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Position locking of a resonant gain assisted metallic/dielectric nano-shell in Optical Tweezers

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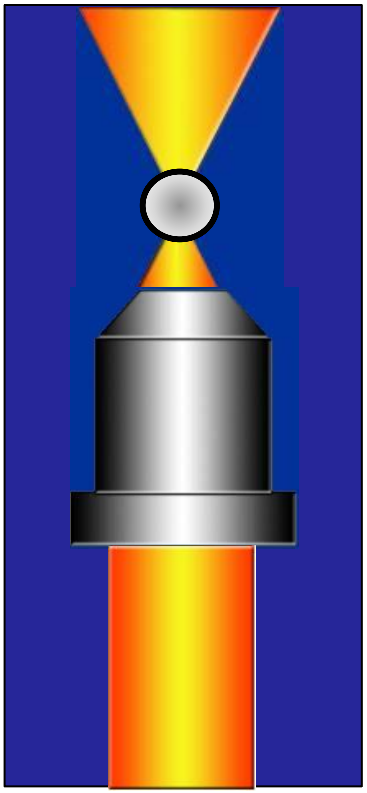
Outline

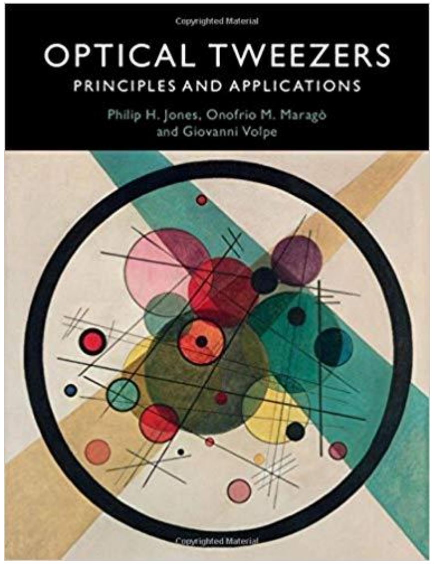
- Introduction
- Trapped resonant gain metal/dielectric nanoshell
- Non-linear Optical Trapping
- Brownian Dynamics Simulation
- Optomechanical Position Locking and Channeling
- Conclusions and perspectives

Optical Tweezers

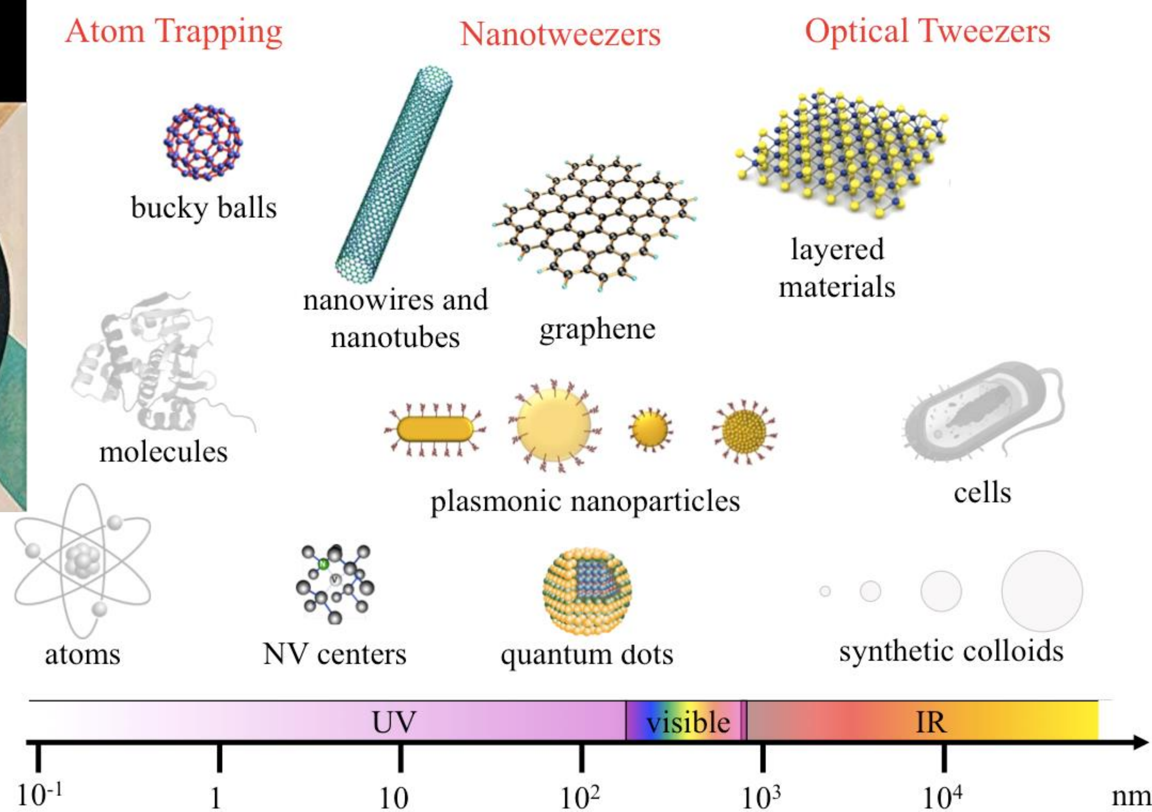
A device for the contactless trapping and manipulation of micro- and nanostructures is called **Optical Tweezers.**

