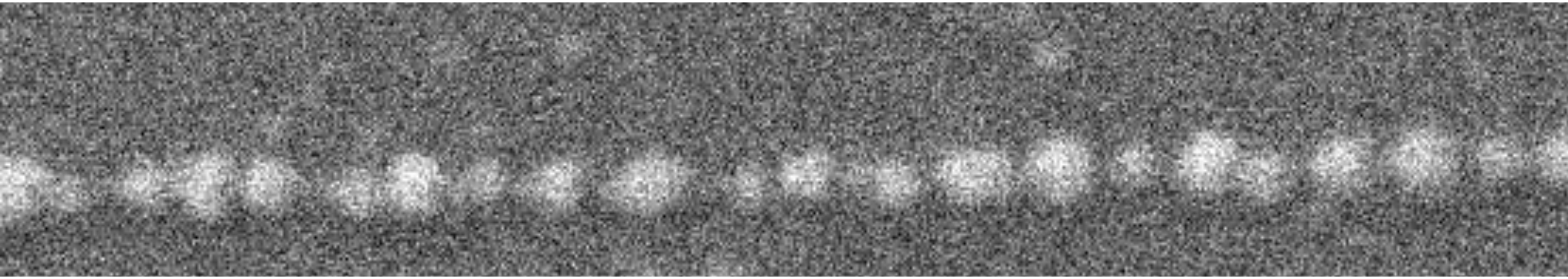
Novel features of plasmon-assisted solid-state lasers at the nanoscale



Luisa E. Bausá

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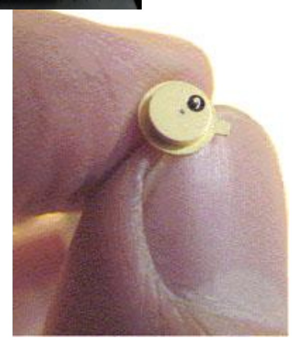
Universidad Autónoma de Madrid (Spain)

Miniaturization of lasers

Different gain media, operation modes, designs, sizes…

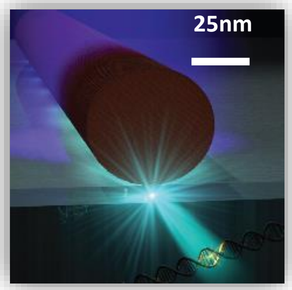


VCSEL

Microlasers
(sub-µm)

Diffraction limit
$\sim\lambda_0/2n$

Plasmon lasers
(nm)



Scaling down of photonic devices

Nanolasers

Plasmon lasers

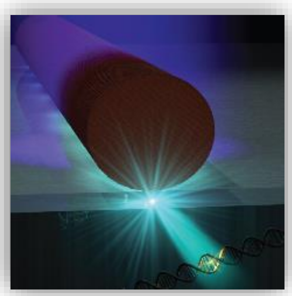
A new class of optical amplification and laser action, which involves charge density waves at the nanoscale

- **High confinement of EM fields** by plasmonic nanostructures

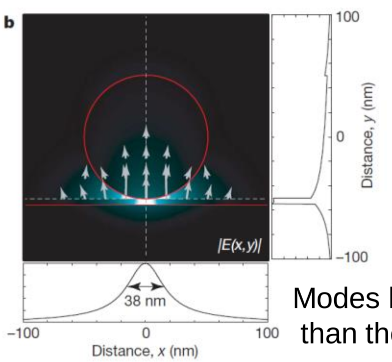
High energy density of coherent light in sub-wavelength confined volumes

Laser volumes
below the diffraction limit

Nanometer-scale plasmonic laser



Hybrid plasmonic waveguide



Modes hundred times smaller than the diffraction limit

R. F. Oulton et al. Nature 461, 629 (2009)

Metallic nanostructures adjacent to a gain medium

GAIN MEDIA:

Semiconductors

- InGaN nanorods
- InGaAs layers
- InAsP quantum Wells
- CdS nanowires
- CdSe nanobelts

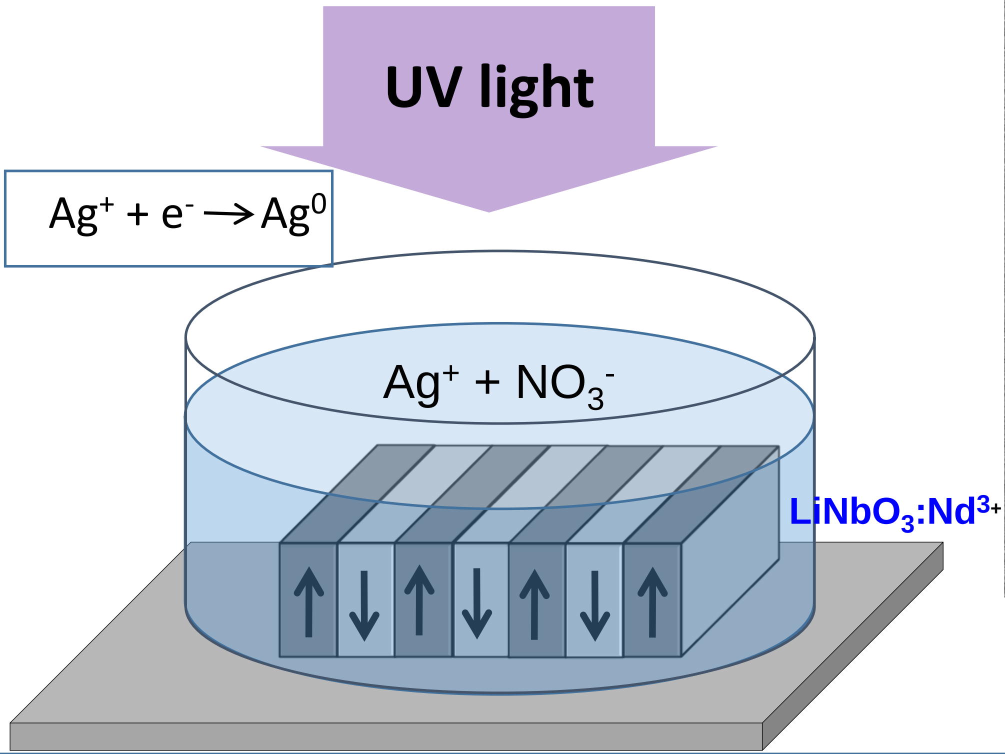
&

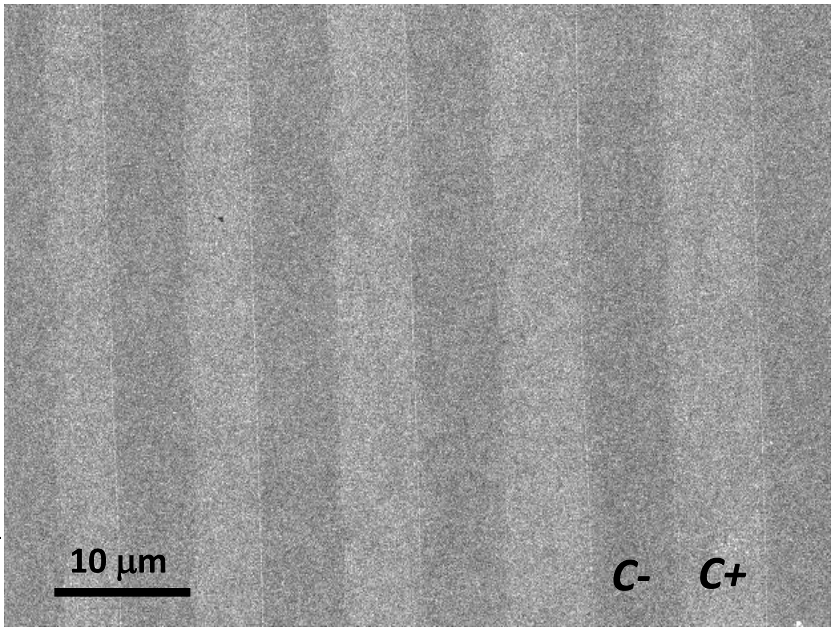
Organic Dyes

Fabrication process: Photochemical formation of metallic nanostructures

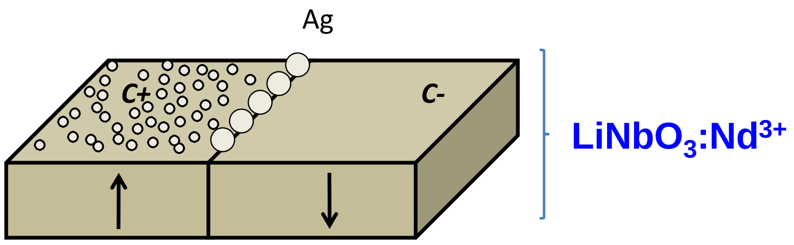
Fabrication process: Photochemical formation of metallic nanostructures

Silver: lowest Ohmic damping in VIS –IR → highest electromagnetic field enhancement



