PHILIPS

FOM Institute AMOLF

Plasmonics for efficient and directional light-emitting devices

Gabriel Lozano
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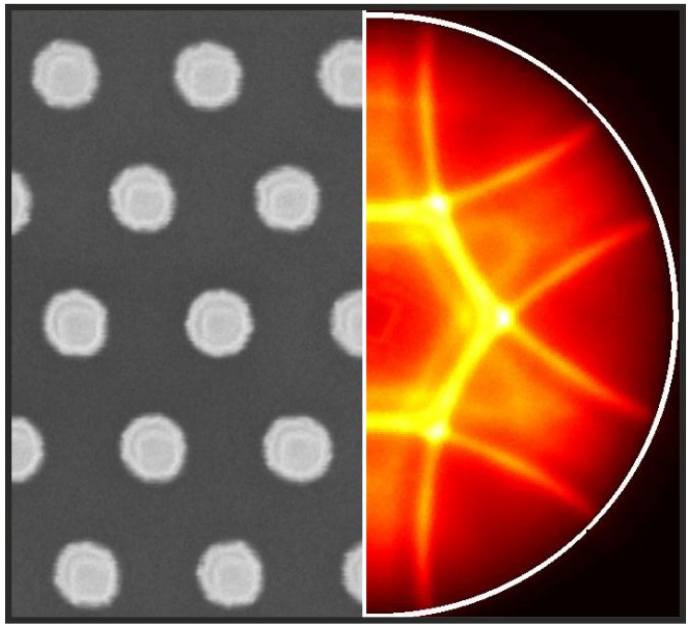
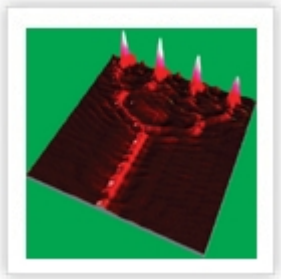
g.lozano@csic.es





Nanolight, **Benasque 02/03-08/03 2014**

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Grzegorz Grzela
Shunsuke Murai
Jaime Gómez Rivas

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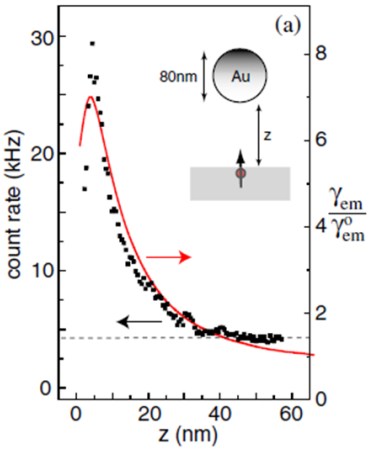
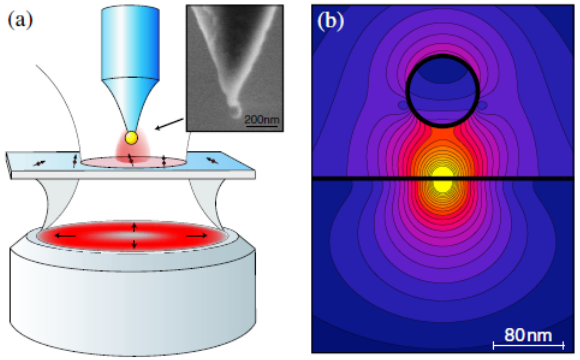
Ke Guo
Eva de Leo
Remco van Brakel
Manuela Lunz
Dick de Boer
Marc Verschuuren
Hans van Sprang

nanonextnl
innovating with micro and nanotechnology

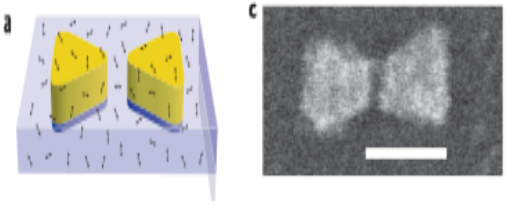
Surface plasmons and emission

PRL **96**, 113002 (2006); *PRL* **97**, 017402 (2006)

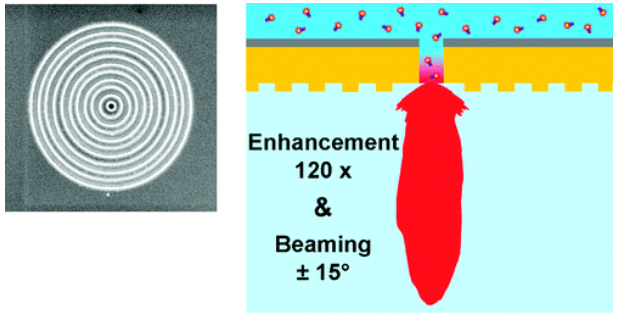




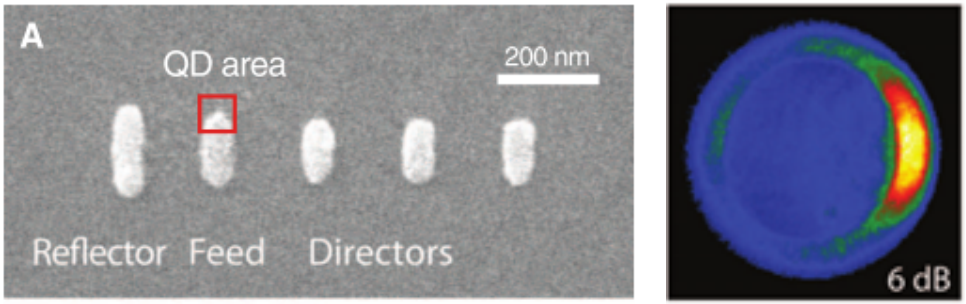
Nat. Photon. **3**, 654 (2009)



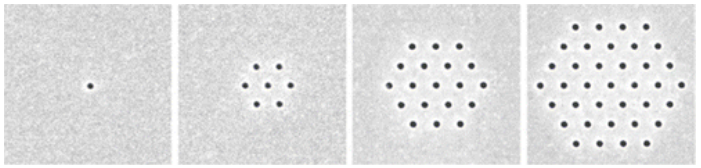
Nano Lett. **11**, 637 (2011)



Science **329**, 930 (2010)



ACS Nano, **7** 8840 (2013)

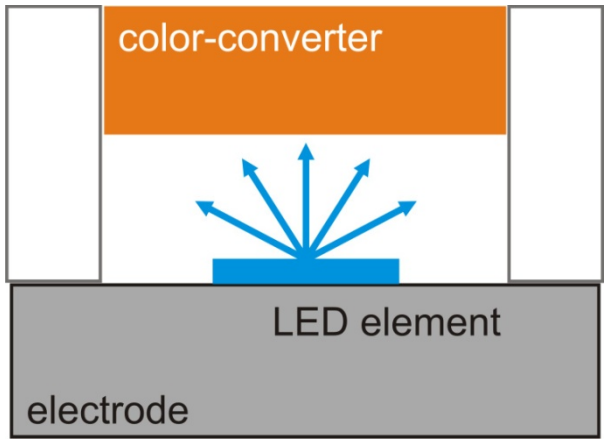


emission enhancement depends strongly on positioning and efficiency

- few emitters
- far red region of the spectrum
- low PL quantum yield

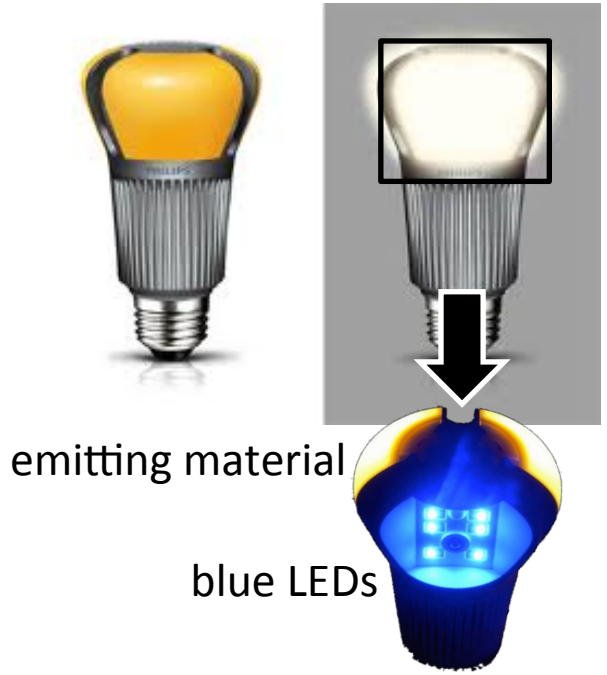
} Plasmonics for SSL?

