Lecture 12 – Nanophotonics in Microscopy

EECS 598-002 Winter 2006
Nanophotonics and Nano-scale Fabrication
P.C.Ku
Schedule for the rest of the semester

- Introduction to light-matter interaction (1/26):
  - How to determine $\epsilon(r)$?
  - The relationship to basic excitations.
- Basic excitations and measurement of $\epsilon(r)$. (1/31)
- Structure dependence of $\epsilon(r)$ overview (2/2)
- Surface effects (2/7):
  - Surface EM wave
  - Surface polaritons
  - Size dependence
- Case studies (2/9 – 2/16):
  - Quantum wells, wires, and dots
  - Nanophotonics in microscopy
  - Nanophotonics in plasmonics
- Dispersion engineering (2/21 – 3/7):
  - Material dispersion
  - Waveguide dispersion (photonic crystals)
**Principles of optical microscopy**

- The information contained in the object/image is carried by the light wave to the detector (e.g. eyes).

- Information = \( F(x, y) \Rightarrow F(k_x, k_y) \)
Optical vs electron microscopy

- Advantages of optical microscopes
  - Photon energy is low (~ eV). Electron energy is high (~10-100 keV)
  - Photon momentum is low (~ 10^-27 kg m/s). Electron momentum is high (~ 10^-23 - 10^-22 kg m/s)
  - Especially good to study optical processes (including nonlinear optical response) in the sample
  - Ultra-short optical pulse is available to study ultra-fast processes
  - Can make the fluorescence work → useful for biological imaging

- Disadvantages of optical microscopes
  - Photon does not have charge. Cannot study the Coulomb interaction in the sample.
  - Photon does not reveal information regarding the chemical composition of the sample (unless we go to the x-ray wavelength).
Resolution limits of optical microscopes

- Small features correspond to large \((k_x, k_y)\) components.
- In traditional optical microscopes, the detector sees the light in the far field region.

\[
\begin{align*}
k^2 &= \omega^2 \mu_0 \varepsilon = k_x^2 + k_y^2 + k_z^2 \\
\Rightarrow \sqrt{k_x^2 + k_y^2} &< \omega n / c \Rightarrow |k_{||, \text{max}}| = 2\pi n / \lambda
\end{align*}
\]

Resolving power
\[
= \frac{\lambda}{(2n)} \equiv \frac{\lambda_{\text{eff}}}{2}
\]

= diffraction limit
Finite-size lens

- In a real system, the cutoff spatial frequency is often limited by the size of the lens which is quantitatively described by a numerical aperture (NA).

\[
\text{NA} \equiv n \sin \theta \\
\Rightarrow \frac{k_{\parallel,\text{max}}}{k} = \sin \theta \Rightarrow k_{\parallel,\text{max}} = \frac{2\pi}{\lambda} \text{NA}
\]

Resolving power \( \rightarrow \)

\[
\lambda / (2\text{NA}) = \lambda_{\text{eff}} / 2
\]

where \( \lambda_{\text{eff}} = \lambda / \text{NA} \)
Resolution enhancement

- Shortening of wavelength:
  - Decrease the wavelength of light source
  - Increase the refractive index (e.g. immersion microscope)
  - Using nonlinear optical effect (e.g. frequency doubling)
  - Increase the detectable spatial frequency
    - Moire grating
    - Near field optics to detect the evanescent waves

Ref: S. Kawata, chapter 2, figure 1.
Scanning Near-field Optical Microscope

Light wavelength ($\lambda$) 500 nm

Probe:
aperture size ($a$) 25-100 nm
evanescent field $a/\pi$
tip-sample gap 5-50 nm

Sample:
feature size $<\lambda$
skin depth 0- $\infty$

Optics:
Far-field detector 1-100 nm
Interference effects $\lambda/4$

Transmission ($\lambda=488$nm)  
Fluorescence ($\lambda>515$nm)
Different modes of SNOM

Ref: Prasad, chapter 3, figure 7.
Detection of near field intensity modulation

- The modulation of the near-field intensity can be detected at the far-field region:

  e.g. Thin slab photon tunneling

\[ d = \frac{\text{wavelength}}{4} \]
Configuration of SNOM

Ref: Prasad, chapter 3, figure 8.
Near-field probes

Ref: S. Kawata, chapter 2, figure 6.

Green: evanescent wave

Ref: S. Kawata, chapter 2, figure 6.
Advantages of apertureless probes

- No cutoff frequency as existing in a metal-coated fiber optics probe
- Field enhancement due to surface plasmon polaritons
- The probe size can be made much smaller
Controlling the probe-sample distance

The tip-sample distance changes the damping of the resonance oscillator.

Ref: Prasad, chapter 3, figure 9.
Laser trapping for probe

Ref: S. Kawata, chapter 8.

e.g. 2.5W Nd-YLF traps a gold particle (~ 10-100 nm) with a 100X NA=1.35 objective (oil immersion)
Examples of SNOM images 1

- Single molecule fluorescence detection

Examples of SNOM images 2

- Single quantum dot

Examples of SNOM images 3

- Dynamics using pump-probe technique

Examples of SNOM images 4

Topography

Taken from presentation materials of WITEC.
Examples of SNOM images 5

MFM - Magnetic Force Microscopy

80 microns scan range  20 microns scan range  5 microns scan range

PC hard drive

Taken from presentation materials of WITEC.
Examples of SNOM images 5

Semiconductor Surface Study

InGaN films

- 20% In
  - Topography (a)
  - (b)

- 24% In
  - (d)
  - (e)

- 27% In
  - (g)
  - (h)

Jeongyong Kim et al., University of Illinois, see also APL Vol. 80, 6, 989 (2002).

10 microns scan range

Taken from presentation materials of WITEC.
Examples of SNOM images 7

Topography

Adhesion

5 microns scan range

Bodyguard adhesive tape

Taken from presentation materials of WITEC.
Reading

- S. Kawata, chapter 2.