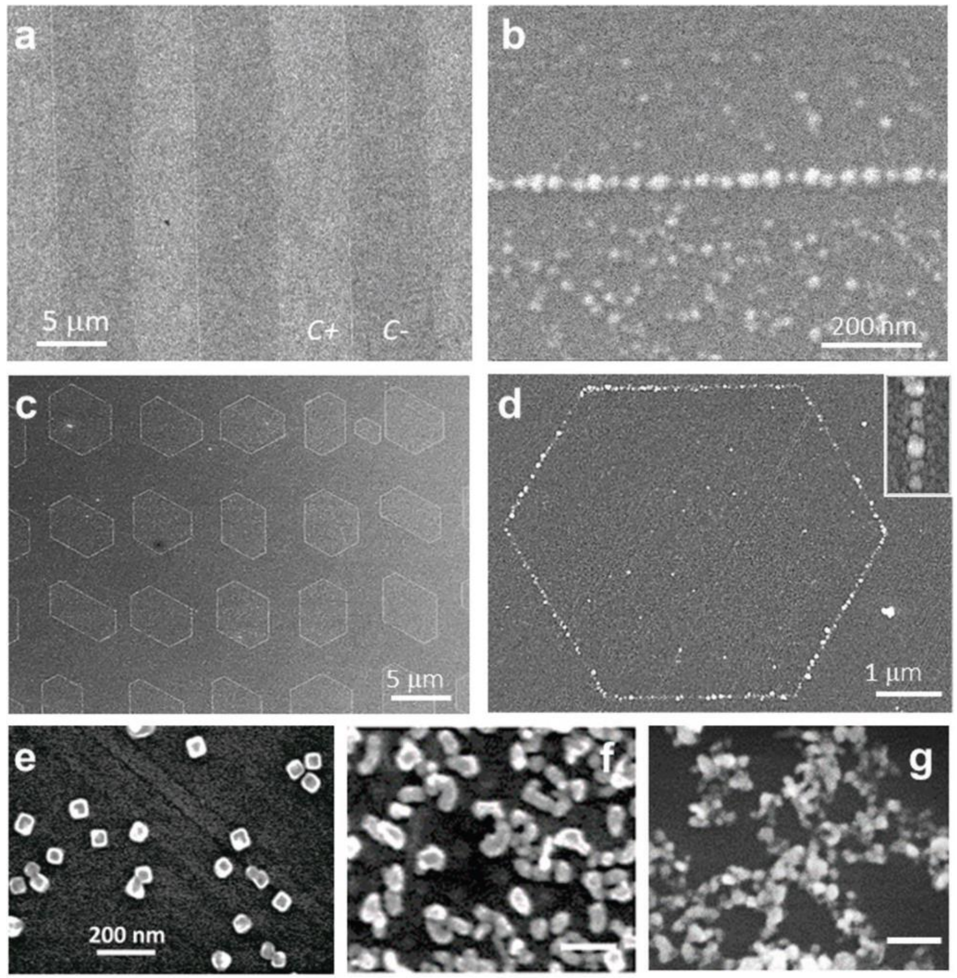


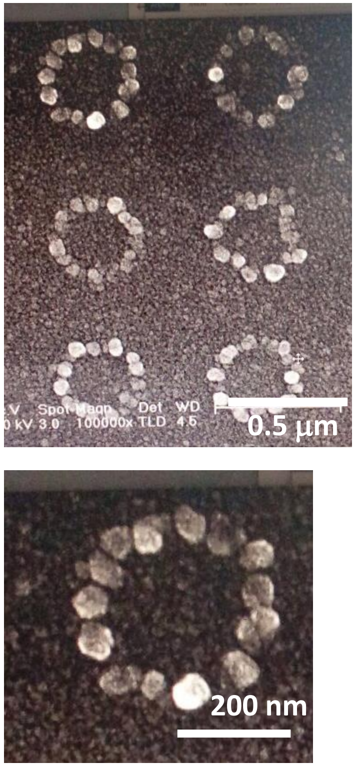
Ag nanoparticle sizes
- ~20 nm (domain surface)
- ~40- 70 nm (domain boundary)



Arrays of Ag NPs on ferroelectrics formed by photo-chemical procedure

$LiNbO_3$





RTP

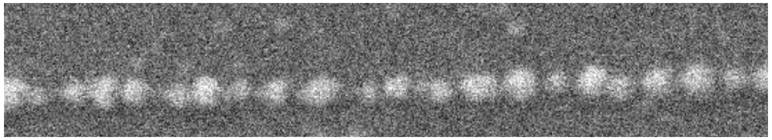
Plasmonic metasurfaces obtained by a simple and cost effective method

Adv. Mater. 2019, 1901428

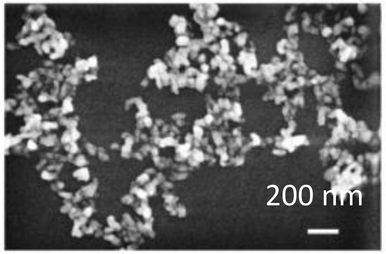
Different types of plasmonic arrangements of NPs

To improve the spectroscopic and lasing properties of Rare Earth ions at the nanoscale

I. Effect of **linear chains** of silver nanoparticles on the properties of a **Nd^{3+}** doped SSL



II. Effect of **Disordered Plasmonic Networks** (DPNs) of silver nanoparticles on the optical performance of a **Yb^{3+}** doped SSL



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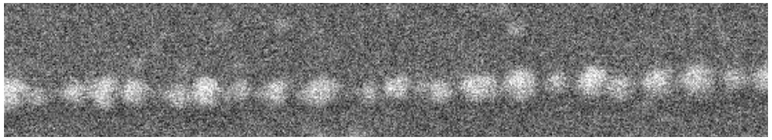
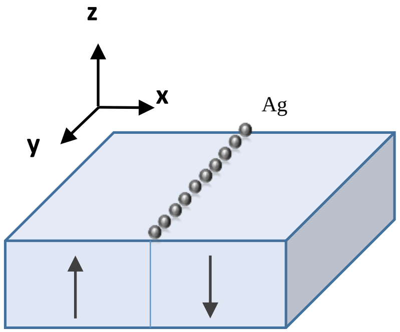
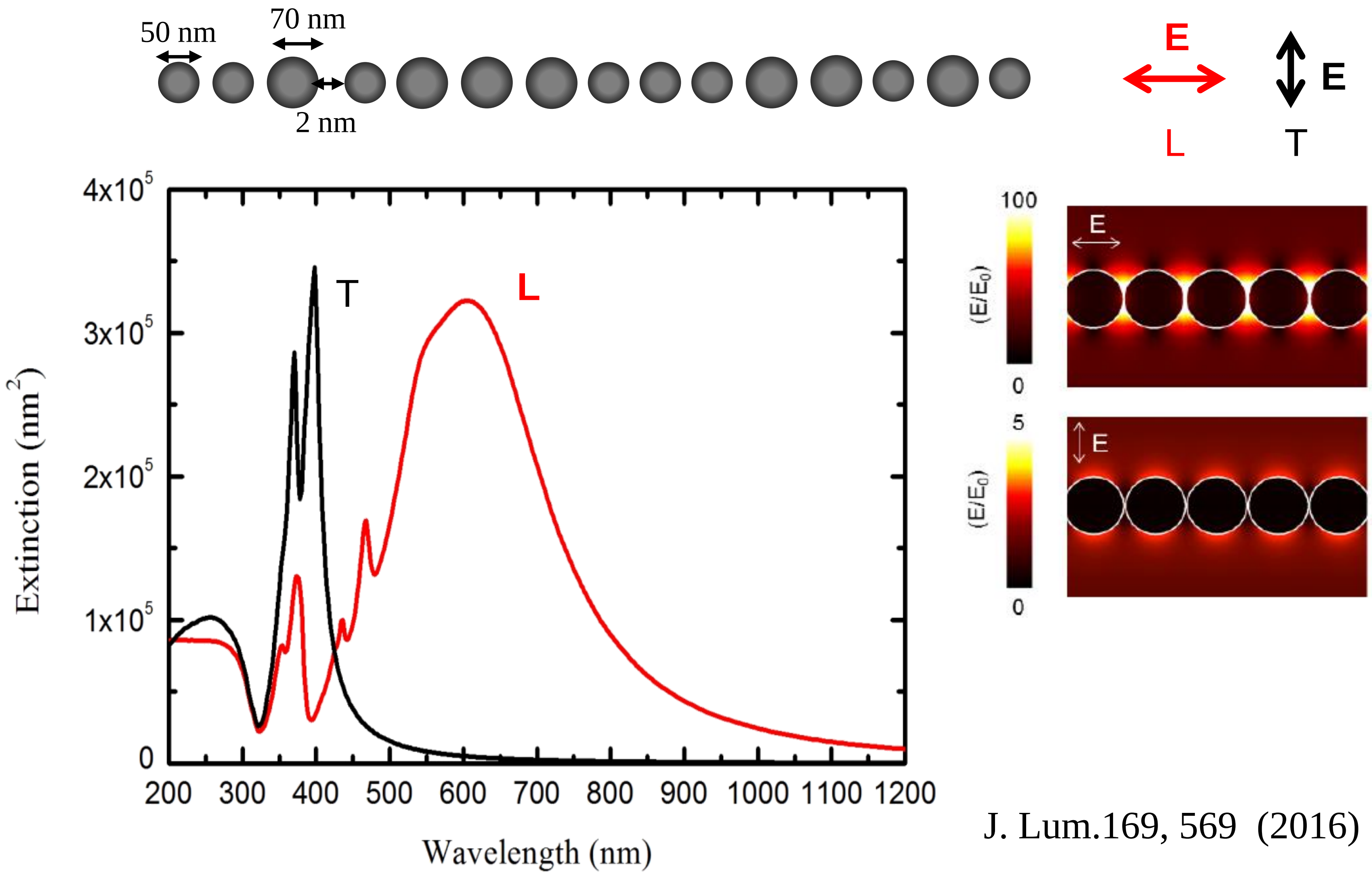