Plasmonics for SSL

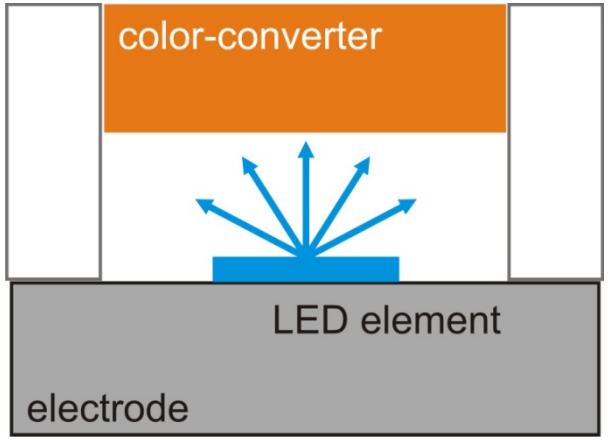


Phosphor-LEDs

Nat. Photon. **3**, 180 (2009)

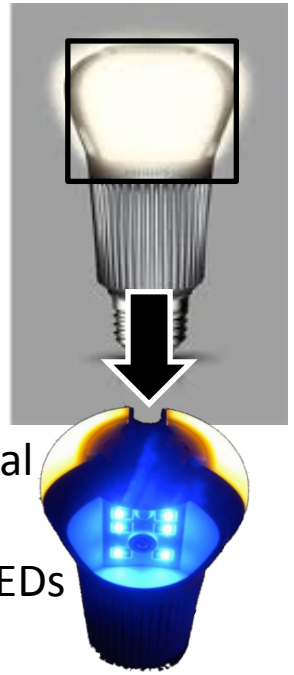


Plasmonics for SSL



Phosphor-LEDs

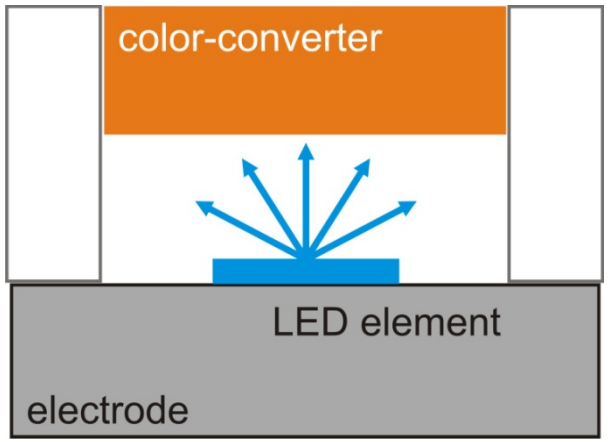
Nat. Photon. **3**, 180 (2009)



secondary optics for directional

LED modules: bulky and not so efficient

Plasmonics for SSL



Phosphor-LEDs

Nat. Photon. **3**, 180 (2009)

secondary optics for directional
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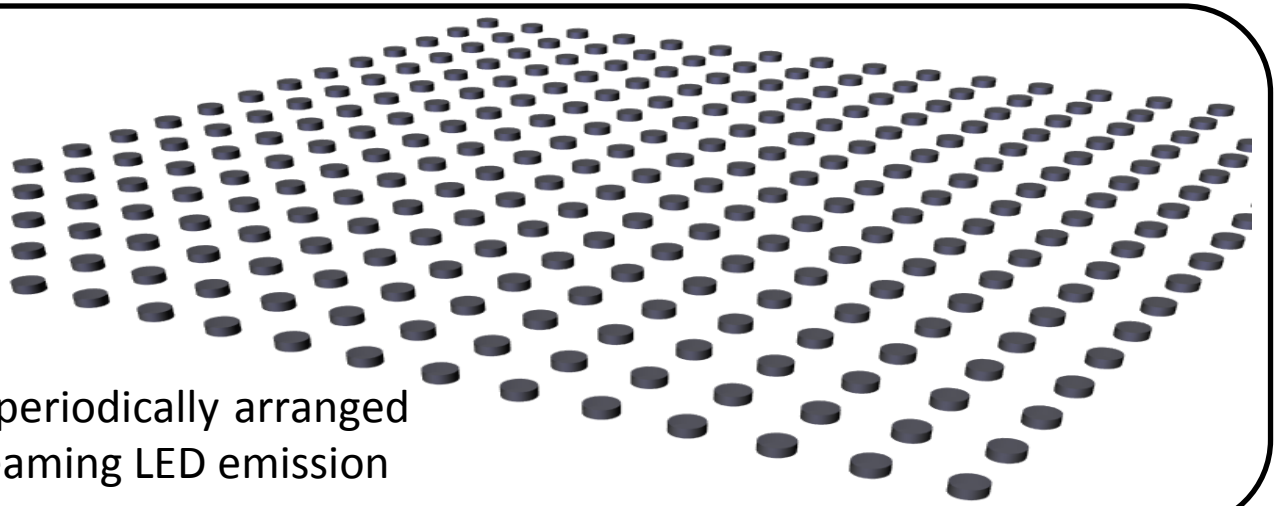


