Probing radiation patterns of single plasmonic and metamaterial structures

Ivana Sersic
Christelle Tuambilangana
Femius Koenderink

Center for Nanophotonics
Radiation patterns of single scatterers

To understand how nano-scatterers scatter we need to measure where-to they scatter

- We need: Controlled phase and amplitude of the driving \((E,H)\)
- We fight: Weak signal per object \(\sigma_{\text{scatt}} \ll 0.2 \, \mu m^2\)

Curto et al., Science (2010)
The incident $k_\parallel$ is fixed

The objective back aperture images wave vectors scattered by the sample

Objective transmission function $T(\theta)$ from fluorescence of dye-doped fluorescent beads

M. A. Lieb, JOSA B 21, 6 (2004); N. Le Thomas, JOSA B 24, 12 (2007)
Fourier microscope set up

Supercontinuum light source (Fianium) + AOTF

Objective (NA=0.95)

Back aperture

Fourier lens

Tube lens

CCD

\[ \lambda = 600 \text{ nm} \]

Real space
Au nanobar array

Fourier space
Grating orders

SEM image of an array of 200x50x30 nm Au nanobars on glass, lattice spacing 4 \( \mu \text{m} \)
Radiation pattern of Au nanobars

A single dipole: donut shaped radiation pattern $\sin^2 \theta$

z-oriented dipole
Fourier microscopy of an array of ultra short Au nanobars

- No pinhole, sparse array
- Grating orders
- Sparse sampling of radiation patterns of sub-wavelength nanoscaterrers

\[ \lambda = 600 \text{ nm} \]

\[ \sin^2 \theta \]

Analyzer

cross-section through data

Intensity (x10^8 cts/pxl/ms/mW)
Fourier microscope set up

- Supercontinuum light source (Fianium) + AOTF
- Objective (NA=0.95)
- Pinhole
- Fourier lens
- Tube lens
- CCD

\[ \lambda = 600 \text{ nm} \]

Real space:
- Au nanobar array
- Fourier space:
- Fourier orders

Fourier image of single plasmonic structure

Au nanobars on glass, lattice spacing 4 µm
Fourier microscope set up

Supercontinuum light source (Fianium) + AOTF

\( \lambda = 725 \text{nm} \)

Objective (NA=0.95)

Back aperture

Fourier lens

Pinhole

Tube lens

CCD

1 \( \mu \text{m} \) Au rod

2 \( \mu \text{m} \) Au rod

Intensity (x10^7 cts/pix/mW)

-1 0 1

1 0 -1

\( k_x \) 0 \( k_y \)
Radiation pattern of Au nanobars: vertical bars

A line of dipoles: donut $\times$ sinc function

$$E(k_z) = E_{\text{dip}}(k_z) \frac{e^{ik_0f}}{f} \int_{-L/2}^{L/2} e^{-ik_yy} dy$$

$$\propto E_{\text{dip}}(k_z) \text{sinc}(k_zL/2)$$
Polarization analysis

\[ \lambda = 650 \text{ nm} \]
Radiation pattern of Au nanobars: horizontal bars

- Incident $k_{\parallel}$ outside of the NA
- Wings of $\text{sinc}((k_{in}+k_{\parallel})L/2)$
- Lower wavelengths (< 725 nm) show plasmonic character

$I_z(z) = I_{\parallel} e^{ik_{\parallel}z} + I_{\pm p} e^{\pm ik_{\parallel}z}$

Dorfmuller et al., Nano Letters 10 (2010)
Current effort: split ring $\alpha$

Quantify magneto-electric dipole response:

$$\begin{pmatrix} p_x \\ m_z \end{pmatrix} = \begin{pmatrix} \alpha_E & i\alpha_{EH} \\ -i\alpha_{EH} & \alpha_H \end{pmatrix} \begin{pmatrix} E_x \\ H_z \end{pmatrix}$$

- Control both incident $E$ and $H$
- Radiation pattern will reveal $p$ and $m$
Conclusion

We can measure radiation patterns and quantify $\alpha$ of single and sub-wavelength plasmonic and metamaterial scatterers.

Thank you for your attention!

Congratulations Dr. Soukoulis!