# Optical Forces and Field Dynamics in Gain-Enhanced Plasmonic Nanostructures: Toward Single-Particle Nanolasers

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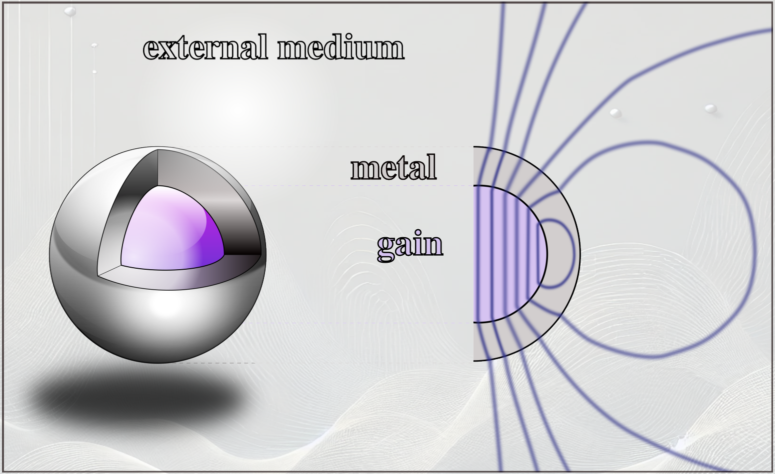
Consiglio Nazionale delle Ricerche

IPCF

NQSTI National Quantum Science and Technology Institute

# System under investigation

A core made of a active gain material surrounded by a metal shell



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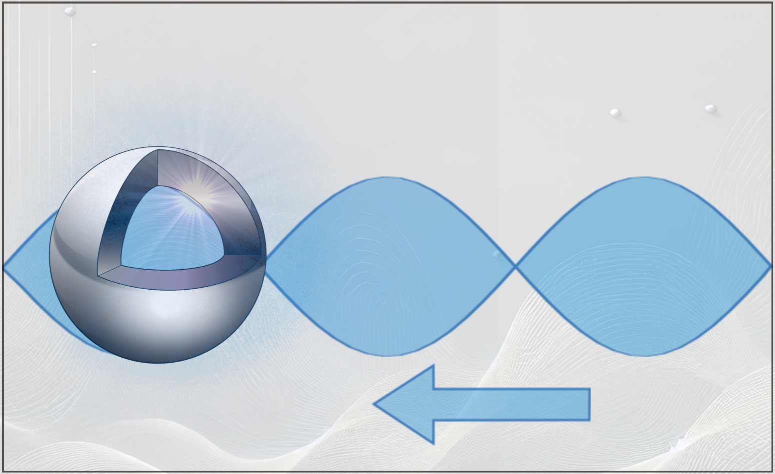
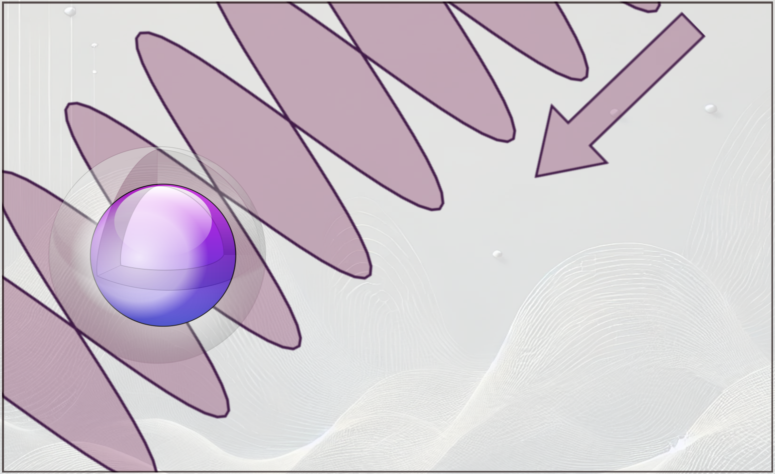


# System under investigation

A core made of a active gain material surrounded by a metal shell which is externally pumped



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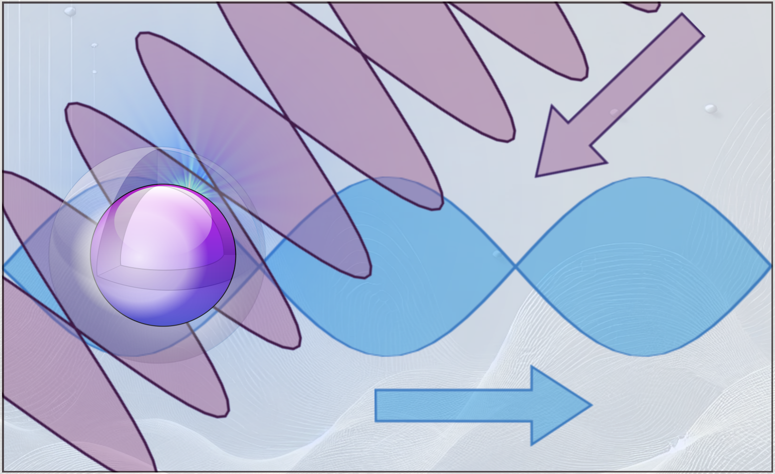