Nd^{3+} doped $LiNbO_3$ (PPLN) crystal

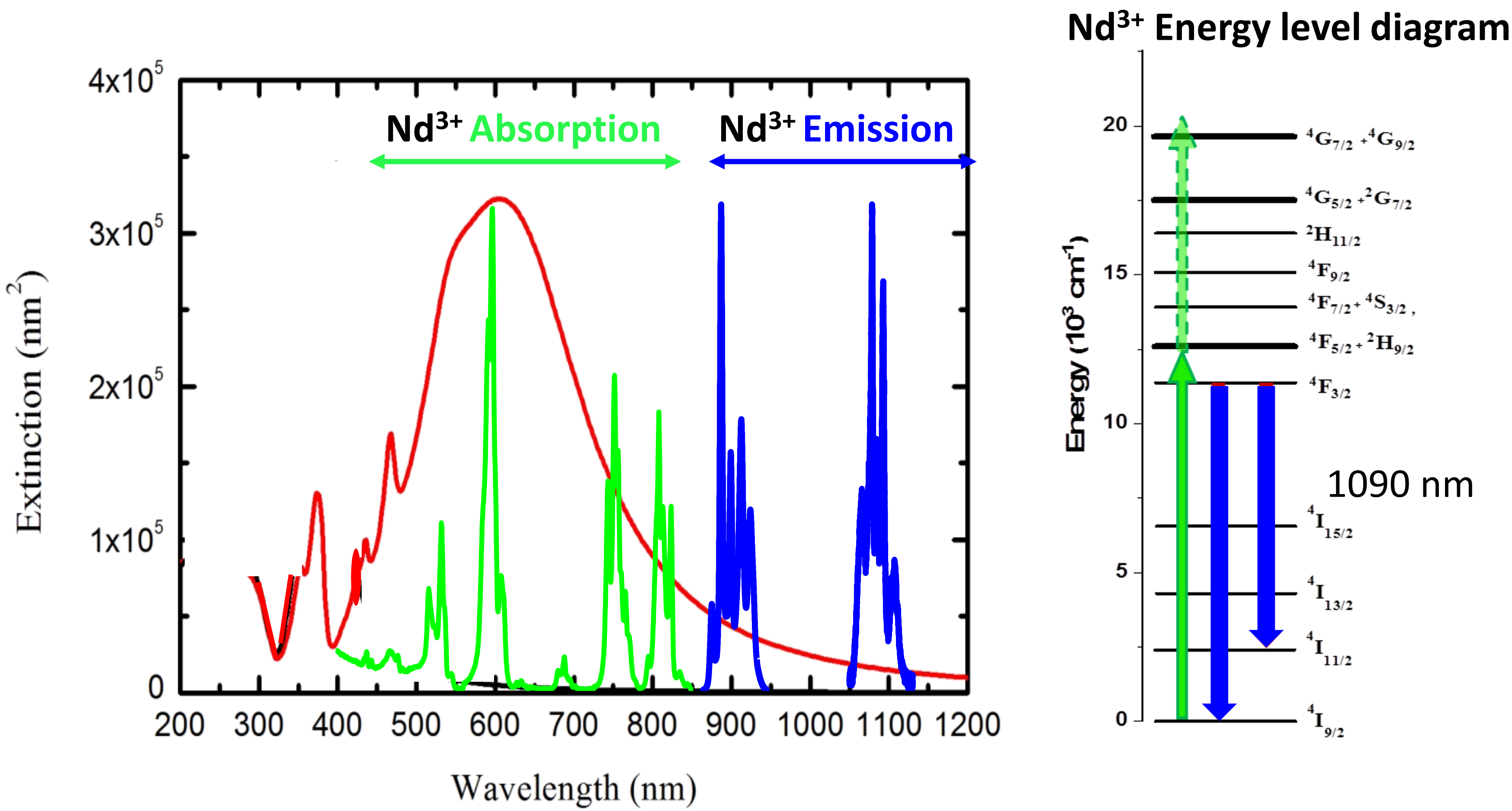
Far-field spectra of the Ag NPs chains



J. Lum.169, 569 (2016)

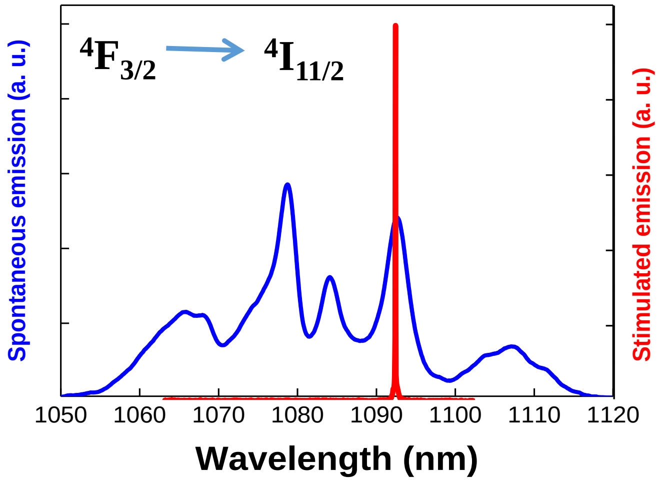
The long-wavelength mode excited for electric field parallel to the chain (L) is a strongly radiative mode.

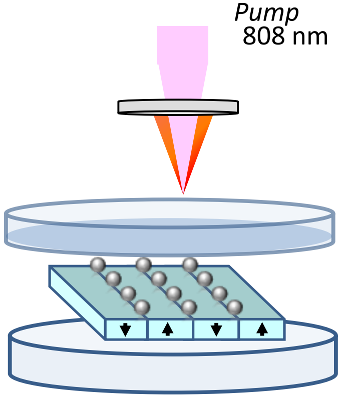
L plasmon mode spectral overlaps the optical transition of Nd^{3+} ions



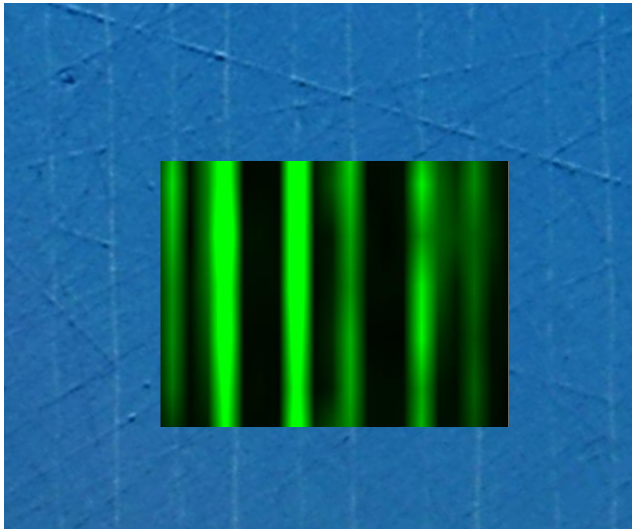
Matching between Ag NPs plasmon and Nd^{3+} absorption/emission bands

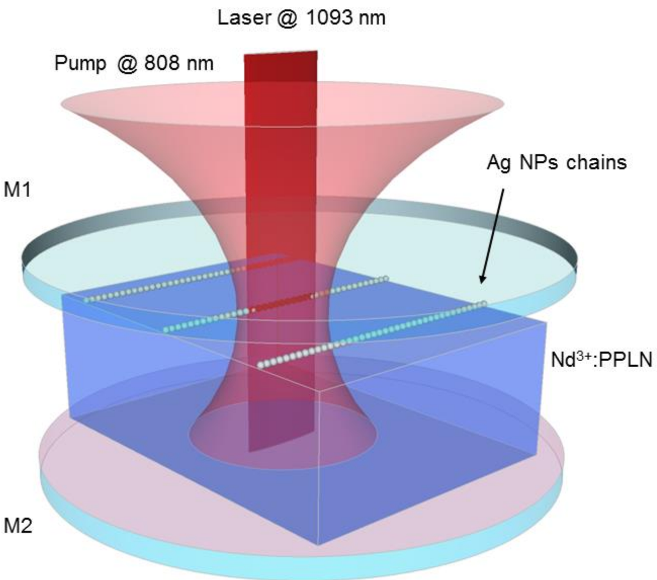
Lasing around the Ag NPs chains on Nd^{3+} :LNB



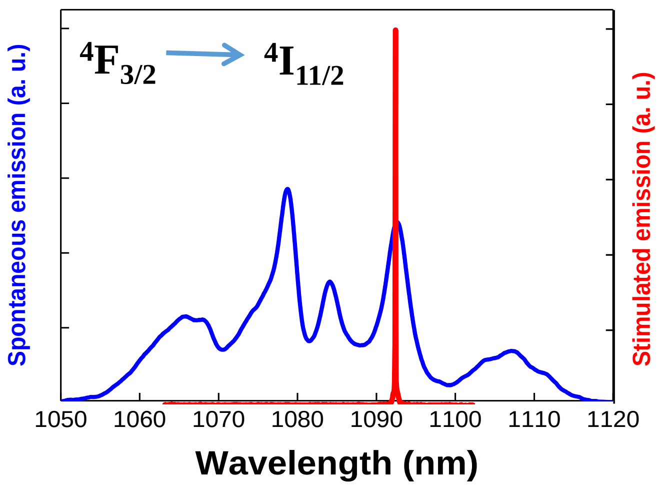


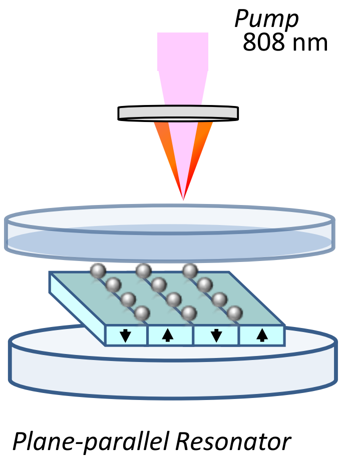
Plane-parallel Resonator



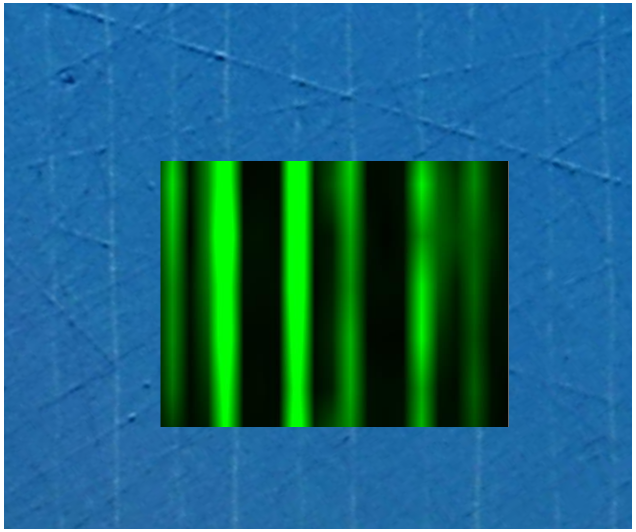


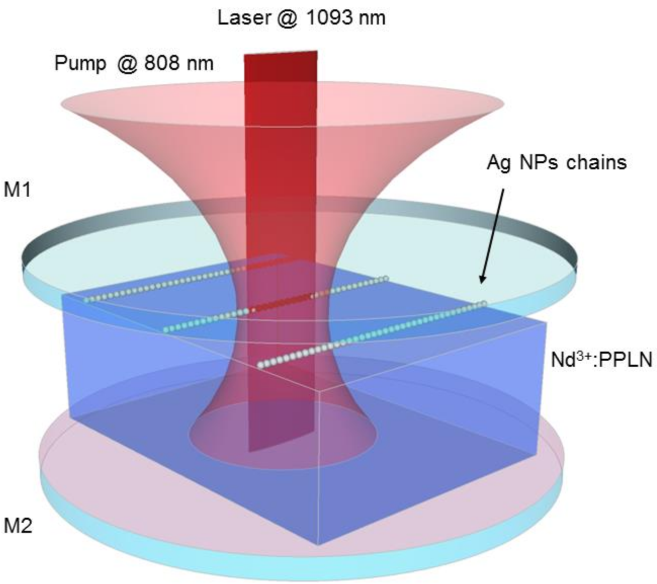
Lasing around the Ag NPs chains on Nd^{3+} :LNB