O. M. Maragò, P. H. Jones, P. G. Gucciardi, G. Volpe, and A. C. Ferrari, *Nat. Nanotechnol.* (2013)





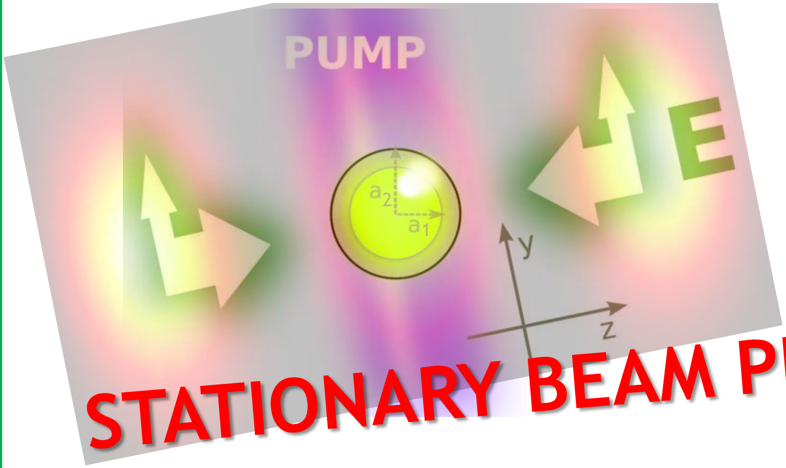
- F. Borghese et al., *PRL* (2008)
- P. Polimeno et al., *JQSRT* (2018)



Optical trapping can be realized through a single laser beam and a high *NA* objective

Trapped resonant gain metal/dielectric nanoshell

Silver nanoshell with externally **pumped optical gain material** on its core excited by an external electric field.



STATIONARY BEAM PROBE

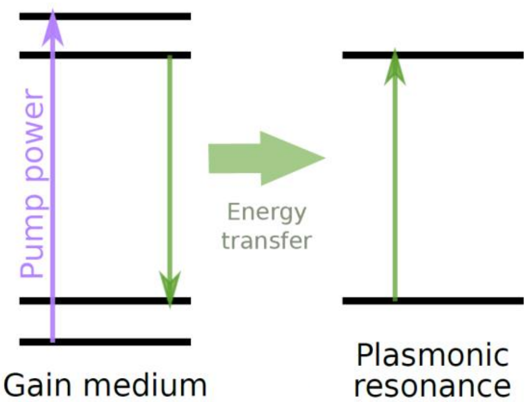
$$\rho = \frac{a_1}{a_2}$$

a_1 int. radius

a_2 ext. radius

A. Veltri and et., *Sci. Rep.* (2016)

rhodamine molecules



In our model: ρ = 0.77 and a_2 = 20 nm

Under a pumping threshold, nano-shell shows a **stable dipolar field**.

