4 Scanning Near Field Optical Microscope & its Applications

Contents

Working principle

The Scanning Near-Field Optical Microscope (SNOM) is a scanning probe microscope that allows optical imaging with spatial resolution beyond the diffraction limit. A nanoscopic light source, usually a fiber tip with an aperture smaller than 100 nm, is scanned very closed to the sample surface in the region called "optical near-field".

Operation principle

The operational principle behind near-field optical imaging involves illuminating a specimen through a sub-wavelength sized aperture whilst keeping the specimen within the near-field regime of the source. Broadly speaking, if the aperture-specimen separation is kept roughly less than half the diameter of the aperture, the source does not have the opportunity to diffract before it interacts with the sample and the resolution of the system is determined by the aperture diameter as oppose to the wavelength of light used. An image is built up by raster-scanning the aperture across the sample and recording the optical response of the specimen through a conventional far-field microscope objective.

Research into far-field optical microscopy has accumulated centuries of experience and produced many alternative contrast techniques such as polarization contrast, phase contrast, fluorescence, etc. These can also be achieved in the near-field making near-field optical microscopy a potentially powerful analytical technique, but don't forget that the advantages are balanced (but not quite outweighed) by other difficulties the user encounters with a near-field system. Such is life. Bugger.

http://spm.phy.bris.ac.uk/techniques/SNOM/

Operation procedures

Four steps：

1. Light source coupling
2. Alignment between optical axis and sample
3. Alignment between optical axis and probe
4. Adjustment of resonant frequency

NSOM working modes

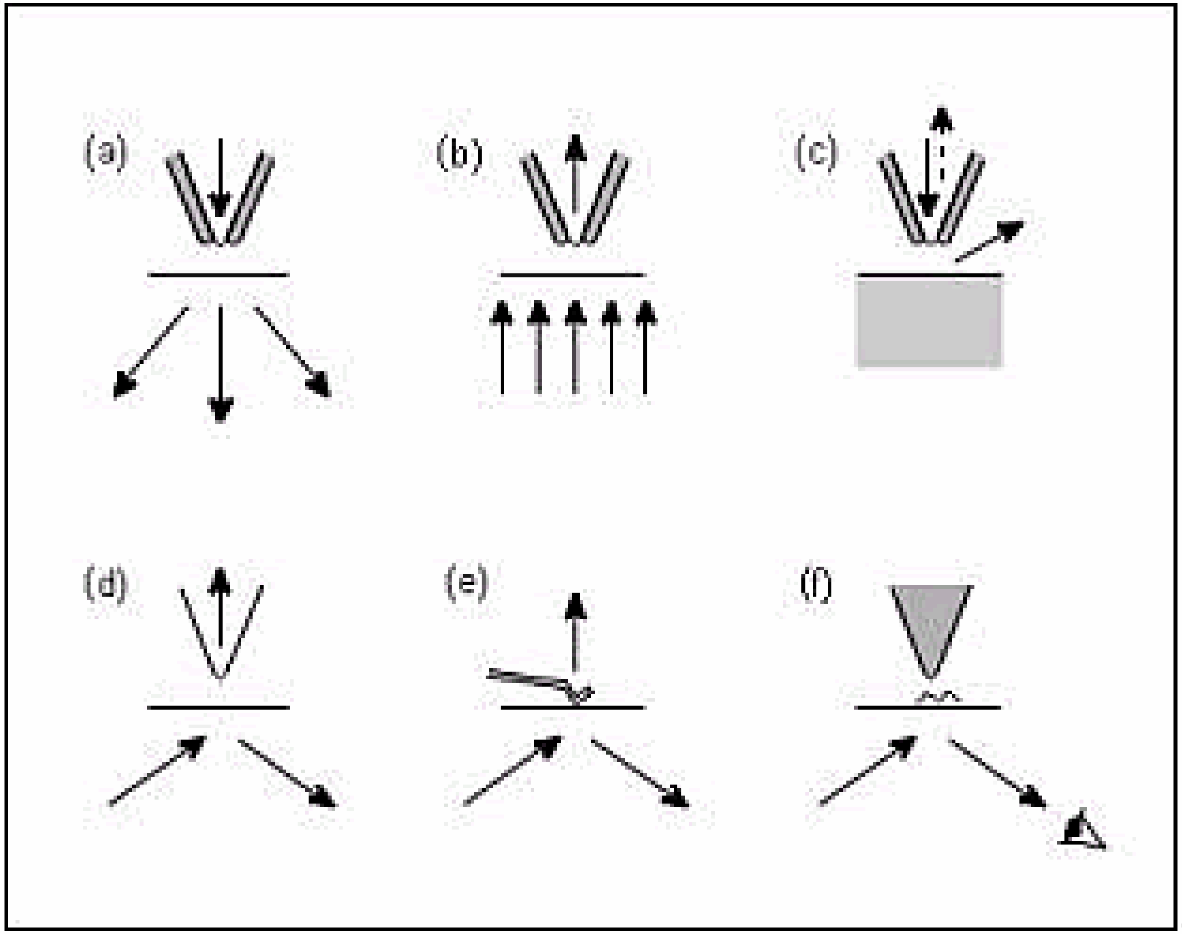
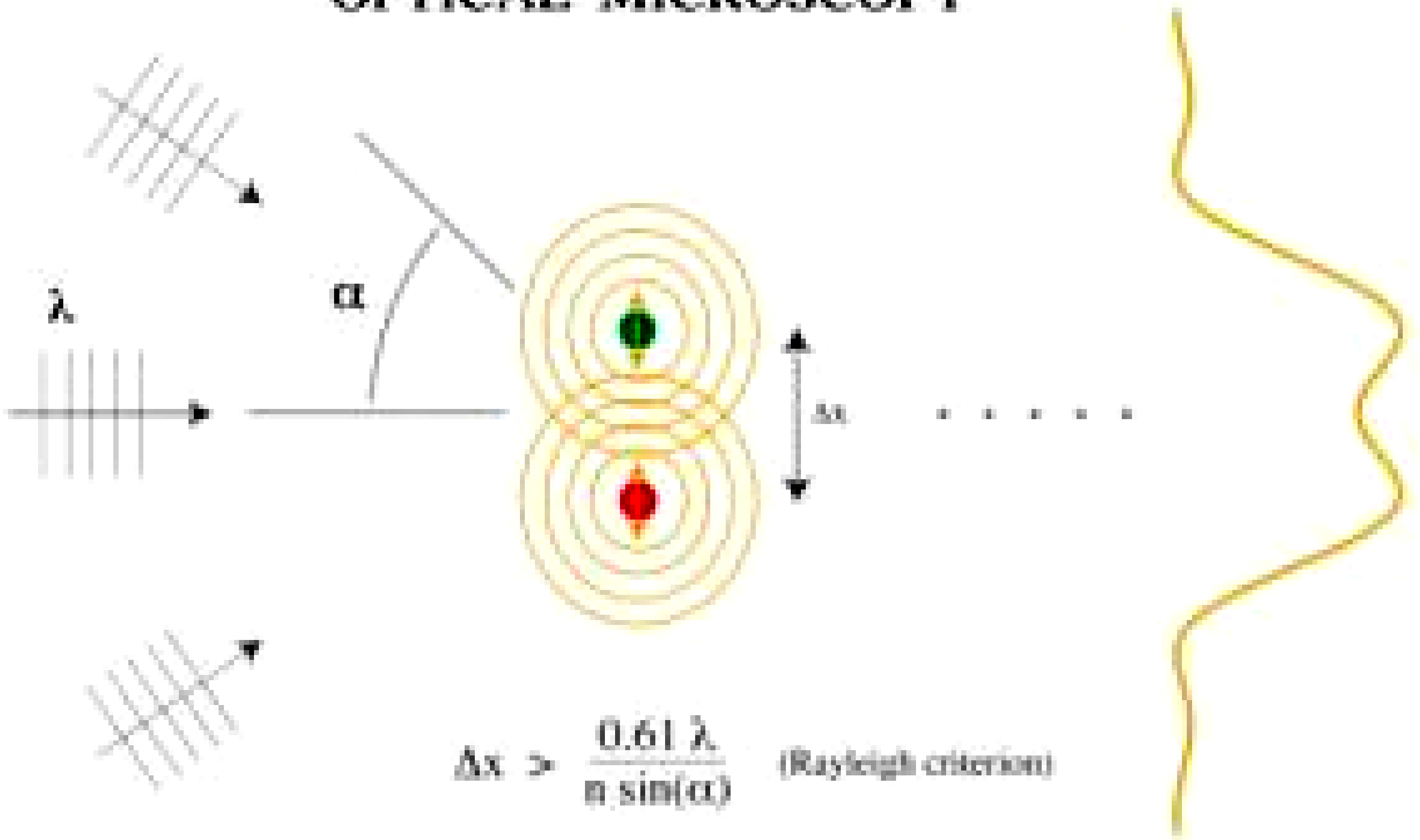


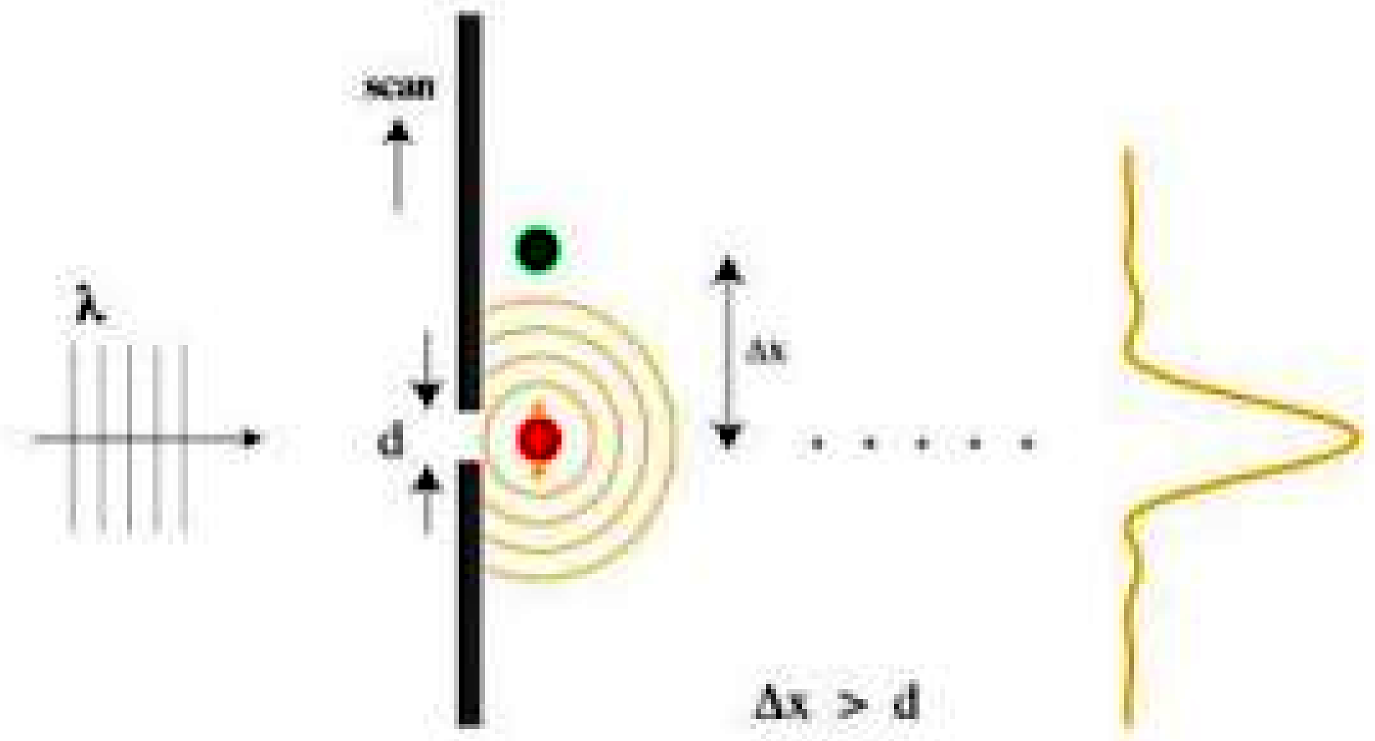
Figure 5. Diagram showing different methods of operation for Scanning Near-Field Optical Microscopy (SNOM).

OPTICAL MICROSCOPY



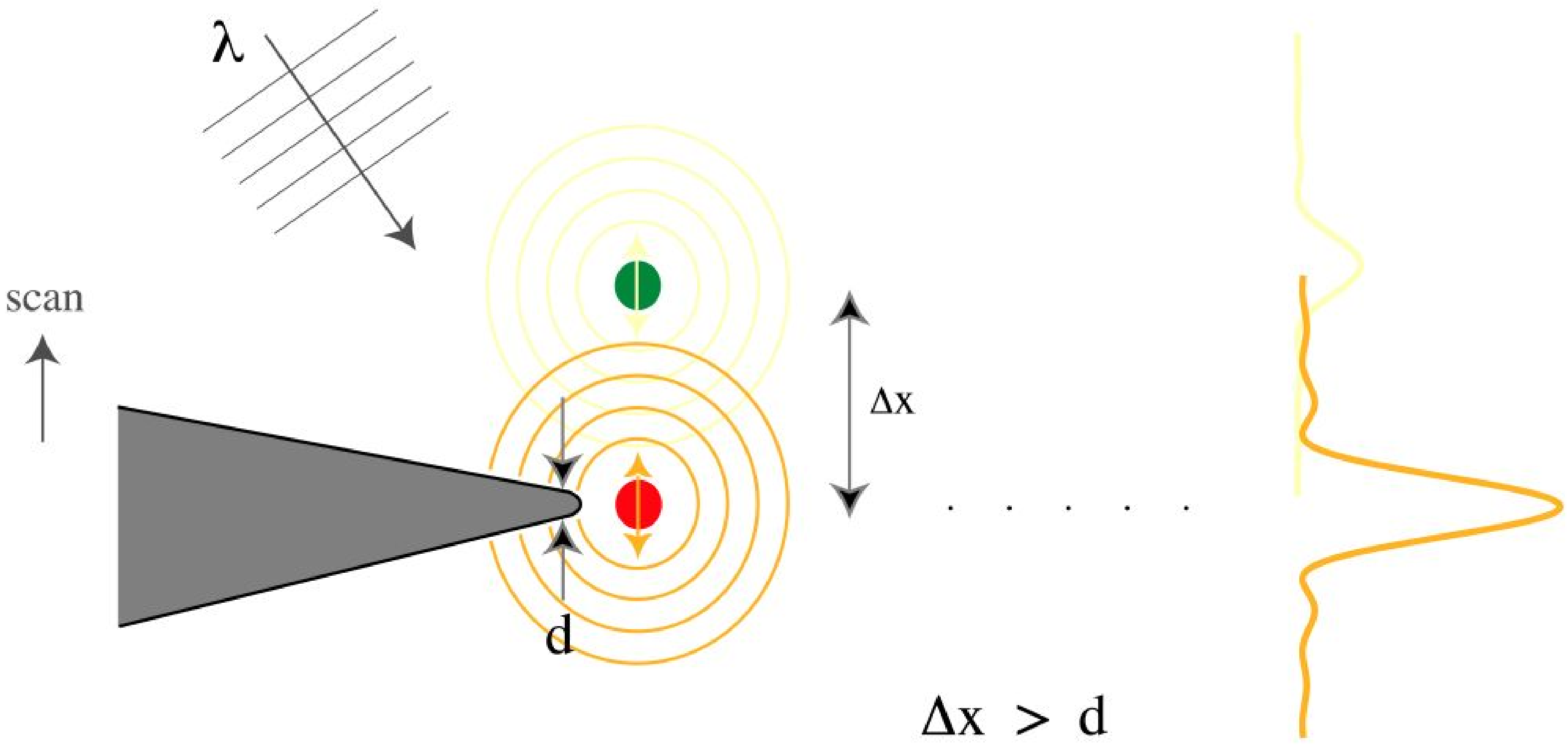
$$\Delta x \geq \frac{0.61\,\lambda}{n\,\sin(\alpha)} \quad \text{(Rayleigh criterion)}$$

APERTURE NEAR-FIELD MICROSCOPY



E.H. Synge, Phil.Mag. **6**, 356, 1928 . D.W. Pohl et al., Appl.Phys.Lett. **44**, 651, 1984

FIELD ENHANCEMENT MICROSCOPY



H. Furukawa and S. Kawata, Opt. Commun.**148**, 221, 1998
L. Novotny et al., Ultramicroscopy **71**, 21, 1998

This enhancement is localized to the tip, which has a typical diameter of 10 nm. As this tip is scanned over the surface, an image can be formed with a resolution as fine as the tip.

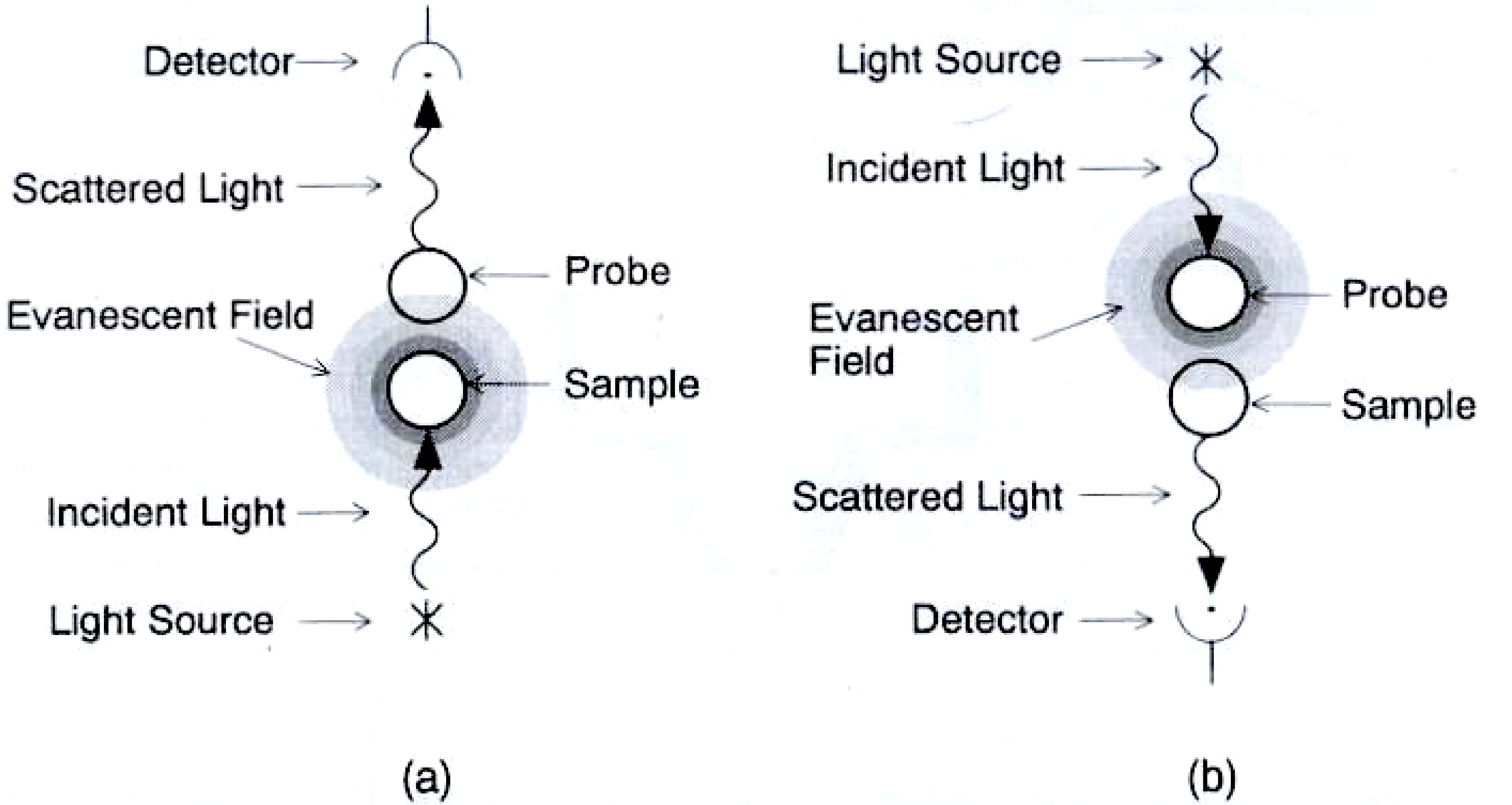


Figure 3.1. Basic NOM configurations: (a) Collection mode (C-mode). (b) Illumination mode (I-mode).

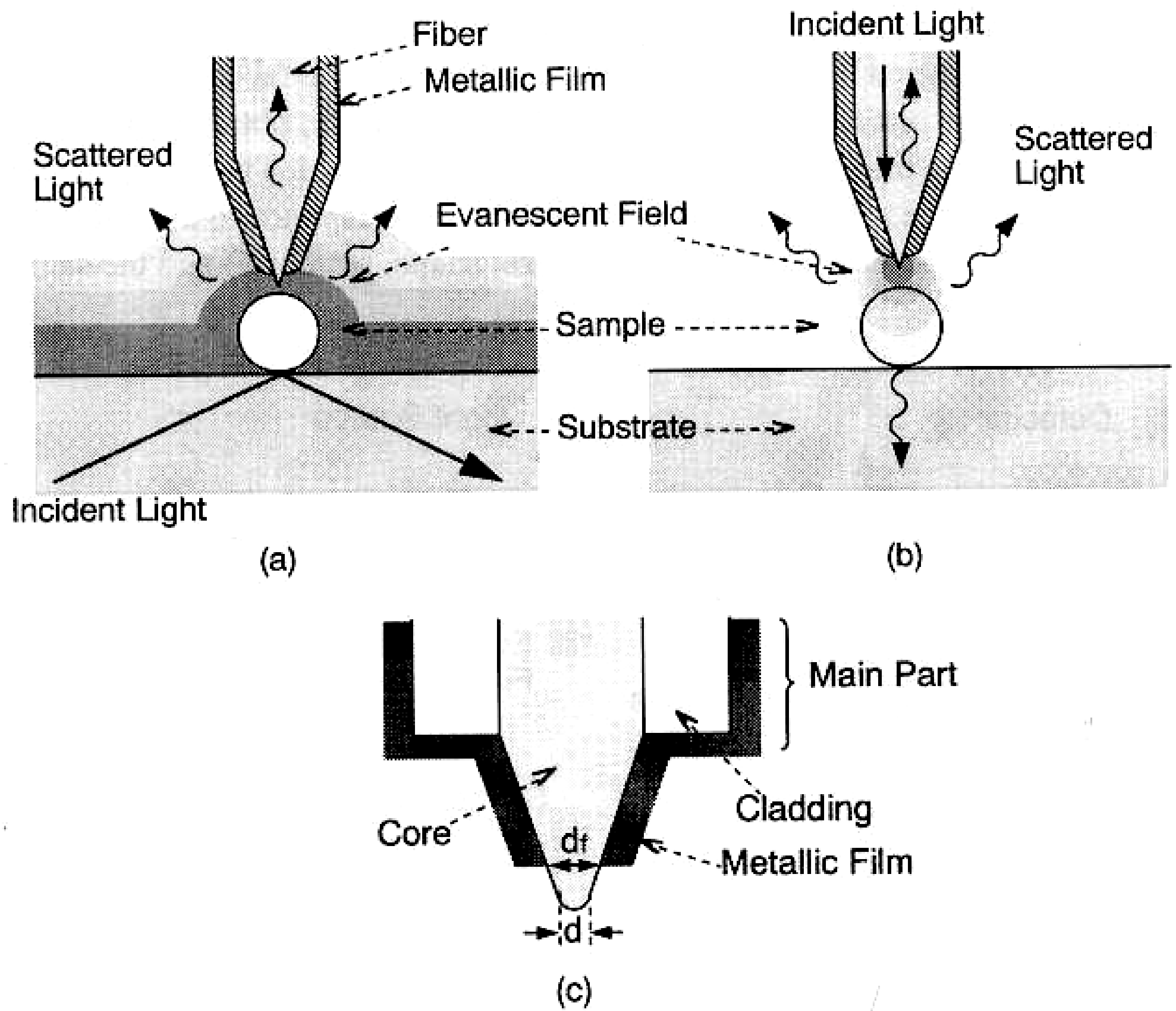


Figure 3.2. Practical basic structure of the NOM using an inverted conical probe, which is a sharpened fiber core protruding from the metal film. (a) Collection mode (C-mode). (b) Illumination mode (I-mode). (c) Definition of the foot diameter d_f and apex diameter d.

System setup for collection mode

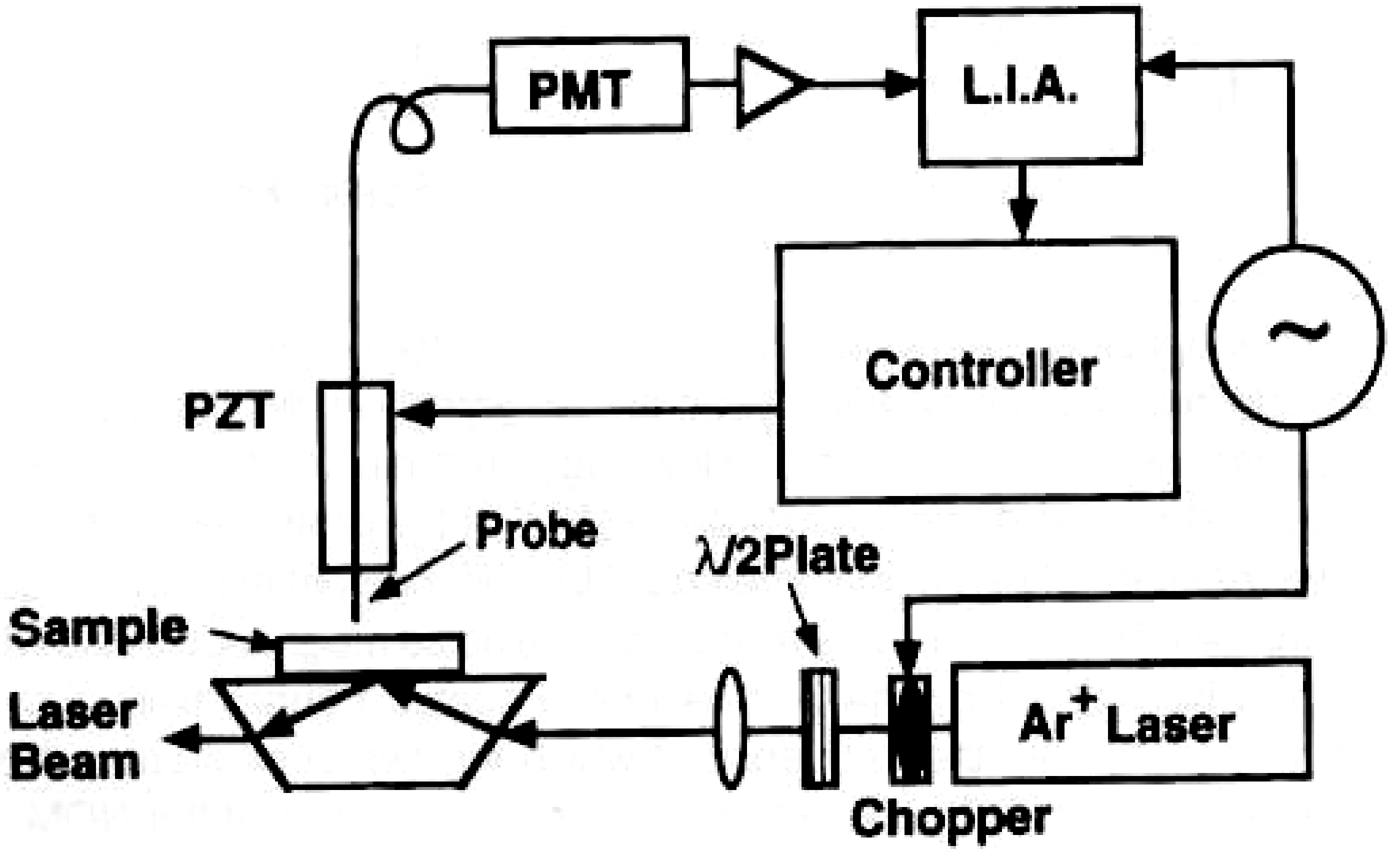


Figure 3.4. The experimental setup of the C-mode NOM. L.I.A., Lock-in amplifier; PMT, photomultiplier tube; PZT, pieozoelectric transducer.