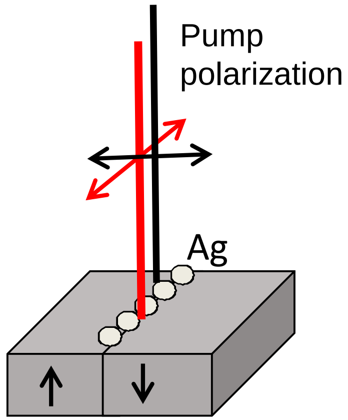


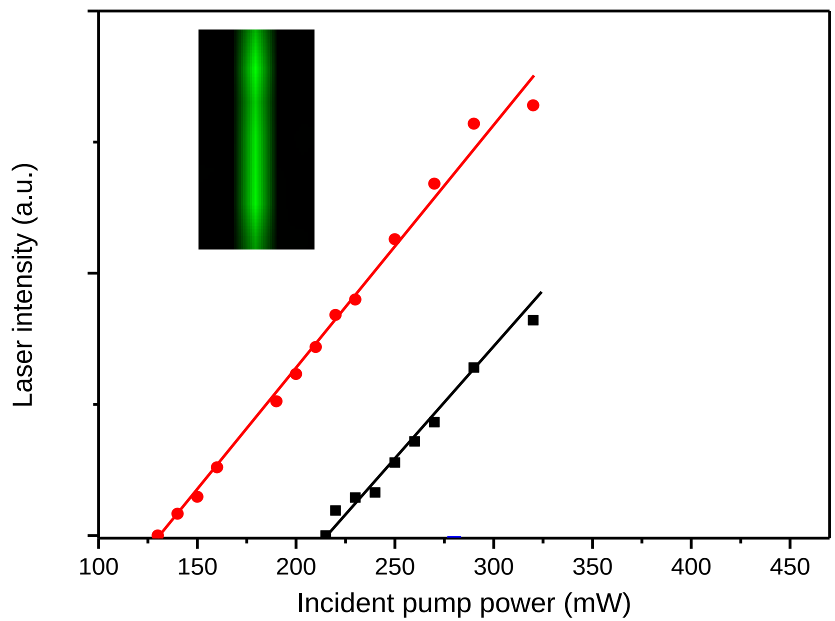
Room temperature CW laser action at the nanoscale





Laser performance at room temperature





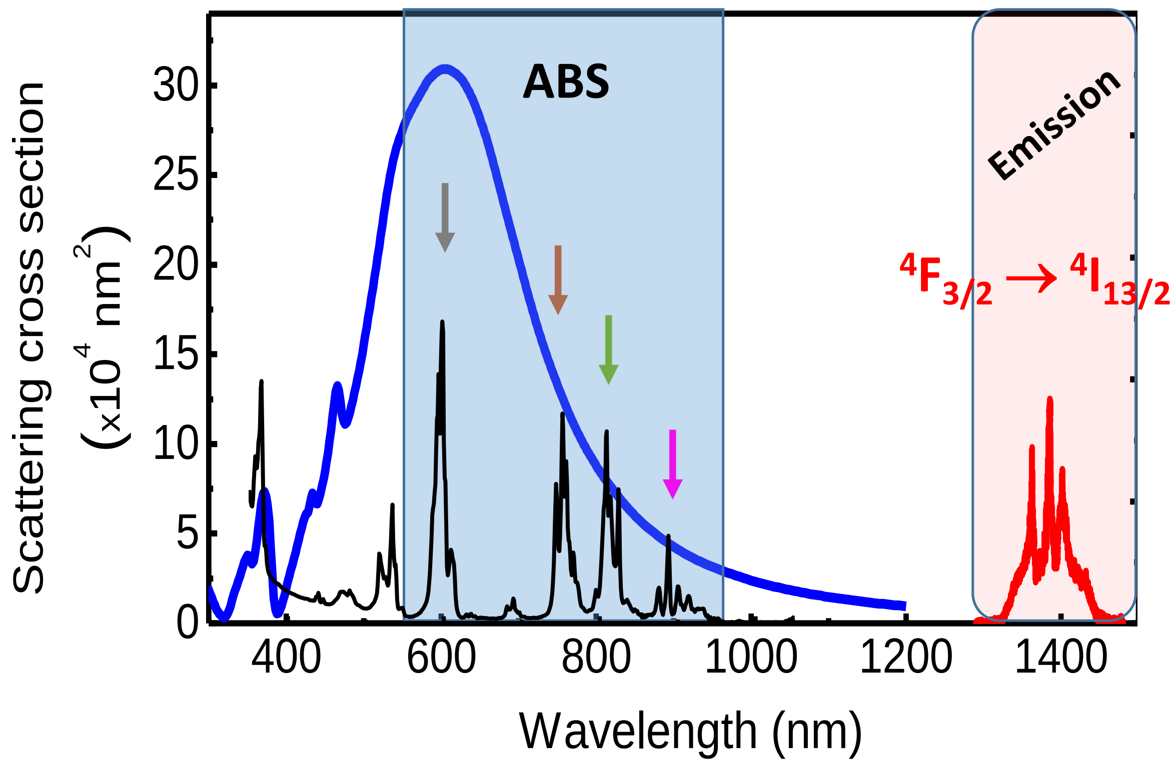
RT & CW Laser performance along the *c* axis at 1093 nm, pumping at 808 nm

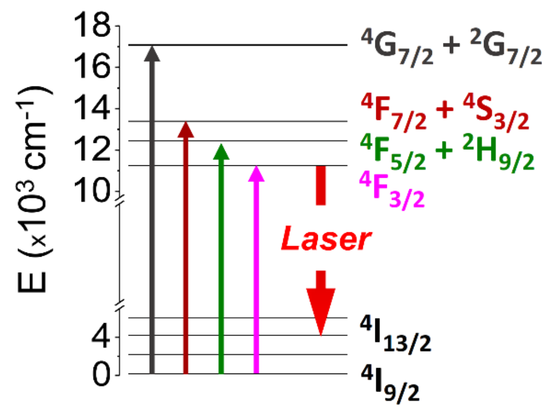
→ The pump power at threshold is half the value of the bulk mode operation

