Sub-Rayleigh lithography using an *N*-photon absorber

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Outline

- Motivation
- Quantum lithography
- Multi-photon lithographic recording material
- Proof-of-principle experiments
- Experimental results
- Conclusion & future work

Motivation

- In optical lithography, the feature size is limited by diffraction, called the ‘Rayleigh criterion’.

  - **Rayleigh criterion** : ~ $\lambda/2$

- Ultraviolet & deep UV lithography (248 nm, 193 nm and less) has been developed.

  - Problem : absorption & birefringence of optics

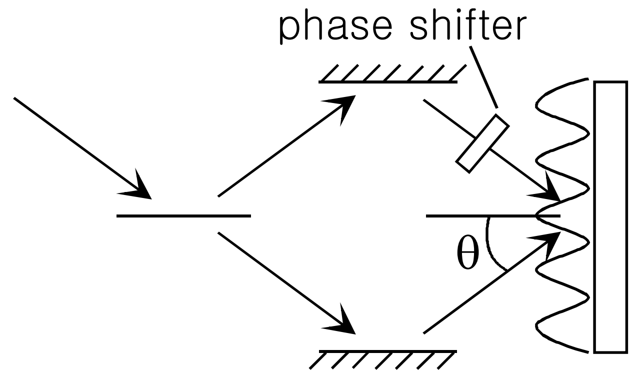
- **Quantum lithography** using an **N-photon lithographic recording material & entangled light source** was suggested to improve optical lithography.

- We suggest PMMA as a good candidate for an N-photon lithographic material.

Quantum lithography

- Classical interferometric lithography

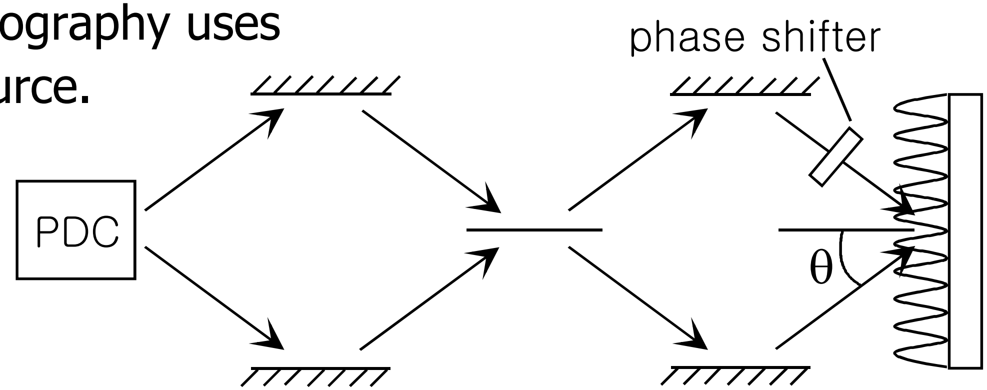
  - $I = \frac{1}{2}\left(1 + \cos(Kx)\right)$, where K = λ/(2sinθ)



- Resolution : ~ λ/2 at grazing incident angle

- Quantum interferometric lithography uses entangled N-photon light source.

  - $I = \frac{1}{2}\left(1 + \cos(NKx)\right)$



- Resolution : ~ λ/2*N*

- Advantage : high visibility is possible even with large resolution enhancement.