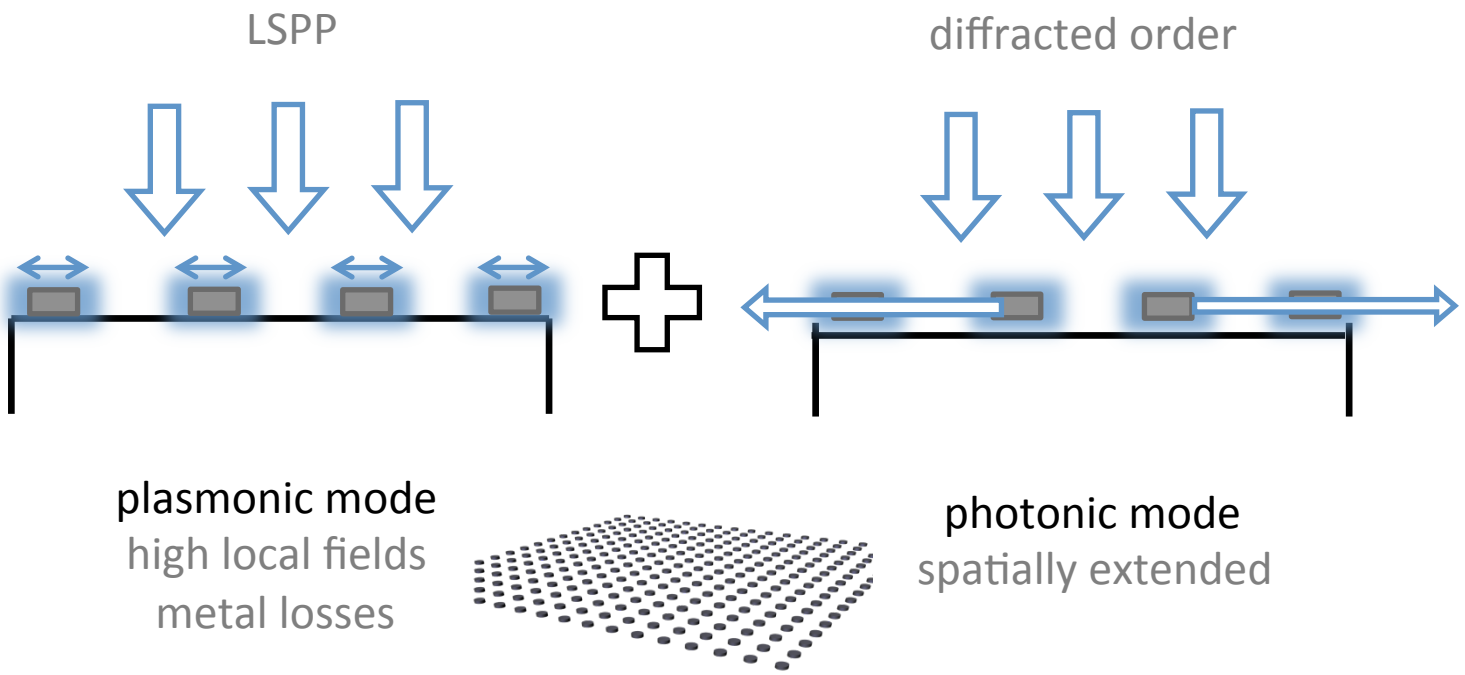
coherent scattering from periodically arranged
metal nanoparticles for beaming LED emission

Hybrid lattice modes

theory: *JOSAB* **3**, 430 (1986); *JCP* **120**, 10871 (2004); *PRL* **95**, 233901 (2005)

exper-extinction: *PRL* **91**, 183901 (2003); *PRL* **101**, 087403 (2008); *APL* **93**, 181108 (2008); *PRL* **101**, 143902 (2008)

exper-emission: *PRL* **102**, 146807 (2009); *PRL* **105**, 266801 (2010); *APL* **100**, 111103 (2012); *Nat. Nanot* **8**, 506 (2013)

