NEO LAB
The laboratory for Nanoscale Electro Optics

Manipulation of Harmonics and Hybrid Light-Matter States with Optical Metasurfaces

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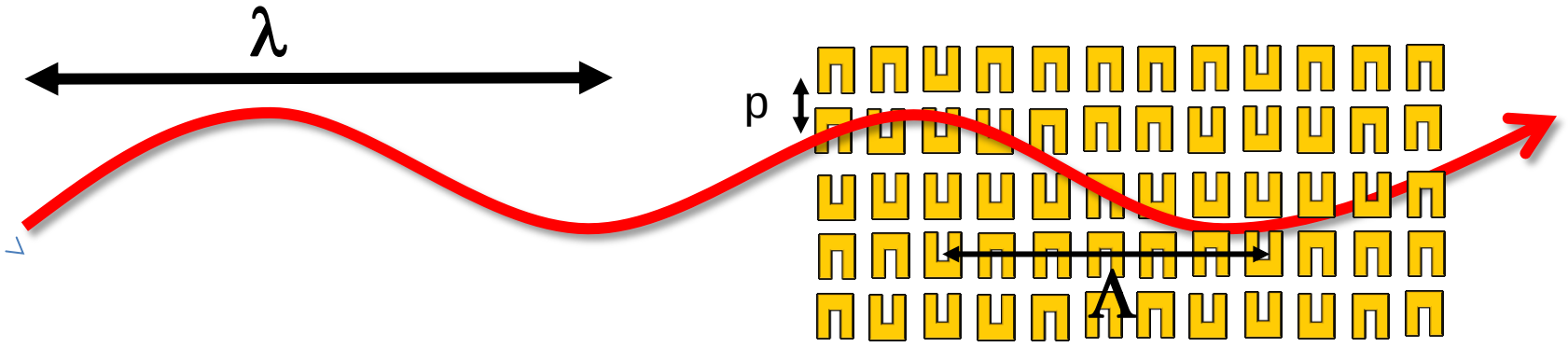
website: www.eng.tau.ac.il/~tal/neolab

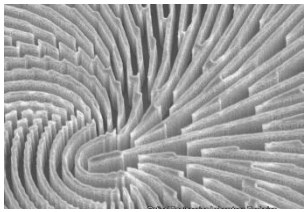


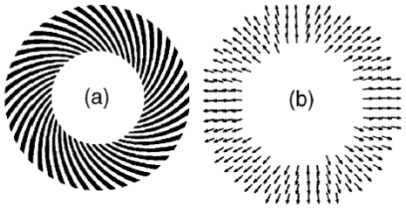
Metasurfaces New Physics and Applications

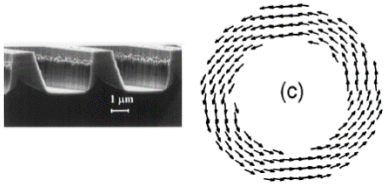
Hasman's group

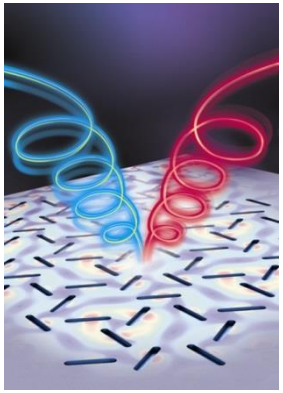
Space variant sub-wavelength gratings

Spinoptical Metamaterials









Science 340 (2013)

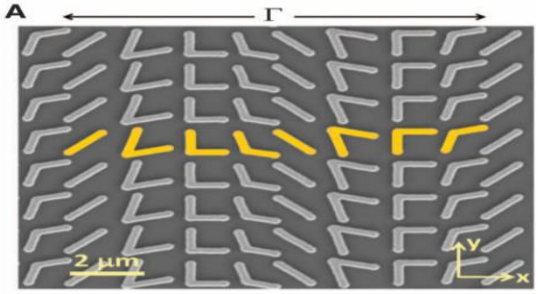
Pancharatnam phase

Opt. Lett. 27, 285-287 (2002)
Opt. Lett. 29, 238-240 (2004)
Opt. Commun. 251, 306 (2005)

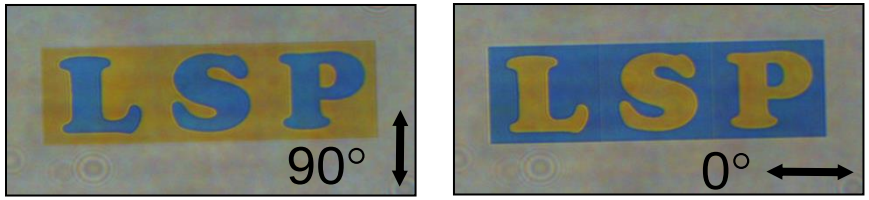
Generalized Snell's Law

Science 334 (2011)

Science 335 (2012)

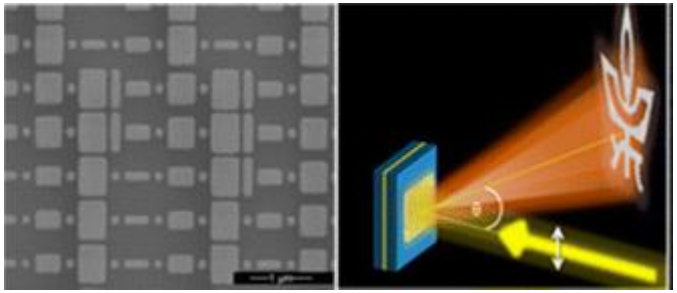


Chromatic Plasmonic Polarizers



Ellenbogen et. al Nano Lett. 12, 1026-1031 (2012)

Broadband Holography

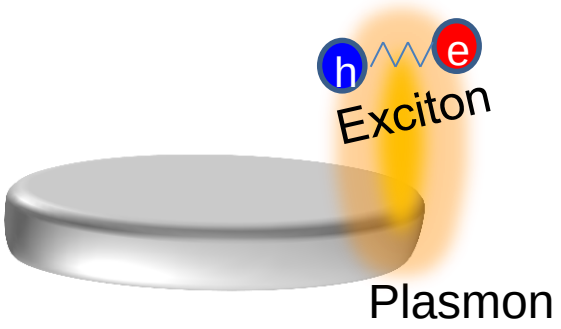


Yifat et. al Nano Lett. 14, 2485-2490 (2014)