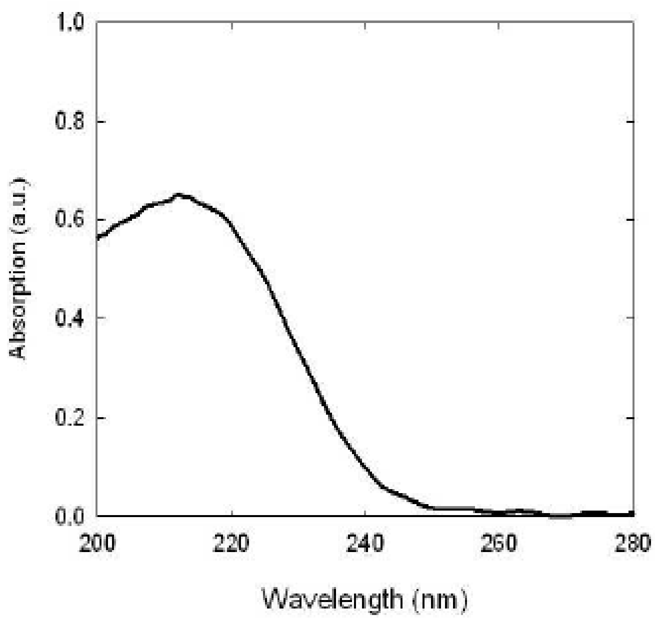
The Institute of OPTICS

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

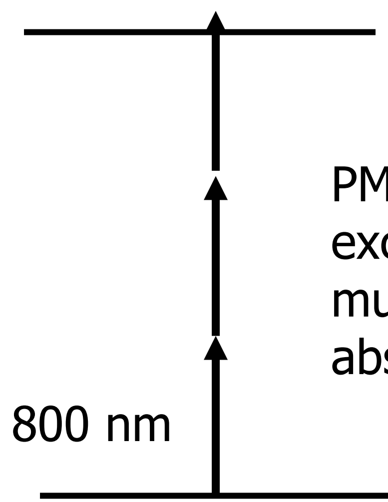
Nonlinear Optics

PMMA as a multi-photon absorber

- PMMA is a positive photo-resist, is transparent in visible region and has strong absorption in UV region.
- 3PA in PMMA breaks chemical bonds, and the broken bonds can be removed by developing process. (*N* = 3 at 800 nm)



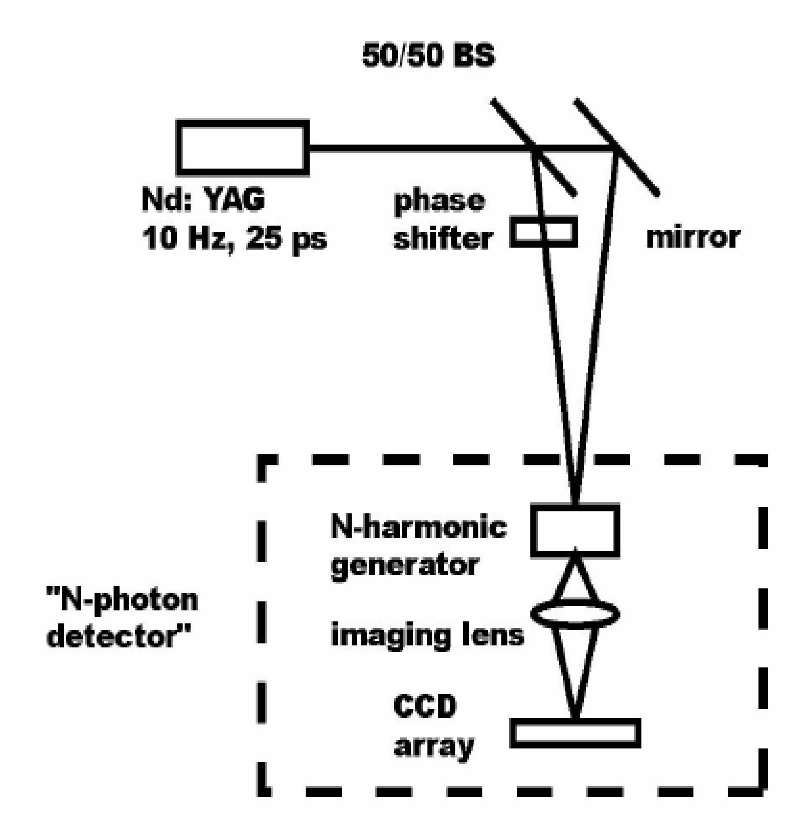
UV absorption spectrum of PMMA



PMMA is excited by multi-photon absorption

Enhanced resolution with a classical light source

Phase-shifted-grating method



- We wrote a fringe pattern on an N-photon absorber with M laser pulses.
- The phase of mth shot is given by $2\pi m/M$.
- The fringe pattern is

$$I = \sum_{m=1}^{M} \{1 + \cos[Kx + 2(m-1)\pi / M]\}^N$$

- Example (as N = 2, M = 2)