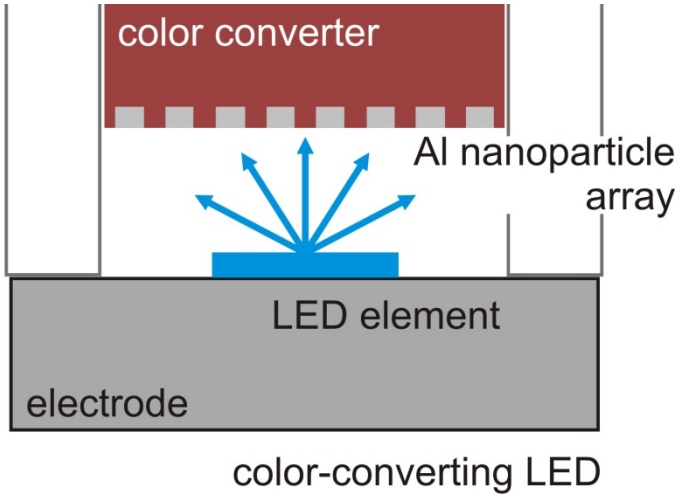


hybrid lattice mode

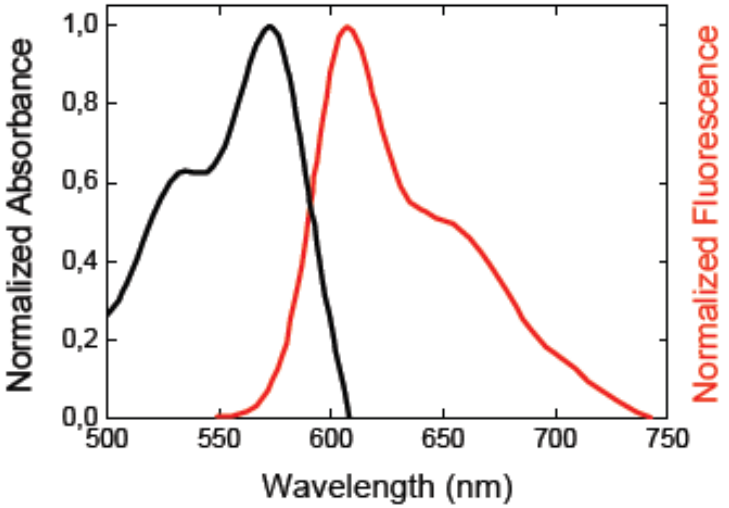
high local fields and weakly confined

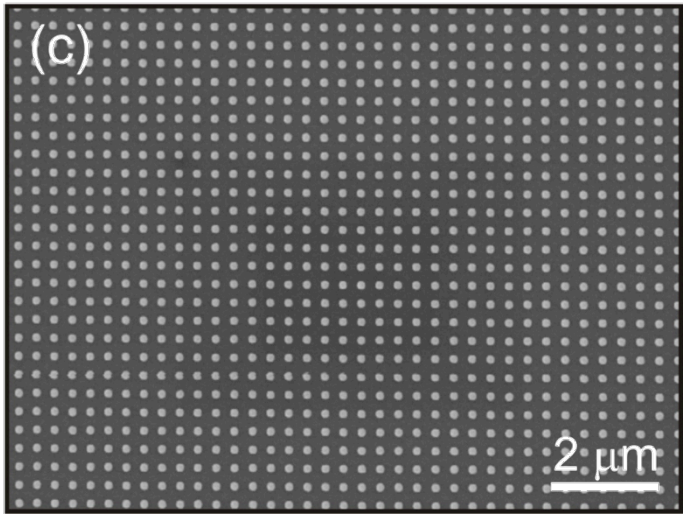
low losses

Plasmonic color-converter



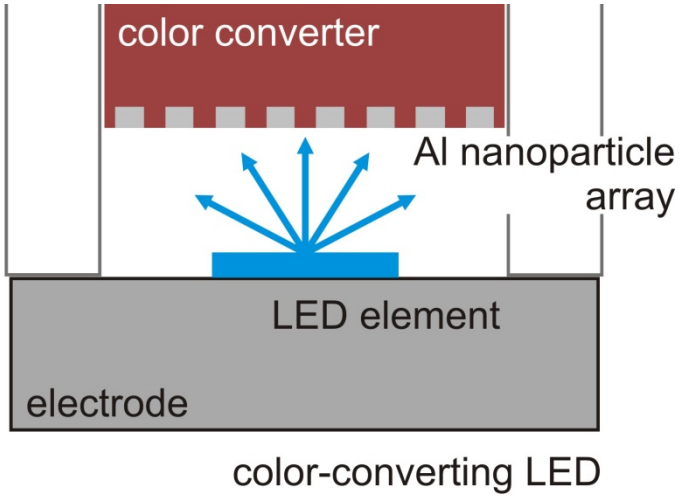
color-converting LED



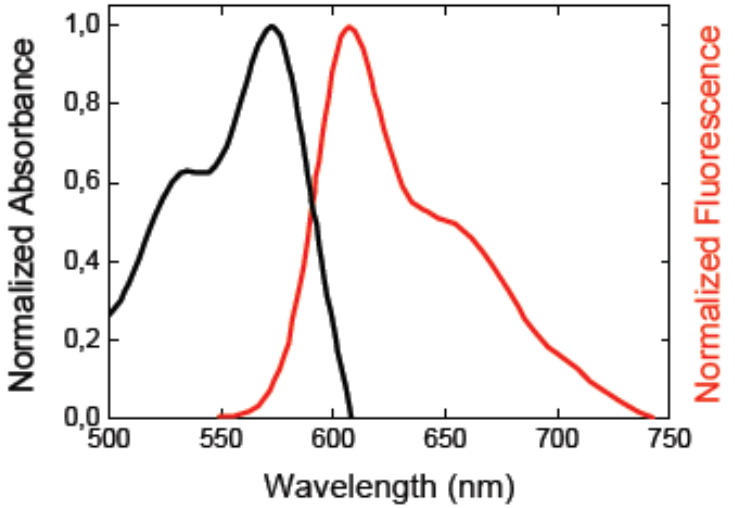


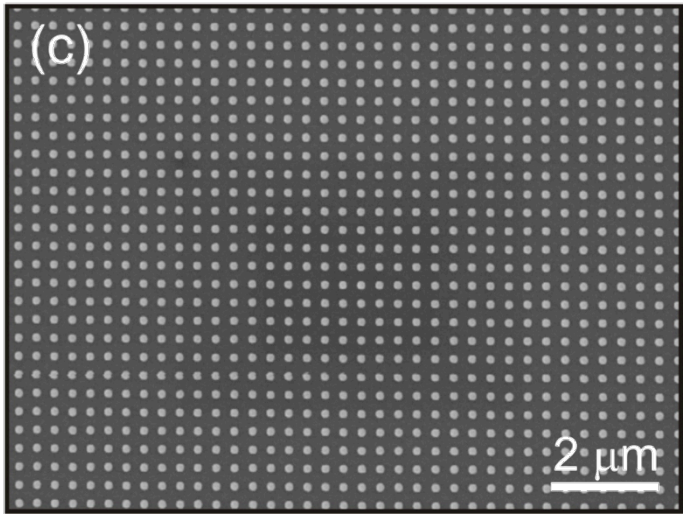
combination of large area metallic arrays with close-to-one QY dye molecules

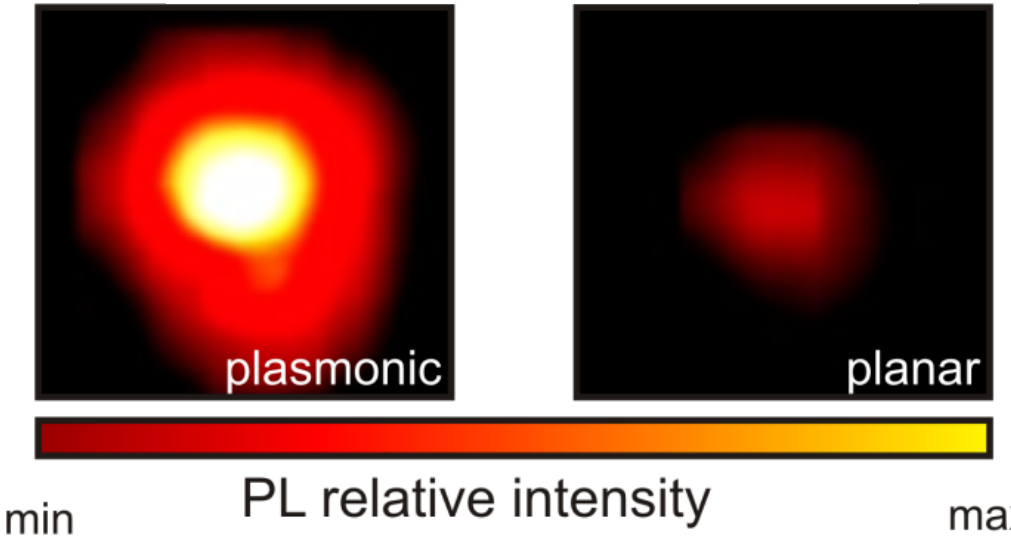
Plasmonic color-converter



color-converting LED



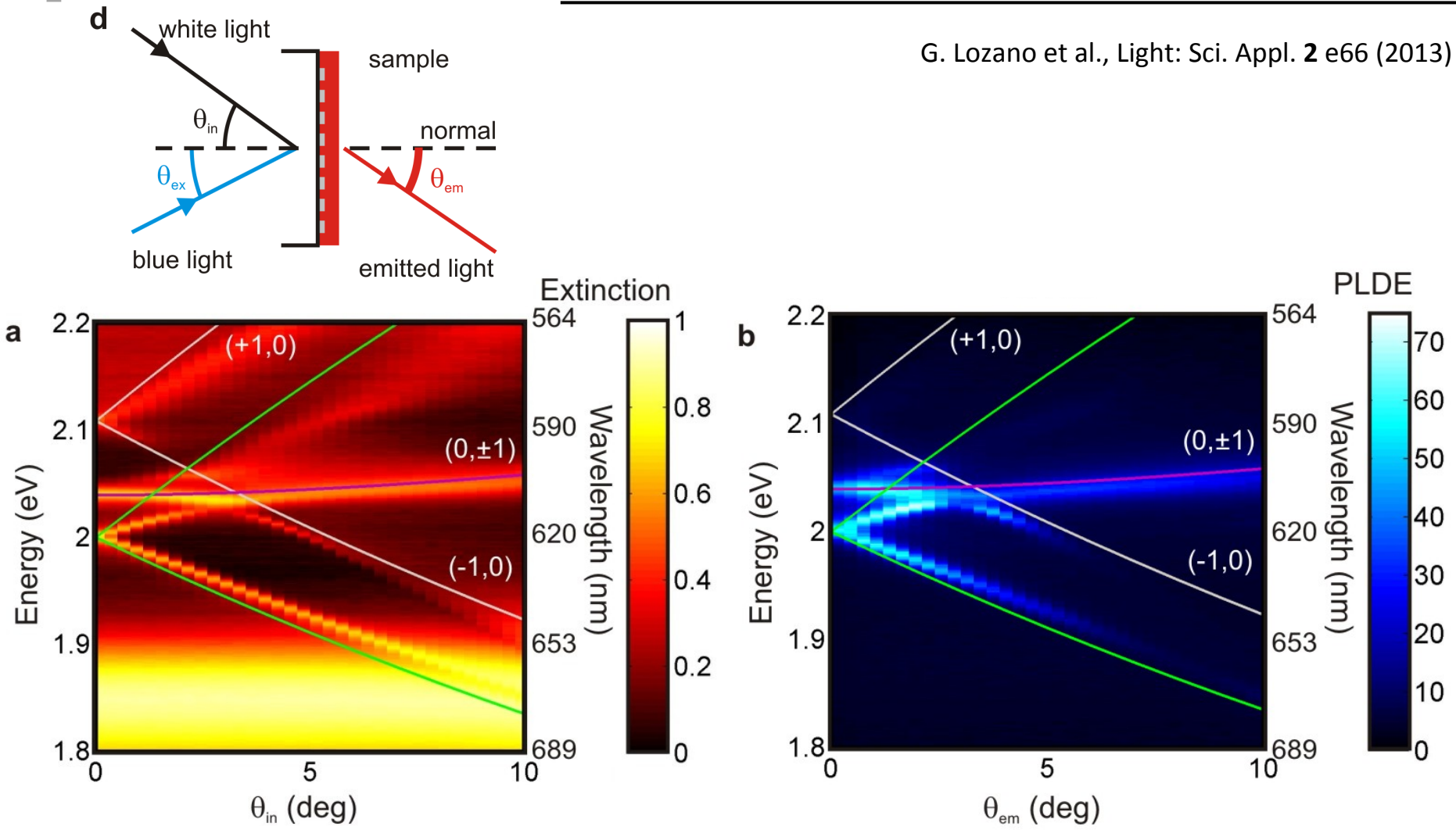




combination of large area metallic arrays with close-to-one QY dye molecules

Optical characterization

G. Lozano et al., Light: Sci. Appl. **2** e66 (2013)



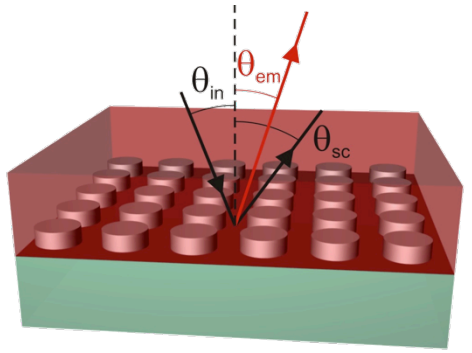
fluorescence is largely enhancenced in a very narrow angular range close to the normal to the sample