A. Veltri and A. Aradian, *Phy. Rev. B* (2012)
A. Veltri et al., *Sci. Rep.* (2016)

$$\bar{\mathbf{p}} = \frac{\alpha_{\mathrm{NUM}}(\varepsilon_1, \varepsilon_2, \varepsilon_3, \rho)}{\alpha_{\mathrm{DEN}}(\varepsilon_1, \varepsilon_2, \varepsilon_3, \rho)} \bar{\mathbf{E}}$$

$$\alpha = a_2^3 \frac{(\varepsilon_2 - \varepsilon_3)(\varepsilon_1 + 2\varepsilon_2) + \rho^3(\varepsilon_1 - \varepsilon_2)(\varepsilon_3 + 2\varepsilon_2)}{(\varepsilon_2 + 2\varepsilon_3)(\varepsilon_1 + 2\varepsilon_2) + 2\rho^3(\varepsilon_2 - \varepsilon_3)(\varepsilon_1 - \varepsilon_2)}$$

ε_2 single metallic nanoparticle permittivity (Drude model)

ε_3 water (solvent) dielectric permittivity

Steady State Gain dielectric permittivity

$$\varepsilon_1 = \varepsilon_b - \frac{G\Delta}{2(\omega - \omega_{21}) + i\Delta} \qquad \Delta = \frac{2}{\tau_2}$$

ε_b dielectric host permittivity

$$G = \Im[\varepsilon_1(\omega_{21})] = -\frac{n\mu^2\tau_2}{3\hbar\varepsilon_0}\tilde{N}$$

Optical Trapping in Dipole Approximation

- Particle size parameter is small, $x = k_m a \ll 1$ $\quad \mathbf{p}(\mathbf{r},t) = \alpha_p \mathbf{E}(\mathbf{r},t)$
- Dipole interaction between laser field and particle in a dielectric medium
- The (harmonic) trapping potential is defined by the incident light intensity

$$\langle \mathbf{F} \rangle_{\mathrm{DA}} = \frac{1}{2}\frac{n_{\mathrm{m}}}{c\varepsilon_{\mathrm{m}}}\Re\{\alpha_{\mathrm{p}}\}\nabla I(\mathbf{r}) + \frac{n_{\mathrm{m}}}{c}\sigma_{\mathrm{e}} I(\mathbf{r})$$

Gradient force

Scattering force

$$U_{\mathrm{dip}} = -\underline{p}\cdot\underline{E}$$

$$\underline{F}_{\mathrm{grad}} \propto \underline{\nabla} I(\underline{r}) = -\kappa_i x_i$$

J. R. Arias-González and M. Nieto-Vesperinas, *JOSA A* (2003)

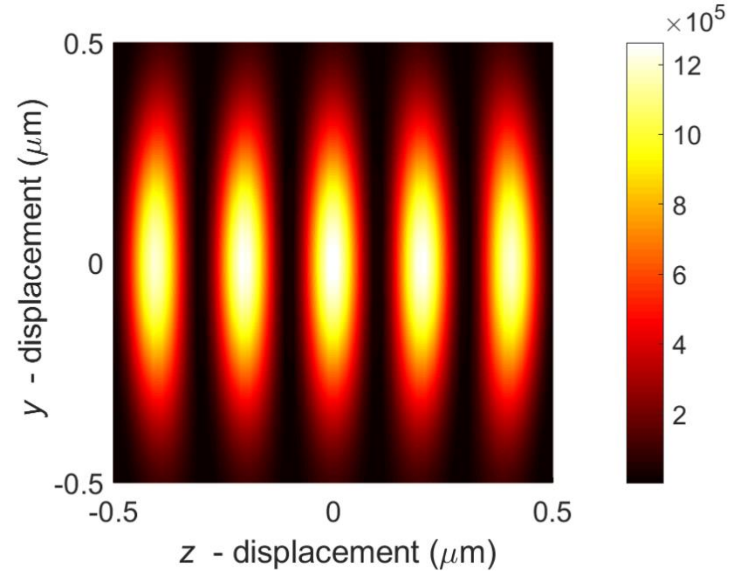
Counter-propagating Gaussian beam

$$\kappa_\rho^{\mathrm{c.p.}} = 8\frac{\Re\{\alpha_{\mathrm{p}}\}}{c n_{\mathrm{m}}}\frac{I_0}{w_0^2}.$$

$$z_0 = \frac{k_{\mathrm{m}} w_0^2}{2} \qquad w_0 = 0.5\ \lambda_0/NA$$

$$\kappa_z^{\mathrm{c.p.}} = 4\frac{\Re\{\alpha_{\mathrm{p}}\}}{c n_{\mathrm{m}}}\left(2 - 2k_{\mathrm{m}} z_0 + k_{\mathrm{m}}^2 z_0^2\right)\frac{I_0}{z_0^2}.$$