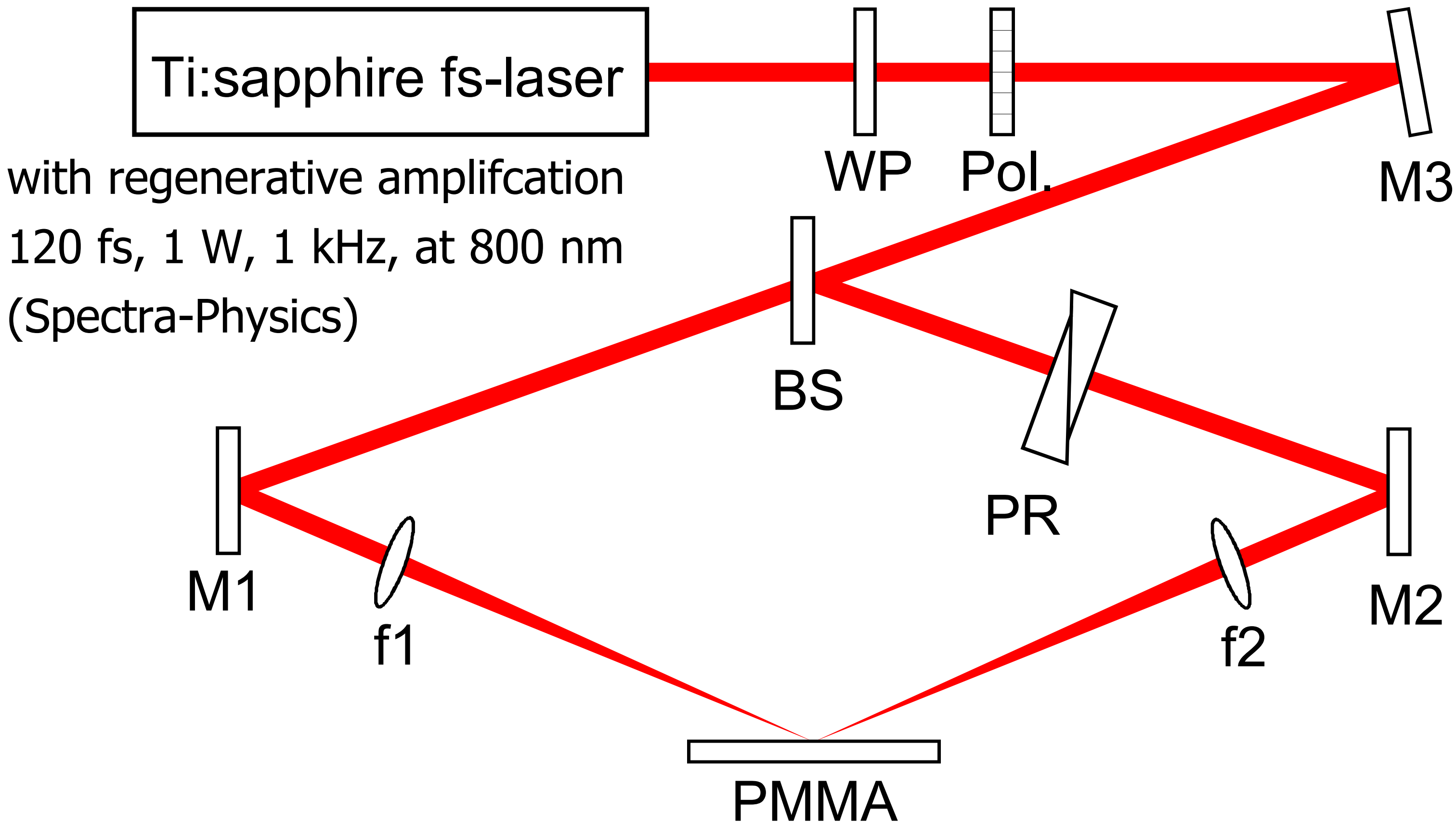
  - The interference pattern is

$$I = (1 + \cos Kx)^2 + (1 + \cos(Kx + 2\pi / 2))^2$$
$$= 3 + \cos 2Kx$$

- The resolution is enhanced by a factor of 2.