Enhancement contributions

$$\mathrm{PLE}\left(\lambda_{ex}, \Omega_{ex}, \lambda_{em}, \Omega_{em}\right) = \frac{\int_V \eta\left(\vec{r}, \lambda_{em}, \Omega_{em}\right) \left|E\left(\vec{r}, \lambda_{ex}, \Omega_{ex}\right)\right|^2 dV}{\int_V \eta_{ref}\left(\vec{r}, \lambda_{em}, \Omega_{em}\right) \left|E_{ref}\left(\vec{r}, \lambda_{ex}, \Omega_{ex}\right)\right|^2 dV}$$

LDOS: quantum yield
+directionality

excitation



total enhancement is the result of phenomena taking place at the emission and the excitation frequency of the dye

Enhancement contributions

$$\mathrm{PLE}\left(\lambda_{ex},\Omega_{ex},\lambda_{em},\Omega_{em}\right)=\frac{\int_V \eta\left(\vec{r},\lambda_{em},\Omega_{em}\right)\left|E\left(\vec{r},\lambda_{ex},\Omega_{ex}\right)\right|^2 dV}{\int_V \eta_{ref}\left(\vec{r},\lambda_{em},\Omega_{em}\right)\left|E_{ref}\left(\vec{r},\lambda_{ex},\Omega_{ex}\right)\right|^2 dV}$$

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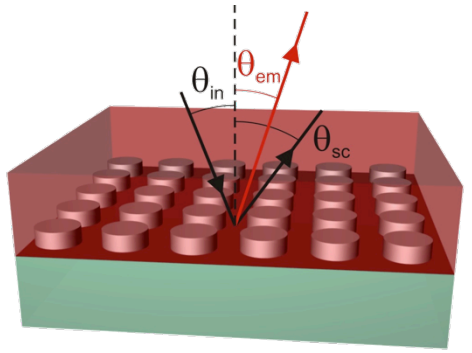
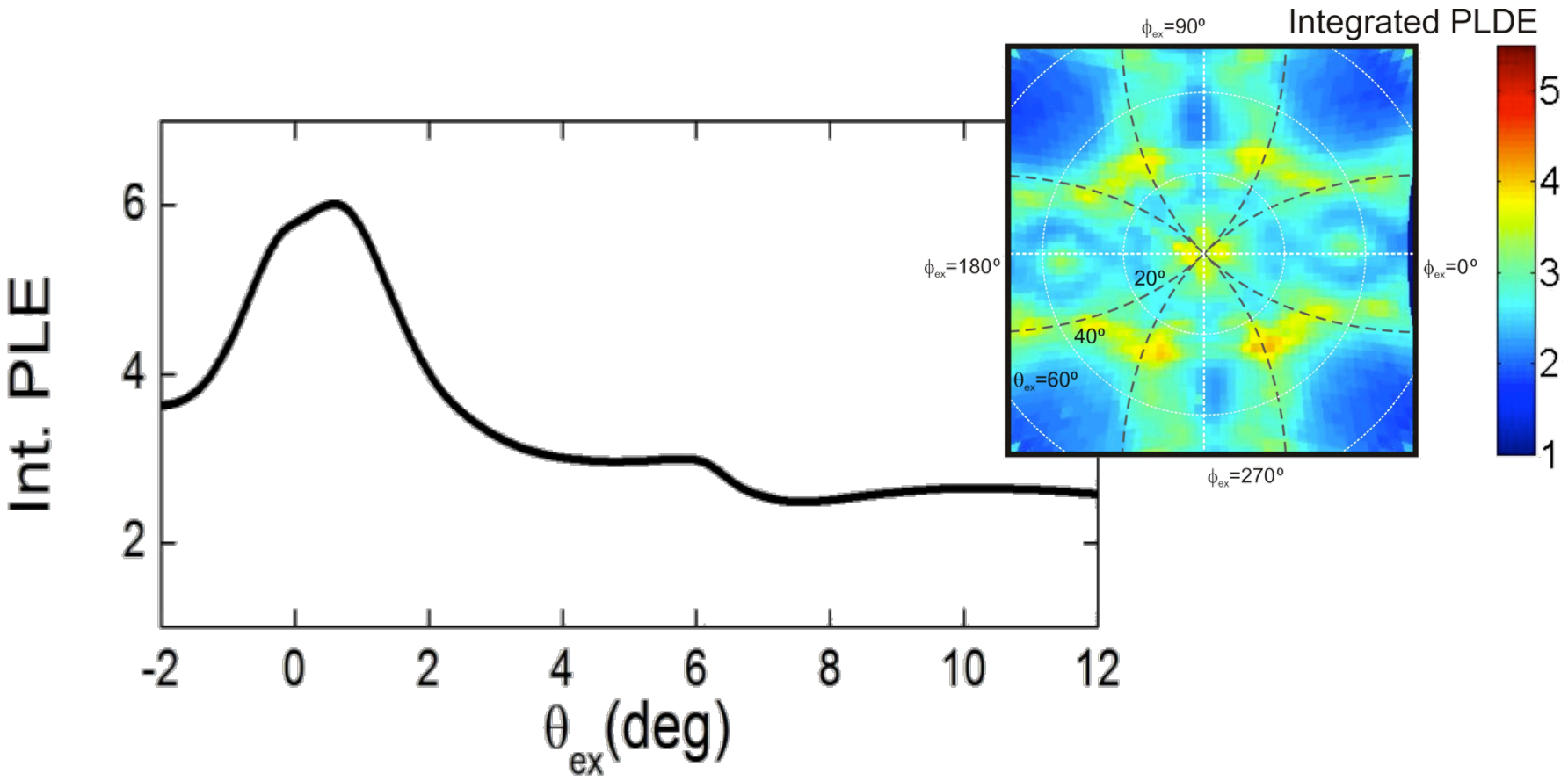


total enhancement is the result of phenomena taking place at the emission and the excitation frequency of the dye

Enhancement contributions. Excitation

G. Lozano et al., *New J. Phys.* **16**, 013040 (2014)

excitation enhancement map measured using a *time-reversed Fourier microscope*



Emission enhancement depends strongly on the illumination angle

Enhancement contributions

$$\mathrm{PLE}\left(\lambda_{ex},\Omega_{ex},\lambda_{em},\Omega_{em}\right)=\frac{\int_V \eta\left(\vec{r},\lambda_{em},\Omega_{em}\right)\left|E\left(\vec{r},\lambda_{ex},\Omega_{ex}\right)\right|^2 dV}{\int_V \eta_{ref}\left(\vec{r},\lambda_{em},\Omega_{em}\right)\left|E_{ref}\left(\vec{r},\lambda_{ex},\Omega_{ex}\right)\right|^2 dV}$$

