Near Field Scanning Optical Microscopy (NSOM)

PH 575 Presentation

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Outline

What is NSOM?

- Near Field Scanning Optical Microscopy (NSOM), also known as Scanning Near-field Optical Microscopy (SNOM), is a microscopy technique that surpasses the diffraction limit of light.
- It uses a subwavelength probe to scan the sample at a very close distance (within the near field).
- Provides high spatial resolution beyond conventional optical microscopes.
- Traditional optical microscopy is limited by diffraction to about half the wavelength of light (≈ 200 nm for visible light).
- NSOM breaks this barrier, achieving resolution in the range of 20-100 nm.
- Enables the study of biological samples, semiconductors, and nanostructures at a higher resolution.

NSOM Setup

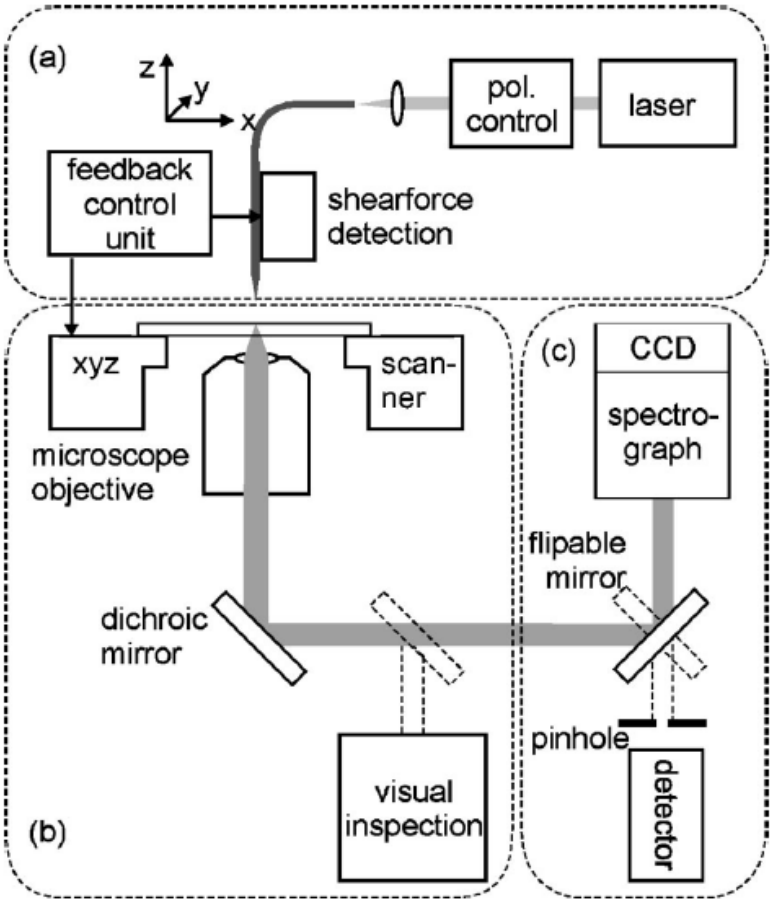


FIG. 2. Standard SNOM setup consisting of (a) an illumination unit, (b) collection and redistribution unit, and (c) a detection module.

Figure: Image taken from J. Chem. Phys. 112, 7761–7774 (2000).

1. Optical Unit: Components

- **Laser Source**:
  - Provides coherent light necessary for near-field measurements.
  - Common types: Semiconductor lasers.
- **Optical Fibers**:
  - Transmits laser light to the SNOM probe with minimal loss.
  - Can be single-mode or multi-mode, depending on application.
- **SNOM Probe**:
  - Equipped with a sharp tip (typically made of metal) for near-field interaction.
  - Small aperture size (10-100 nm) to achieve high spatial resolution.
- **Shear Force Sensor**
  - Used for feedback mechanism

2. Scanning Stage Unit

- **High-Precision Scanning Stage**:
  - Allows for three-dimensional movement of the SNOM probe.
- **Feedback Mechanisms**:
  - Ensures consistent distance from the sample for accurate measurements.
- Moves the probe relative to the sample in a controlled manner.
- Maintains optimal height for accurate near-field measurements using real-time feedback.
- Capable of rapid scanning over large areas while maintaining high precision.
- Ensures the probe tip remains within the near-field zone for effective signal collection.