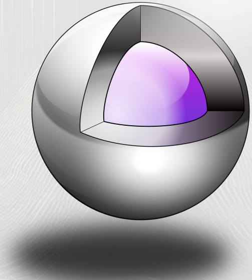
# System under investigation

A core made of a active gain material surrounded by a metal shell

**Free electron model**

① $$\frac{d^2\mathbf{r}}{dt^2} + 2\gamma\frac{d\mathbf{r}}{dt} = \frac{e}{m_e}\mathbf{E}_m,$$

- $m_e$ is the electron mass;
- $e$ is the electron charge;
- $\gamma$ is the ionic collisions friction coefficient;



② $$\frac{d\rho_{12}}{dt} - \left(i\omega_{21} + \frac{1}{\tau_2}\right)\rho_{12} = \frac{iN\boldsymbol{\mu}\cdot\mathbf{E}_h}{\hbar},$$
$$\frac{dN}{dt} + \frac{N - N_0}{\tau_1} = \frac{2i(\rho_{12} - \rho_{21})\boldsymbol{\mu}\cdot\mathbf{E}_h}{\hbar}.$$

- $\boldsymbol{\mu}$ is the dipole moment of the gain element;
- $\tau_2$ and $\tau_1$ are phase and energy relaxation time;
- $\omega_{21}$ is the transition frequency;
- $N$ measures the population inversion;
- $N_0$ is a phenomenological pump rate;

**Optical Bloch equations**

# Time evolution and steady state

**Time Evolution**

- **Gain:** Optical Bloch Equations
- **Metal:** Free electron model

**Rotating Wave Approximation:**

$$\tilde{\mathbf{q}}(t) = Re[\boldsymbol{q}(t)e^{-i\omega t}]$$

**Steady State**

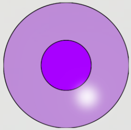
- **Gain:** Lorentzian line-shape
- **Metal:** Drude model

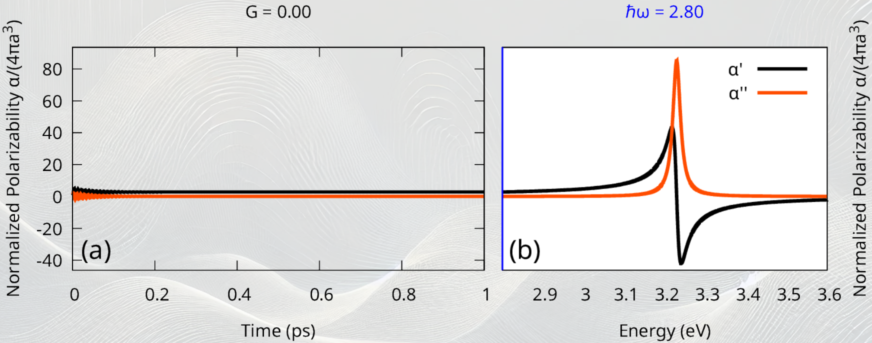
**Steady State Polarizability:**

$$\frac{\alpha(\omega)}{4\pi a^3} = \frac{[\epsilon_g(\omega) + 2\epsilon_m(\omega)][\epsilon_m(\omega) - \epsilon_e] + \rho^3[\epsilon_g(\omega) - \epsilon_m(\omega)][\epsilon_e + 2\epsilon_m(\omega)]}{[\epsilon_g(\omega) + 2\epsilon_m(\omega)][2\epsilon_e + \epsilon_m(\omega)] + 2\rho^3[\epsilon_g(\omega) - \epsilon_m(\omega)][\epsilon_m(\omega) - \epsilon_e]}$$

- $a$ – external radius
- $\epsilon_m(\omega)$ – metal permittivity
- $\epsilon_g(\omega)$ – gain permittivity
- $\epsilon_e$ – external medium permittivity
- $\rho$ – radius ratio

# Time evolution and steady state





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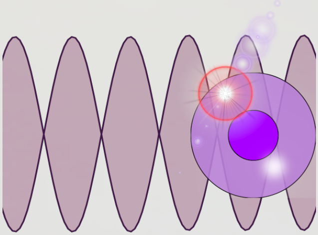

