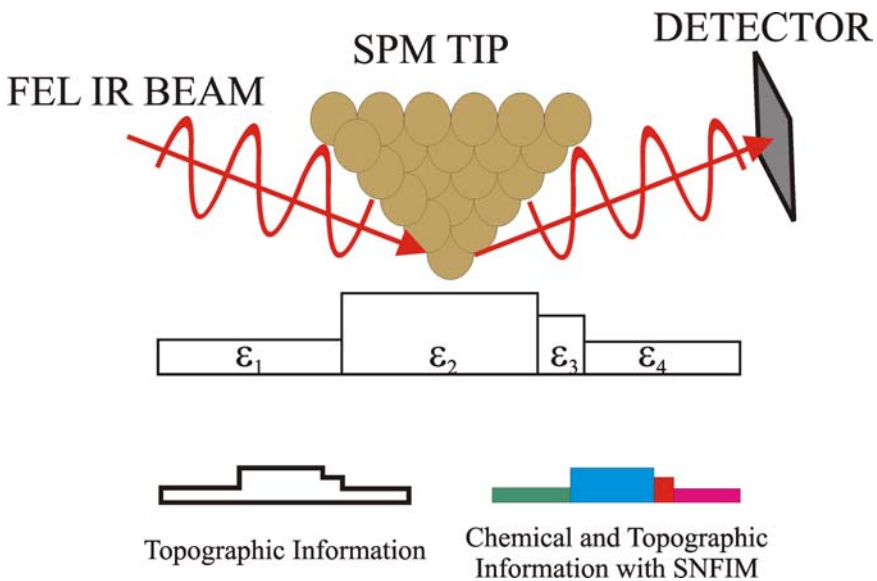
Scanning Near-Field Infrared Microscopy (SNFIM)
LPC, Newport News, VA, January 17, 2002

Edward Gillman (gillman@jlab.org)



Scanning Near-Field Optical Microscope (SNOM)

- The scanning near-field optical microscope (SNOM) is capable of revealing features smaller than the diffraction limit because it relies on near-field probing rather than beam focusing.
- Antenna
  - Micropipette tips
  - Transparent AFM tips
  - Optical Fibers (Wave Guides)
  - Opaque AFM Tips (Apertureless Probes)
- Sensitive Detector or Detector Array

Scanning Near-field Optical Microscope (SNOM)

E. Betzig, J. K. Trautman, T. D. Harris, J. S. Weineran and R. L. Kostelak, Science **251**, 1468 (1991).

- SEM
- Optical Microscope
- SNOM
- SNOM (Fourier Filtered)

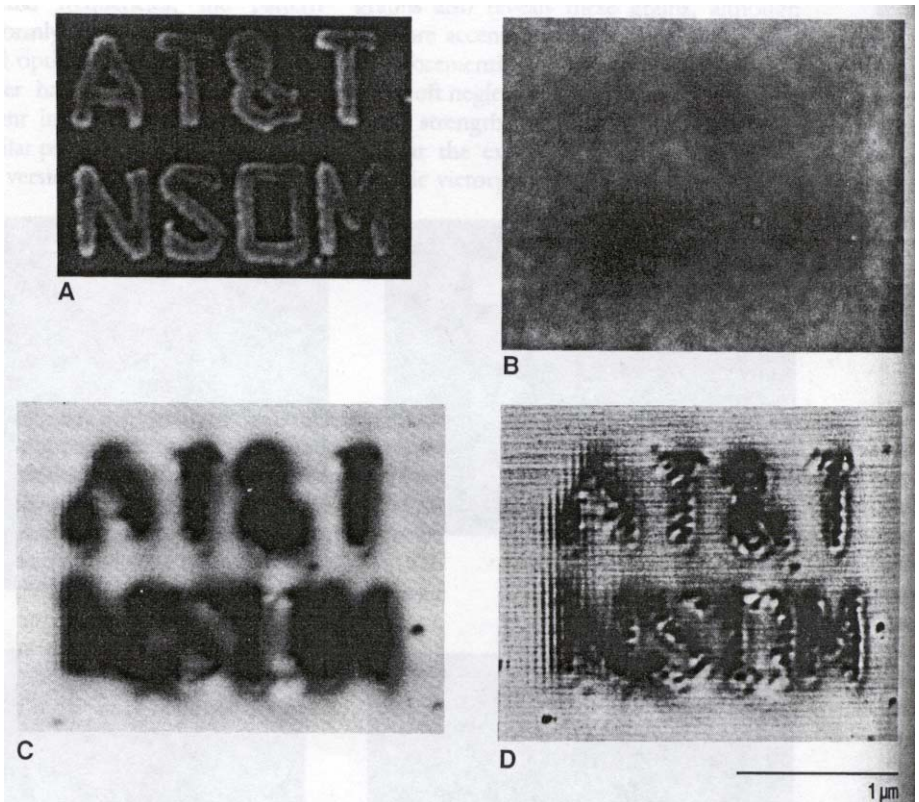
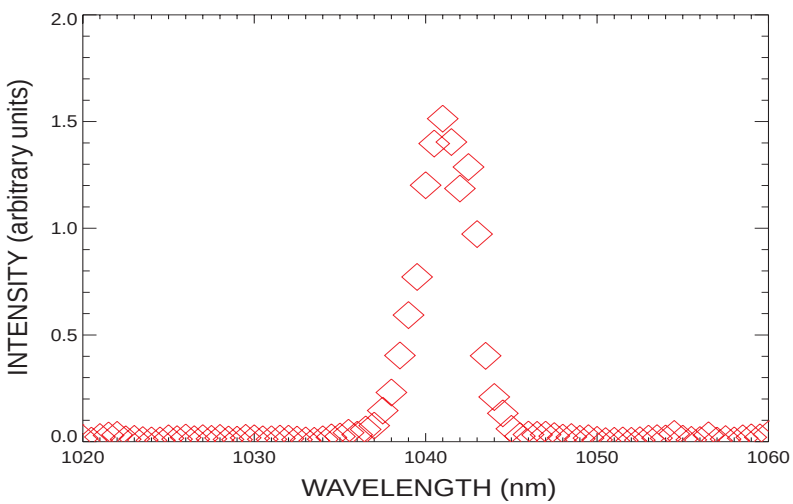