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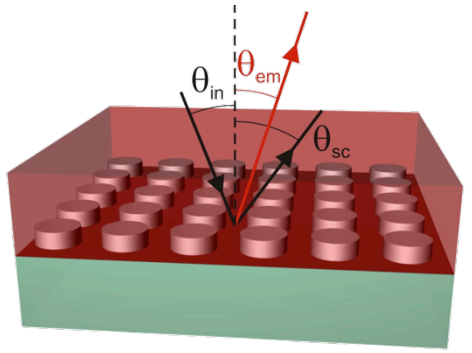

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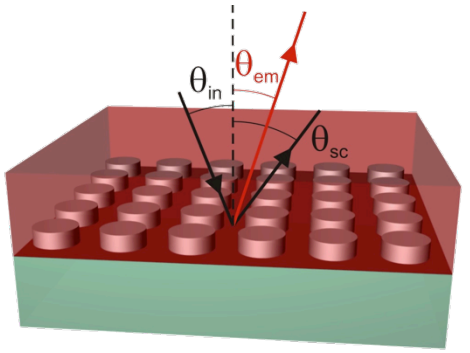

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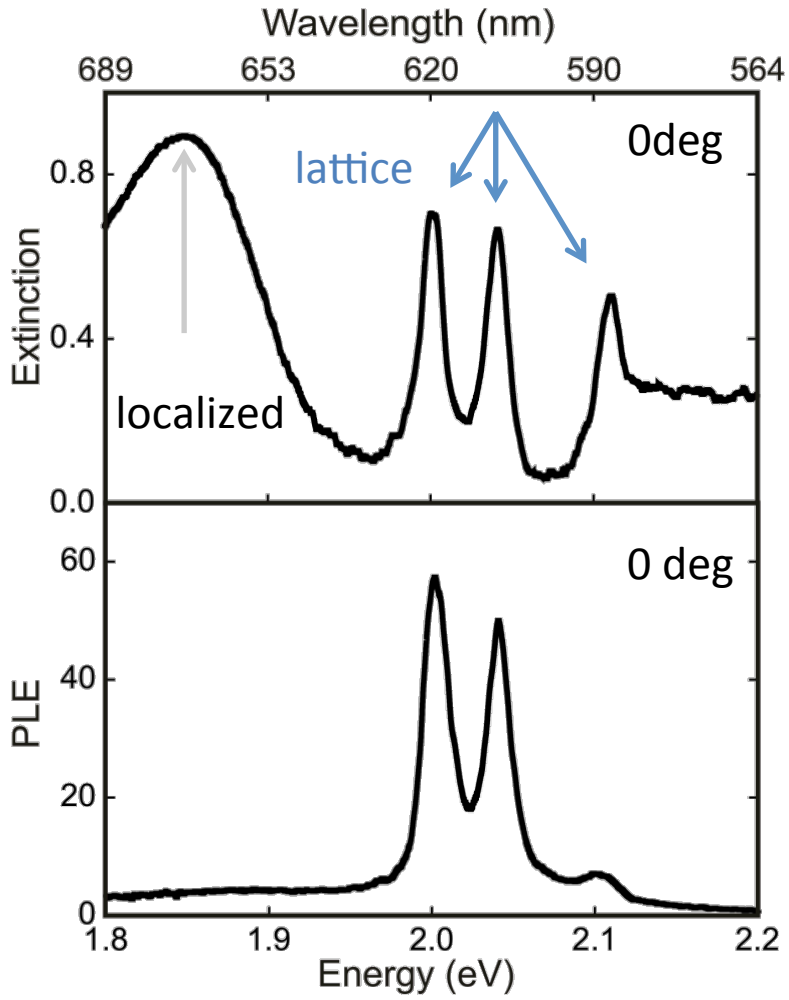
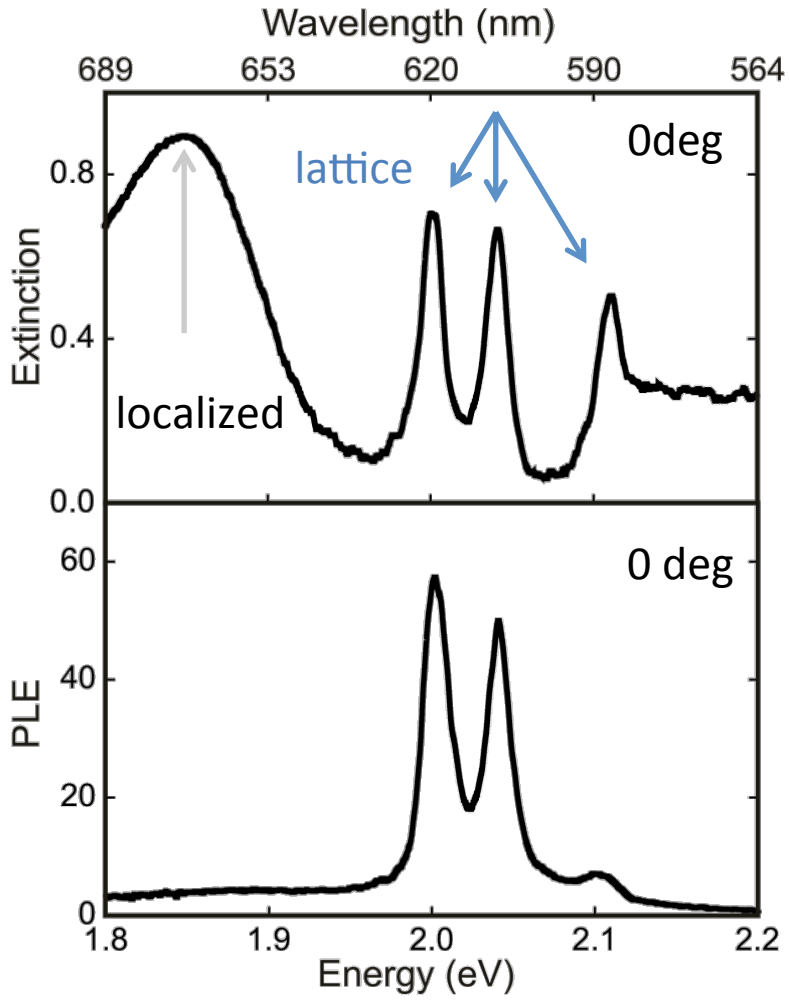
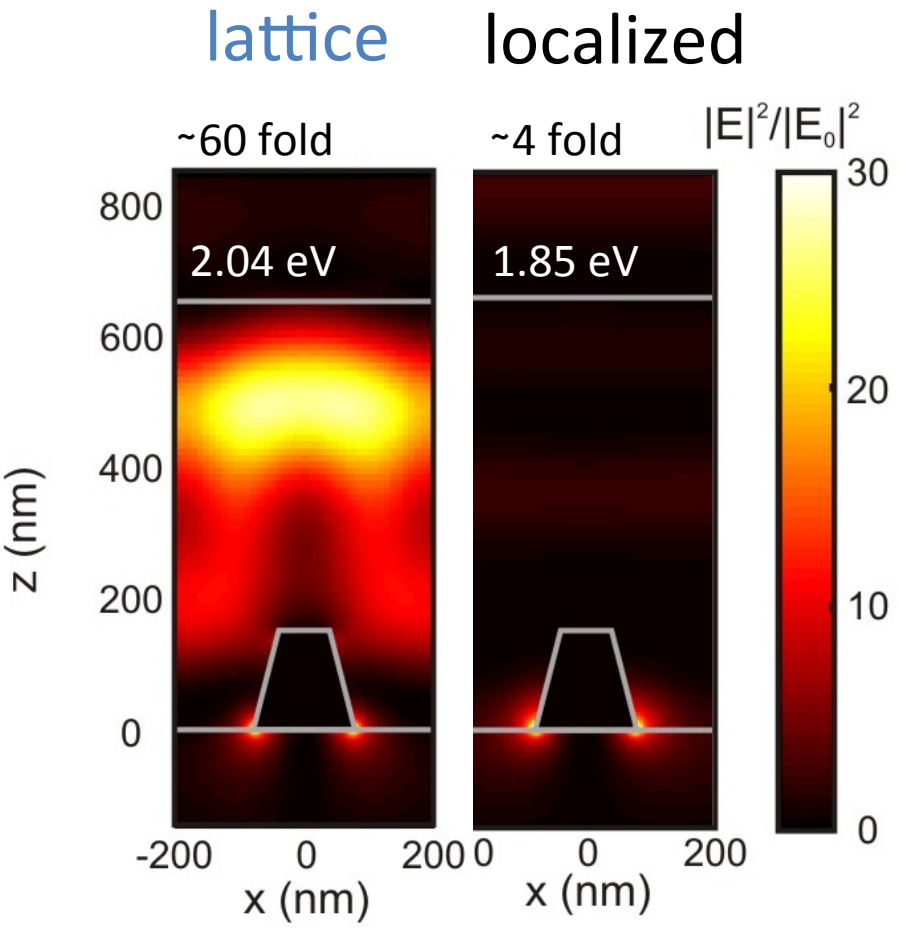
Enhancement contributions. Directionality



