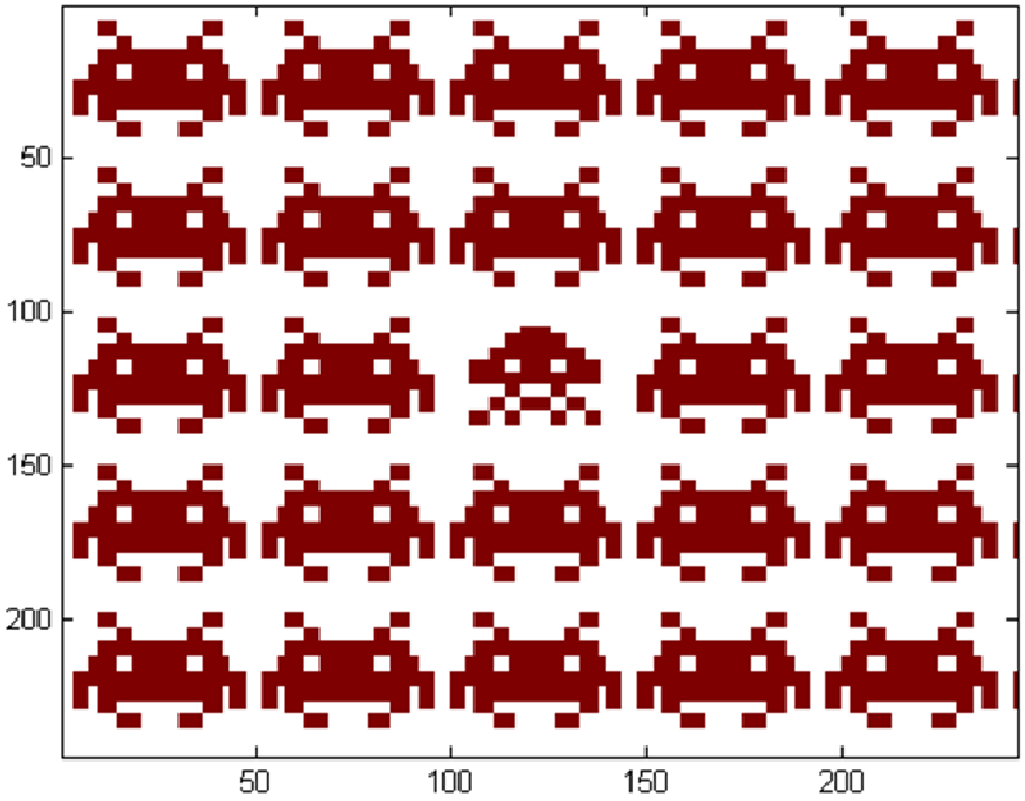
My Experience

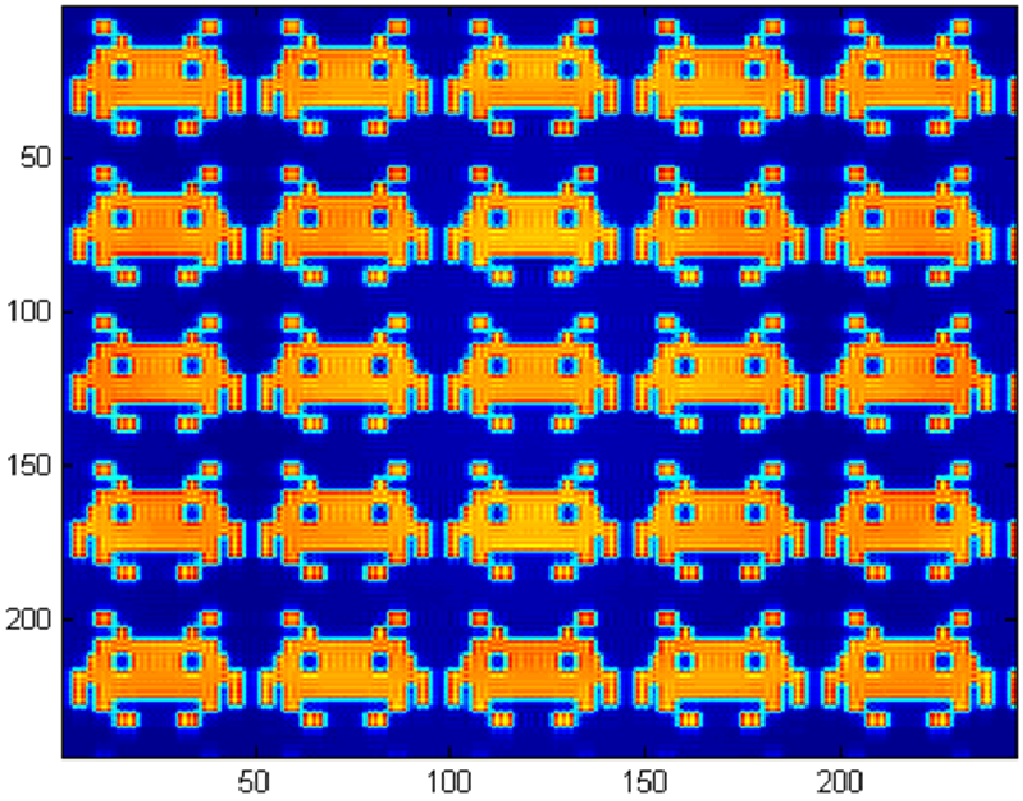
EUV
An NSF Engineering Research Center

Colorado State University

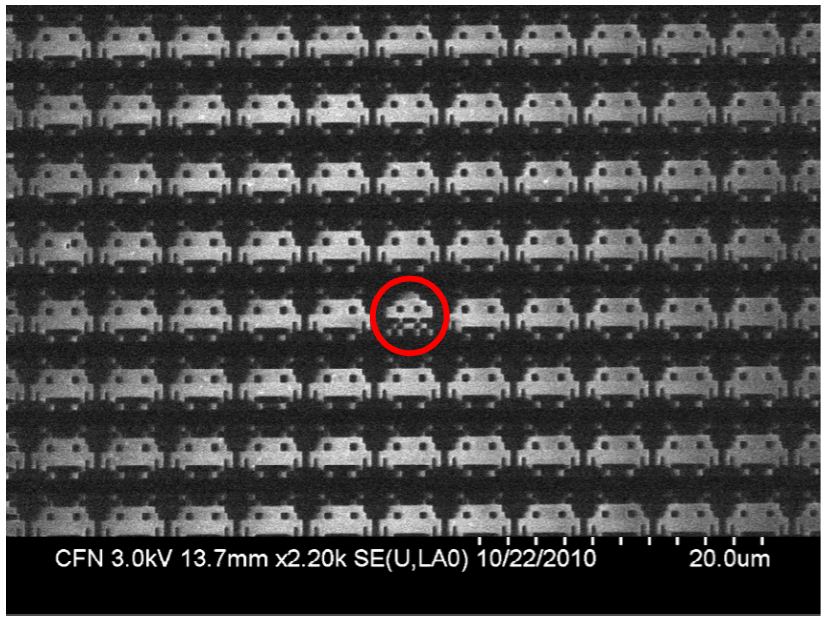
Center for Functional Nanomaterials
Brookhaven National Laboratory