Fig. 1. Images of a test pattern as obtained by (**A**) scanning electron microscopy; (**B**) conventional optical microscopy (100×, 0.9NA objective in transmission); (**C**) NSOM (unprocessed, λ = 514.5 nm); and (**D**) NSOM (after Fourier deconvolution). Vertical lines at the left of (**C**) and (**D**) are artifacts caused by high speed scanning. The frame time was 1 s.

A Near-Field Example We Have Already Used! Harmonic Lasing of the FEL

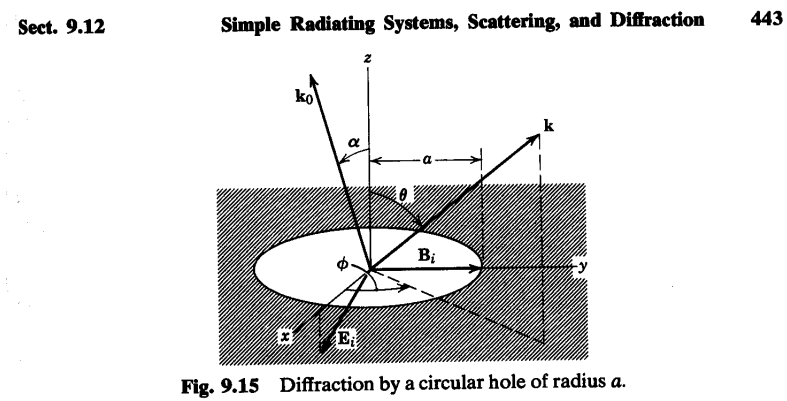
Spectrum observed from fifth harmonic lasing of the IR-DEMO FEL



Fundamental = 5164nm

λ = 1041nm

$\Delta\lambda/\lambda = .38\%$



Classical Electrodynamics, 2nd Ed., J. D. Jackson, John Wiley and Sons (1975).

For ka << 1 and normal incidence

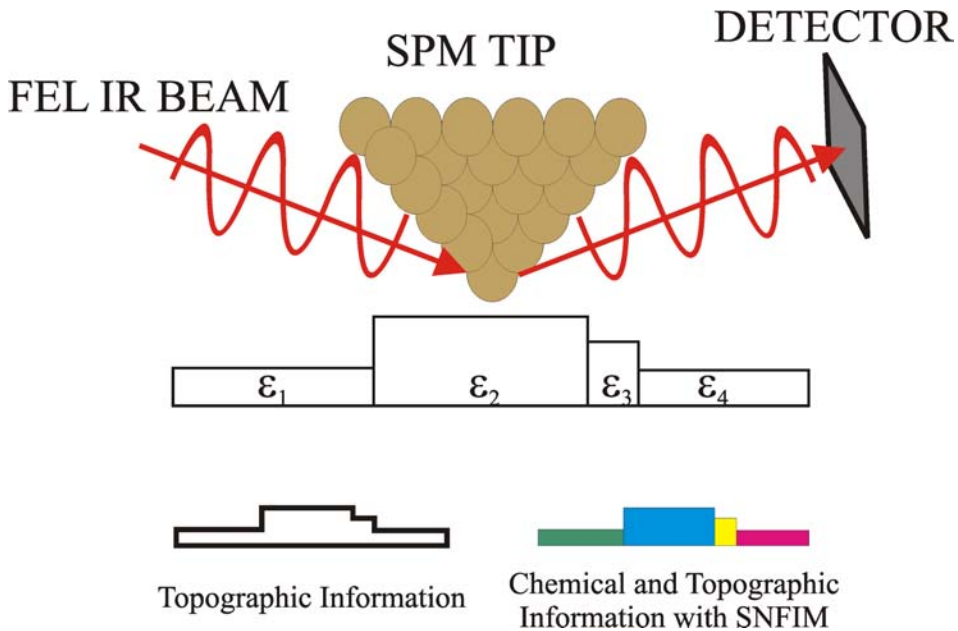
$$T = \int_0^{\pi/2} J_1^2(ka\sin\theta)\left(\frac{2}{\sin\theta} - \sin\theta\right)d\theta$$