→ The efficiency increases in a factor of 15

P. Molina et al. Nano Letters16, 895 (2016)

Plasmon-induced spectral Narrowing in a Subwavelength Solid-State Laser

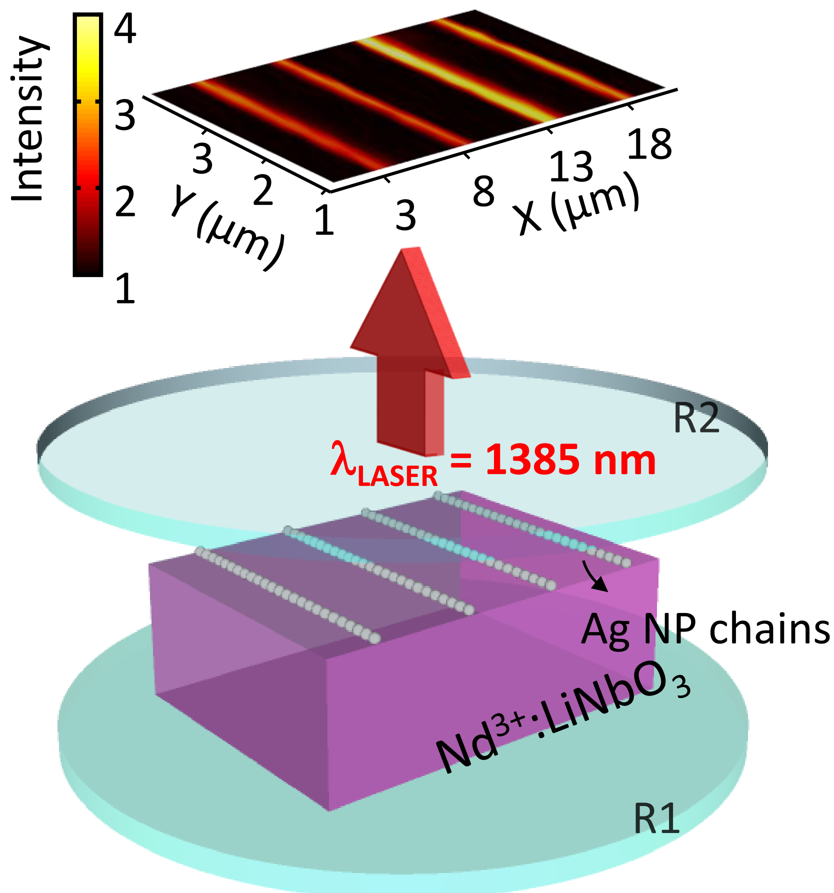


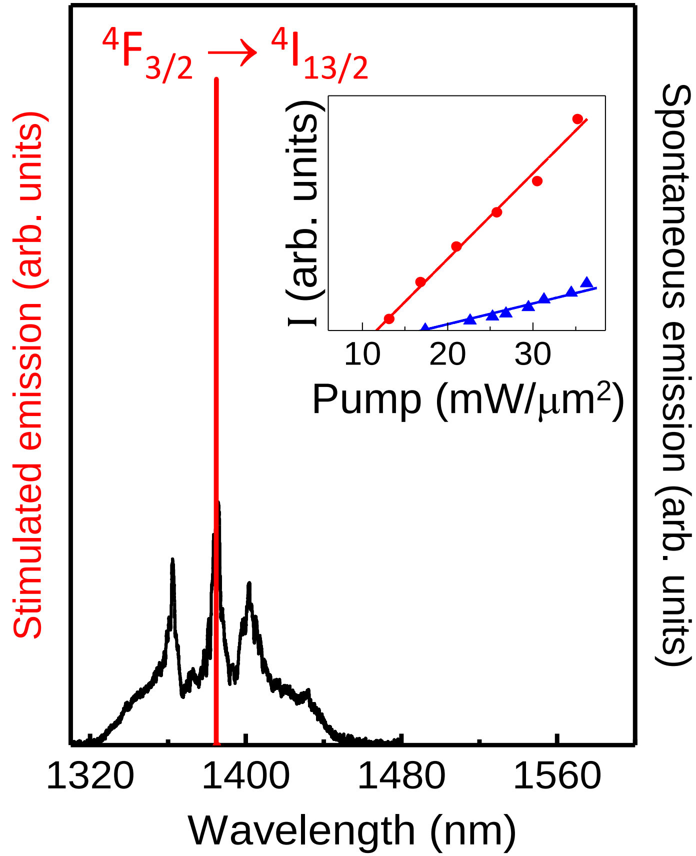


Effect of the absorption enhancement on the laser emission linewidth

Nd^{3+} emission at 1385 nm is located well outside the spectral region of the LSP

Lasing performance in the vicinities of the Ag NP chains at 1.38 μm

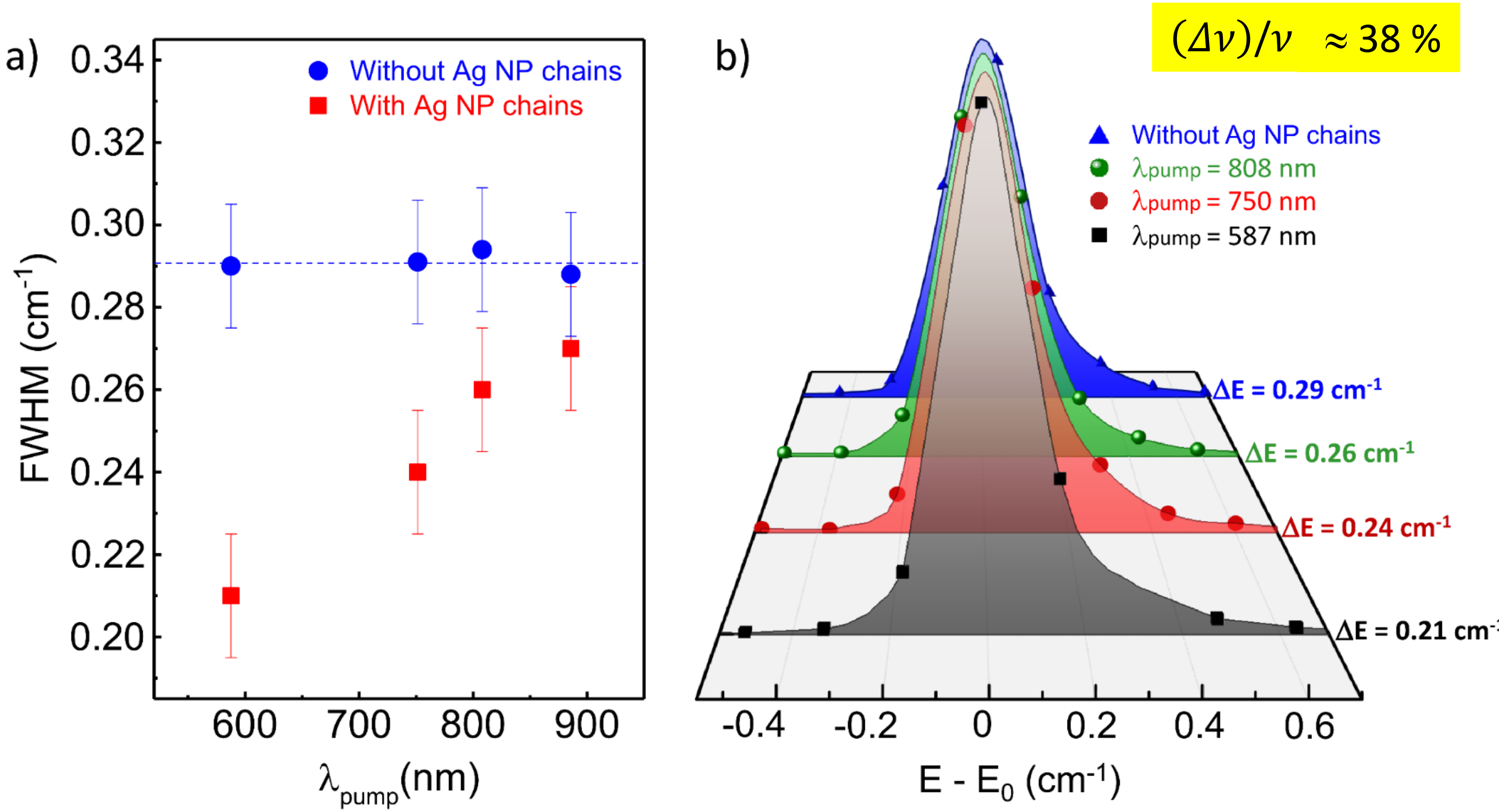




Lasing at the nanoscale in the TELECOM optical E-band

A significant **threshold reduction** & **increase in the slope efficiency** were achieved in the vicinities of the Ag NPs

Effect of the LSP on the monochromaticity of the laser emission



A systematic decrease of the laser linewidth is observed as the pump wavelength approaches the maximum of the plasmonic response

Microscopical origin of the laser linewidth narrowing

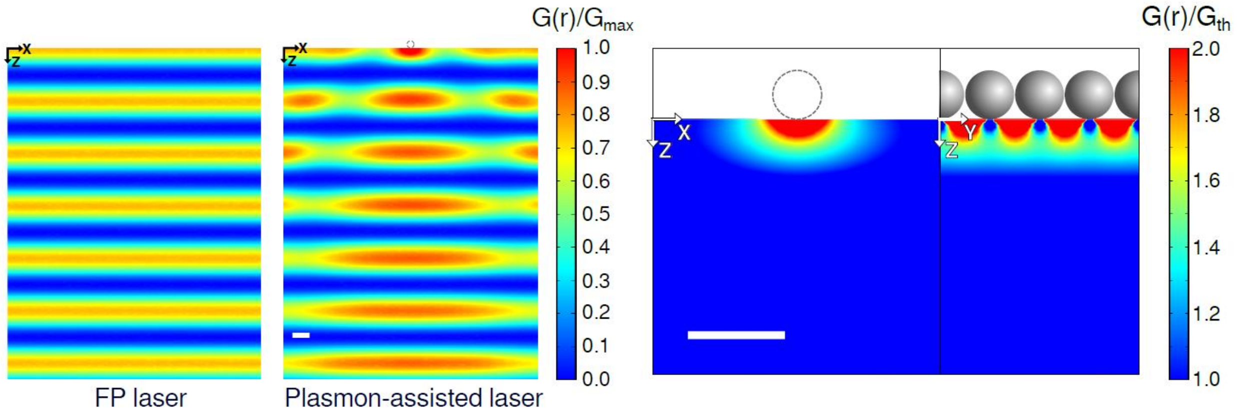
Semianalytical theory based on a rate equations system
(J. Cuerda et al. *Phys. Rev. B* **91** (2015)

$$(\Delta\nu)_{laser} = \frac{\xi}{Q^2 \Gamma R_p}$$

The pump rate that is effectively transferred (via the active medium) to the lasing mode is given by

$$R_p = K_a \int_{Va} d^3\mathbf{r} |\mathbf{E}_a(\mathbf{r})|^2 |\mathbf{E}_e(\mathbf{r})|^2$$

$G(\mathbf{r}) = |\mathbf{E}_a(\mathbf{r})|^2 |\mathbf{E}_e(\mathbf{r})|^2$ **optical gain distribution inside the active medium**

