Scanning Near-field Optical Microscopy
and Visible-Wavelength Photonic Crystal Slabs

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The Diffraction Limit in Optics

Point Source

Incoherent Point Sources

Intensity Point Spread Function (PSF):

\[ I(r) = \left( \frac{2J_1(kr \sin \theta)}{kr \sin \theta} \right)^2 \]

Full Width at Half Maximum:

\[ \text{FWHM} \approx \frac{\lambda}{2NA} \]

where \( NA = n \sin \theta \)

Rayleigh resolution criterion:

\[ \Delta x = \frac{0.61 \lambda}{NA} \]

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Improving Spatial Resolution
Near-field Scanning Optical Microscope (NSOM)

Near-field magneto-optic image of domains written in thin-film magneto-optic (MO) material
from: Betzig et al., Appl. Phys. Lett. 61, 142 (1992)

Optical transmission: ~0.001 to 0.01%

~50 nm opening at end of tip

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Improving Spatial Resolution — Solid Immersion Lens

SOLID IMMERSION MICROSCOPY

![Diagram showing Solid Immersion Lens (SIL) principle](https://via.placeholder.com/150)

\[ \text{NA}_{\text{obj}} = \sin \theta \]

Solid Immersion Lens

- \( \text{n}_{\text{SIL}} \approx 2.0 \)
- (\( \text{Si}_3\text{N}_4 \) at visible \( \lambda \))


- Improvement in spatial resolution
- High optical throughput (near unity)
- No need to put oil on sample (c.f. oil immersion)

Reduction in spot size due to SIL:

- FWHM (no SIL) ~ \( \lambda / (2 \text{NA}_{\text{obj}}) \) ~ 180 nm
- FWHM (with SIL) ~ \( \lambda / (2 \text{NA}_{\text{obj}} - \text{n}_{\text{SIL}}) \) ~ 90 nm

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Talk Outline

I. Solid Immersion Microscopy with Micromachined Lenses
   • Surface micromachining fabrication method for silicon nitride lenses
   • Scanning optical microscope based on micromachined lenses

II. Optical Antennas for Scanning Nearfield Optical Microscopy
   A. Theory and Simulation
      • Finite Difference Time Domain Method (FDTD) simulations
      • Maximizing optical field enhancement in optical antennas
   B. Experimental Results
      • Fabrication and testing methods
      • Comparison between theory and experiment

III. Visible-wavelength Photonic Crystal Devices
   • Experimental realization

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Near-field Effects in the SIL

Light rays incident upon bottom face of SIL at less than critical angle for total internal reflection (TIR)

Propagating waves

Light rays incident upon bottom face of SIL at greater than critical angle for total internal reflection (TIR)

Evanescent waves

SIL Air gap Sample

SIL Air gap Sample

\[ \theta_C \]

\[ \theta_{NA} \]
Near-field effects in the SIL–air gap

Scalar approximation to PSF:

\[ E(r,\Delta z) = \int_0^{\sin(\theta_{NA})} \exp(i2\pi n_{gap} \gamma' \Delta z)\rho J_0(2\pi n_{SIL} \rho r) \, d\rho \]

where \( \gamma' \) is the complex propagation constant:

\[ \gamma' = \left[1 - \rho^2 \left(\frac{n_{SIL}}{n_{gap}}\right)^2\right]^{1/2} \]

- \( n_{SIL} \) is refractive index of SIL
- \( n_{gap} \) is refractive index of gap (e.g., 1.0 for air)

\( n_{SIL} = 2.0, \lambda = 400 \text{ nm}, NA = 0.8 \)
Near-field effects in the SIL – air gap

**Contribution of transmitted rays to PSF**

- \( \Delta z = 0 \text{ nm} \)
- \( \Delta z = 50 \text{ nm} \)
- \( \Delta z = 100 \text{ nm} \)

**Contribution of TIR rays to PSF**

- \( \Delta z = 0 \text{ nm} \)
- \( \Delta z = 50 \text{ nm} \)
- \( \Delta z = 100 \text{ nm} \)

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Solid Immersion Lens Cantilever - Process Flow