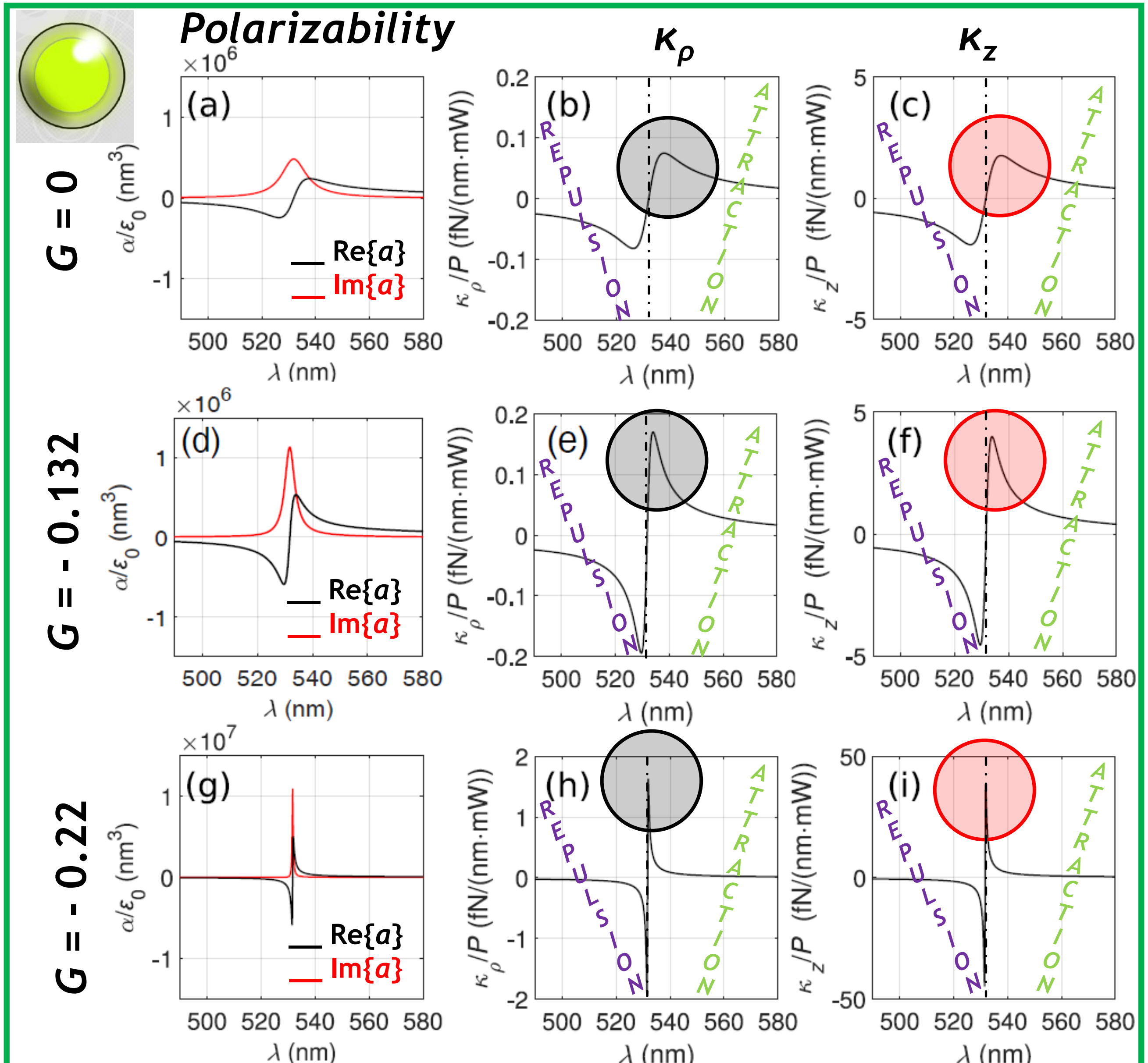
$$I_0 = 2P/\pi w_0^2$$



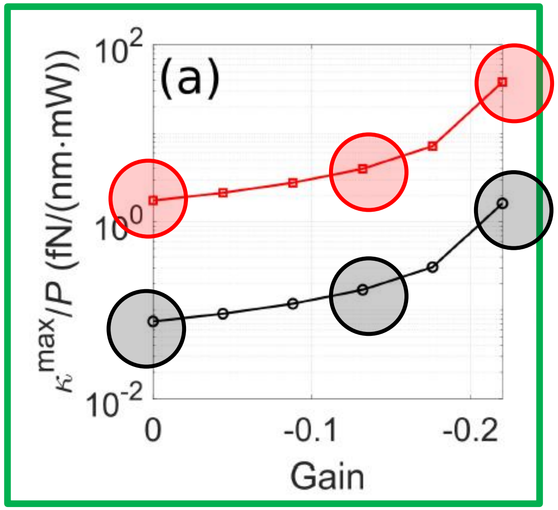
O. Brzobohatý et. al., *Opt. Exp.* (2015)

Non-linear Optical Trapping

$$F_{\text{grad}} \propto \underline{\nabla} I(\underline{r}) = -\kappa_i x_i$$



P = 50 mW



Logarithmic scale

P. Polimeno et al., *ACS Photonics* (2020)

Brownian Dynamics Simulation

G. Volpe and G. Volpe, *Am. J. Phys.* (2013)