$$= 1 - \frac{1}{ka}\sum_{m=0}^{\infty} J_{2m+1}(2ka)$$

Apertureless Scanning Near-field Optical Microscope (SNOM)

Optical Antenna

At sufficiently high frequencies any inhomogeneties exposed to a field becomes a source of radiation; an antenna. This radiation can be detected many wavelengths from its origin in the far-field. In the far-field the scattering observed depends on the on near-field zone that surrounds the source, its dielectric and magnetic properties and the mode of excitation.



Complex Dielectric Constant

For N molecules per unit volume and f_i electrons per molecule with binding frequency ω_i and damping constant γ_i:

$$m\left[\ddot{\mathbf{x}} + \gamma\dot{\mathbf{x}} + \omega_0^2\mathbf{x}\right] = -e\mathbf{E}(\mathbf{x},t)$$

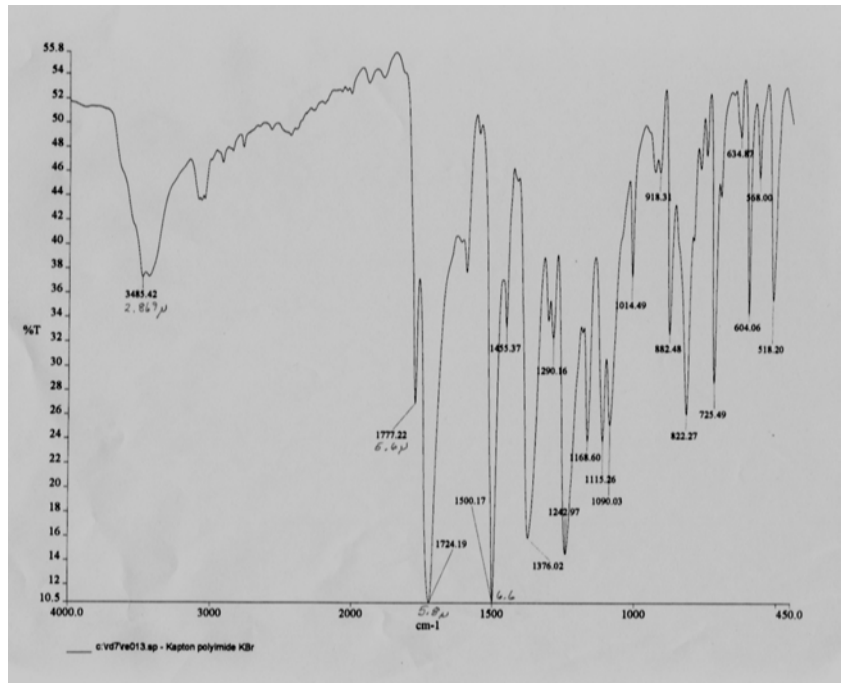
$$\mathbf{p} = -e\mathbf{x} = \frac{e^2}{m}\left(\omega_0^2 - \omega^2 - \mathrm{i}\omega\gamma\right)^{-1}\mathbf{E}(\mathbf{x})$$

$$\mathbf{E} = \mathbf{E}(\mathbf{x})e^{-i\omega t}$$

$$\varepsilon(\omega) = 1 + \frac{4\pi \mathrm{Ne}^2}{\mathrm{m}}\sum_i f_i\left[\omega_i^2 - \omega^2 - \mathrm{i}\omega\gamma_i\right]^{-1}$$