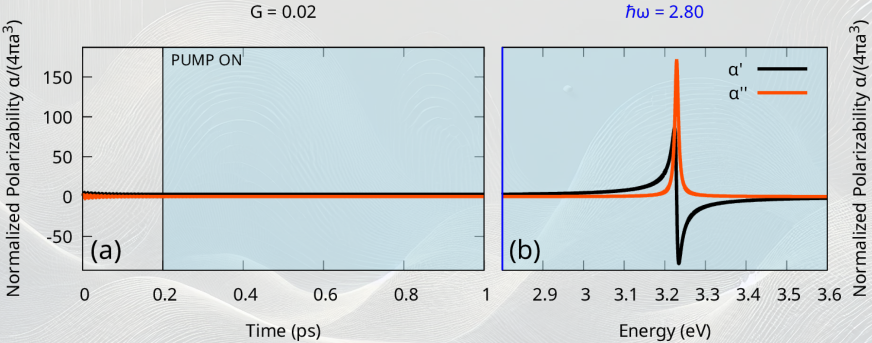

# Core-shells and Nano-shells

Journal of the Optical Society of America B
OPTICAL PHYSICS

**Gain-driven singular resonances in active core-shell and nano-shell plasmonic particles**

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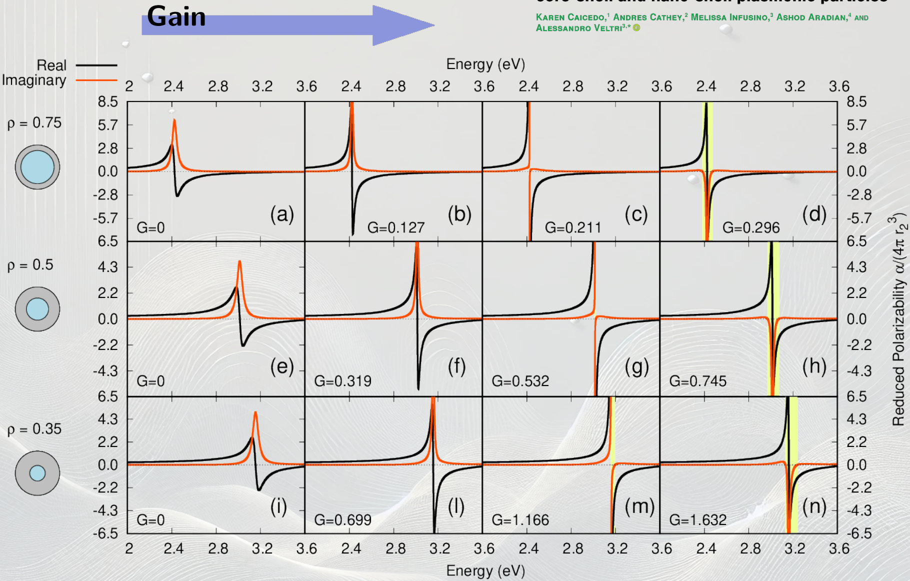

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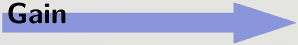
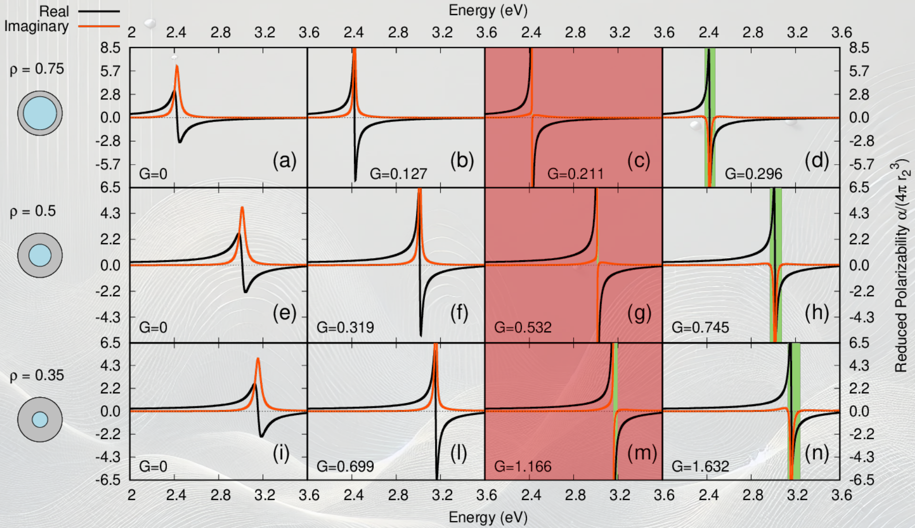
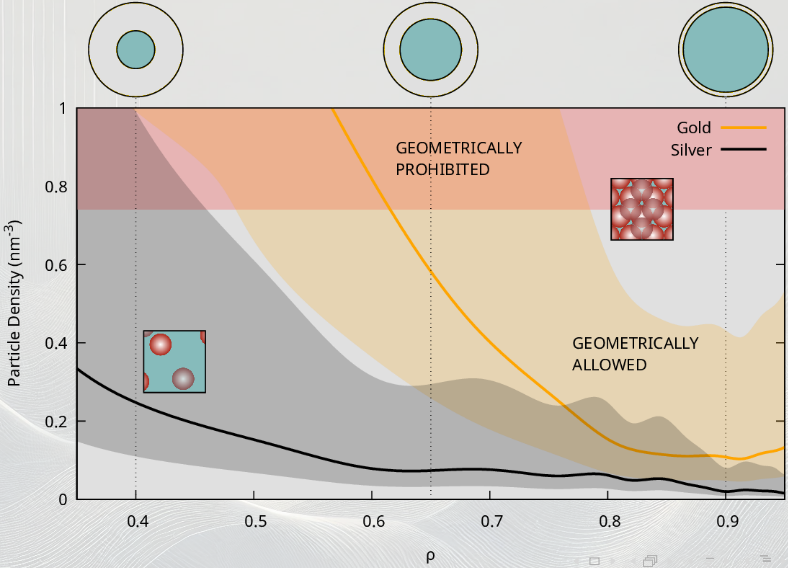


