Plasmonics, Metamaterials and Their Applications in Light Manipulations

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**Light Manipulation**

- **Nanoscale**
- **Optical Control Devices**
- **Fundamental Science**
- **Nanolithography**
  - Energy harvesting
  - Bioimaging & sensing
  - LEDs and detectors

- **Applied**
  - High resolution
  - High speed
  - High sensitivity
  - High efficiency

- **Nanophotonics**
- **Plasmonics**
- **Nano-materials**
- **Light matter interactions**

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Optical Materials

New materials properties provide new possibilities!

(a) \( \varepsilon < 0, \mu > 0 \)
- Ag, Au...

\varepsilon < 0, \mu < 0
- Negative Index Media

(b) \( \varepsilon > 0, \mu > 0 \)
- Most materials

\varepsilon > 0, \mu < 0
- Fe, Co...

Strong Anisotropic Media

Most materials
Optical Imaging Systems

Telescope  Eye  Microscope

3D imaging system

Skull
Upper lid
Cornea
Lower lid
Conjunctiva
Optical Microscope

- 1590’s
- 1900’s
- 1998

The First Compound Microscope

Nikon’s First Microscope (circa early 1900s)

The Olympus Provis AX-7 (circa 1998)
The Foundations of Optical Microscopy

The light illumination

The material -- glass

The theoretical limit

August Köhler (1866 - 1948)
Otto Schott (1851 - 1935)
Ernst Abbe (1840 - 1905)

The diffraction limit

\[ d = \frac{\lambda}{2 \sin \alpha} \]
What is Diffraction Limit

\[ E(x, y, z) = E_0 e^{ik_xx} e^{ik_yy} e^{ik_zz} \]

\[ k_z = \sqrt{(n \frac{\omega}{c})^2 - (k_x^2 + k_y^2)} \]

- \( k_x^2 + k_y^2 < (n\omega/c)^2 \) \( \Rightarrow k_z \) is real \hspace{0.5cm} \text{propagating waves}
  \hspace{0.5cm} \text{big features of the object}

- \( k_x^2 + k_y^2 > (n\omega/c)^2 \) \( \Rightarrow k_z \) is imaginary
  \hspace{0.5cm} \text{Amplitude exponentially decay} \hspace{0.5cm} \text{evanescent waves}
  \hspace{0.5cm} \text{small features of the object}

Evanescent waves are lost at the image plane \hspace{0.5cm} \text{Diffraction limited resolution}
Methods to Improve Resolution

\[ \Delta x \approx \frac{\lambda}{n} \sin(\theta) \]

Reduce working \( \lambda \)
- Light
  - EUV
  - X-ray
  - Electron beam
  - Ion beam

Increase \( n \)
- Air
  - Oil immersion (1.0-1.8)
  - Solid immersion (n=1.5~2)
A slab of negative refractive index material (NRIM) can perform as a perfect lens according to Snell’s law:

\[
\frac{\sin \theta}{\sin \theta_0} = -1
\]

Fresnel equation:

\[
T_p(k_x, d) = \frac{t_{01}t_{12}}{\exp(-ik_{z_1}d) + r_{01}r_{12} \exp(i k_{z_1}d)}
\]

A metamaterial (or meta material) is a material which gains its properties from its structure rather than directly from its composition.
Metamaterials at MW

NIM, UCSD, Science, 2001

Boeing, bulk NIMs

High n, KAIST, Nature, 2011
Metamaterials: from MW to Optical

Optical Metamaterials – More bulky and less lossy

\[
\varepsilon = \begin{bmatrix}
\varepsilon_{xx} & 0 & 0 \\
0 & \varepsilon_{yy} & 0 \\
0 & 0 & \varepsilon_{zz}
\end{bmatrix}
\]

→ FOM: order of magnitude improvement
→ Fabrication: order of magnitude easier

Practical Optical Metamaterials:
Plasmonic metamaterials \( \Rightarrow \mu = 1 \)
Superlens Imaging Using Metal

40nm Ag film @3.48eV
Simulated resolution <80nm

New Imaging Paradigm: Plasmon Optics

Surface plasmons (SPs) are collective free electron oscillations at a conductor surface.