the field enhancement of SLRs extends away from the nanoparticles leading to an enhancement of the emission over a large volume

Enhancement contributions. Directionality





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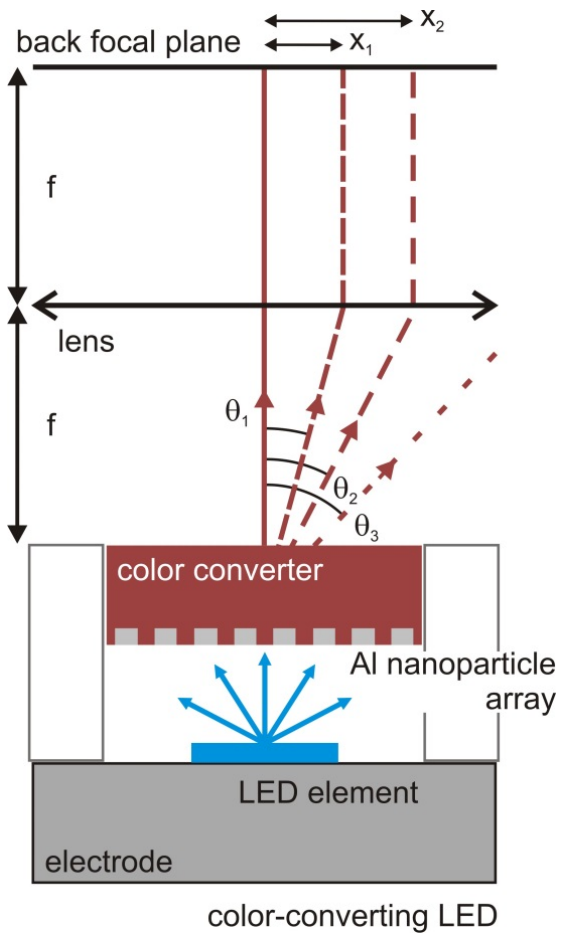
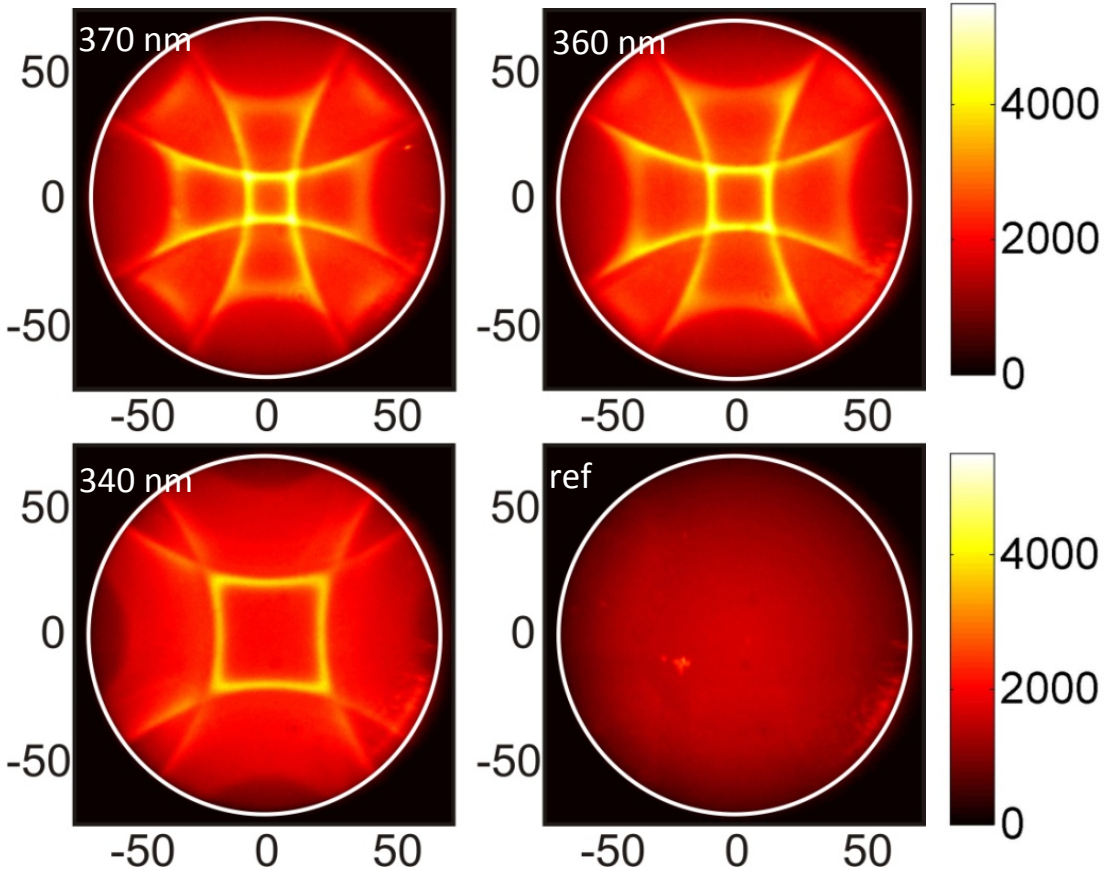
Tailor-made directional emission

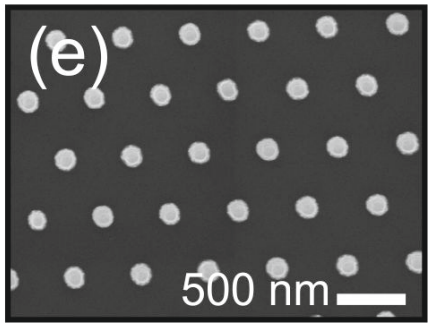


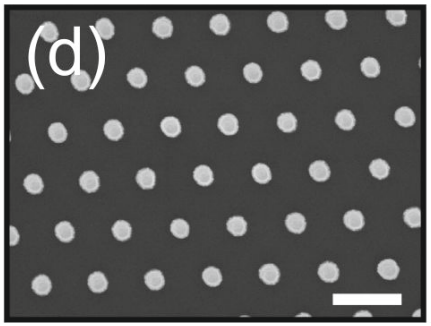
square lattice

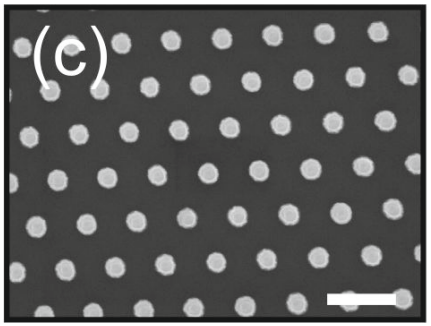


Fourier microscopy allows for an accurate characterization of the directionality of light-emitting devices