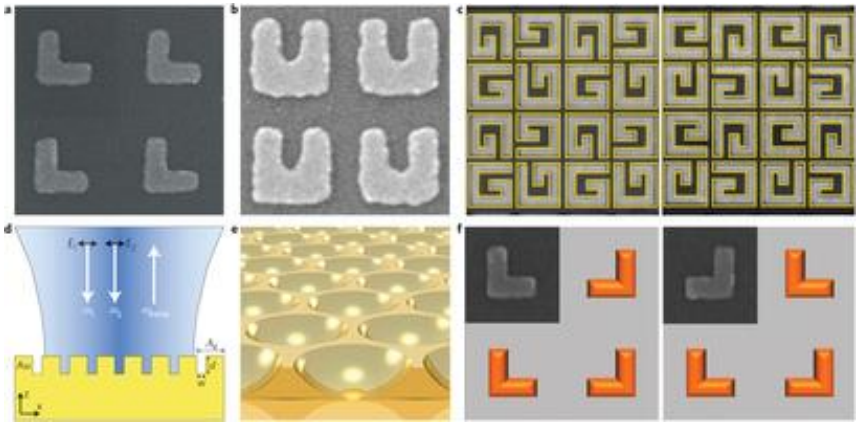
Exploring active metasurfaces

I Structural quadratic Nonlinearity

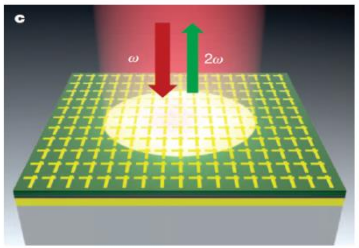
II Exciton-plasmon hybridization

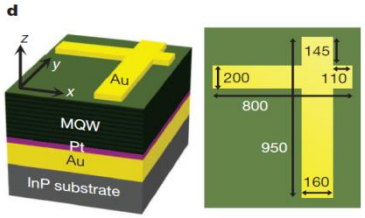


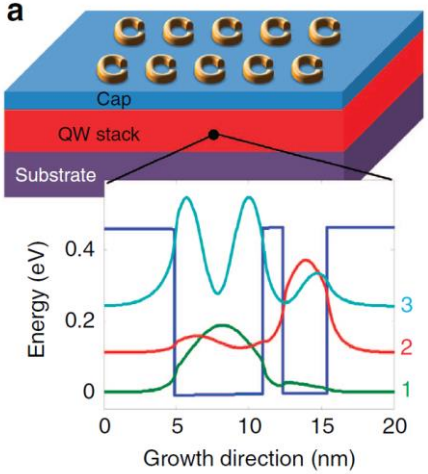
Nonlinear Metamaterials – Enhanced Nonlinearity and Functionality



M. Kauranen and A. V. Zayats, *Nat. Photonics* **6** (2012)

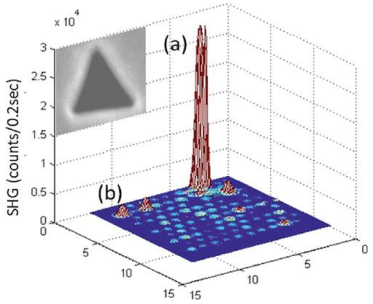






O. Wolf, et al., Nat. Commun. **6**, 7667 (2015)
J. Lee, et al., Nature **511**, 65 (2014)

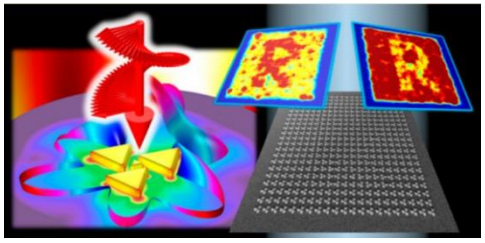
Resonant $\chi^{(2)}$ **3-5 orders of magnitude** larger nonlinearity



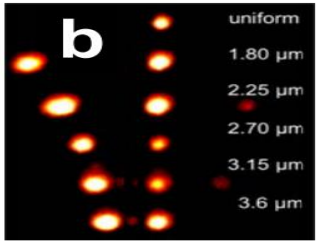
Shape based quadratic nonlinearity

A. Salomon, M. Zielinski, R. Kolkowski, J. Zyss, and Y. Prior, *J. Phys. Chem. C* **117** (2013)

Functionality



Kolkowski et al. ACS Photonics **2** (2015)



Almeida et al. Nat. Commun. 7 (2015)

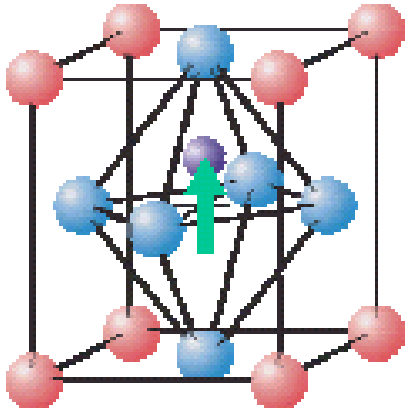
Symmetry considerations Quadratic Optical Nonlinearity

$$P_i = \varepsilon_0[\chi_{ij}^{(1)}E_j + \chi_{ijk}^{(2)}E_jE_k + \chi_{ijkl}^{(3)}E_jE_kE_l + \ldots]$$

Inversion symmetry $P(-E) = -P(E)$ $\chi^{(even)}=0$

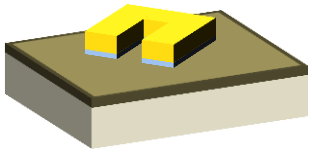
Breaking symmetry

Bulk

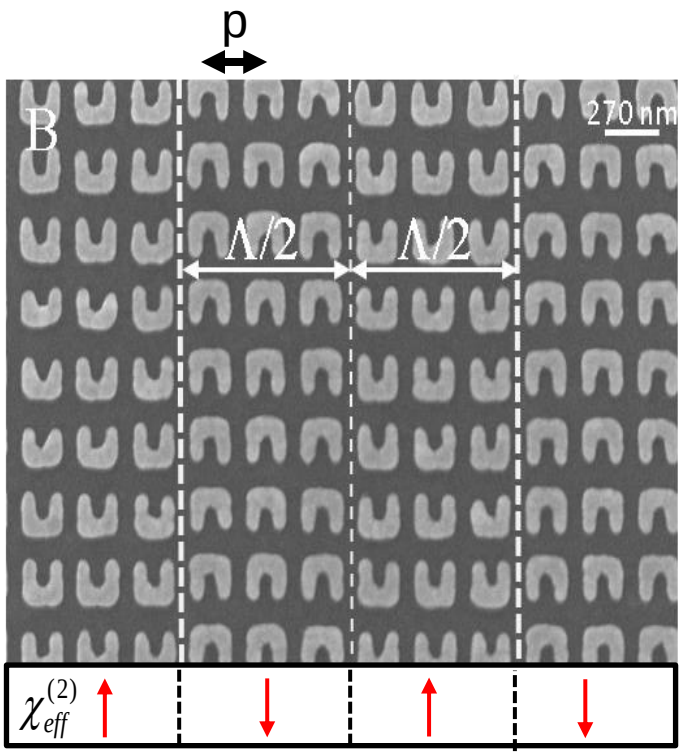


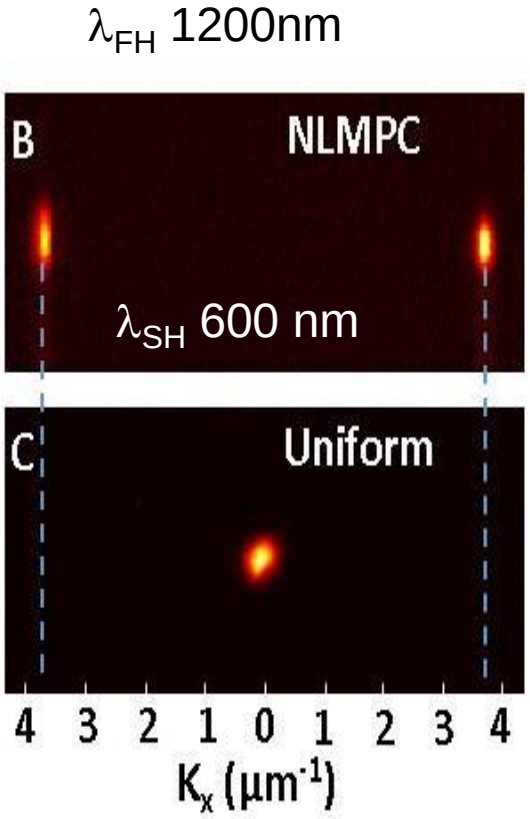
Surface/Shape

Experimental Results – Nonlinear Diffraction from Metamaterial based Photonic Crystal