Main features of SPs

- Shorter wavelength (comparing with excitation light)
- Bound to the surface
- Propagation along the surface
- Evanescent enhancement

Evanescent Enhancement by Metal Film

- Evanescent field enhancement increase with increasing silver film thickness.
- Loss play an important role when the film is thicker than 50nm

The super-resolution image only exist at the near-field of the lens.
Far-field Superlens

Evanescent waves:
- 

Propagating waves:
- 

Sub-\(\lambda\) object

\(\lambda=405\) nm

100nm

Ag

150nm


Compress the wavevector from evanescent to propagating
Principle of Optical Hyperlens

Support wave propagation with very high wavevector

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

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

\[ n = \sqrt{\varepsilon} < 2.4 \]

No naturally existing materials
An Example

Artificial Metamaterials with extraordinary material properties

Metal: \(- \varepsilon\)
Dielectrics: \(+ \varepsilon\)

Metal/dielectric multilayer

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

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

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

\[ \begin{align*}
\n\therefore & \text{There is no cut-off for } k_\theta \\
\n\therefore & k_\theta \text{ gets compressed with increasing } R \\
\n\therefore & k_\theta \text{ finally can be propagating}
\end{align*} \]

(Engheta, PRB, 2006 and Narimanov, Opt. Express, 2006)
Optical Hyperlens

Anisotropic metamaterial: Metal/dielectrics multilayer

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

Experimental Demonstration

\[ \lambda = 365 \text{nm} \]

\[ \lambda = 410 \text{nm} \]

Flat Hyperlens


High Speed High Resolution Bio-imaging

Neurontransmitter Dynamics

Cell membrane dynamics
Nanowires Based Bulky Plasmonic Metamaterials

- Positive Phase Index, Broadband and Low Loss

Yao, Liu et., al., *Science* 2008

Indefinite medium sample

Nanowire array

Collaboration with Prof. Angelica Stacy, Berkeley
Experimental Results – Negative Refraction

\( n_{\text{TE}} = 2.2 \)
\( n_{\text{TM}} = -4.0 \)

Negative Refraction Flat Lens @ VIS

(a) Full-wave Simulation

(c) Effective Slab

→ No focal length can be defined

→ Material supports super resolution, but impossible to achieve in the flat geometry

Collaboration with Prof. Yuh-Lin Wang, Academia Sinica

All-angle negative refraction and active flat lensing of ultraviolet light
New Optical Phenomena
Conventional Optical Lens

Lens: the most fundamental transformation element

- Plane wave focusing (OFT)
- Imaging

1. Resolution: diffraction limited
   \[ \Delta x \approx \frac{\lambda}{NA} \]

2. Imaging Equation
   \[ \frac{1}{s_1} + \frac{1}{s_2} = \frac{1}{f} \]
Superlenses

- **Perfect lens concept**
  J. B. Pendry, PRL 85, 3966 (2000)

- **Near-field superlens**
  N. Fang et al., Science 308, 534 (2005)

- **Hyperlens**
  Z. Liu et al., Science 315, 1686 (2007);

- **Super resolution**
  - high $k$-vector included in image.

- **No plane wave focusing**
  - no Fourier transform (FT)
To Make a Lens by Plasmonic Metamaterials

To develop three phase compensation mechanisms in the Metalens

- Metamaterial shaping
- Plasmonic waveguide array to introduce phase modulation
- Gradient index metamaterial

- The super resolution is enabled by the metamaterial properties.
- The hyperbolic metalens (i.e. the plasmonic metamaterial has hyperbolic dispersion) experiences negative refraction at air/metamaterial interface

Metamaterial Immersion Lenses (MIL)

The most fundamental property of a lens – plane wave focusing (Fourier transform)

Metamaterial + interface shaping

C. Ma and Z. Liu, Opt. Express 18, 4838 (2010)
Metalenses

To introduce precise phase modulation by introducing a plasmonic waveguide array

(i) Elliptic Dispersive Metamaterial
FWHM = 59 nm ~ λ/6

(ii) Hyperbolic Dispersive Metamaterial
FWHM = 52 nm ~ λ/6

(a) 2.2 μm
3.6 μm

(b) 117 nm

(c) 1.9 μm
2.8 μm

(d) 210 nm

GRIN Metalens

C. Ma, M. Escobar, and Z. Liu, Phys. Rev. B 84, 195142 (2011)
An Intriguing Hyperbolic Metalens

C. Ma, and Z. Liu, Opt. Express 20, 2581 (2012)
# Conventional Lens ↔ Metalens

(Comparison for imaging characteristics)

## For conventional optical lens

<table>
<thead>
<tr>
<th>Object</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Type</td>
</tr>
<tr>
<td>$\infty &gt; s_o &gt; 2f$</td>
<td>Real</td>
</tr>
<tr>
<td>$s_o = 2f$</td>
<td>Real</td>
</tr>
<tr>
<td>$f &lt; s_o &lt; 2f$</td>
<td>Real</td>
</tr>
<tr>
<td>$s_o = f$</td>
<td></td>
</tr>
<tr>
<td>$s_o &lt; f$</td>
<td>Virtual</td>
</tr>
</tbody>
</table>