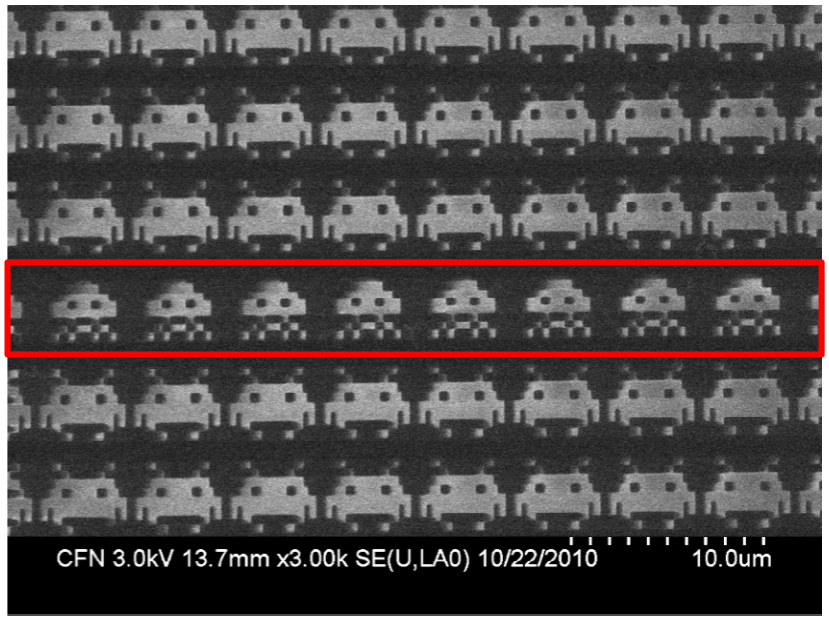
Defected Mask: Numerical Simulation

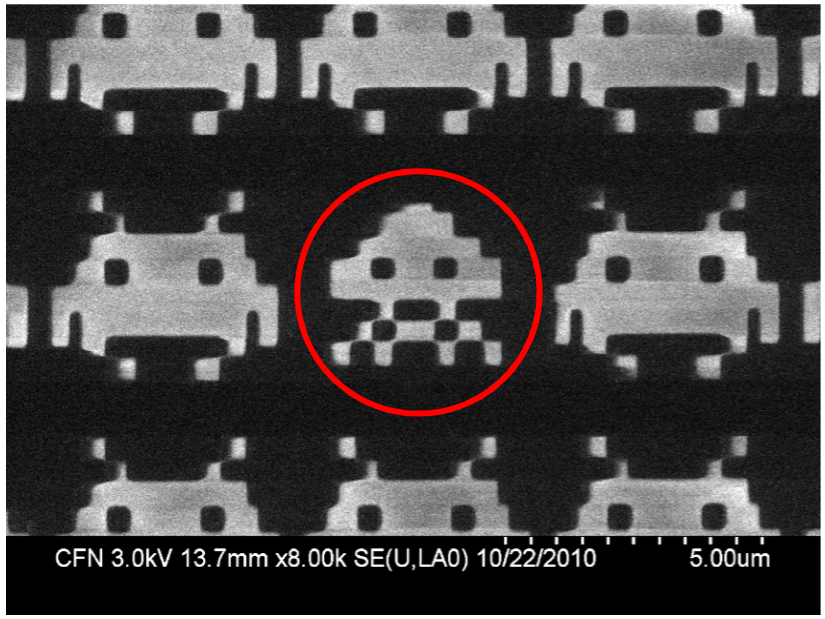


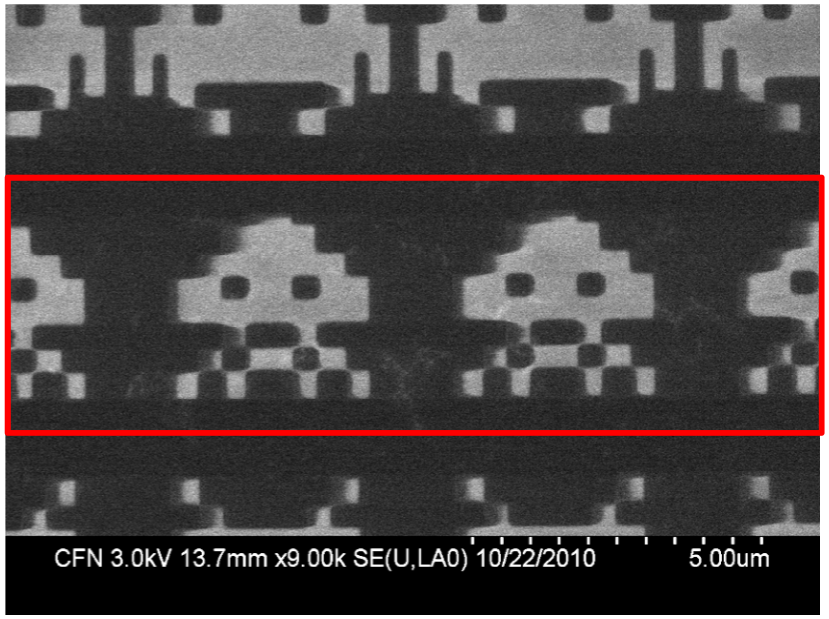


Experimental Verification: Mask Design

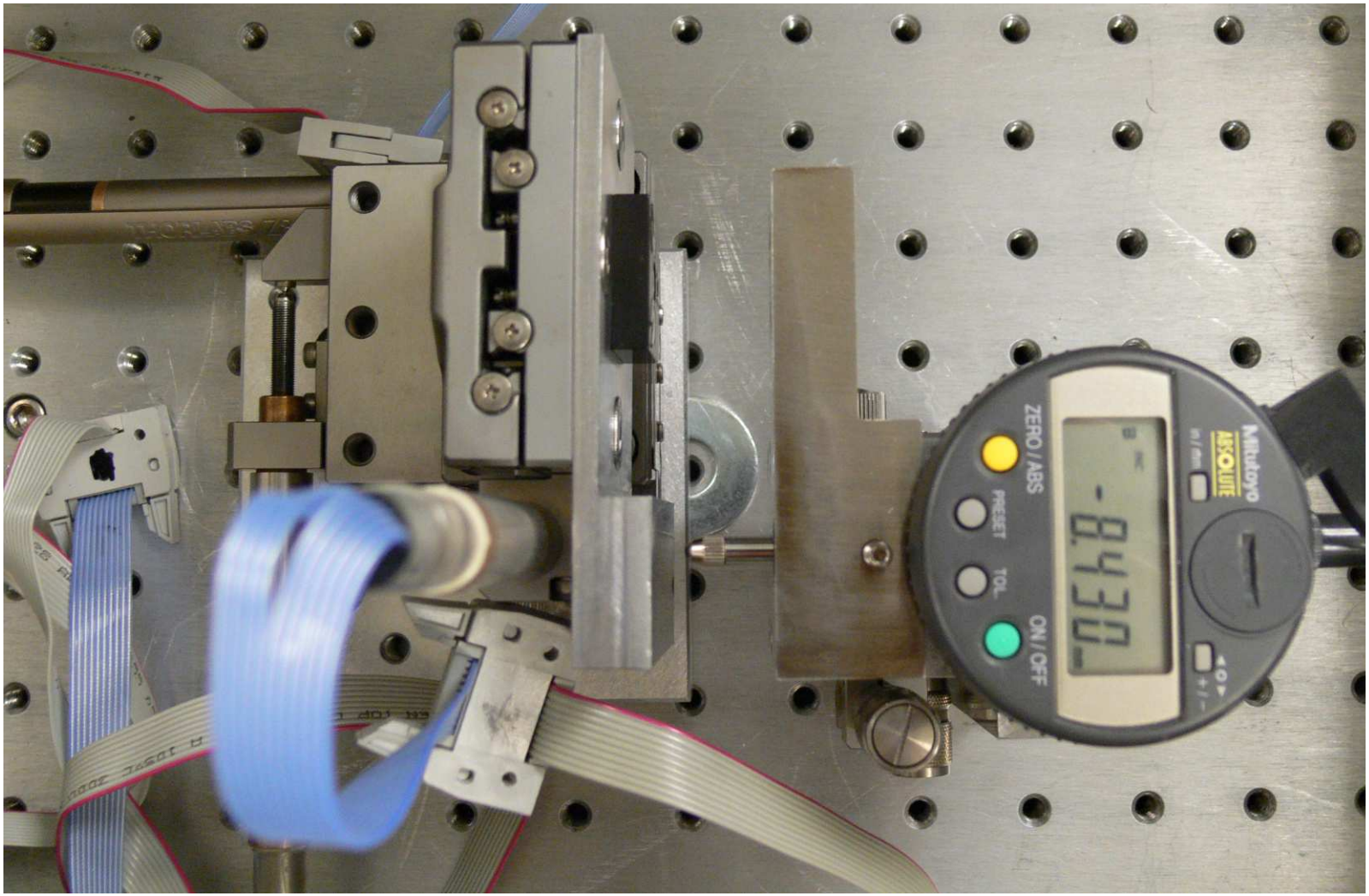








Experimental Verification: Setup

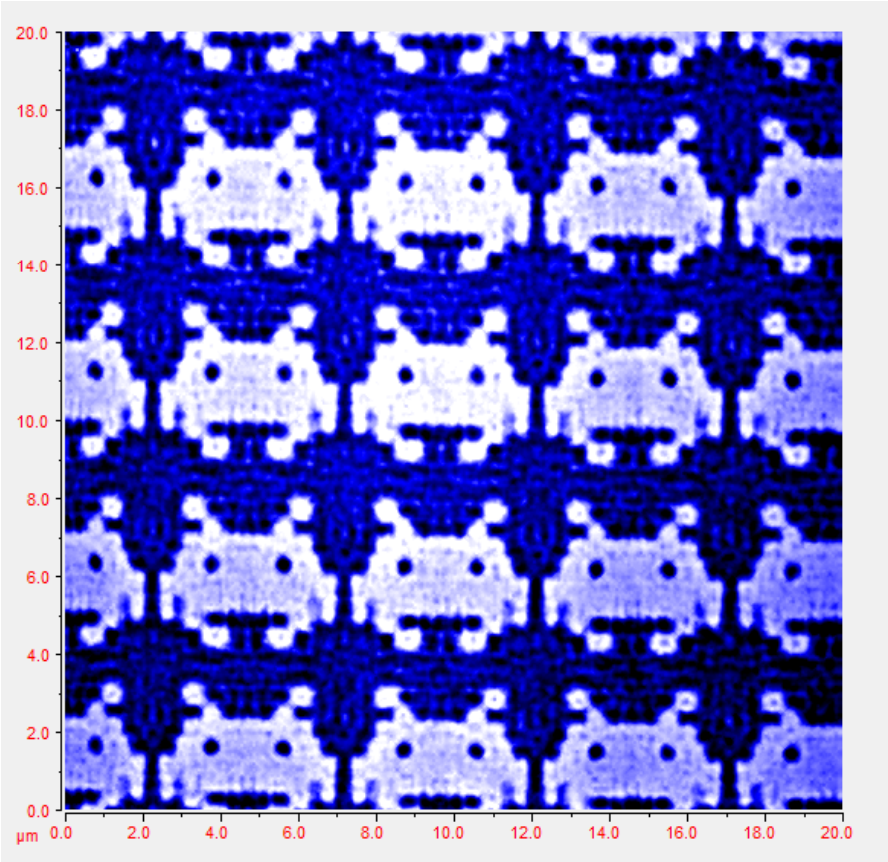


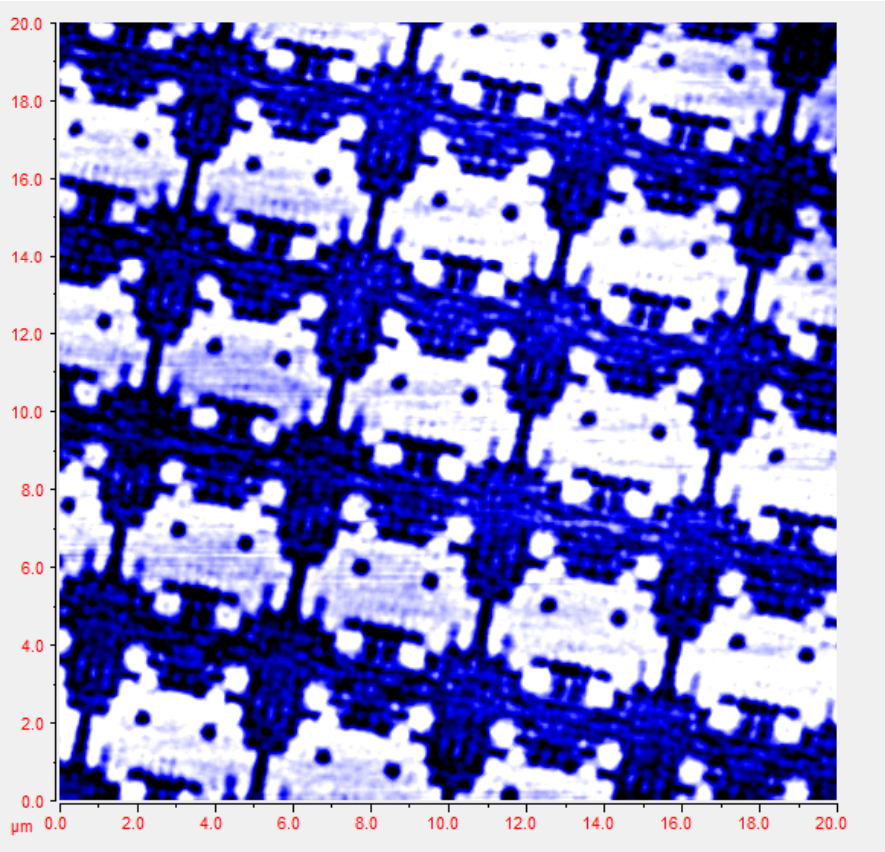
EUV
An NSF Engineering Research Center

Colorado State University

Center for Functional Nanomaterials
Brookhaven National Laboratory

Experimental Verification: Results





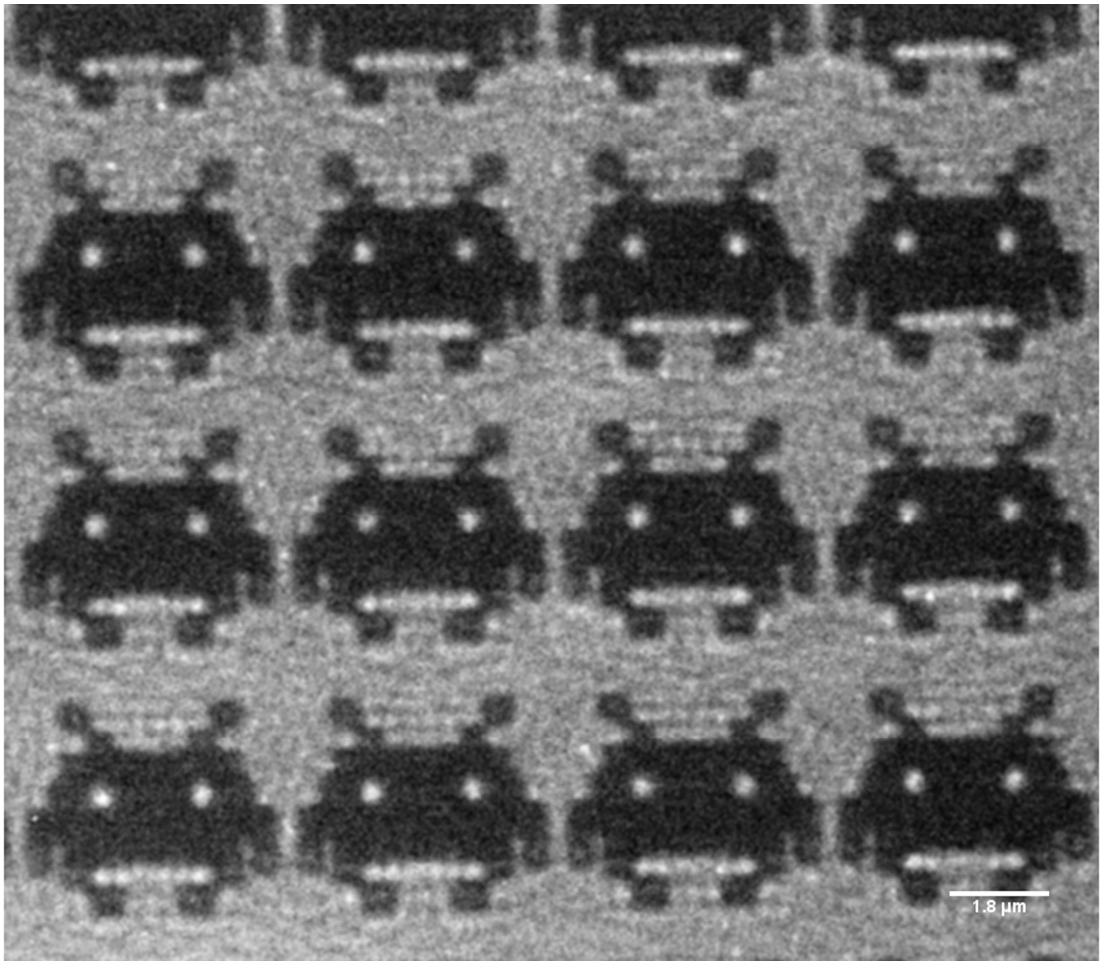
Atomic Force Microscope Scan of patterned resist (PMMA) 20x20micron^2

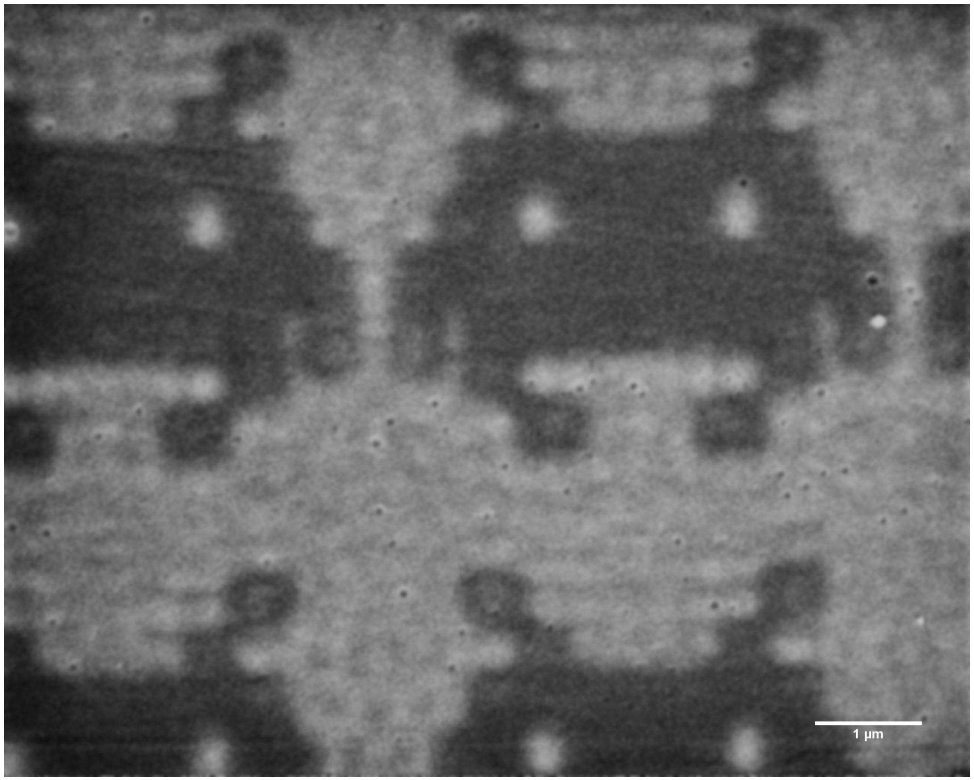
EUV
An NSF Engineering Research Center

Colorado State University

Center for Functional Nanomaterials
Brookhaven National Laboratory

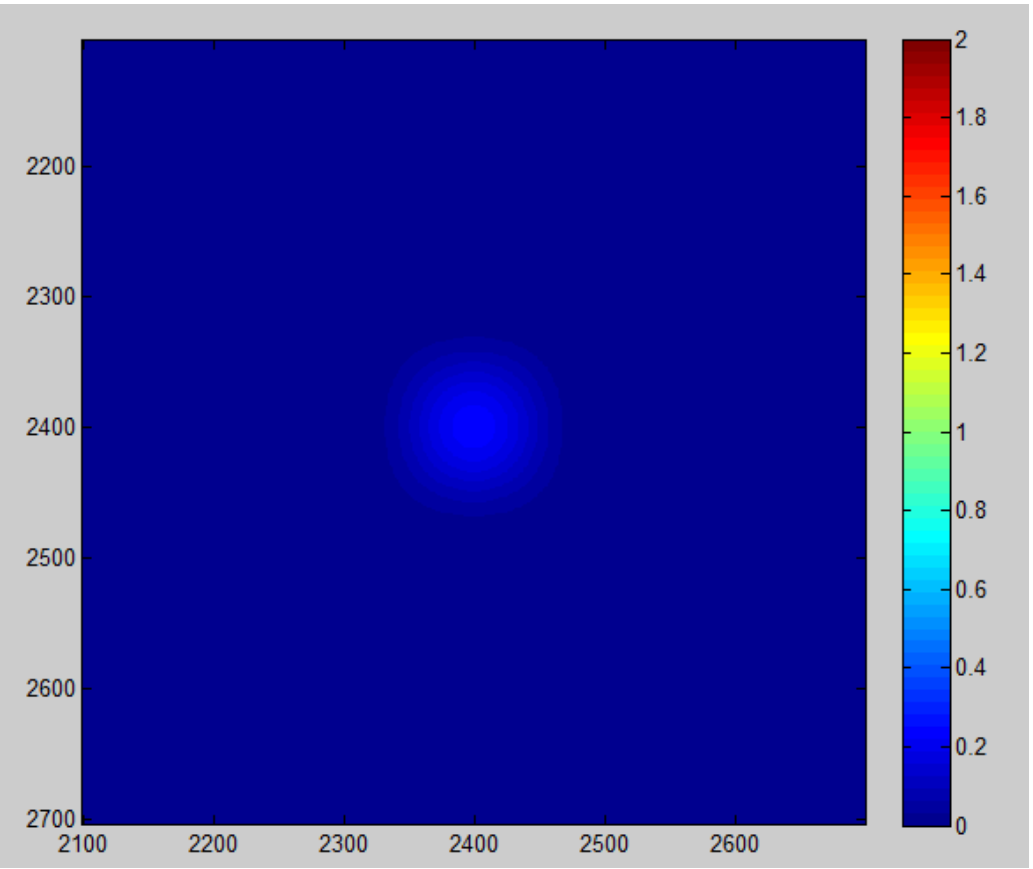
Experimental Verification: Results

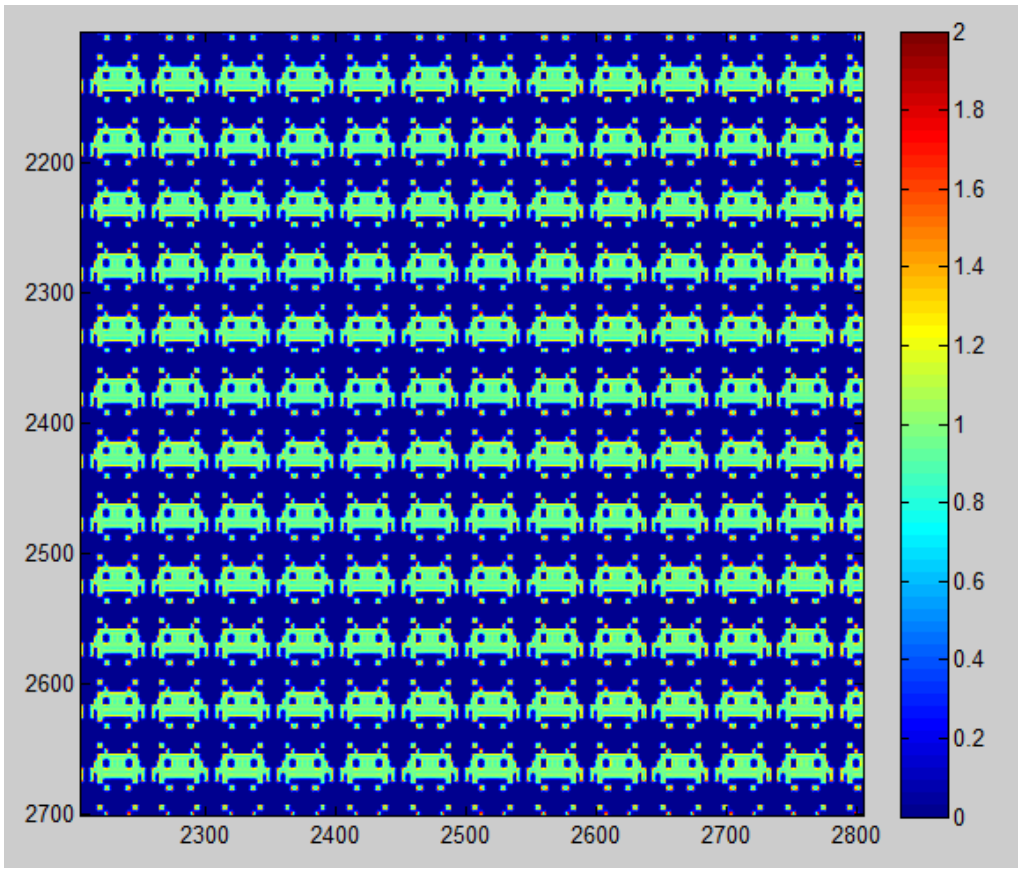




Electron Microscope Scan of patterned resist (PMMA)