Gold 30 nm
Ti 3 nm
ITO
Glass





N. Segal, S. Keren-Zur, N. Hendler and T. Ellenbogen, Nature Photon. **9**, 180-184 (2015)

Experimental Results – NLMPC

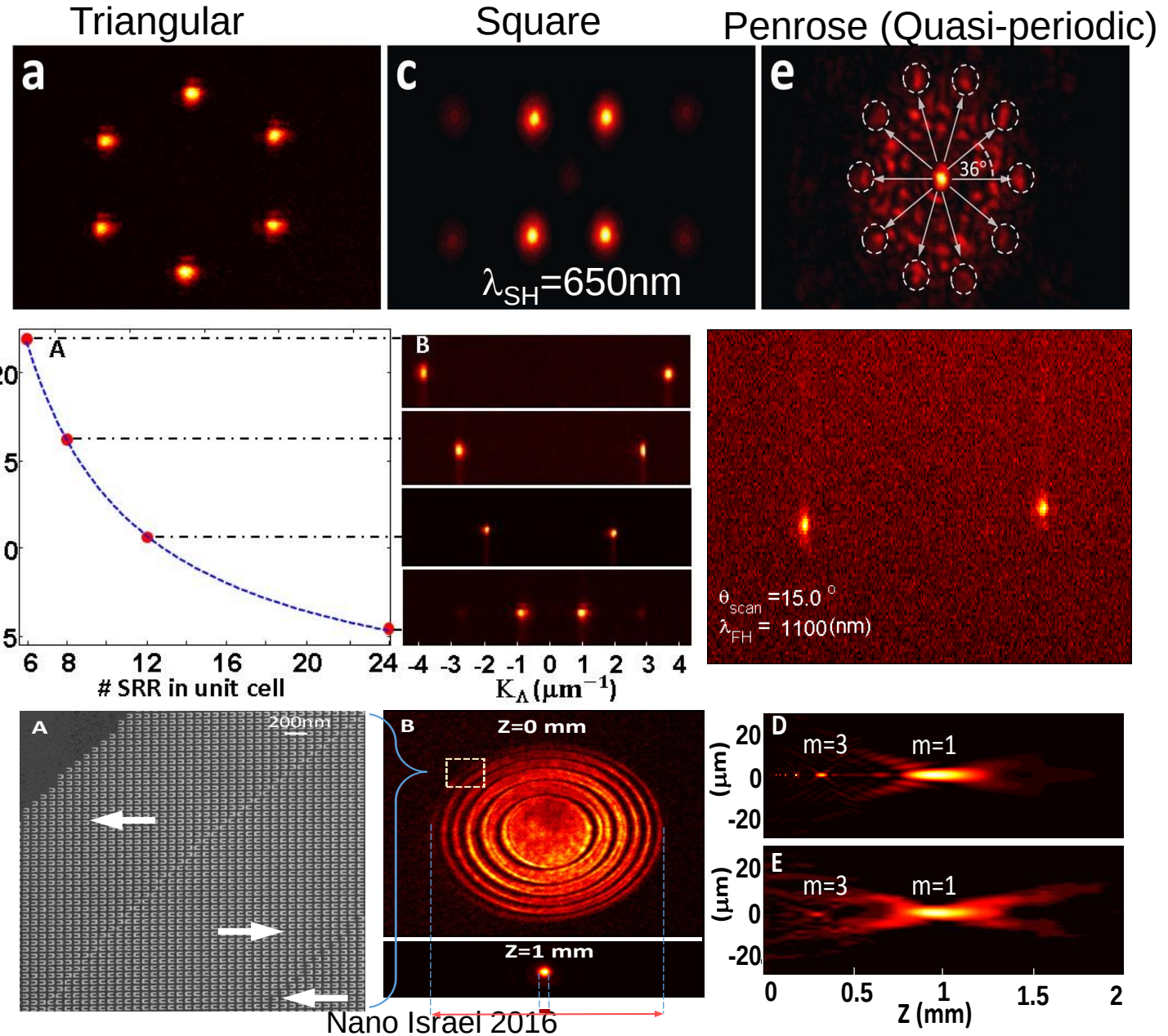
Nonlinear diffraction from 2D Crystals

All-Optical Scanning

$$\sin\theta_{SH} = m\lambda_1/2\Lambda$$

Nonlinear Focusing of SH

Nature Photon. **9**, 180-184 (2015)



Nano Israel 2016

Beam shaping with metasurface based nonlinear computer generated holograms

$$\chi_{eff}^{(2)}(x,y) = \chi_{SRR}^{(2)} sign\left\{cos\left[\frac{2\pi x}{\Lambda} - \varphi(x,y)\right] - cos[\pi q(x,y)]\right\}$$

$\varphi(x,y)$ – encodes phase
$q(x,y)$ - encodes the amplitude

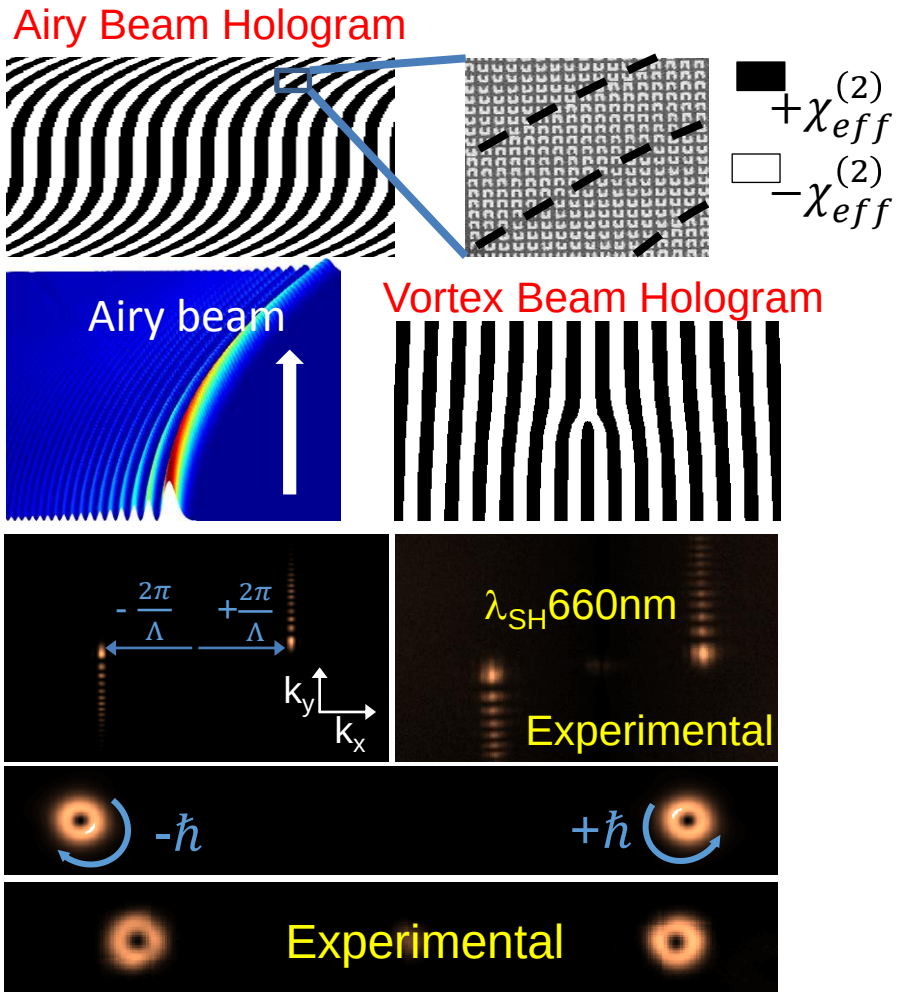
A. Shapira, R. Shiloh, I. Juwiler, and A. Arie, Opt. Lett. **37**, 2136 (2012)