$$\varepsilon(\omega) = 1 + 4\pi\chi_{\mathrm{e}}$$

$$\sum_{\mathrm{i}} \mathrm{f_i} = \mathrm{Z}$$



Principles of the SNFIM Experiment

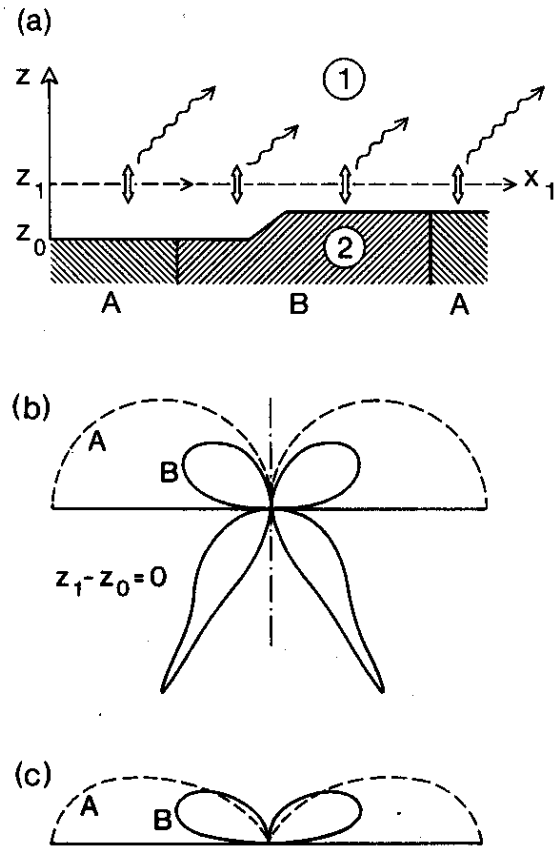


Fig. 7.10. **(a)** SNOM principle: radiation power from point light source depends on immediate environment (materials A, B; gap width $z_1 - z_0$). **(b, c)** Polar diagrams of radiation patterns of vertical electric dipoles next to a perfect conductor (dashed curves, "A") and a dielectric $\tilde{\varepsilon}_2 = 4$ (solid curves, "B"). The gap width is zero in (b), and $\lambda/4$ in (c). Part (a) from [7.19], parts (b) and (c) from [7.41]

- M.J.O. Strutt, Ann. Physik, **V I**, 721-772 (1929).
- D. W. Pohl Scanning Near-Field Optical Microscopy (SNOM), in *Advances in Optical and Electron Microscopy*, 241-243

Scattering and Extinction Cross-section

B. Knoll and F. Keilmann, Nature **399**, 134 (1999).

$$\sigma = f(k_\alpha, \varepsilon_s, \varepsilon_t, d, a)$$

$$\alpha_\perp^{eff} = \frac{\alpha(1+\beta)}{1-\left[\frac{\alpha\beta}{16\pi(a+d)^3}\right]}$$

$$\beta = \frac{\varepsilon_{sample}-1}{\varepsilon_{sample}+1}$$

$$\alpha = 4\pi a^3 \frac{\varepsilon_{tip}-1}{\varepsilon_{tip}+2}$$

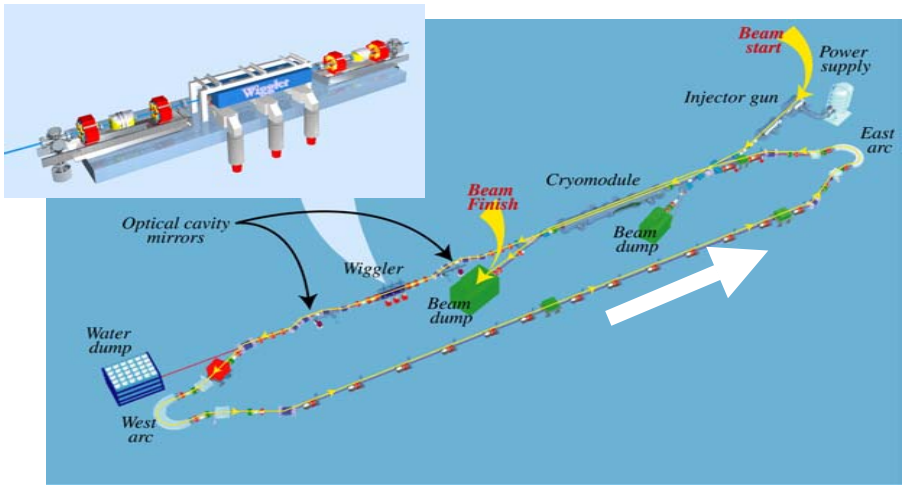
a = tip radius
d = tip sample distance

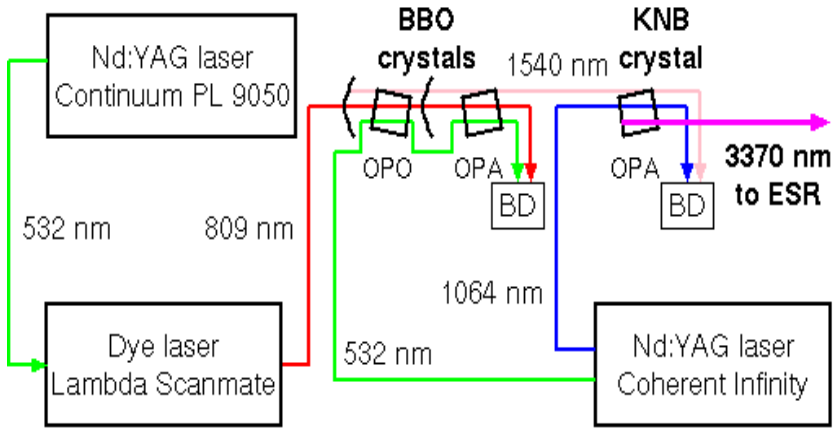
$\lambda > d$
$\lambda \approx d$
$\lambda < d$

