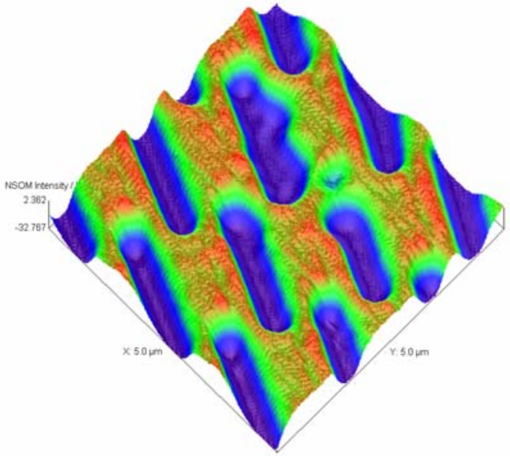
Nano Scale Optics with Nearfield Scanning Optical Microscopy (NSOM)



Presentation Overview

- Motivation for nearfield optics
- Introduction to NSOM
- What is NSOM today?
- What can you do with NSOM?

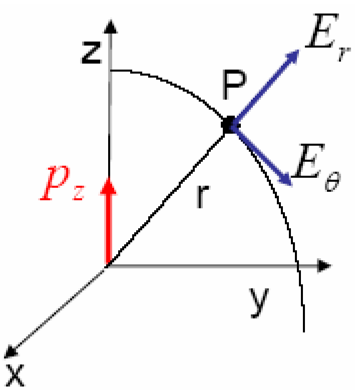
Motivation of NFO

"And God said, `Let there be light,' and there was light. God saw that the light was good, and he separated the light from the darkness." Genesis 1:3,4

- Diffraction imposes a natural limit to available 'resolution' with conventional optics.
  - 'Best' microscopes can obtain ~ 250nm resolution: confocal microscopy
- Oscillating Dipole:

$$E_\theta = \frac{1}{4\pi\varepsilon_r}\left(\frac{1}{r^3} - \frac{ik}{r^2} - \frac{k^2}{r}\right)\sin\theta\, p_z(t) e^{ikr}$$

$$E_r = \frac{1}{4\pi\varepsilon_r}\left(\frac{2}{r^3} - \frac{2ik}{r^2}\right)\cos\theta\, p_z(t) e^{ikr}$$



- To probe the 'nearfield' – require to be within 100 nm of object
- The nearfield scanning optical microscope was developed as the device to do this.

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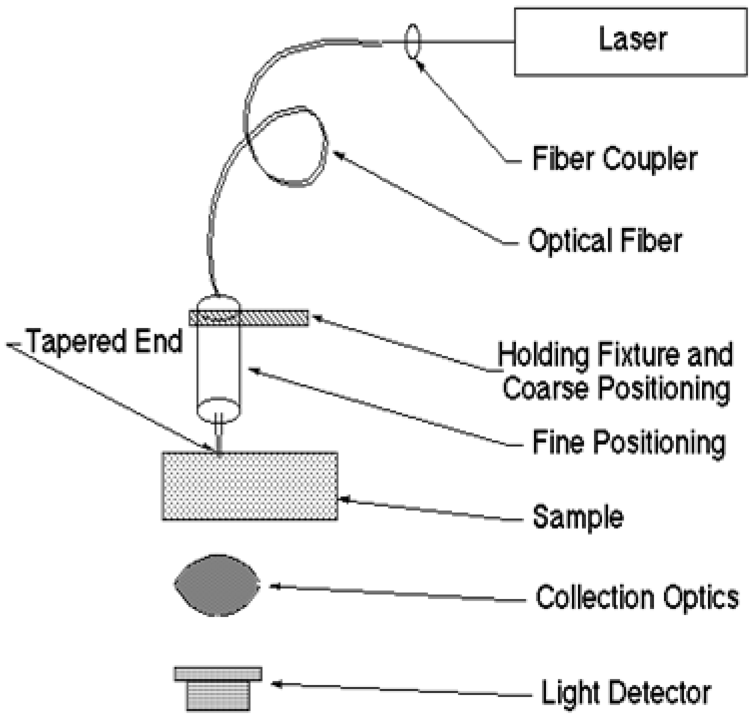
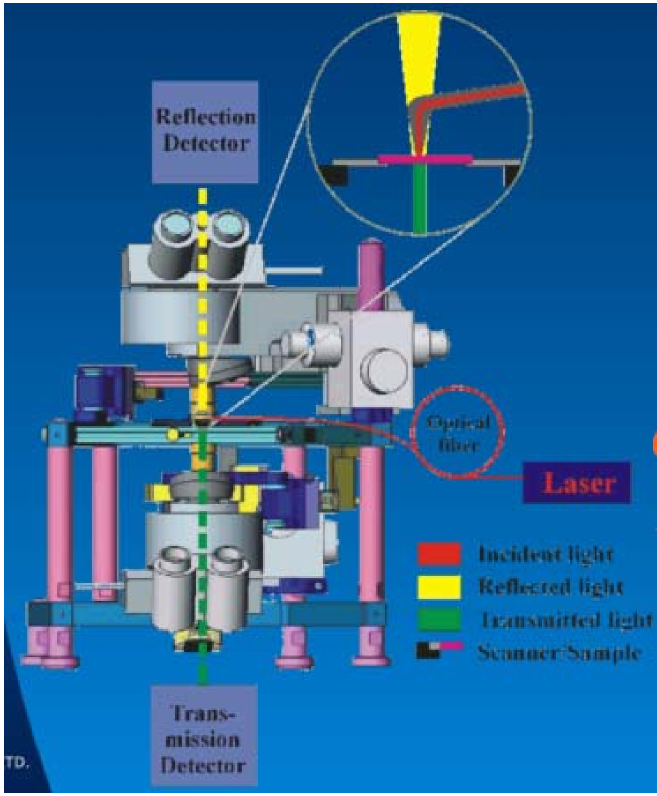
NSOM Instrumentation / Idea



http://www.physics.ncsu.edu/optics/nsom/NSOMintro.html



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History of NSOM

- Conception of an instrument
  - E.H. Synge, "A suggested method for extending the microscopic resolution into the ultramicroscopic region," Phil. Mag. 6, 356 (1928).
  - E.H. Synge, "An application of piezoelectricity to microscopy," Phil. Mag. 13, 297 (1932).

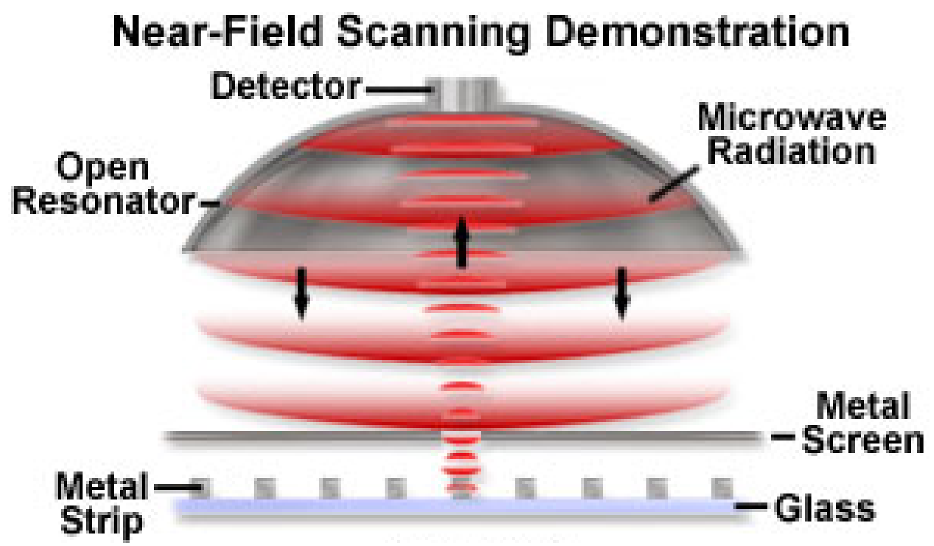
- Proof of Concept with microwaves
  - E.A. Ash and G Nichols, Nature 237, 510 (1972).

- Experiments in the visible
  - D.W. Pohl, W. Denk, and M. Lanz, APL 44, 651-3 (1984).
  - A. Lewis, M. Isaacson, A. Harootunian, and A. Murray, Ultramicroscopy 13, 227 (1984).