Airy Beam Hologram

$$\chi_{eff}^{(2)}(x,y) = \chi_{SRR}^{(2)} sign\left[\cos\left(\frac{2\pi}{\Lambda}x - f_c y^3\right)\right]$$

Vortex Beam Hologram

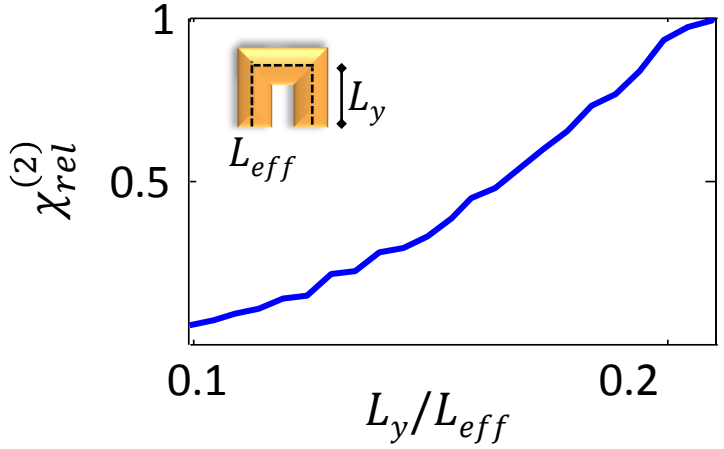
$$\chi_{eff}^{(2)}(x,\phi) = \chi_{SRR}^{(2)} sign\left[\cos\left(\frac{2\pi}{\Lambda}x - l\phi\right)\right]$$

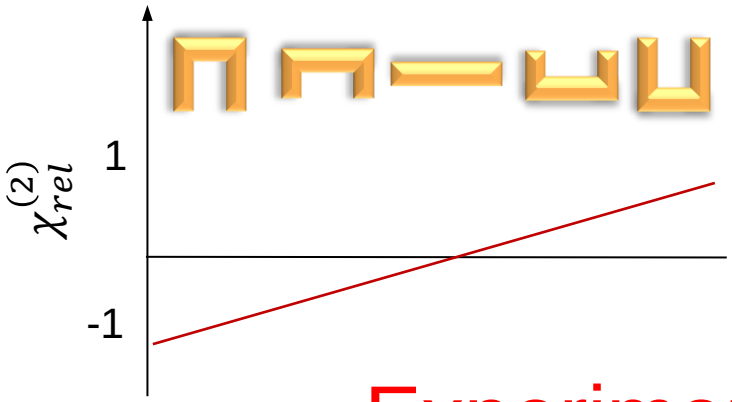


S. Keren-Zur, O. Avayu, L. Michaeli, and T. Ellenbogen, ACS Photonics **3**, 117-123 (2016)

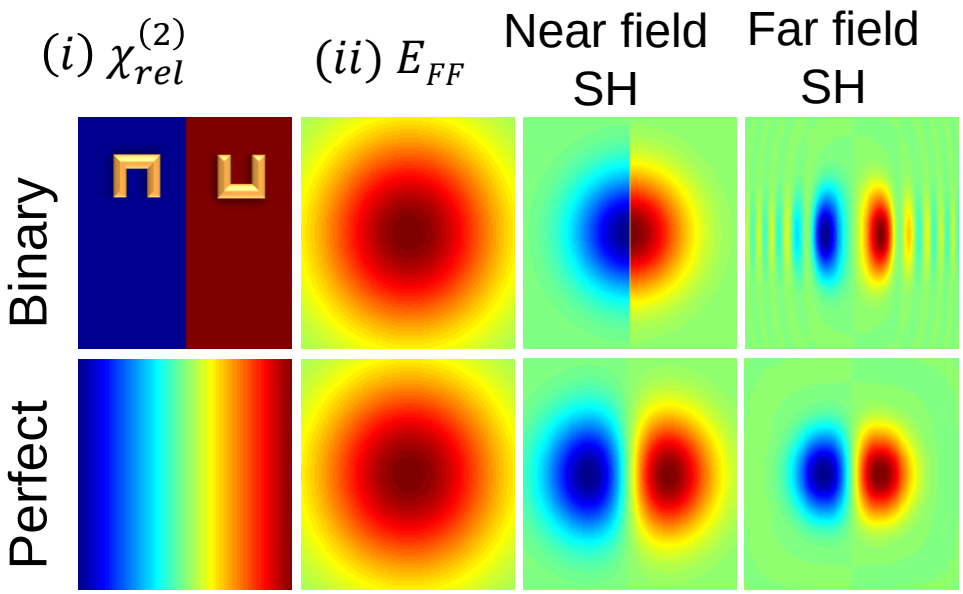
Perfect beam shaping metasurfaces HG_{01}

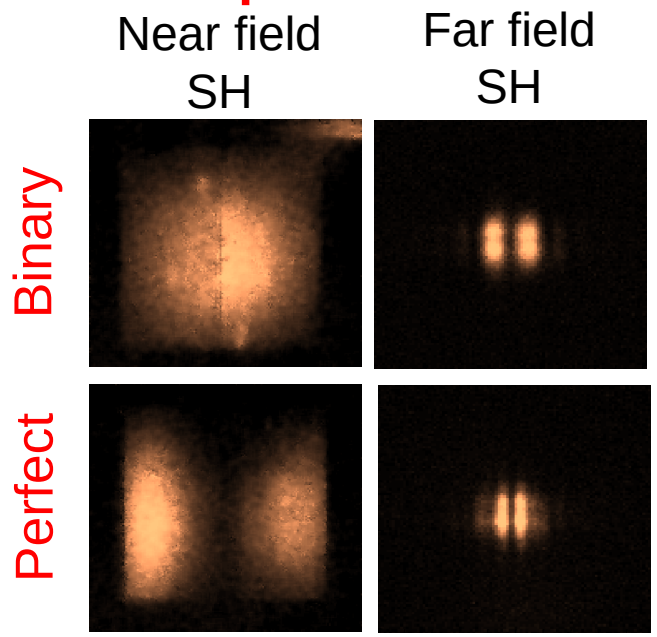
K. O'Brien, H. Suchowski, et. al., Nat. Mater. **14**, 379 (2015).