Unit cell - sized defect vs. Healthy mask @ Talbot plane

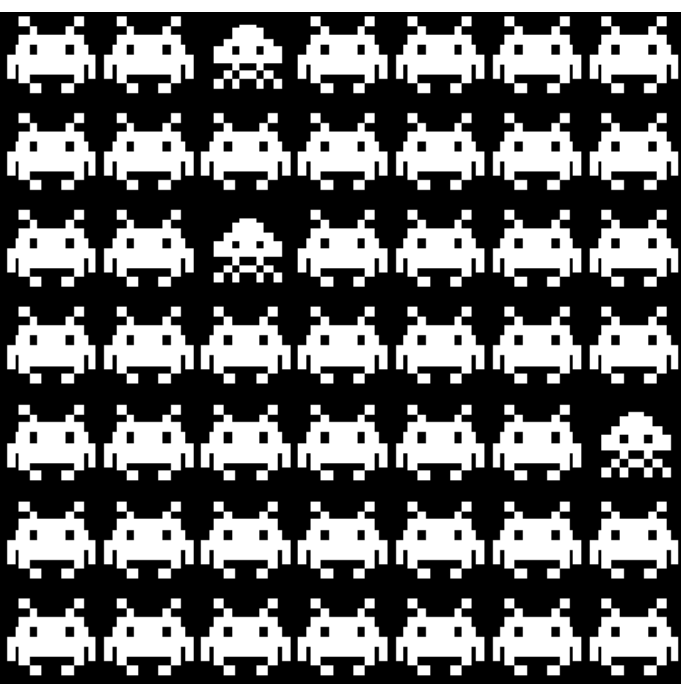


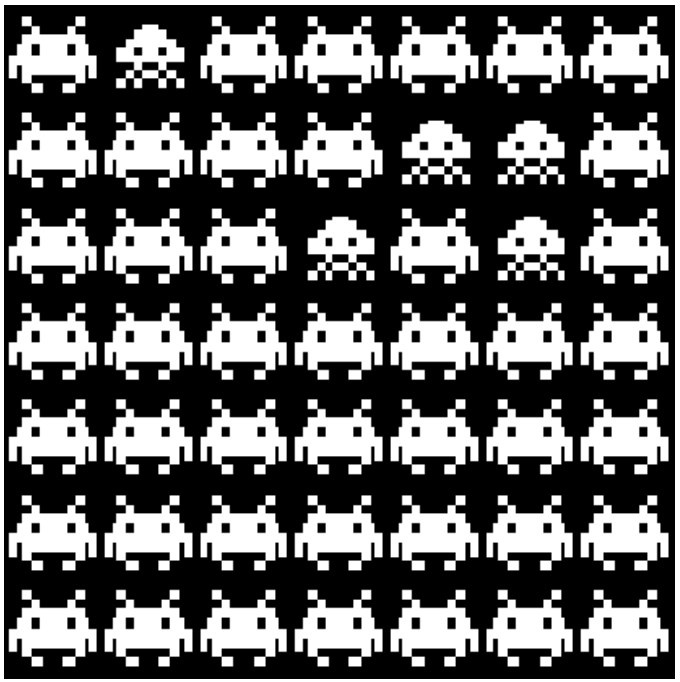


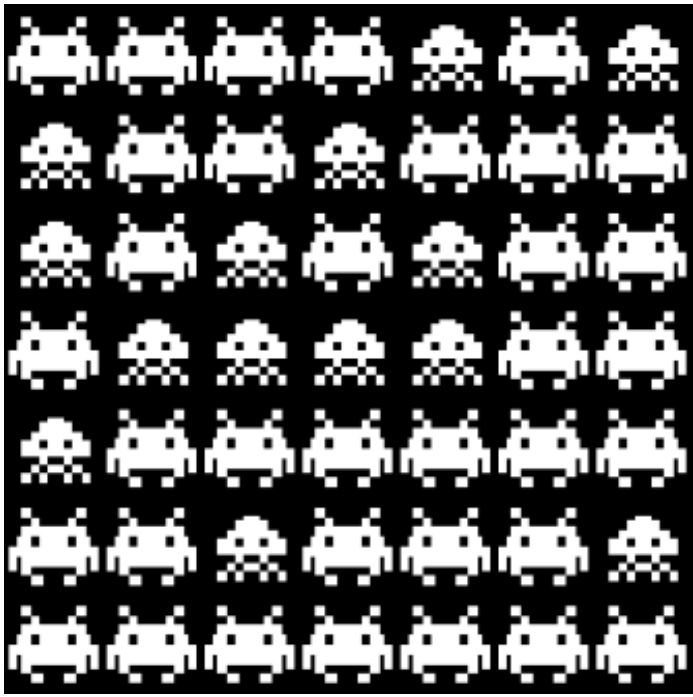
My TO DO List

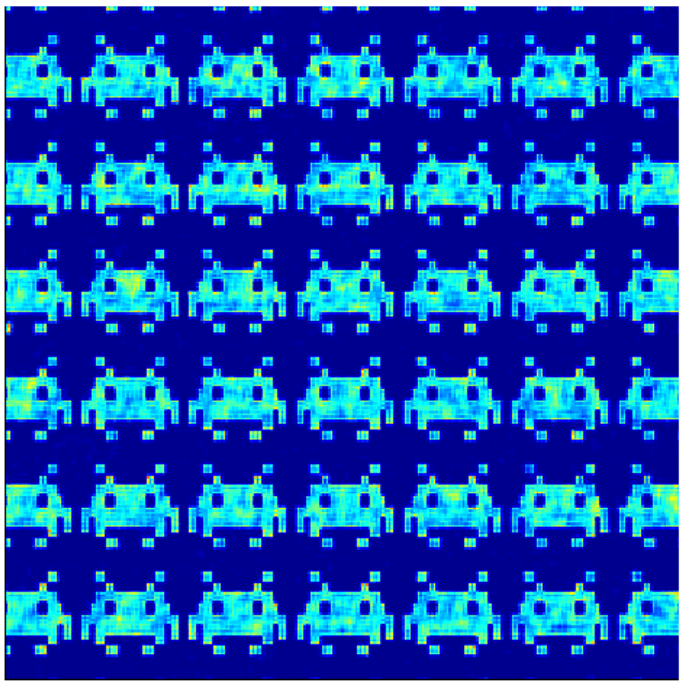
1. Randomly Distributed Defect Analysis in GTI,
   a) Analysis and Uniform Description of Defect Tolerance,
2. High NA GTI,
3. CGH Reconstruction.

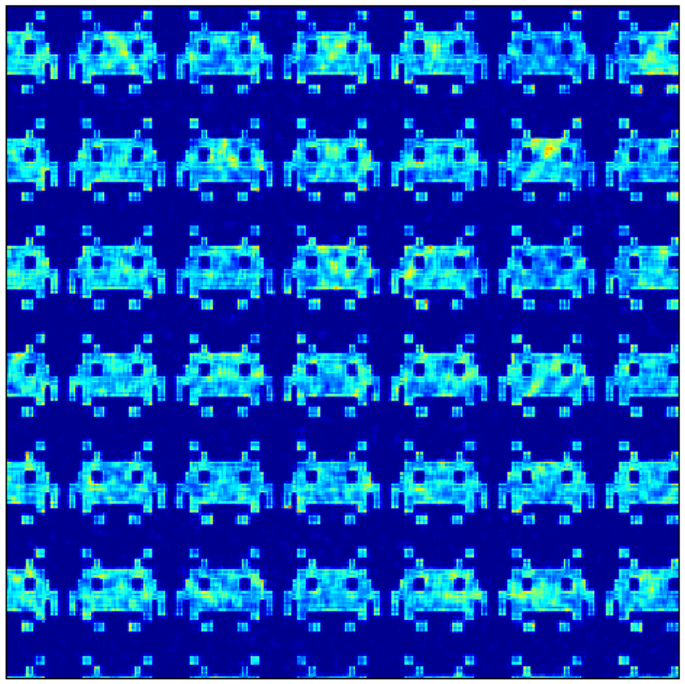
1. Randomly Distributed Defect Analysis in GTI