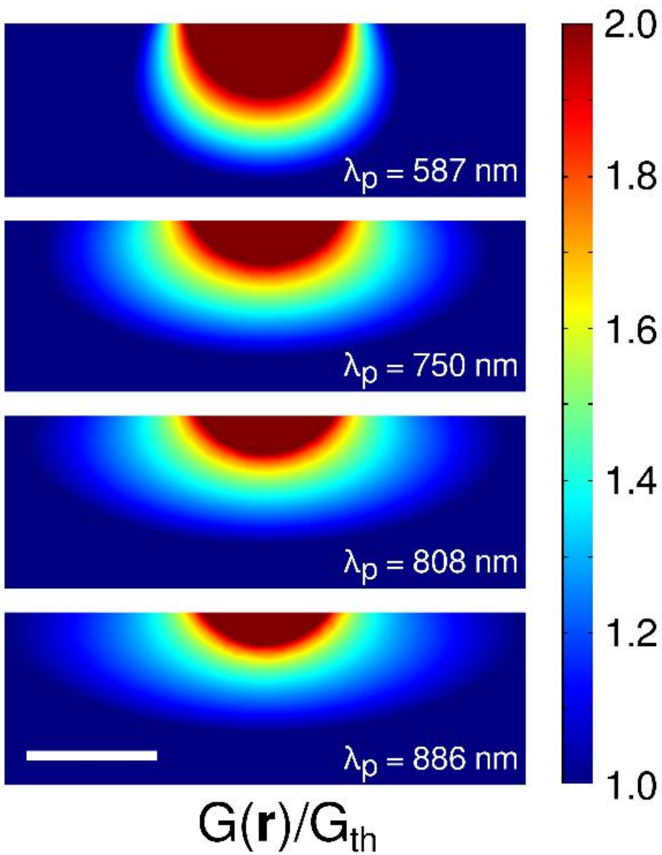


Highly localized gain distribution

Regular emission pattern
FP cavity mode + Uniform profile of the pump field

Complex pattern
Efficient excitation of the longitudinal LSP of the chain

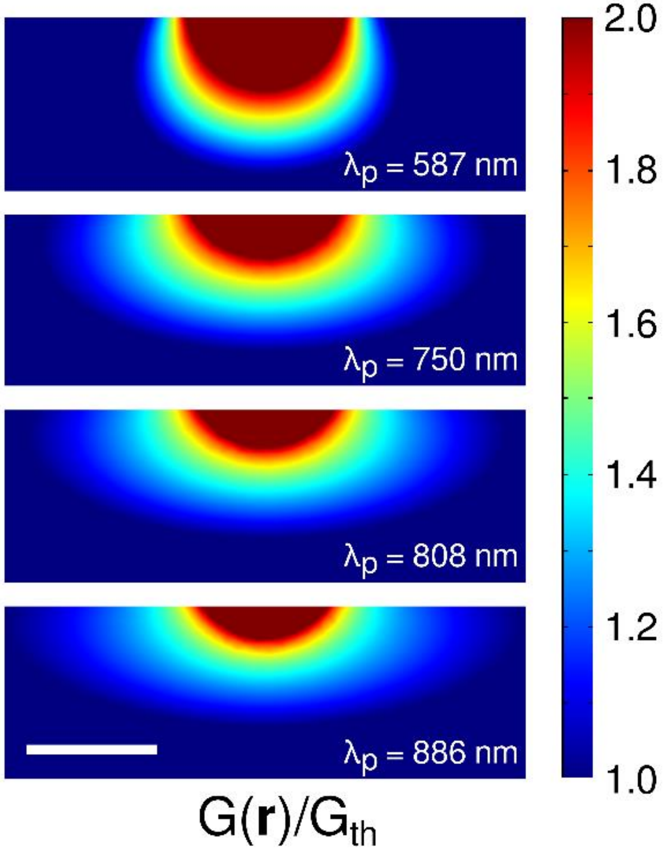
Optical gain profile near the crystal surface for different pump wavelengths



Further enhancement of the optical gain in the vicinities of the plasmonic nanostructures

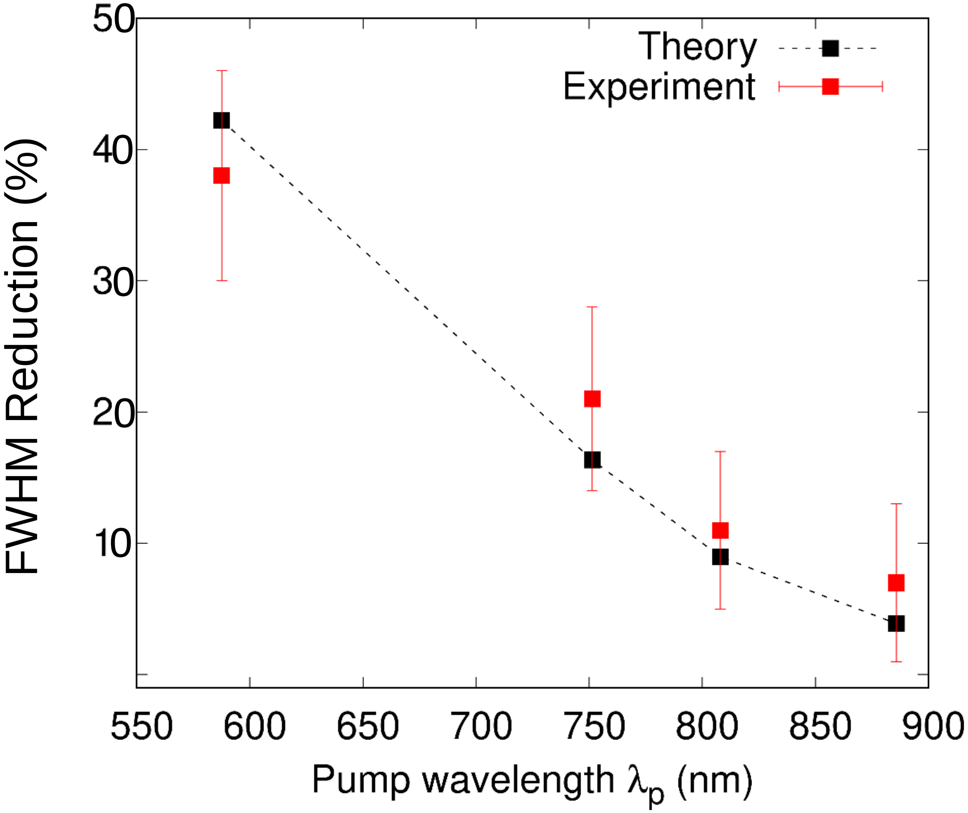
Higher degree of confinement, leading to nanolaser emission from an increasingly ultra-small volume

Laser linewidth narrowing as a function of the pump wavelength



$$(\Delta\nu)_{laser} = \frac{\xi}{Q^2 \Gamma R_p}$$

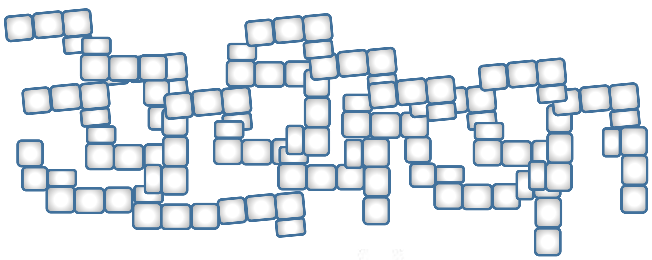
$$(\Delta v)_{pl} / (\Delta v)_b \approx R_p^{\,b} / R_p^{\,pl}$$



D. Hernández Pinilla et al. ACS Photonics 6, 2327 (2019)

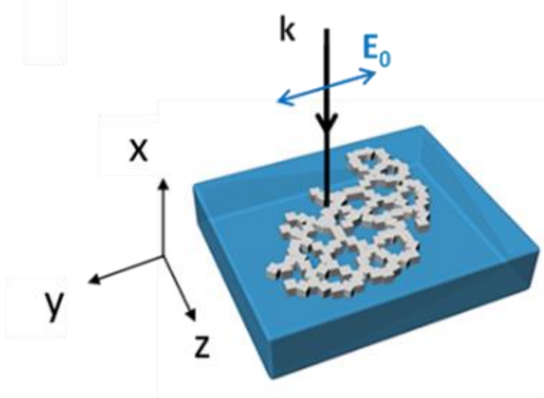
II. Effect **Disorder Plasmonic Networks** (DPNs) of silver nanoparticles on the optical performance of **Yb^{3+}** doped RTP

Ag NP connected forming Disorder Plasmonic Networks (DPNs)



- **Spectrally broad field amplification which is extended over large areas**
- **Spectral shift of the plasmonic resonance from the visible region to the near-IR**

VIS → NIR

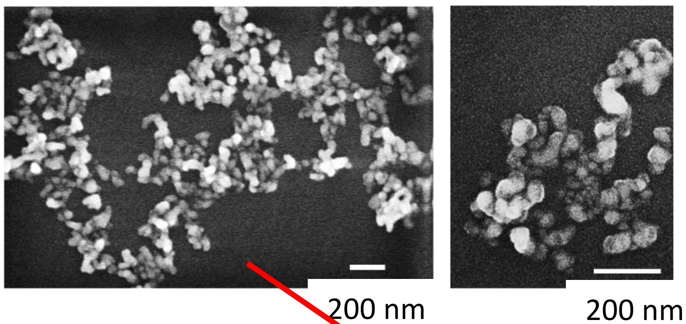


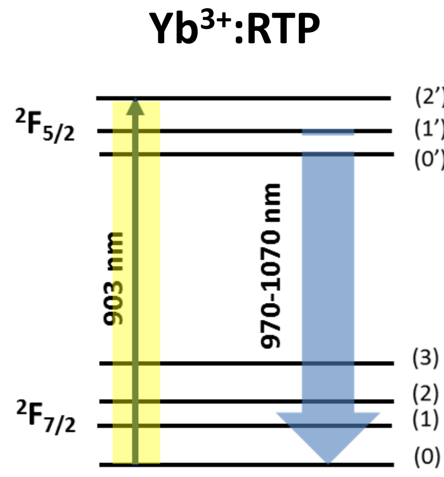
Yb^{3+} doped $RbTiOPO_4$ (RTP) crystal

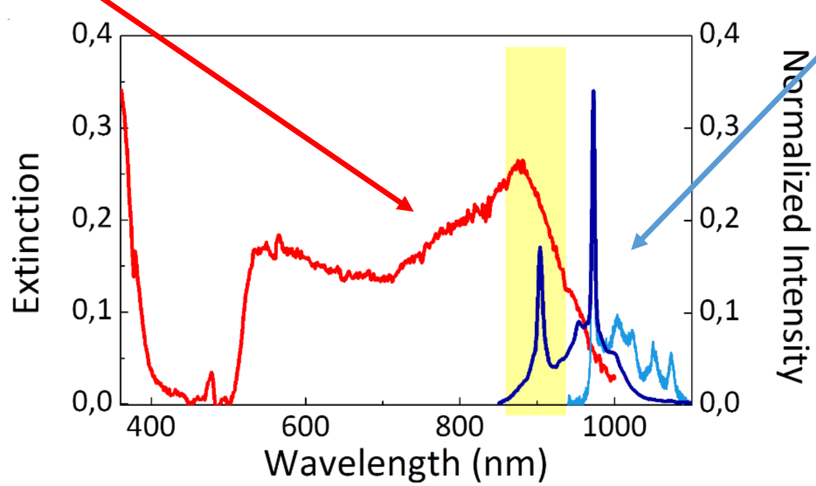
Spectral response of DPNs + Yb^{3+}

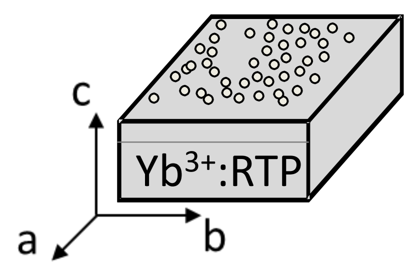
Disordered plasmonic networks (DPNs)