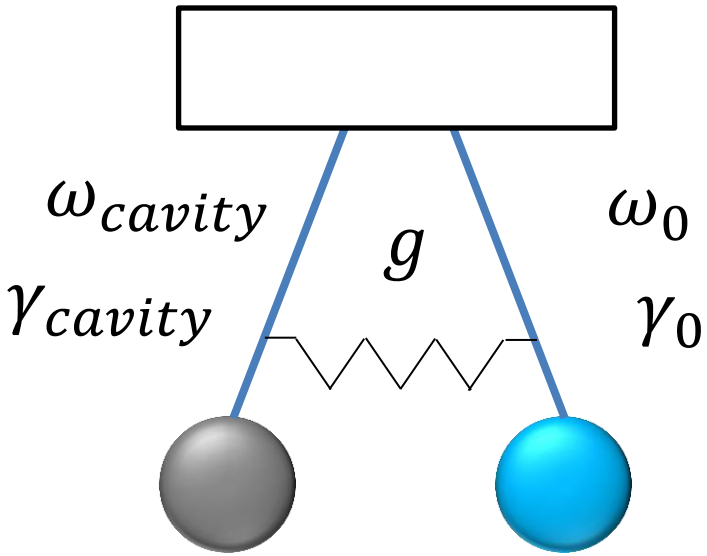
Experiment

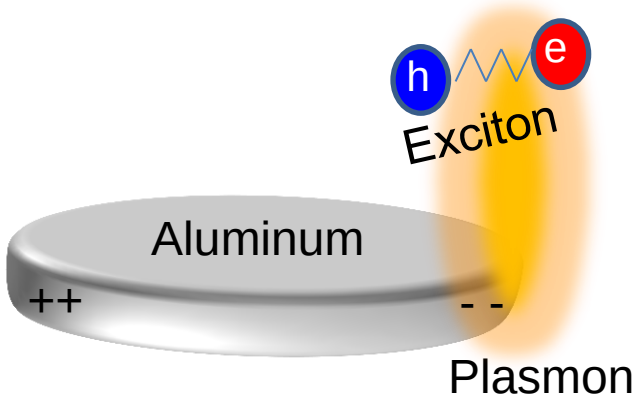




S. Keren-Zur, O. Avayu, L. Michaeli, and T. Ellenbogen, ACS Photonics **3**, 117-123 (2016)

Exciton Plasmon as Coupled Oscillators

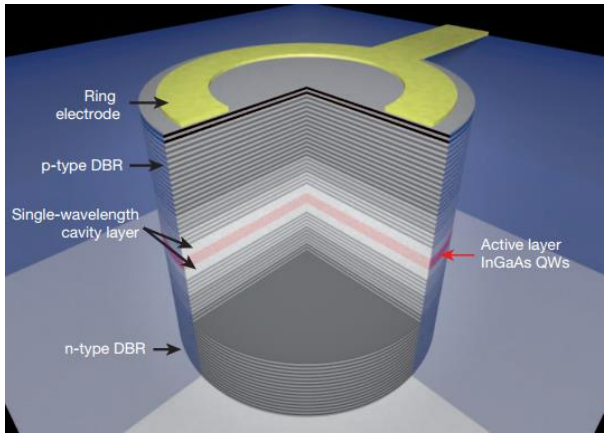




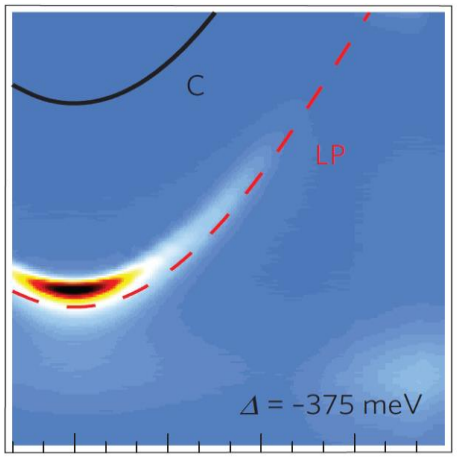
$$\begin{pmatrix} U_{cavity} - i\frac{\gamma_{cavity}}{2} & g \\ g & U_0 - i\frac{\gamma_0}{2} \end{pmatrix} \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = U_{LP,UP} \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$$U_{LP,UP} = \frac{1}{2}\left[U_0 + U_{cavity} - i\left(\frac{\gamma_0}{2} + \frac{\gamma_{cavity}}{2}\right) \pm \sqrt{4g^2 + \left(U_0 - U_{cavity} - i\left(\frac{\gamma_0}{2} - \frac{\gamma_{cavity}}{2}\right)\right)^2}\right]$$

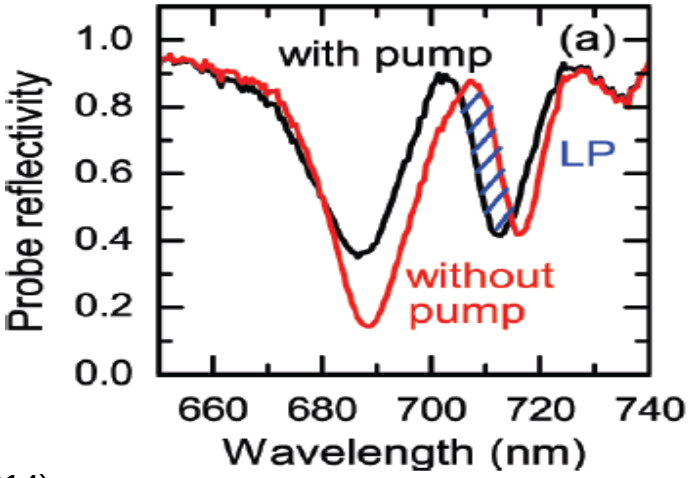
Fundamental Science and Applications



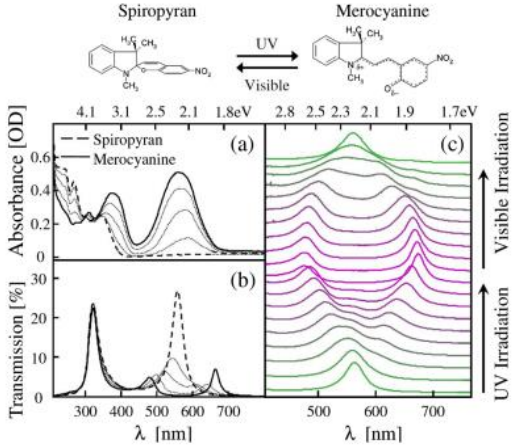
Schneider,…, Reitzenstein, et al., Nature 497 (2013)

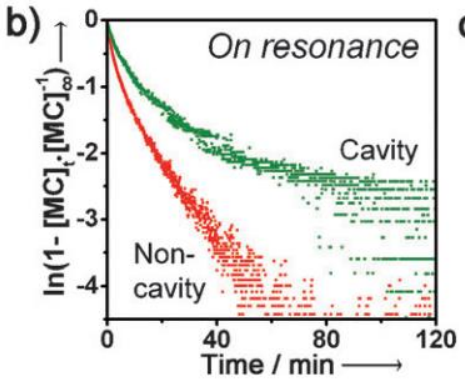


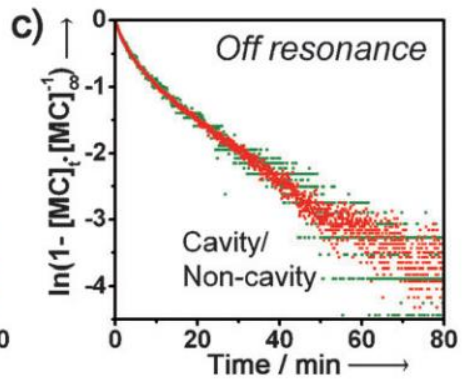
Daskalakis, et al. *Nat. Mater. 13* (2014)



Vasa, P. et al. *ACS Nano 4 (*2010)

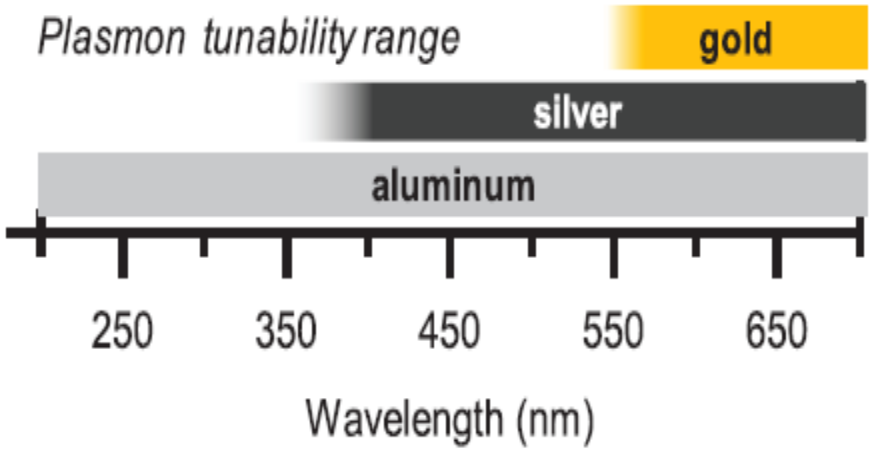


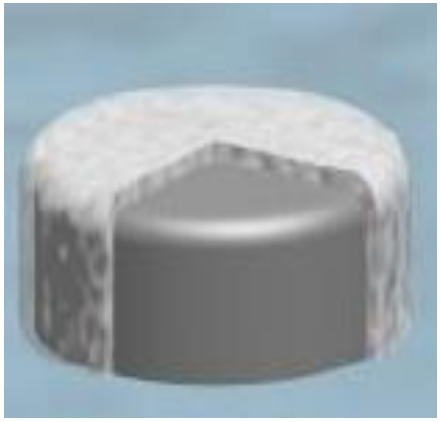




J. Hutchison, D. O'Carroll, T. Schwartz, et al., Angew. Chem. Int. Ed. 50 (2011).
T. Schwartz, et al., Phys. Rev. Lett. 106 (2011).
J. Hutchison, T. Schwartz, et al. Angew. Chem. Int. Ed. 51 (2012).
T. Schwartz et al., ChemPhysChem 14 (2013).