$$\sigma = \frac{k^4 \left|\alpha_\perp^{eff}\right|^2}{6\pi} + k\,\mathrm{Im}\left(\alpha_\perp^{eff}\right)$$

Light Sources

Jefferson Lab FEL
Fred Dylla, Friday, 9:40 Room 113
(EL+SE+TF-FrM5)

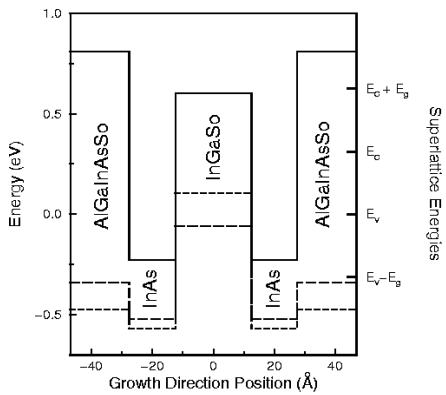




High Power Tunable Infrared Laser Source
M.Würtz[a], S.Borneis[b], T.Kühl[b], F.Laeri[a], T.Tschudi[a]
[a] Institut für Angewandte Physik, TU Darmstadt; [b] GSI Darmstadt

DEOS™ MID-IR-2 RF-excited,frequency-doubled-CO2-waveguide laser system (4.6-5.8 μm)

Quantum Confinement Laser



MID-INFRARED (NARROW GAP) SEMICONDUCTOR LASER EFFORT 2-5 μm - Optical Science and Technology Center – University of Iowa

Scanning Near-field Infrared Microscopy

•A. Piednoir, C. Licope, and F. Creuzet, Opt. Commun. **129,** 414 (1996). - Hollow metal wave guide. (FEL)

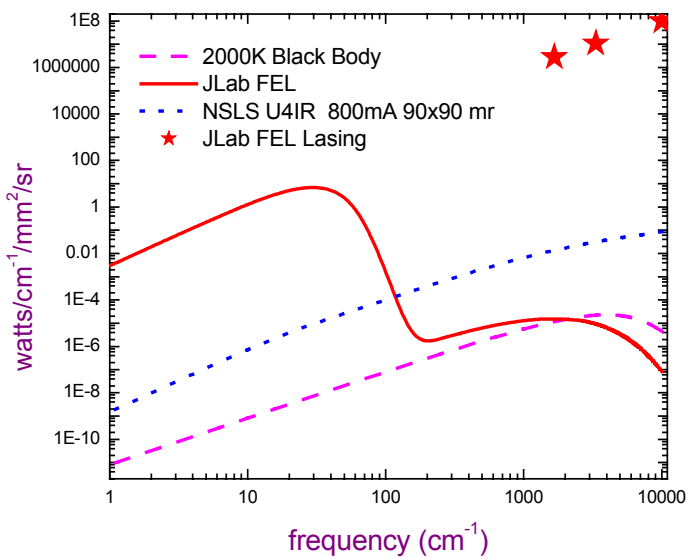
•M. K. Hong, A. G. Jeung, N. V. Dokholyan, T. I. Smith, H. A. Schwettman, P. Huie and S. Erramilli, Nucl. Instrum. Methods Phys. Res. B **144,** 246 (1998). - Application in Biophysics; Imaging single living cells. (FEL).

•C. A. Michaels, S. J. Stranick, L. J. Richter and R. R. Cavanagh, J. Appl. Phys. **88**, 4832 (2000). – Metal coated, tapered single mode fluoride fiber and broad bandwidth, ultrafast IR laser.

