NQSTI National Quantum Science and Technology Institute

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

Alessandro Veltri[1,2], Melissa Infusino[1,2], Rosalba Saija[1,3], Onofrio M. Maragò[1], Maria A. Iatì[1]

1. *CNR-IPCF, Istituto per i Processi Chimico-Fisici, I-98158, Messina, Italy*
2. *Colegio de Ciencias e Ingenieria, Universidad San Francisco de Quito, Ecuador*
3. *Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra, I-98166, Università degli Studi di Messina, Italy*

Abstract: We study optical forces and trapping of hybrid quantum-plasmonic nanoparticles with a metal nanoshell and a gain-enriched core, below and above the emission threshold. This open perspectives for single-particle nanolaser with potential for quantum-enhanced plasmonics.

Optical tweezers [1] are tools made of light for the contactless trapping and manipulation of particles [2] from single atoms to microplastics [3]. In our earlier study [4], we analyzed the optical forces acting on a trapped plasmonic nanoparticle with a metal nanoshell and a gain-enriched core, operating below the emission threshold. This work provided insights into the interplay between quantum and optical phenomena in such structures. Recently, we extended this framework [5] by modeling the electromagnetic fields around the same structure above the emission threshold and describing the field dynamics. Our analysis reveals the critical transitions from sub-threshold to super-threshold regimes of emission, emphasizing the role of quantum-enhanced plasmonics in advancing nanophotonic technologies. By modeling the electromagnetic fields above the emission threshold, we provide a comprehensive framework to understand the interplay of gain and plasmonic effects. This enables exploration of the optical forces and trapping in the emissive regime and could reveal critical changes in the transition from sub-threshold to super-threshold operation.

These findings pave the way for designing systems that could experimentally demonstrate and characterize a single-particle nanolaser in the near field, highlighting the potential of quantum-enhanced plasmonics for advancing nanophotonic applications.

References

[1] Ciarlo, A., Bronte Ciriza, D., Selin, M., Maragò, O. M., Sasso, A., Pesce, G., Volpe, G., Goksör, M. Deep learning for optical tweezers. Nanophotonics **13**, 3017–3035 (2024).

[2] Bronte Ciriza, D., Callegari, A., Donato, M. G., Çiçek, B., Magazzù, A., Kasianiuk, I., Kasianiuk, D., Schmidt, F., Foti, A., Gucciardi, P. G., Volpe, G., Lanza, M., Biancofiore, L., Maragò, O. M. Optically driven Janus microengine with full orbital motion control. ACS Photonics **10**, 3223-3232 (2023).

[3] Rezaei, S., Bronte Ciriza, D., Hassanzadeh, A., Kheirandish, F., Gucciardi, P. G., Maragò, O. M., Saija, R., Iatì, M. A. Faster Calculations of Optical Trapping Using Neural Networks Trained by T-Matrix Data: An Application to Micro-and Nanoplastics. ACS Photonics **11**, 3424-3432 (2024).

[4] Polimeno, P., Patti, F., Infusino, M., Sánchez, J., Iatì, M. A., Saija, R., Volpe, G., Maragò, O. M., & Veltri, A. Gain-Assisted Optomechanical Position Locking of Metal/Dielectric Nanoshells in Optical Potentials. ACS Photonics **7**, 1262–1270 (2020). https://doi.org/10.1021/acsphotonics.0c00213

[5] Aradian, A., Caicedo, K., Cathey, A., Mora, M., Recalde, N., Infusino, M., & Veltri, A. Emission Dynamics and Spectrum of a Nanoshell-Based Plasmonic Nanolaser Spaser. Nanophotonics **13**, 4817-4837 (2024). https://doi.org/10.1515/nanoph-2024-0491