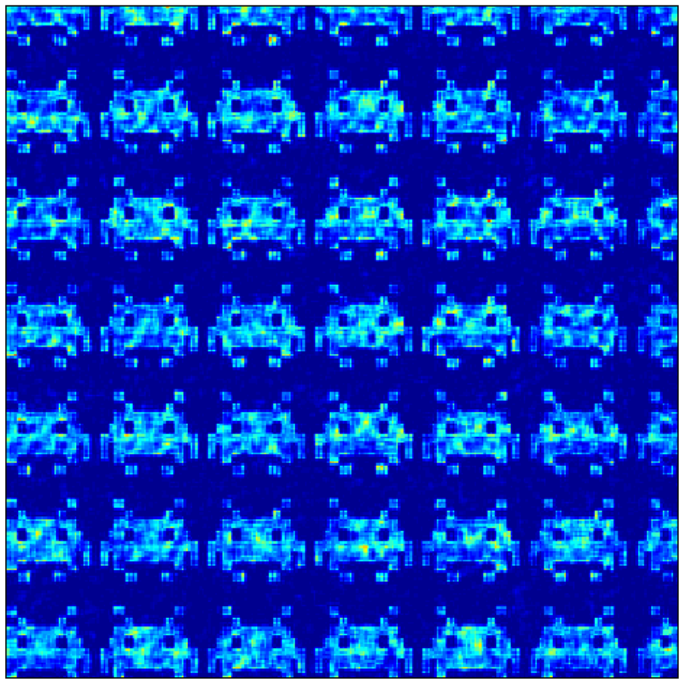










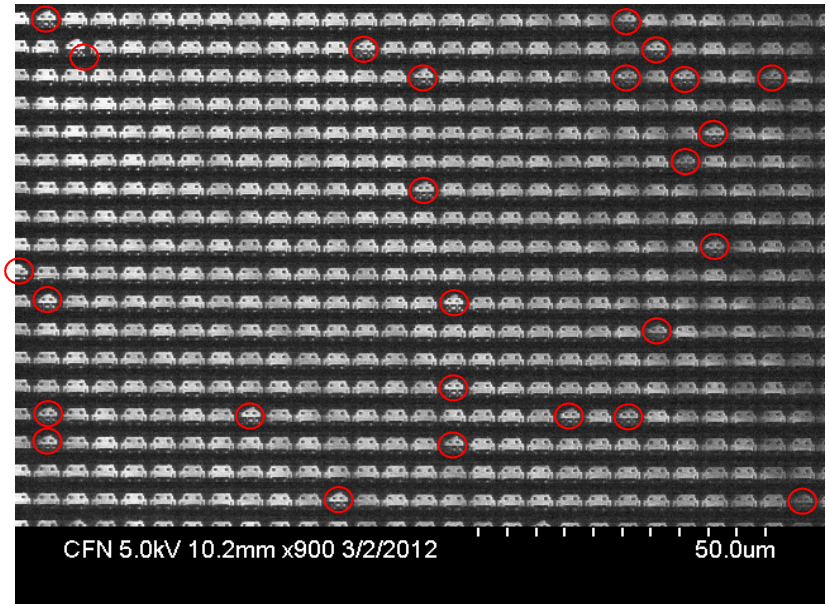


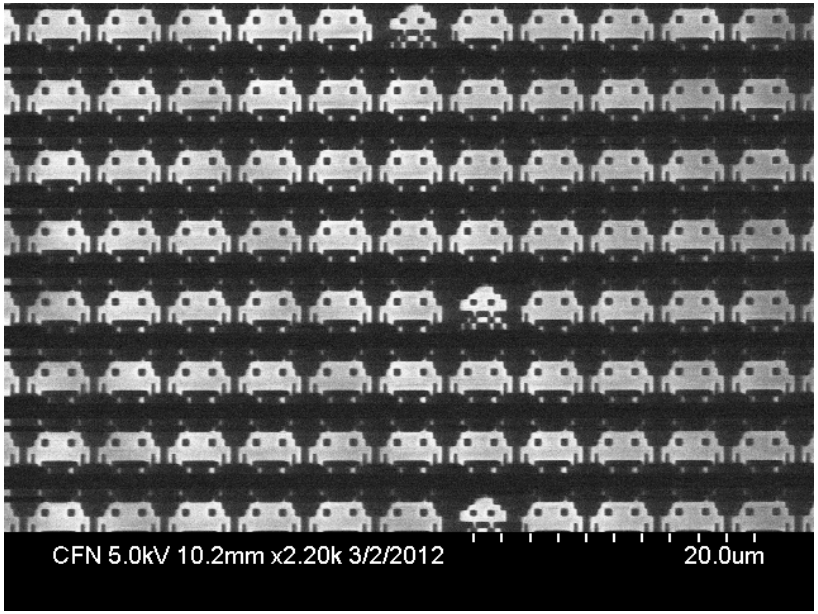
5%

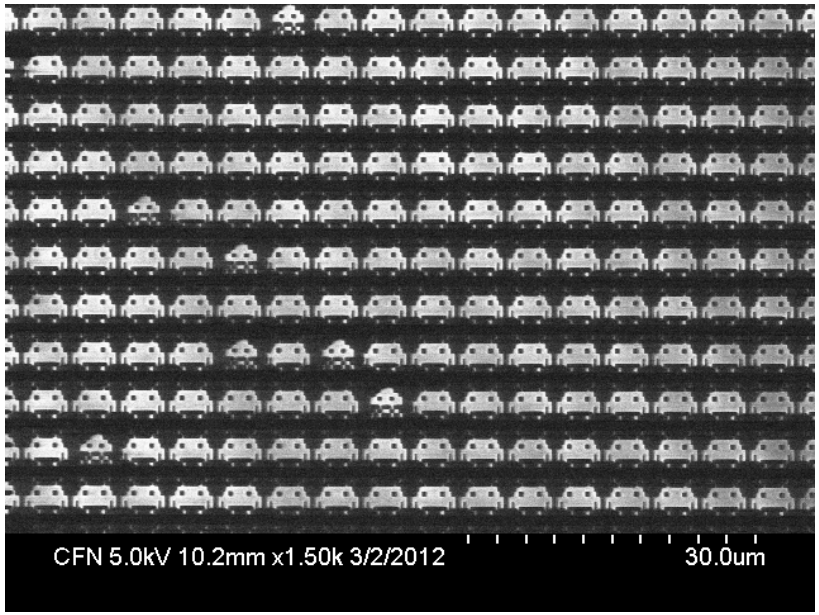
10%

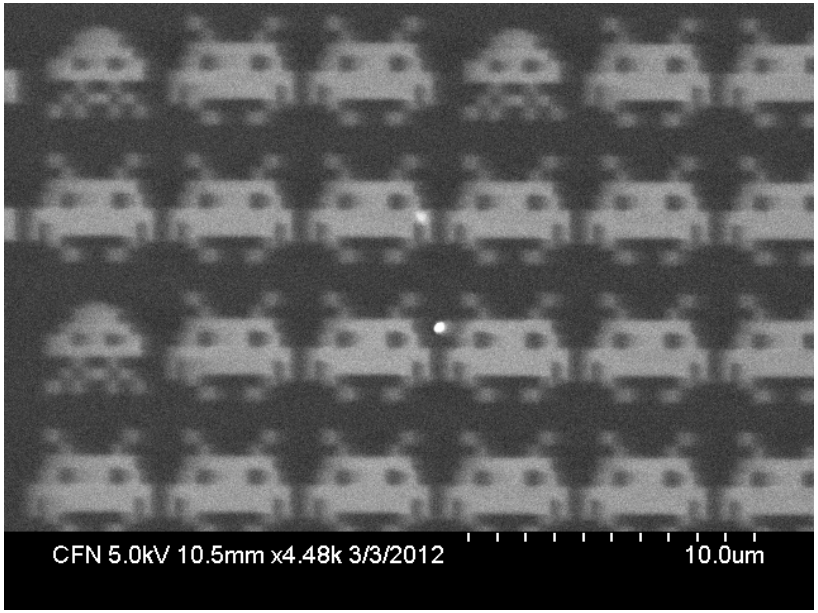
20%

Randomly Distributed Defect Analysis in GTI

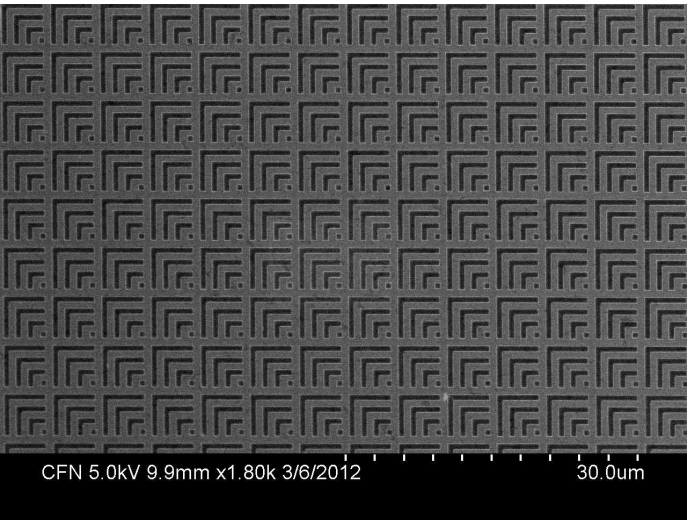


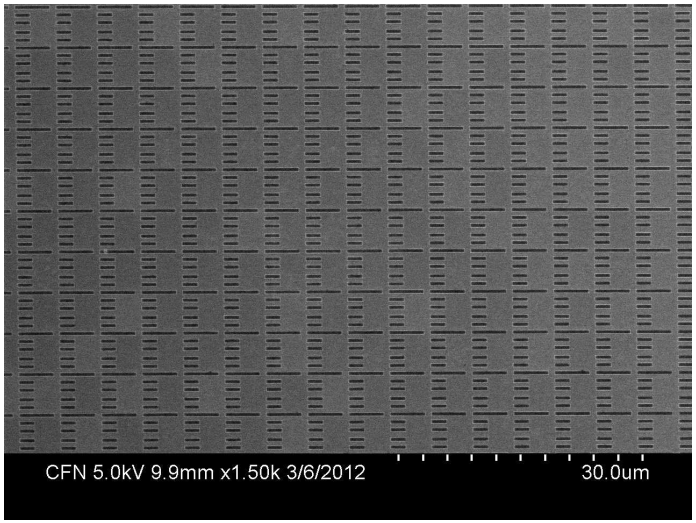


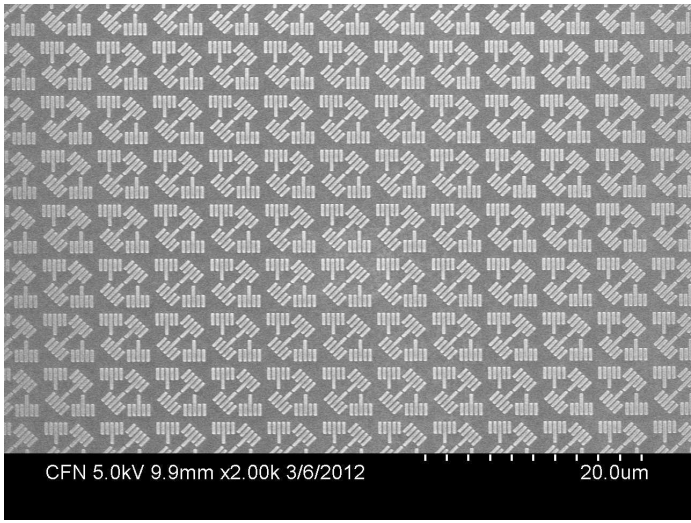


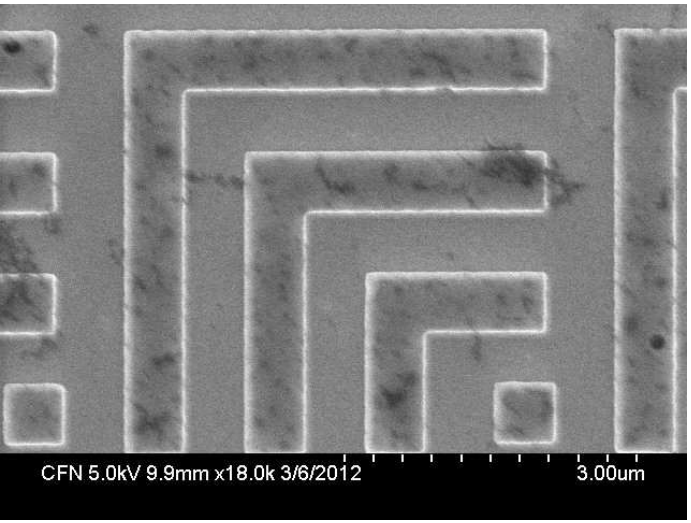


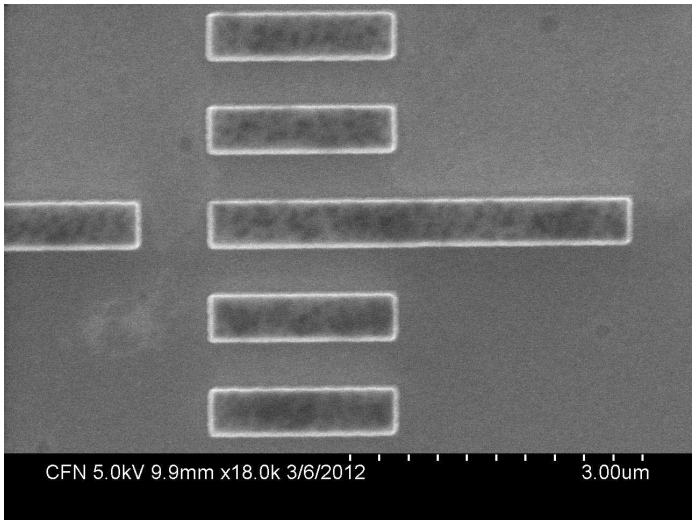
2. High NA GTI Lithography

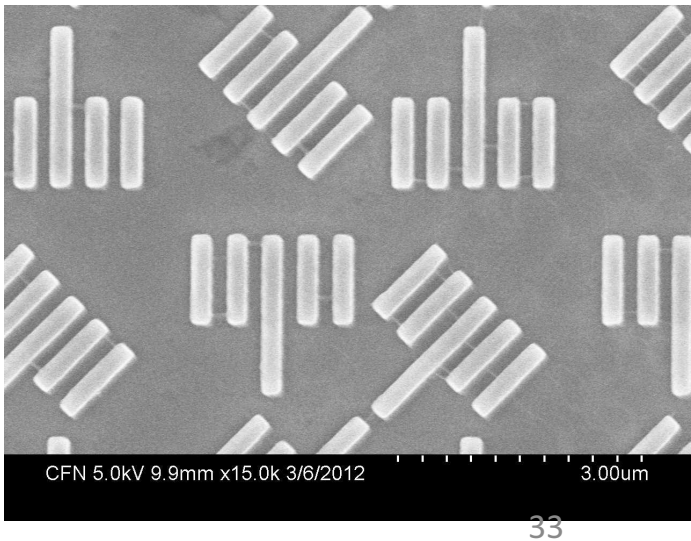




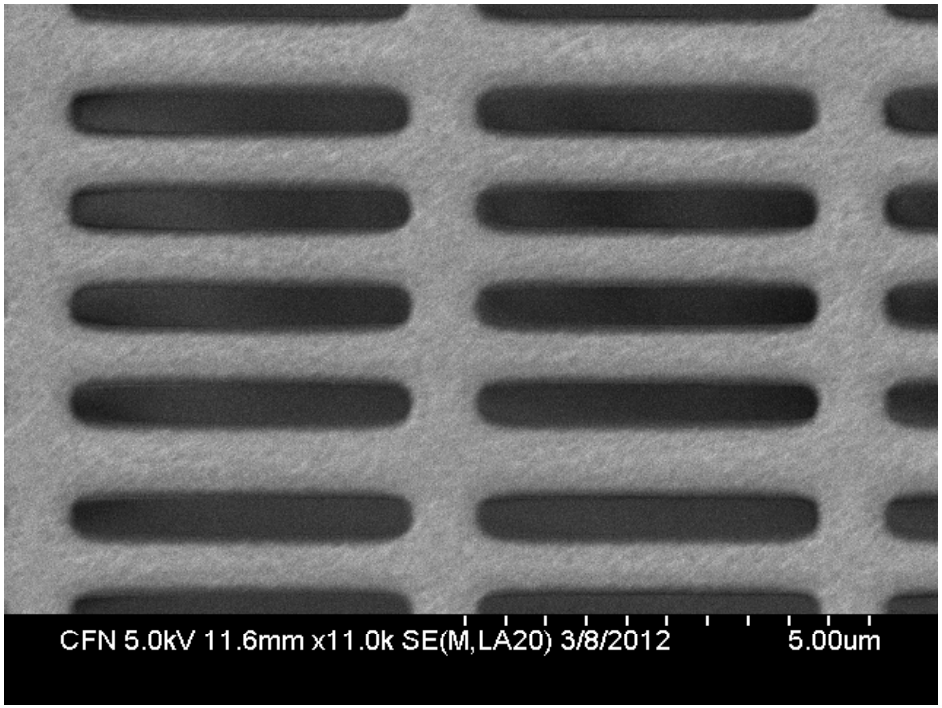


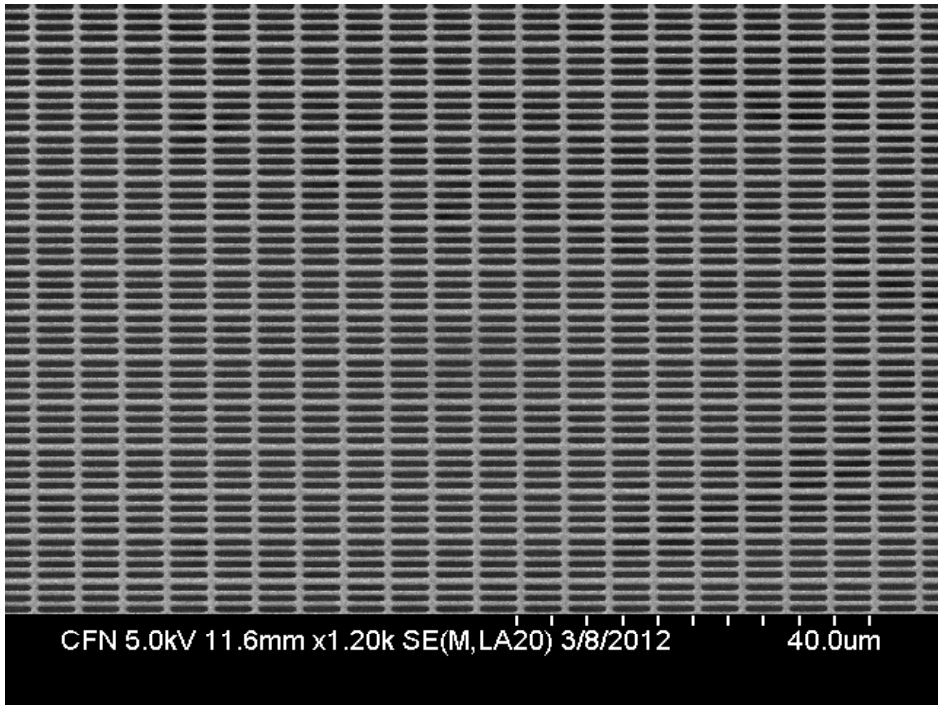


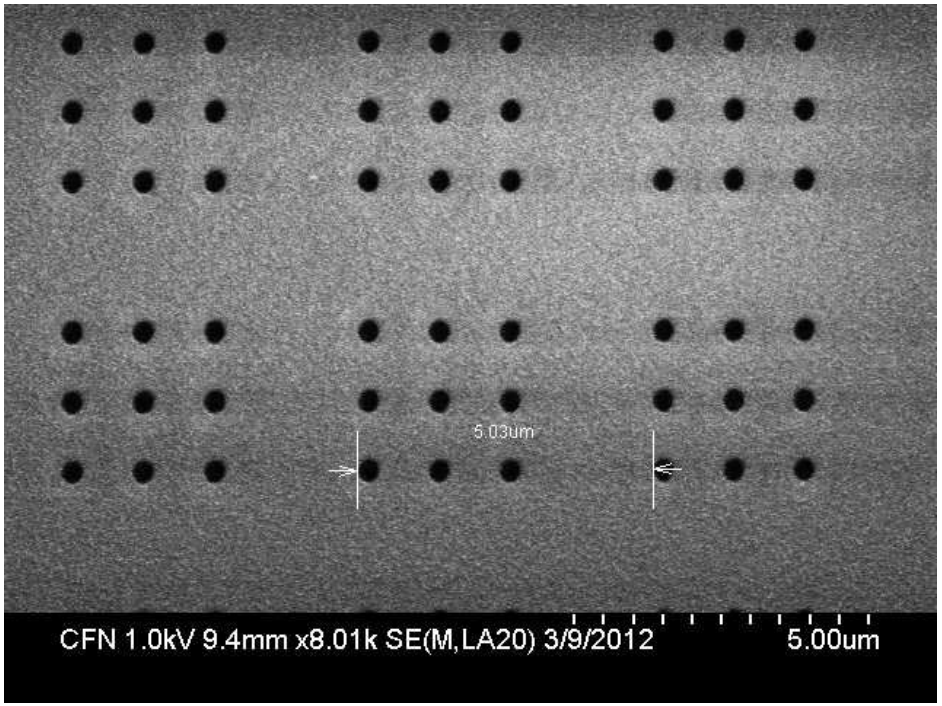




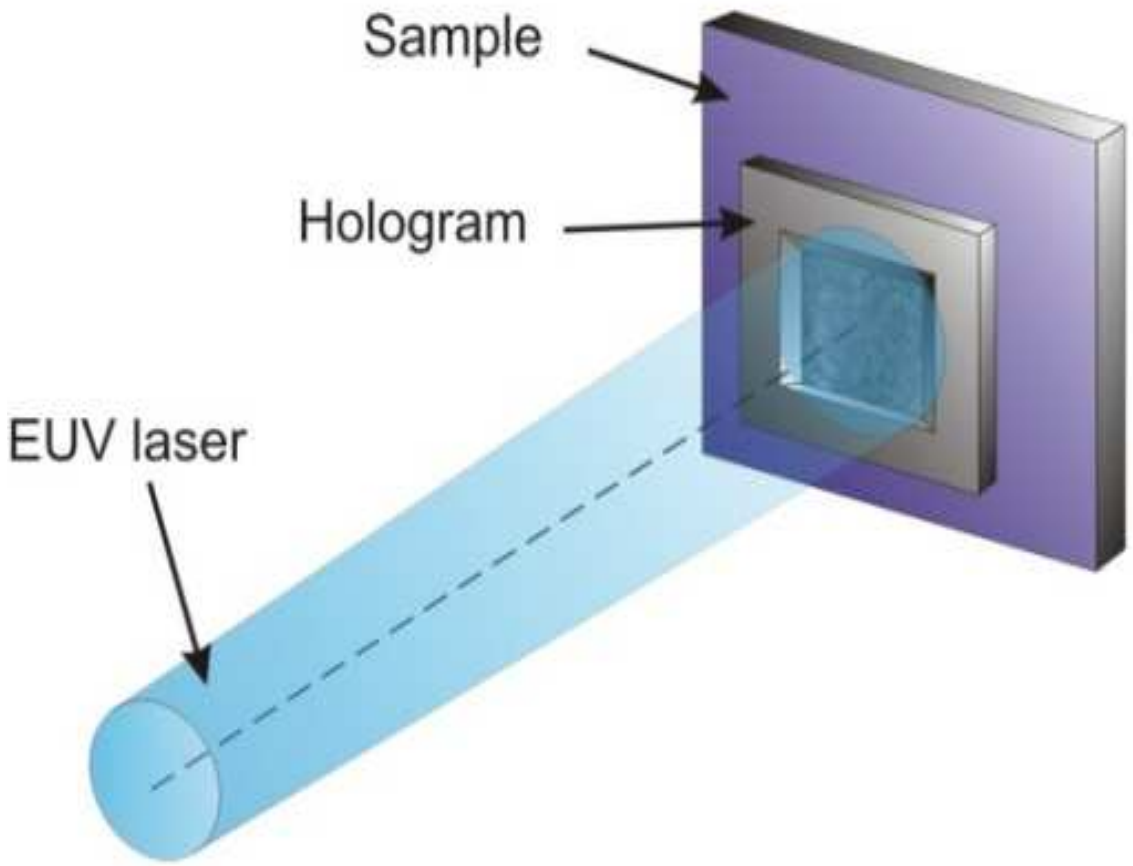
2. Possibile Applications



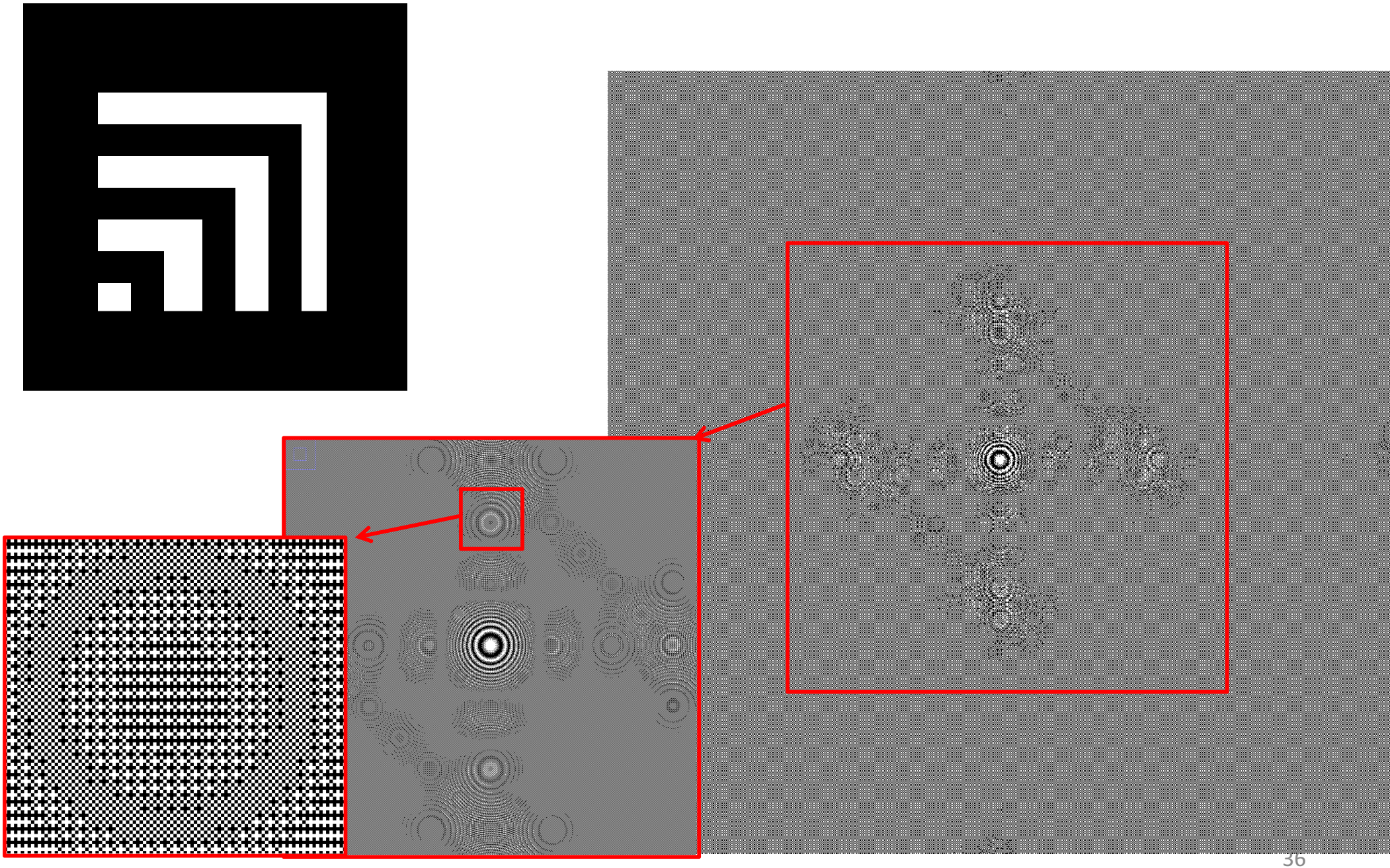




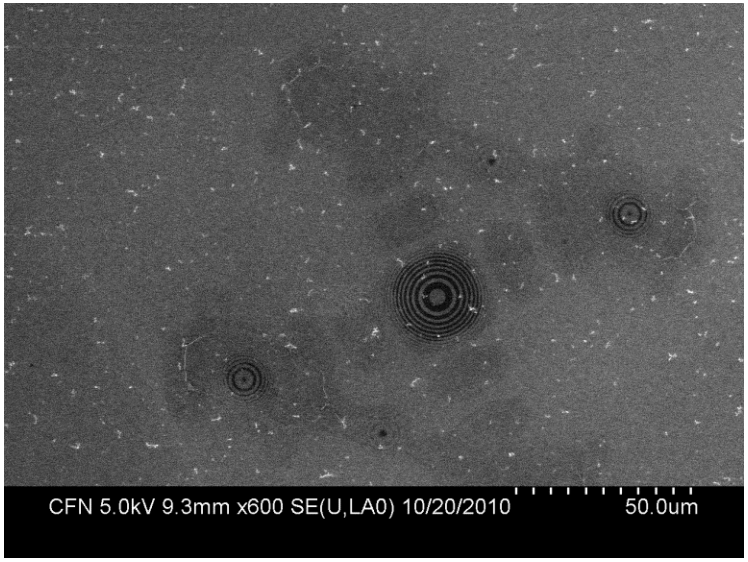
3. Computer Generated Hologram Reconstruction

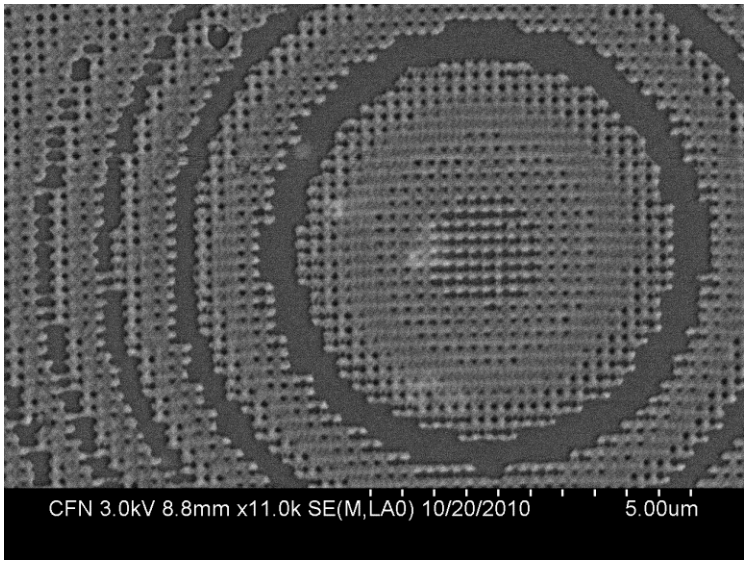


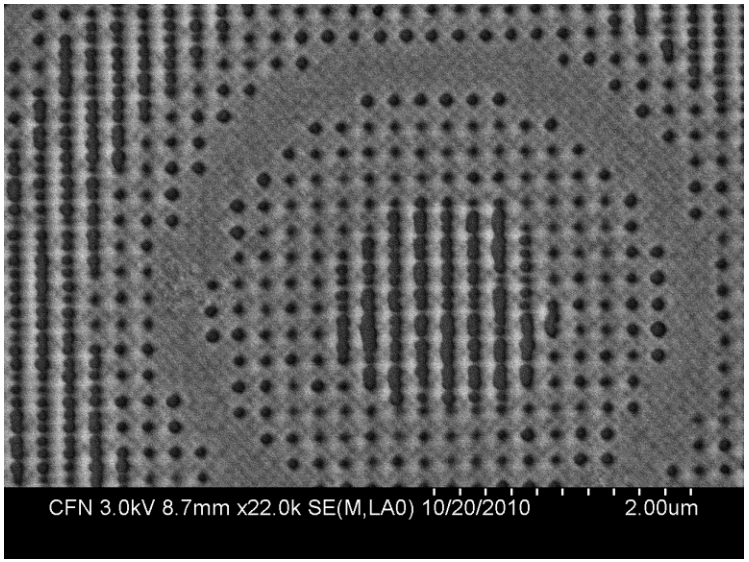
Computer Generated Hologram

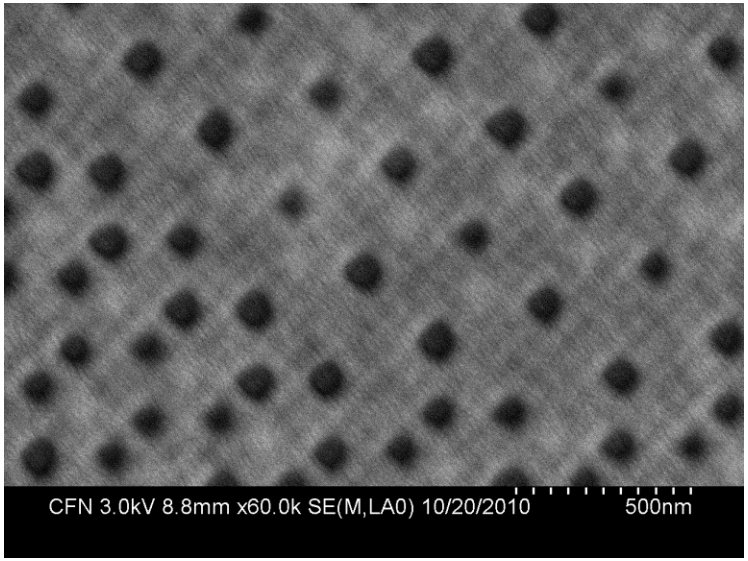


Computer Generated Hologram

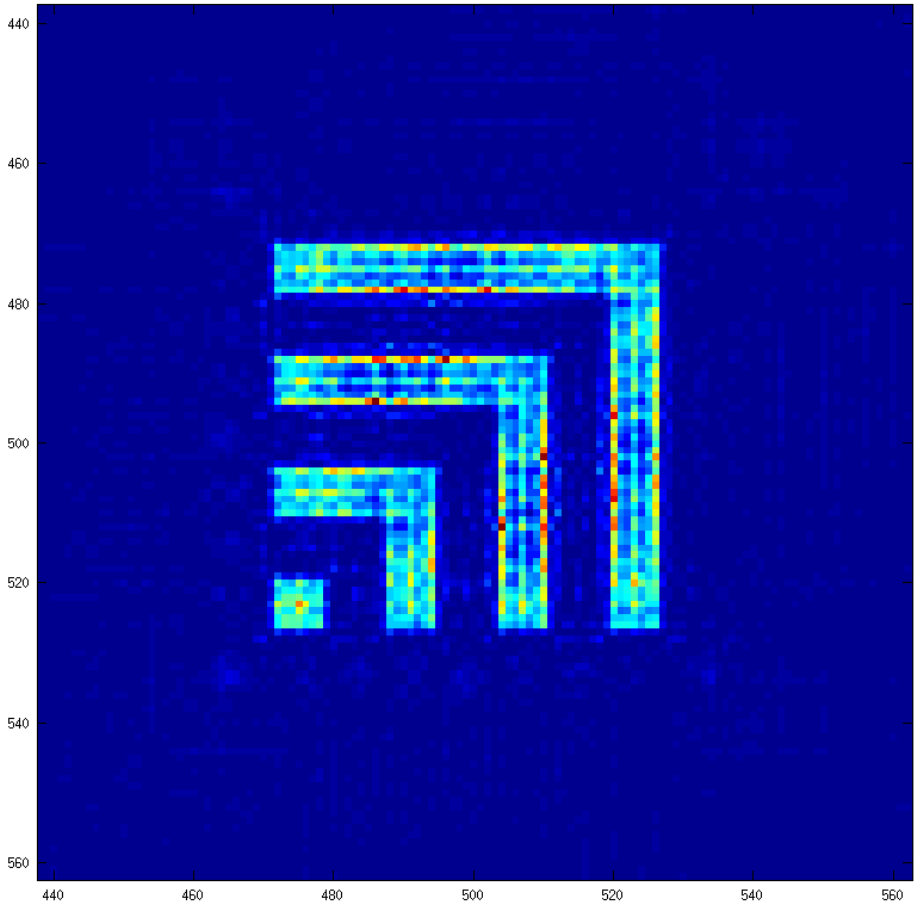