$$\frac{d}{dt}r(t) = -\frac{1}{\gamma}\frac{d}{dr}U(r) + \xi(t)$$

Overdamped Langevin equation

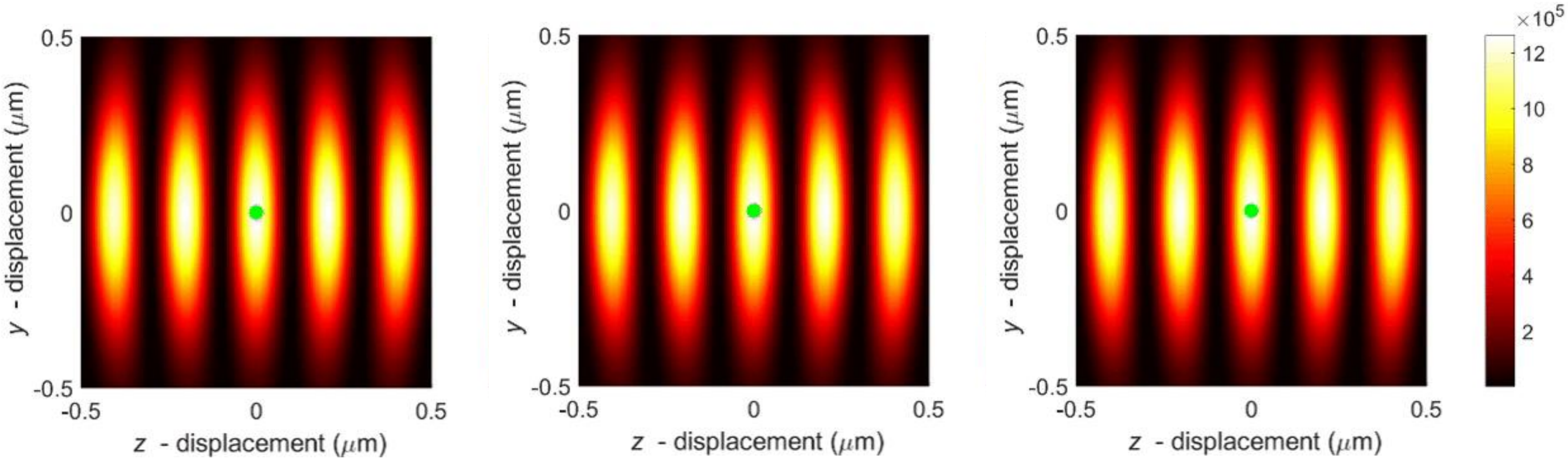
P = 50 mW
t = 1 ms
Δt = 2 ns

Integrating

$$\begin{cases} x_i &= x_{i-1} - \frac{\kappa_x}{\gamma} x_{i-1}\Delta t + \sqrt{2D\Delta t}\, w_{x,i} \\ y_i &= y_{i-1} - \frac{\kappa_y}{\gamma} y_{i-1}\Delta t + \sqrt{2D\Delta t}\, w_{y,i} \\ z_i &= z_{i-1} - \frac{\kappa_z}{\gamma} z_{i-1}\Delta t + \sqrt{2D\Delta t}\, w_{z,i} \end{cases}$$