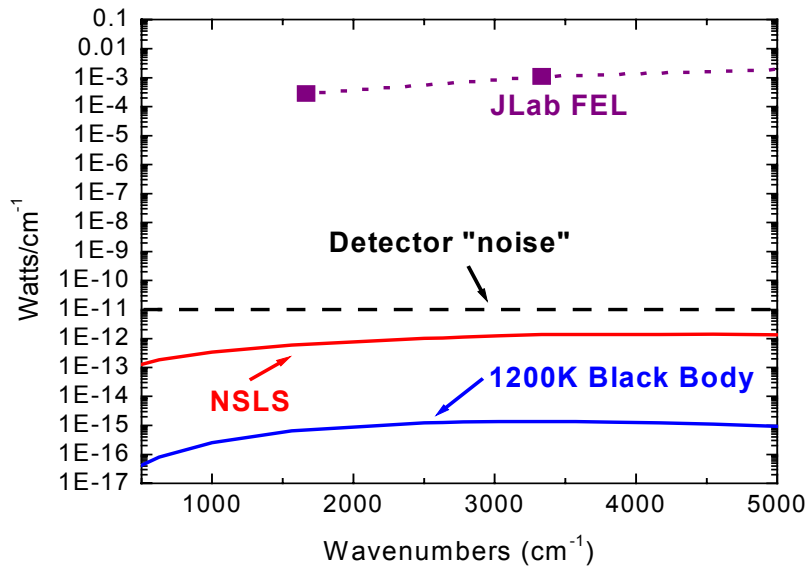
•B. Knoll and F. Keilmann, Nature **399**, 134 (1999). – Tunable CO_2 laser and SPM tip.

Limitations of Light Sources

Brightness of IR Sources



Signal into a 0.01 micron area at f/1



- Coupling of Infrared Radiation to an optical fiber.
- Incident power on an SPM tip resulting in a change of mechanical properties.
- Maximum power into a 10μ spot is ~100mW

Experimental Method

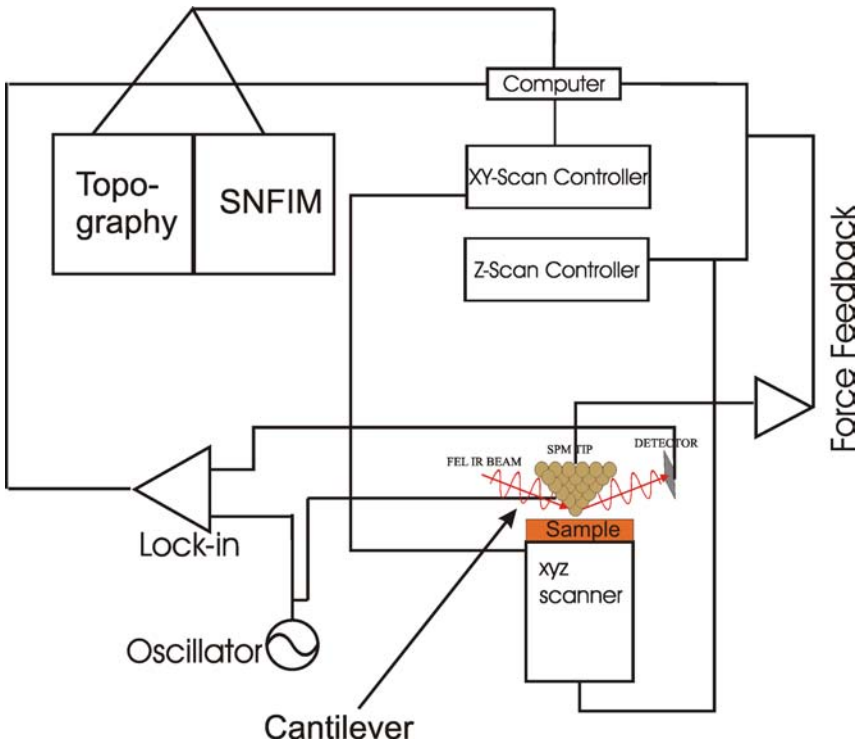
- The proposed experiment will use an aperture-less design based on the work of Knoll and Keilmann[1]. In this experiment infrared radiation incident on a metal-coated AFM tip acts as the antenna. The infrared radiation is scattered into a detector in the far field while a sample is being scanned in close proximity to the tip (near-field).

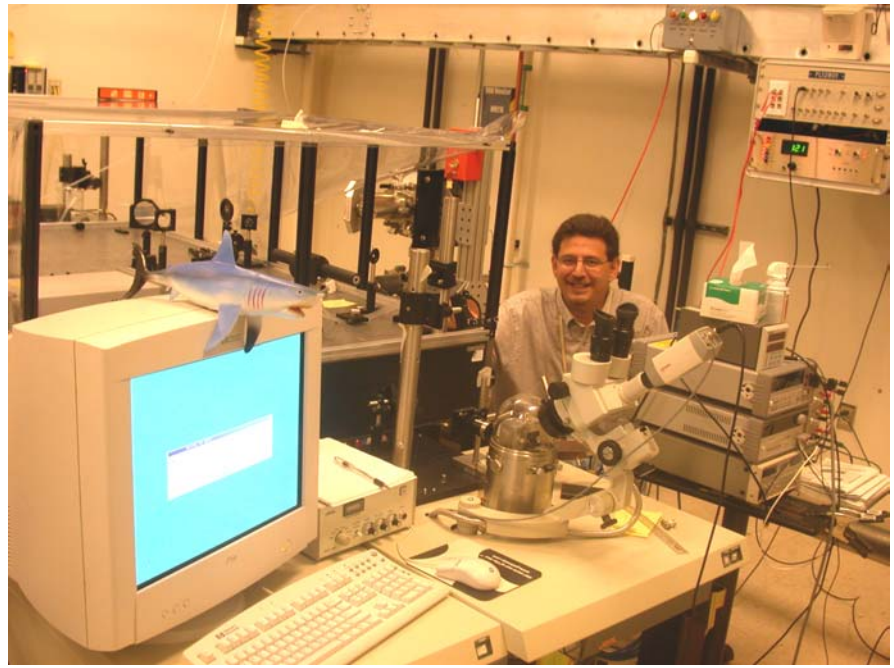
[1]B. Knoll and F. Keilmann, Nature, **399**, 134 (1999).