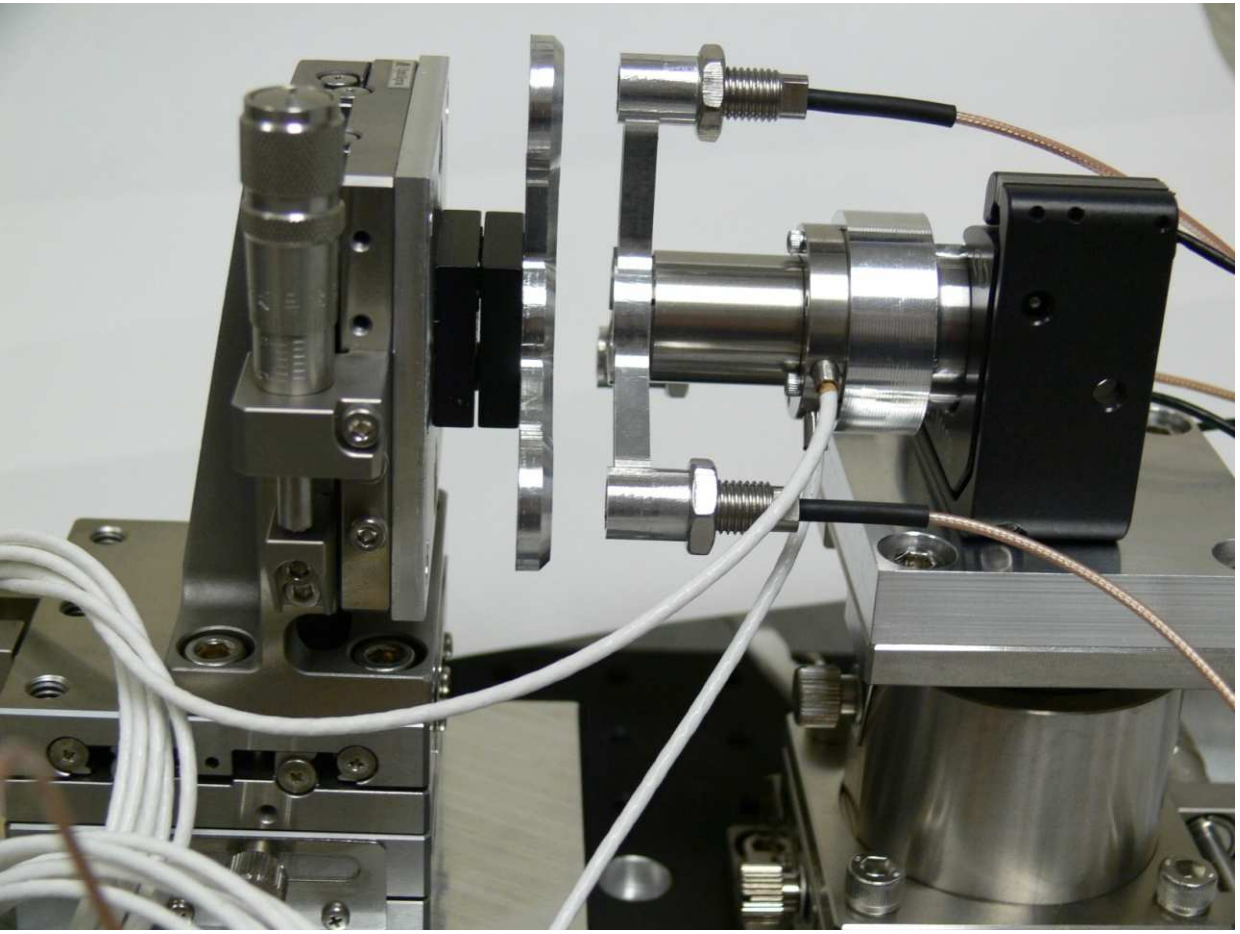
Computer Generated Hologram



λ=46.9nm
pix size: 25nm
Filed: 162.5µm
Wd: 250µm
NA: 0.325
Res: 88nm
DOF: 444nm

Numerical reconstruction of a CGH

Computer Generated Hologram: Experimental Setup



Summary: Publications, Conferences & Awards

Publications

- Urbanski, L.; Marconi, M. C.; Meng, L. M.; Berrill, M.; Guilbaud, O.; Klisnick, A.; Rocca, J. J. Phys. Rev. A **85**, 033837 (2012)
- Urbanski, L.; Marconi, M. C.; Isoyan, A.; Stein, A.; Menoni, C. S. & Rocca, J. J. *JVST B AVS,* **2011***, 29*, 06F504
- Isoyan, A.; Jiang, F.; Cheng, Y. C.; Cerrina, F.; Wachulak, P.; Urbanski, L.; Rocca, J.; Menoni, C. & Marconi, M. *JVST B, AVS,* **2009***, 27*, 2931-2937
- L. Urbanski ,L. M. Meng, M. C. Marconi, M. Berril, O. Guilbaud, A. Klisnick, J. J. Rocca *SPIE Proc.* **2011***, 8140*, 81400Y,
- M. C. Marconi, P. Wachulak, L. Urbanski, C.S Menoni and J. J. Rocca, A. Isoyan, F. Jiang, Y. Cheng, F. Cerrina SPIE Proc Vol. 7271 72713O-3
- Urbanski L, Marconi M, Stein A, Menoni C, Rocca J, „Defect Tolerant EUV Lithography Technique". Optics Letters (manuscript in preparation)