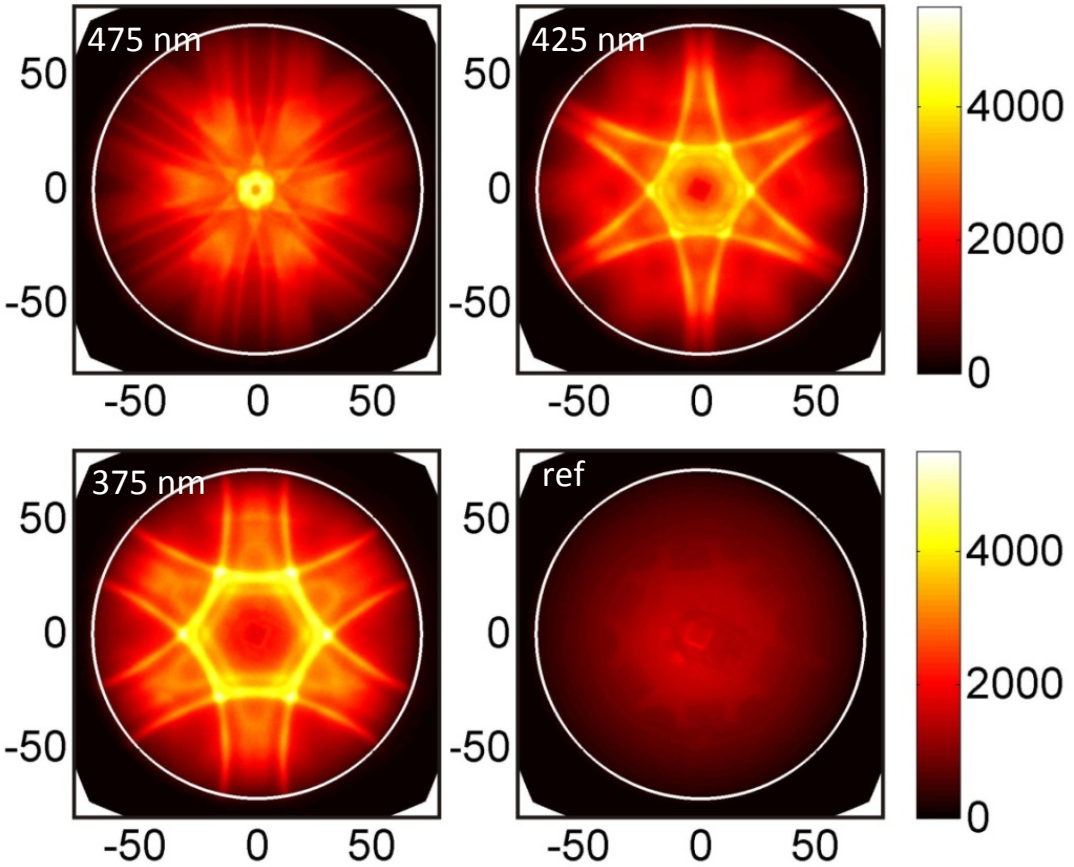
Tailor-made directional emission







hexagonal lattice



the emission directionality can be designed tailoring the separation between the metallic nanoparticles in the array

Conclusions

- plasmonics provides a reliable platform for state-of-the-art lighting applications

- arrays of metallic nanoparticles can improve the performance of already efficient emitters by enhancing the absorption and directing the emission

recent related publications:

S. Rodríguez et al. *Applied Phys. Lett.* 100, **111103 (2012)**
S. Rodríguez et al., *Phys. Rev. Lett.* 109, **166803 (2012)**
S. Murai et al., *Optics Express* 21, **4250 (2013)**
G. Lozano et al., *Optics Express* 21, **5636 (2013)**
S. Rodríguez et al., *Optics Letters* 38, **1238 (2013)**
G. Lozano et al., *Light: Science & Applications* 2, e66 (2013)
G. Lozano et al., *New J. Phys.* 16, **013040 (2014)**

Nanocilinder helpt bundel led-licht beter richten

Leds, of light emitting diodes, hebben samen met andere typen spaarlampen geleid tot een omwenteling in verlichtingstechniek, die de klassieke gloeilamp op een Europees verbod kwam te staan.

Maar toch viel er nog wel wat aan te verbeteren, namelijk de richting van het licht, stellen Gabriel Lozano van het AMOLF-instituut en Philips Research, samen met collega's van onder andere de Technische Universiteit Eindhoven in het het nieuwe vakblad *Light: Science & Applications*.

Leds zenden licht uit in alle richtingen, terwijl toepassingen, van autoverlichting tot richtspots, vaak een gerichte bundel vereisen. Je kunt het licht natuurlijk richten met spiegels of lenzen, maar dat levert extra volume en kosten op, en ook verliezen in efficiëntie.

Lozano en collega's laten zien dat een laagje van kleine aluminium nanocilinders in een vast rooster, boven de led geplaatst, het licht ook in één richting kan dwingen. Zo'n laagje is klein, goedkoop, en precies op maat te maken, prijzen de onderzoekers hun eigen vinding aan.

Het is een van de eerste, snel toepasbare vondsten uit een nieuw vakgebied: plasmonica. Dat draait om oppervlakteplasmonen, ofwel trillingen van elektronen aan het oppervlak van metalen. In metalen kunnen elektronen vrij bewegen. Plasmonen zijn de golven in de elektronenzee. De afgelopen jaren bleek dat lichtgolven gemakkelijk samen kunnen vloeien met die elektronenzeegolven, om verderop weer los te laten en alleen verder te reizen.

De aluminium cilindertjes van Lozano c.s. hebben een diameter van 140 nanometer (een nanometer is een miljoenste millimeter) en een onderlinge afstand van 400 nm. Door de elektronentrillingen werken ze als miniantennes die het licht gemakkelijk opvangen, om het vervolgens weer door te zenden.

Bepalend voor de richtingsgevoeligheid is het verschijnsel dat de trillingen in naburige antennes met elkaar in de pas gaan lopen. Door zulke synchrone collectieve trillingen worden de lichtgolven loodrecht op het vlak versterkt, terwijl licht in andere richtingen juist uitdooft.

Bovenop het antennelaagje ligt een dun laagje kleurstof, dat blauw licht opneemt en weer uitzendt in de vorm van groen en rood licht. Daardoor oogt het resultaat, een combinatie van alle golflengten, wit.

BRUNO VAN WAYENBURG

NRC Handesblad

Nanocylinders help beaming LED light

Light: Science & Applications (2013) 2, e66; doi:10.1038/lsa.2013.22

www.nature.com/lsa

ORIGINAL ARTICLE

Plasmonics for solid-state lighting: enhanced excitation and directional emission of highly efficient light sources

Gabriel Lozano[1], Davy J Louwers[2], Said RK Rodríguez[1], Shunsuke Murai[1,3], Olaf TA Jansen[2], Marc A Verschuuren[2] and Jaime Gómez Rivas[1,4]

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Thanks!