System setup for collection mode

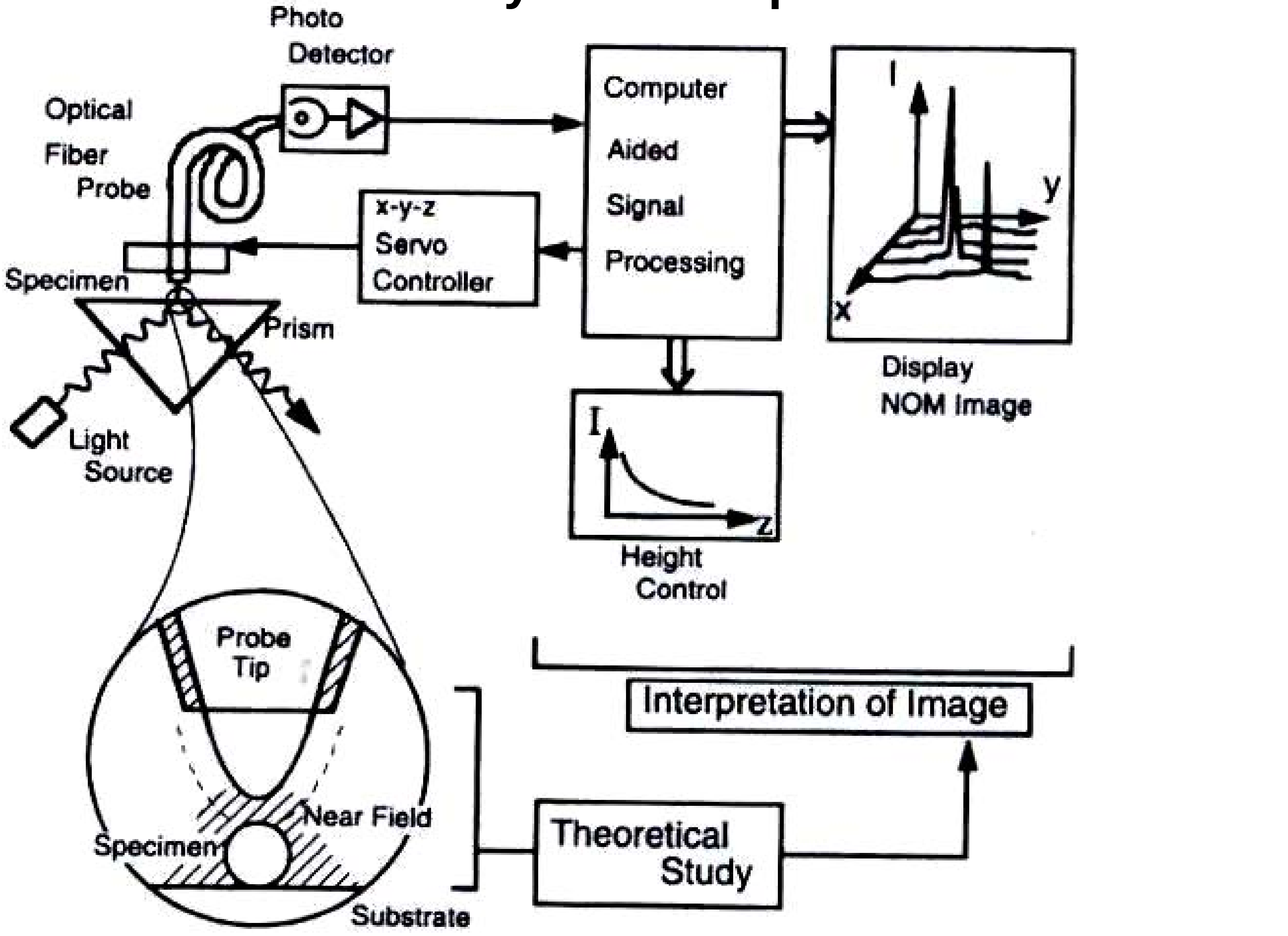
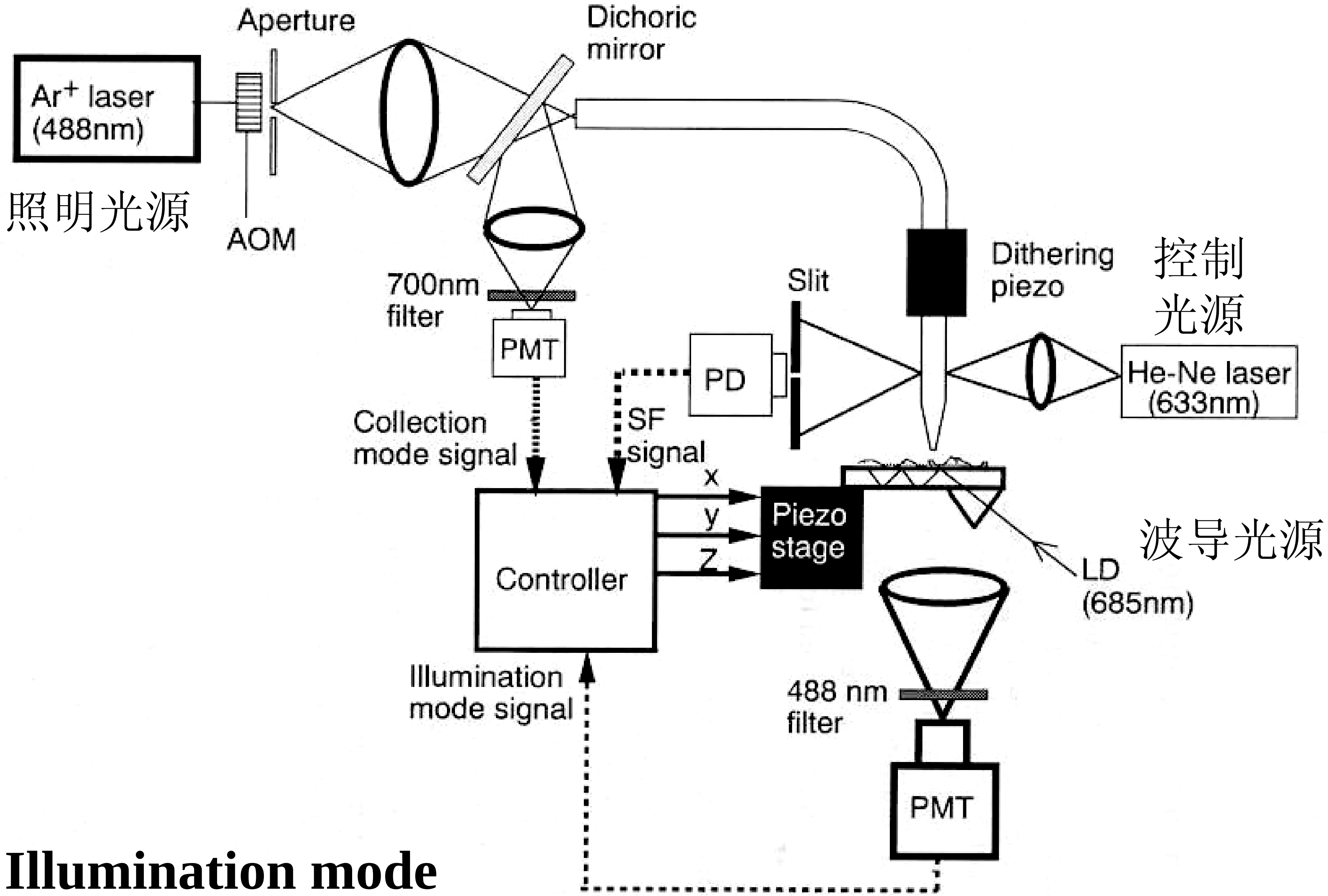


Figure 2.1. Typical setup of a near-field optical microscope (NOM). An optical fiber probe and collection-mode operation are employed in this case.



Illumination mode

Figure 3.10. Experimental setup of the I-mode NOM utilizing the secondary evanescent field generated from a light source with different wavelength for controlling the sample–probe separation. LD, Diode laser; PD, photodiode; PMT, photomultiplier tube; AOM, acoustooptic modulator.

Simplified illumination mode

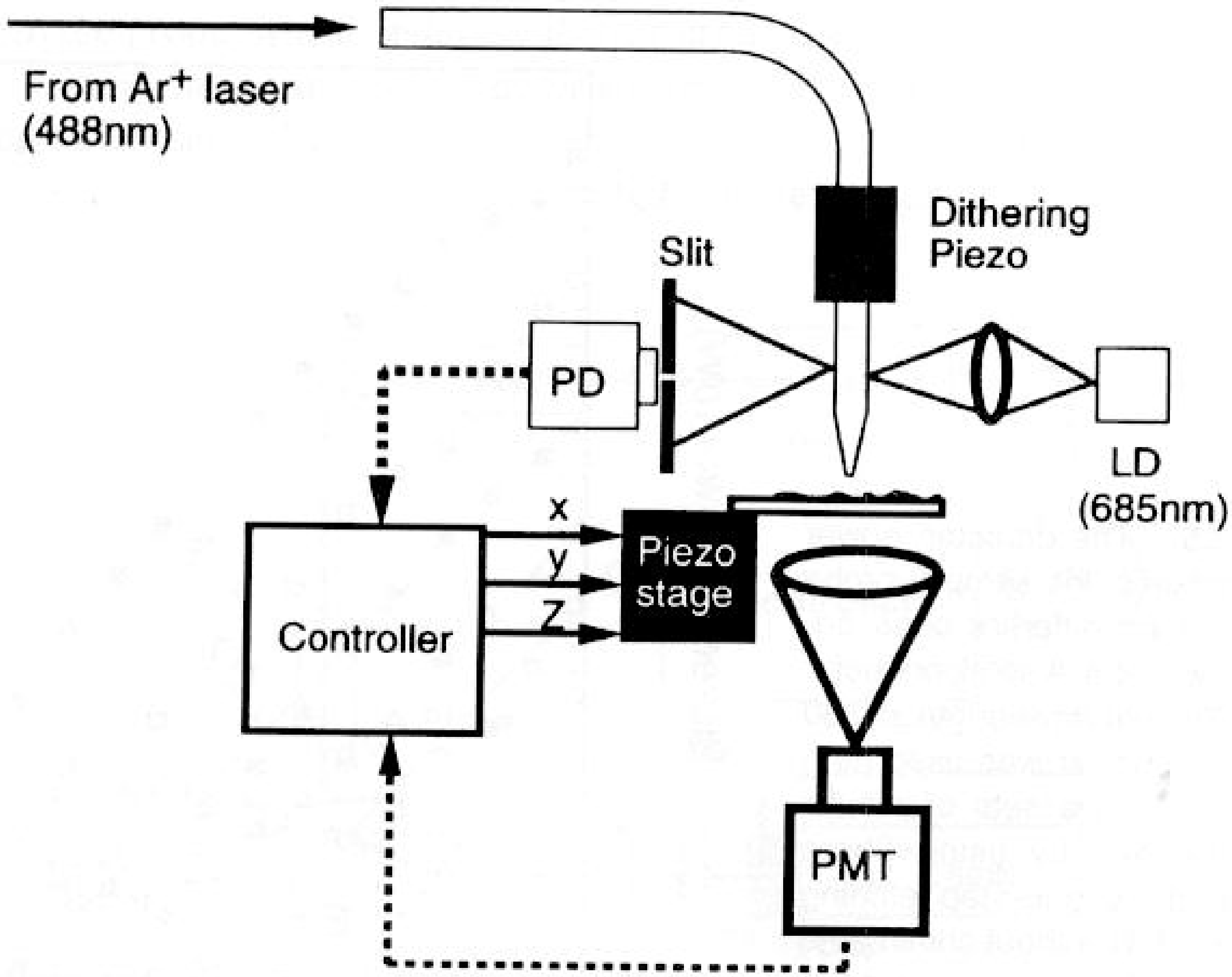


Figure 3.6. The experimental setup of the I-mode NOM. LD, Diode laser; PD, photodiode; PMT, photomultiplier tube.

SNOM for fluorescent signal detection

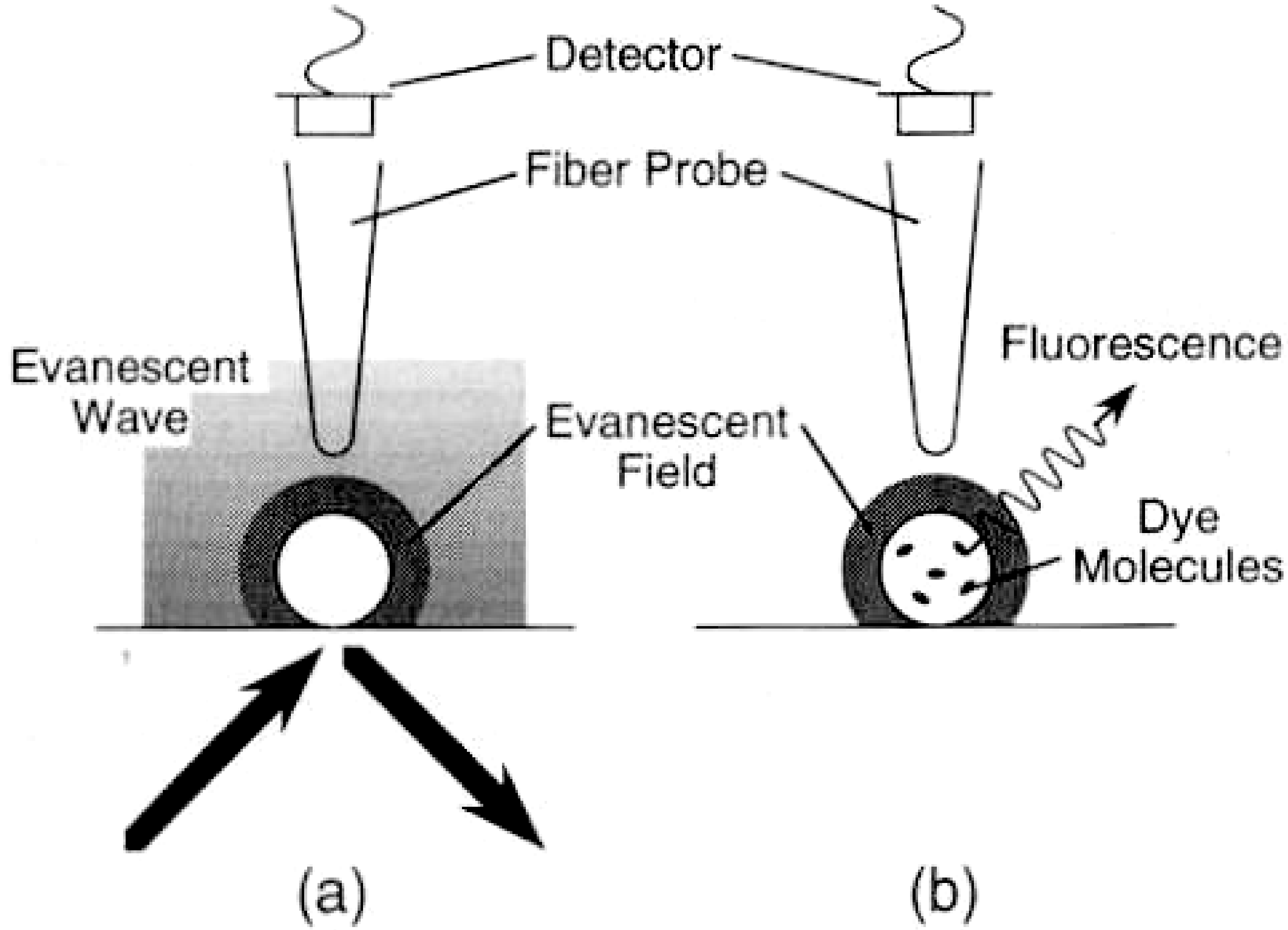


Figure 5.1. Experimental configuration for measuring the decay length of an evanescent field. (a) Conventional C-mode NOM. (b) C-mode NOM with wavelength conversion by detecting selectively the fluorescence from dye molecules doped in a subwavelength-size sphere. Excitation light is omitted for clarity.

SNOM system setup for fluorescent signal detection

(Collection mode)

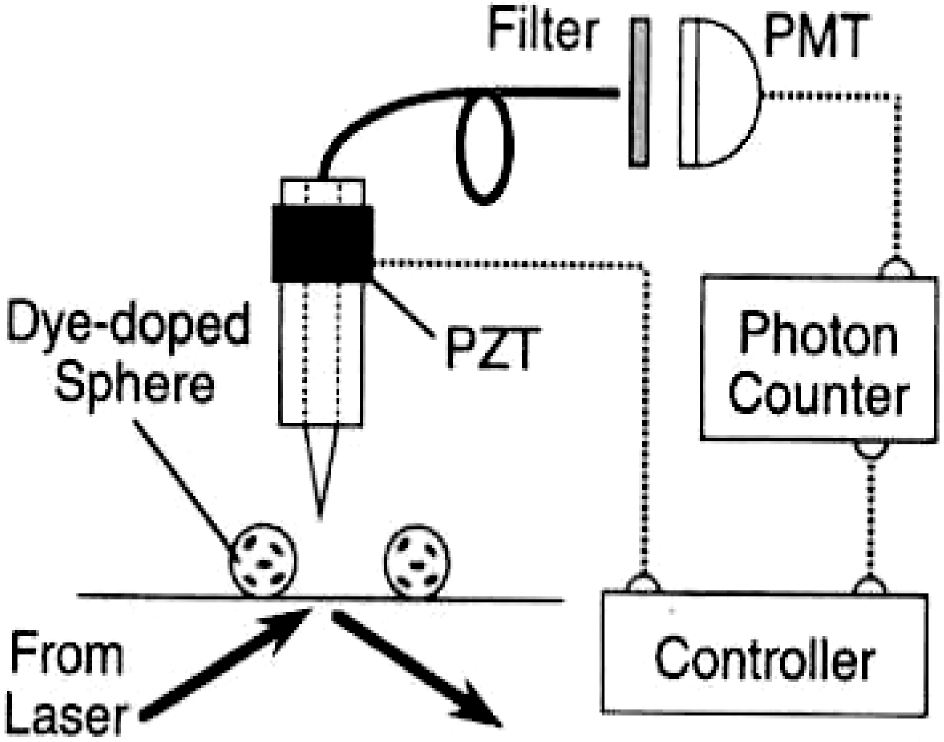


Figure 5.2. Experimental setup of a C-mode NOM for fluorescence detection. PZT, Piezoelectric transducer; PMT, photomultiplier.

Size range

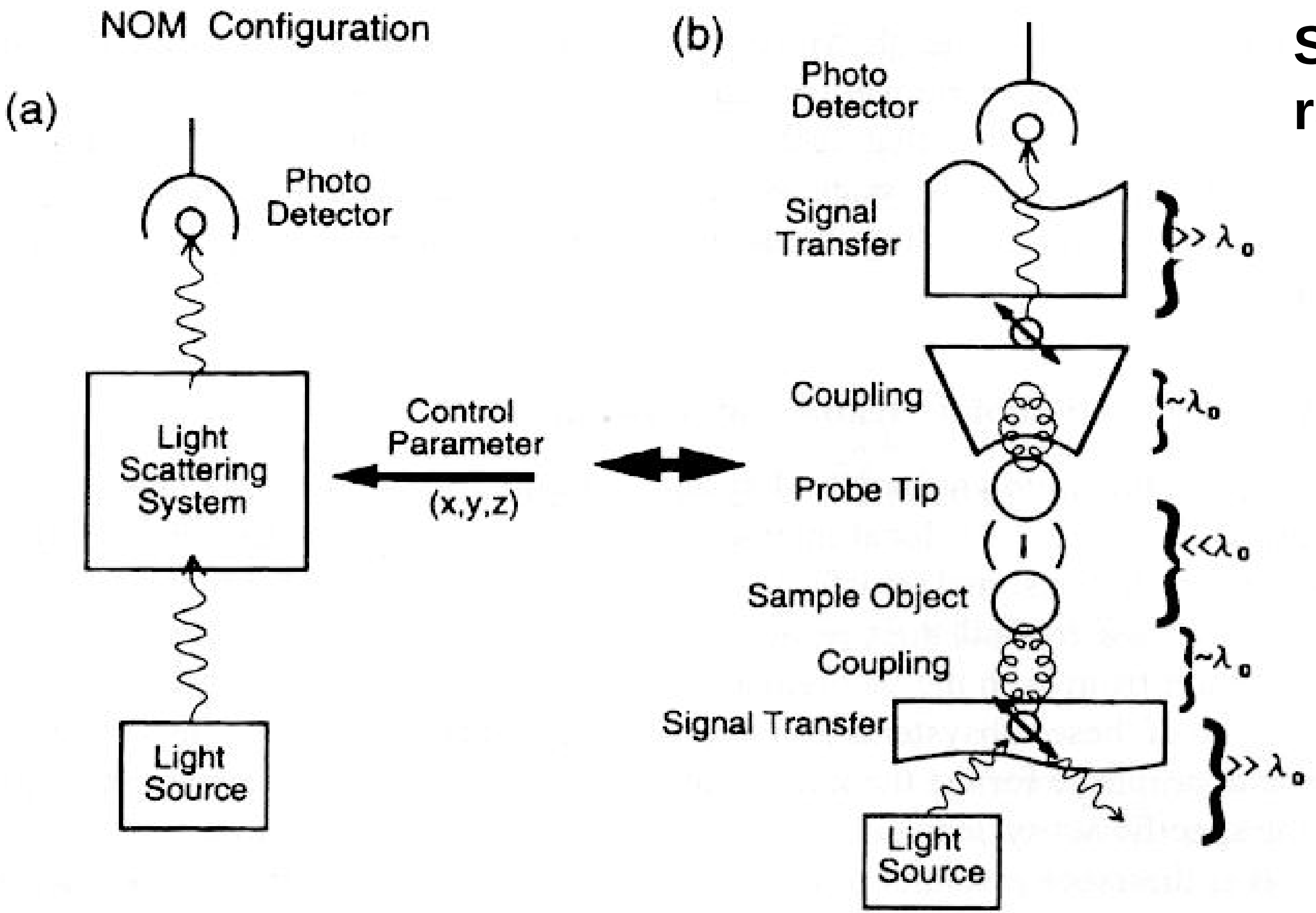
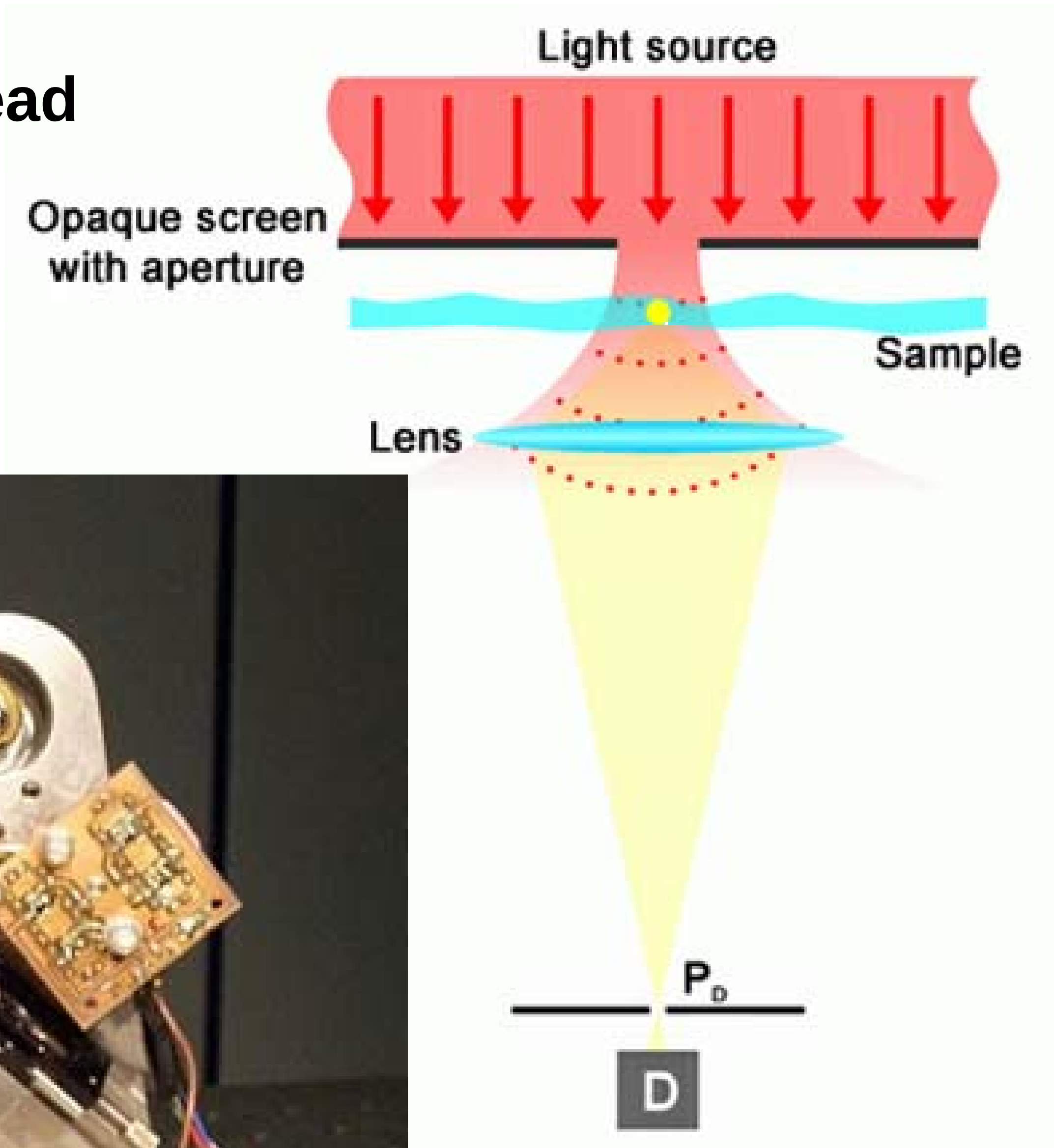
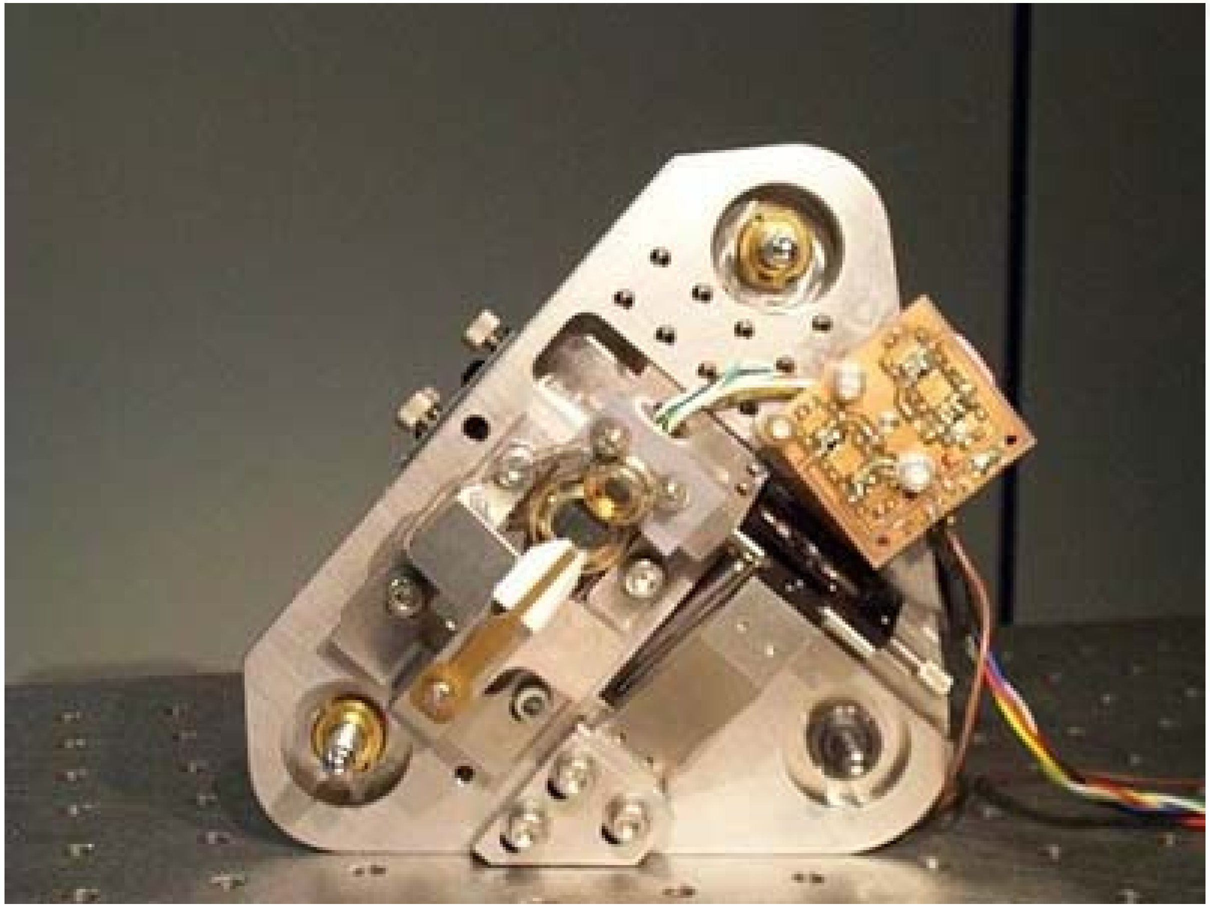


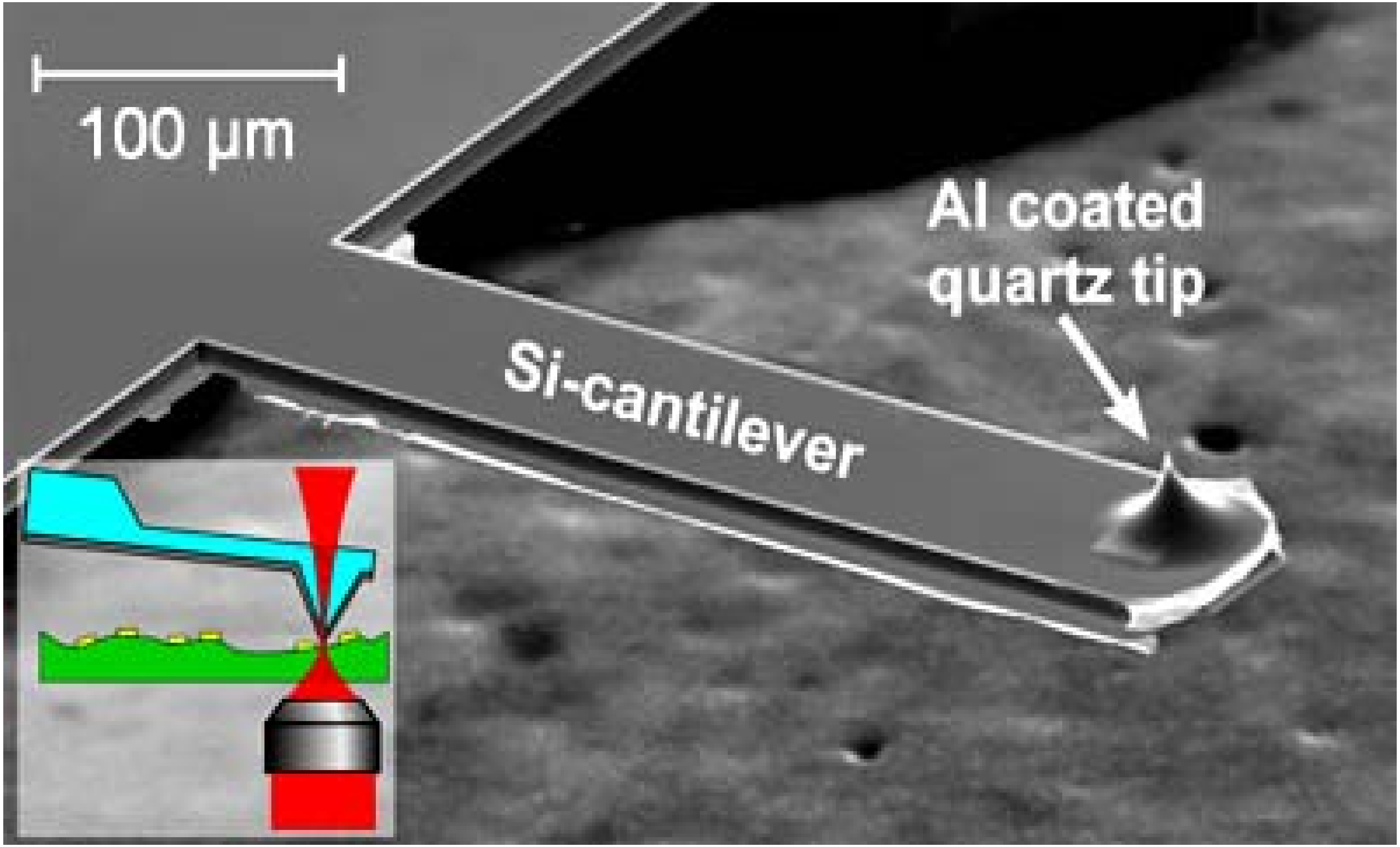
Figure 2.4. (a) The NOM configuration as an optical process and (b) characteristic interaction processes with several distinguishing scales. There are three fundamental parts: the local electromagnetic interaction in the near-field regime ($<< \lambda_0$), near- to far-field coupling on the mesoscopic scale ($\sim\lambda_0$), and illumination and light transfer at the macroscopic scale ($>> \lambda_0$).

