Lecture 14

Superlensing – Far Field
Near-field Optical Superlens

The super-resolution image only exist at the near-field of the lens
Goal

Optical Nanoscope at super speed (>1KHz) and super resolution (<50nm)
Far-field Superlens Microscopy

An optical imaging system based on far-field superlens (FSL)

- Evanescent field enhancement
- Evanescent wave to propagating wave conversion in a designed manner
How a FSL Works?

Grating coupling: $k_{\text{out}} = k_{\text{in}} + m k_{\Lambda}$ \quad $m = 0, \pm 1, \ldots$

One propagating wave has multiple origins -- “Wavevector mixing” issue

Solution: Optical transfer function (OTF) engineering

For Imaging: One-to-one projection of evanescent wave to propagating wave
An Exampled FSL

**Ag structured FSL**

![Diagram of Ag structured FSL]

- Attenuate the propagating waves
- Enhance evanescent waves

**Silver slab:**

- Convert evanescent waves to propagating waves

**Silver grating:**

- Convert evanescent waves to propagating waves

\[ a=35\text{nm}, \quad b=45\text{nm} \]
\[ c=105\text{nm}, \quad d=55\text{nm} \]

@ 377nm

FSL Imaging of a Pair of Nanowires

SEM image of one testing object

Conventional OM image (NA=1.4)

FSL reconstruction image using both \textit{TM} \& \textit{TE} polarization

Comparison (averaged along vertical direction)

\textit{\~}50nm features can be resolved in far-field

Nano Letters, 7, 3360 (2007)
2D Far-field Superlens

FSL for 2D Imaging

Nano Letters, 7, 3360 (2007)
Compress the wavevector from evanescent to propagating
Principle of Optical Hyperlens

Support wave propagation with very high wavevector

\[ \frac{k_x^2}{\varepsilon_y} + \frac{k_y^2}{\varepsilon_x} = k_0^2 \]

\( \varepsilon_x > 0, \varepsilon_y > 0 \)

\( \sqrt{\varepsilon, k_0} \)

\( n = \sqrt{\varepsilon} < 2.4 \)

\( \varepsilon_x > 0, \varepsilon_y < 0 \)

\( \sqrt{\varepsilon, k_0} \)

No naturally existing materials
What are Metamaterials

Nature Materials

Unit: atoms

1 nm

Metamaterials

Unit: Meta “atoms” Artificial nanostructures

10 nm -100 μm
Artificial Metamaterials with extraordinary material properties

Metal: $\varepsilon$
Dielectrics: $+\varepsilon$

Effective Media:

$$\varepsilon_x = \varepsilon_m d_m + \varepsilon_d d_d$$
$$\varepsilon_y = (d_m + d_d)\varepsilon_m \varepsilon_d / (\varepsilon_d d_m + \varepsilon_m d_d)$$

$\varepsilon_x > 0$, $\varepsilon_y < 0$
Optical Hyperlens

Compress the wavevector by geometry

\[ \varepsilon_\theta > 0, \quad \varepsilon_r < 0 \]

Hyperbolic dispersion

\[ \frac{k_r^2}{\varepsilon_\theta} + \frac{k_\theta^2}{\varepsilon_r} = k_0^2 \]

\[ R \cdot k_\theta = \text{Constant} \]

- There is no cut-off for \( k_\theta \)
- \( k_\theta \) gets compressed with increasing \( R \)
- \( k_\theta \) finally can be propagating

A Hyperlens can magnify a sub-diffraction limited object into a diffraction limited image
Experimental Demonstration

Sample Fabrication

1. Cr coating
2. FIB mask fab.
3. Wet etching
4. Remove Cr
5. Ag/Al$_2$O$_3$ deposition
   -- Hyperlens
6. Cr deposition
   -- Object
7. FIB object fab

First Hyperlens Demonstration

SEM Image

Diffraction limited resolution: 260nm

Hyperlens Image
Mag≈2.3

130nm
Hyperlens with 2D Magnification

Nature Communications 1, 143 (2010)
Transformation Optics

\[ x = r_0 \cos \phi e^{\ell/\ell_0}, \quad y = r_0 \sin \phi e^{\ell/\ell_0}, \quad z = Z \]
Lens Engineering via Transformation Optics

Other Versions
Other Versions
Other Hyperlens

Rolled-Up Hyperlens

Acoustic Hyperlens

Phys. Rev. Lett. 102, 163903 (2009)

Nat Mater, 2009, 8: 931–934