Synge's original proposal

- required fabrication of a 10-nanometer aperture (much smaller than the light wavelength) in an opaque screen
- A specimen was scanned very close to the aperture
- As long as the specimen remained within a distance less than the aperture diameter, an image with a resolution of 10 nanometers could be generated.
- Technical difficulties to overcome:
  - fabricating the minute aperture
  - achieving a sufficiently intense light source
  - specimen positioning at the nanometer scale
  - maintaining the aperture in close proximity to the specimen

Implementation in Microwave region



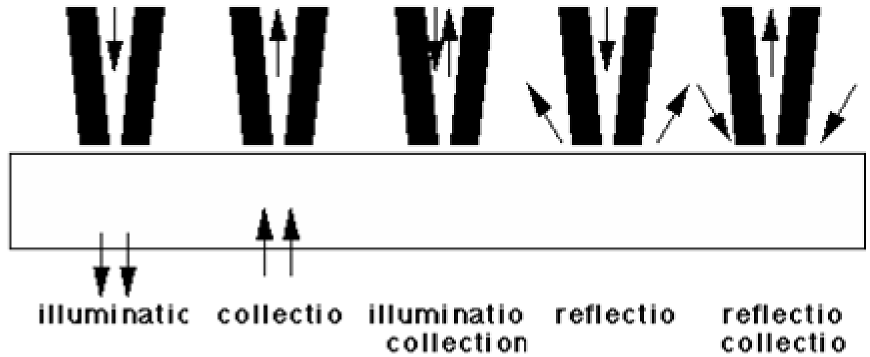
http://www.olympusmicro.com/primer/techniques/nearfield/nearfieldintro.html

- Microwaves with a wavelength of 3 cm
- Aperture diameter of 1.5 mm
- Probe scanned over a metal grating with periodic line features
- 0.5 mm gaps and lines were resolvable
- Subwavelength resolution of ~ 1/16 lambda

Optical Implementation

- The IBM researchers employed a metal-coated quartz crystal probe on which an aperture was fabricated at the tip, and designated the technique scanning near-field optical microscopy (**SNOM**).
- The Cornell group used electron-beam lithography to create apertures, smaller than 50 nanometers, in silicon and metal.
- The IBM team was able to claim the highest optical resolution of 25 nanometers, or one-twentieth of the 488-nanometer radiation wavelength, utilizing a test specimen consisting of a fine metal line grating.

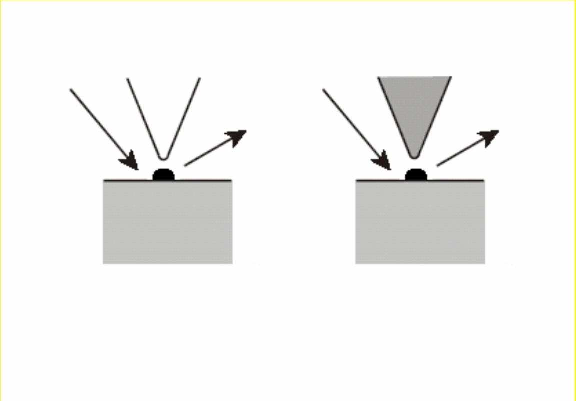
NSOM modes of Operation



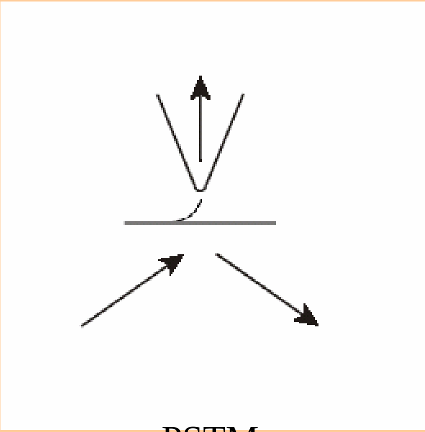
http://www.physics.ncsu.edu/optics/nsom/NSOMintro.html

- Illumination by the tip is probably the easiest to interpret, and gives the most signal. It requires a transparent sample, so can’t always be used.
- Reflection modes give less light, and are more dependent on the details of the probe tip, but allow one to study opaque samples.
- The illumination/collection mode provides a complement to the reflection modes, but the signal contains a large background from the light reflected without ever making it out of the probe tip. (This is removed by oscillating the tip vertically and measuring the signal at that frequency.)

NSOM modes of Operation



Apertureless NSOM



PSTM
(Photon Scanning Tunneling Microscopy)

Comparison to far-field microscopy

- Two fundamental differences between near-field and far-field (conventional) optical microscopy:
  - In NF microscopy the NF interaction region at a single instant is much smaller than the FF interaction area for conventional microscopy
  - NF microscopy has a subwavelength distance between the radiation source and the sample while FF microscopy has a much larger distance

Limitations of near-field optical microsopy

- Practically zero working distance and an extremely small depth of field.
- Extremely long scan times for high resolution images or large specimen areas.
- Very low transmissivity of apertures smaller than the incident light wavelength.
- Only features at the surface of specimens can be studied.
- Fiber optic probes are somewhat problematic for imaging soft materials due to their high spring constants, especially in shear-force mode

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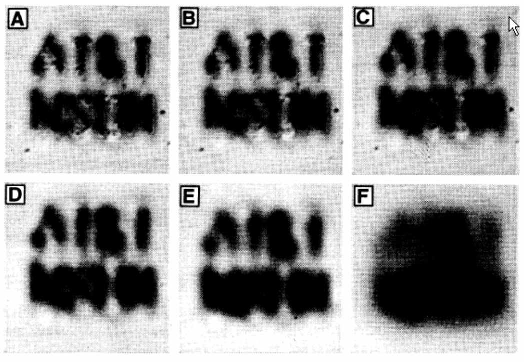
NSOM Today: Similar to Standard Scanning Probe Microscopy with an Optical Channel

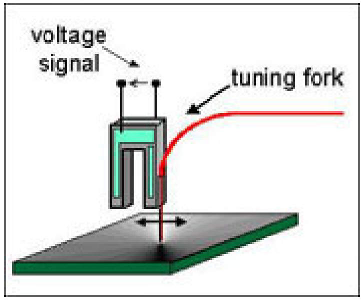
- Mechanical
  - Translation stage, piezoelectric scanner
  - Feedback Control (Z distance)
  - Anti-vibration optical table
- Electrical
  - Scanning drivers for piezoelectric scanner
  - z distance control
  - Amplifiers, Signal processors
  - Software and Computer
- Optical
  - Light source (lasers), Fiber, Mirrors, Lenses, Objectives
  - Photon detectors (Photon Multiplier Tube, Avalanche Photo Diode, Charge Coupled Devices)
  - Probe to provide the window to the near-field

Z Distance Control

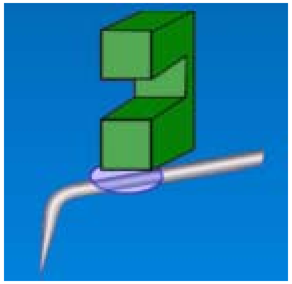
- Shear force
- Normal force



Science, 257, 189-195 (1992).



Veeco Instruments



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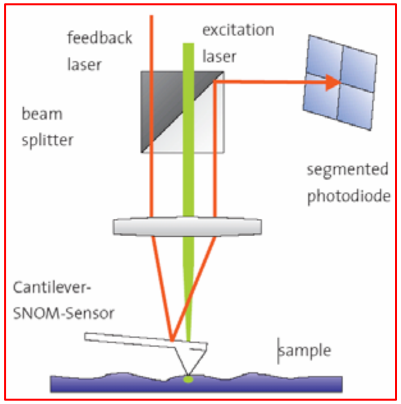
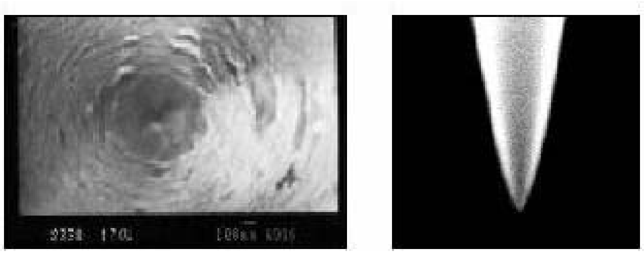


Witec GmbH

NSOM Probes

- Aperture type
  - Taped fiber, multiple-taped fiber
  - Cantilevered AFM/NSOM tips (Si_3N_4, SiO_2)
  - Other kinds, such as tetrahedral tip, Fluorescent tip
  - Metal Coating Optional
- Apertureless type
  - Dielectrics, semiconductors or metals
  - Other kinds, such as nano-particle attached tip



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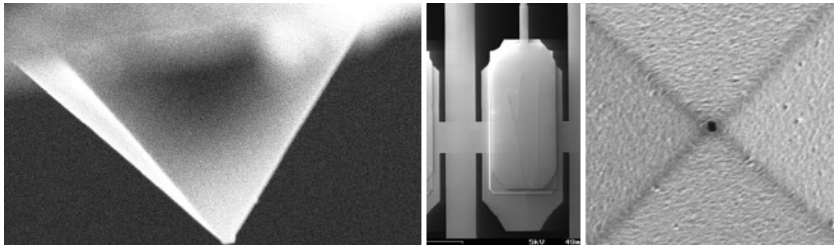