Experimental Method

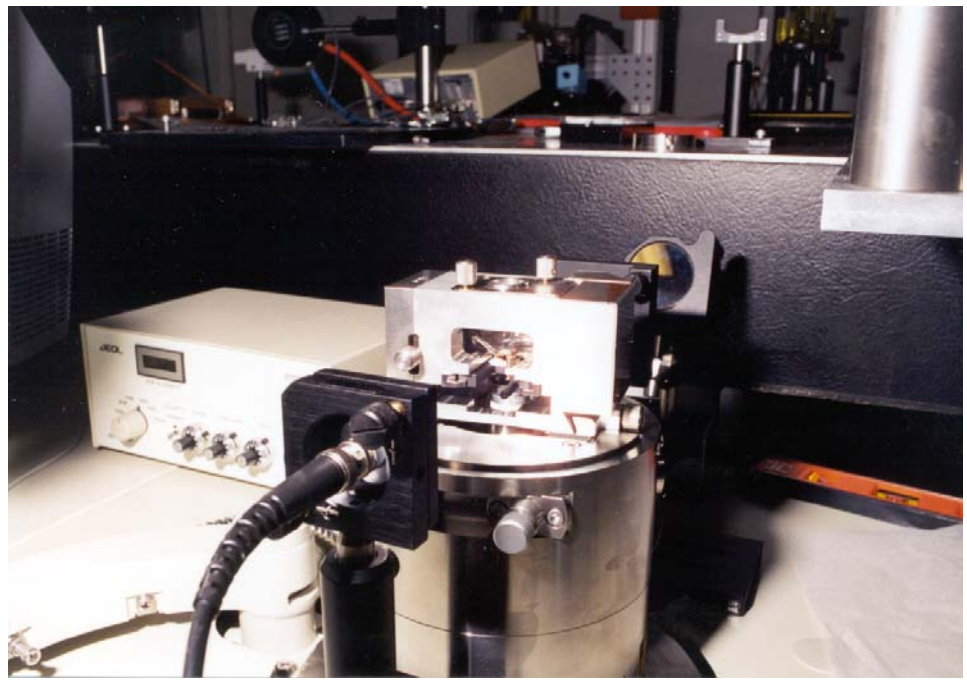
- Two images are collected simultaneously, the AFM image, which reveals structural information about the sample and the infrared image, which supplies chemical information from absorbing species. At the conclusion of the scan the images are superimposed and the chemistry is correlated with the features observed in the AFM scan.