Why use Aluminum for Plasmonics





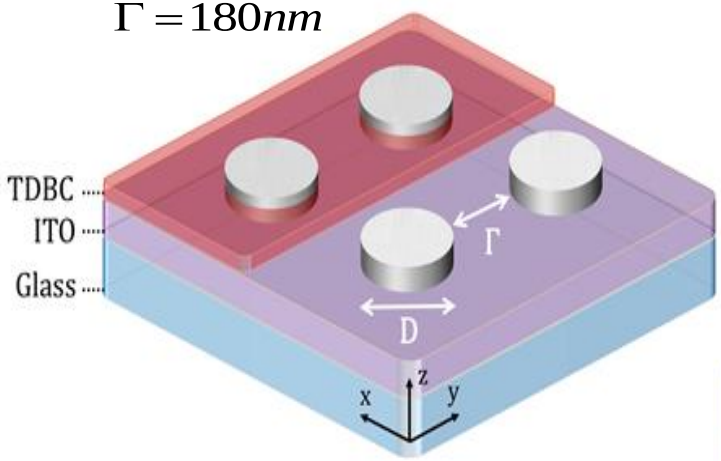
2-3nm stable oxide

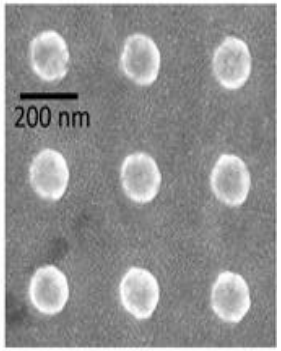
- ✓ Support LSPs from visible to UV frequencies.
- ✓ Durable due to the stable oxide layer.
- ✓ Cheap and abundant.
- ✓ Was not used before for X-LSP.

- ❑ Knight, M et al. *ACS Nano 8 (*2014)

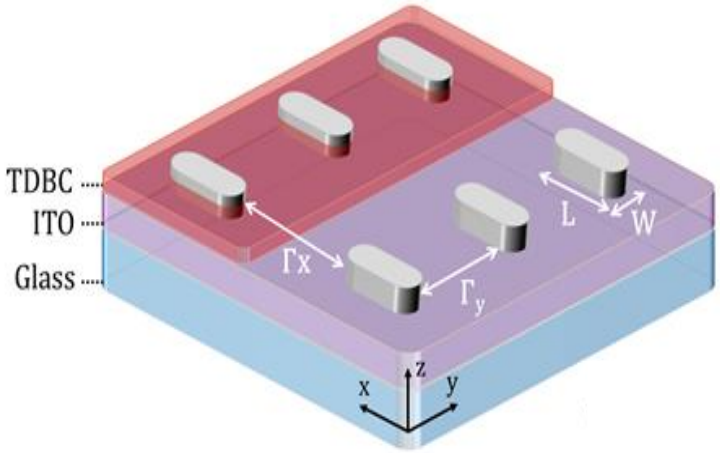
Aluminum Polaritonic Metasurface

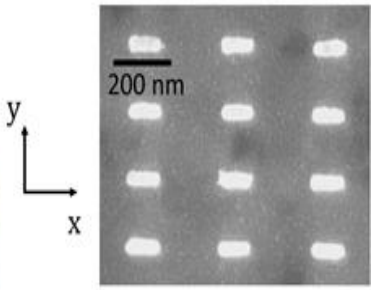
$\Gamma = 180nm$



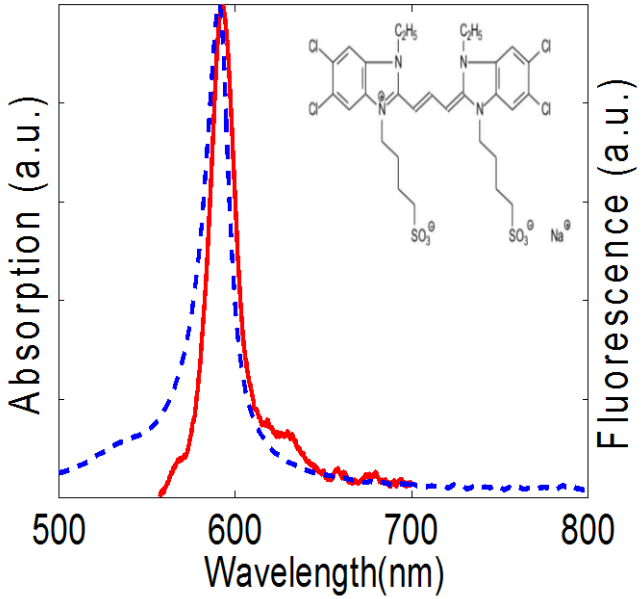


$\Gamma_x = 200nm, \Gamma_y = 150nm, W = 40nm$





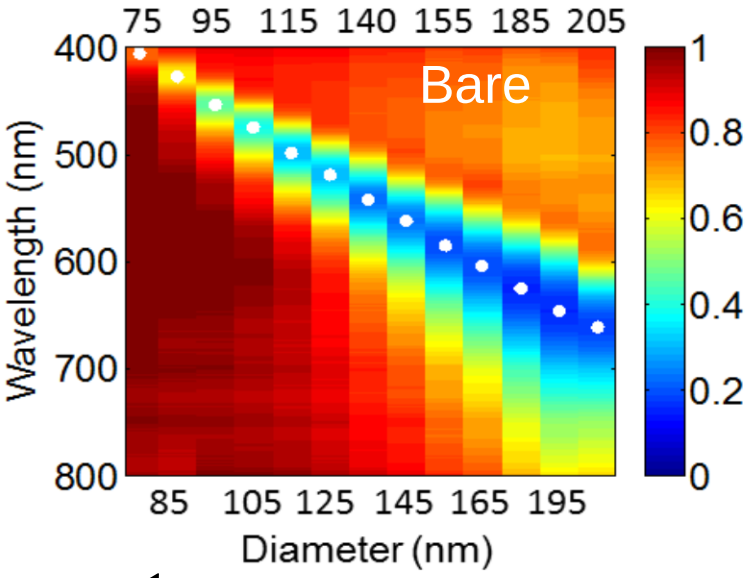
Molecular J-Aggregates

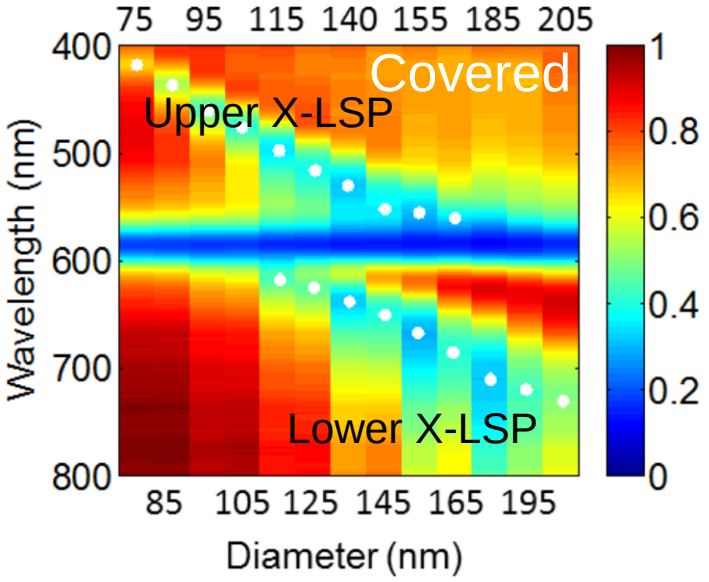


- ✓ Large transition dipole moment.
- ✓ Narrow absorbance and emission spectra.
- ✓ The excitation is delocalized.