Feedback Mechanism in the Scanning Stage

- **Purpose**:
  - Maintain optimal probe-sample distance for accurate measurements.
- **Types of Feedback Mechanisms**:
  - **Tunneling Current Feedback**:
    - Monitors tunnelling current to keep a constant distance.
  - **Shear Force Feedback**:
    - The fiber probe is vibrated at its mechanical resonance parallel to the sample surface
    - Amplitude and phase of the fiber's oscillation are monitored using a suitable displacement sensor
    - As the probe approaches the sample (0–20 nm), shear forces cause a detuning of the resonance frequency, resulting in a decrease in amplitude and a phase shift
- **Benefits**:
  - Ensures stability and enhances resolution.
  - Improves accuracy by compensating for position deviations.

3. Detection and Data Acquisition Unit

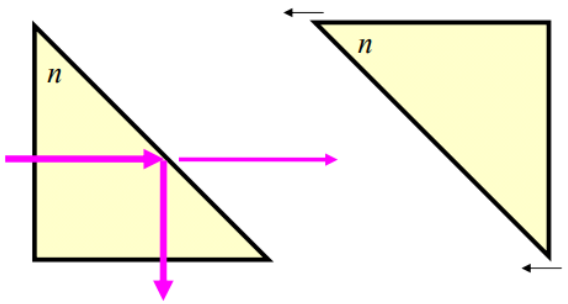
- **Components**:
  - Detectors (e.g., PMTs)
  - Signal processing electronics
  - Data acquisition systems
- **Function**:
  - Collects light emitted/scattered from the sample
  - Converts intensity into electrical signals for analysis and image formation
- **Transmission Mode:**
  - The light is transmitted through the sample
  - Useful for thin samples or transparent materials
  - Provides information about the internal structure and properties
  - Typically used in studies of layered materials and biological samples
- **Reflection Mode:**
  - Detects light reflected from the sample surface
  - Ideal for opaque materials where light cannot pass through

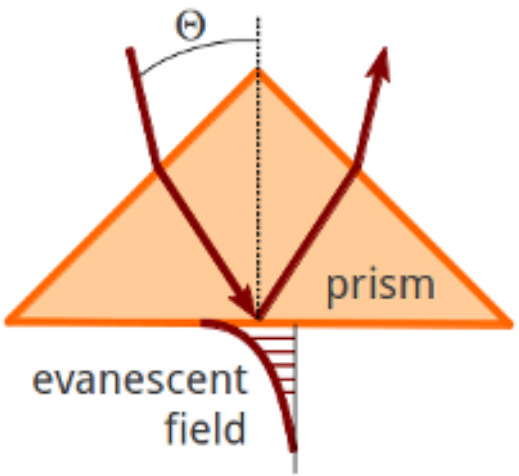
Detection Modes in SNOM (Cont.)

- **Reflection Mode:**
  - Provides surface topography and optical property information
  - Can reveal features like roughness and composition differences
- **Collection Mode:**
  - The probe collects scattered light from the sample surface
  - Sensitive to local features and can detect changes in optical properties
  - Useful for studying localized phenomena such as fluorescence and surface plasmon resonance
  - Enables high-resolution imaging of nanostructures and biomolecules
- **Comparison of Modes:**
  - Each mode has specific applications and advantages depending on the sample type
  - Modes can be combined for multi-modal imaging, enhancing the depth of analysis

A thought Experiment

Suppose I have a glass prism, oriented as shown, with a laser beam undergoing total internal reflection from the internal surface.
Question: at what point do I see a transmitted beam?
Answer: when the prisms are close together, but not yet touching!





Evanescent Waves and Optical Resolution

- **Evanescent Waves:**
  - Generated when light undergoes total internal reflection (TIR) at an interface.
  - Characterized by an exponentially decaying amplitude in the near-field region.
  - Electric and magnetic fields in a harmonic wave can be described as:

$$E = E_0 e^{i(k\cdot r - \omega t)}, \quad H = H_0 e^{i(k\cdot r - \omega t)}$$

- **Total Internal Reflection (TIR):** Occurs when light incident on an interface exceeds the critical angle:

$$\sin\theta_c = \frac{n_2}{n_1}$$

where n_1 and n_2 are the refractive indices of the media, and θ_c is the critical angle.

Evanescent Waves and Optical Resolution

- **Evanescent Wave Equation:** For angles greater than the critical angle, the transmitted wave becomes evanescent, with an exponentially decaying amplitude:

$$E_t = E_0 e^{-\alpha y}$$

where $\alpha = k_t \sqrt{\sin^2\theta - \left(\frac{n_2}{n_1}\right)^2}$ is the decay constant.

- **Skin Depth:** The skin depth δ in the visible spectrum (e.g., for metals) is given by:

$$\delta = \frac{1}{\alpha}$$

Typical values for the skin depth in good conductors are around 10 nm in the visible spectrum.