S.J. Bentley and R.W. Boyd, Optics Express, 12, 5735 (2004)

Experimental setup



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

Experiment – material preparation

- Sample preparation

  1) PMMA solution

     PMMA (Aldrich, Mw ~120,000) + Toluene : 20 wt%

  2) PMMA film : Spin-coat on a glass substrate

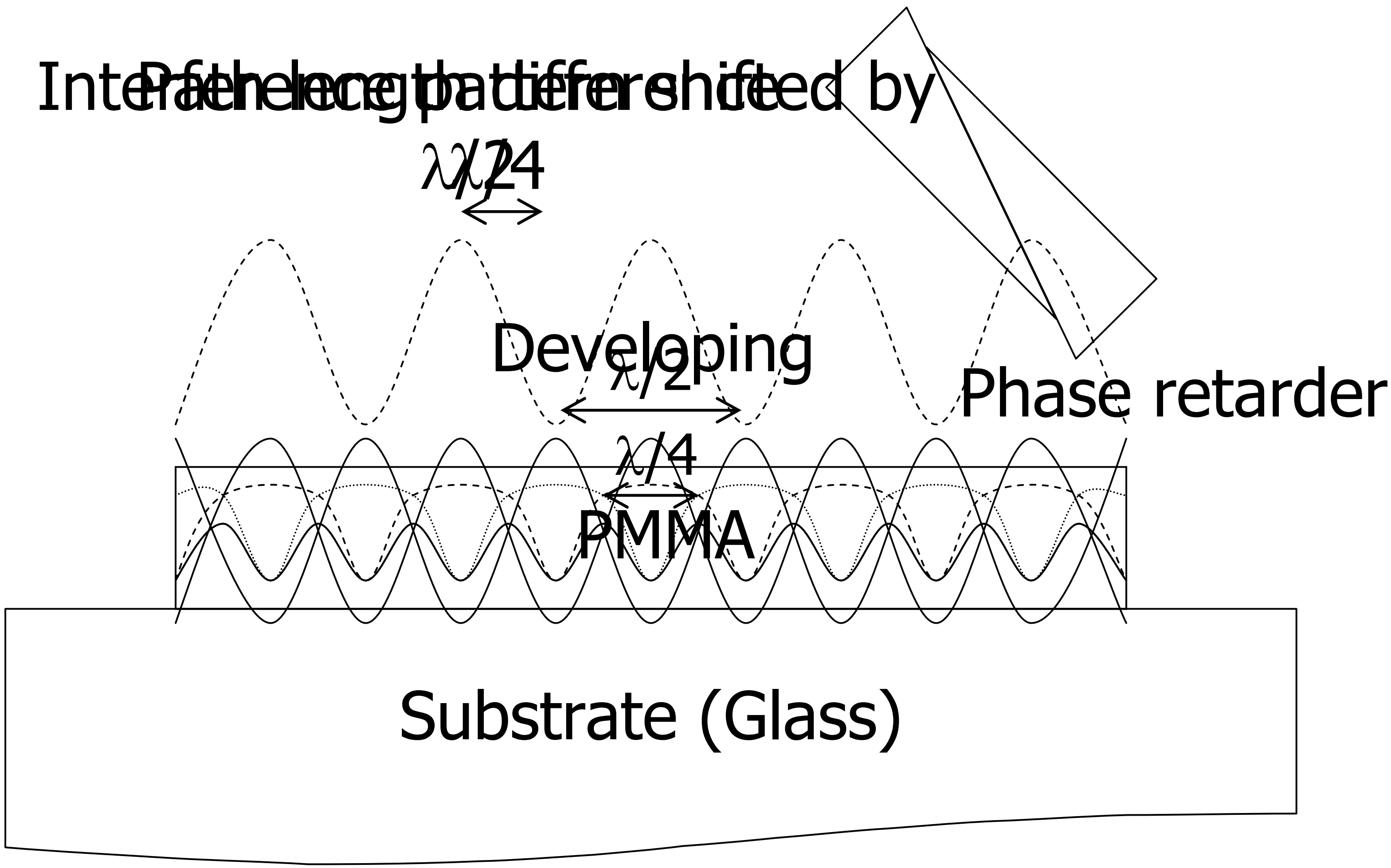
     Spin coating condition : 1000 rpm, 20 sec, 3 times

     Drying : 3 min. on the hot plate

- Development

  1) Developer : 1:1 methyl isobutyl ketone (MIBK) to Isopropyl Alcohol
  2) Immersion : 10 sec
  3) Rinse : DI water, 30 sec
  4) Dry : Air blow dry