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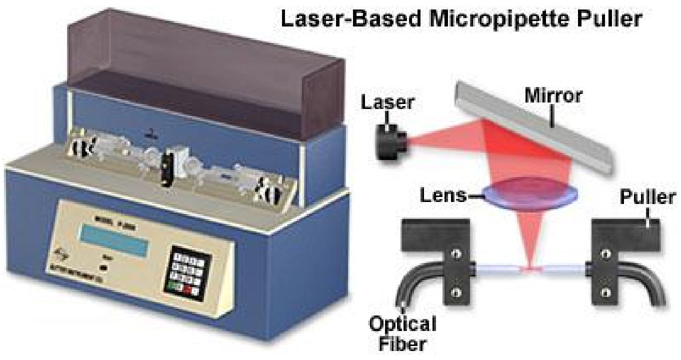
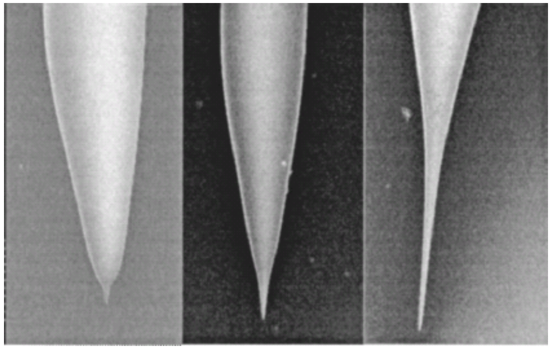
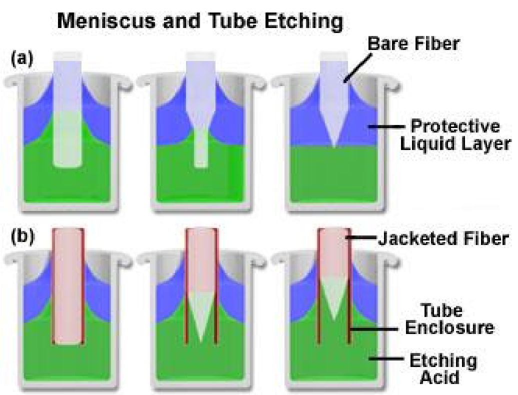
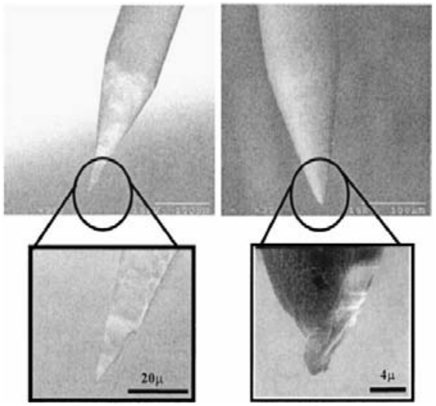
Probe Fabrication: Fiber probes









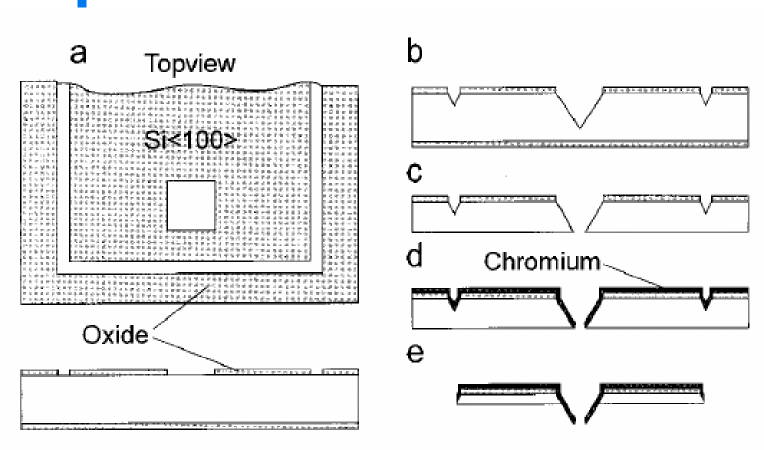
Lazarev, A., Rev. Sci. Inst., ***74***, *3679-3688 (2003).*

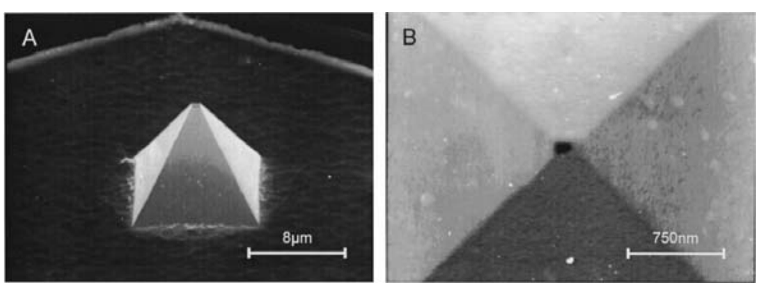
http://www.olympusmicro.com/primer/techniques/nearfield/nearfieldprobes.html

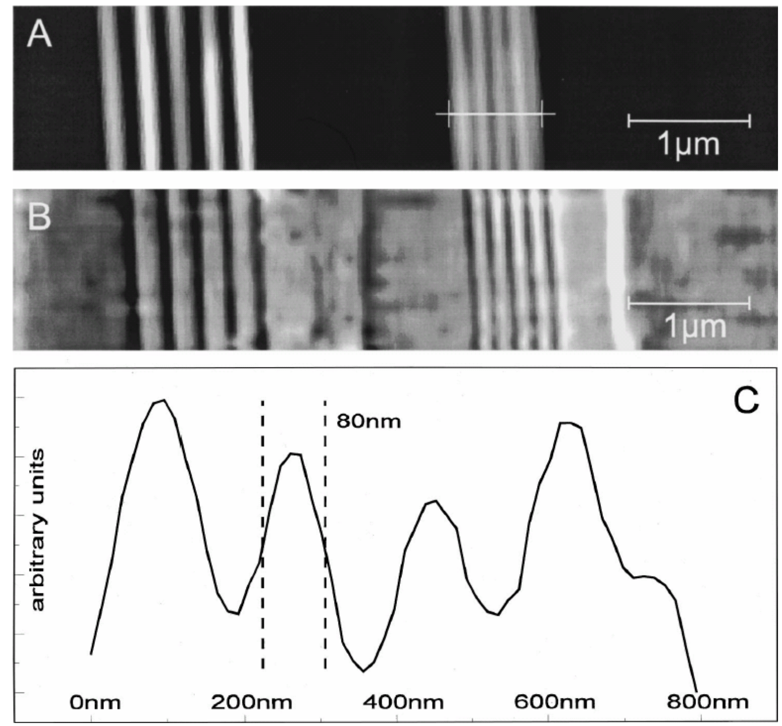
Probe Fabrication:
Cantilevered probes

- Mircofabrication
- Rubbing
- Focus ion beam milling
- Special techniques, such as solid electrolysis, self-terminated corrosion

Mirco-fabrication: a batch process



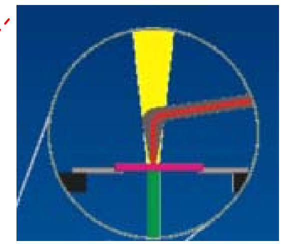


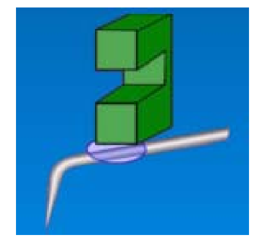


App. Phy. Lett., 68, 3531-3533 (1996).

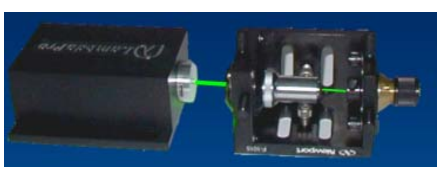
Commercial NSOM: Nanonics MultiView 2000

APD

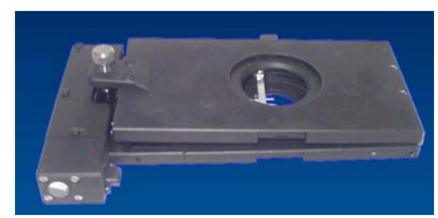




Probe



Laser



Scanner

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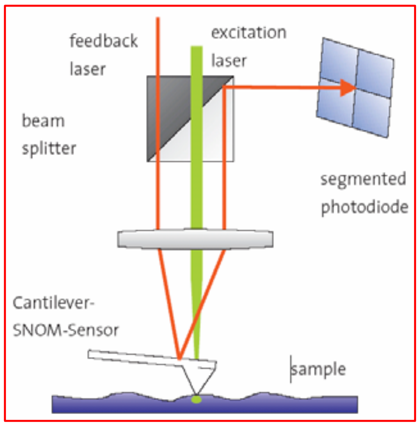
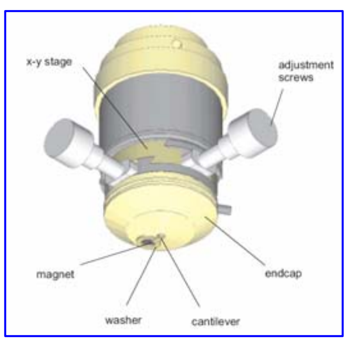
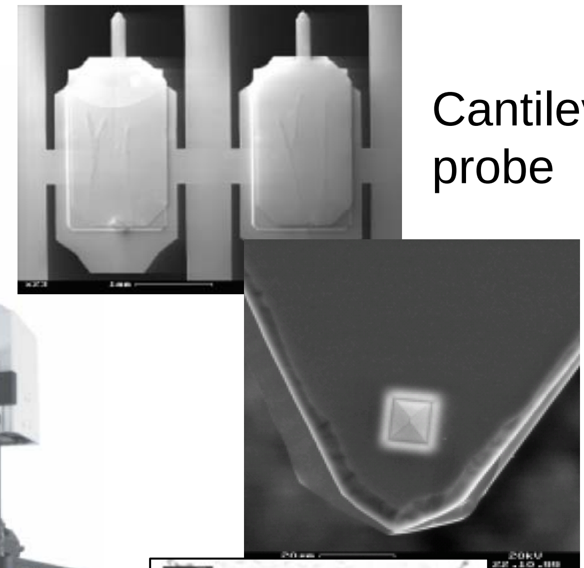
Commercial NSOM: Witec ALphaSNOM