1. Deposit oxide
   Deposit polysilicon
   Etch 1 \( \mu \text{m} \) hole in polysilicon

2. Etch oxide in hydrofluoric acid (HF)

3. Etch polysilicon
   Etch oxide (HF) - optional

4. Deposit \( \text{Si}_3\text{N}_4 \)

5. Pattern photoresist
   Reflow photoresist (oven)

6. Etch tip (\( \text{CHF}_3/\text{O}_2 \) plasma)

7. Etch cantilever (\( \text{CHF}_3/\text{O}_2 \) plasma)

8. Etch backside silicon
   (\( \text{SF}_6/\text{C}_4\text{F}_8 \) plasma)

9. Etch oxide (HF)
Microfabricated Solid Immersion Lenses — Silicon Nitride

Lens radius = 3.5 μm
Tip height = 2.1 μm

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Scanning Optical Microscope Based on Micromachined Solid Immersion Lens (SIL) ($\lambda = 400$ nm)

Scanning Optical Microscope based on Micromachined Solid Immersion Lens built on optical bench

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Solid Immersion Microscope Edge Response — Experimental Results

→ imaging signal as edge of metal line is scanned

Transmission Mode Imaging

Reflection Mode Imaging

Edge response with the SIL is ~ 100 nm. This is ~ 1.9 times better than without the SIL

Wavelength: $\lambda = 400$ nm
Objective lens: NA = 0.80
Solid Immersion Lens refractive index: $n = 1.96$

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Solid Immersion Microscope Point Spread Function — Experimental Results

Transmission Mode Imaging

- Wavelength: $\lambda = 400$ nm
- Objective lens: NA = 0.80

Reflection Mode Imaging

- Solid Immersion Lens refractive index: $n = 1.96$

Spot size (FWHM) with the SIL is $\sim 130$ nm.

SIL optical transmission efficiency $\sim 71\%$ (absorption and scattering losses)

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Solid Immersion Microscope Images

0.36 \mu m lines and 0.22 \mu m spaces
\lambda = 400 nm
Transmission mode images

No SIL

With SIL

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Solid Immersion Microscope Images — line scans

0.36 μm lines and 0.22 μm spaces
λ = 400 nm

Transmission

Reflection

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Optical Resolution below the Diffraction Limit with Optical Antennas

FOCUSSING (NO SIL)
Resolution $\sim \lambda/2$

SOLID IMMERSION LENS
Resolution $\sim \lambda/(2\,n)$

OPTICAL ANTENNA
Intense optical field generated at end of antenna
Resolution $\sim \lambda/40$

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Field Enhancement in Optical Antennas

Plane wave illumination

Antenna

$k$, $H_{inc}$, $E_{inc}$
1. Tangential component of electric field ($E_T$) on antenna must be zero. Hence tangential scattered field ($E_T^s$) must balance incident field ($E_T^{inc}$):

$$E_T = E_T^s + E_T^{inc} = 0$$

2. Incident field causes currents to flow on antenna. These currents are the origin of the scattered field $E^s$:

$$E^s = -j\omega\mu_0\vec{A} + \frac{1}{j\omega\varepsilon_0} \nabla(\nabla \cdot \vec{A})$$

where $\vec{A}(r) = \int G(r,r')J_s(r')\,dr'$

$G(r,r') =$ free space Green's function

3. Decreasing current at antenna ends requires that charges appear on surface. Normal component of electric field is proportional to surface charge density ($\rho_s$).

$$\nabla \cdot J_s + j\omega\rho_s = 0$$

$$E_N = \frac{\rho_s}{\varepsilon_0}$$
Numerical Simulation of Fields in Optical Antenna

Illumination wavelength: $\lambda = 10.375 \, \mu m$

Gold thickness = 60 nm
Tip radius of curvature = 120 nm
$\alpha = 15$ degrees

$L = 1.56 \, \mu m$

Half maximum $<|E|^2>$ contour at tip

$\sim 260 \, nm \sim \lambda/40$

$\sim 150 \, nm \sim \lambda/70$

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Resonant Wavelength

Resonant length \( L \sim \frac{\lambda}{2n} \)

\( n = \) refractive index of substrate

\( \lambda = L \times 2n \)

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Optical Antennas — Experimental Work

ROD

ISOSCELES

CIRCLE

EQUILATERAL

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Experimental set-up for far-field transmission measurements on optical antennas