Experimental process



Demonstration of writing fringes on PMMA

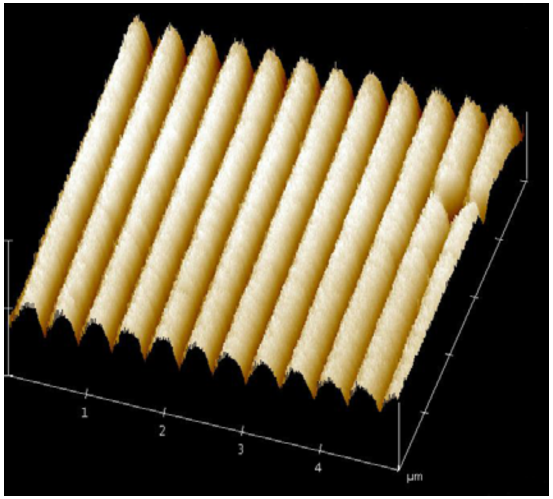
Recording wavelength = **800 nm**

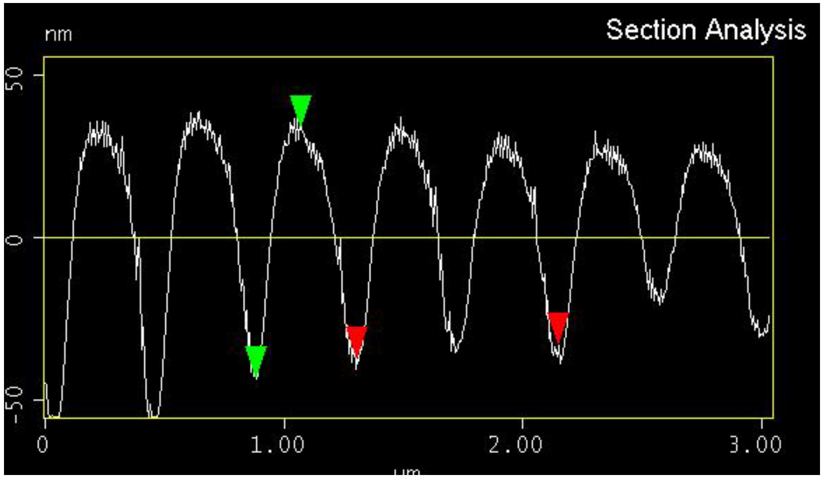
Pulse energy = 130 μJ per beam

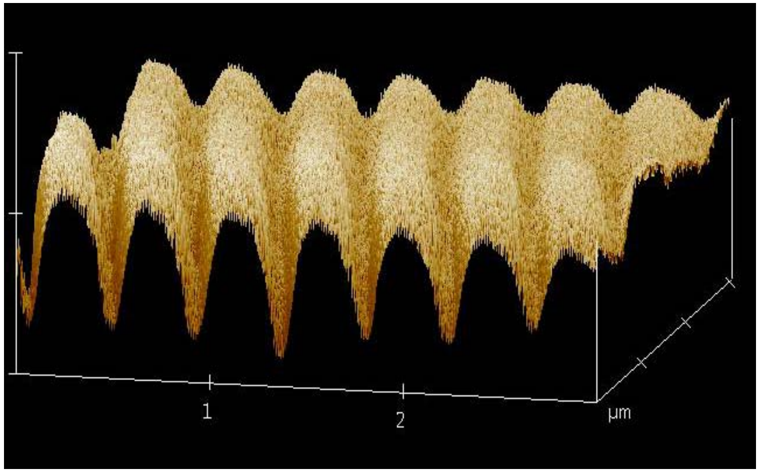