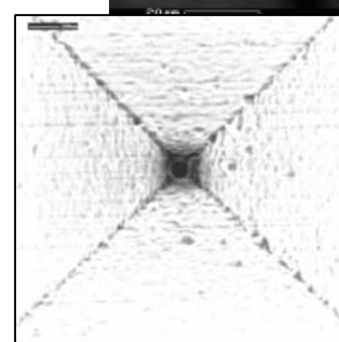


Probe Mounting

Witec GmbH

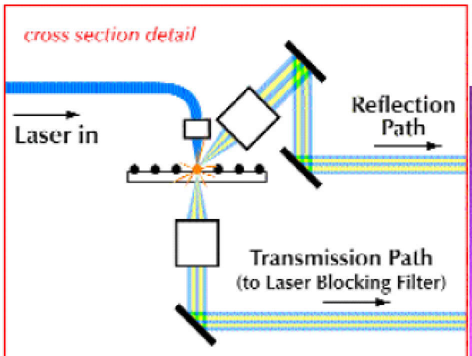


Cantilevered probe

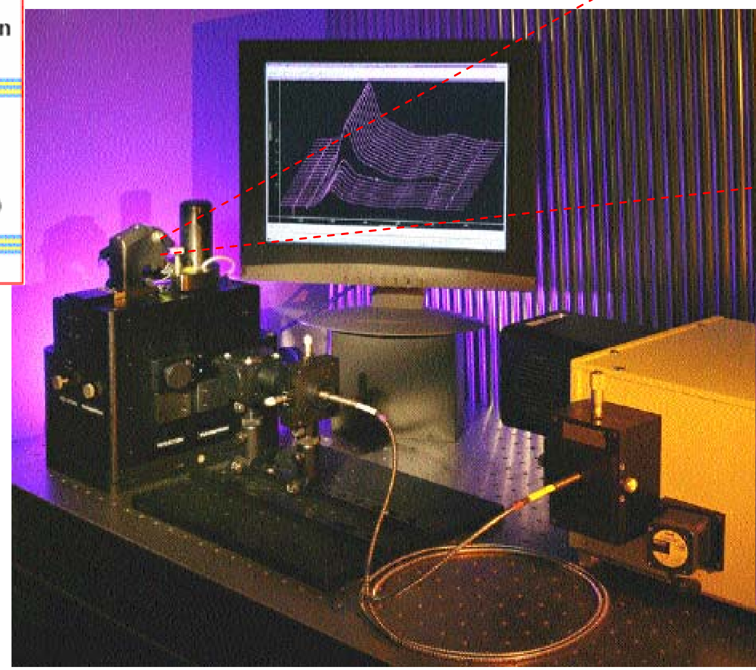


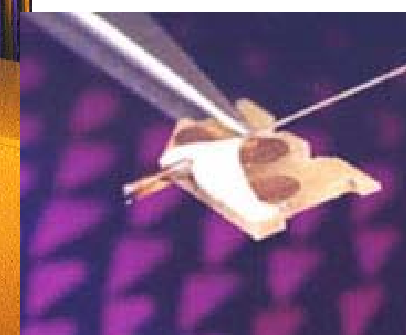
Aperture

Commercial NSOM: Veeco Aurora3

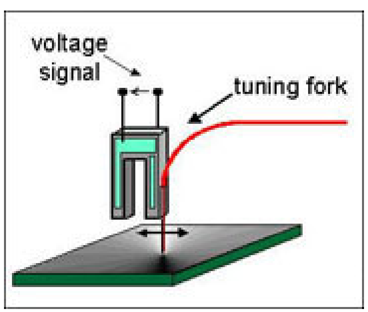


System schematic





Fiber mounting

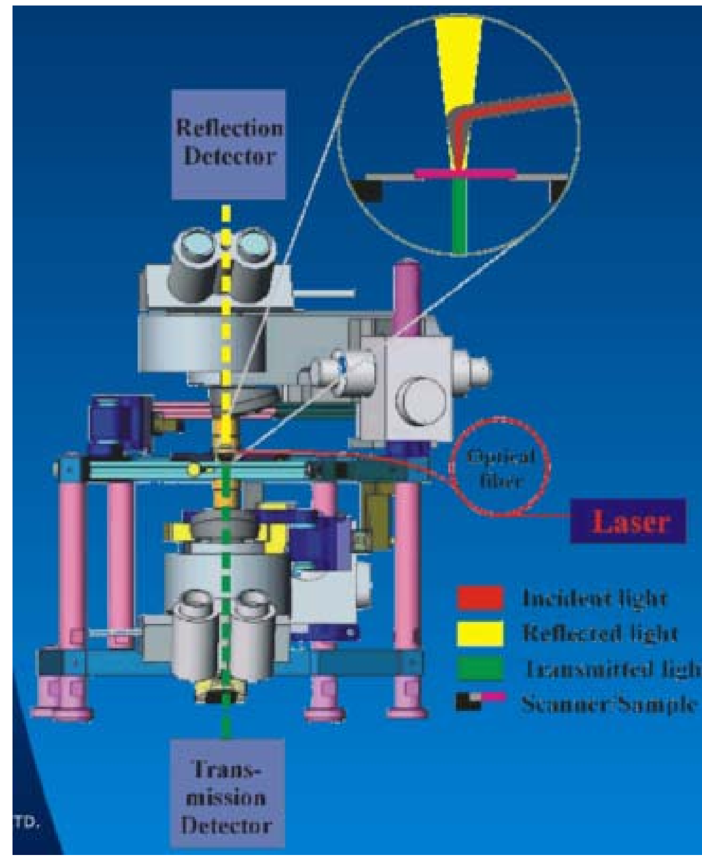


Feedback control

Veeco Instruments

Nanonics System at Purdue

- Nanonics MultiView 2000
- NSOM / AFM
- Tuning Fork Feedback Control
  - Normal or Shear Force
- Aperture tips down to 50 nm
- AFM tips down to 30 nm
- Radiation Sources:
  - (532, 633, 785) nm
  - Supercontinuum 480-1500+ nm



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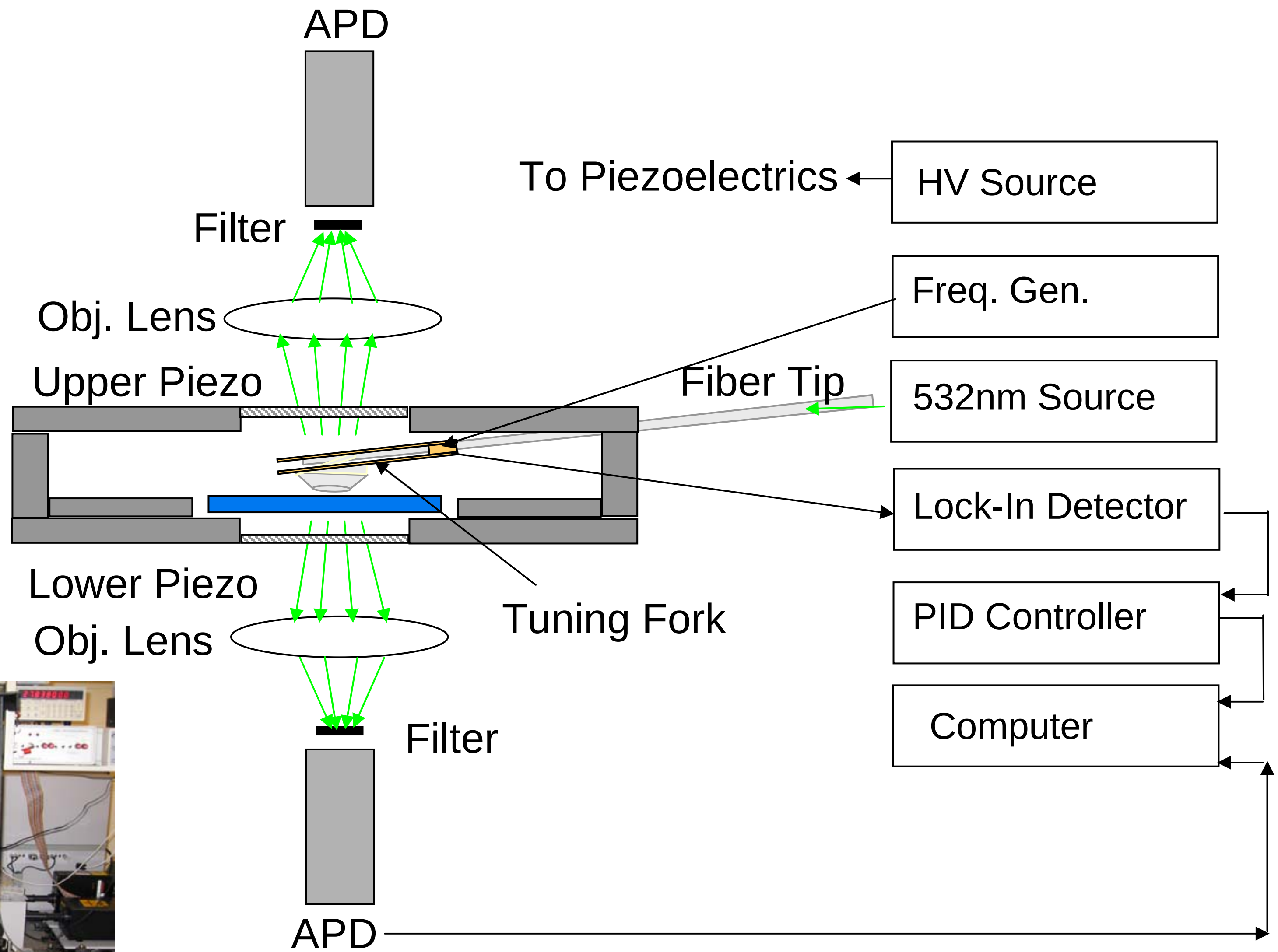
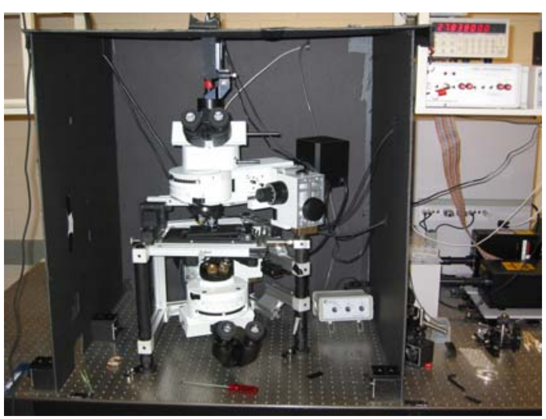
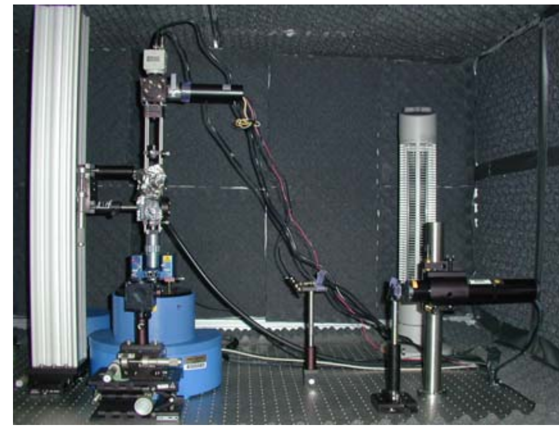