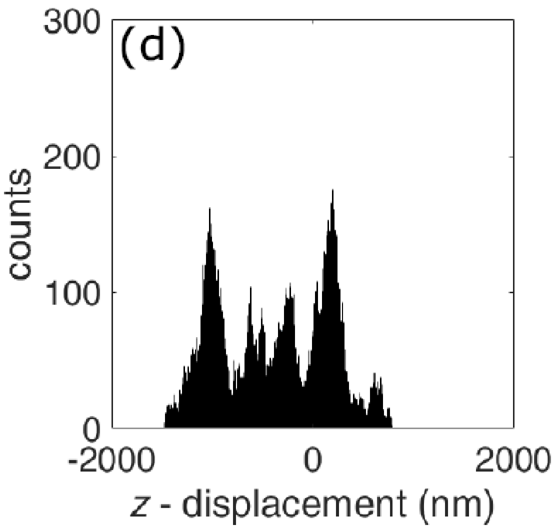
P. Polimeno et al., *ACS Photonics* (2020)

G = - 0.022 **G = - 0.132** **G = - 0.22**

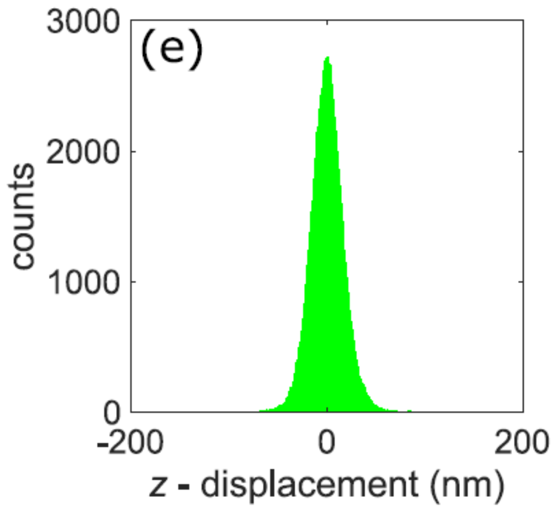


Brownian Dynamics Simulation

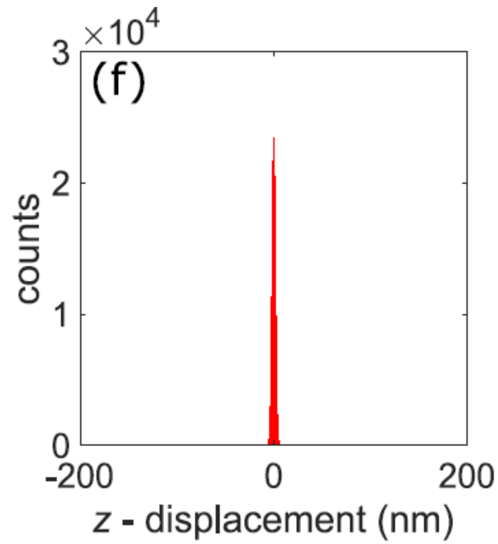