Pulse duration = 120 fs

Recording angle, θ = 70 degree

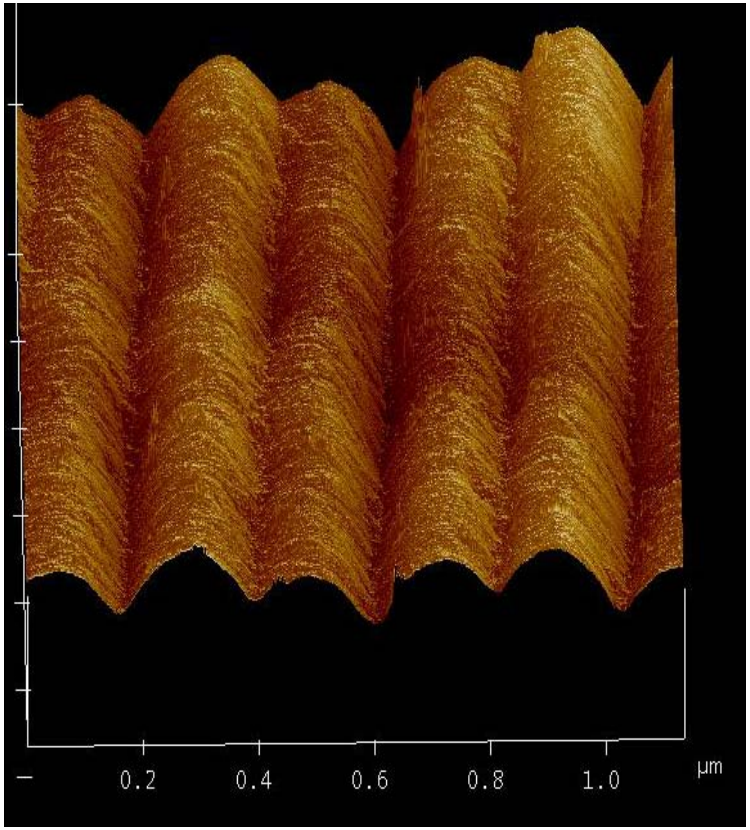
Period λ/(2sinθ) = **425 nm**



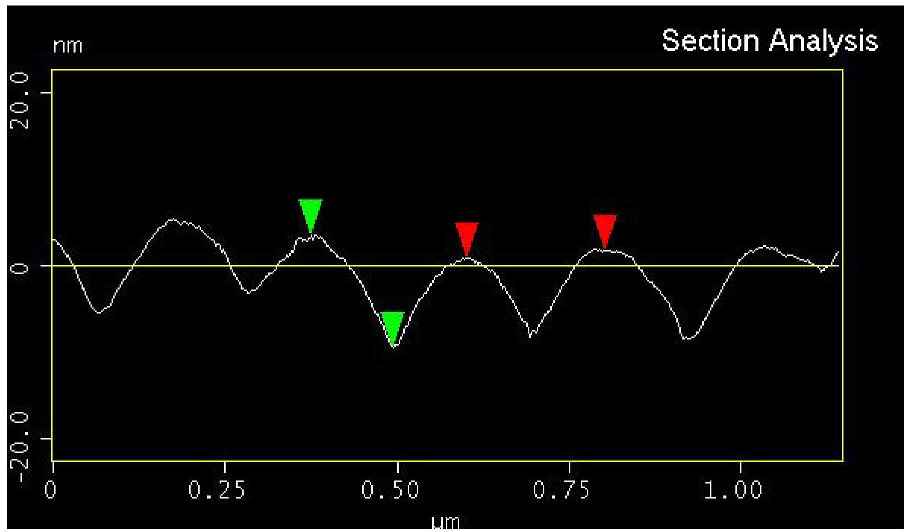




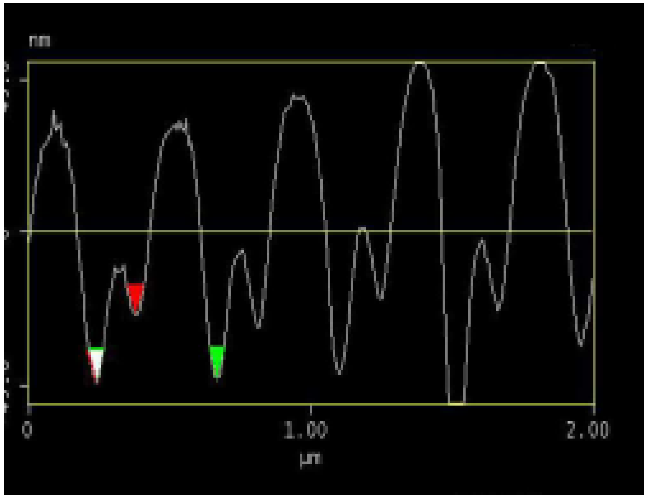
Sub-Rayleigh fringes ~λ/4 (M = 2)