Prof. Shalaev's group Internal to Purdue

Purdue Homemade NSOM Developed from Commercial AFM

- Scanning: micro stages, piezoelectic scanner and probe head
- Imaging: optics with video monitor, white source and HeNe laser



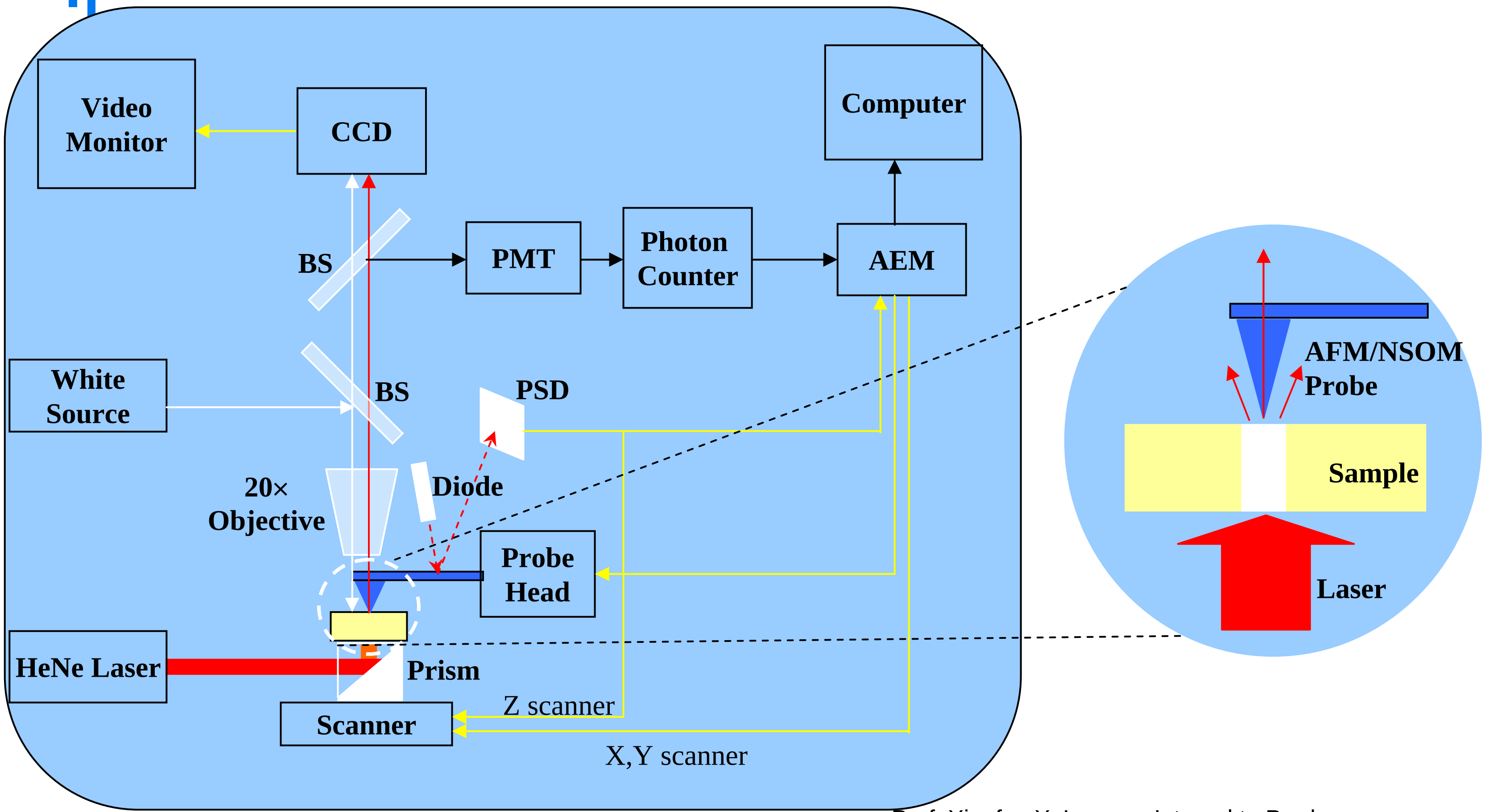
System Setup

User Interface

- Light detection: Photomultiplier tube (PMT), photon counter
- Signal Processing: AutoProbe Electronic Module (AEM), Proscan software

Prof. Xianfan Xu's group Internal to Purdue

Schematic of Purdue Home-made NSOM



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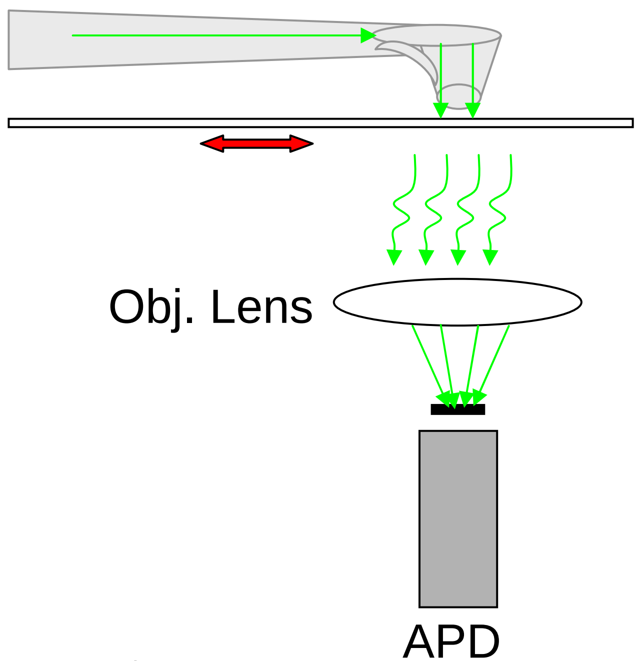
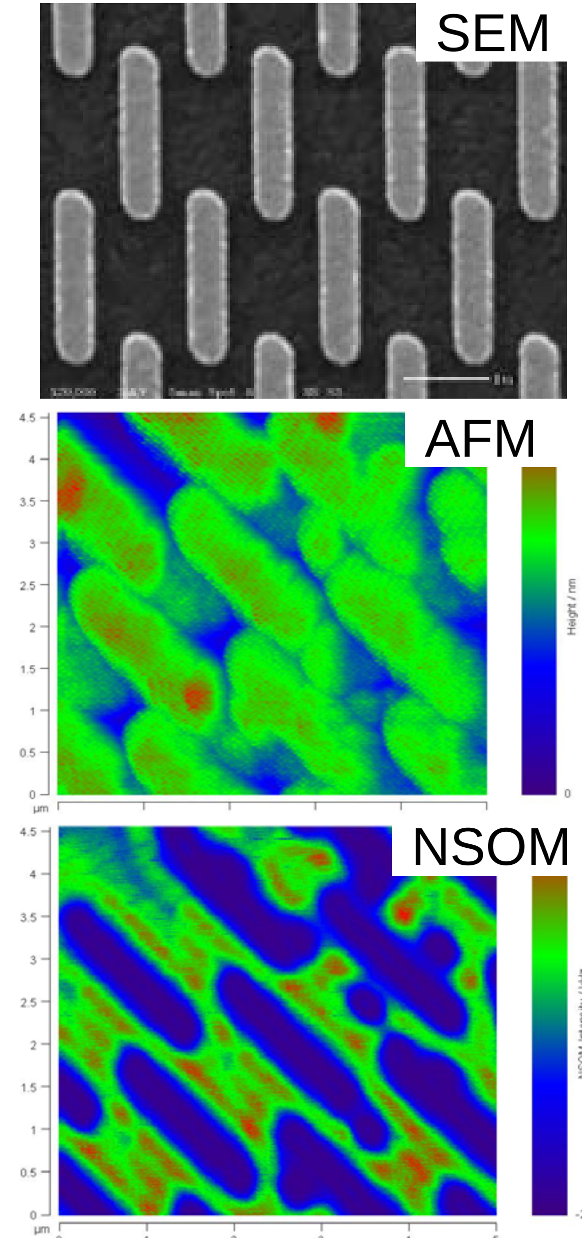
What Can you do with NSOM?