***G* = - 0.022**

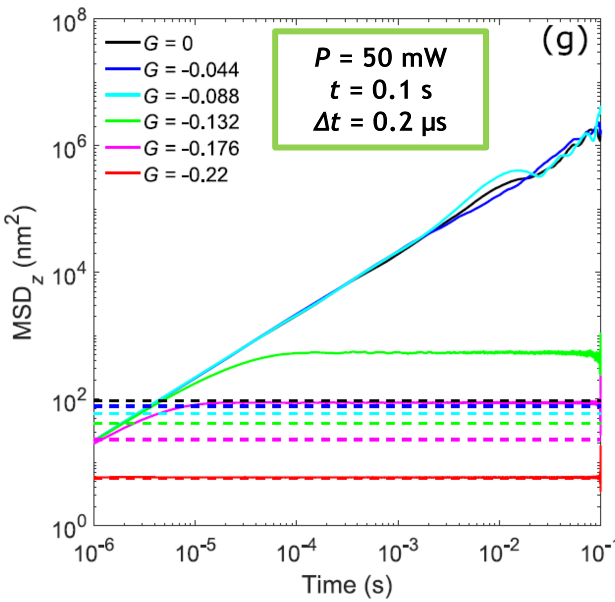


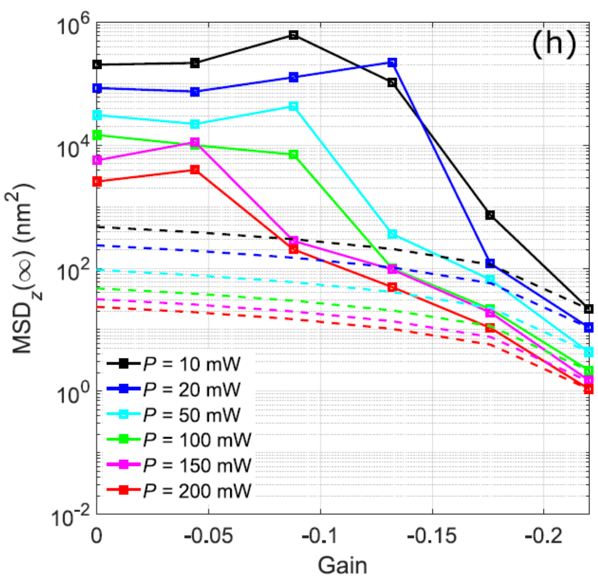
***G* = - 0.132**



***G* = - 0.22**







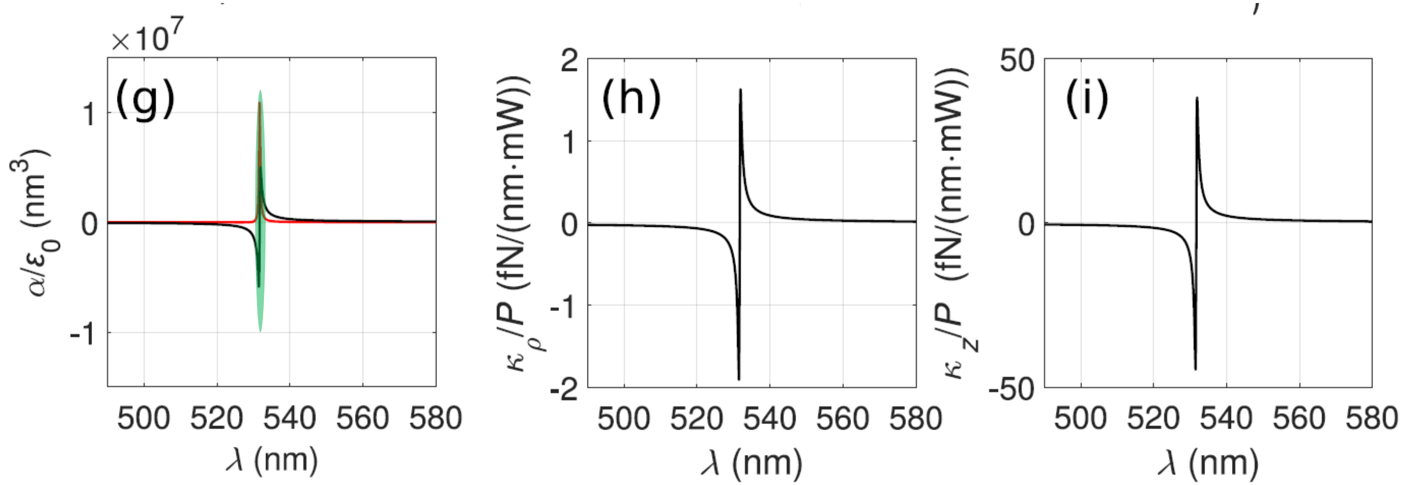
***P* = 50 mW**
***t* = 0.1 s**
***Δt* = 0.2 μs**