## For Hyperbolic Metalens

3, 1205 (2012)

<table>
<thead>
<tr>
<th>Object</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Type</td>
</tr>
<tr>
<td>$\infty &gt; v_d &gt; 0$</td>
<td>Real</td>
</tr>
<tr>
<td>$\infty &gt; v_m &gt; 2f_m$</td>
<td>Virtual</td>
</tr>
<tr>
<td>$v_m = 2f_m$</td>
<td>Virtual</td>
</tr>
<tr>
<td>$f_m &lt; v_m &lt; 2f_m$</td>
<td>Virtual</td>
</tr>
<tr>
<td>$v_m = f_m$</td>
<td></td>
</tr>
<tr>
<td>$v_m &lt; f_m$</td>
<td>Real</td>
</tr>
</tbody>
</table>

Imaging equation

$$\frac{1}{S_o} + \frac{1}{S_i} = \frac{1}{f}$$

Imaging equation

$$\frac{1}{v_d} + \frac{\varepsilon_z'/\sqrt{\varepsilon_x'}}{v_m} = \frac{\varepsilon_z'/\sqrt{\varepsilon_x'}}{f_m}$$

$$\frac{1}{v_d} + \left(\frac{\varepsilon_z'/\sqrt{\varepsilon_x'}}{v_m}\right)/v_m = 1/f_d$$

Subscription $d$ and $m$ means the location in either dielectrics or metamaterials

- Metalens enables exotic imaging systems that previously thought impossible
- A review article in Nature Communications, 3, 1205 (2012)
Object in Air

Real image always formed!

Conventional optical lens
Compound kinoform plasmonic lenses

Structured illumination Microscopy (SIM)

- Resolution improved *twice* in fluorescent microscopy

Structured Illumination Microscopy

Object

(a)

Illumination

(b)

Image

(c)

Detection

(a)

Illumination

(b)

Image Info

(c)
Light interference $\rightarrow$ Surface plasmon wave interference (better resolution)

$\omega = ck$

Photon

Surface Plasmon

$\lambda = 365\text{nm}$

$\lambda = 514\text{nm}$

Resolution Issue

Conventional OM

\[ \Delta x = \frac{\lambda_{emi}}{2NA} \]

Conventional SIM

\[ \Delta x = \frac{\lambda_{emi}}{2NA + 2NA\lambda_{emi}/\lambda_{abs}} \]

Plasmonic SIM (PSIM)

\[ \Delta x = \frac{\lambda_{emi}}{2NA + 2NA_{eff}} \]

The \( NA_{eff} \) is only determined by the plasmonic structure NOT the objective.

For instance, \( NA \) of the objective is 0.5

\( NA_{eff} \) of the plasmonic structure can be 1.5
Plasmonic Structured Illumination Microscopy

Resolution: >3X resolution enhancement (50-100nm)
Speed: >30 frames/second (faster than real movie speed)

Current work (2): PSIM
PSIM: example design (1)

PSIM excitation wavelengths: 442nm
PSIM detection wavelength: 508nm
Detection NA: 0.85

Resolution: ~80nm
Enhancement factor: ~3.8


Current work (2): PSIM
Super Resolution Lithography
Surface Plasmon Interference Nanolithography (SPIN)

Metal: Al
Working λ: 266nm
Simulation

FSL for Lithography

APPLIED PHYSICS LETTERS 93, 111116 (2008)
(a) 2D transfer function for a 12 pairs of 35 nm Ag and 21 nm SiO$_2$ multilayer at a wavelength of 405 nm. (b) The simulated $|E|$ field at the plane 3 nm after the multilayer.

APPLIED PHYSICS LETTERS 93, 111116 (2008)
Hyperlens for Lithography

(a) Input surface

(b) $|H|$ vs. position (nm)

(c) $|E/120\pi|$ vs. position (nm)
A simple design of flat hyperlens for lithography and imaging with half-pitch resolution down to 20 nm
Plasmonic Super Contrast Imaging

Dark-filed Microscopy
Dark-Field Microscopy

Can NOT be used for imaging
Plasmonic Dark-Field (PDF) Microscopy

**Conventional dark field microscopy:**
- use bulky and expensive condenser;
- has limited resolution.

**Plasmonic dark field microscopy:**
- High contrast;
- High resolution;
- Compact;
- Low-cost;
- Energy saving;
- Alignment free.