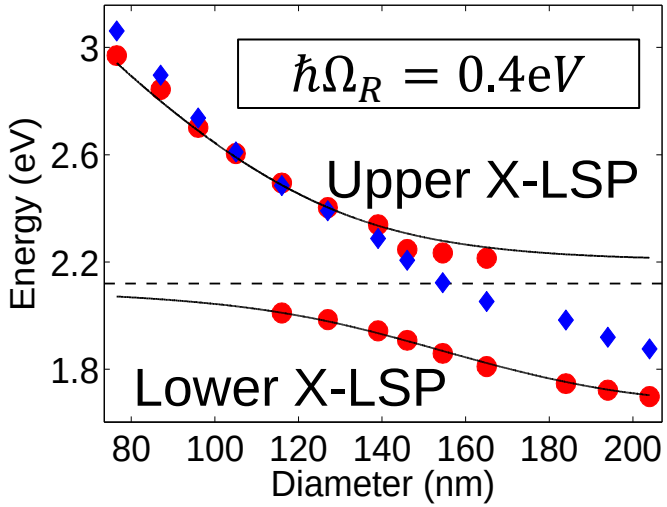
- E. Eizner, et al., Nano Letters **15**, 6215-6221(2015).

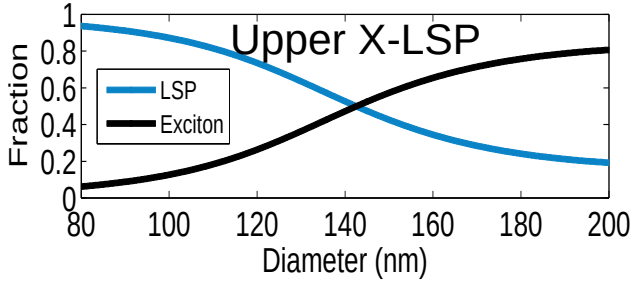
Probing Polaritons by Nanodisks transmission

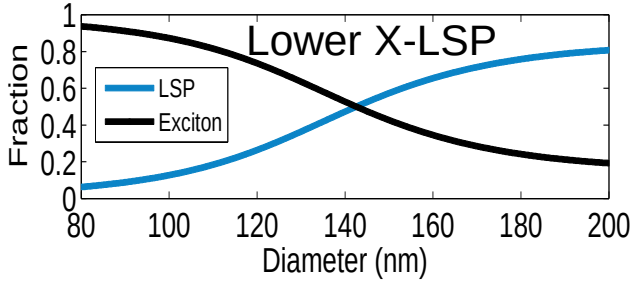




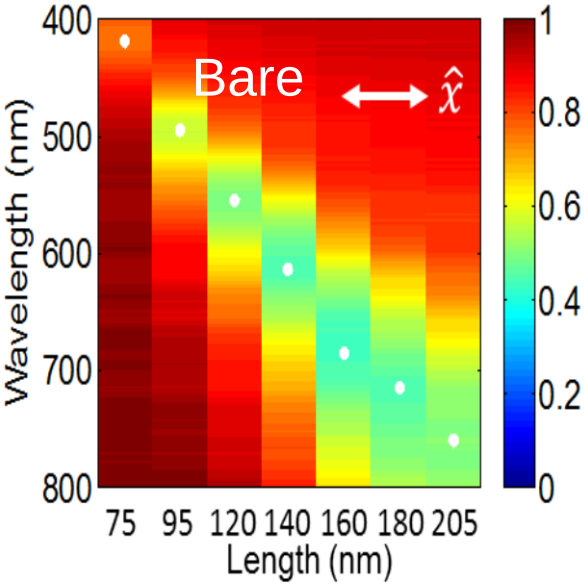
$$U_{LP,UP} = \frac{1}{2}[U_x + f \cdot U_{LSP} \pm \sqrt{4g^2 + (U_X - f \cdot U_{LSP})^2}]$$

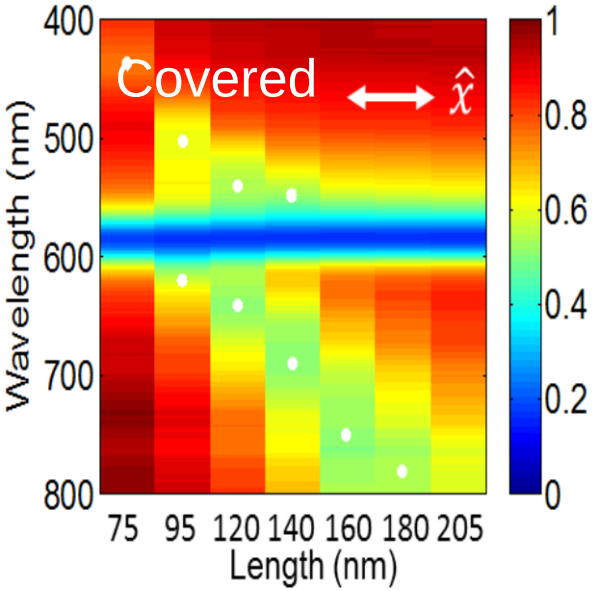


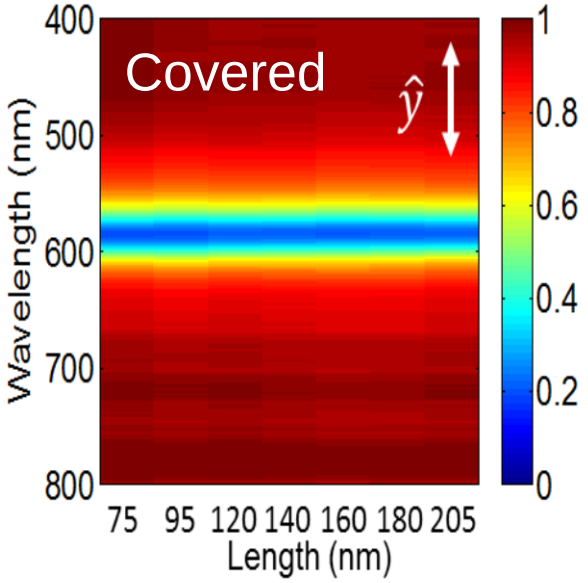




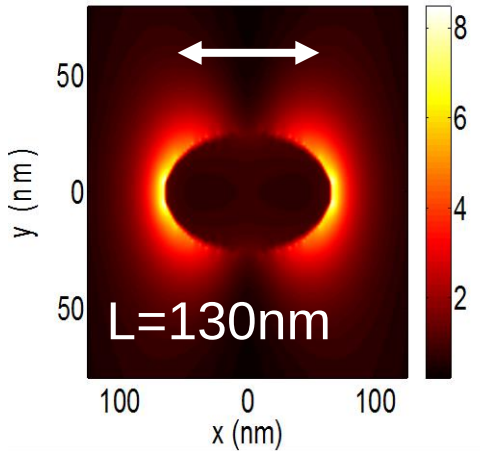
Nanorods transmission –Polarized Polaritons