Formed by Ag NPs with sizes in the range 60-90 nm connected in a disordered network-like arrangement









Spectral overlap between the plasmonic response of the Ag DPN and the optical absorption of Yb^{3+}

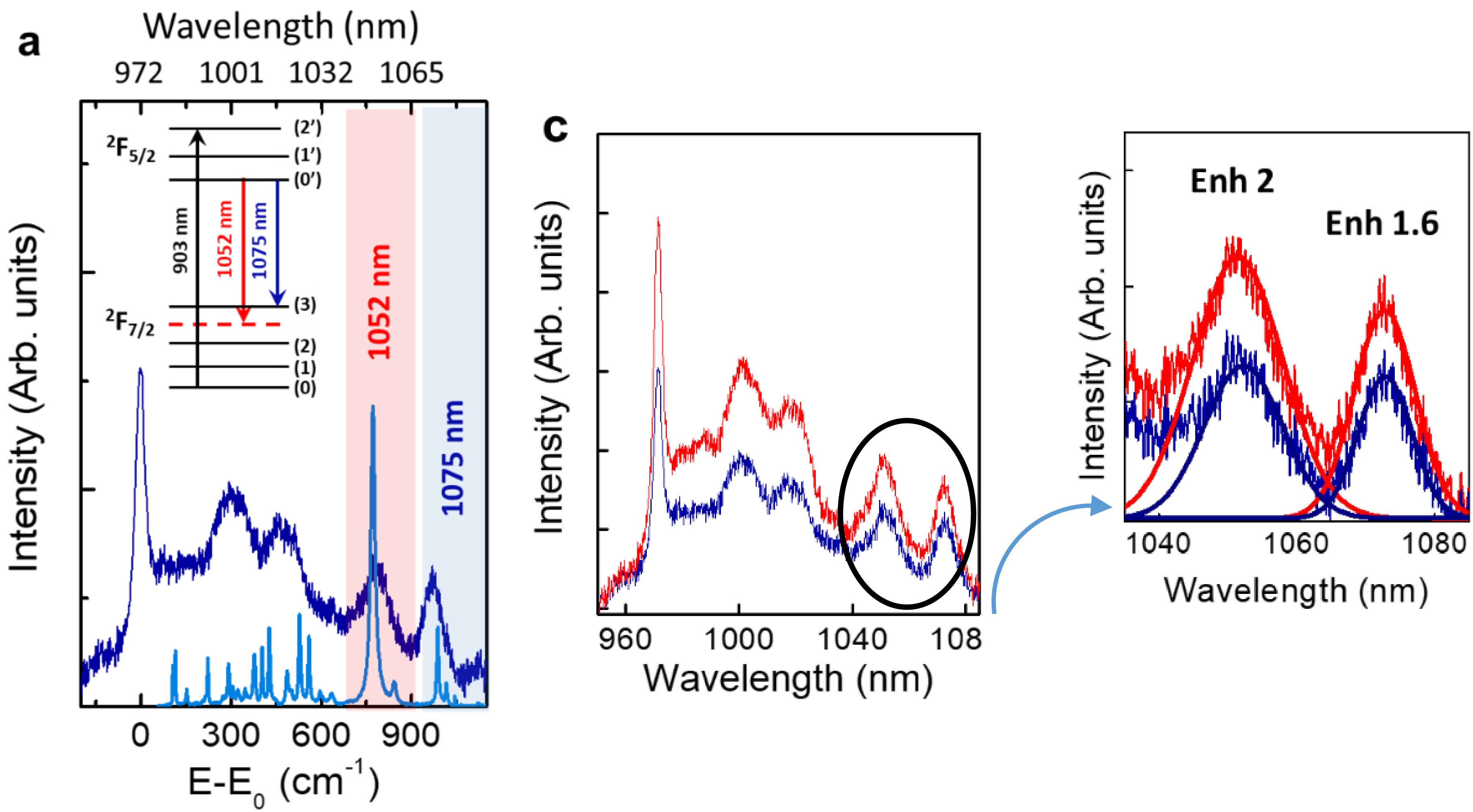
Disordered plasmonic networks induce drastic modifications in the optical properties of Yb^{3+}:RTP

→ INCREASE THE EXCITATION RATE OF Yb^{3+} ions and remarkable enhancement of the photoluminescence

→ PLASMON-INDUCED DUAL WAVELENGTH LASER

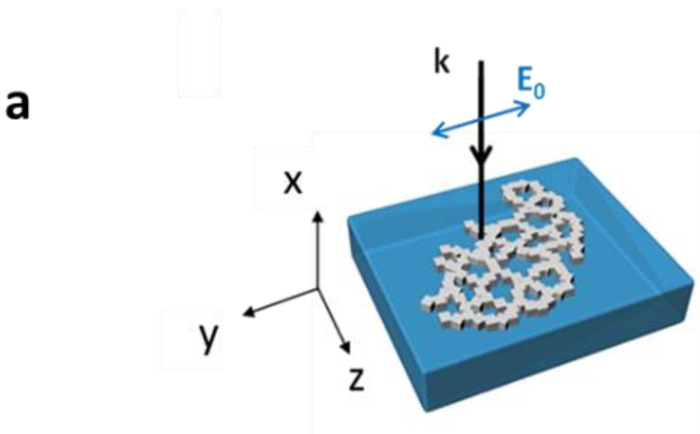
Simultaneous oscillation of two different laser lines due to the effect of the DPNs deposited on the surface of the Yb^{3+} doped RTP laser crystal

Plasmon-induced dual wavelength Yb^{3+} laser

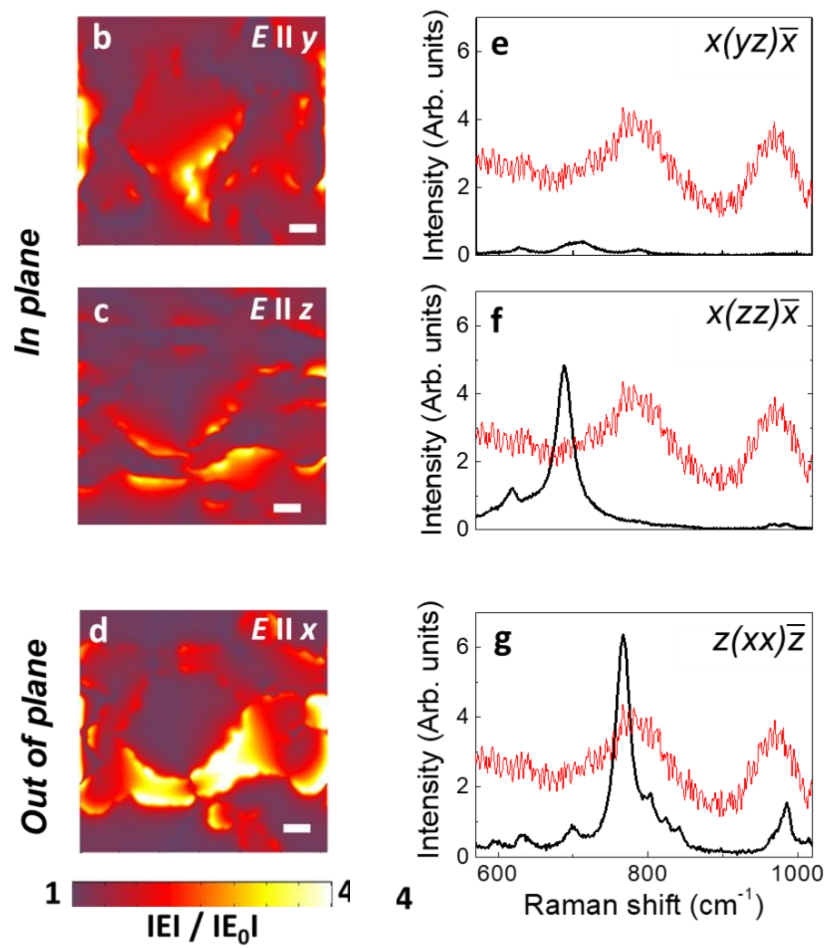


The emission at 1052 with a strong vibronic character is preferentially enhanced by the DPNs
about 20% larger than that of the emission at 1075 nm

Selective enhancement of Yb^{3+} vibronic transition by Ag DPNs



Geometric configuration of the RTP crystal used in the lasing experiments

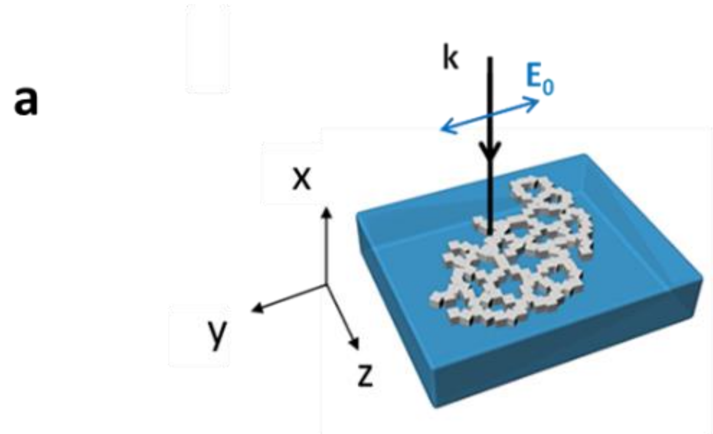


Presence of an **out-of-plane polarization** component **additional** to those of the incident field