## Core-shells and Nano-shells

Particle density needed to produce a "singular behavior"

(when using $5D \leq \mu \leq 15D$)

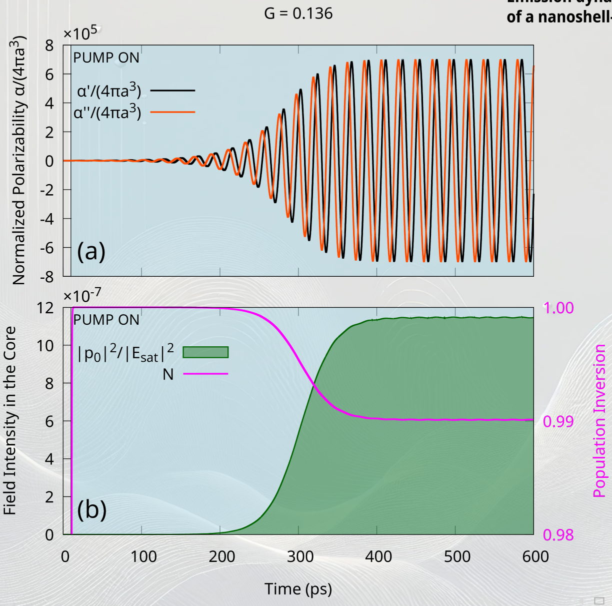


# Beyond the Emission threshold

DE GRUYTER
Nanophotonics 2024; aop
Research Article

Ashod Aradian, Karen Caicedo, Andres Cathey, Milena Mora, Nicole Recalde, Melissa Infusino and Alessandro Veltri*

**Emission dynamics and spectrum of a nanoshell-based plasmonic nanolaser spaser**



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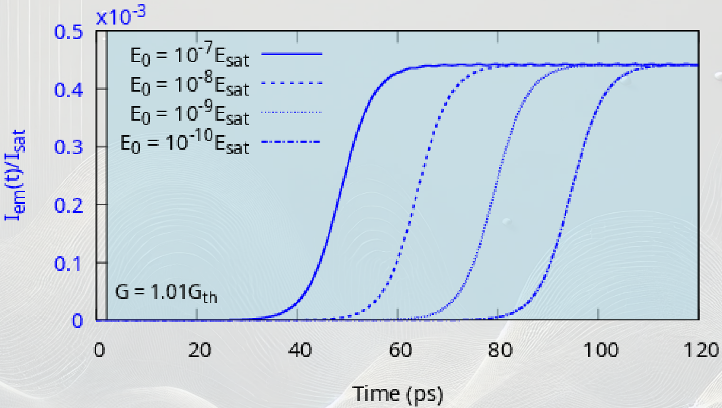
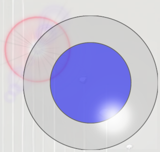


# Nanoshell: Above emission



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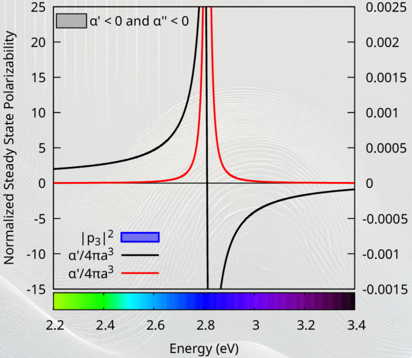