Assembly of scanning head





Probe I: cantilever probe



Probe II: optical fiber probe

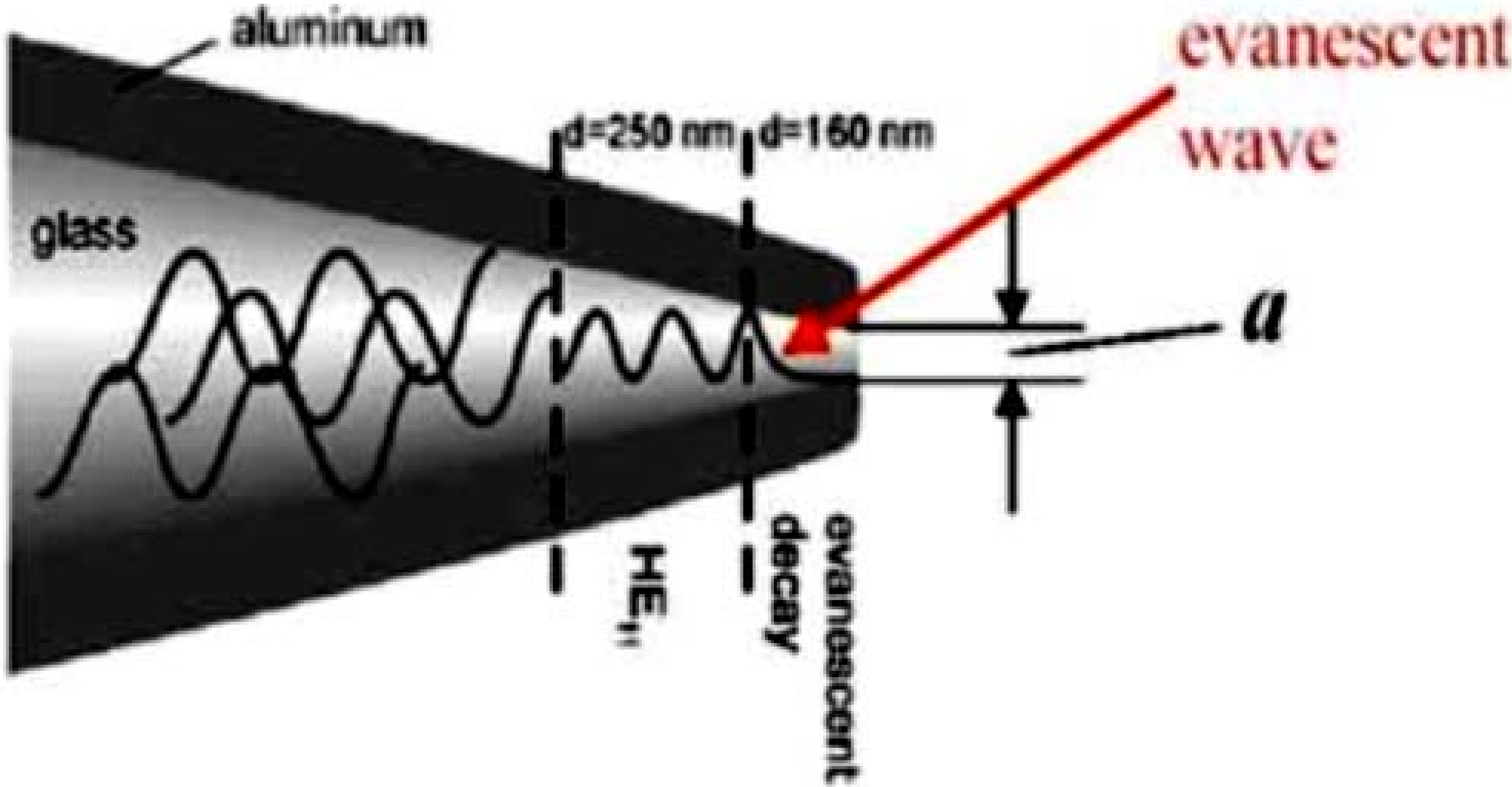
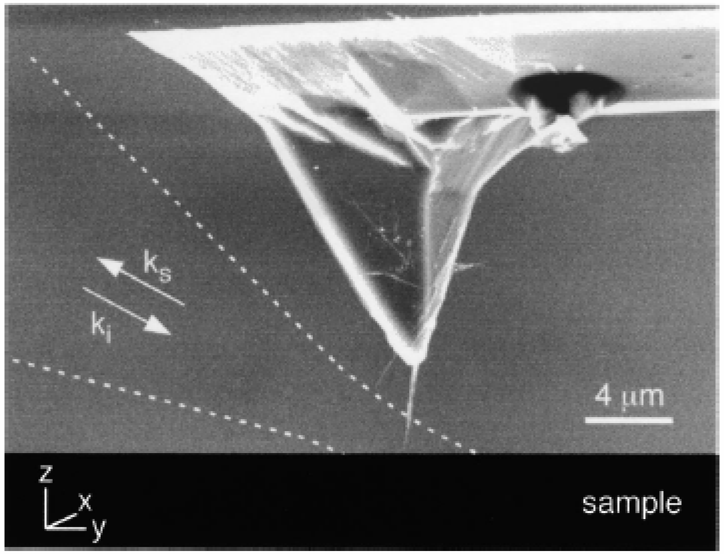
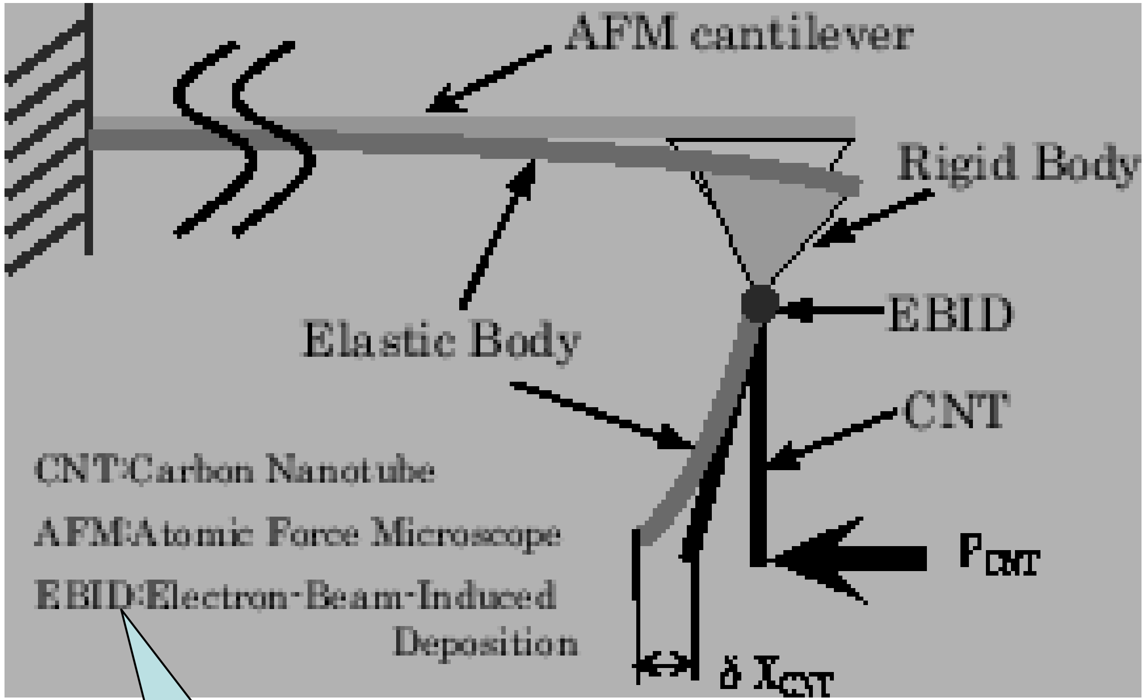


Figure 1. Scheme of a pulled optical fiber with an aluminium coating (the most diffused probe for SNOM systems).

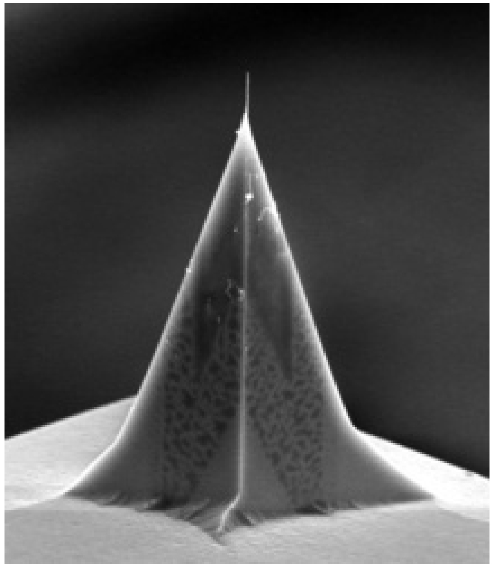
Nano-tube-based NSOM probe



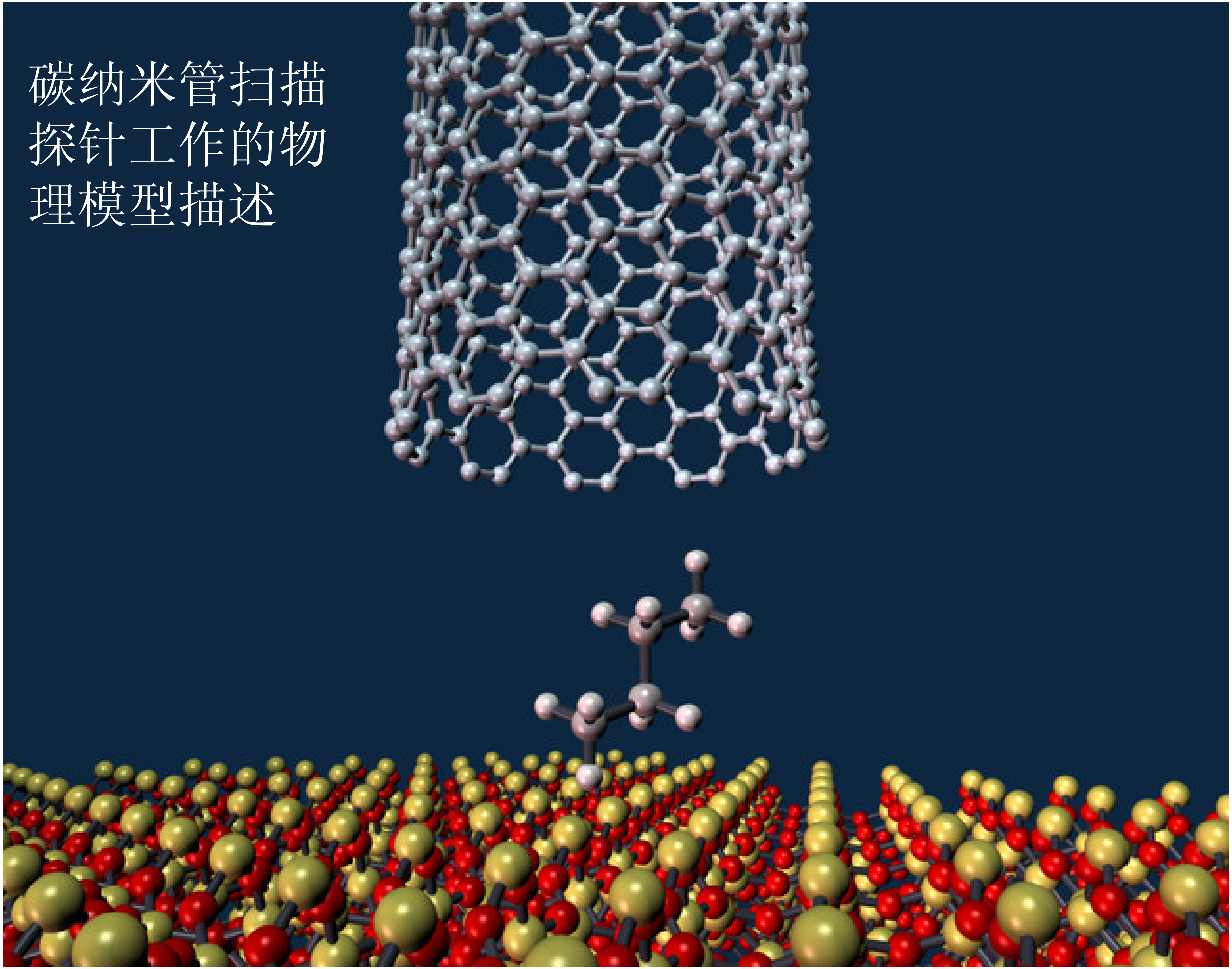
APL 83, 368 (2003).



Focused ion beam deposition



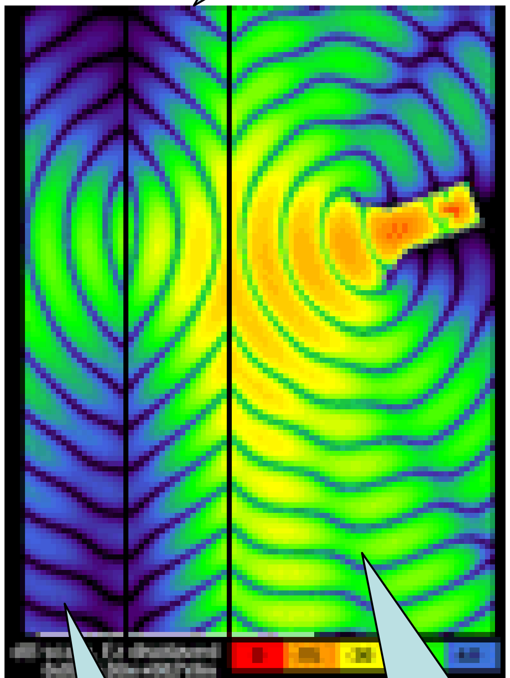
碳纳米管扫描探针工作的物理模型描述



NSOM Tip Design

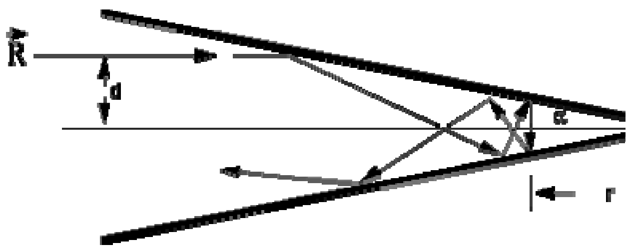
—— Near-field Diffraction Simulation

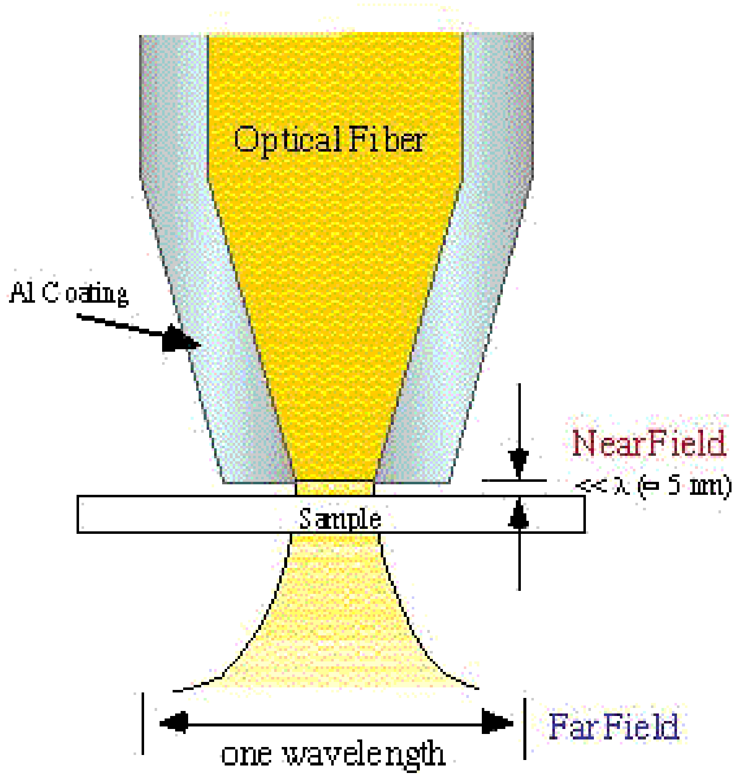
Near field



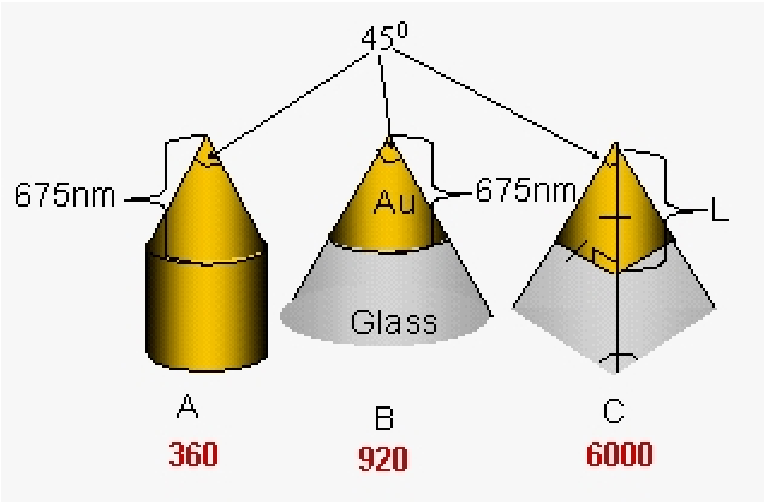
Far field

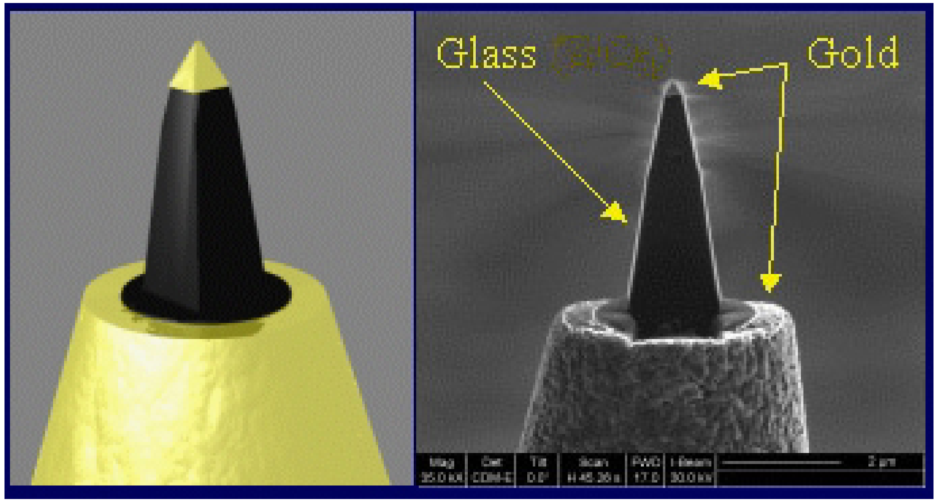
Cone of probe





Options of NSOM tip





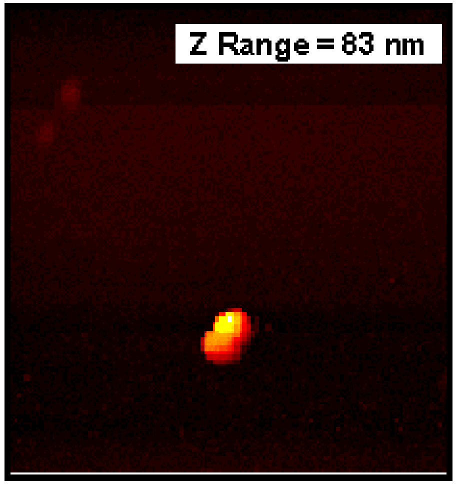
http://bernstein.harvard.edu/research/nearfield.html

Optimization and near-field simulation is needed for the probe design (determine cone angle and type) before microfabrication.

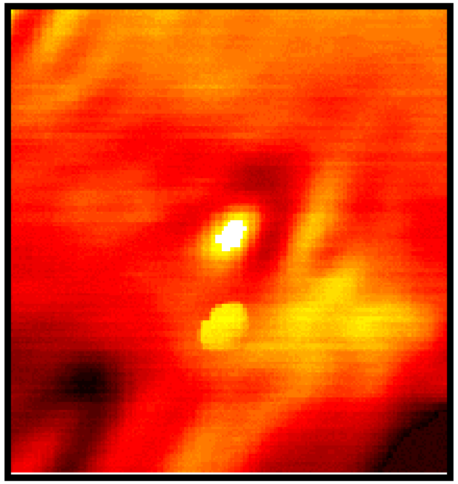
Example: metallic nanoparticle detection

2 μm x 2 μm Images of 100 nm Au Particle Scattering of 488 nm Light.

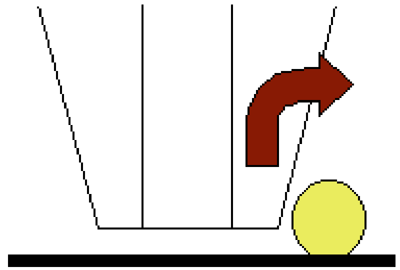
Topography



Reflection



Topographically Induced Optical Contrast



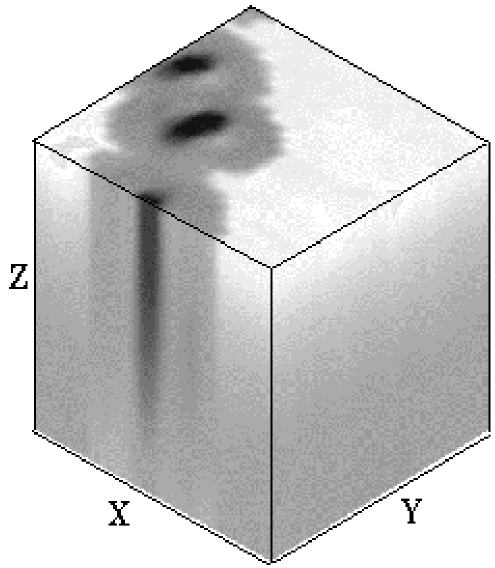
$e^{-z/l}$ decay of near-field results in extreme sensitivity to tip-sample separation

An NSOM instrument based on feedback control will simultaneously provide topographic and optical information about the sample surface, making NSOM uniquely multi-tasked. However, operating an NSOM in this mode, referred to as constant-gap mode, on rough surfaces has been shown to cause optical artifacts that often swamp any *true* optical contrast (Hecht B, Bielefeldt H, Inouye Y, Pohl DW, & Novotny L, *J. Appl. Phys.* 81, 1997).

4D NSOM Image of 100 nm Colloidal Au Particles on Glass

X,Y Scan Range = 1500 nm; Z Scan Range = 100 nm + topography (70 nm)

Transmission mode NSOM cube



Shown above is a cube of NSOM data collected in four dimensions, three spatial (X, Y, Z) and one optical (transmission intensity). In this image the gray scale represents the optical dimension.

Simulation tool: FDTD

FDTD has been applied to the study of NSOM in the past. Unfortunately, the large computational burden associated with this technique made three dimensional simulations quite difficult. Two dimensional calculations (e.g. R.X. Bian *et al.*, Phys. Rev. Lett. **75**, 4772 (1995).) have generated insight into the aperture method of NSOM. We have utilized a commercial FDTD package

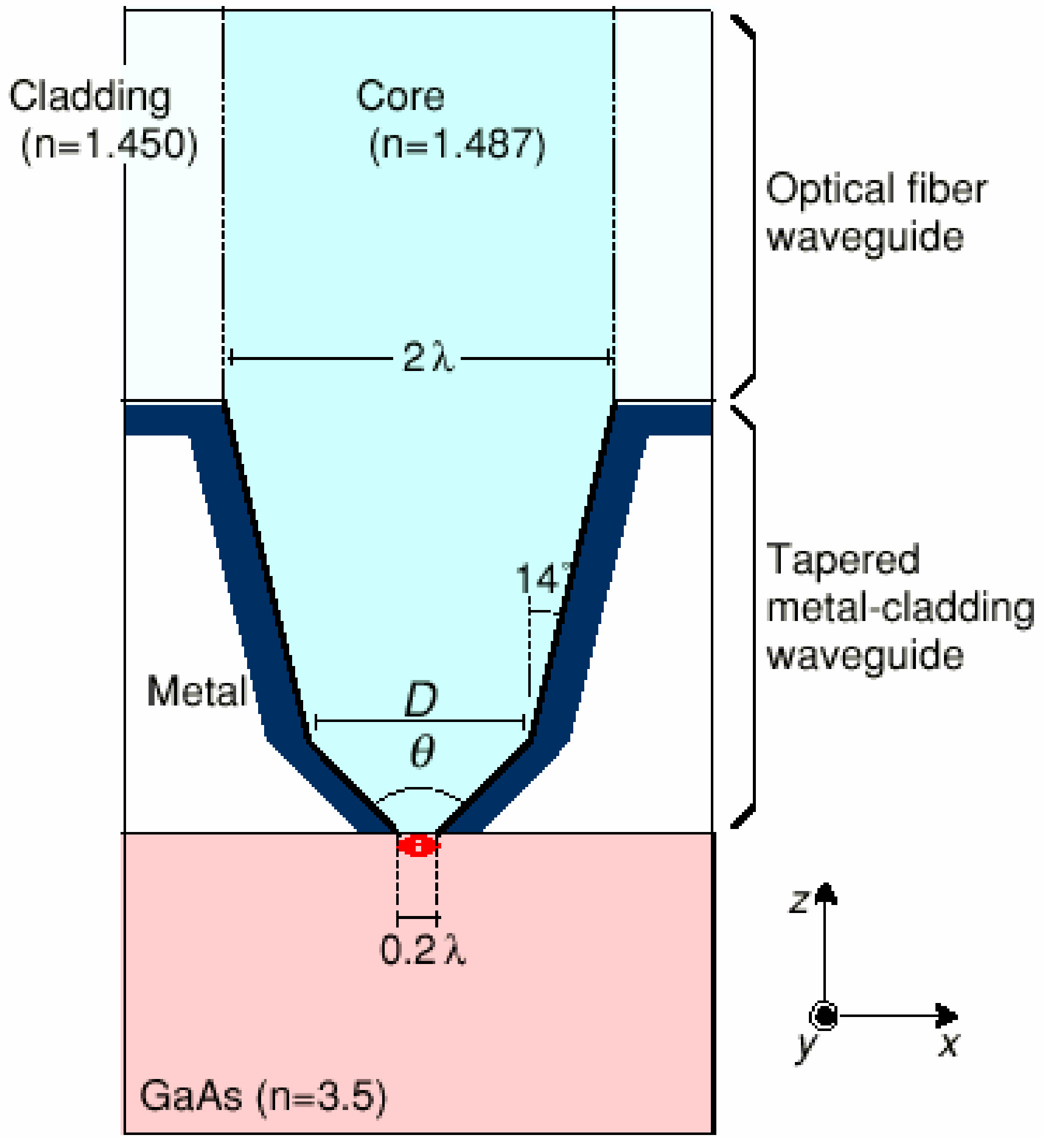
(http://www.remcom.com/html/index.html)

3D ELECTROMAGNETICS

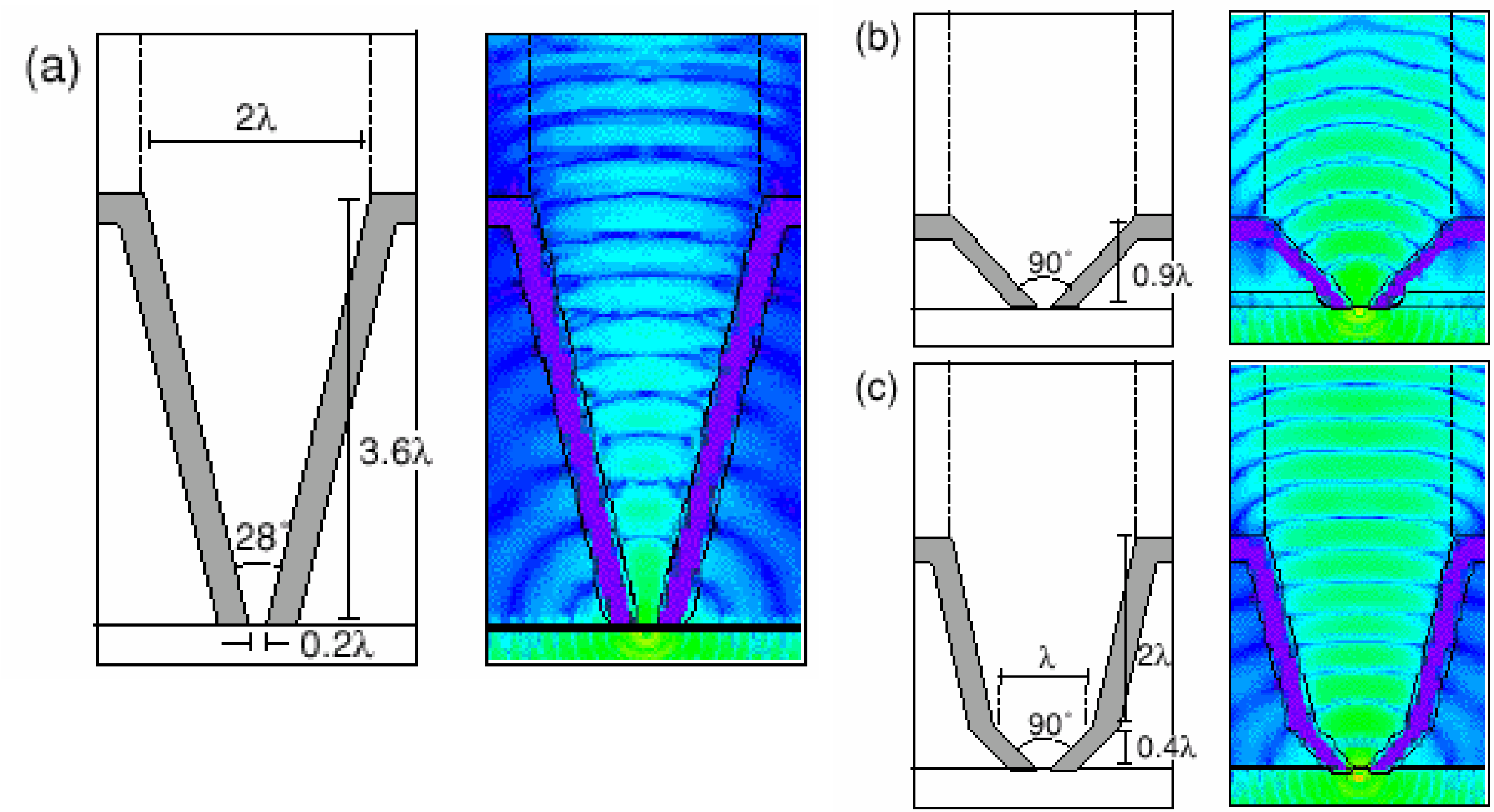
FIDELITY - FINITE DIFFERENCE TIME DOMAIN

APPLICATIONS

- RF & Wireless Antennas
- Wave Guide Analysis
- Nanophotonics Devices
- EMI & EMC Analysis



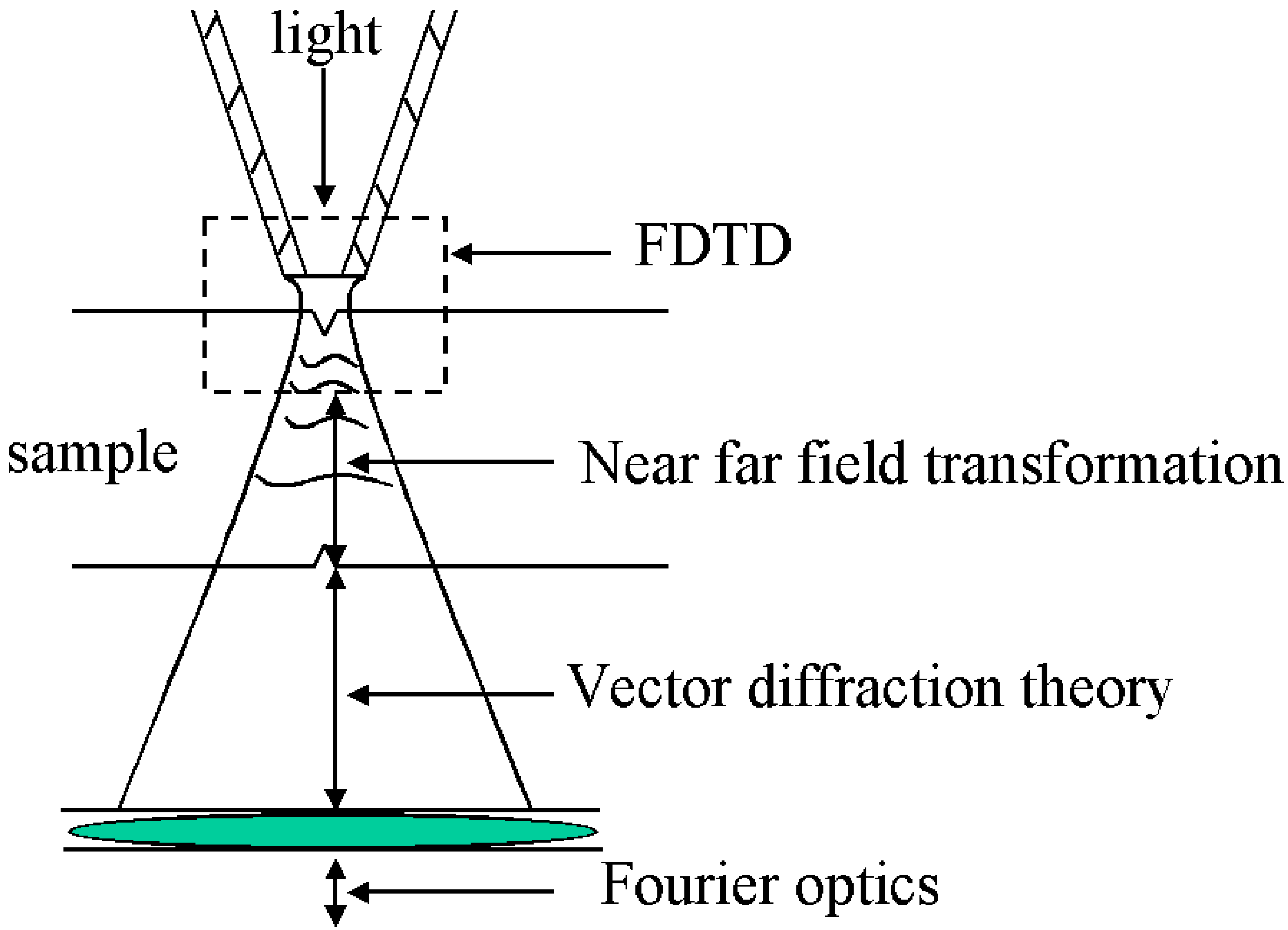
Cross-sectional view of the FDTD geometry of the three-dimensional NSOM model.