- Ultrahigh resolution OPTICAL Imaging / Plamonic studies
- Spectroscopy
  - Nearfield Surface Enhanced Raman Spectroscopy
  - Local Spectroscopy of Semiconductor Devices
  - Near-field Broadband Spectroscopy
- Modification of Surfaces
  - Subwavelength photolithography
  - Ultra High Density data storage
  - Laser Ablation
- Nearfield femtosecond studies

High Resolution Optical Imaging

83 nm Optical resolution seen with “100” nm tip





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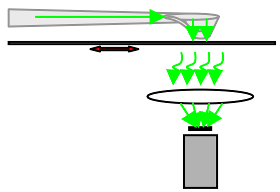
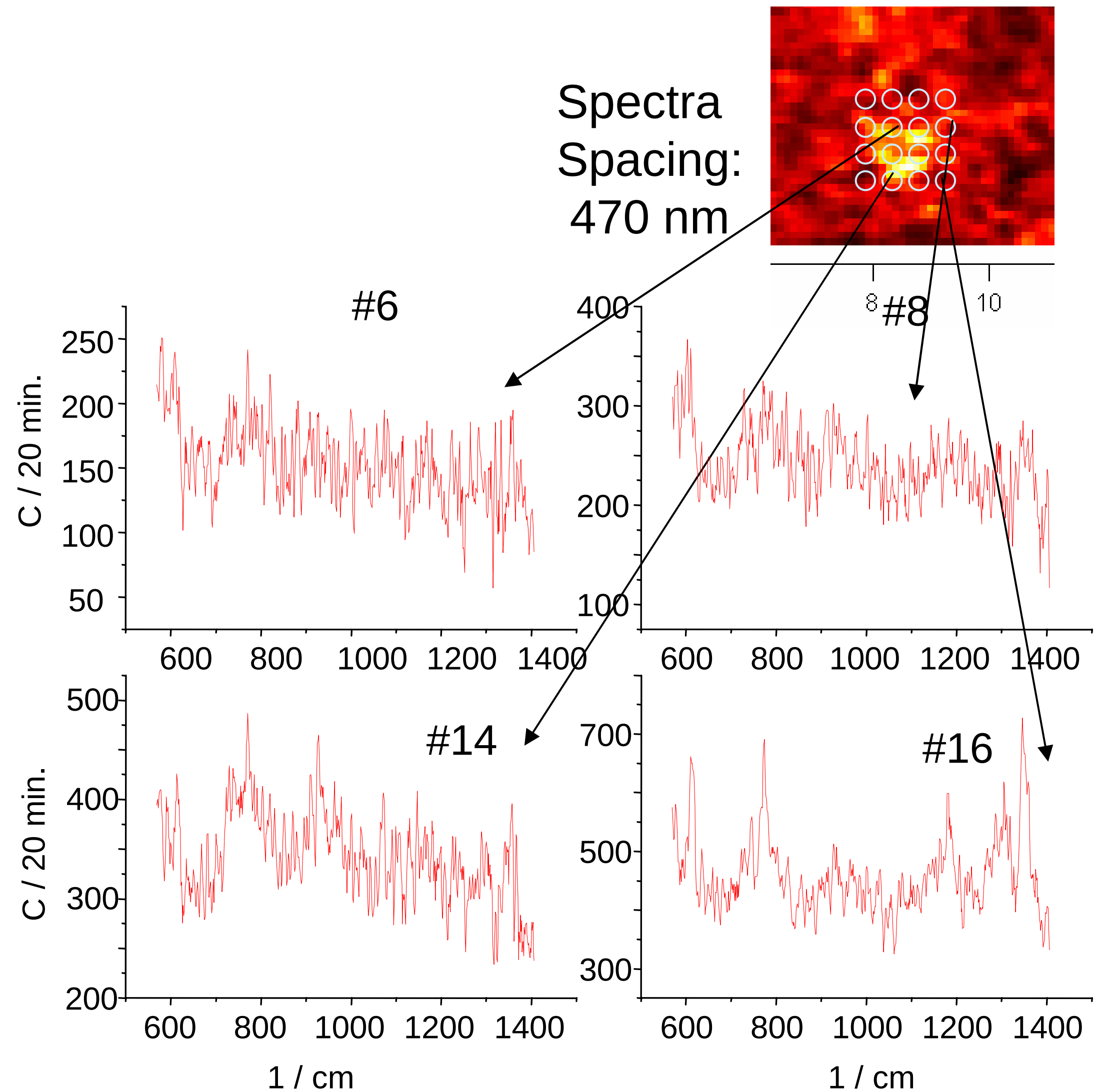
NF Surface Enhanced Raman Spectroscopy (SERS)

- What is Raman spectroscopy?
  - Incident light scattered by a molecule will scatter at different wavelengths than the incident light. Measuring the spectrum of such scattered light provides powerful a “fingerprinting” technique for identification.
- What is surface enhanced Raman spectroscopy (SERS)?
  - Typical Raman signals are rather weak. The electromagnetic fields carrying the fingerprinting information can be enhanced by many orders of magnitude.
- Add in NSOM:
  - The addition of nearfield optics to such techniques enables localization of illumination or collection of light. This provides the means to detect trace amounts that would otherwise be undetectable.

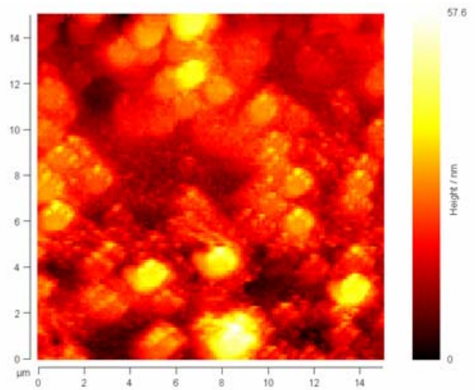
Nearfield SERS of R6-G on a semi continuous metal film