The largest values of the local field enhancement correspond to the out-plane field component

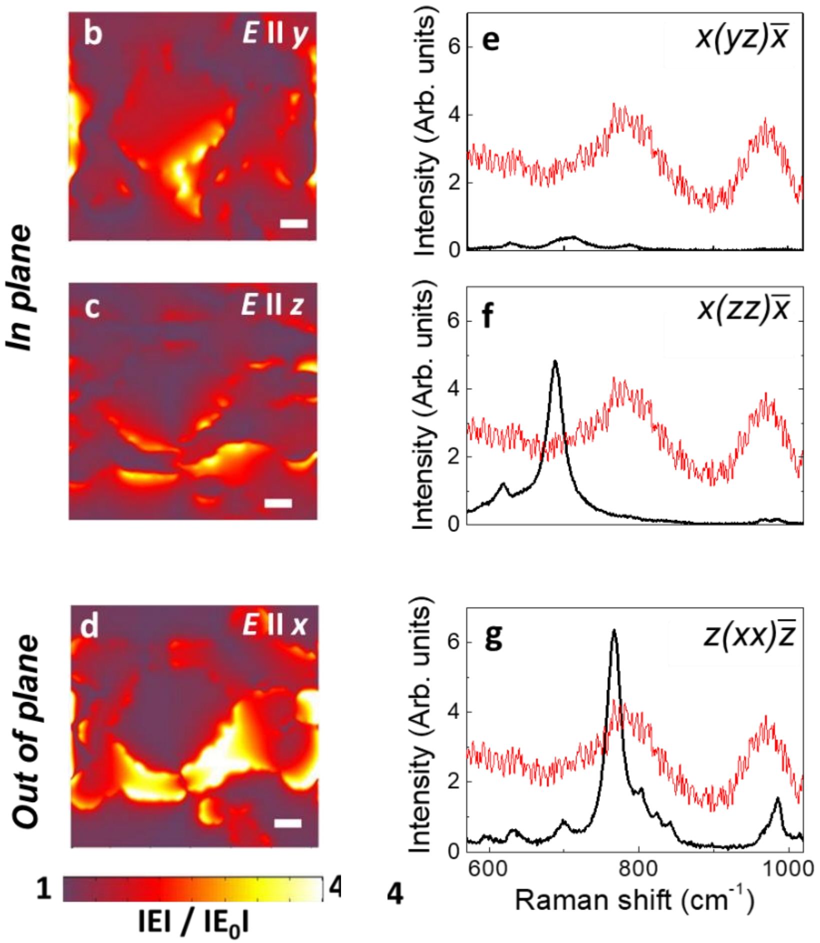
-----Emission spectrum of Yb^{3+} :RTP in the lasing spectral region
-----Raman spectra

Selective enhancement of Yb^{3+} vibronic transition by Ag DPNs



Geometric configuration of the RTP crystal used in the lasing experiments

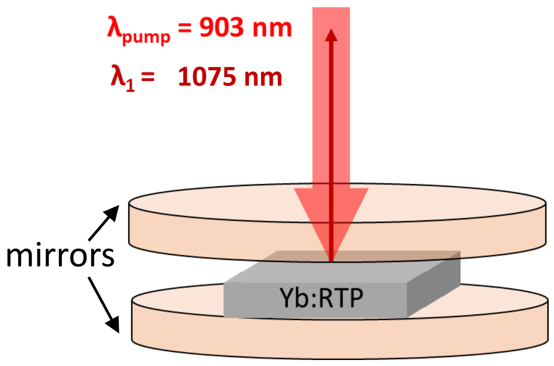
This out-of-plane component allows the excitation of the vibrational modes, not accessible without the presence of DPNs, with the subsequent enhancement of the phonon-terminated transition at 1052 nm.

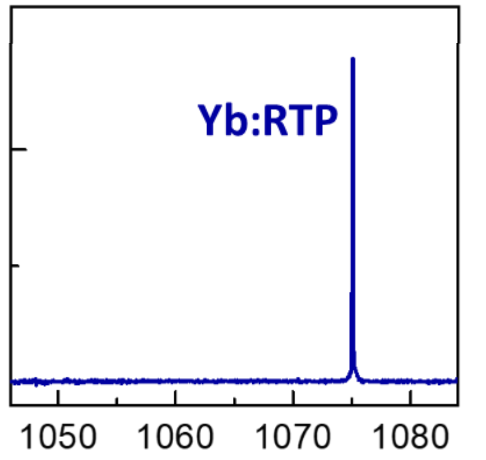


-----Emission spectrum of Yb^{3+} :RTP in the lasing spectral region

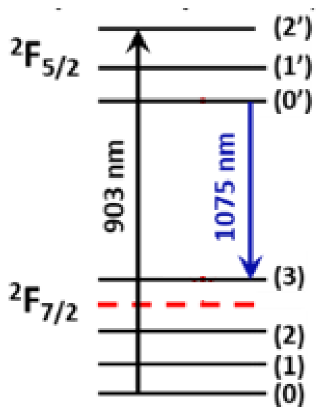
-----Raman spectra

Plasmon-induced dual wavelength Yb^{3+} laser





Yb^{3+} → quasi 3-level laser

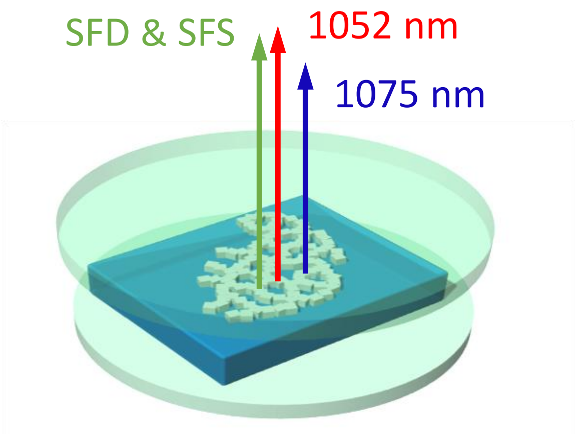


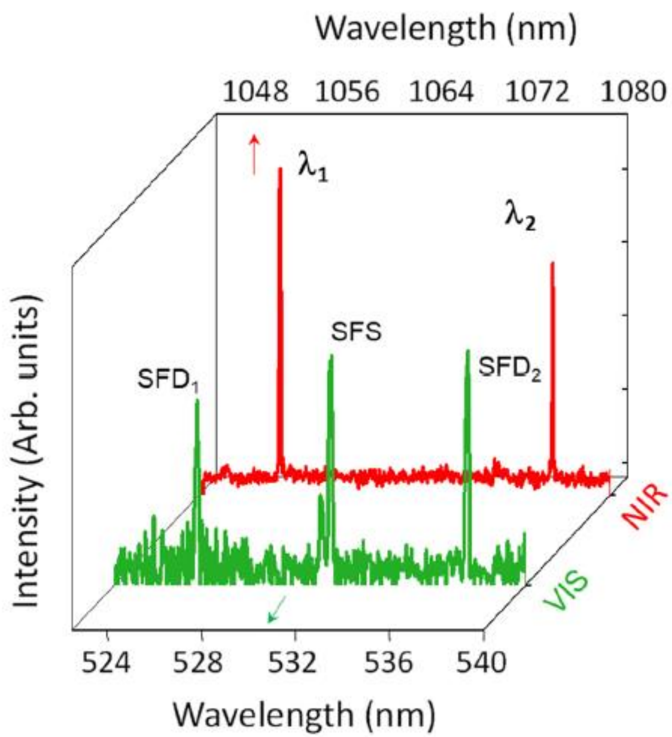
Dual wavelength laser behavior induced by the plasmonic resonances of Ag DPNs

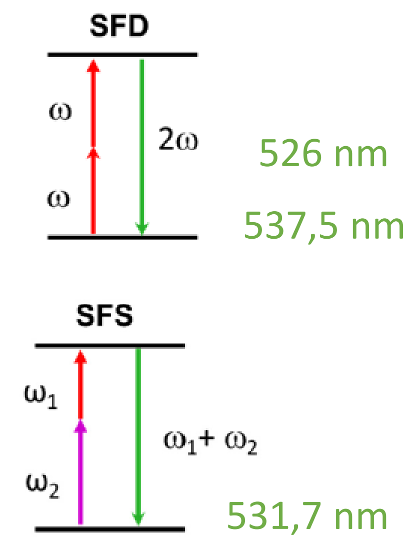
L. Sánchez-García, et al. *Light Sci. Appl.* ***8***, 14 (2019)

Multiline visible radiation in the vicinities of DPNs

RTP matrix: large $\chi^{(2)}$ coefficients







Multiline green radiation is achieved via SFS and SFD processes involving the plasmon-mediated laser line

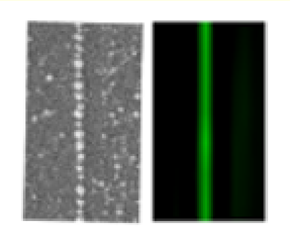
L. Sánchez-García, et al. *Light Sci. Appl.* ***8***, 14 (2019)

Summary

Effects of arrays of Ag NPs on nonlinear solid-state gain media

1. Demostration of plasmon-assisted solid state lasers at the nanoscale

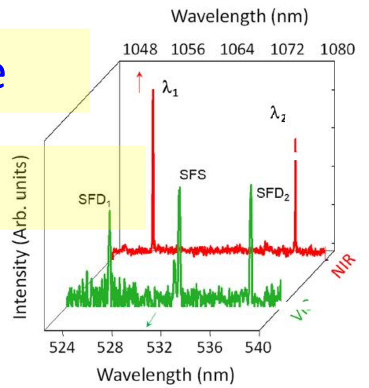
- **Improved performance** with respect to conventional bulk laser operation
  - → Threshold reduction and gain increase
  - → Laser linewidth reduction



- **New functionalities** → Dual wavelength lasing operation

2. Enhancement of frequency conversion processes at the nanoscale

Multiline operation from a single plasmonic nanolaser



The results can be extended to the large diversity of solid-state lasers with the subsequent impact on the applications