Calculated distribution of the electric field intensity for three types of probes. (a) single-tapered probe with a cone angle θ=28°, (b) single-tapered probe with θ=90°, and (c) double-tapered probe with θ=90° and neck diameter D=λ.

Simulation of Near Field Scanning Microscopy (NSOM)

Modeling of Near-field scanning optical microscopy requires several electro-magnetic wave simulations.



Conclusions

- By making the cone angle larger and shortening the cutoff region,much radiation power can be directed towards the tapered region.

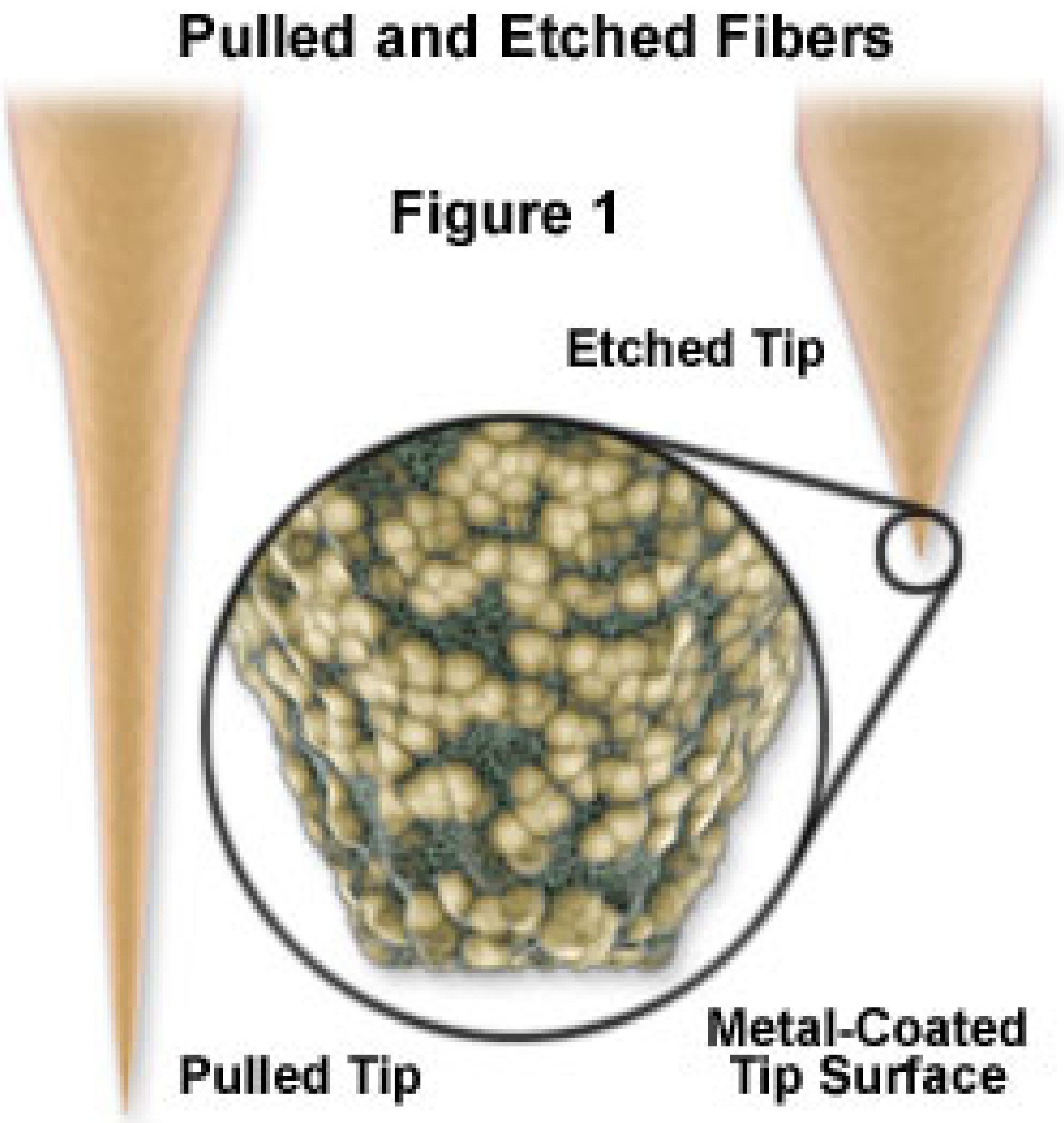
- Field intensity will increase monotonously as θ approaches 180° . In case of realistic metal aperture, a large θ will cause diminished spatial resolution due to the finite skin depth of the metal.

- The optimum value of θ should be chosen by balancing the collection efficiency with the spatial resolution.

- Taper angles in the range of 30° -50° offer optimum conditions for transmission and spot size.
- 50-100 nm Al is coated.
- Tips with 80-100 nm diameter apertures can deliver tens of nanowatts coupled into the fiber.

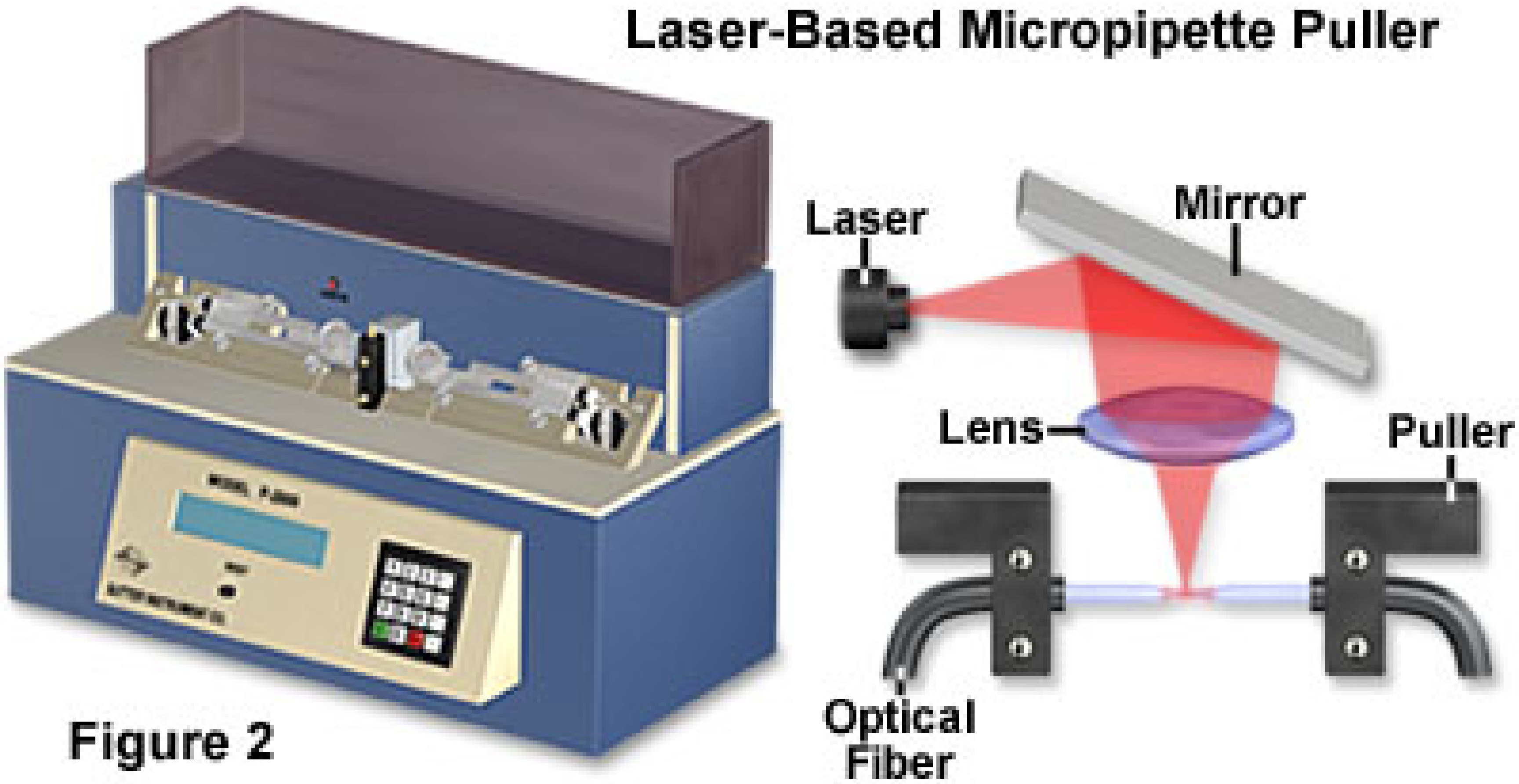
Applied Physics Letters, 71(20), 17 November 1997.

Comparison of different methods

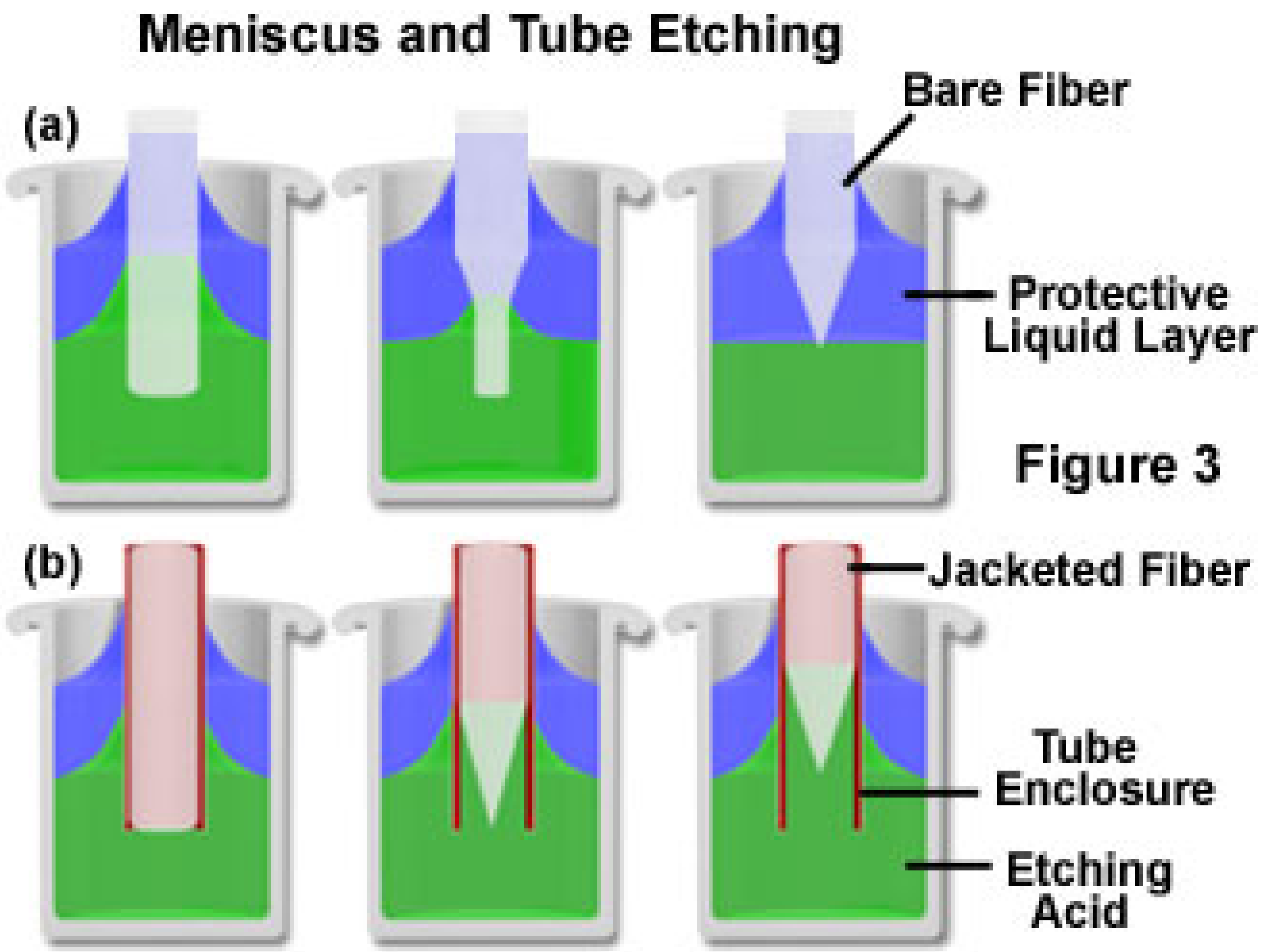


Fiber Probe Fabrication

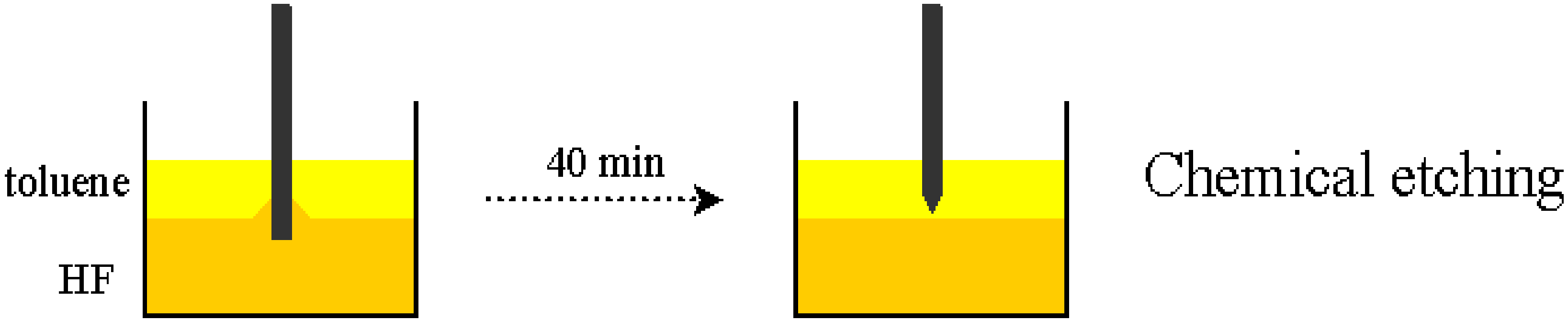
Pulling Method

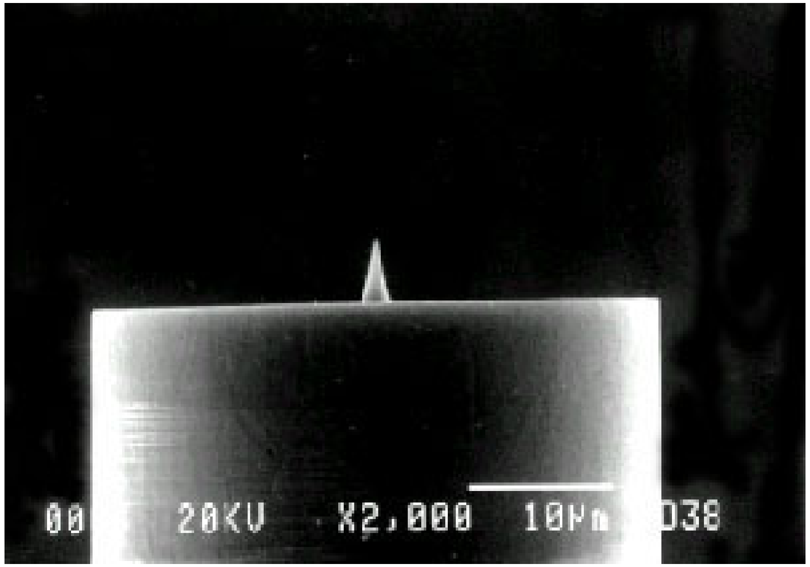


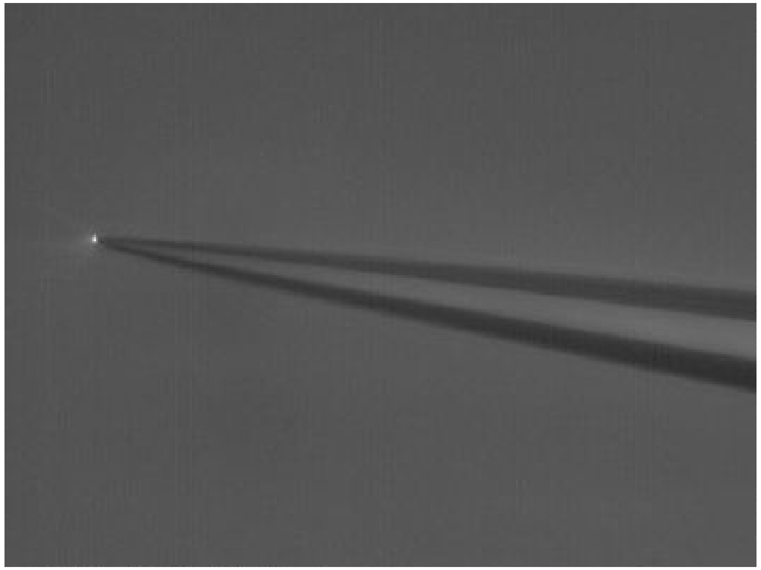
Meniscus Etching



HF chemical Etching







Apertureless and Alternative Probe Designs

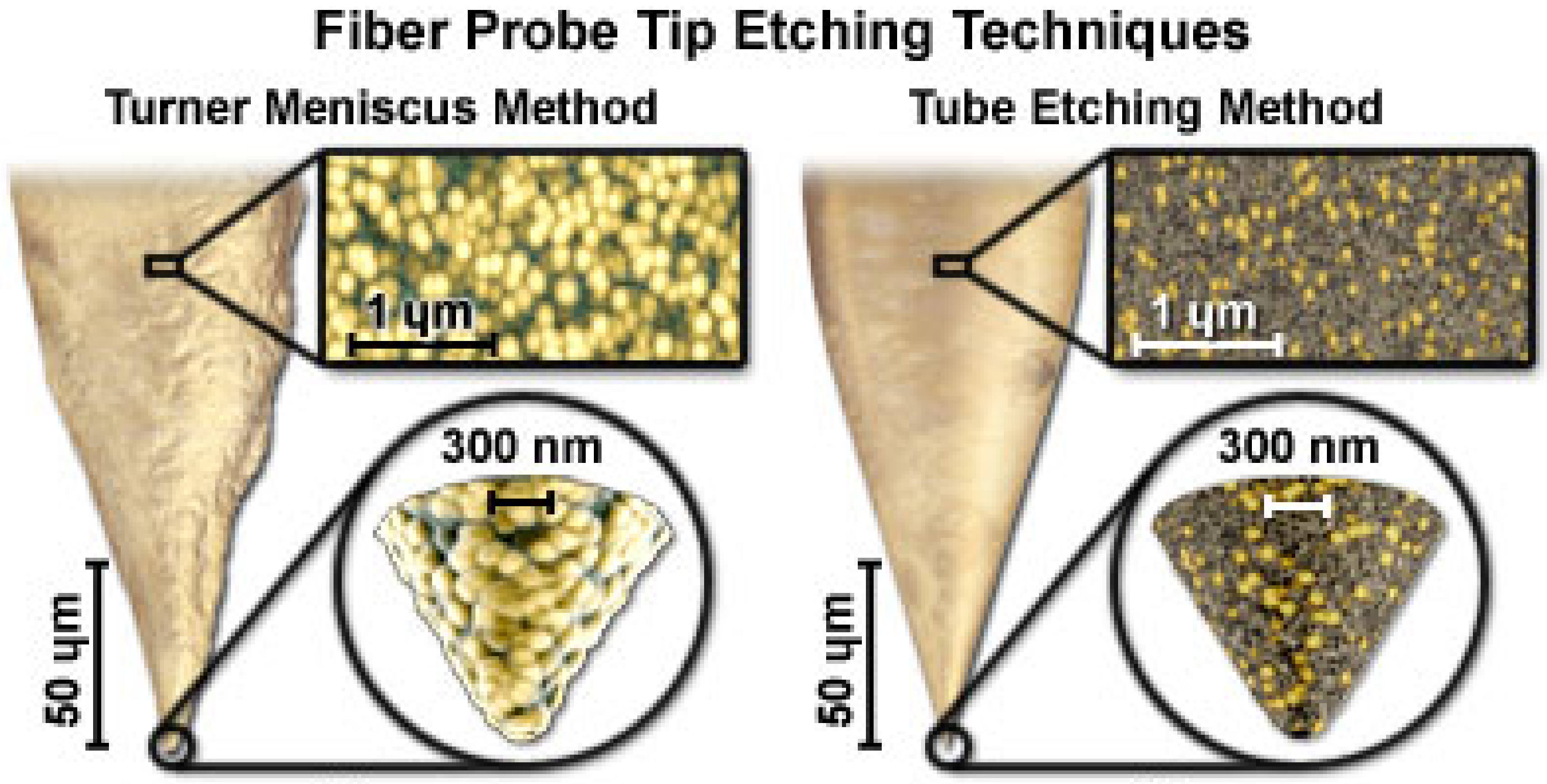
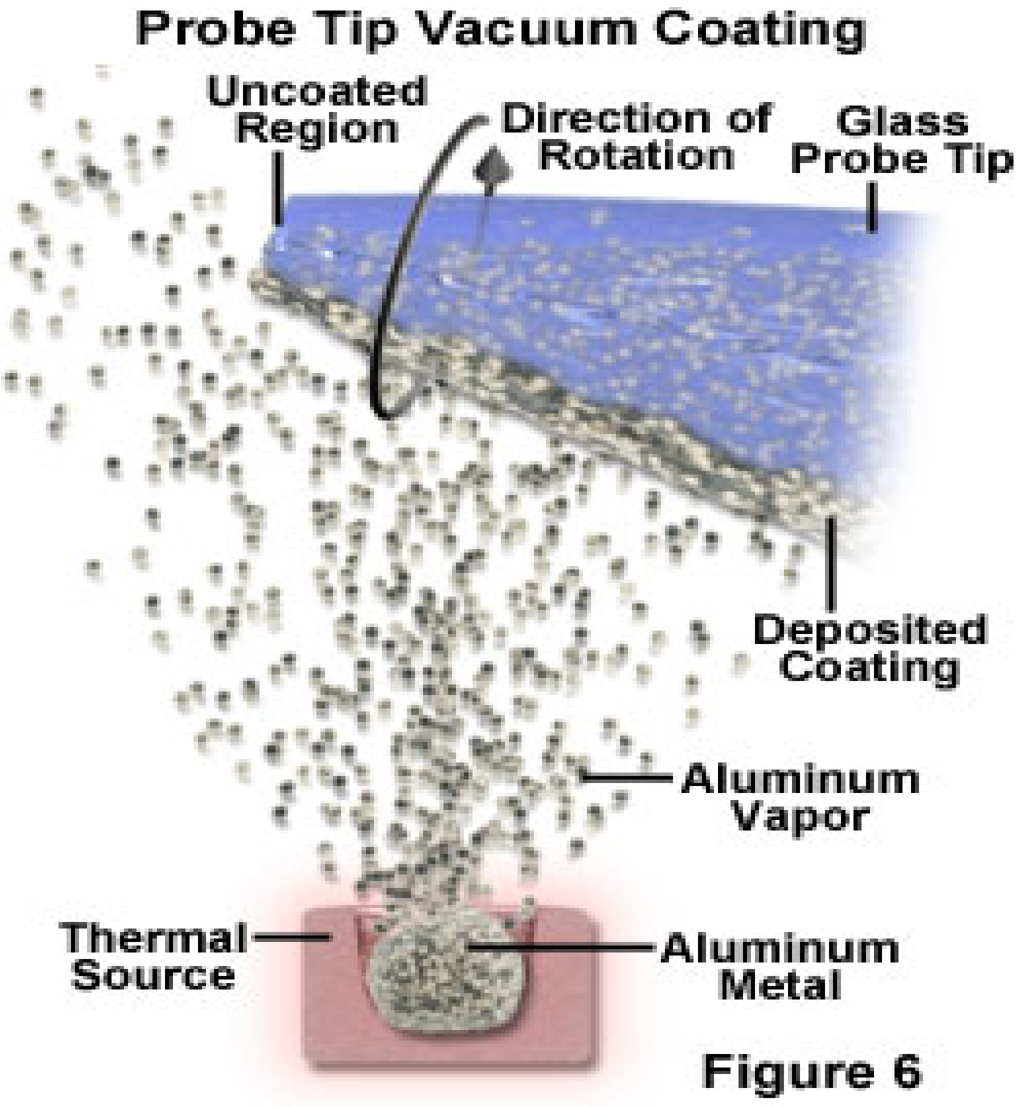


Figure 4

Metallic Probe Coatings

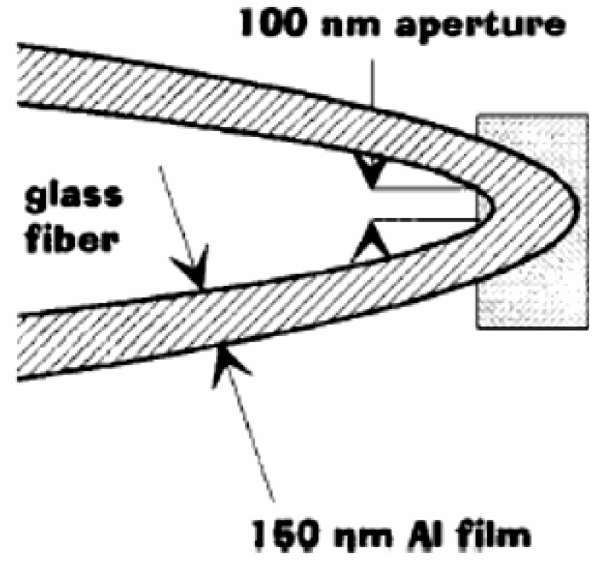


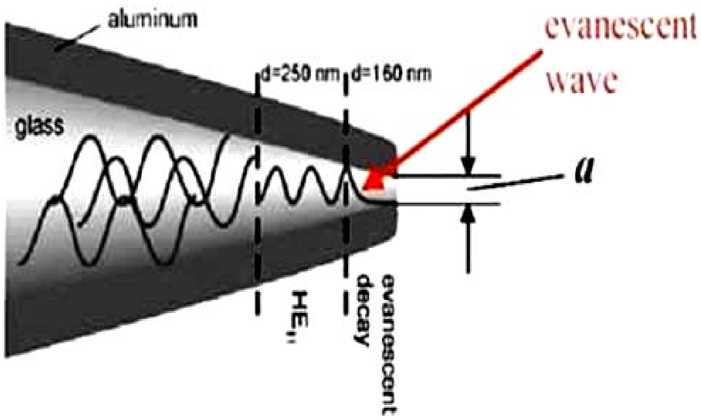
Evaporation coating of Al 100nm in thickness

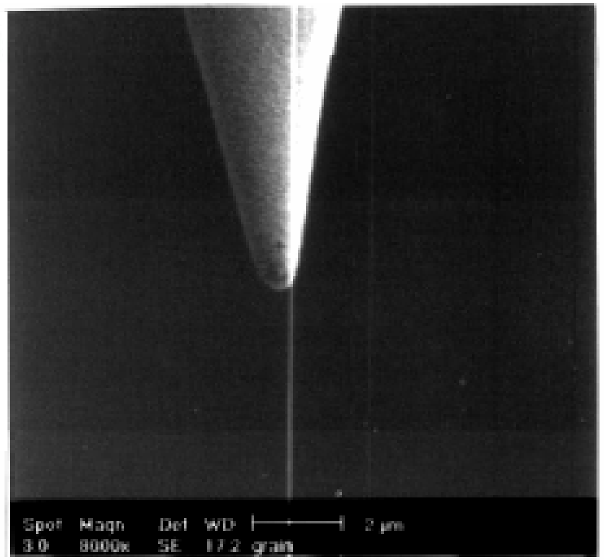
Shortage:

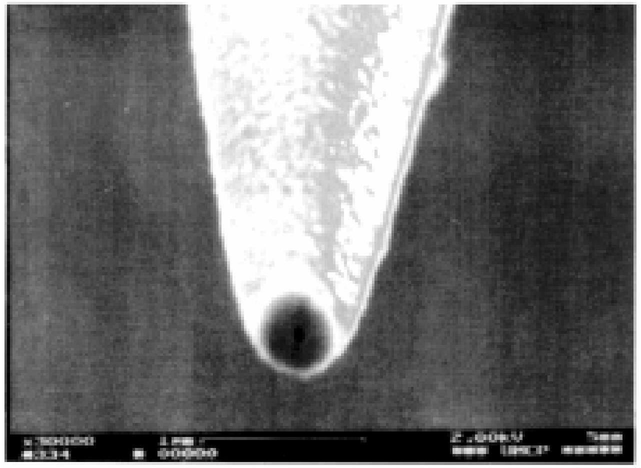
Aperture size is uncontrollable.