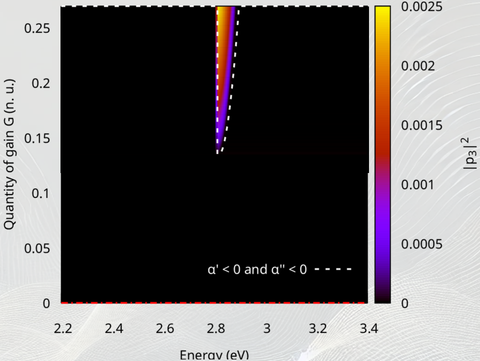

# Nanoshell: Above emission

DE GRUYTER Nanophotonics 2024; aop

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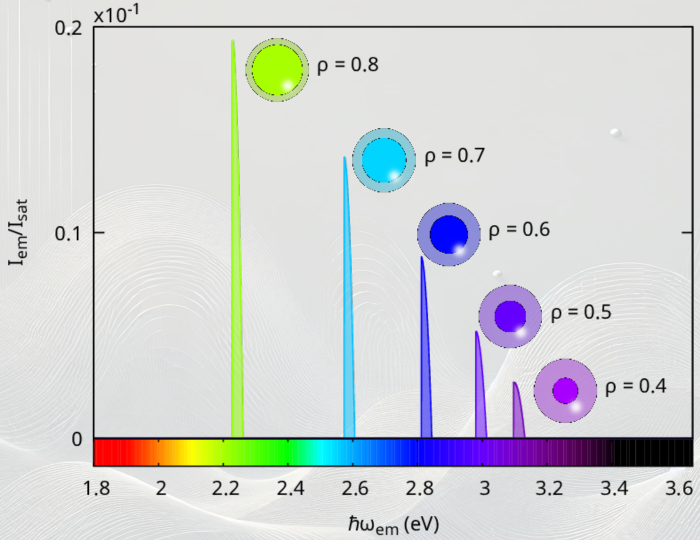
**Emission dynamics and spectrum of a nanoshell-based plasmonic nanolaser spaser**

Tuning the emission frequency



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lexwolf Merge pull request #9 from lexwolf/dev ✓ 6aebfdb · last week 22 Commits

| | | |
|---|---|---|
| .github/workflows | Update and rename c-cpp.yml to make.yml | last week |
| bin | Initial commit of nanoshell project | 2 weeks ago |
| data | Delete data/input/nanosphere_eV.dat.bak | last week |
| img | Initial commit of nanoshell project | 2 weeks ago |
| scripts | Remove unnecessary test script: _rangeE0.gp | 2 weeks ago |
| src | Initial commit of nanoshell project | 2 weeks ago |
| tests | Update test code time_behavior.cxx | last week |
| .gitignore | Add .gitignore file | 2 weeks ago |
| LICENSE | Initial commit of nanoshell project | 2 weeks ago |
| Makefile | Initial commit of nanoshell project | 2 weeks ago |
| README.md | Update README.md | last week |
| configure | Initial commit of nanoshell project | 2 weeks ago |

**About**

Simulation of nanoshell amplification/emission/spasers with time-dependent behavior.

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# Nano-shell: Below emission

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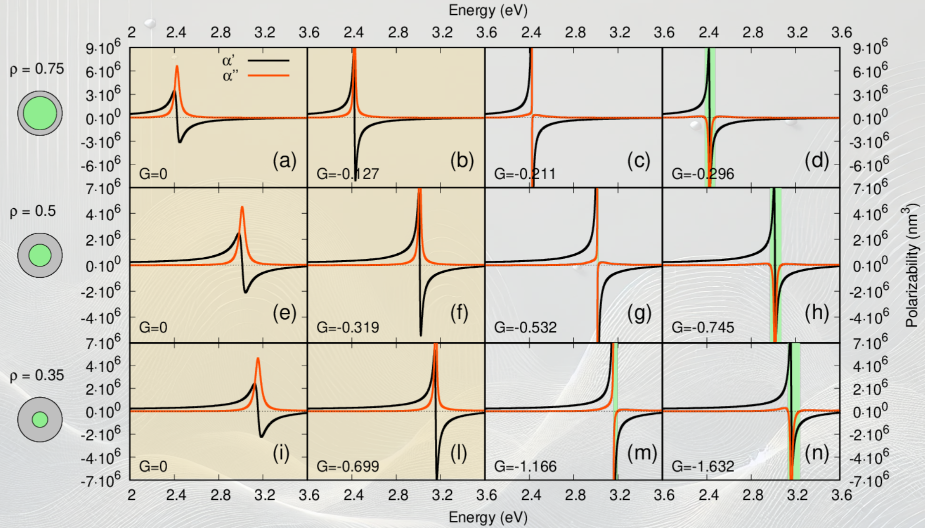
**Gain**

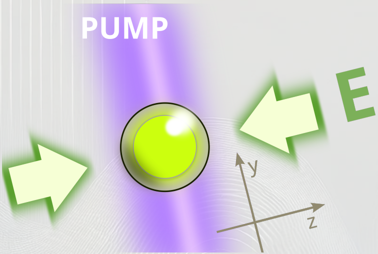


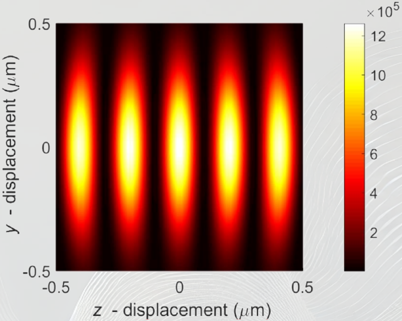
# Optical Forces

ACS Photonics
pubs.acs.org/journal/apchd5
Article

**Gain-Assisted Optomechanical Position Locking of Metal/Dielectric Nanoshells in Optical Potentials**

In order to neglect scattering forces, our trap is realized using a counter-propagating laser beam