Working Principle of NSOM

- NSOM captures near-field evanescent waves, which decay quickly over distance but carry high spatial frequency information.
- A nanoscale probe is placed extremely close to the sample, within a few nanometers, to detect these near-field interactions.
- The probe interacts with the sample, converting damped waves into propagating waves, which are then detected to form a sub-wavelength resolution image.
- The probe in NSOM is often a tapered optical fiber coated with metal, with apertures as small as 10-100 nm. For aperture SNOM, the resolution is determined by the probe's aperture, while apertureless SNOM relies on scattering at a sharp tip.
- In a nutshell, Light interacts in the near-field region, allowing for the detection of light scattered, absorbed, or phase-shifted due to sample interactions, with high-resolution images formed from these localized fields

Probe and Light Interaction

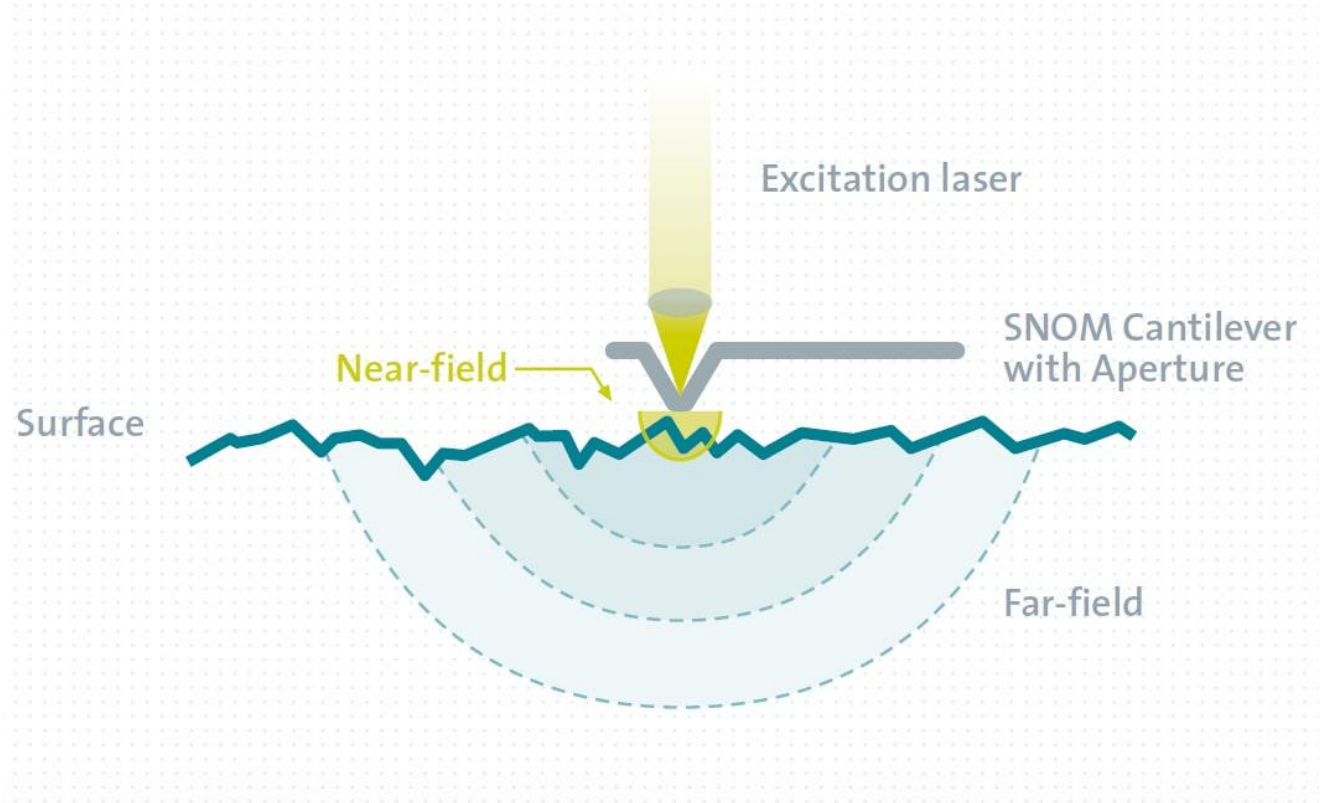


Figure: Probe and Light interaction

Applications of NSOM

- High-resolution imaging of nanostructures and biological samples, with applications in detecting defects, dopants, and molecular structures in semiconductors.
- Combining SNOM with Raman spectroscopy enables high spatial resolution (down to 30 nm) for studying molecular structures and phases.
- Single molecule detection is easily achievable.
- Dynamic properties can also be studied easily at sub-wavelength scales.