Conferences

- L. Urbanski, L. Meng, M. Marconi, et al."Line width measurement of a capillary discharge soft x-ray laser." SPIE Proceedings, 05 Oct 2011
- L. Urbanski, P. Wachulak, A. Isoyan, et al. "Table top nanopatterning by de-magnified Talbot effect using a capillary discharge soft x-ray laser." SPIE Proceedings, 05 Oct 2011
- P.W. Wachulak; R. L. Sandberg; A. Isoyan; L. Urbanski; A. Bartnik; R. A. Bartels; C.S. Menoni; H. Fiedorowicz; J. J. Rocca; M. C. Marconi; "Nanometer scale imaging with table top extreme ultraviolet sources." (Proceedings Paper) Published: 14 Dec 2010
- L. Urbanski , A. Klisnik , L. Meng , M. C. Marconi, J.J. Rocca. "Linewidth measurement of table top EUV laser". American Physical Society 4 Corners Fall Meeting. Ogden, UT, October 15-16 2010
- M. C. Marconi; P. W. Wachulak; L. Urbanski; A. Isoyan; Fan Jiang; Yang Chun Cheng; J. J. Rocca; C. S. Menoni; F. Cerrina; "Tabletop soft x-ray lithography." (Proceedings Paper), 28 September 2009
- L. Urbanski, P. Wachulak, F. Cerrina, A. Isoyan, F. Jiang, Y. C. Cheng, C.S. Menoni, J.J. Rocca and M.C. Marconi. "Nanopatterning using Coherent Imaging Techniques". International Conference on X-ray Lasers. Korea, 2010;
- L. Urbanski, P. Wachulak, A. Isoyan, F. Jian, Y. Cheng, J.J. Rocca, C.S. Menoni, F. Cerrina, M. C. Marconi. "Talbot nano-patterning with a table top soft X-ray laser". American Physical Society 4 Corners Fall Meeting. Golden, CO, October 24-25 2009;
- L. Urbanski, Isoyan, F. Jian, Y. Chung-chen, P. Wachulak, J.J. Rocca, C.S. Menoni, M.C. Marconi, F. Cerrina. "New Approaches to Extreme Ultraviolet Lithography";Colorado Photonics Industry Association, Boulder 2010
- L. Urbanski, P. Wachulak, J.J. Rocca, C.S. Menoni, M.C. Marconi, "Development of photonic devices using nano-fabrication in photosensitive glass with extreme ultraviolet lasers"; Colorado Photonics Industry Association, Boulder 2008;
- L. Urbanski, Isoyan, F. Jian, Y. Chung-chen, P. Wachulak, J.J. Rocca, C.S. Menoni, M.C. Marconi, F. Cerrina. "Printing of arbitrary shape nano patterns by coherent projection holographic and Talbot self imaging"; Colorado Photonics Industry Association, Boulder, CO, 2009;
- L. Urbanski, Isoyan, F. Jian, Y. Chung-chen, P. Wachulak, J.J. Rocca, C.S. Menoni, M.C. Marconi, A. Stein F. Cerrina." "Extreme Ultraviolet lithography by de-magnified generalized Talbot imaging";American Physical Society in Tucson, AZ, 2011;
- M. Marconi, P. Wachulak, L. Urbanski, A. Isoyan, J. Fan, Y.C. Chen, J.J. Rocca, C.S. Menoni, F. Cerrina. "Table top Soft X-ray lithography". Soft X-Ray Lasers and Applications. San Diego, 4-6 August 2009.
- P. W. Wachulak, A. Isoyan, L. Urbanski, A. Bartnik, R. A. Bartels, C. S. Menoni, H. Fiedorowicz, J.J. Rocca and M. C. Marconi, "Nanometer scale imaging with table top extreme ultraviolet sources", X-ray and XUV Plasma sources and applications, Czech Technical University in Prague, FNSPE – Dept. of Physical Electronics, Prague, Czech Republic, November 24, (2010);
- P. W. Wachulak, R. Sandberg, A. Isoyan, F. Brizuela, L. Urbanski, A. Bartnik, M.C. Marconi, R. Bartels, C. S. Menoni, J. J. Rocca and H. Fiedorowicz, "Nanometer scale imaging with table top extreme ultraviolet sources", 17th Slovak-Czech-Polish Optical Conference, Wave and Quantum Aspects of Contemporary Optics, SOREA Máj Hotel, Liptovský Ján, Slovakia, 6-10 September (2010);
- M.C. Marconi, P. Wachulak, L. Urbanski, C.S. Menoni, J.J. Rocca, A. Isoyan, F. Jiang, Y.C. Cheng, F. Cerrina. "Extreme ultraviolet lasers demonstrate new nanopatterning schemes". IEEE Photonics Society Meeting. Denver, Nov. 7-11 (2010);
- M.C. Marconi, P. Wachulak, L. Urbanski, C.S. Menoni, J.J. Rocca. "Nano-imaging and nano-patterning with compact EUV lasers: new opportunities in nanotechnology with a table-top system". 17th International Conference on Advanced Laser Technologies, Antalya, Turkey, 26 Sept-1 Oct 2009;
- Isoyan, F. Jiang, Y.-C. Cheng, P.W. Wachulak, L. Urbanski, C.S. Menoni, J.J. Rocca, M. C. Marconi, F. Cerrina, "Self-Imaging Of Complex Structures With A Table-Top EUV Laser", International Conference on Electron, Ion and Photon Beam Technology and Nanofabrication. Marco Island, FL, May 2009;
- Isoyan, F. Jian, Y. Chung-chen, P. Wachulak, L. Urbanski, J.J. Rocca, C.S. Menoni, M.C. Marconi, F. Cerrina. "Coherent imaging nanopatterning with extreme ultraviolet laser illumination". CLEO-IQEC 09. Baltimore, May 31-June 5 2009;
- Isoyan, F. Jiang, Y. Chun Cheng, P.W. Wachulak, L. Urbanski, J.J. Rocca, M.C. Marconi, F. Cerrina. "Extreme-ultraviolet holographic lithography with a table-top laser source". Advanced Lithography, San Jose, CA, 22-27 February 2009;

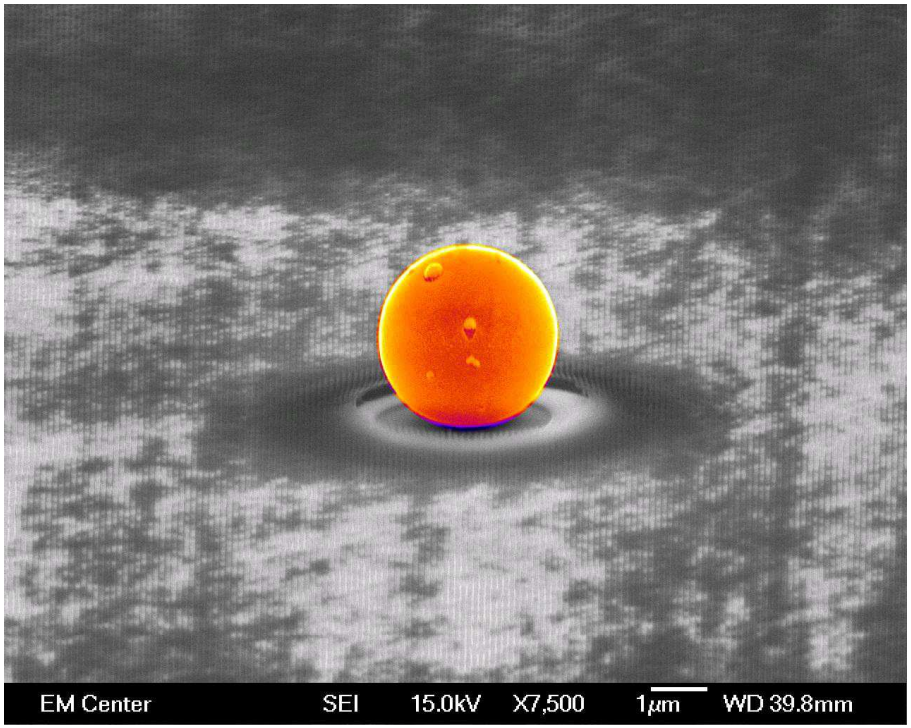
Awards

- Best Poster Award Colorado Photonics Industry Assoc. 2010,
- Best Poster Award Colorado Photonics Industry Assoc. 2009

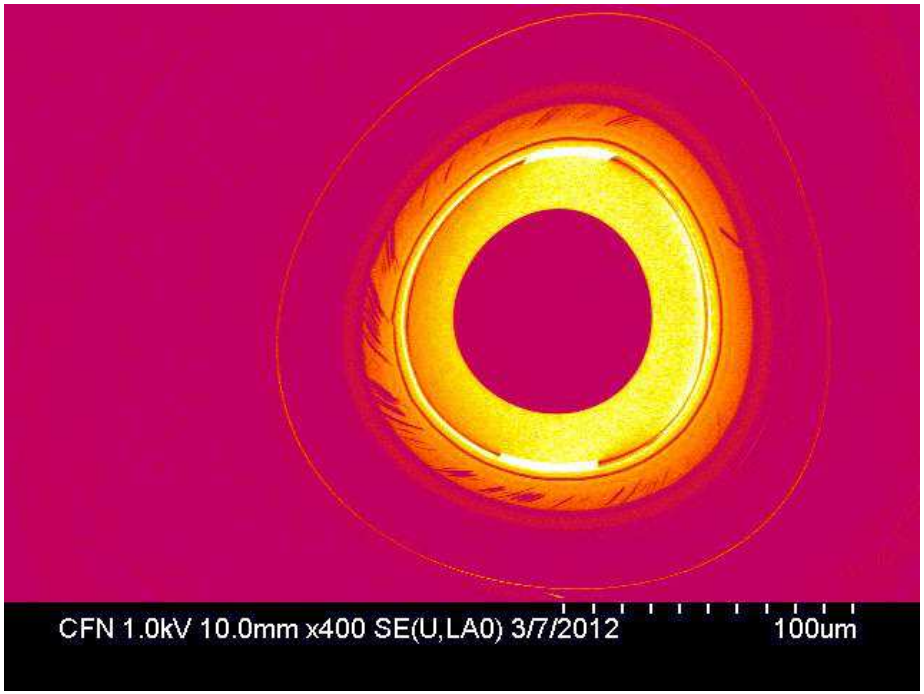
Acknowledgements

♥ Małgorzata Urbańska,
- Prof. Mario Marconi,
- Prof. Carmen Menoni,
- Prof. Vakhtang Putkaradze,
- Prof. Randy Bartels,
- Илья Кузнецов (Ilya Kuznetsov),
- 李炜 (Wei Li),
- Nils Monserud,
- Christopher Brown,
- Erik Malm.

Dessert



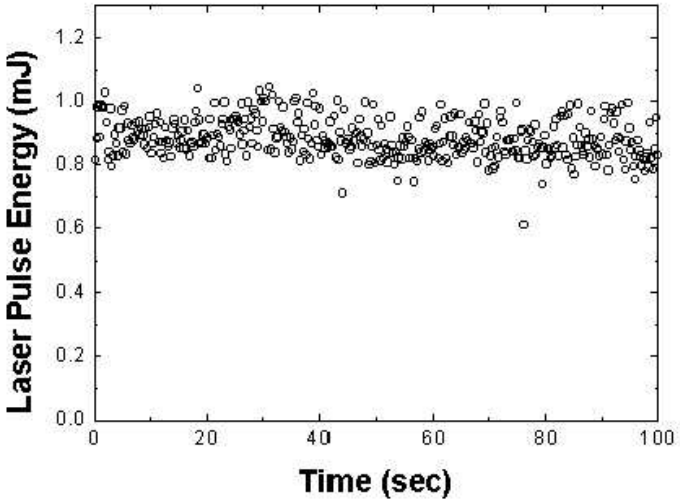
Splash One.
Atempt of electroplating gold onto a patterned resist.

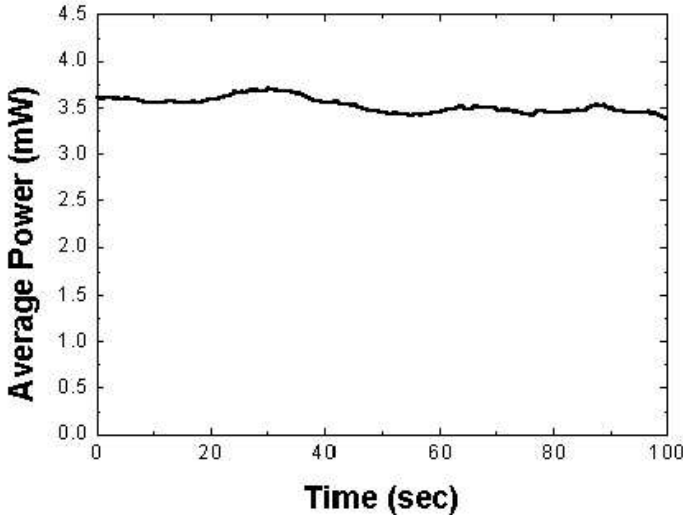


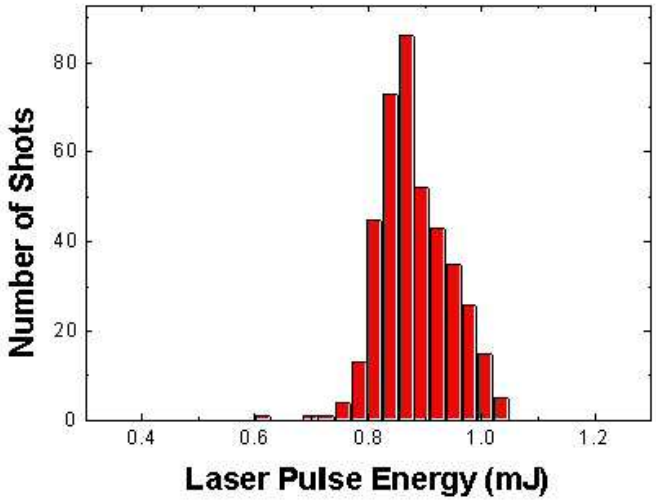
The Persistence of Charge.
SEM imaging of thick ZEP520 resist

Repetitive operation generates high average powers

3.5 mW Average Power Demonstrated at 46.9 nm
(0.88 mJ/pulse at 4 Hz)



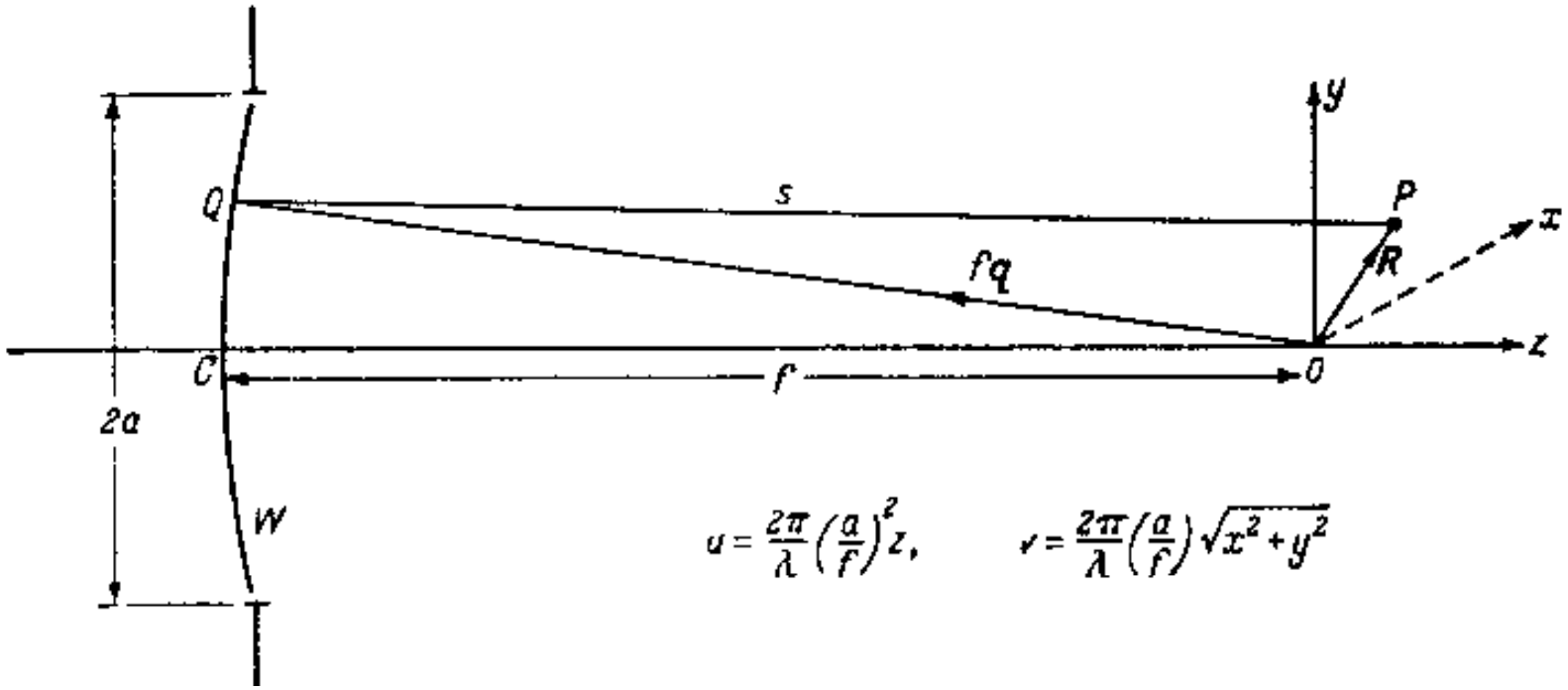




Other Laser Output Parameters:

- Peak Power : 0.6 MW
- Pulsewidth : 1.2 - 1.5 ns
- Beam divergence : 4.6 mrad

Experimental Verification: Analysis



$$u = \frac{2\pi}{\lambda}\left(\frac{a}{f}\right)^2 z, \qquad v = \frac{2\pi}{\lambda}\left(\frac{a}{f}\right)\sqrt{x^2+y^2}$$

$$U(P) = -\frac{i}{\lambda} A \int\int_{\Omega} e^{-ikq\,.\,R}\, d\Omega,$$

$$U(P) = -\frac{2\pi i a^2 A}{\lambda f^2}\, e^{i\left(\frac{f}{a}\right)^2 u} \int_0^1 J_0(v\rho) e^{-\frac{1}{2}iu\rho^2} \rho d\rho.$$

$$2\int_0^1 J_0(v\rho) e^{-\frac{1}{2}iu\rho^2} \rho d\rho = C(u,v) - iS(u,v),$$

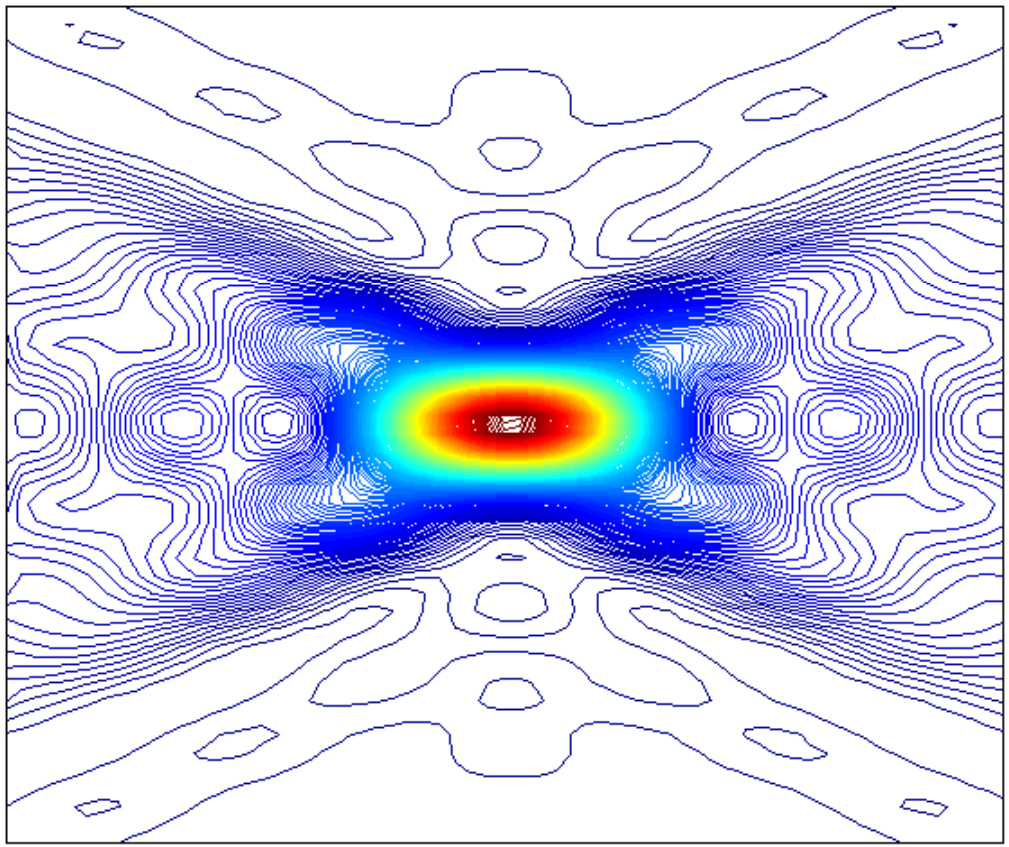
$$\left.\begin{aligned} C(u,v) &= 2\int_0^1 J_0(v\rho)\cos\left(\tfrac{1}{2}u\rho^2\right)\rho d\rho, \\ S(u,v) &= 2\int_0^1 J_0(v\rho)\sin\left(\tfrac{1}{2}u\rho^2\right)\rho d\rho. \end{aligned}\right\}$$

Experimental Verification: Analysis

$$\left.\begin{aligned} U_n(u,v) &= \sum_{s=0}^{\infty} (-1)^s \left(\frac{u}{v}\right)^{n+2s} J_{n+2s}(v), \\ V_n(u,v) &= \sum_{s=0}^{\infty} (-1)^s \left(\frac{v}{u}\right)^{n+2s} J_{n+2s}(v), \end{aligned}\right\}$$

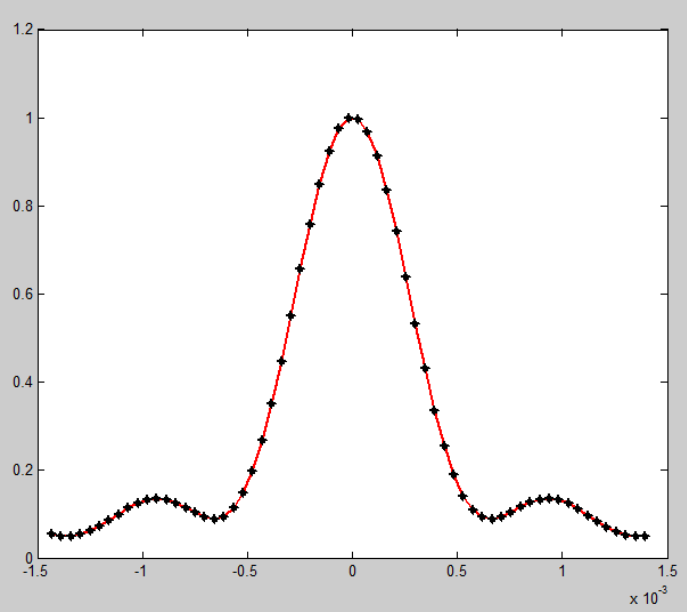
Distribution of Intensity

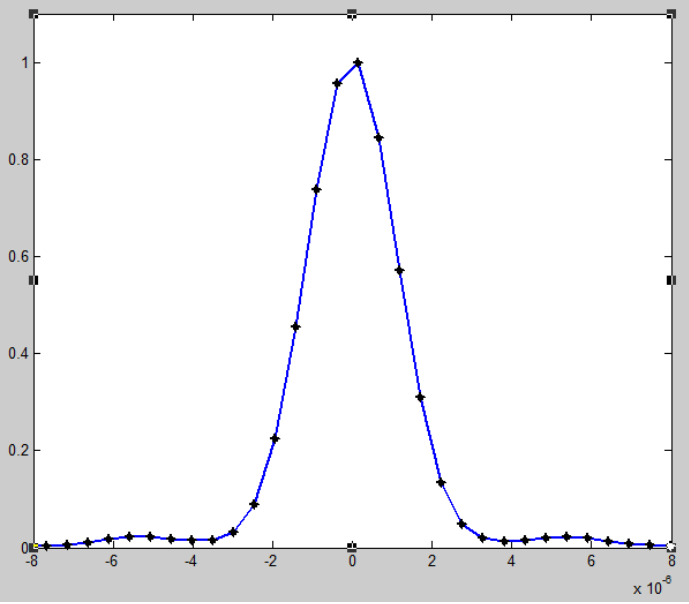
$$I(u,v) = \left(\frac{2}{u}\right)^2 [U_1^2(u,v) + U_2^2(u,v)]\, I_0,$$



Experimental Verification: Analysis

Special Cases:





Special case: Intensity on axis

$$d = 1.9\sqrt{f\lambda}$$

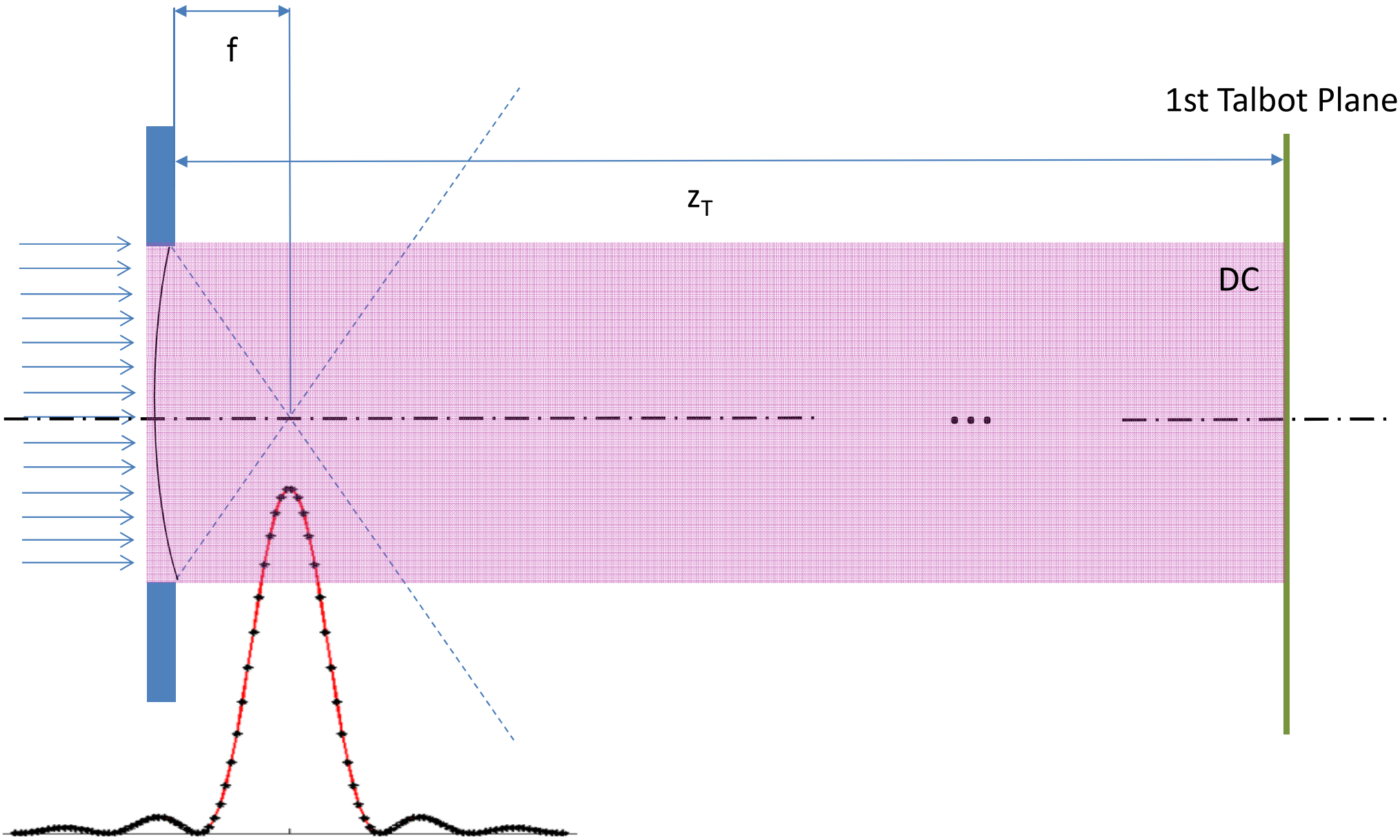
Example:

Focus produced by a
5 micron opening
illuminated with 46.9nm light

$$f = \frac{d^2}{(1.9)^2 \lambda}$$

f = 0.125mm
a = 0.005mm
NA = 0.0200
DOF = 0.117mm

Experimental Verification: Analysis



Diffraction pattern vs. Coherence radius

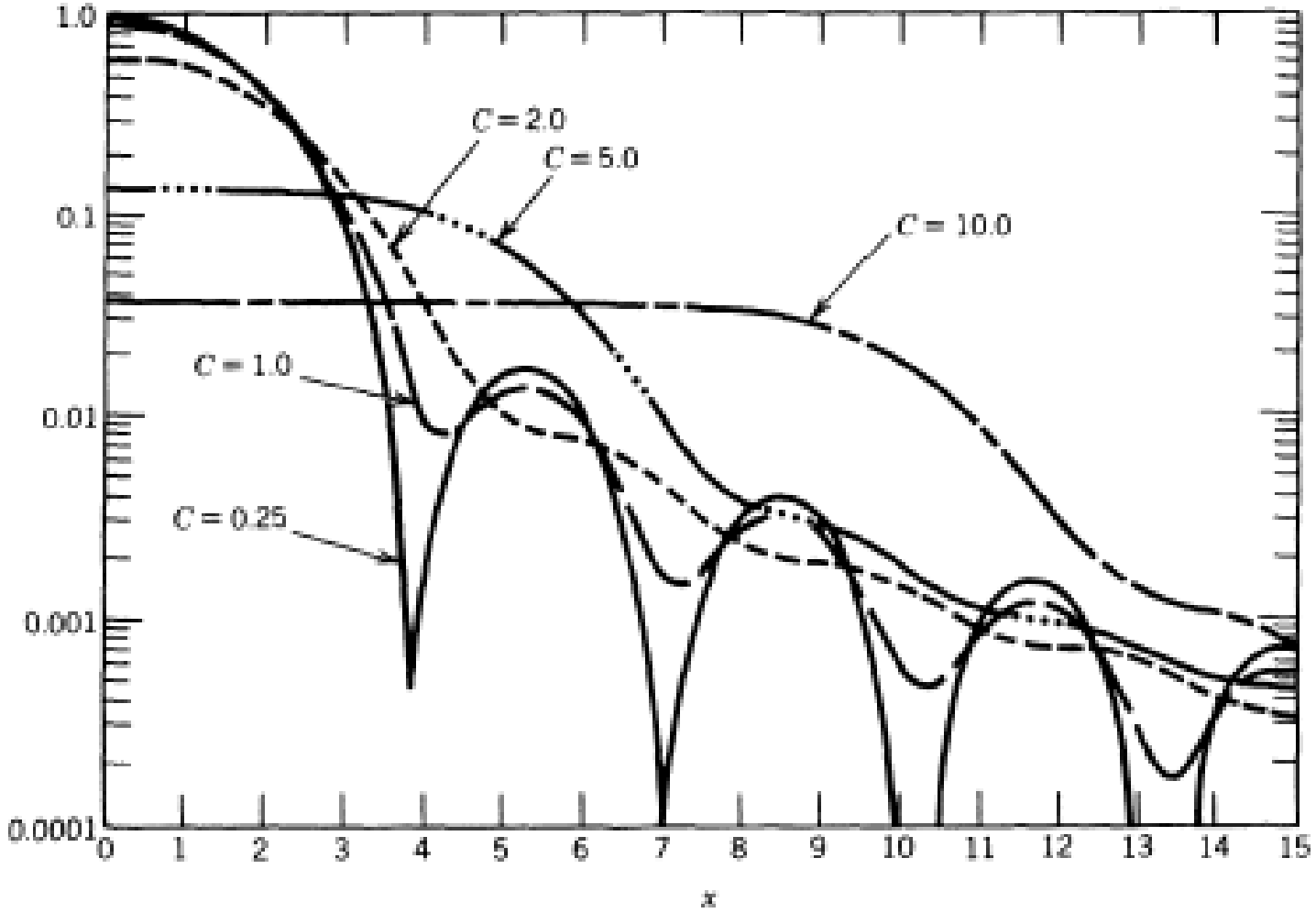


Figure 5-23. Diffraction pattern of a circular aperture for various states of transverse coherence. The parameter C represents the ratio of the area of the circular aperture to a coherence area. A circular incoherent source was assumed. The variable x has been normalized. (Ref. 5-34). (Courtesy of B. J. Thompson and the Optical Society of America.)

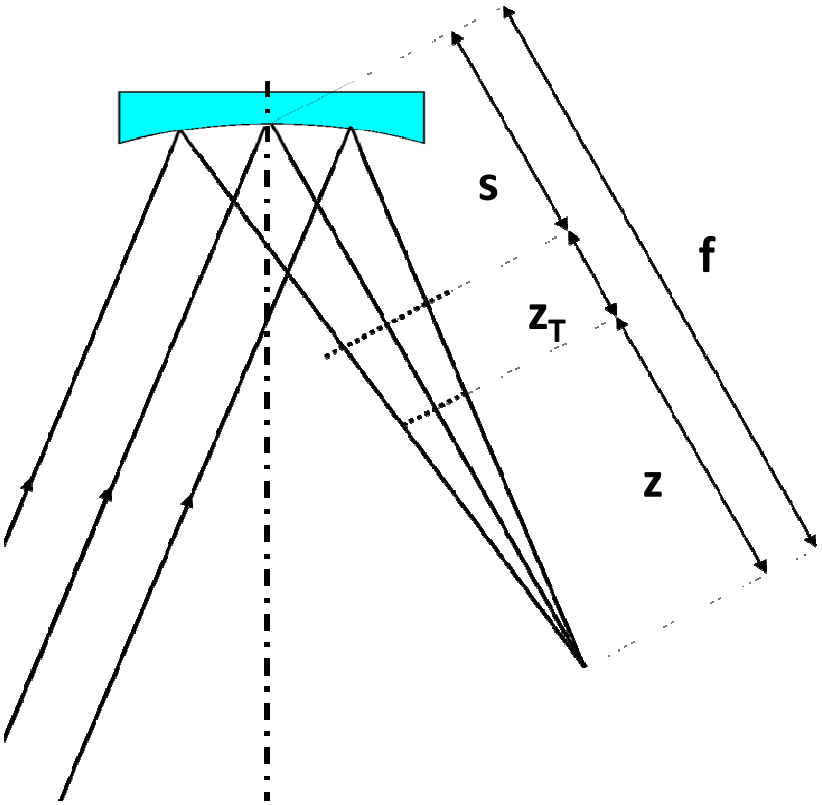


TABLE 5.1
Relations between operators.