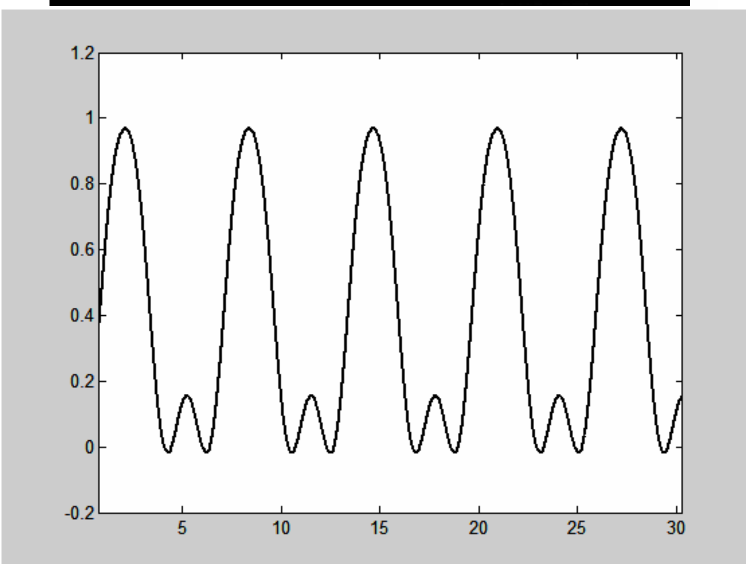


Recording wavelength = 800 nm
Two pulses with π phase shift
Pulse energy = 90 μJ per beam
Pulse duration = 120 fs
Recording angle, θ = 70 degree
Fundamental period $\lambda/(2\sin\theta)$ = 425 nm
Period of written grating = **213 nm**



Non-sinusoidal fringes





- PMMA is a 3PA at 800 nm. (N=3)
- Illumination with two pulses. (M=2)
- If the phase shift of the second shot is

  $\pi + \Delta$, where $\Delta = \dfrac{\pi}{3}$,

  the interference fringe is

  $$I = (1 + \cos(Kx))^3 + (1 + \cos(Kx + \pi + \Delta))^3$$

- Numerical calculation is similar to the experimental result.
- This shows the possibility of 3-fold enhancement of resolution

Conclusion

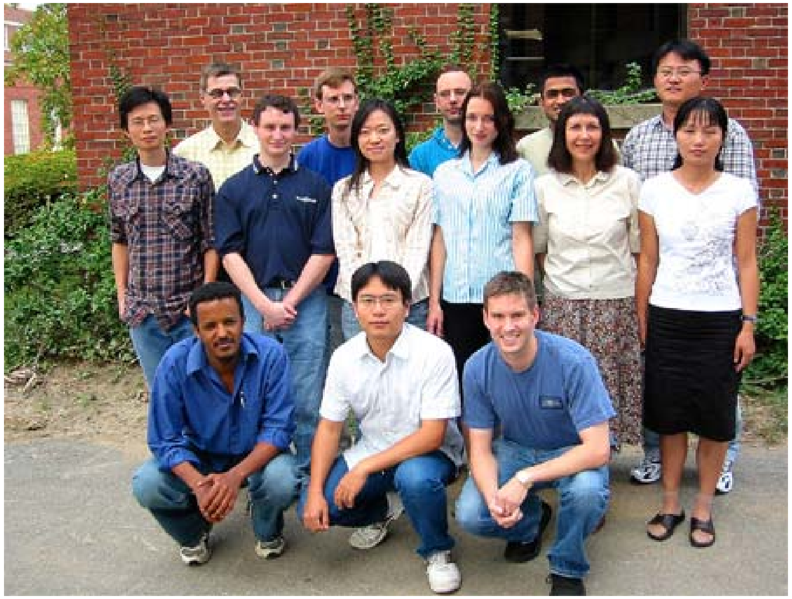
- The possibility of the use of PMMA as a multi-photon lithographic recording medium for the realization of quantum lithography.
- Experimental demonstration of sub-Rayleigh resolution by means of the phase-shifted-grating method using a classical light source.

  - writing fringes with a period of $\lambda/4$
- Quantum lithography (as initially proposed by Dowling) has a good chance of becoming a reality.

Future work

- Higher enhanced resolution (M = 3 or more)
- Build an entangled light source with the high gain optical parametric amplification.
- Realization of the quantum lithography method.

Acknowledgement



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Thank you for your attention!

http://www.optics.rochester.edu/~boyd