In this configuration the the time-averaged optical force experienced by the nanoshell is:

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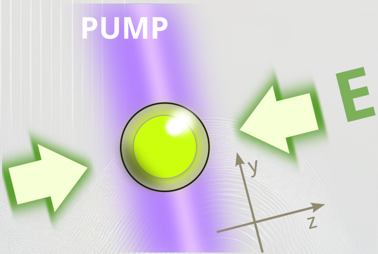


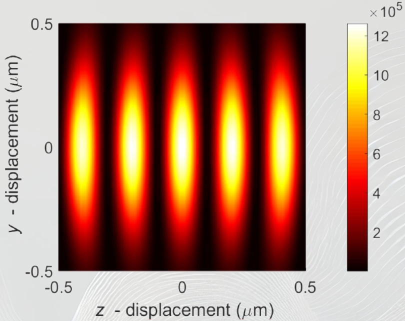


In this configuration the the time-averaged optical force experienced by the nanoshell is:

$$\mathbf{F}_{DA}(\mathbf{r},\omega) = \frac{n_3 \Re\{\alpha(\omega)\}}{2c\varepsilon_0\varepsilon_3} \nabla I(\mathbf{r})$$

- $n_3$ is the solvent refractive index (water $n_3 = 1.33$) and $\varepsilon_3$ the corresponding permittivity
- $\varepsilon_0$ is the vacuum permittivity and $c$ is the speed of light
- $I(\mathbf{r}) = \dfrac{n_3 c |\mathbf{E}(\mathbf{r})|^2}{2}$ is the intensity of the electric field

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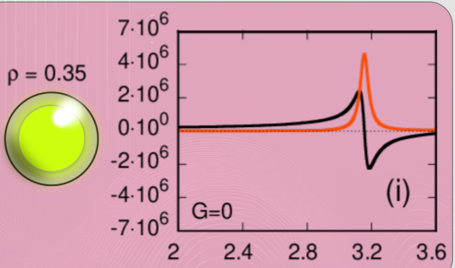
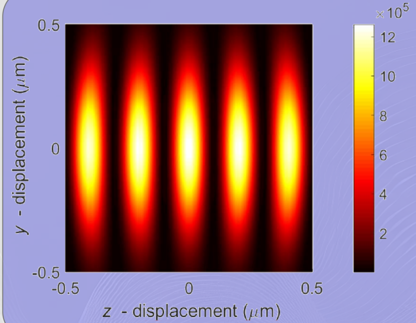


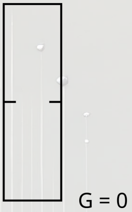



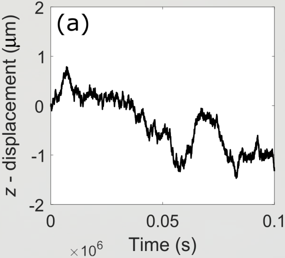

frequency dependency

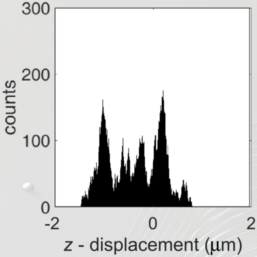
$$\mathbf{F}_{\mathrm{DA}}(\mathbf{r},\omega) = \frac{n_3 \Re\{\alpha(\omega)\}}{2c\varepsilon_0\varepsilon_3}\nabla I(\mathbf{r})$$

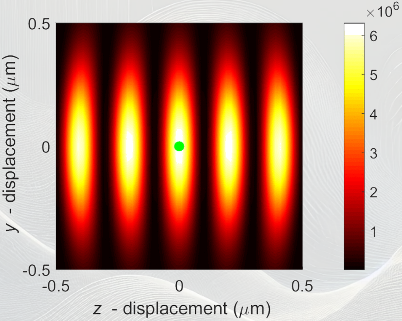
spacial dependency

# Trapping and Nano-channeling



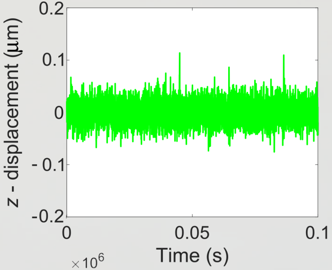



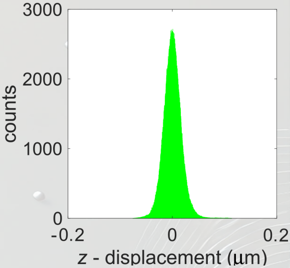



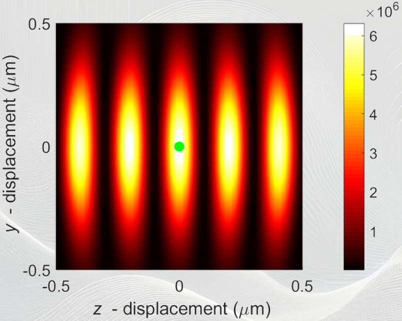

**Simulation parameters:**

- $P = 20$ mW
- $t = 1$ ms
- $\Delta t = 2$ ns

# Trapping and Nano-channeling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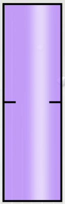