(10) Aperture drilling of FIB-trimmed NSOM probe

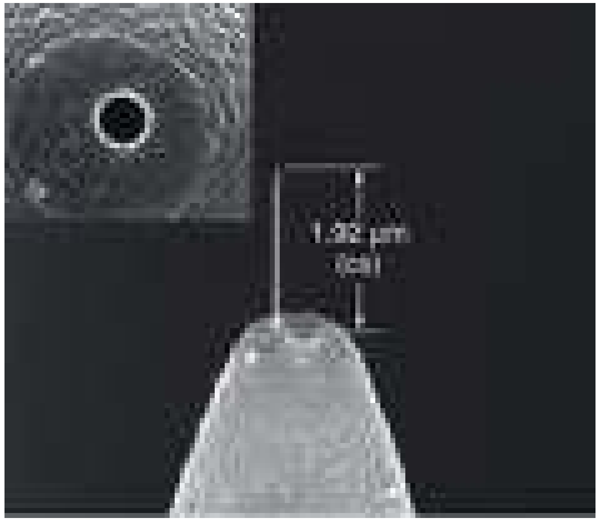


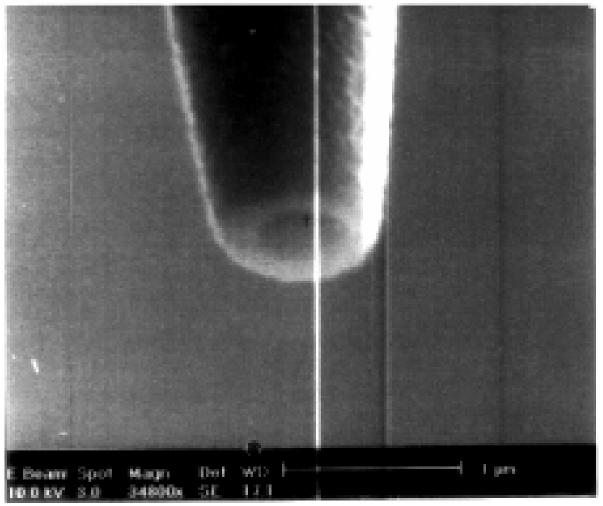






Aperture: 100nm

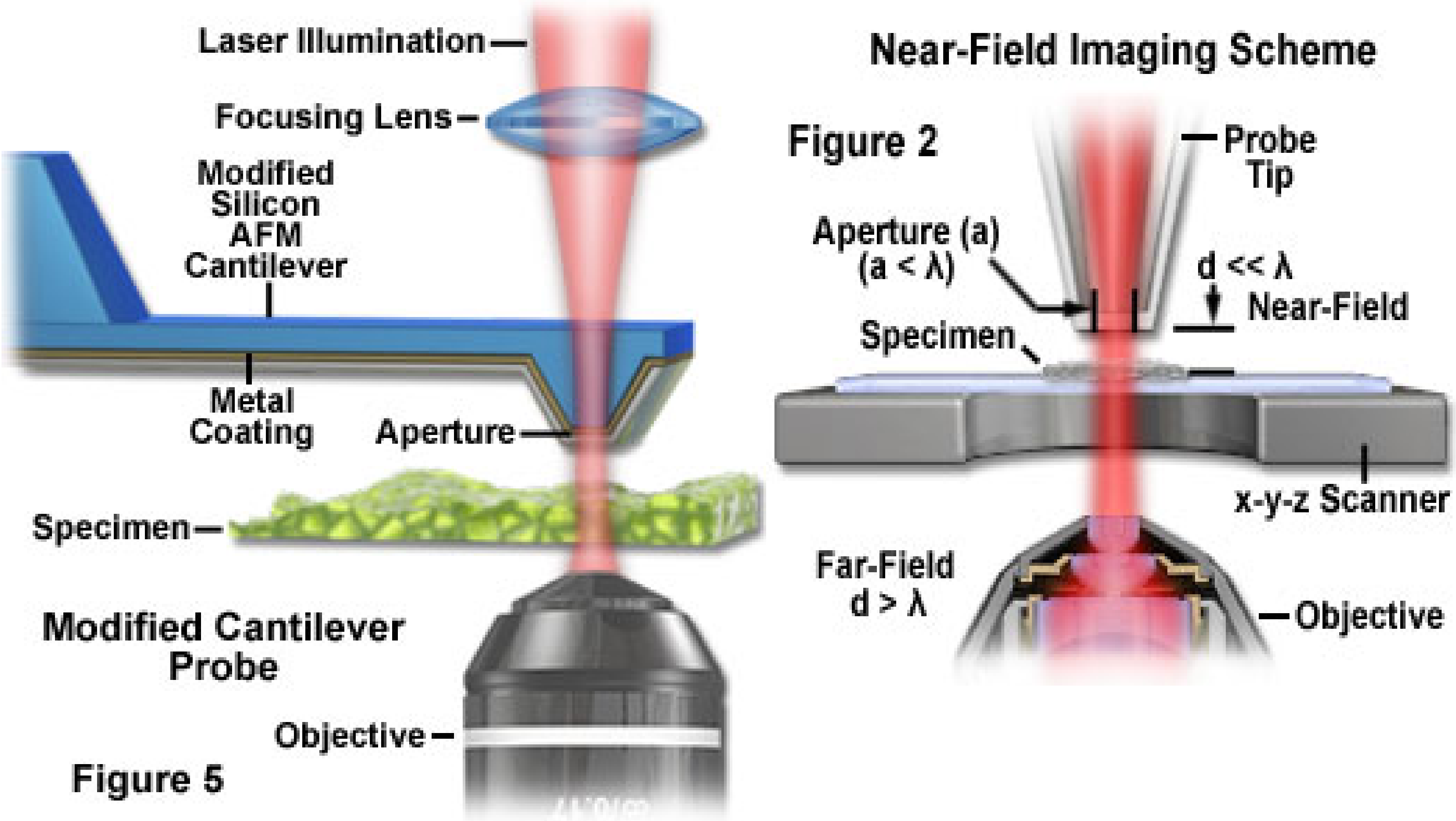


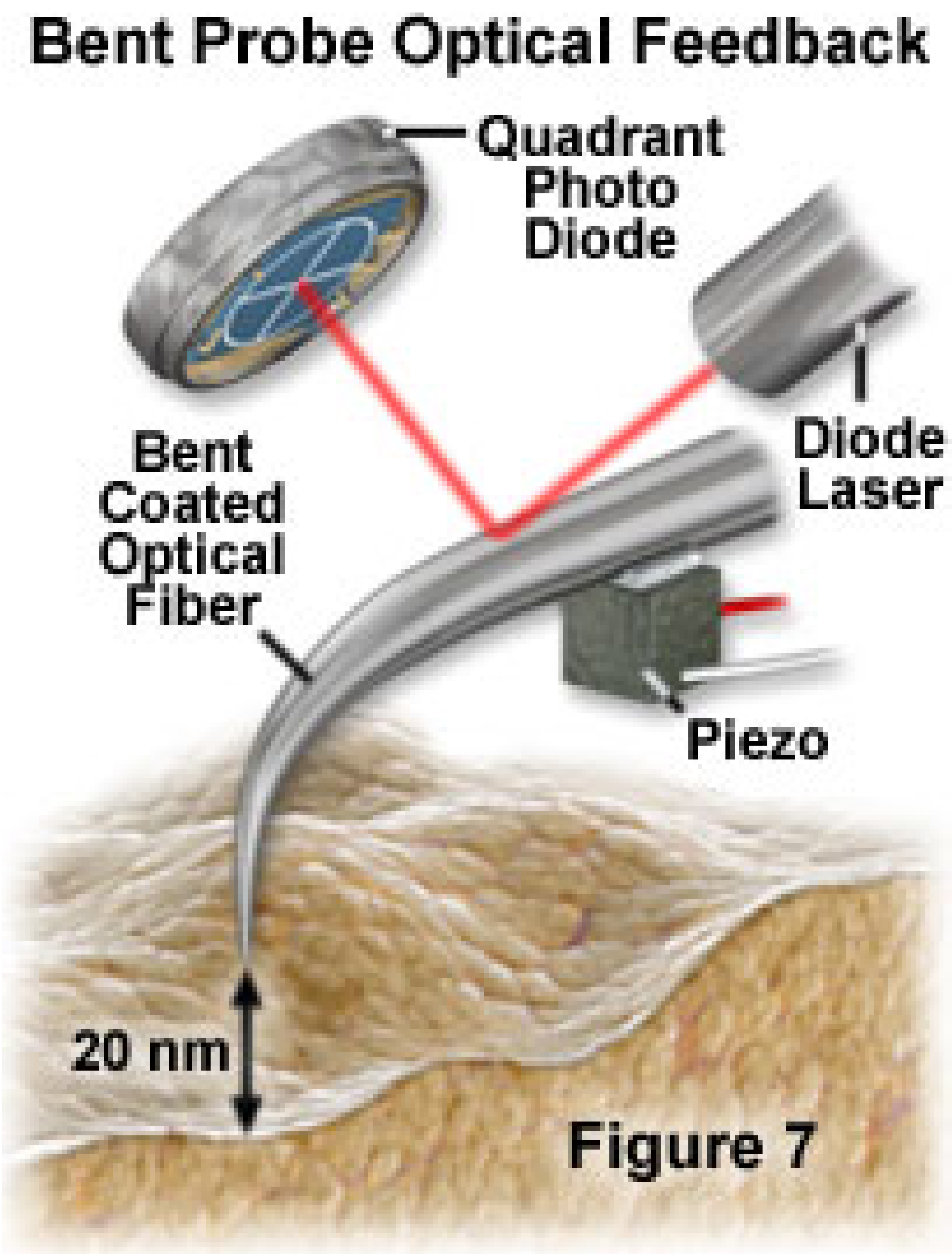


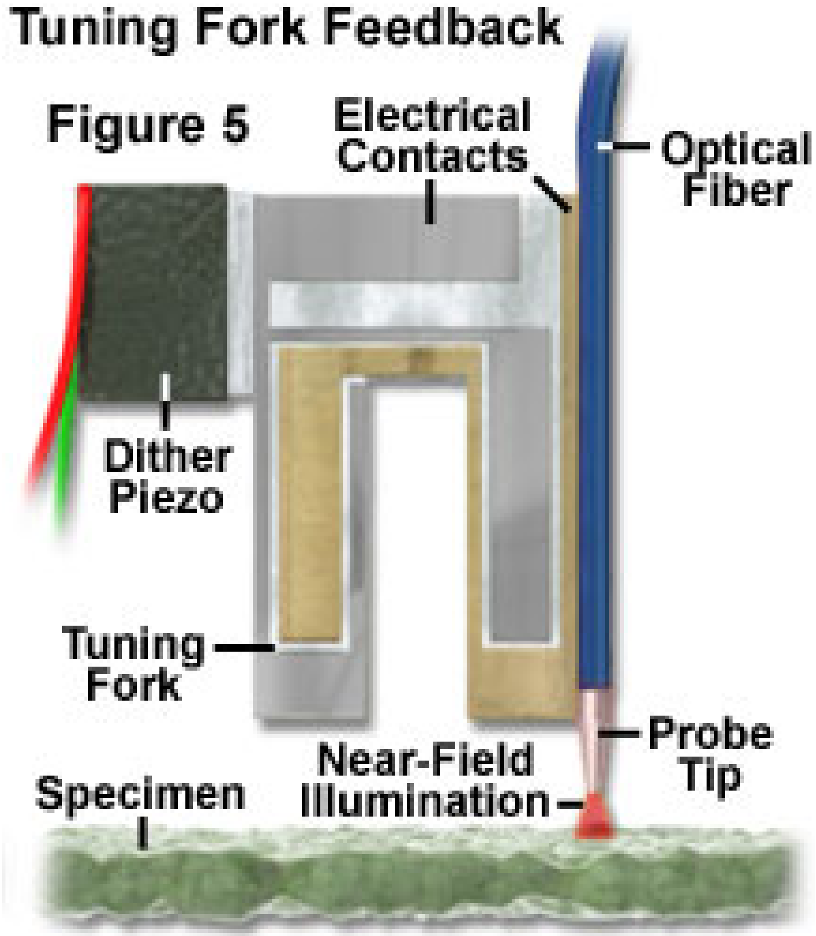
Aperture: 200nm

Saeed Pilevar et al., Appl. Phys. Lett. 72, 3133 (1998).

System layout of NSOM

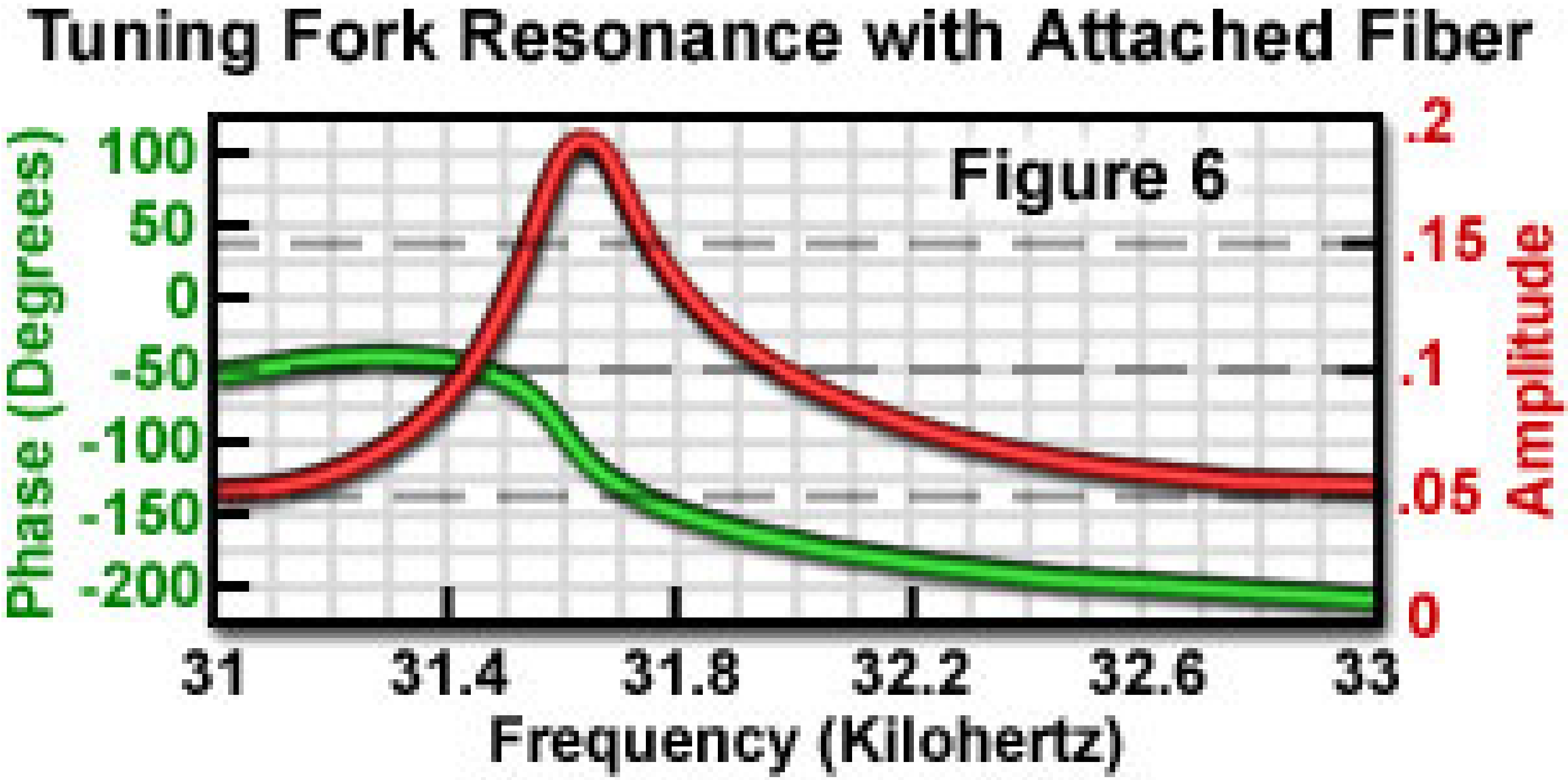



Bent Probe Optical Feedback
Quadrant
Photo
Diode
Diode
Laser
Bent
Coated
Optical
Fiber
Piezo
20 nm
Figure 7

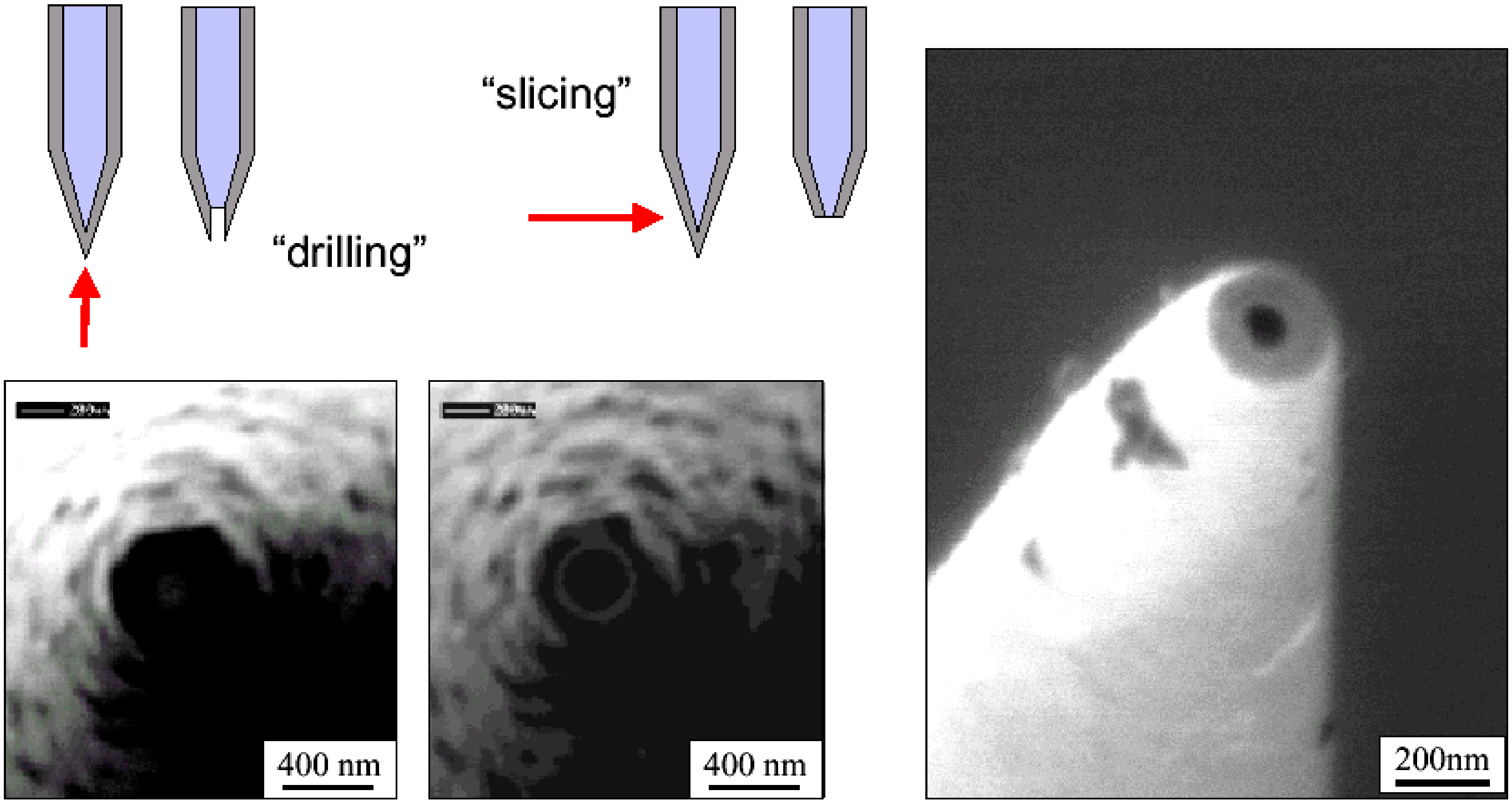

Tuning Fork Feedback
Figure 5
Electrical
Contacts
Optical
Fiber
Dither
Piezo
Tuning
Fork
Probe
Tip
Near-Field
Illumination
Specimen

Resonant curves：

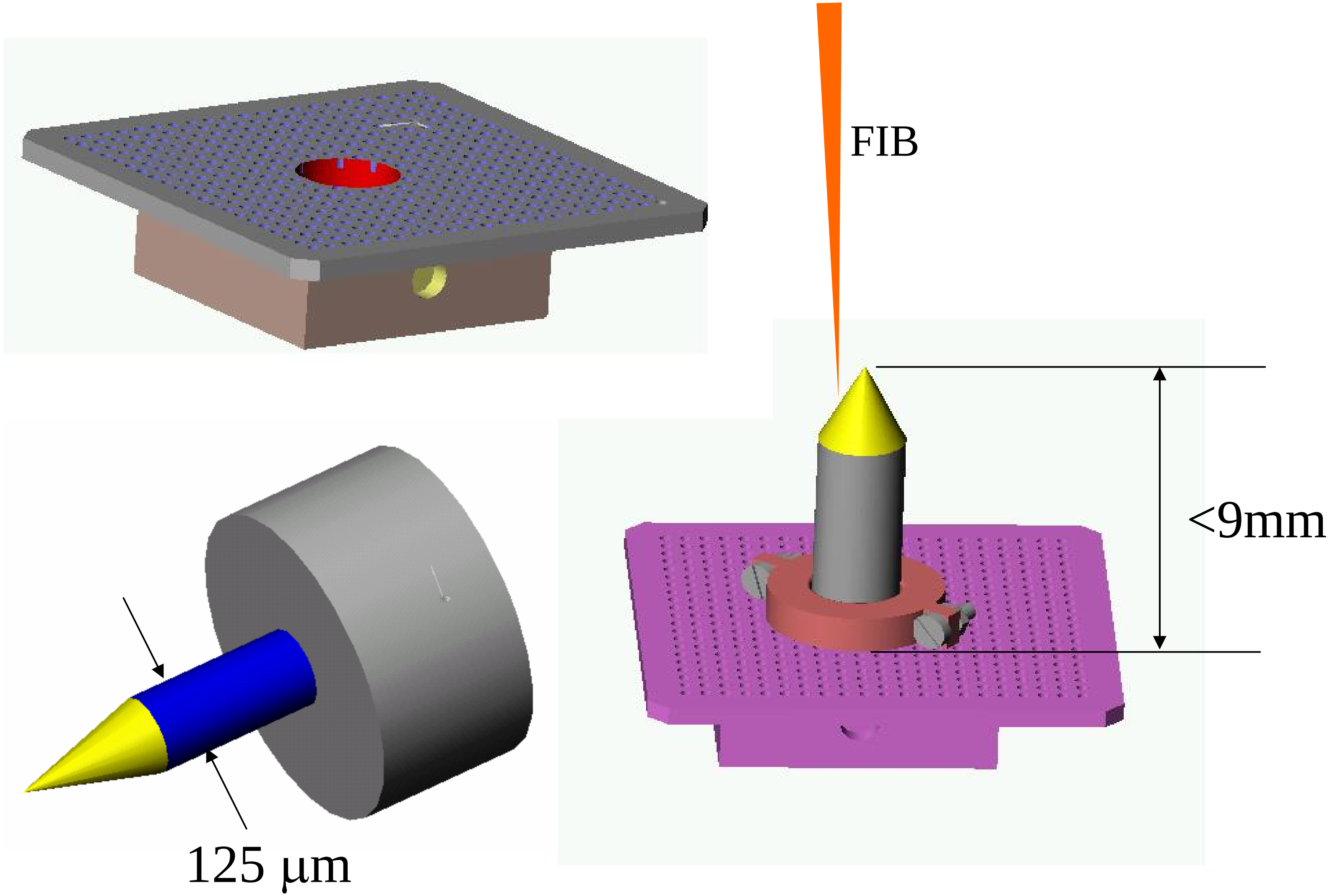
Strongly depends on quality and installation location of the probe.



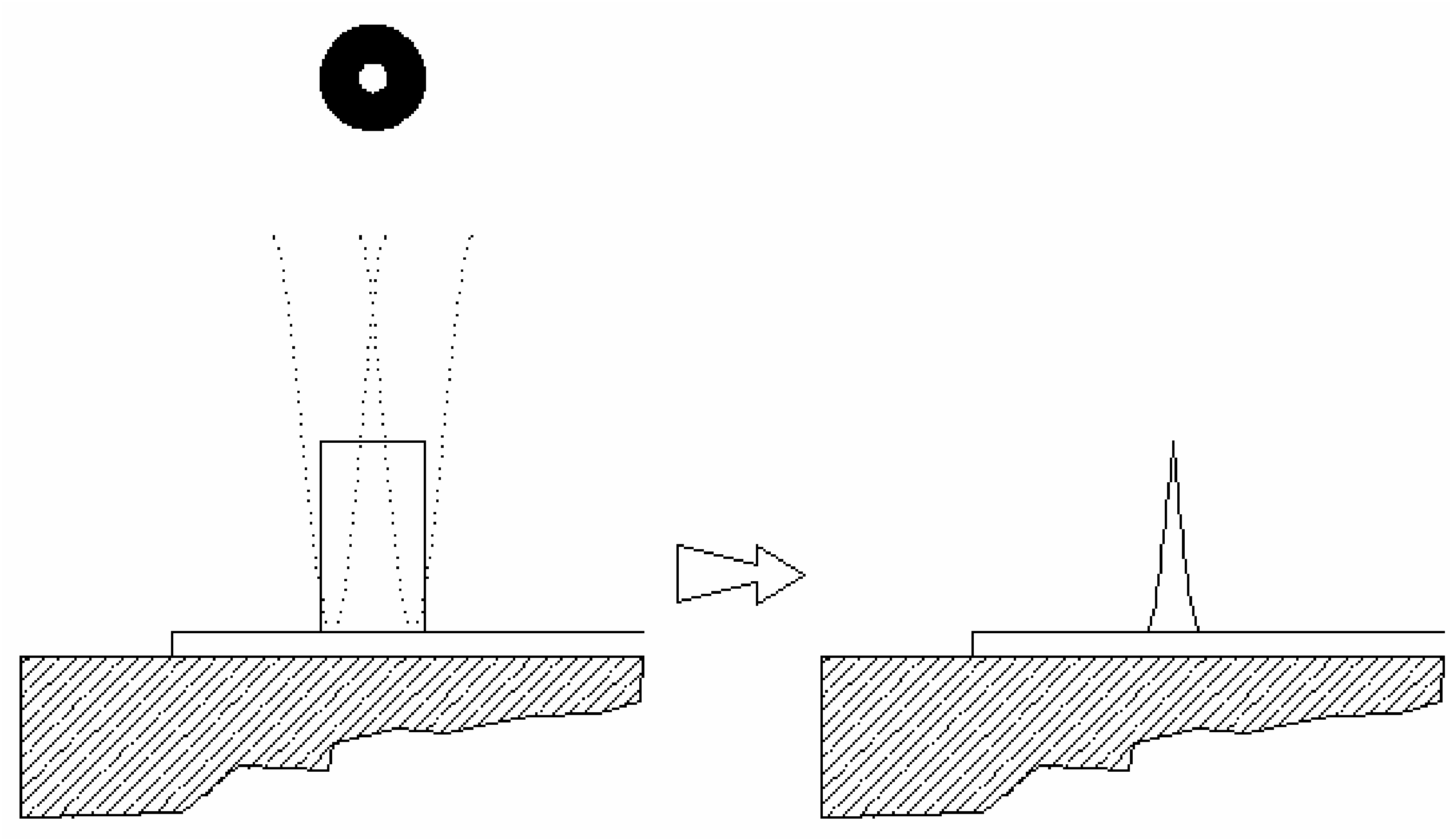
Probe modification – focused ion beam drilling



2. FIB top cutting

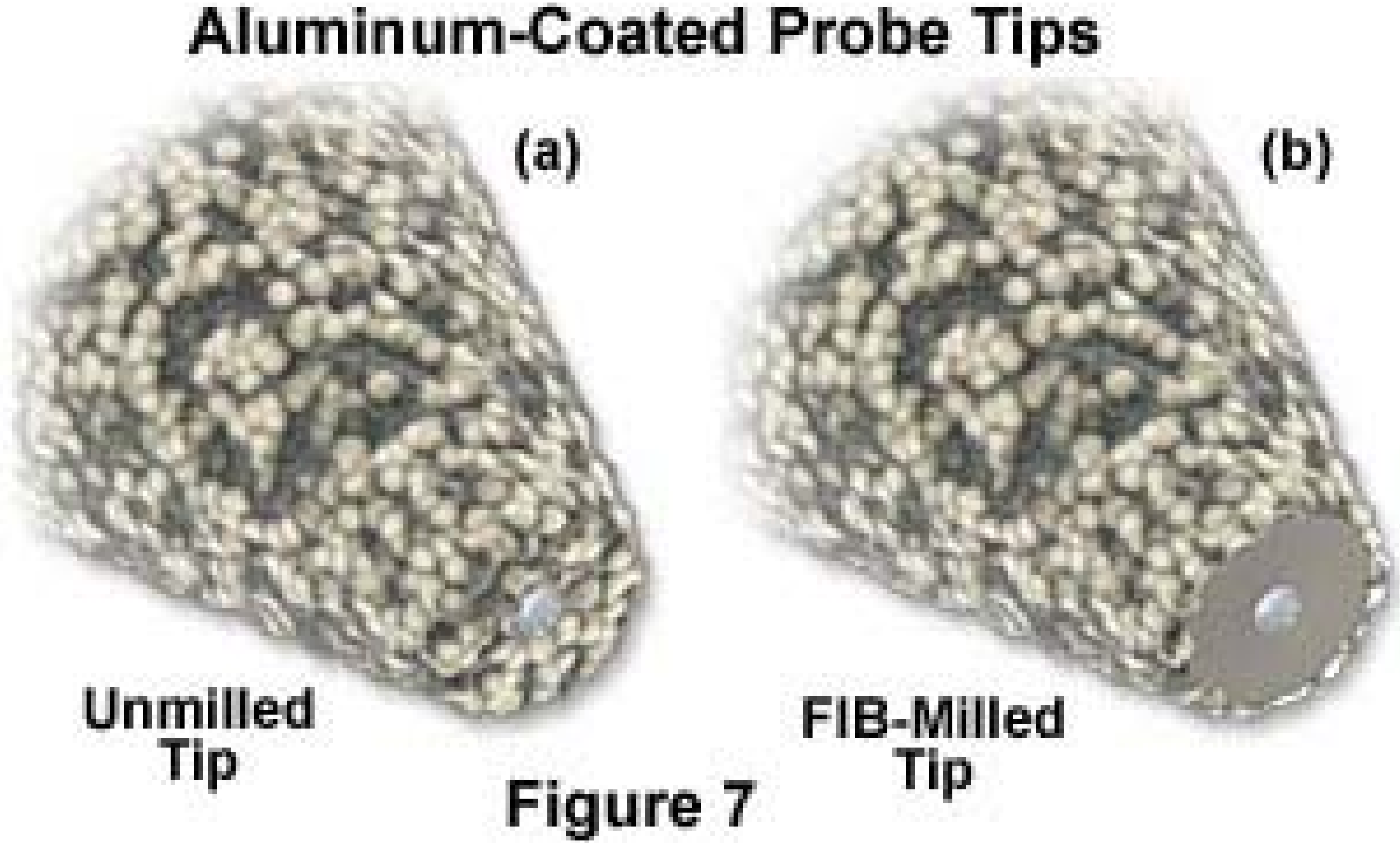


Cutting principle



Schematic of tip cutting by use of FIB milling

Focused Ion Beam Milling



Ultimate NSOM Resolution Limit

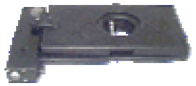
The fundamental resolution limit of NSOM is governed by four parameters**:**

1. Skin depth of the metal coating.
2. The grain size of the metal coating.
3. The probe aperture diameter.
4. Inherent noise in the optical signal and electronics.