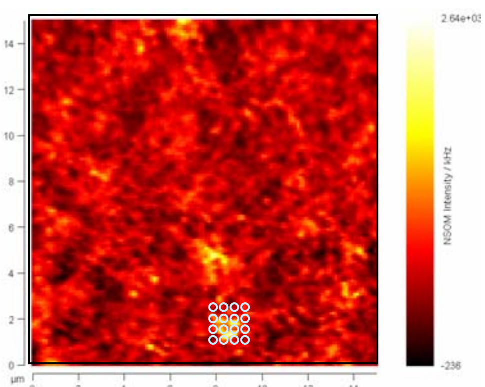
Spectrometer



AFM



Reflection NSOM



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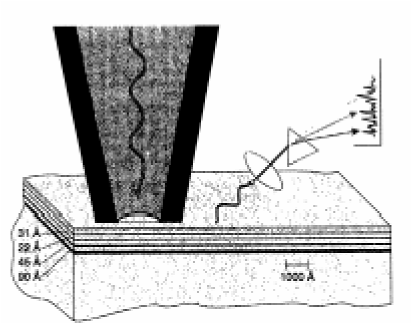
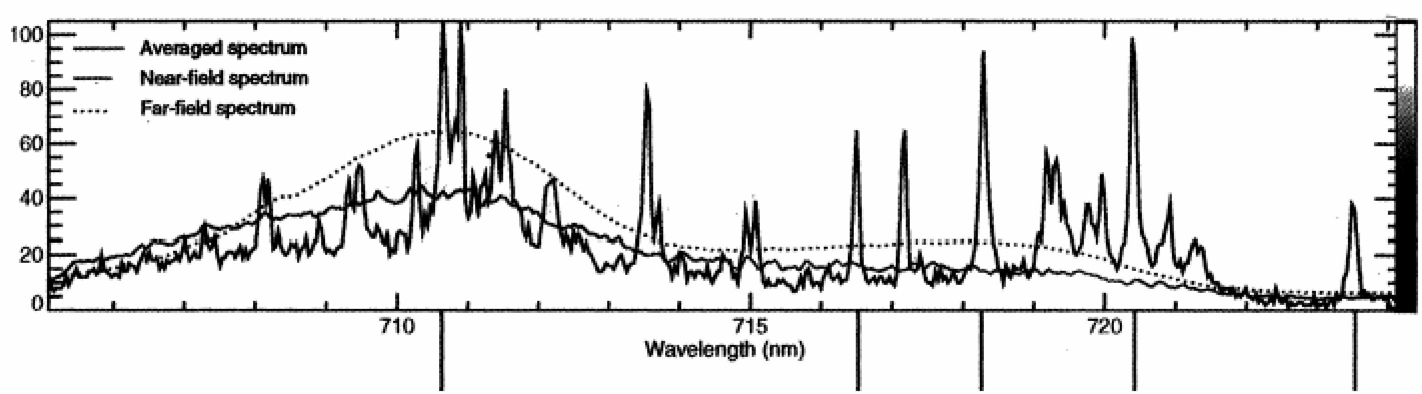
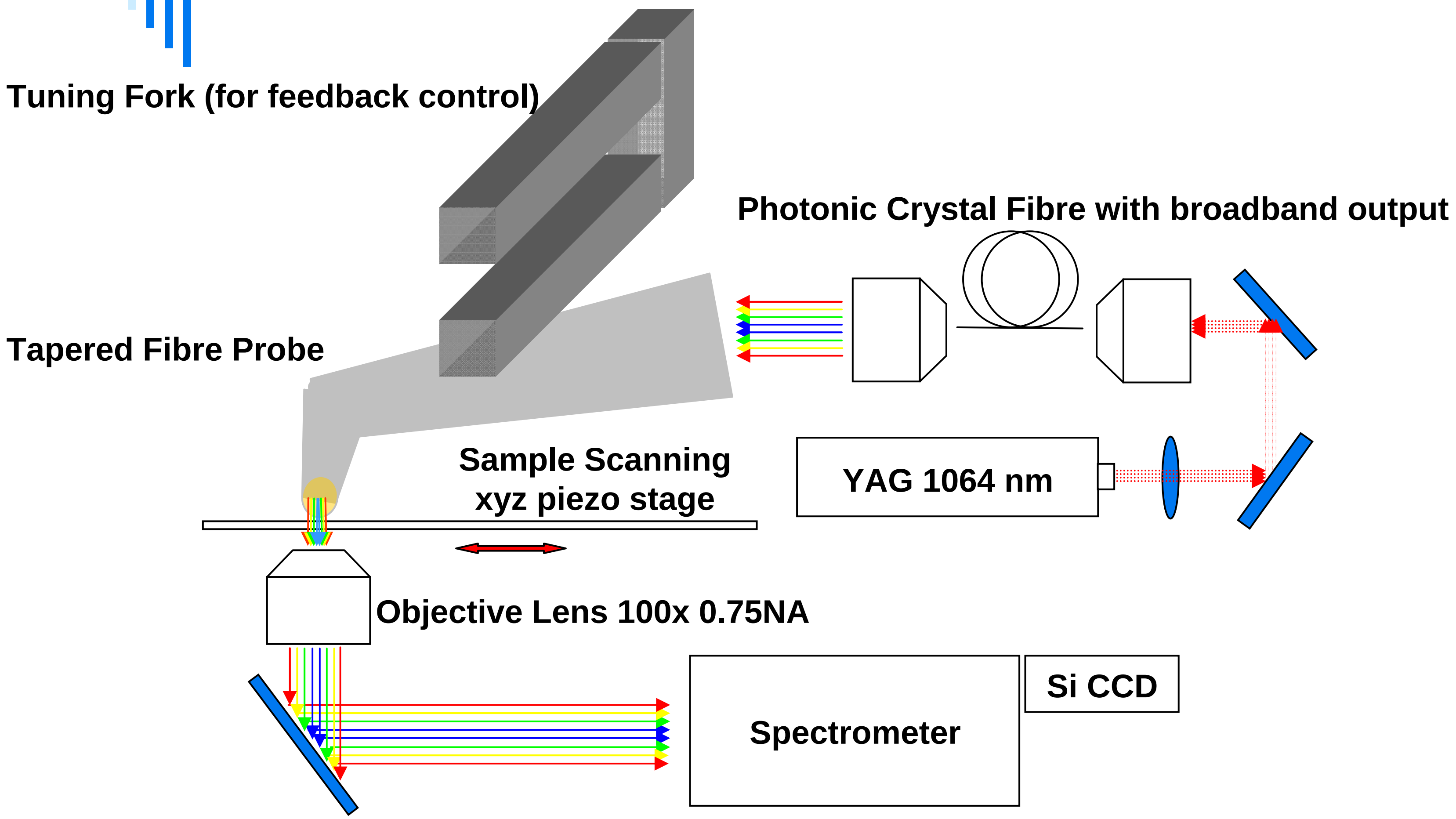
NF Spectroscopy:
Quantum Device





Science 264, 1740 (1994)

NF Spectroscopy: Broadband



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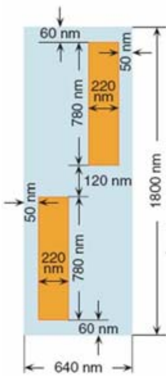
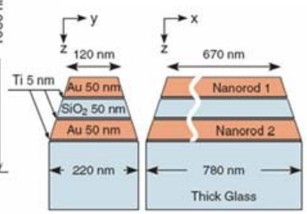
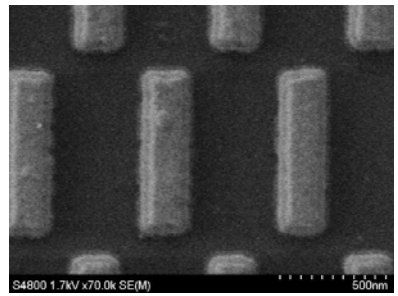
NF Broadband Spectroscopy Local Transmittance



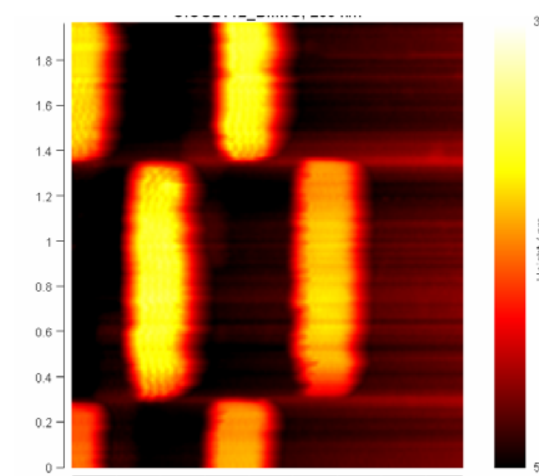
Laser Phys. Lett. 3, No. 1, 49–55 (2006)

Optics Letters, Vol.30, No.24, 3356 (2005)





Representative AFM

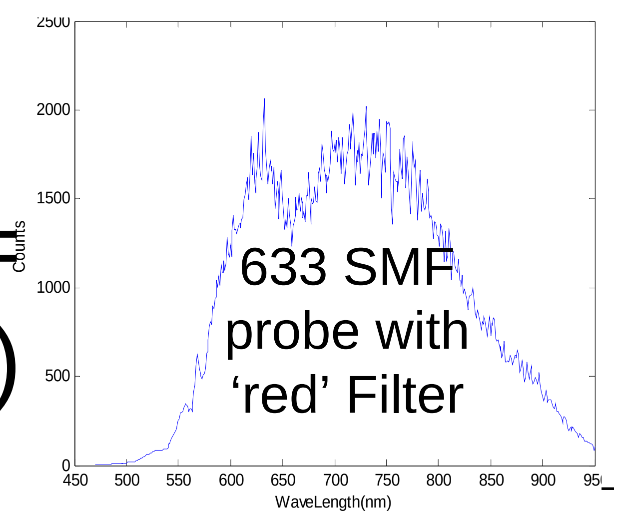


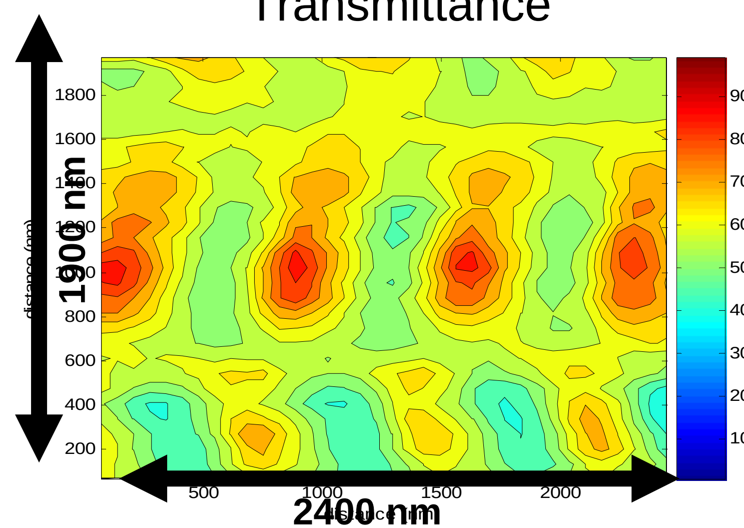
Reference Spectrum

500-950nm 'integrated' Transmittance

Mapping Function:

$$T(x,y,\lambda) = I(x,y,\lambda)/I_o(\lambda)$$

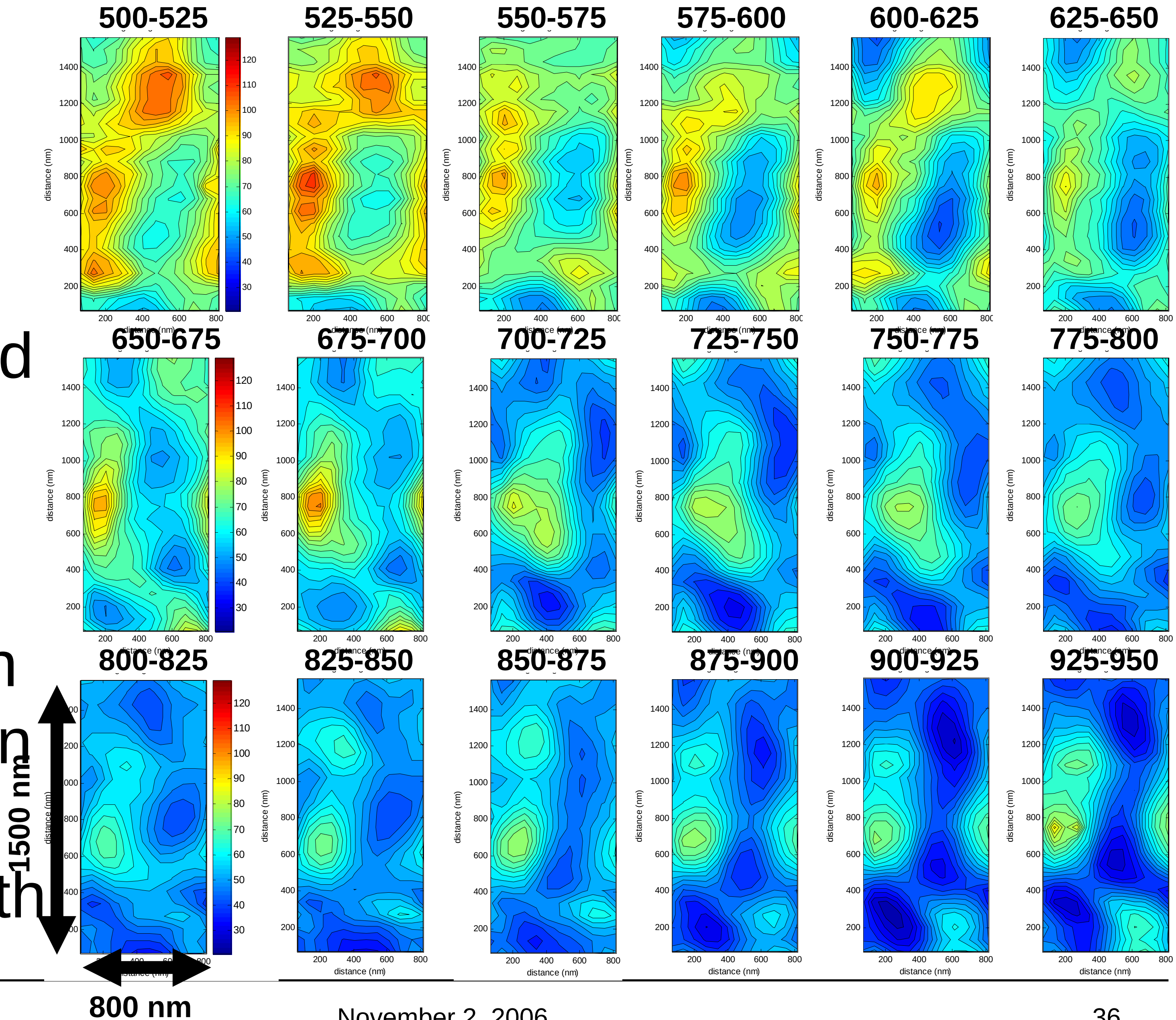




Prof. Shalaev's group Internal to Purdue

NF Broadband imaging

Mode Transition as function of Wavelength



Subwavelength Photolithography

- Use NSOM to write patterns into a photoresist
- Can use aperture NSOM in illumination mode
- Can use apertureless NSOM utilizing two photon absorption at the metallic tip

Ultrahigh Density Data Storage

- Can use aperture NSOM in illumination mode to both write and read data on magneto-optical material
- When writing, probe heats the medium under the probe. The domain under the write beam becomes magnetized opposite of the surrounding material.
- This varying domain of magnetization can then be read using the same probe, but with a lower output power.

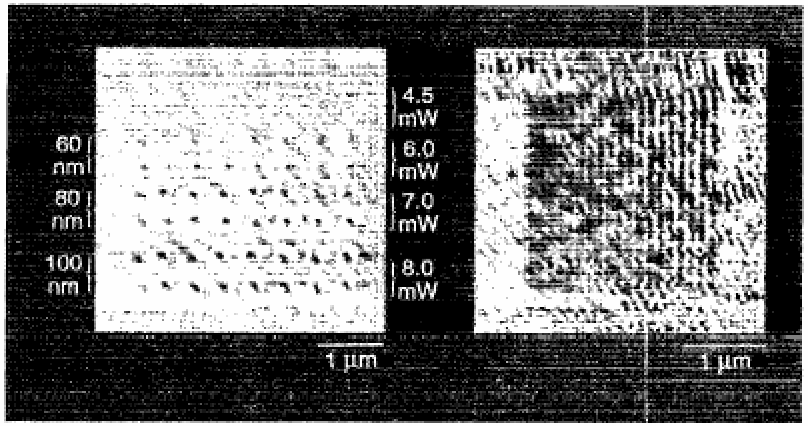
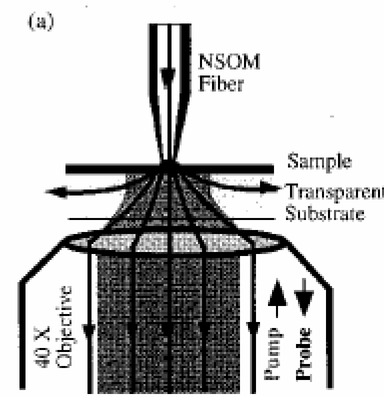


FIG. 4. (a) Domain size vs write power within the near-field probe. (b) A 20×20 array of domains with 120 nm periodicity in both directions, corresponding to a storage density of ~45 Gbits/in.[2]

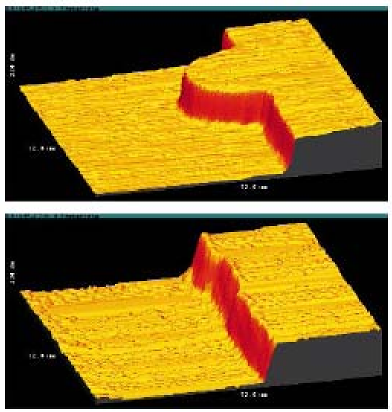
Appl. Phys. Lett. 61, 142-144 (1992)

Nearfield femtosecond studies

- Pump – Probe techniques
  - NSOM allows this technique to employ spatial localization to measure carrier dynamics. (eg – in semiconductor devices)
- Localized laser ablation
  - Currently in use for photomask repair
  - Nanolithography



Rev. Sci. Inst. 70, 2758 (1999)



J. Microscopy 194, 537 (1999)

Other things done with NSOM

- Fluorescent spectrum studies of biological cells, molecules and DNA
- Atom trapping and Manipulation
- Local probing of luminescent devices
- Low temperature NSOM
- Surface plasmon / Local field enhancement

Recap – Nearfield Scanning Optical Microscopy (NSOM)

- NSOM is a relatively new technology that defeats the diffraction limit for optical measurements. Utilizes the near field portion of electromagnetism to window down to ~ 10 nm spatial resolution.
- NSOM instrumentation has progressively developed over the past 15 years, to the point where several different basic techniques are available as commercial instruments
- The principles of NSOM are very much in play within the research community. It has many different applications ranging from biological studies to nanofabrication.
- Up to Date Near-Field Optics Research
  - NSOM Conference: NFO9 http://www.nfo9.org/
    - September 2006, look for conference proceedings in the Journal of Microscopy, 2007
- Quick and Easy Resources
  - Review Articles:
    - R.C. Dunn. Chemical Reviews, 99 (1999) 2891.
    - B. Hecht, B. Sick, U.P. Wild, V. Deckert, R. Zenobi, O.J.F. Martin, and D.W. Pohl. Journal of Chemical Physics, 112 (2000) 7761.
  - Website: Olympus Microscopy (nearfield section)
    - http://www.olympusmicro.com/primer/techniques/nearfield/nearfieldhome.html