**Replacing conventional condenser with plasmonic condenser (PC):**
- Chip scale;
- Surface plasmon illumination;
- Integration of light source;
- No light stop;
- Cheap and massive fabricatable.

**Algorithms for high resolution image reconstruction:**
- Algorithms (applicable to other microscopy);
- Software package with user friendly interface.

OVERVIEW OF THE PROPOSED PROJECT
Preliminary Imaging Results on PS Beads

(a) Conventional dark field image

(b) PDF image

Conventional dark field image

Plasmonic dark field image

Experimental Results
LED Based PDF

(a) 200nm Al cathode
n type GaN
45 nm Ag
p type GaN
200nm Al cathode

(b) 45nm Ag film
p type GaN, doping level 8x10^{17} cm^{-3}, d_1 = 155nm
Multi quantum well, 5 period InGaN/GaN=2nm/10nm
n type GaN
doping level 5x10^{18} cm^{-3}, d_2 = 3.22\mu m
sapphire substrate

(c)

(d) log current (A)

(e) 6 \mu m

(f)
Plasmonic Super Contrast Imaging

Phase Contrast Microscopy
Phase Contrast Microscopy

- Current methods:
  - Convert phase information, via optical path differences, into intensity variation.

- Problem:
  - Not practical for very thin samples or very fine features

Can the same be done with plasmonics? Simpler? Better?
Plasmonic Metamaterial Waveguide

a) Conventional dielectric waveguide
no > n1 > 1

NA ~ 0.15

b) Bragg photonic band gap waveguide
n1 > no ≥ 1

NA ~ 0.2

c) Dual SP/hollow waveguide

1) Hollow ATR/Leaky Guidance
   metamaterial cladding
   0 < ε_r < 1, ε_θ > 1
   No = 1
   d < λ

2) SP Guidance
   metamaterial cladding
   ε_r < 0, ε_θ > 0
   No = 1
   d < λ

3) SP & Core Coupling
   metamaterial cladding
   ε_r < 0, ε_θ > 0
   No = 1
   d < λ

4) SP Guidance
   metamaterial core
   ε_r < 0, ε_θ > 0
   No = 1
   d < λ

Nano. Lett. 10, 1 (2010), collbrated with O. G. Schmidt group at IFW Dresden, Germany
Plasmonic Metamaterial Waveguide

Nano. Lett. 10, 1 (2010), collaborated with O. G. Schmidt group at IFW Dresden, Germany
Special Properties

a) 

b) 659nm

c) 323nm

Zhaowei Liu Research Group

UCSD
Light Plasmonic Metamaterial Interactions

Optical plasmonic metamaterials

Fluorescence molecules
Semiconductor QW, WD

Optical Pump

Electrical Pump

Quantum Efficiency (intensity)
Plasmonic Enhancement

Life-time (speed)
Fluorescence ~ns
Plasmonics ~10-100fs
Plasmonic Enhanced PL

- Near field coupling between LED and SPs on metal film
- Surface structure convert SPs into free space photons

Plasmonic Enhancement


SP resonance $\leftrightarrow$ Light emission peak
Hyperbolic Metamaterial Enhanced PL

\[ \tau = 2 \text{ ns} \]

\[ \tau = 1.1 \text{ ns} \]

[APB 100,215 (2010)]

[Science 336, 205 (2012)]

Jacob, Shalaev, Menon, Noginov

[OL 35,1863 (2010)]
Hyperbolic Metamaterials + Light Emitters
Continue
Structured Hyperbolic Metamaterials

Couple non-radiative SPs to propagating photons!
Metamaterial Enhanced Fluorescence

[Diagram and images]
Experiment: Emission Speed Enhancement

(a) glass

(b) glass

(c) glass

(d) 

- t=0.07ns
- t=0.1ns
- t=0.4ns
- t=3.8ns

~50X Enhancement

To appear in Nature Nanotechnology

Zhaowei Liu Research Group
Experiment: Brightness Enhancement

To appear in Nature Nanotechnology
Major Other Research Topics

- Quantum plasmonics and Thermoelectronics
- Ultrafast LEDs and communications
- 3D real time brain imaging
- Nonlinear plasmonics
Summary

- **Passive light propagation control**
  - super resolution microscopy
  - super contrast microscopy
  - plasmonic/metamaterial waveguides

- **Active light emission control**
  - Plasmonic/metamaterial LEDs

What nature can do ??
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