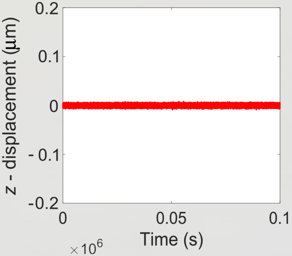


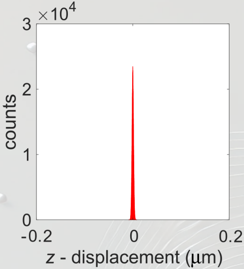


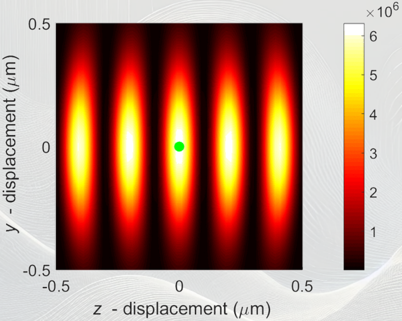


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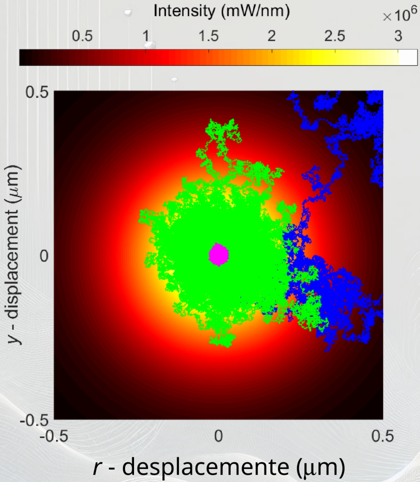


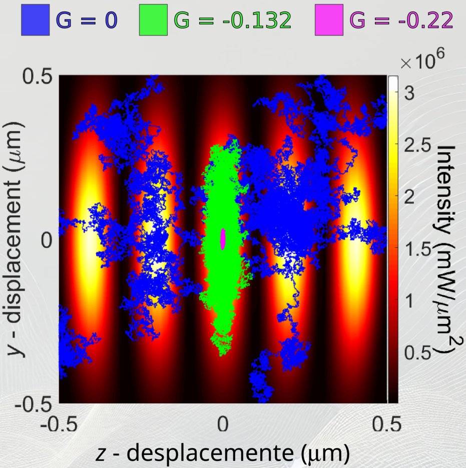

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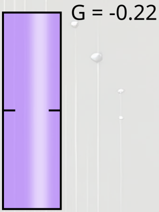


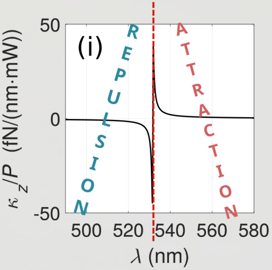

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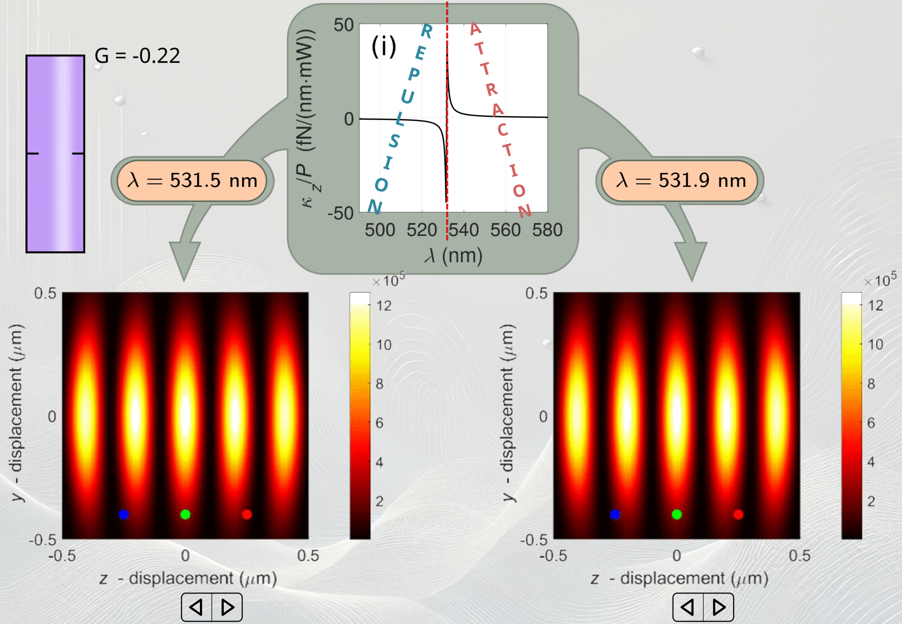
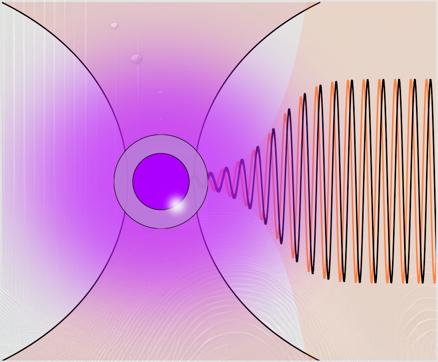