Crucial Aspects

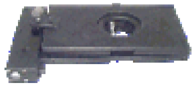
The achievable optical resolution is mainly determined by the aperture size of the optical probe and the probe-surface gap. A SNOM instrument must therefore feature:

- a feedback system keeping the probe at constant distance from the surface. As a benefit, this allows to record the samples topography simultaneously
- a high quality near-field probe

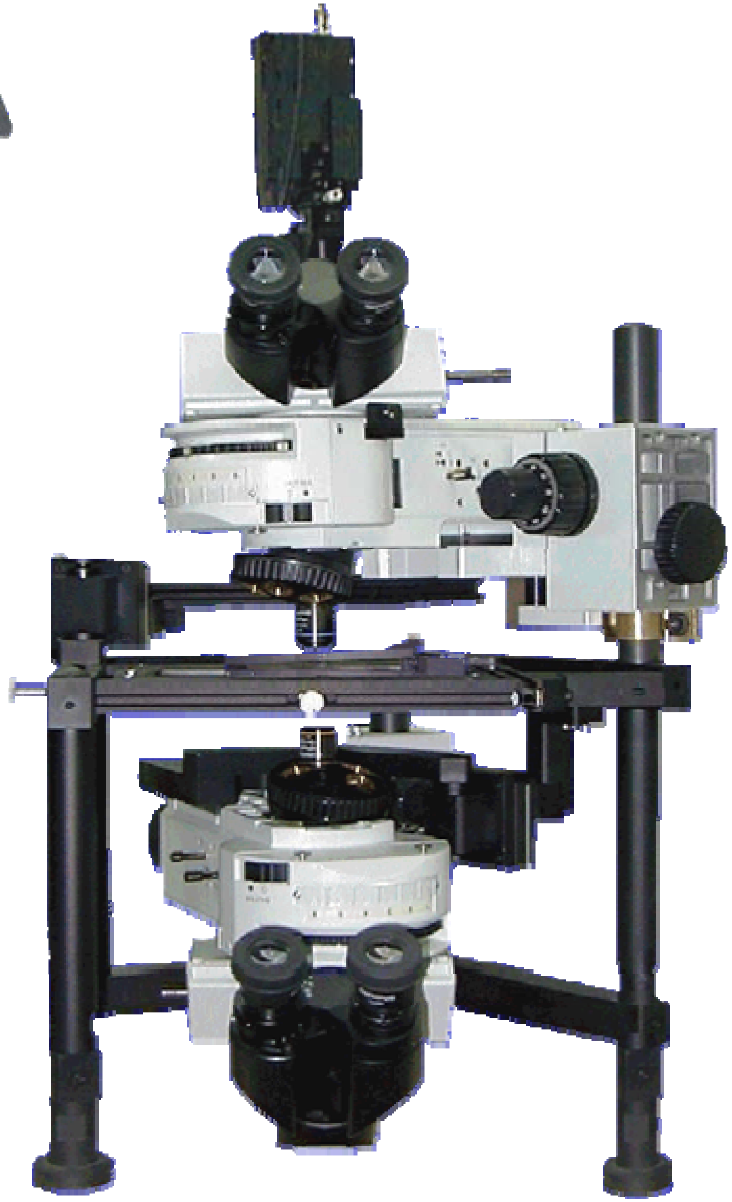


Nanonics
MultiView 2000™

MultiView 2000 ™ Complete System



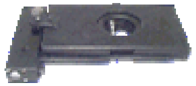
Modes of Operation



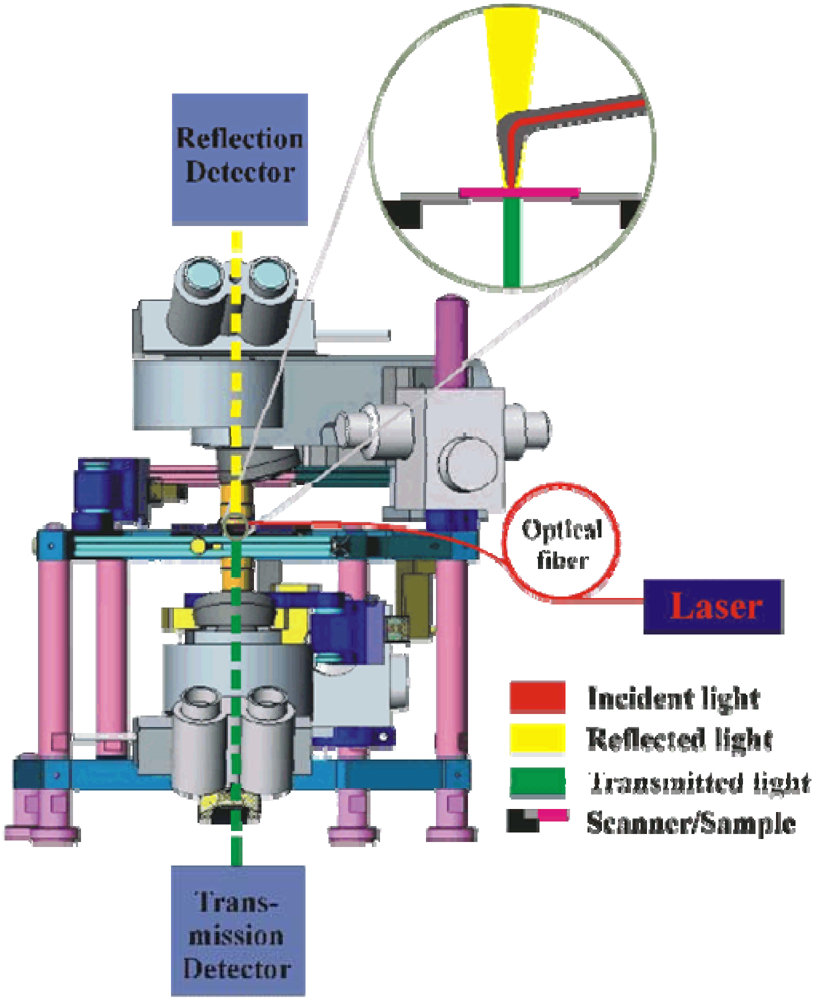
SPM modes:
- ***AFM contact***
- ***AFM Intermittent contact mode***
- ***Electrical Measurements***

Near Field Modes (NSOM):
- ***Reflection***
- ***Transmission***
- ***Collection***
- ***Fluorescence***
- ***Photo-Luminescence***

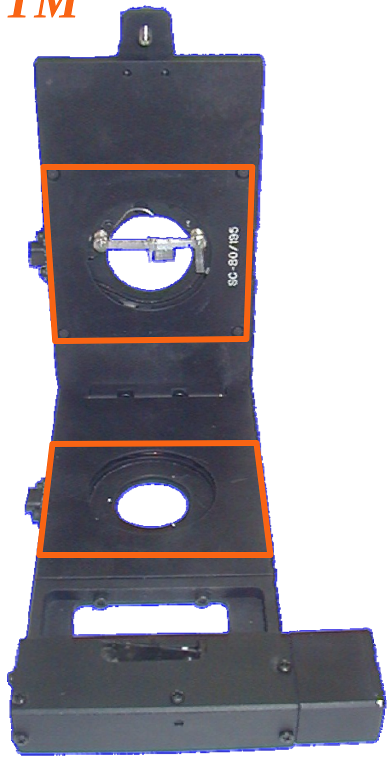
Far Field Methods:
- ***Standard Microscope Imaging***
- ***Fluorescence***
- ***Confocal***

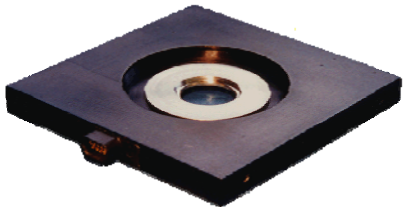


Modes of Operation



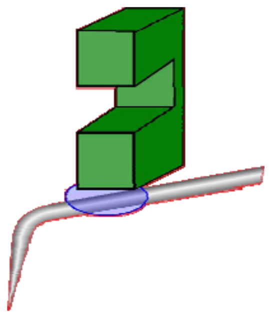
Enabled by patented 3D- FlatScan™ Technology



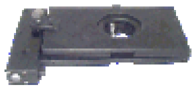


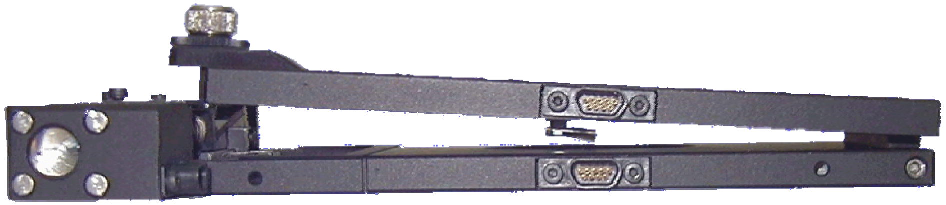
&

Cantilevered NSOM/AFM probes

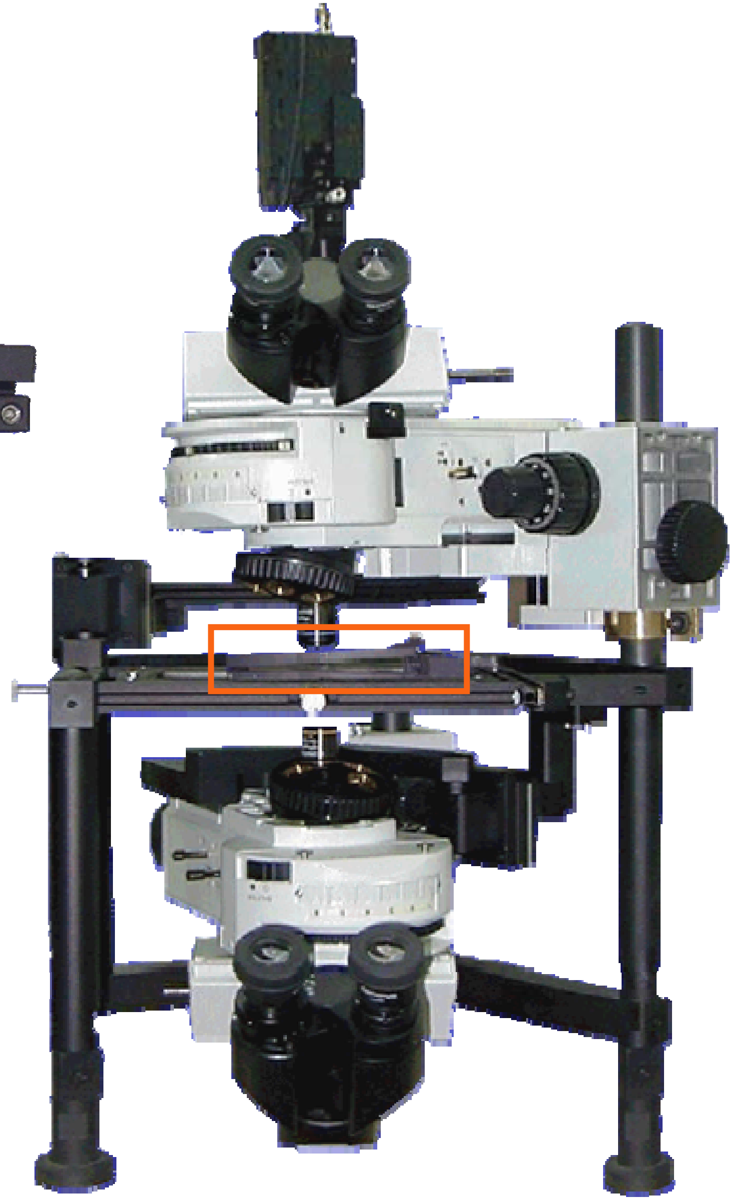


Easy Integration with Optical Microscopes

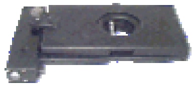


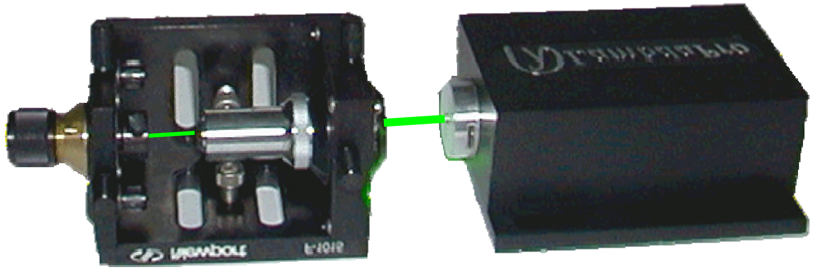


Dual - Upright /Inverted Optical Microscope



Illumination Sources



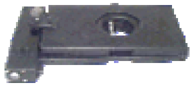


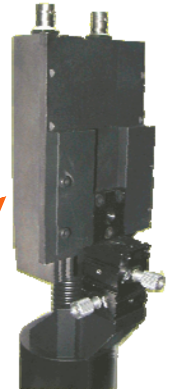
Fiber coupler and laser

Illumination through the fiber using a Fiber Coupler

- *Nd-YAG Laser (532 nm)*
- *Ar^+-Laser (488 & 515 nm)*
- *HeCd-Laser (325 nm)*
- *Diode Laser (Vis – IR)*
- *Femtosecond Laser*

Detection System



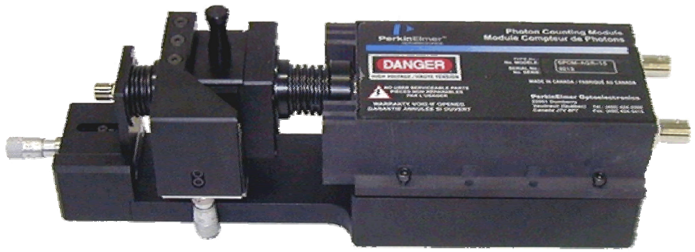


Reflection mode detector

Detectors on the Microscope ports

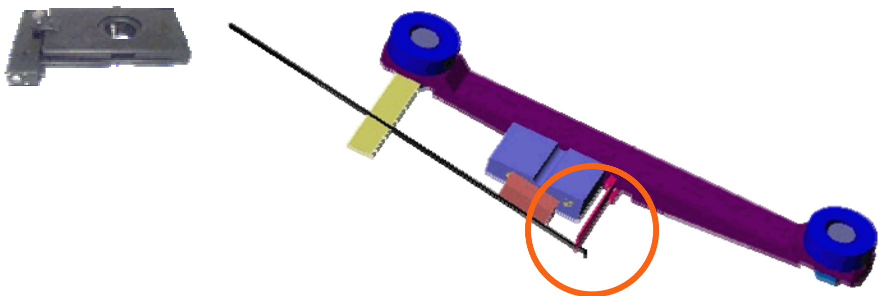
- *APD (Vis)*
- *PMT (UV – VIS)*
- *InGaAs (IR)*
- *Fiber adapter for the connection to a Spectrometer or Monochromator*
- …

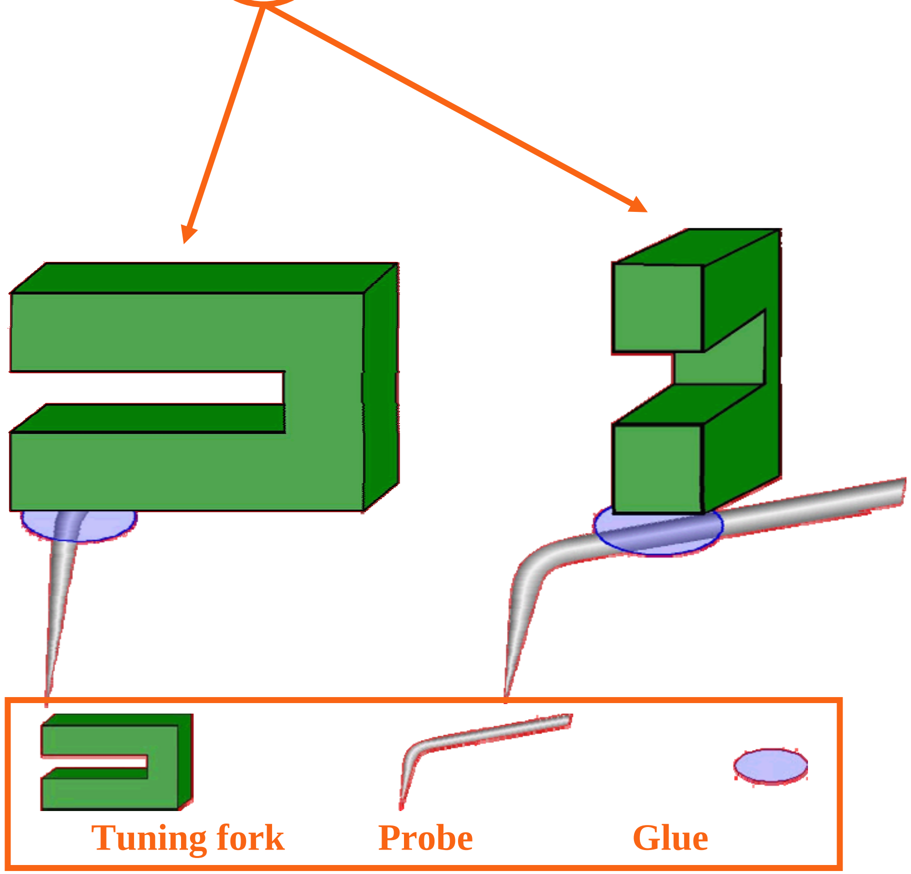
Transmission mode detector



Collection mode detector

Tuning Fork Feedback

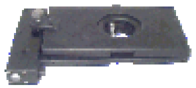


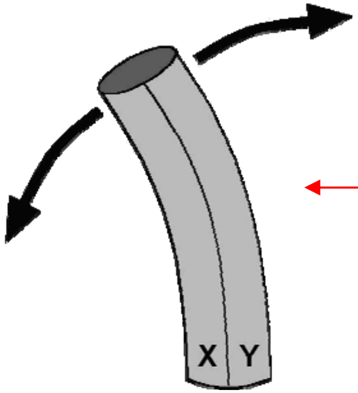


Unique tuning fork technology using a tapered and cantilevered NSOM or AFM probe.

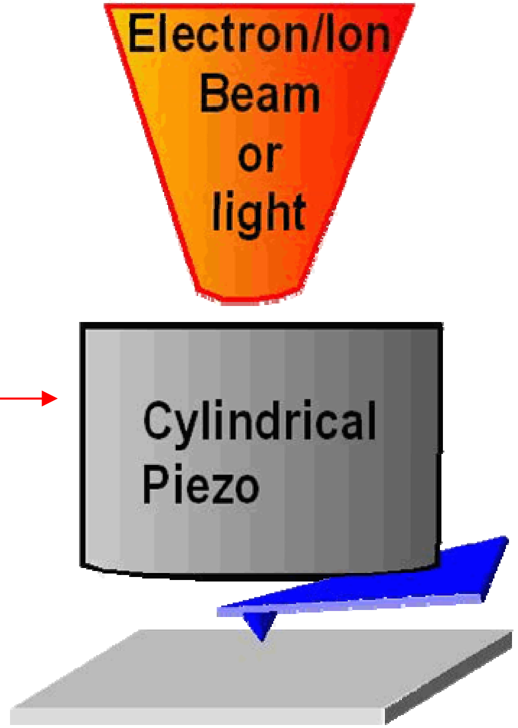
Probes are premounted on the tuning fork.

Standard NSOM/SPM Technology





Cylindrical Piezo



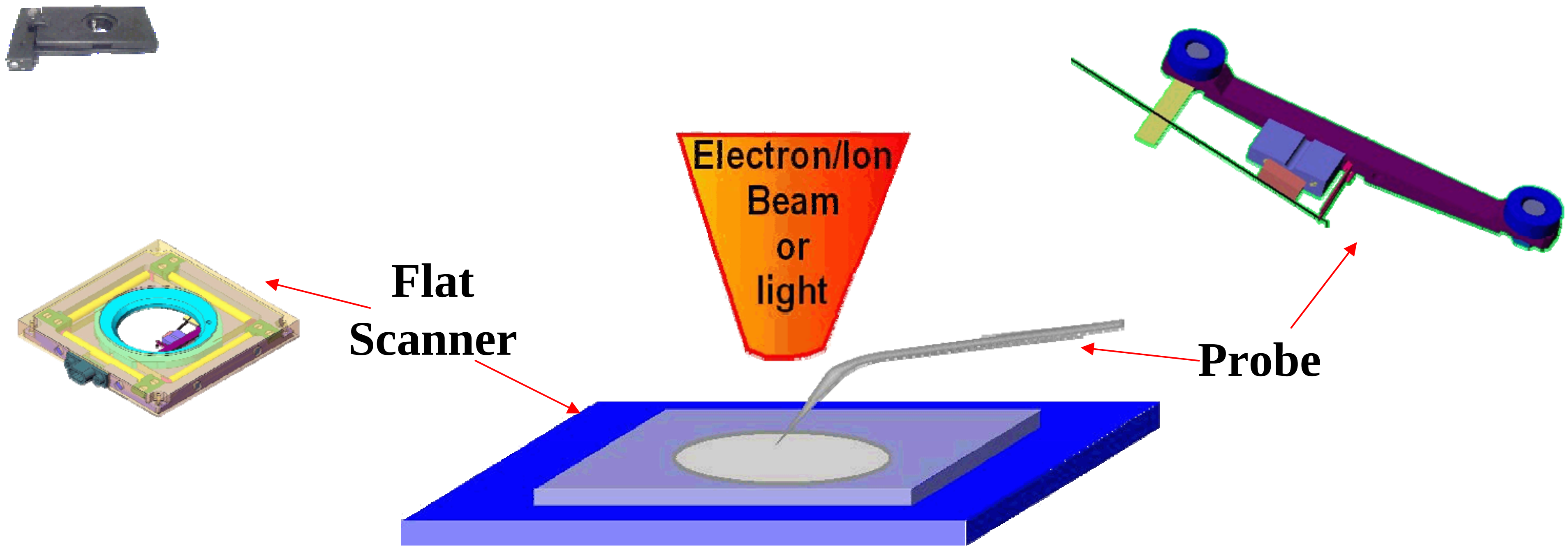
Probe

is not

Optical, microRaman or Electron/Ion Beam Friendly

neither from the top nor bottom

The MultiView 2000 ™ Technology

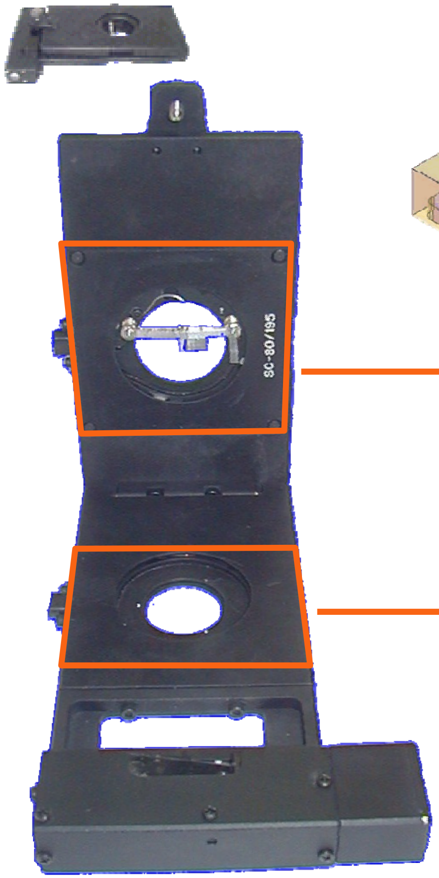


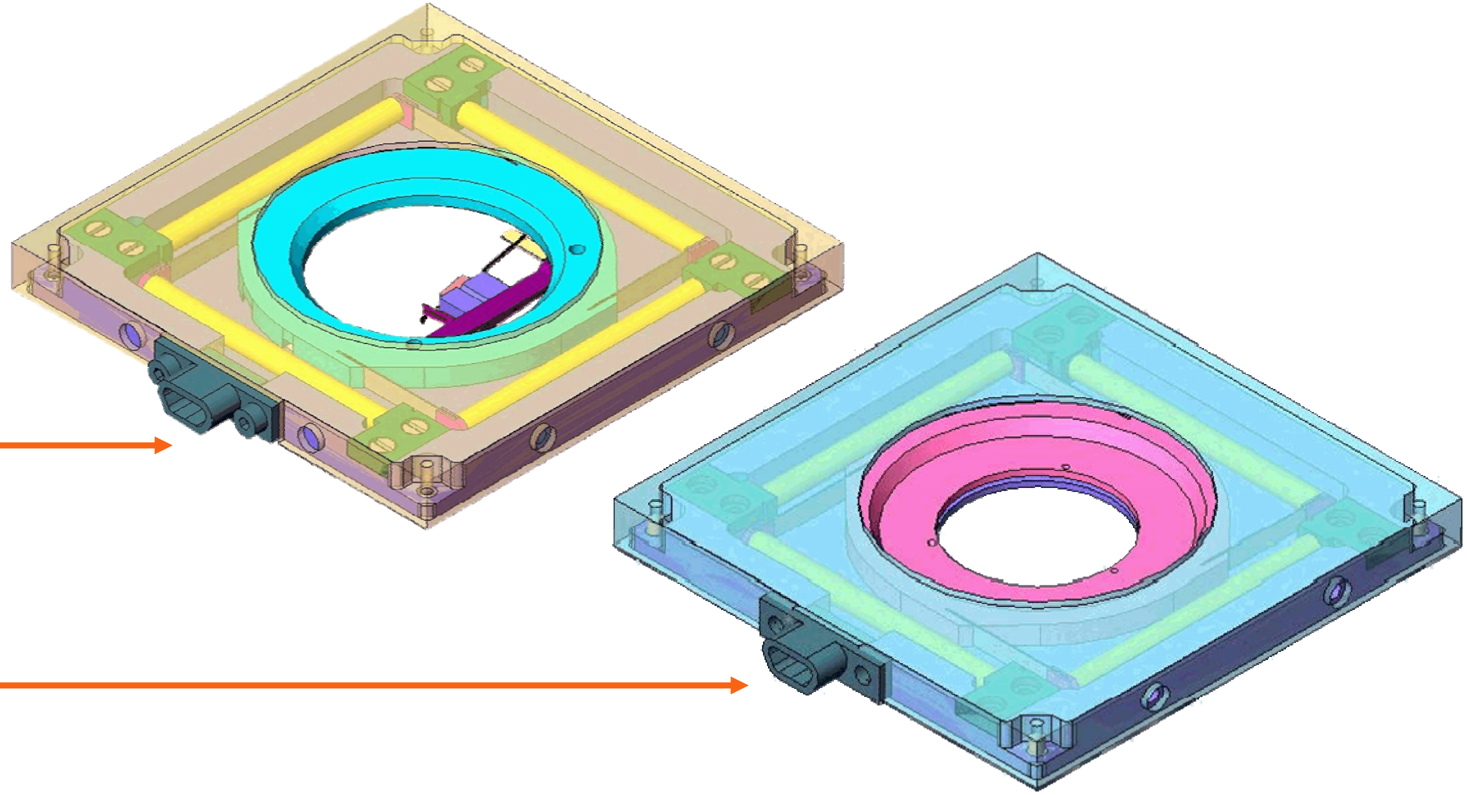
is

Optical, microRaman or Electron/Ion Beam Friendly

from the top and the bottom

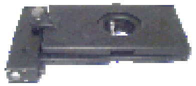
Nanonics 3D-Flatscan™

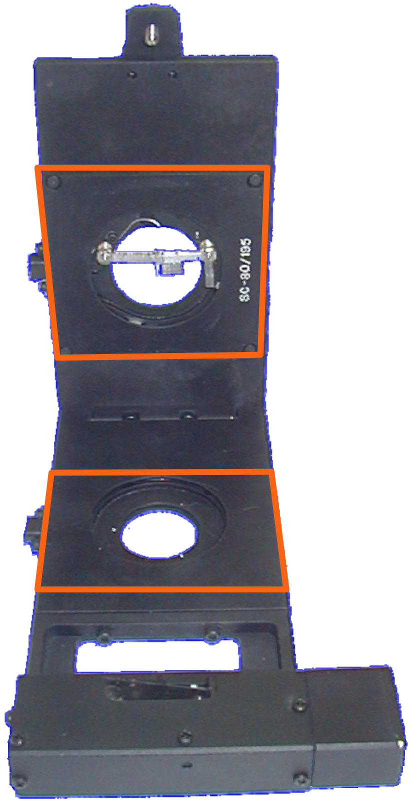


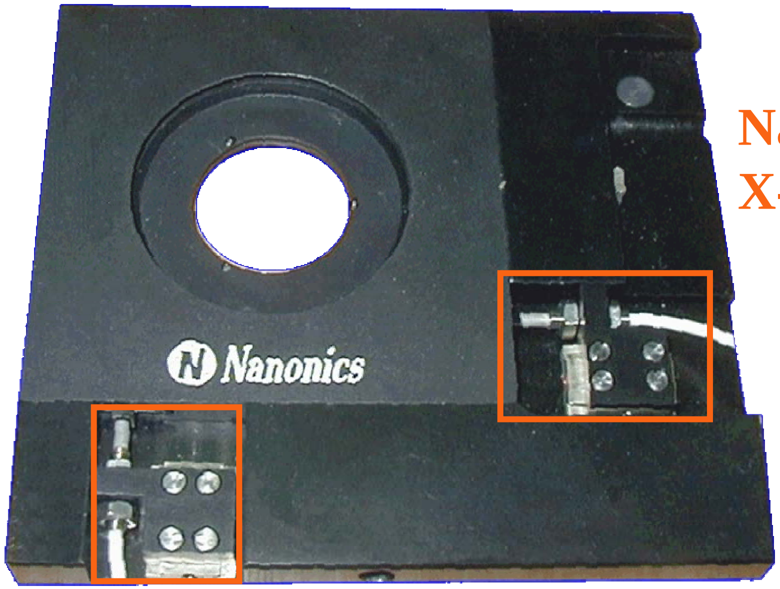


- 2 Flat Scanner: sample scanning and/or tip scanning
- Only 7 mm thick
- 140 µm X-Y-Z scan range
- Central opening providing clear optical axis
- Inertial motion positioning of sample (6 mm)