λ = 2 – 16 µm

Transmission = \( \frac{P_{\text{OUT}}}{P_{\text{IN}}} \)

\( P_{\text{OUT}} \) = Detector signal measured with sample in place

\( P_{\text{IN}} \) = Detector signal measured with no sample in place

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Extinction cross section measurements on optical antennas

Detector signal:

No antenna: \( U = S_i \cdot A \)
\[ = U_{\text{inc}} \]

where \( S_i = \) incident intensity (\( \mu \text{W}/\mu \text{m}^2 \))
\( A = \) detector area (\( \mu \text{m}^2 \))

With antenna: \( U = U_{\text{inc}} - S_i \cdot C_{\text{ext}} \)

\( C_{\text{ext}} = \) extinction cross section (\( \mu \text{m}^2 \))
\[ = \text{equivalent ‘geometric shadow’ of antenna} \]
\[ = C_{\text{abs}} + C_{\text{sca}} \]

where \( C_{\text{abs}} = \) absorption cross section (\( \mu \text{m}^2 \))
\( C_{\text{sca}} = \) scattering cross section (\( \mu \text{m}^2 \))
Optical Antennas: Experimental Results

Optical antennas are gold on silicon substrates
Gold is 60 nm thick with 5 nm Cr sticking layer
Silicon substrate is transparent at mid-IR wavelengths

Extinction efficiency:

$$Q_{\text{ext}} = \frac{C_{\text{ext}}}{G}$$

where

$$C_{\text{ext}} = \text{extinction cross section (\(\mu\text{m}^2\))}$$
$$G = \text{antenna physical area (\(\mu\text{m}^2\))}$$

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Extinction Cross Section: Theory and Experiment
I. Equilateral triangle antennas
Optical Antennas: Experimental Results

Resonant wavelength (μm) vs antenna length (μm)

- Black circles: Al triangles, data
- Red circles: Ag triangles, data
- Blue circles: Au triangles, data
- Red line: Theory: length = λ/(2n)

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Scanning Near-field Optical Microscope: Proposed Application of Optical Antenna

Focused laser beam

Cantilever with lens

Sample

Optical antenna at end of tip.
Intense fields generated at tip.
Surface-Enhanced Raman Scattering (SERS) with Ag or Au colloids

Raman scattering

\[ P_{RS}(\nu_S) = N \sigma_{\text{free}}^R I(\nu_L) \]

10^{-30} cm^2 per molecule
c.f. 10^{-16} cm^2 for fluorescence

Surface-enhanced Raman scattering with Ag or Au colloids

\[ P^{SERS}(\nu_S) = N' \sigma_{ads}^R |A(\nu_L)|^2 |A(\nu_S)|^2 I(\nu_L) \]

enhancement factor for laser field
enhancement factor for scattered field

Single molecule detection using SERS:

S. Nie and S.R. Emory, Science 275, pp. 1102-1106 (1997)

Scanning Near-field Microscope Based on Optical Antenna

Proposed application: Probe-enhanced Raman Spectroscopy

Transmission Electron Micrograph (TEM) of Ag colloids used in Surface-enhanced Raman Scattering (SERS)

Scanning Near-field Optical Microscope Based on Micromachined Optical Antenna Probes

laser

notch filter
to spectrometer

sample (scanned)

Optical antenna at end of tip.

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Raman Spectroscopy of Living Cells Using SERS with Au Colloids

Optical phase contrast image of two living cells

Image of total SERS signal

Raman spectra measured at different places on cell monolayer

\[ \lambda = 830 \text{ nm excitation} \]

Spatial resolution \( \Delta x = 1 \mu m \)


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Photonic Crystal Slabs as Free Space Optical Filters

Multilayer Dielectric Stack Filter

Photonic Crystal Slab Filter

Many dielectric layers required for narrowband notch filtering

Narrowband notch filter possible with a single dielectric layer

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Modes of a Dielectric Slab — continued

\[ \omega = ck/n \]

Light line,
\[ \omega = ck \]

Continuum of states

incident plane wave

transmitted plane wave

reflected plane wave

in-plane wavevector, \( k \) (\( 2\pi/a \))

frequency, \( \omega \) (\( 2\pi c/a \))