Applications of NSOM

SNOM is presented as a powerful tool for the subdiffraction limited chemical and structural characterization of plant cell walls. It provides a detailed knowledge on the macromolecular assembly of plant cell walls.

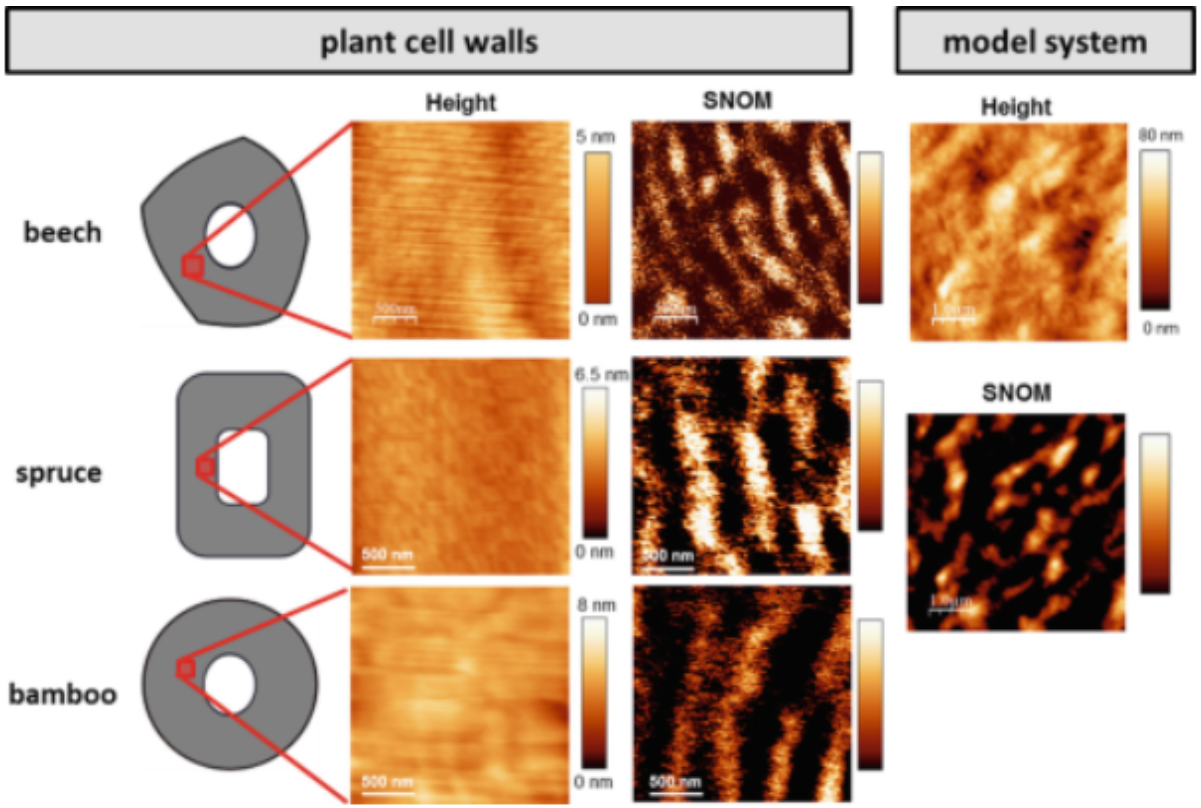


Figure: Analyzing Plant Cell Wall Ultrastructure

Limitations of NSOM

- Probe fabrication, particularly achieving a small and smooth aperture (10-100 nm), is difficult and affects resolution.
- Sample-probe interaction can lead to image artifacts, especially if the tip-sample distance isn't precisely controlled.
- Slow scan rates are a limitation, and the requirement for highly skilled operators further hinders widespread adoption.
- Not conducive for studying soft materials, especially under shear force mode

Recent Developments in NSOM

- Development of aperture-less NSOM for higher resolution.
- Use of plasmonic effects to enhance near-field interactions.
- Hybrid NSOM systems combining AFM for enhanced resolution and contrast.
- Integration of NSOM with spectroscopic techniques for chemical analysis.

Conclusion

- NSOM has proven to be an indispensable tool for studying nano-scale structures that are beyond the resolution of traditional optical microscopy. By capturing near-field light interactions, NSOM offers unmatched spatial resolution for a wide range of applications in material science, biology, and nanotechnology.
- While challenges such as probe fabrication and scan speeds remain, ongoing advancements in probe design, feedback mechanisms, and detection methods are continually improving NSOM's accuracy and resolution

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