Nanonics 3D-Flatscan™ with Closed Loop Sensors



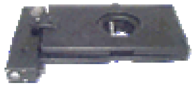




Nanonics 3D-Flatscan ™ with X-Y closed loop sensors

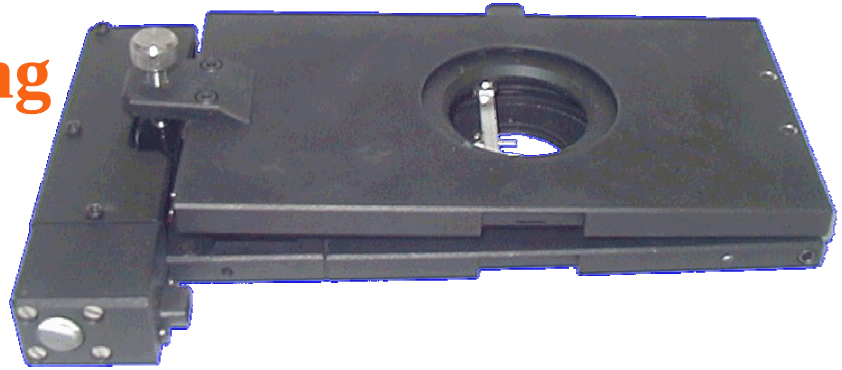
- Capacitive displacement sensors
- Precise positioning and scanning
- Additional Z-sensor available
- Central opening providing clear optical axis
- Inertial motion positioning of sample (6 mm)

Versions of the MultiView 2000 ™



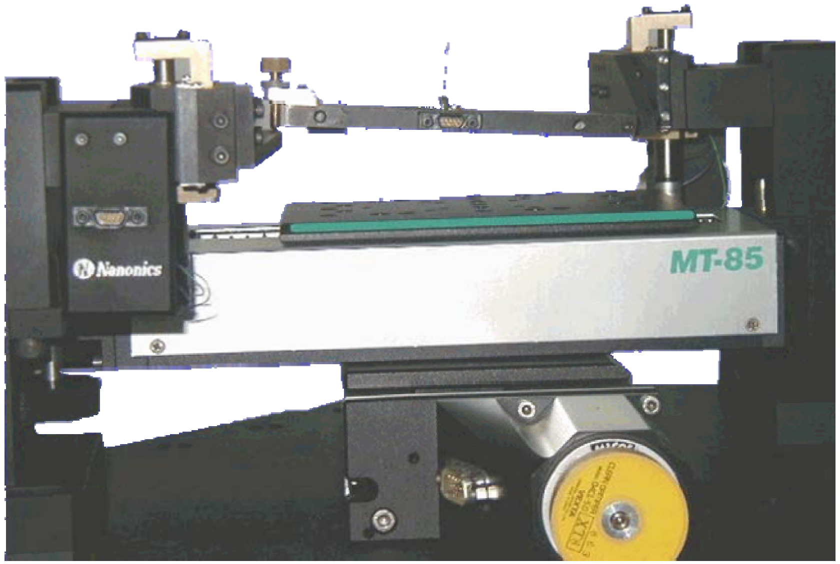
•Tip and sample scanning

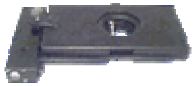
Scanning with the tip, the sample or tip and sample



•Tip scanning

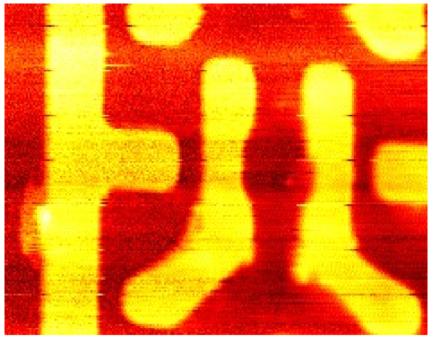
Scanning only with the tip. Free space setup, enabling imaging of large samples.

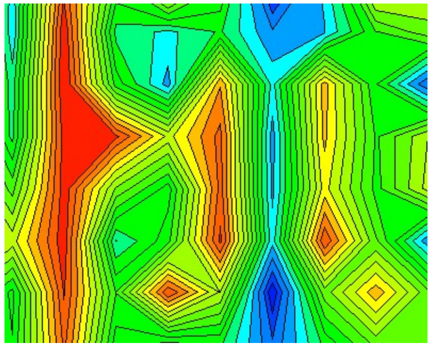


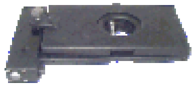


The MultiView 1000™ Combined with a Renishaw Raman Microscope

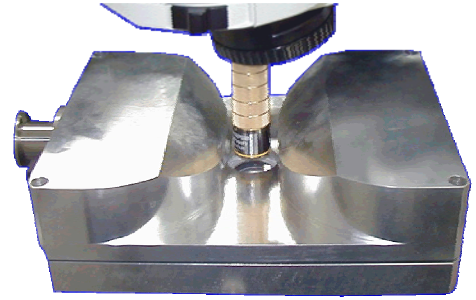
Combined AFM/Raman imaging of a sample is possible (see below).
9x7 μm AFM scan, and Raman-intensity map (at 520 cm^{-1}) in the same area



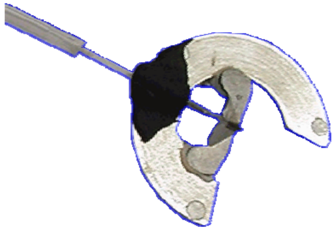




Other Systems Available from Nanonics

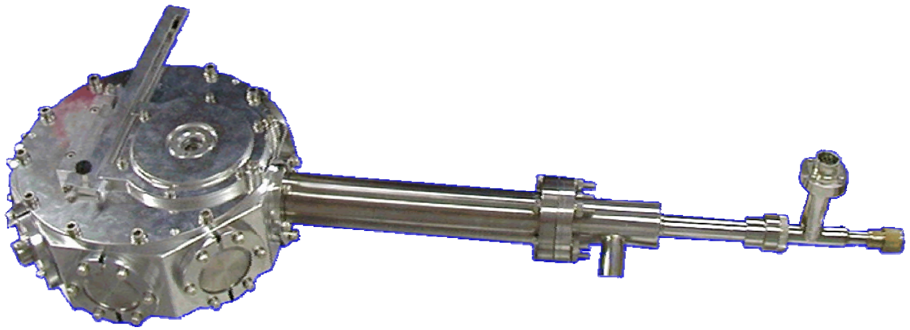


Environmental/High
Vacuum Chamber
AFM/NSOM System

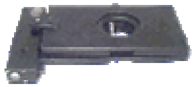


Gas & Liquid
Chemical Delivery
System

Multiview 1000

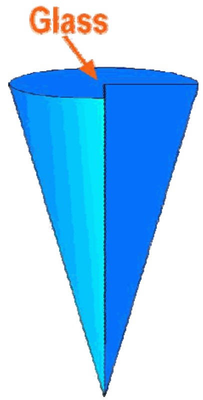


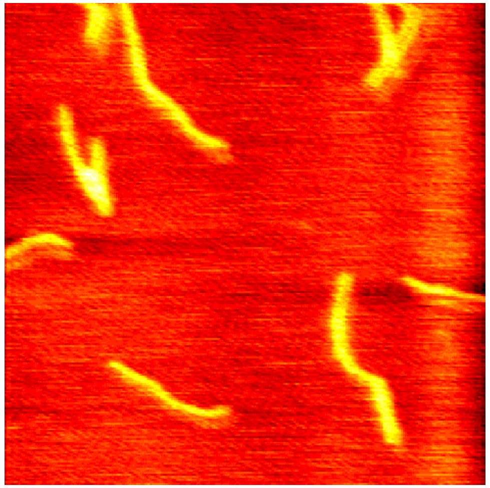
Low Temperature System

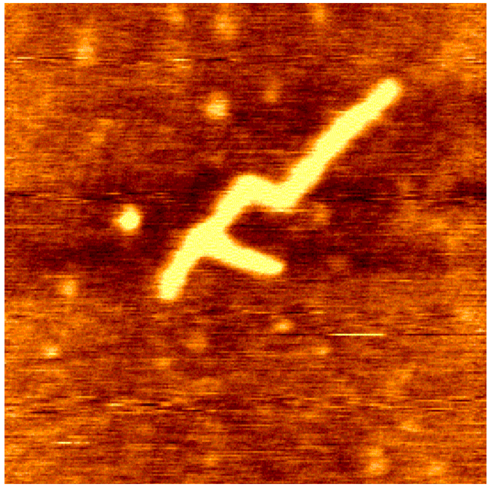


Wide Range of Imaging Possibilities: AFM

AFM / NSOM probe

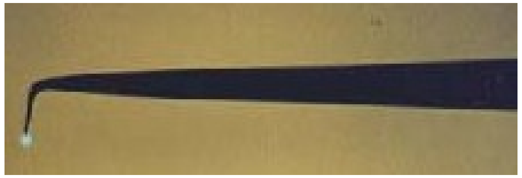




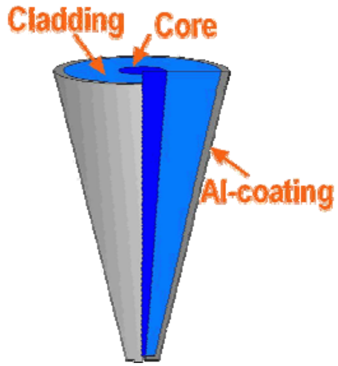


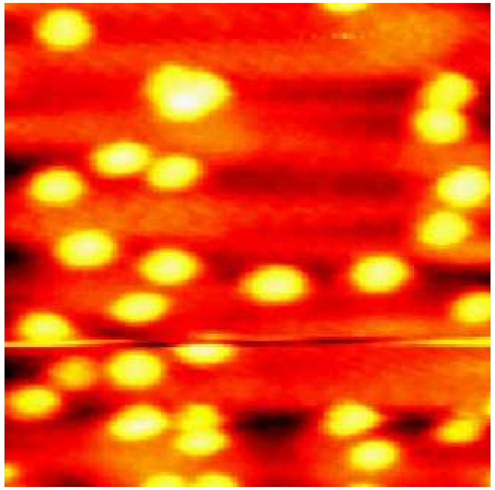
AFM Topography of DNA
Left image 1.6x1.6 mm, z-range 5 nm
Right image 900x900 nm, z-range 2.5 nm

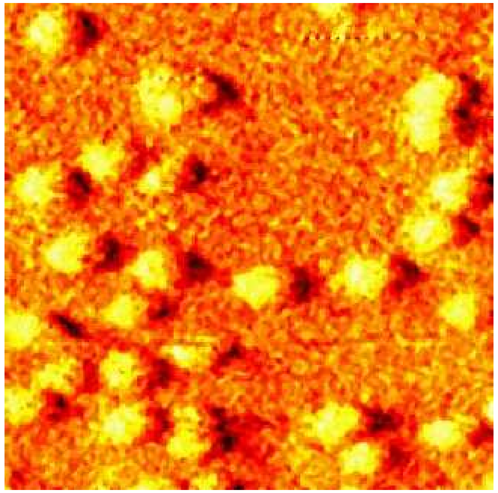
Wide Range of Imaging Possibilities: AFM / NSOM (transmission mode)



AFM / NSOM probe

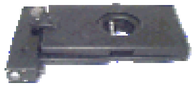




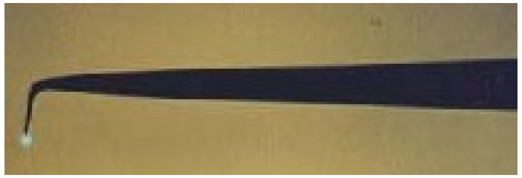


AFM Topography (left) & Transmission NSOM (right) of 30 nm gold balls (Scansize: 1x1 µm)

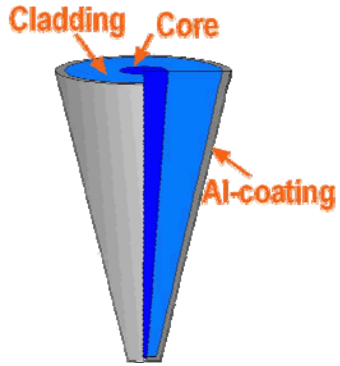
MultiView 2000™
Product
Presentation



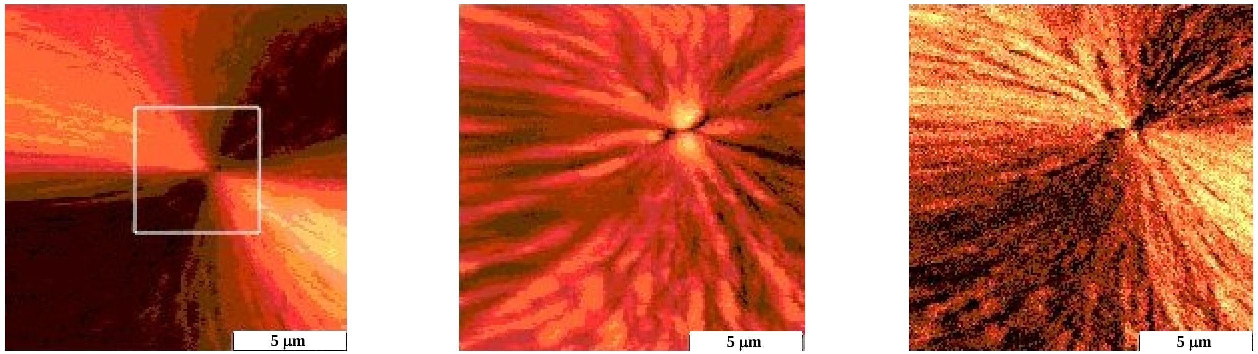
Wide Range of Imaging Possibilities: AFM / NSOM (reflection mode)



AFM / NSOM probe

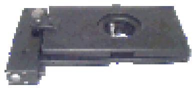


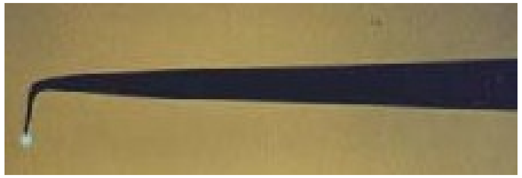
Polarized NSOM



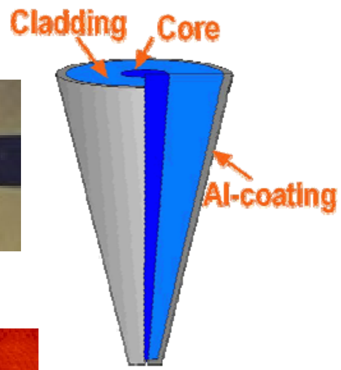
Simultaneous polarized confocal/AFM/ Polarized NSOM of polyethylene thin film

Wide Range of Imaging Possibilities: AFM / NSOM / Resistance

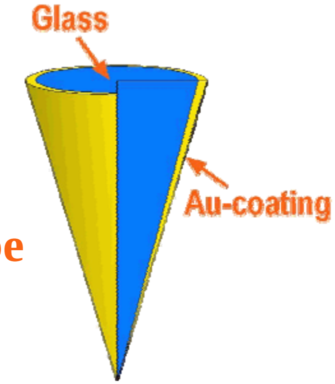


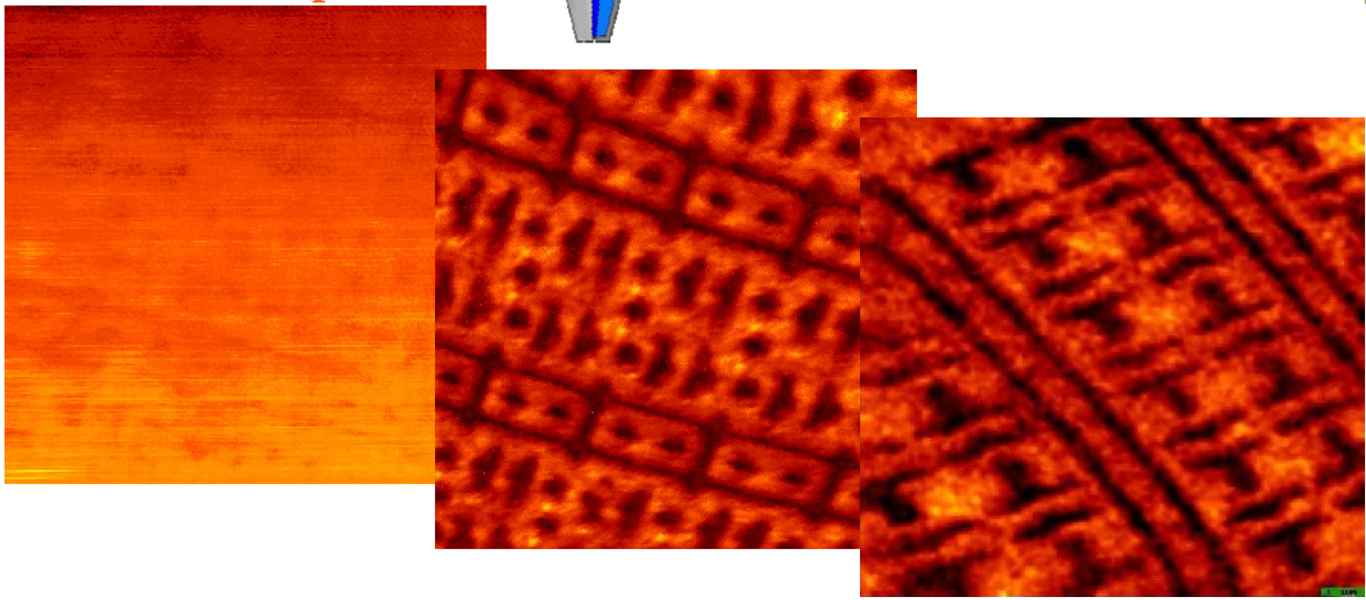


AFM / NSOM probe

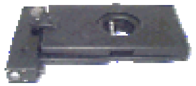


AFM / Resistance probe

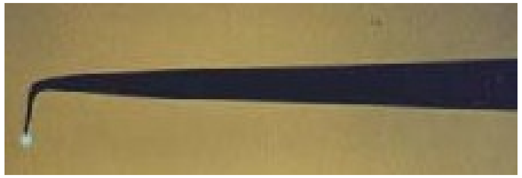




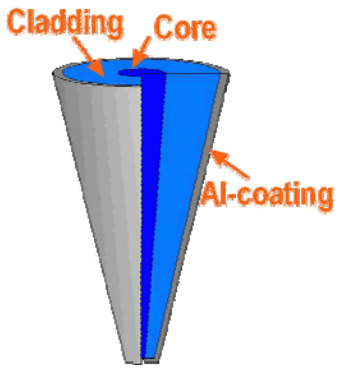
AFM (left) reflection NSOM (middle) & simultaneous spreading resistance image (right) of a chemically mechanically polished SRAM

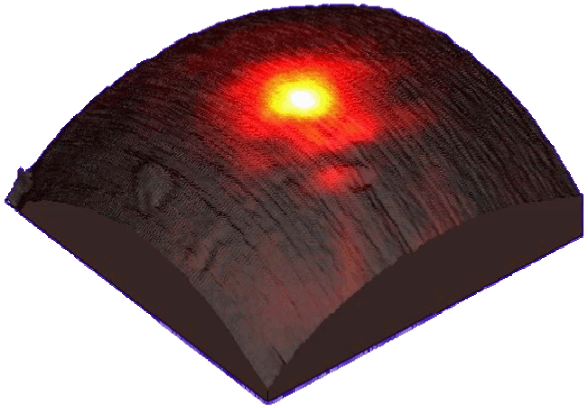


Wide Range of Imaging Possibilities: AFM / NSOM (collection mode)

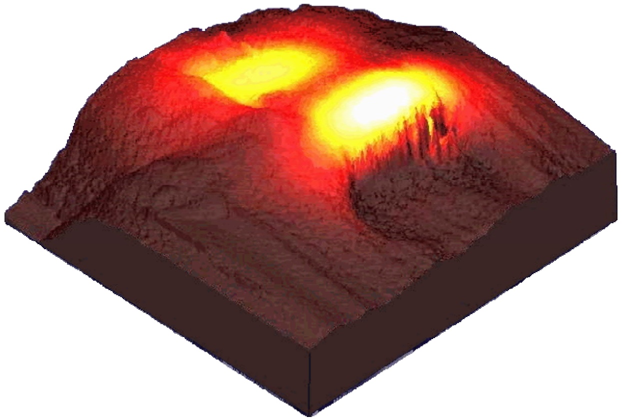


AFM / NSOM probe

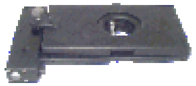




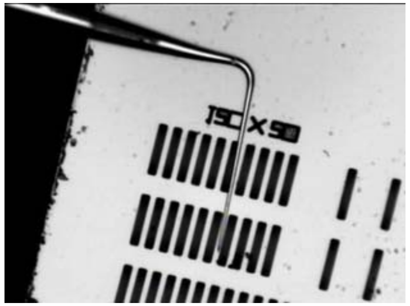
Collage AFM topography & Light Distribution of a fiber lens



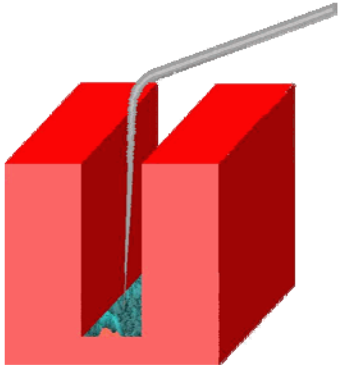
Collage AFM topography & Light Distribution of a diode laser



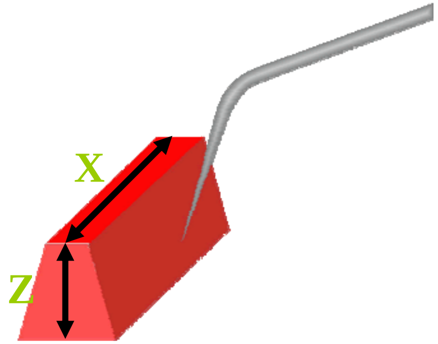
Wide Range of Imaging Possibilities: Deep Trench AFM



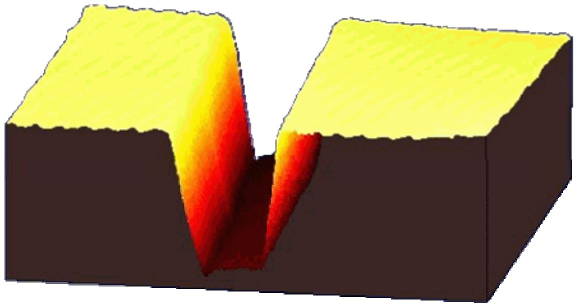
Deep Trench AFM / NSOM probe



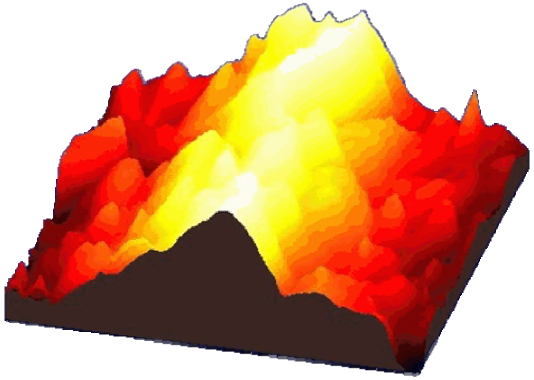
Schematic of deep trench AFM image



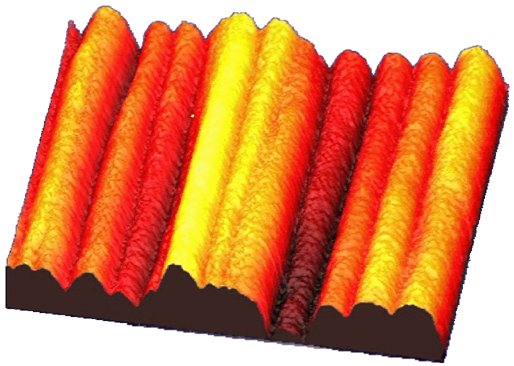
Schematic of side wall AFM image



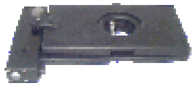
10 x 10 μm AFM image of a 10 μm deep/2 μm wide trench (Z-range 10 μm)



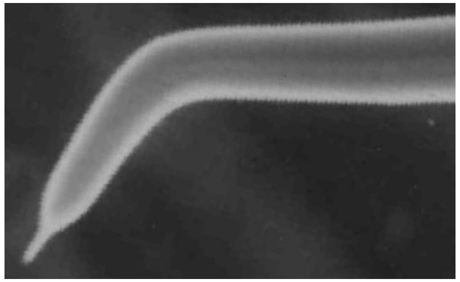
1 x 1 μm AFM image of the bottom of the deep trench (Z-range 100 nm)

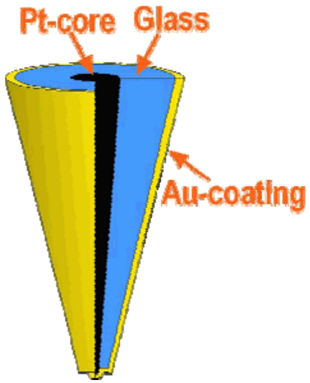


5 x 5 μm X-Z scan of the sidewall of the deep trench (Y-range 150 nm)

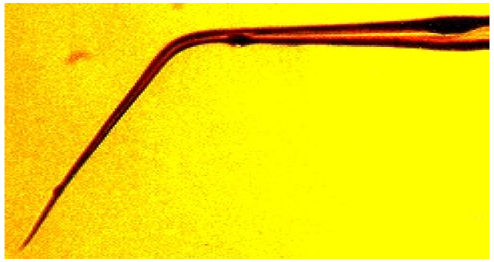


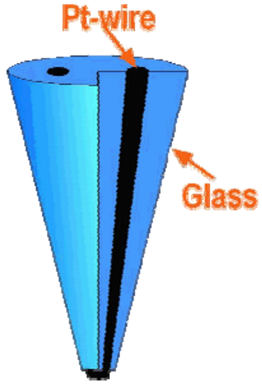
Wide Range of Imaging Possibilities: AFM / Thermal imaging



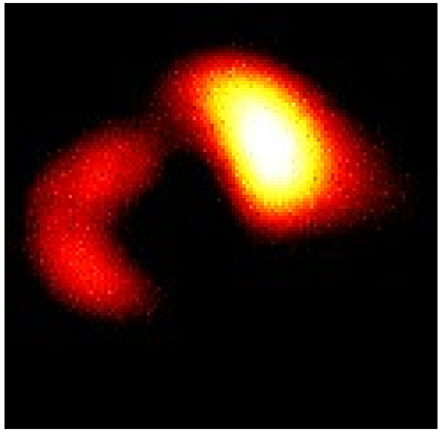


AFM / Thermocouple probe

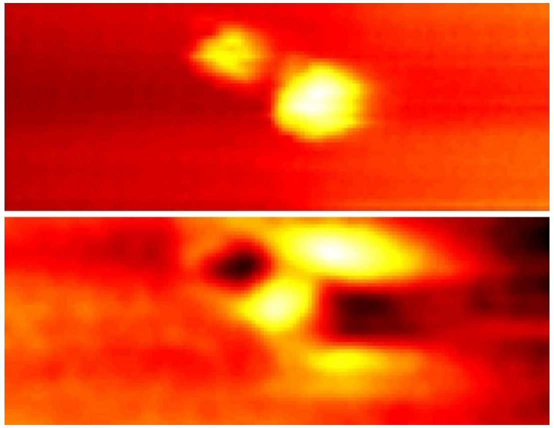




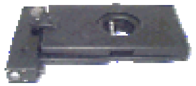
AFM / Thermoresistive probe



Thermal image of cleaved multimode fiber (IR light was colupled into the fiber)

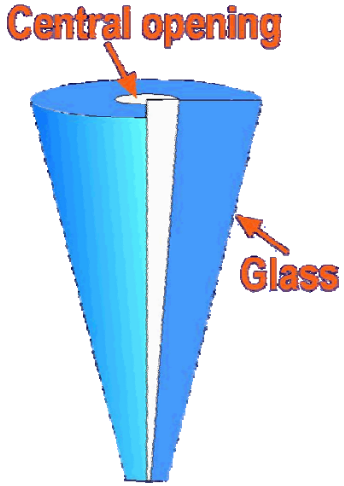


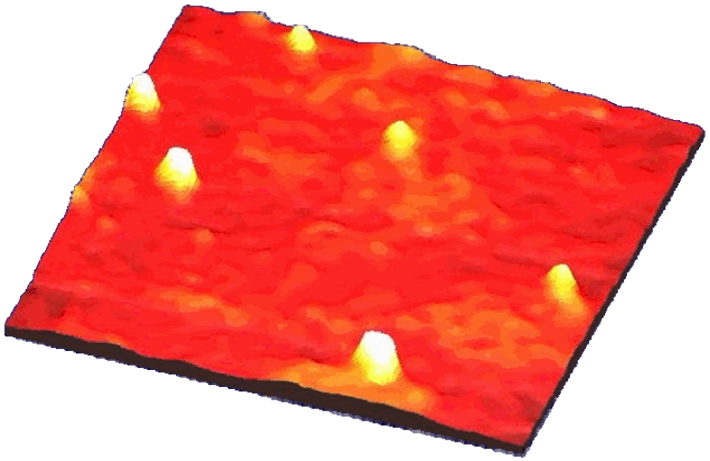
1 x 4 μm AFM (top) and thermal (bottom) image of 500 nm spheres.