# Trapping Beyond the Emission threshold



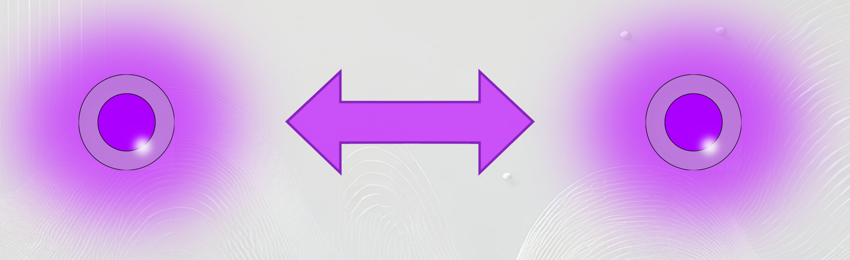
- Being able to measure the change in the optical forces when the system shift from absorption to emission could be a unique route to **measure plasmonic emission in the local field** for the first time;
- It wold also be very interesting to study how this change would affect the **laser cooling** of the nanoparticle, because the *behaviors above and below* the emission threshold should be **strikingly different**.

In general, being able to predict the change of behavior these particles should show in a optical trap on the when the the Emission threshold is overcome, will allow to realization of a completely new experimental tool set, to explore these materials and pave for new nanotecnologic possibilities

# Multiple Particles

Multiple particles interact with each others when trapped together in a optical potential, allowing for the realizations of optical lattices.

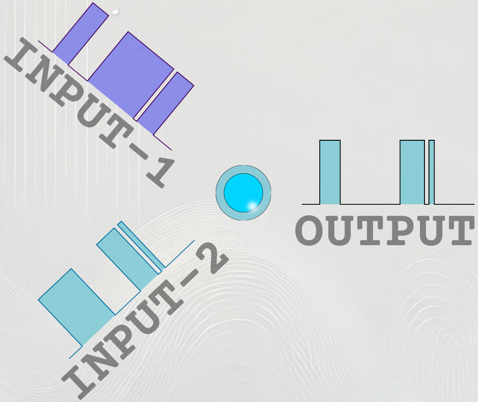
**We expect this interaction to change drastically when the Emission threshold is surpassed**



- Super-Radiance;
- Optical binding;
- Quantum correlations
- 3D - Metamaterials

# Applications

New computational routes?



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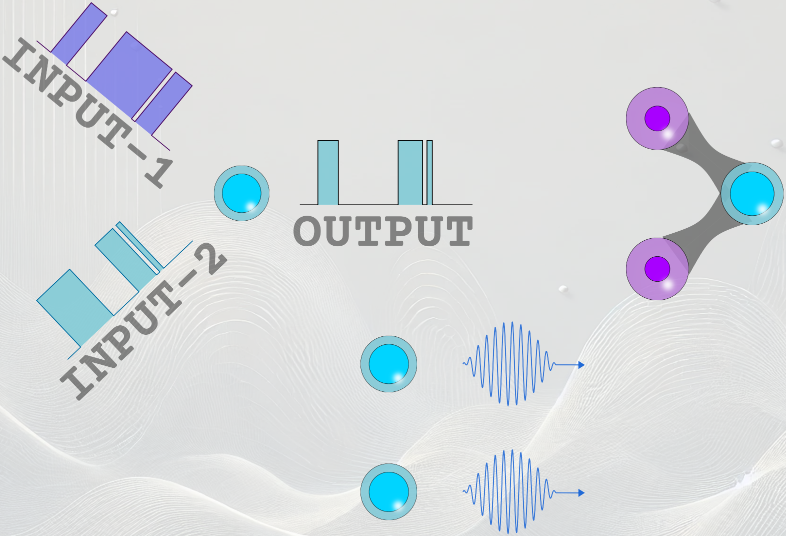

# Thank you for your attention!

## SP17. "Nano-Lasers, Spasers, and Nanostructures with Quantum Elements"

**Organizers:** **Alessandro Veltri** (Universidad San Francisco de Quito, Ecuador) & **Ashod Aradian** (Centre de Recherche Paul Pascal - CNRS, France)

This session aims to bring together researchers to discuss both recent advancements and enduring challenges in this field, which continues to be a fertile ground for innovation in nanophotonics.

**Topics:**

1. Theoretical advancements in the modeling of nano-lasers and spasers
2. Experimental breakthroughs in the fabrication and characterization of these devices
3. Emerging applications of hybrid nanostructures, including sensing, quantum information, and high-speed photonics