	$\mathcal{V}$	$\mathcal{F}$	$\mathcal{Q}$	$\mathcal{R}$
$\mathcal{V}$	$\mathcal{V}[t_2]\mathcal{V}[t_1] = \mathcal{V}[t_2 t_1]$	$\mathcal{V}[t]\mathcal{F} = \mathcal{F}\mathcal{V}\left[\frac{1}{t}\right]$	$\mathcal{V}[t]\mathcal{Q}[c] = \mathcal{Q}[t^2 c]\mathcal{V}[t]$	$\mathcal{V}[t]\mathcal{R}[d] = \mathcal{R}\left[\frac{d}{t^2}\right]\mathcal{V}[t]$
$\mathcal{F}$	$\mathcal{F}\mathcal{V}[t] = \mathcal{V}\left[\frac{1}{t}\right]\mathcal{F}$	$\mathcal{F}\mathcal{F} = \mathcal{V}[-1]$	$\mathcal{F}\mathcal{Q}[c] = \mathcal{R}\left[-\frac{c}{\lambda^2}\right]\mathcal{F}$	$\mathcal{F}\mathcal{R}[d] = \mathcal{Q}[-\lambda^2 d]\mathcal{F}$
$\mathcal{Q}$	$\mathcal{Q}[c]\mathcal{V}[t] = \mathcal{V}[t]\mathcal{Q}\left[\frac{c}{t^2}\right]$	$\mathcal{Q}[c]\mathcal{F} = \mathcal{F}\mathcal{R}\left[-\frac{c}{\lambda^2}\right]$	$\mathcal{Q}[c_2]\mathcal{Q}[c_1] = \mathcal{Q}[c_2 + c_1]$	$\mathcal{Q}[c]\mathcal{R}[d] = \mathcal{R}\left[(d^{-1} + c)^{-1}\right] \cdot \mathcal{V}[1 + cd] \cdot \mathcal{Q}\left[(c^{-1} + d)^{-1}\right]$
$\mathcal{R}$	$\mathcal{R}[d]\mathcal{V}[t] = \mathcal{V}[t]\mathcal{R}[t^2 d]$	$\mathcal{R}[d]\mathcal{F} = \mathcal{F}\mathcal{Q}[-\lambda^2 d]$	$\mathcal{R}[d]\mathcal{Q}[c] = \mathcal{Q}\left[(c^{-1} + d)^{-1}\right] \cdot \mathcal{V}\left[(1 + cd)^{-1}\right] \cdot \mathcal{R}\left[(d^{-1} + c)^{-1}\right]$	$\mathcal{R}[d_2]\mathcal{R}[d_1] = \mathcal{R}[d_1 + d_2]$

$$\mathcal{Q}[c]\{U(x)\} = e^{j\frac{k}{2}cx^2}U(x),$$

$$\mathcal{V}[b]\{U(x)\} = b^{1/2}U(bx),$$

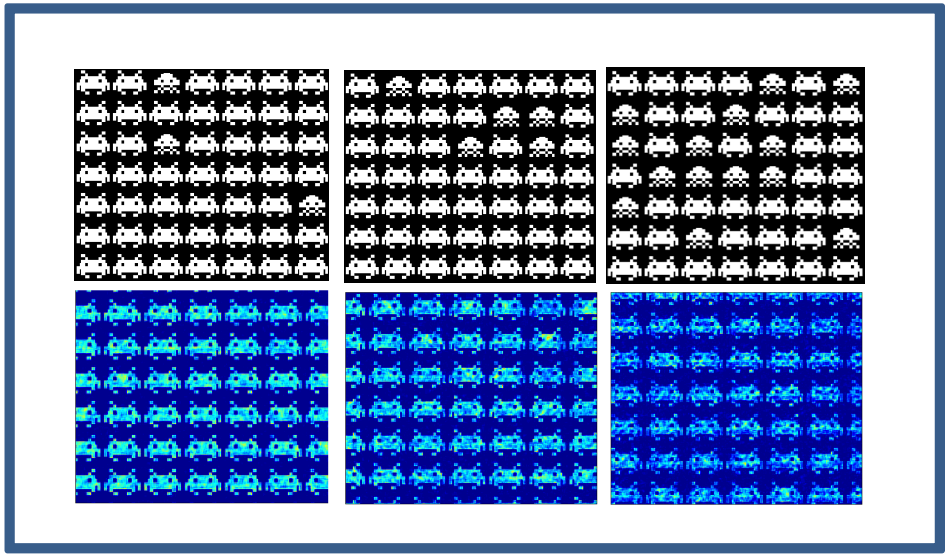
$$\mathcal{R}[d]\{U(x_1)\} = \frac{1}{\sqrt{j\lambda d}}\int_{-\infty}^{\infty} U(x_1)\, e^{j\frac{k}{2d}(x_2 - x_1)^2}\, dx_1,$$

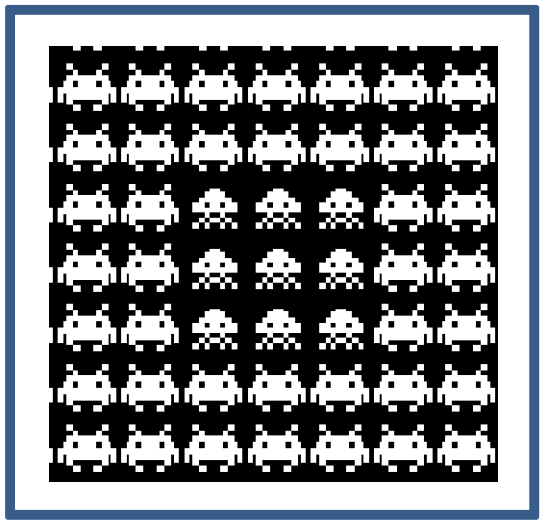
$$S = R[f - s - z] \cdot Q\left[\frac{1}{z}\right] =$$

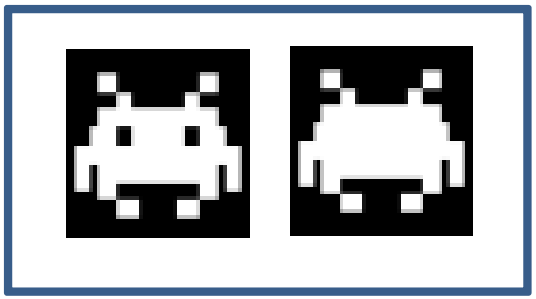
$$\left\{\begin{array}{l} R[d] \cdot Q[c] = \quad Q\left[\left(c^{-1} + d\right)^{-1}\right] \\ \qquad\qquad\qquad \cdot V\left[\left(1 + cd\right)^{-1}\right] \\ \qquad\qquad\qquad \cdot R\left[\left(d^{-1} + c\right)^{-1}\right] \end{array}\right\}$$

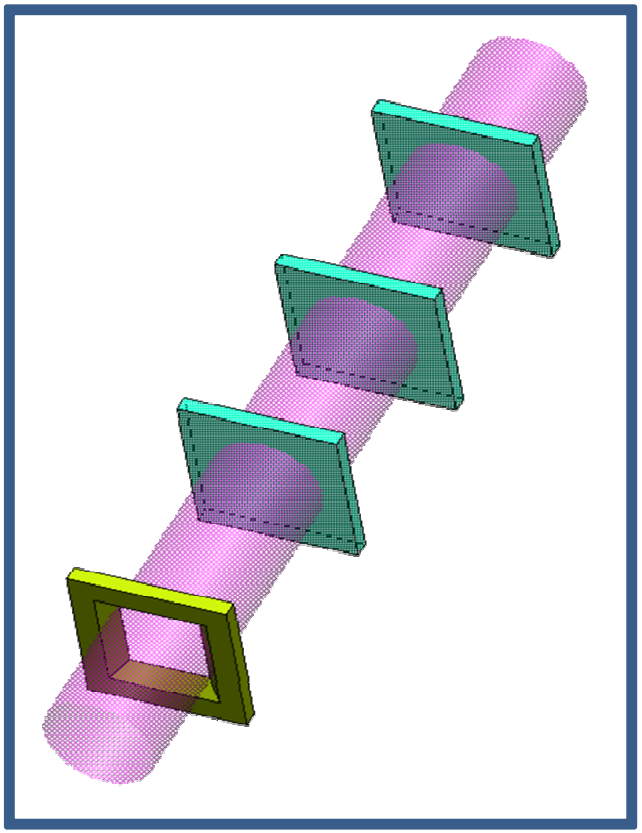
$$= Q\left[\frac{1}{(f - s)}\right] \cdot V\left[\frac{z}{(f - s)}\right] \cdot R\left[\frac{(f - s - z)z}{(f - s)}\right]$$

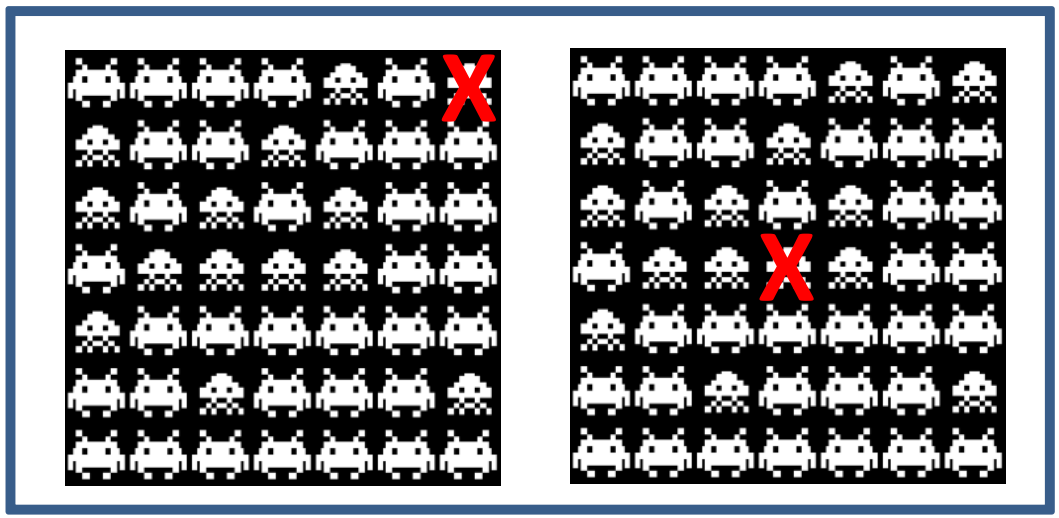
$$U(x) = \exp\left[\frac{ik}{2} c x^2\right] \int_{-\infty}^{\infty} U\left(x_1 \frac{z}{(f - s)}\right) \exp\left[\frac{ikz(x_1 - x)^2}{2(f - s - z)(f - s)}\right] dx_1$$

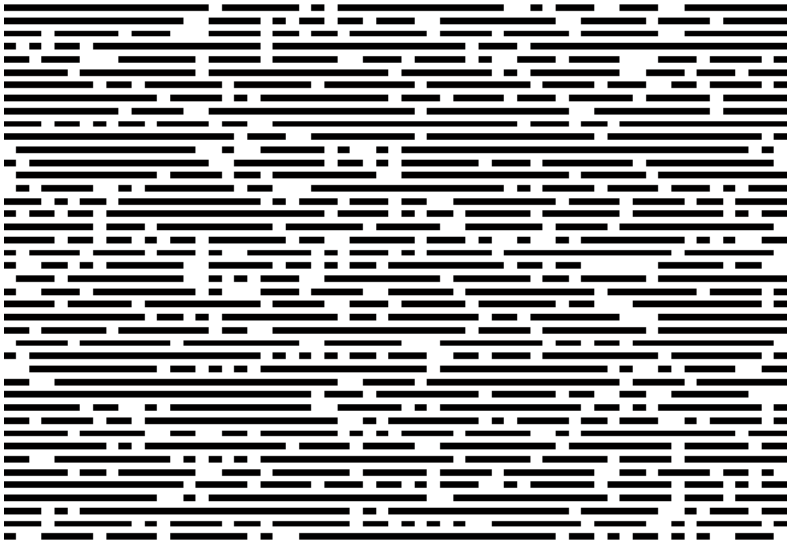









X
X



Q=corr(MASK,RECON)

$$U_{TOT}(x) = D(x) + \sum_m A_m \exp\left(2\pi i m \frac{x}{p}\right).$$

$$\tilde{U}_{TOT}(\nu, z=0) = \tilde{d}(\nu, z=0) + A_0\delta(\nu) + \sum_{m\neq 0} A_m \delta(\nu - m\nu_0)$$
$$= \tilde{d}(\nu, z=0) + A_0\delta(\nu) + \tilde{u}(\nu, z=0).$$

$$\tilde{U}_{TOT}(\nu, z) = \tilde{d}(\nu,0) + A_0\delta(\nu) + \sum_{m\neq 0} A_m \exp\left(-2i\pi m^2 \frac{z}{z_T}\right)\delta(\nu - m\nu_0).$$

$$U_{TOT}(x, z) = D(x, z) + A_0 + \sum_{m\neq 0} A_m \exp\left[-2i\pi\left(m\nu_0 x - m^2 \frac{z}{z_T}\right)\right]$$
$$= D(x, z) + U(x, z + Nz_T).$$

Spatial and Temporal Coherence

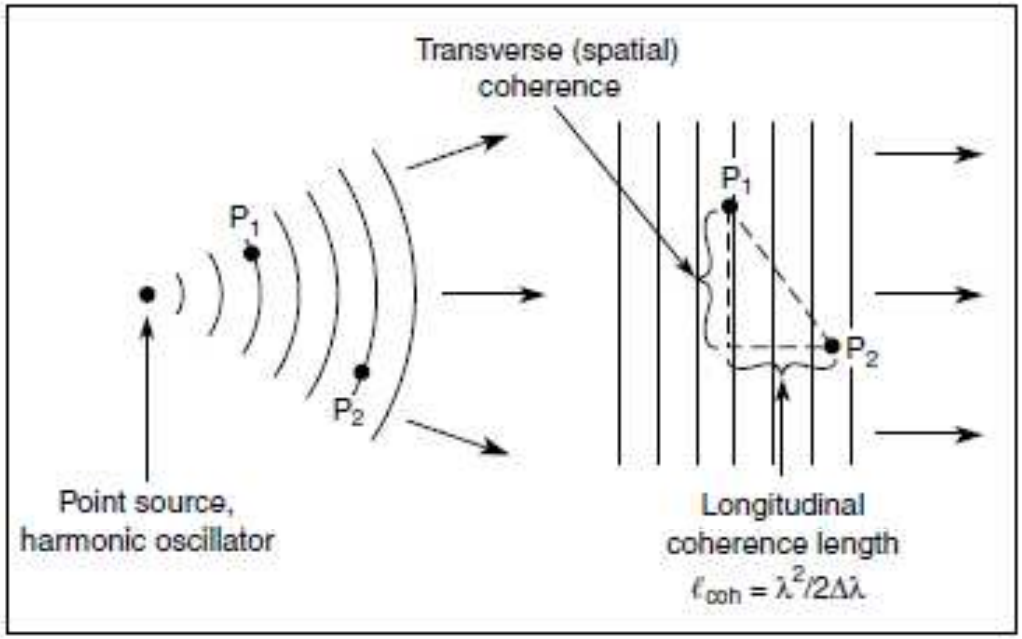
Mutual coherence factor

$$\Gamma_{12}(\tau) \equiv \langle E_1(t+\tau)E_2^*(t)\rangle \qquad (8.1)$$

Normalize degree of spatial coherence (complex coherence factor)

$$\mu_{12} = \frac{\langle E_1(t)E_2^*(t)\rangle}{\sqrt{\langle|E_1|^2\rangle}\sqrt{\langle|E_2|^2\rangle}} \qquad (8.12)$$

A high degree of coherence ($\mu \to 1$) implies an ability to form a high contrast interference (fringe) pattern. A low degree of coherence ($\mu \to 0$) implies an absence of interference, except with great care. In general radiation is partially coherent.



Longitudinal (temporal) coherence length

$$\boxed{\ell_{coh} = \frac{\lambda^2}{2\,\Delta\lambda}} \qquad (8.3)$$

Full spatial (transverse) coherence

$$\boxed{d \cdot \theta = \lambda/2\pi} \qquad (8.5)$$