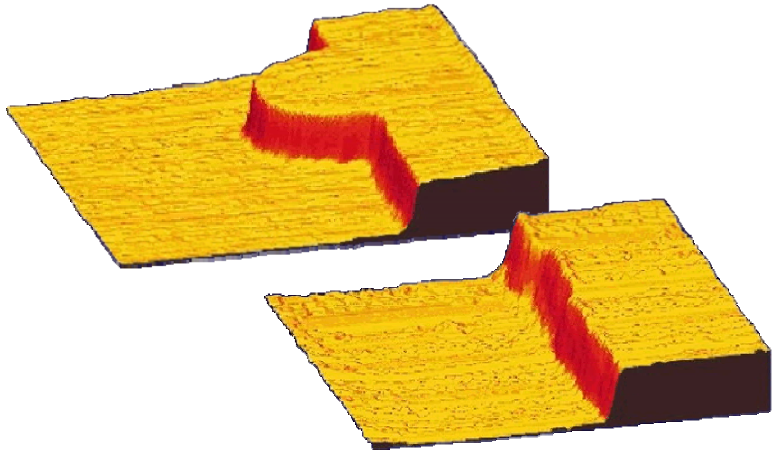
Wide Range of Lithography Possibilities: Chemical delivery / Laser ablation

Nanopipette probe



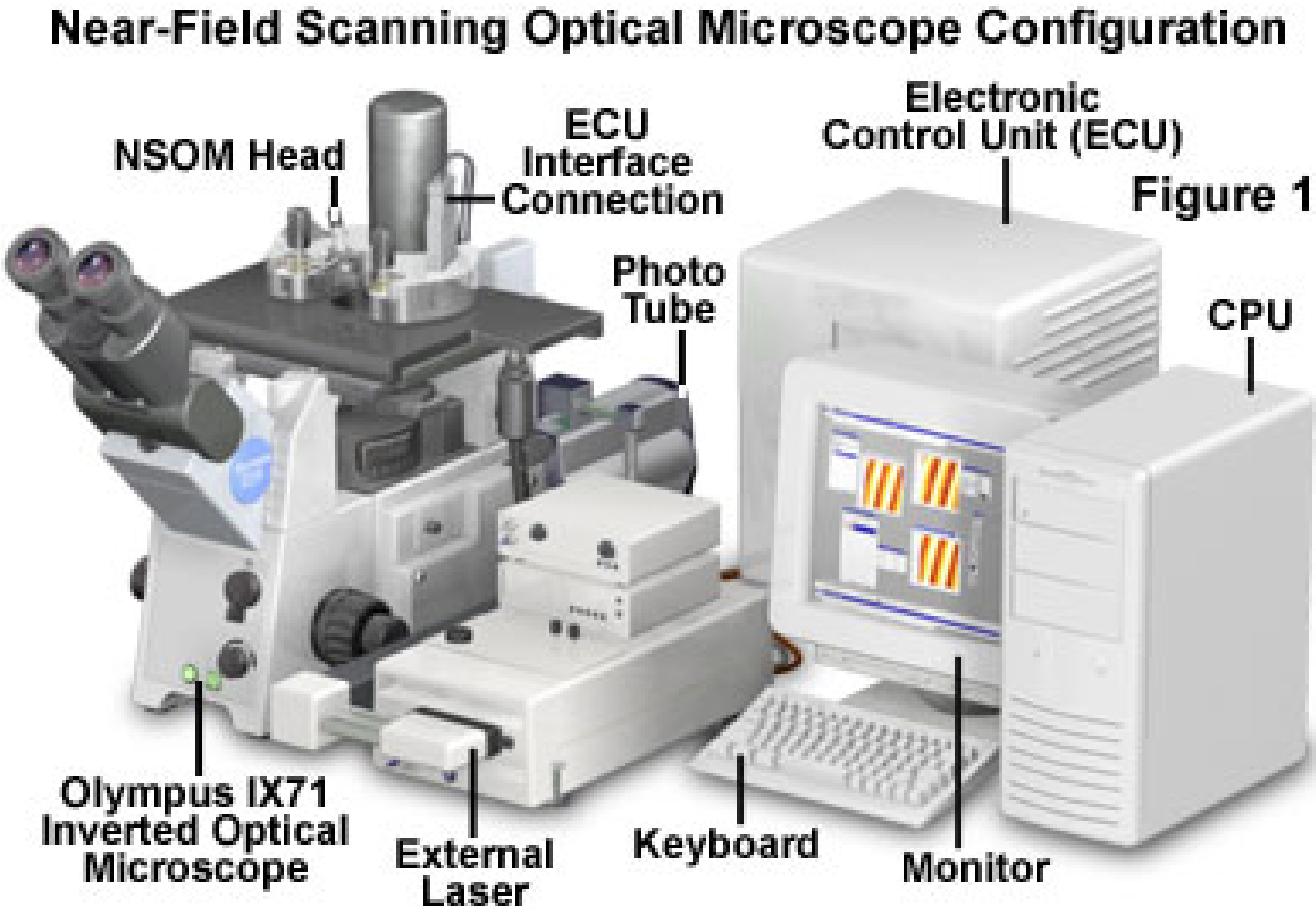


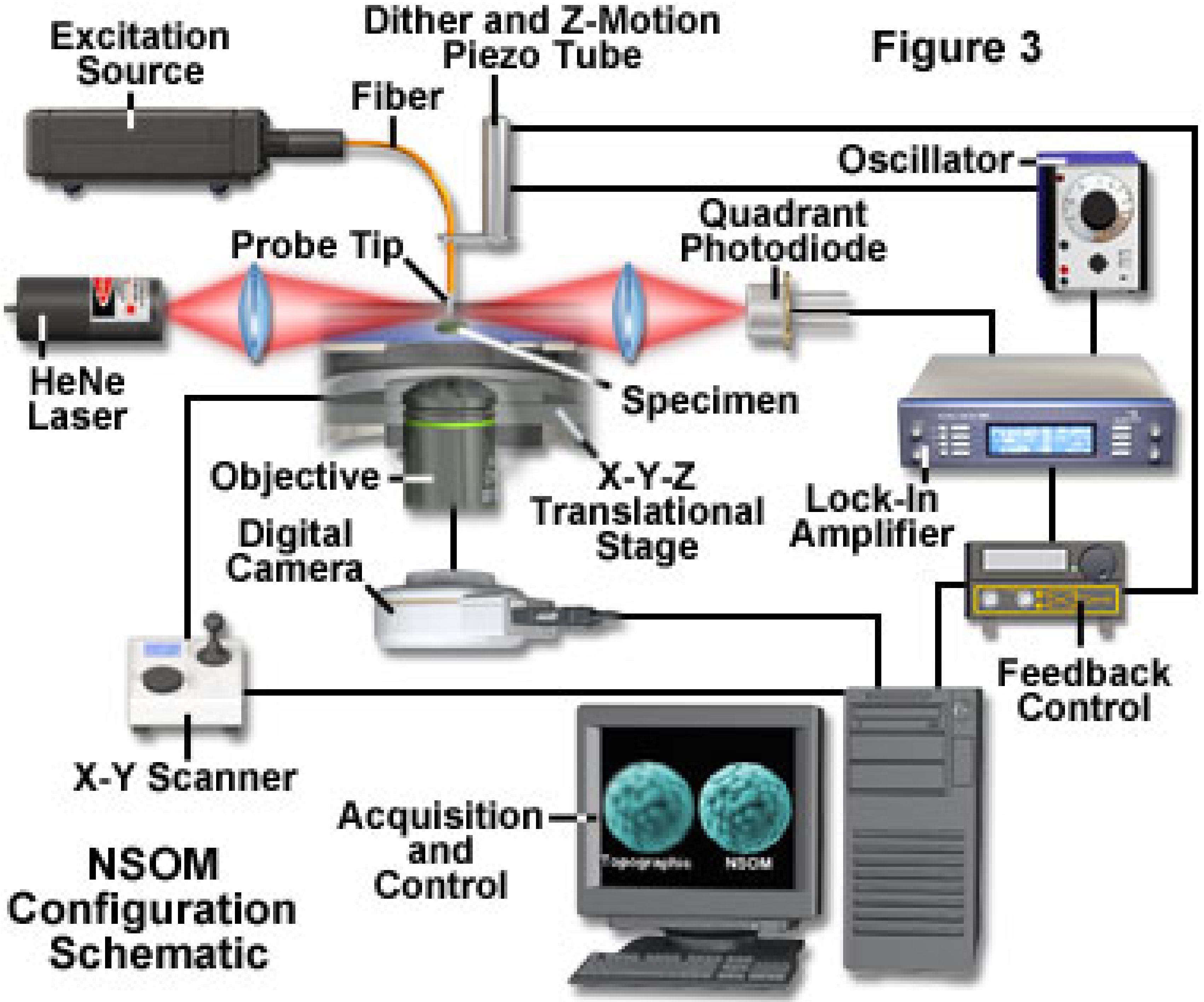
4x4 mm image of protein dots printed using a Nanopipette



Defect before and after repair using laser ablation

Olympus NSOM system




Excitation Source
Dither and Z-Motion Piezo Tube
Figure 3
Fiber
Oscillator
Quadrant Photodiode
Probe Tip
HeNe Laser
Specimen
Objective
X-Y-Z Translational Stage
Lock-In Amplifier
Digital Camera
Feedback Control
X-Y Scanner
Acquisition and Control
NSOM
NSOM Configuration Schematic

Aperture-less probes

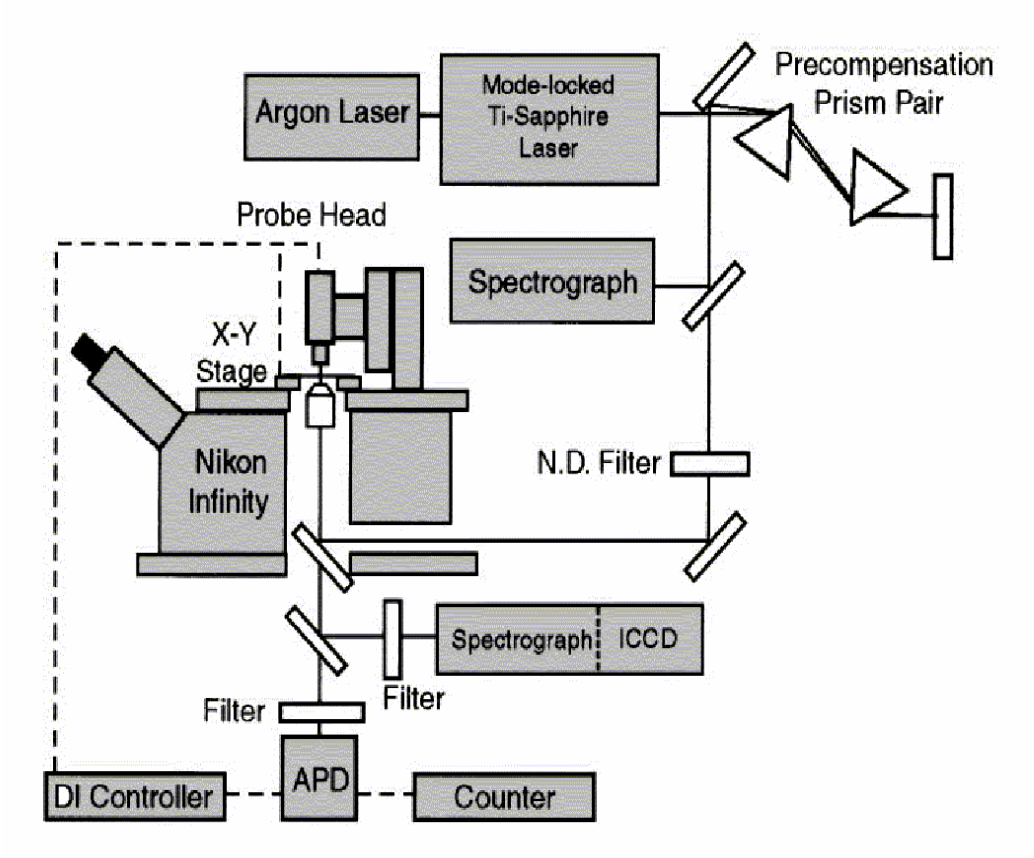
Aperture-less probes

- Origin objective: increase the resolution.
  - 50nm is not good enough at lots of cases.

- First report from H. Kumar Wickramasinghe at IBM lab (1995)
  - 1nm resolution claimed.

- “Tip enhanced near-field optics” concept:
  - A shape laser-illuminated metal tip can generate a enhanced electrical field and becomes a nanoscopic light-source.

A example of aperture-less NSOM



“*Near-Field Fluorescence Microscopy Based on Two-Photon Excitation with Metal Tips*”, E.J. Sanchez, L. Novotny, and X. S. Xie, Phys. Rev. Lett. 82, 4014

Aperture-less NSOM

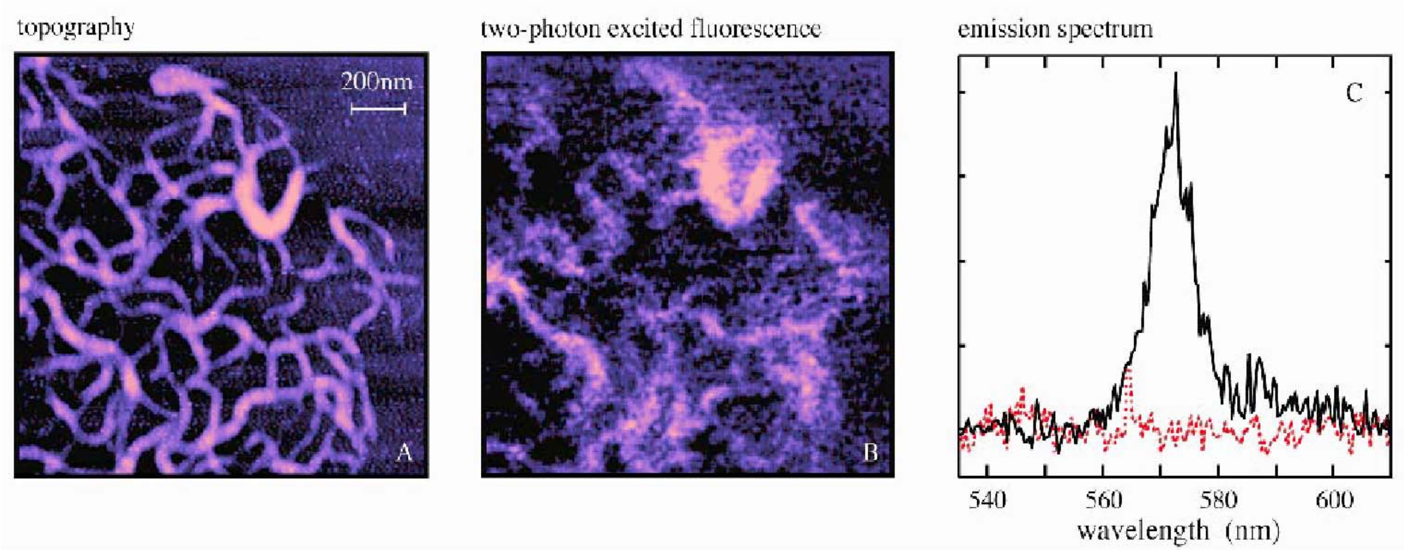


Fig. 9. Simultaneous topographic image (a) and near-field two-photon excited fluorescence image (b) of J-aggregates of PIC dye in a PVS film on a glass substrate. (c) Corresponding fluorescence emission spectrum obtained with (solid line) and without (dashed line) the tip.

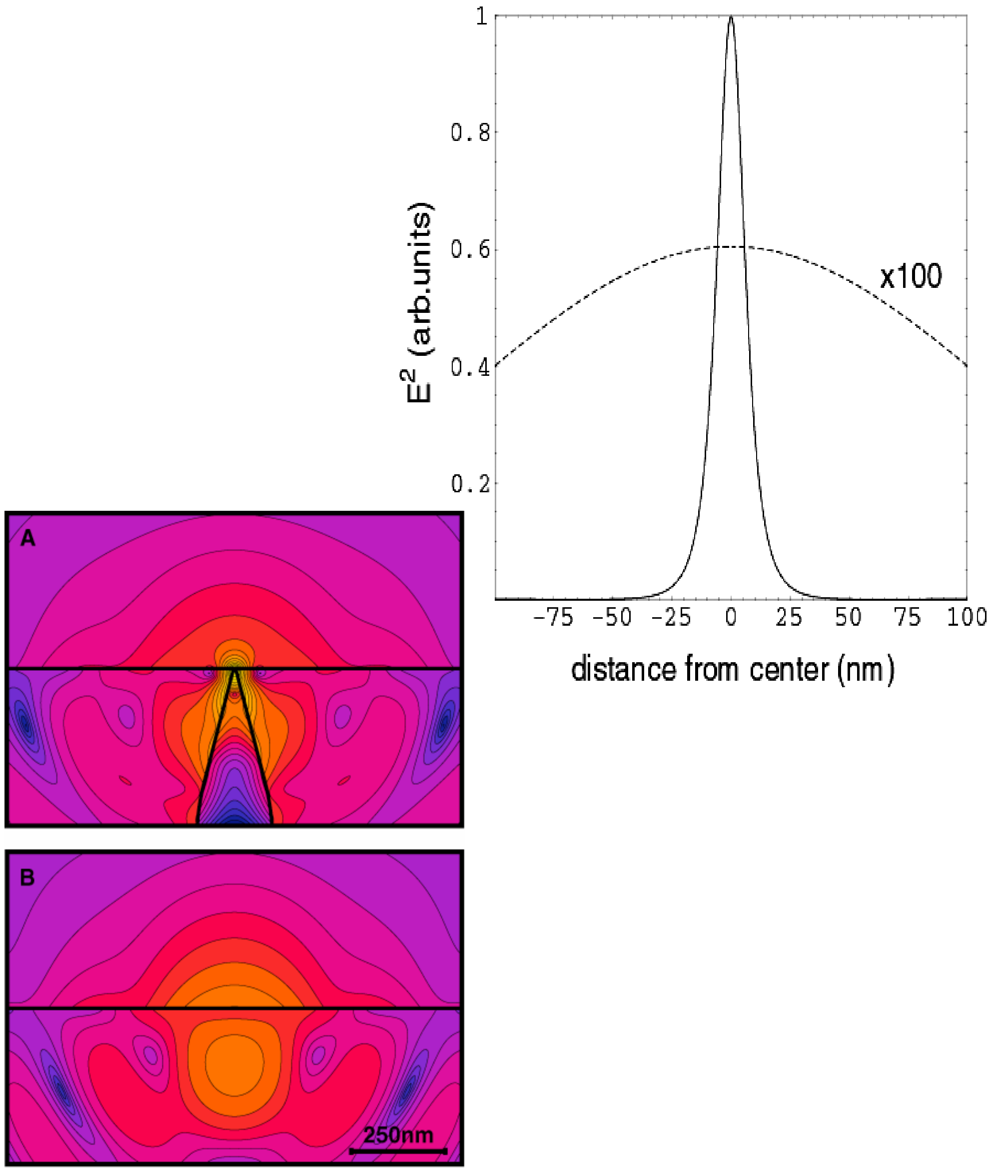
- Two-photon interaction process.
- Fluorescence spectrum is measured.
- 10nm resolution claimed.

Electric field tip enhancement

- Why can a nano-scale metal enhance the electric field: Plasmon resonance.
  - The incident light drives the free electrons in the metal along the direction of polarization. While the charge density is zero inside the metal at any instant of time (*div* $\boldsymbol{E}=0$), charges accumulate on the surface of the metal. The surface charges form an oscillating standing wave (surface plasmons) with wavelengths shorter than the wavelength of the illuminating light.

Electric field tip enhancement

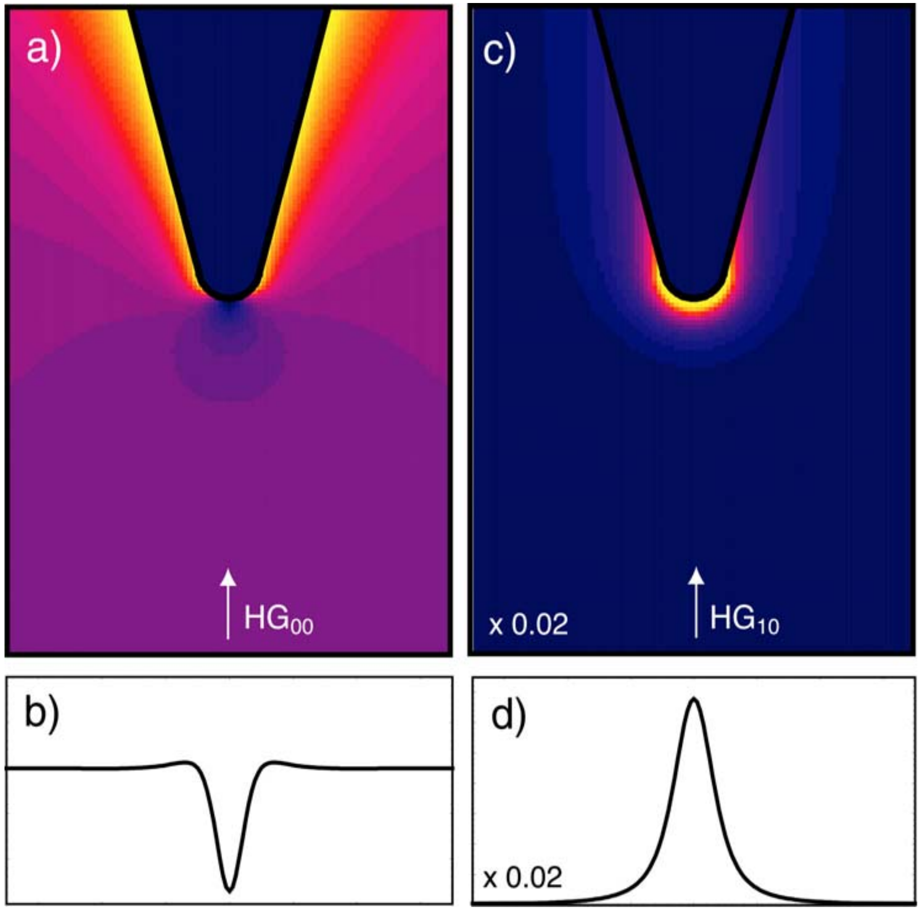
- Strong enhancement.



Calculated field distribution (E2, factor of 2 between adjacent contour lines) for a focused, radially polarized laser beam incident on a dielectric/air interface: (A) with a tip-like aluminum particle close to the interface, (B) without the particle. The boundaries between different media are indicated by solid lines. The metal tip attracts the fields and concentrates them towards the interface. The following parameters were used: wavelength = 800nm, numerical aperture = 1.789, dielectric constant of lower space = 3.2, dielectric constant of upper space = 1, dielectric constant of aluminum tip = -24.1 + i 1.5, end diameter of tip = 10nm, distance of tip from interface = 5nm. (C) Fields evaluated 1nm above the interface with (solid line) and without (dashed line) the metal tip. The peak field strength for the case with tip is ~165 times stronger than without the tip. The full-width at half maximum (FWHM) with tip is on the order of the tip diameter (10nm), without a tip diffraction limited spot is ~300nm.

Electric field tip enhancement

- Polarization Dependence.



Calculated near-field of a gold tip (5nm tip radius) irradiated at λ =810nm with two different focused laser modes along the tip axis. a,b) Gaussian laser mode, and c,d) Hermite-Gaussian (1,0) mode. a,c) show plots of the electric field intensity (E2) and b,d) are linecuts of a,c) evaluated on a transverse line 1nm beneath the tip. The field enhancement is driven by the electric field polarized along the tip axis (longitudinal field). This field is zero for an on-axis Gaussian laser mode whereas it can become stronger than the transverse field for a HG10 mode. Calculations based on the Multiple Multipole (MMP) method.

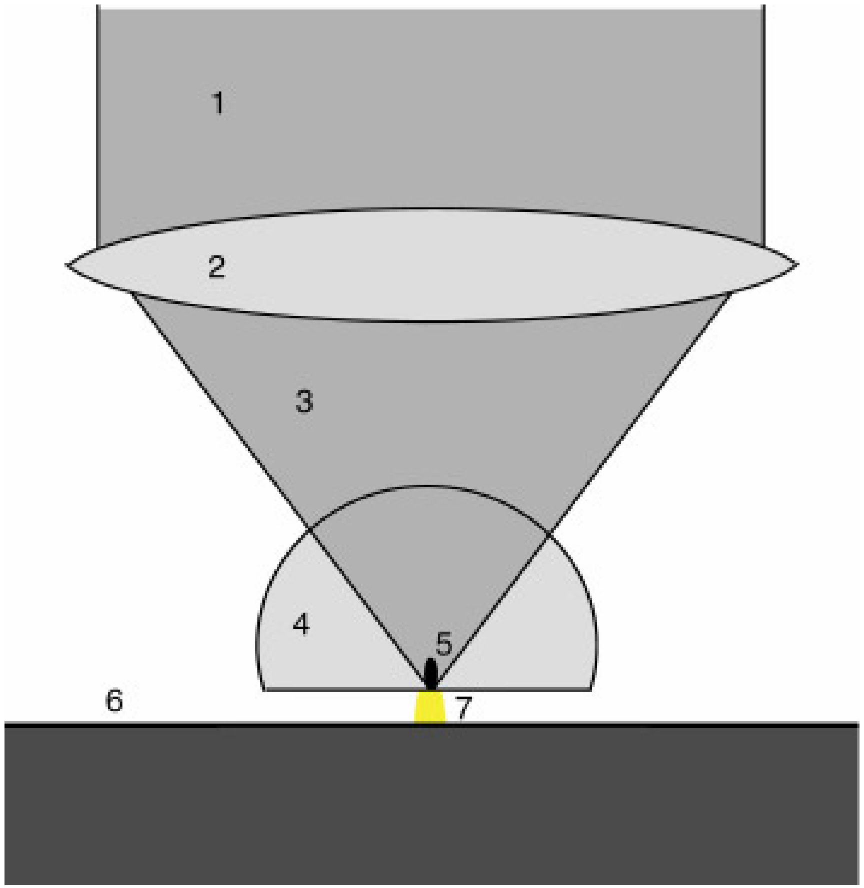
Electric field tip enhancement

- Other tip conditional Dependences:
  - Size: smaller than $\lambda/10$
  - Shape: elongated shape, tetrahedral shape,
  - Materials: Aluminum, Gold, Silver show good results.

Ref. “Strength of the electric field in apertureless near-field optical microscopy”, Y. C. Martin, H. F. Hamann, and H. K. Wickramasinghe”, J. Appl. Phys. 89, 5774 (2001)

Our proposal at NSF:

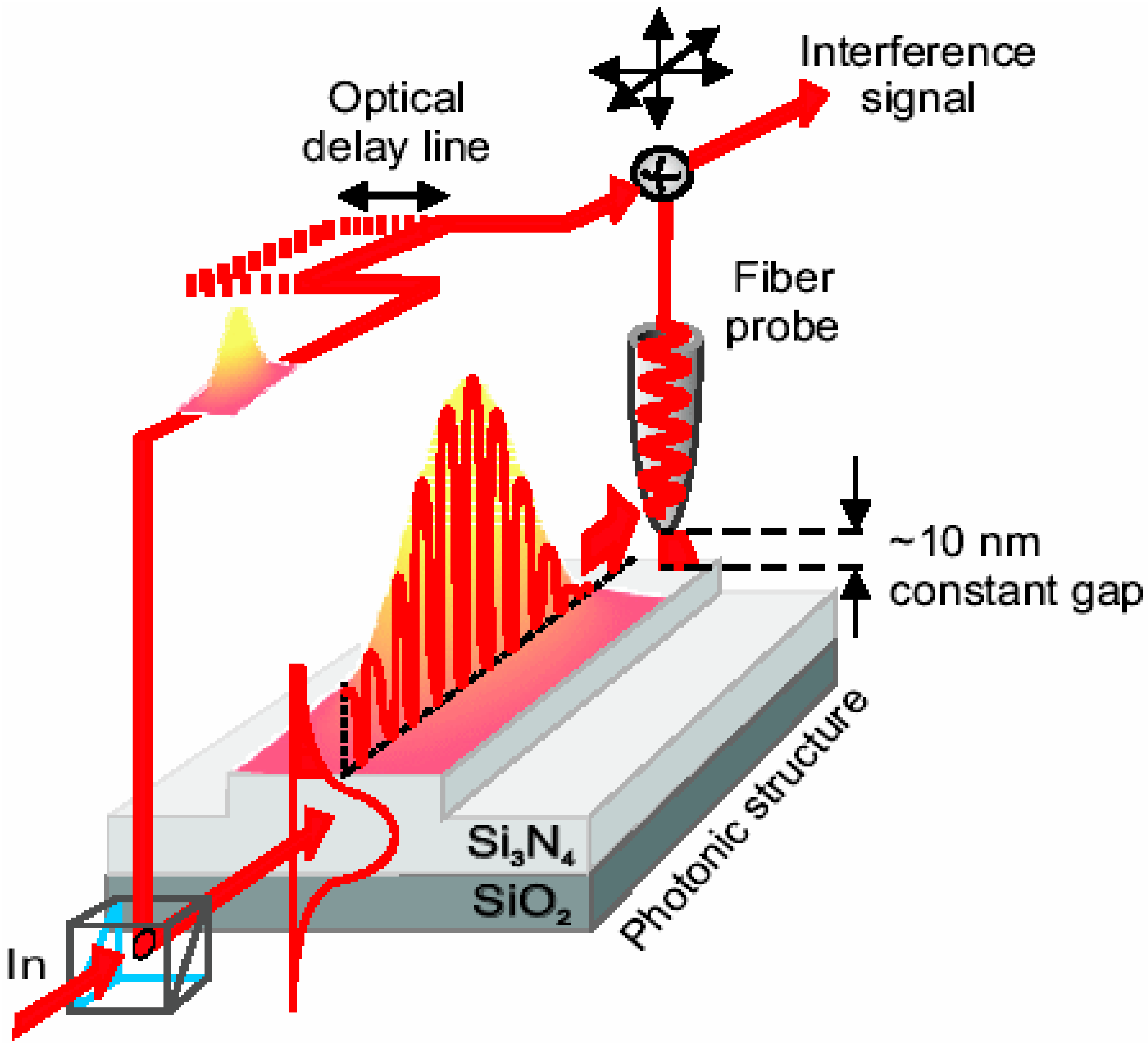
Idea: To combine the Solid Immersion Len (SIL) with tip enhanced optical field.



Combination of SIL with local field enhancement. (1) incoming laser light with a mode profile that provides an electric field in its focal region perpendicular to the surface of the optical element, (2) focusing lens, (3) focused laser light, (4) optical element, (5) small structure able to locally enhance the electric field of the incoming laser light, (6) sample surface to be optically interacted with, (7) localized optical interaction.

Tip enhanced SIL system:

- Keep the strong output of SIL, good for spectrum measurements.
- Increase the resolution (10nm) with Tip Enhanced optical field.



Interference
signal
Optical
delay line
Fiber
probe
~10 nm
constant gap
Si_3N_4
SiO_2
Photonic structure
In