TE, symmetric
TM, symmetric
TE, asymmetric
TM, asymmetric

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Two-dimensional Photonic Crystal Slabs

EVEN MODES – uniform slab

EVEN MODES – photonic crystal slab

\( G = \) reciprocal lattice vector

\[ G = m \frac{2\pi}{a} x + n \frac{2\pi}{a} y \quad (m,n \text{ integers}) \]

Parameters: \( t = 190 \text{ nm}, n = 2.281, a = 452 \text{ nm} \)

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Two-dimensional Photonic Crystals at Visible Wavelengths

SCANNING ELECTRON MICROGRAPH
OF PHOTONIC CRYSTAL

t = 196 nm, a = 452 nm, d = 190 nm

Total extent of photonic crystal: 100 μm * 100 μm
Two-dimensional Photonic Crystals at Visible Wavelengths

EXPERIMENTAL SET-UP

- Illumination wavelengths $\lambda = 450 \text{ nm} - 1100 \text{ nm}$
- Beam has spot size (full width at half maximum FWHM) of $\sim 210 \mu \text{m}$ on photonic crystal
- Collection area from photonic crystal is $\sim 61 \mu \text{m}$
- Photonic Crystal is square lattice of holes (452 nm period), total extent is $100 \mu \text{m} \times 100 \mu \text{m}$

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Two-dimensional Photonic Crystals at Visible Wavelengths

TRANSMISSION THROUGH UNPATTERNED SLAB (i.e., no holes)

TRANSMISSION THROUGH PHOTONIC CRYSTAL SLAB (i.e., with holes)

FDTD Calculation Parameters:

\[ t = 188 \text{ nm}, \quad n = 2.281, \]
\[ d = 188 \text{ nm}, \quad a = 452 \text{ nm} \]
SUMMARY

Micromachined Solid Immersion Lenses

- Developed micromachining process for silicon nitride SILs integrated with AFM cantilevers
- Silicon nitride SILs enable high resolution (130 nm spot size) microscopy with high optical throughput (~71% compared to 0.001–0.01% for tapered fiber NSOMs)

Optical Antennas

- Numerical study of field enhancement in optical antennas
- Demonstrated optical antennas operating at infrared wavelengths ($\lambda \sim 2–10 \ \mu m$)

Photonic Crystals

- Demonstrated that silicon nitride has sufficiently high index and low loss to enable guided resonances at visible wavelengths, opening possibilities for new optical components at these wavelengths

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Short Wavelength Limit

- $\lambda \ll D$ so can use Fraunhofer diffraction

\[
E_{\text{sc}} = -E_{\text{inc}}
\]

\[
\text{Total flux incident within geometric cross section } G
\]
is either scattered or absorbed

\[
C_{\text{ext}} = C_{\text{sc}} + C_{\text{abs}} = 2G
\]
Assume sinusoidal current distribution on resonance:

$$I(y) = I_m \sin \left[ \frac{2\pi}{\lambda} \left( \frac{L}{2} - |y| \right) \right]$$

Power flux of scattered field at P produced by this current:

$$S_{sca} = \frac{1}{2} E_{sca,\theta} H^*_{sca,\phi}$$

$$= \frac{15 I_m^2}{\pi r^2} \left[ \frac{\cos \left( \frac{\pi}{2} \cos \theta \right)}{\sin \theta} \right]^2$$

Scattering cross section:

$$C_{sca} = \int_A S_{sca} \cdot \vec{e}_r \, dA$$

$$= \frac{36.54 I_m^2}{|S_i|}$$

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Finite Difference Time Domain Method (FDTD)*
Calculation of Field Enhancement by Optical Antenna

–calculate electric (E) and magnetic (H) fields using discretized Maxwell curl equations

Computation domain

* TEMPEST 6.0 from Professor Neureuther’s group,
EECS Department, University of California at Berkeley

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**Modes of a Dielectric Slab**

**UNIFORM DIELECTRIC SLAB**

- $t$ = slab thickness
- $n$ = refractive index of slab

**Graph**

- $\omega = ck$
- $\omega = ck/n$

**Slab parameters:** $t = 190$ nm, $n = 2.281$, $a = 452$ nm

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