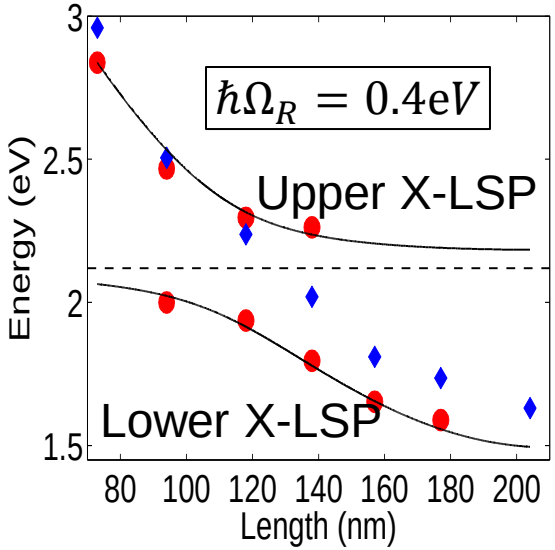




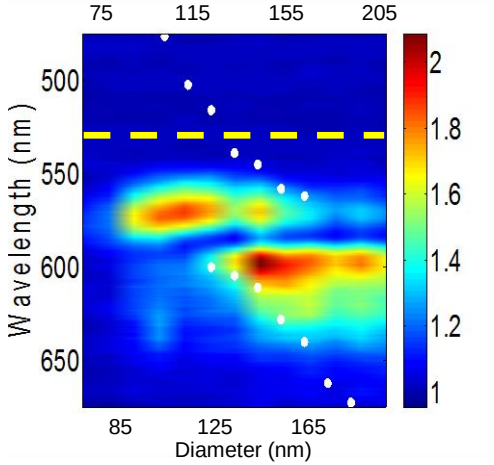


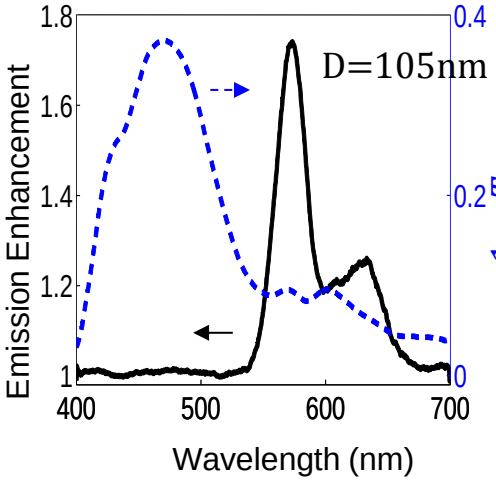
$|E/E_0|$

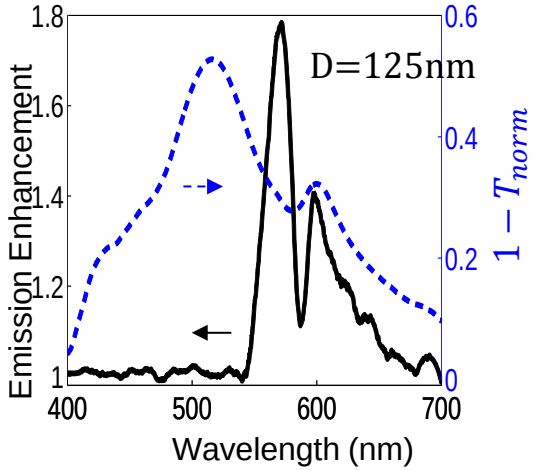


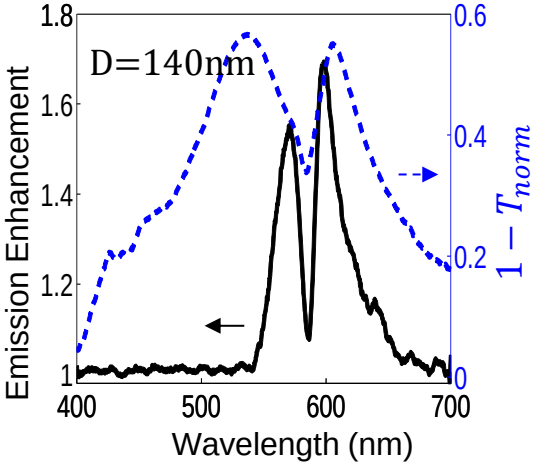


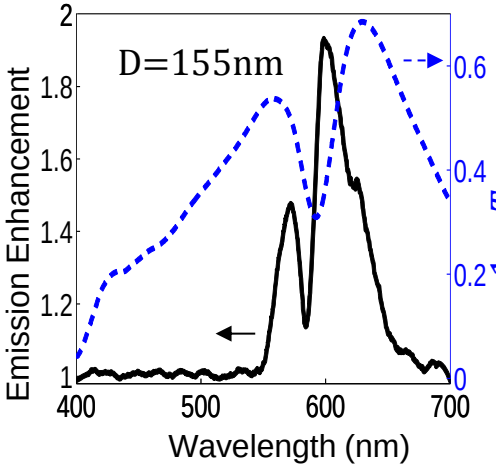
Emission pulling due to near field enhancement and increase of density of states

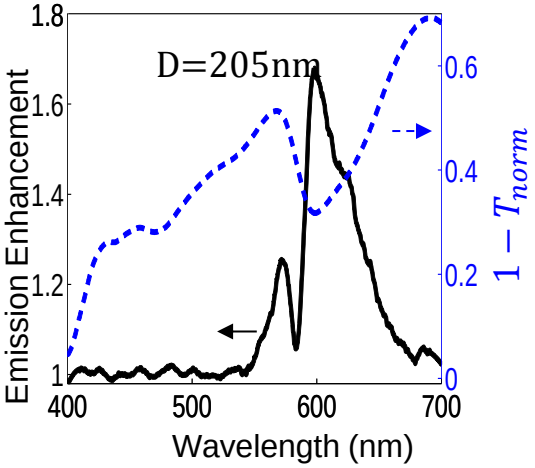












- E. Eizner, O. Avayu, R. Ditcovski, T. Ellenbogen, Nano Letters **15**, 6215-6221(2015).

Sneak Peek to Another Story

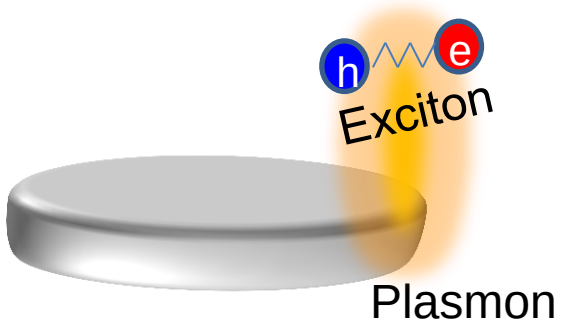
Summary

I Structural quadratic Nonlinearity

- ✓ Enhanced nonlinearity
- ✓ Easy integration
- ✓ Perfect engineering of nonlinearity
- ✓ Functional optical materials:

Nonlinear photonic crystals, Perfect beam shaping, SFG and DFG

II Exciton-plasmon hybridization



- ✓ Aluminum nanoantennas excellent platform for the formation of hybrid exciton-LSPs.
- ✓ Manipulate the polarization of the hybrid states and to confine their mode volumes.
- ✓ We observe enhancement of the emission

Acknowledgments

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