$$MSD(\infty) = 2\frac{\kappa_b T}{k_z}$$

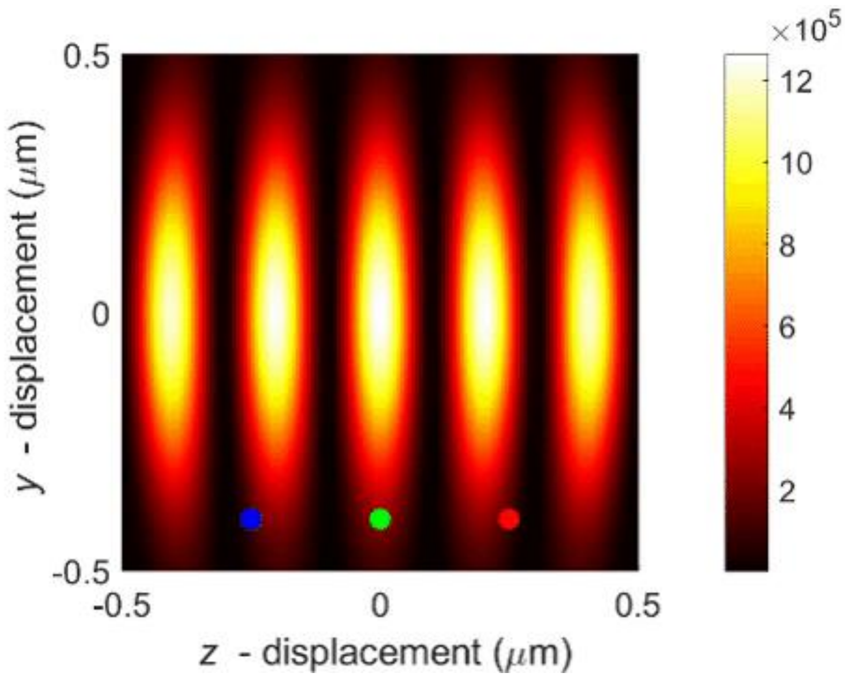
P. Polimeno et al., *ACS Photonics* (2020)

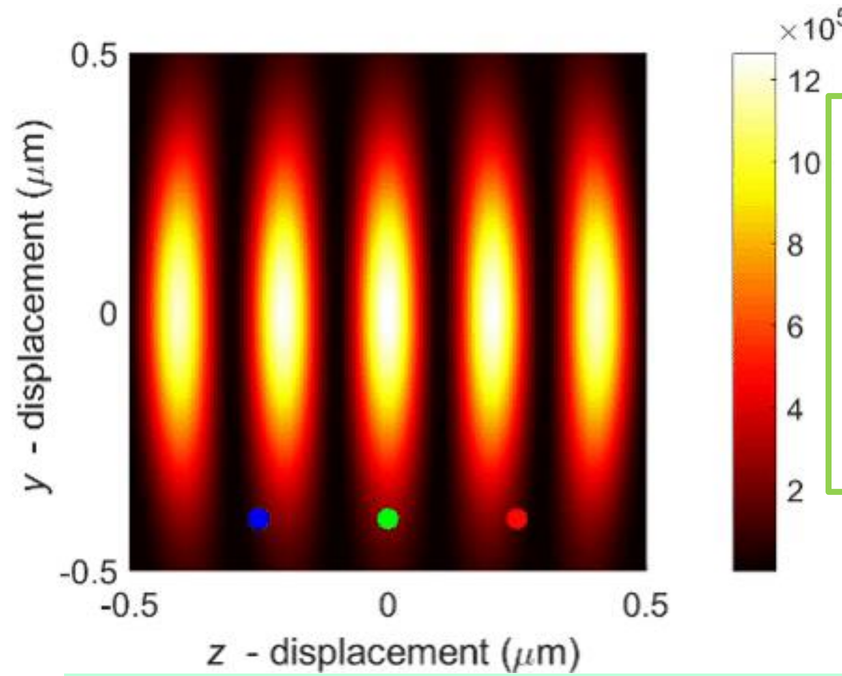
Optomechanical Position Locking and Channelling

G = - 0.22
P = 50 mW
t = 1 ms
Δt = 2 ns



λ = 531.898 nm





λ = 531.472 nm

P. Polimeno et al., *ACS Photonics* (2020)

Conclusions and perspectives

- We studied optical trapping of hybrid core-shell nanoparticles with gain in a Gaussian beam counter-propagating configuration, highlighting the non-linear optical scaling of optical forces.
- We performed Brownian simulations in water, where we directly observe how the particle dynamics is more confined for increasing gain.
- We showed that by changing the light wavelength with respect to the nanoshell resonance it is possible to switch the sign of the optical forces and use the dual-beam configuration for position locking (red detuning) or channelling (blue detuning) of particle in a microfluidic flow.