Schematic Diagram



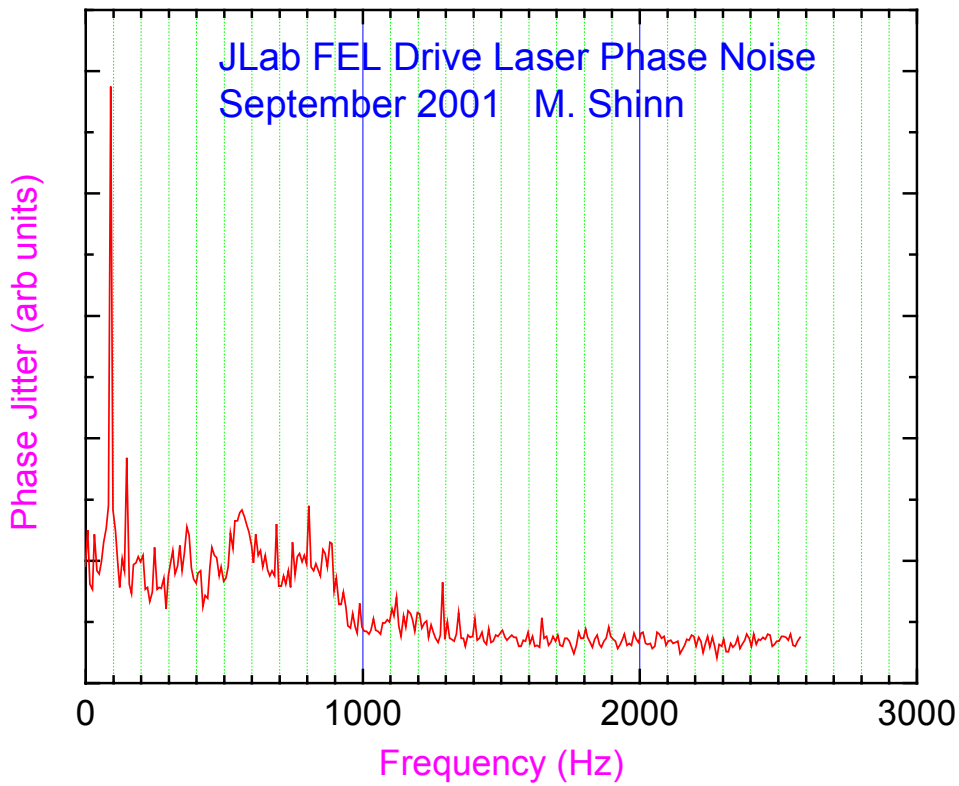


Scanning Near-field Infrared Microscopy

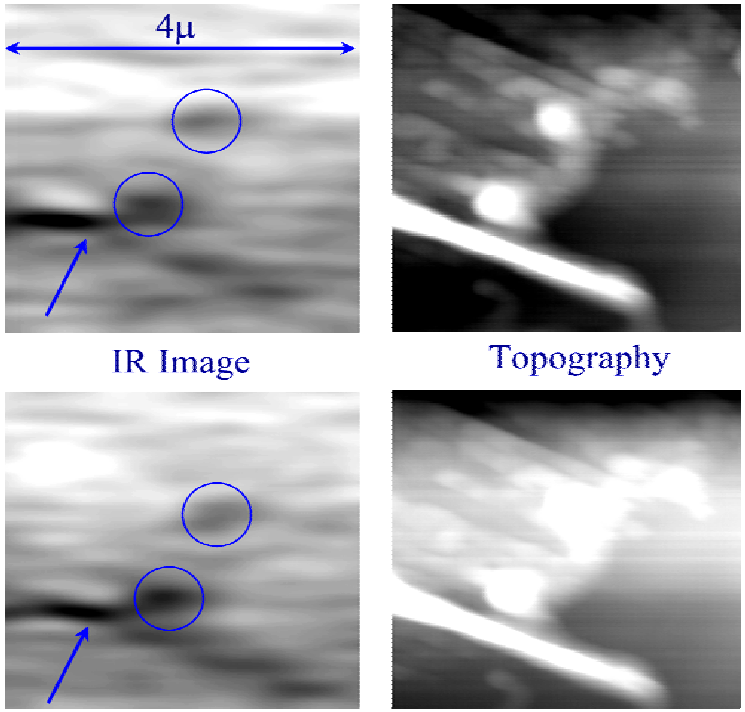


Extracting the Signal

Lock-in Technique: The signal from the infrared detector is modulated by the resonant frequency of the cantilever (~300 kHz), which is set by an external oscillator. The reference from the external oscillator is used by the lock-in to generate a sine wave that is multiplied by the signal from the IR detector.



SNFIM Data MNA*/Si(100)
λ=5140nm



Trial 1

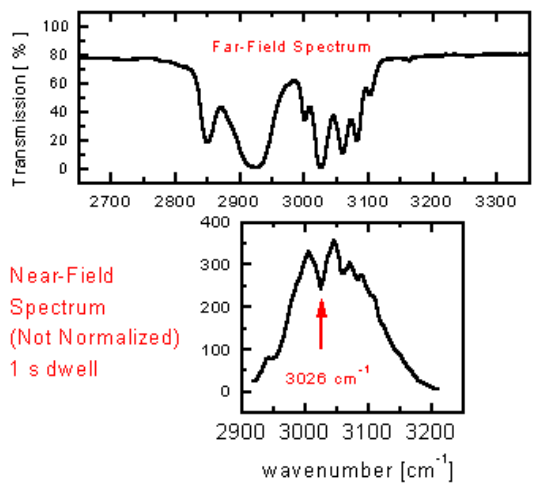
Trial 2

In the micrographs above the images on the left are from the infrared detector. Enhanced contrast due to IR absorption is indicated by the two blue circles and the blue arrow. The fact that this experiment could be repeated is a good indication that this is truly due to IR contrast and is not an artifact of the scan.

*MNA=2-methyl-4nitroanaline

Where do we go from here?

- Improved optics.
- LN2 cooled InSb focal plane array for simultaneous acquisition of infrared spectra.



C. A. Michaels, S. J. Stranick, L. J. Richter and R. R. Cavanagh, J. Appl. Phys. **88**, 4832 (2000).

- New Laser ?
- Wavelength modulation?

SNFIM Acknowledgements

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