Curved Laser Traps for Optical Manipulation of micro/nano-particles and micro-robotics

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Abstract

The goal of this work is presenting a new optical manipulation tool based on 3D holographic curved laser traps in form of arbitrary curve with independently prescribed propelling forces along it. We establish theoretical fundamentals for its creation and experimentally demonstrate it with examples that draw micro robotics functions such as optical transport of numerous micro/nano-particles avoiding obstacles and controlling the curve's traffic.

Principle of the technique and experimental results

Curved Laser trap

- **Design:** A polymorphic beam **[1-3]**

$$E(\mathbf{r}) = \int_0^T g(t) \exp\left[\frac{ik}{2f^2}\xi(t)\,\mathbf{r}^2\right] \exp\left[\frac{-ik}{f}\mathbf{r}\mathbf{R}(t)\right] \mathrm{d}t,$$

  encoded by a hologram, is focused to create the optical trap ($\widetilde{E} = \mathrm{FT}[E(\mathbf{r})]$) in form of arbitrary 3D curve, defined by the coordinates $(\mathbf{R}(t), \xi(t))$. Here, $\mathbf{r} = (x, y)$, $\mathbf{R}(t) = (R(t)\cos t,\ R(t)\sin t)$, while $g(t) = |g(t)| \exp(\mathrm{i}\Psi(t))$ is a function describing the field amplitude and phase distribution along the curve, f is the focal length of the objective lens, k is the wavenumber and the azimuthal angle is $t \in [0, T]$.

- **Uniform intensity** $|\widetilde{E}|^2$ along the curve $\Longleftrightarrow |g(t)| = \sqrt{\mathbf{R}'(t)^2 + \xi'(t)^2}$.

- **Propelling forces along the curve** $\left(\propto \mathbf{j} = |\widetilde{E}|^2 \nabla_{||}\Psi(t)\right)$ are controlled by freely choosing any $\Psi(t)$.

Advantages of the technique

- Non-iterative and fast generation of the trapping beam and its reconfiguration according to the host environment using an automatic path-finding method.
- Change of the propelling optical force without altering the trajectory.
- Simultaneous optical confinement and transport of numerous particles along arbitrary 2D and 3D curves.

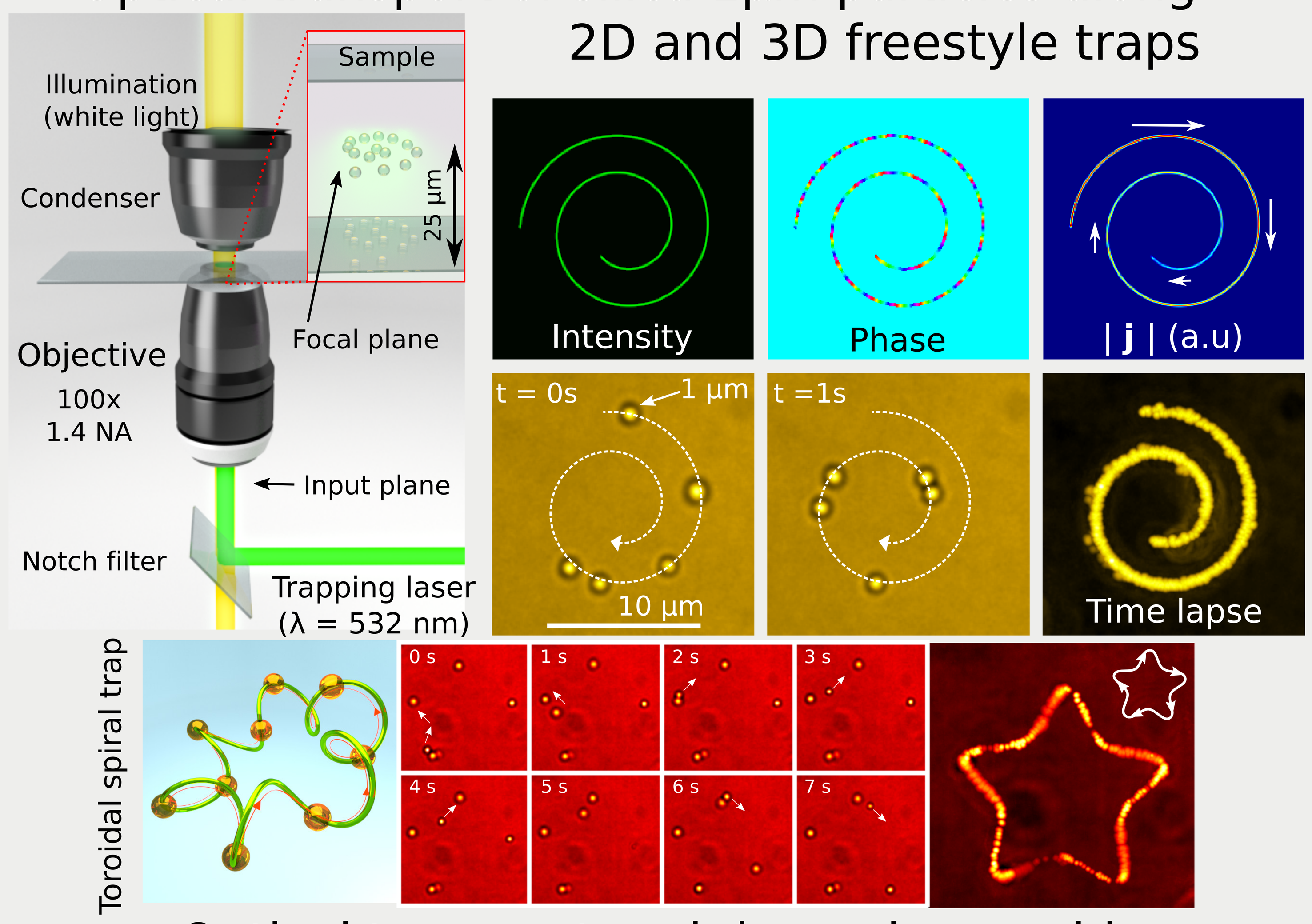
Experimental demonstrations

- Optical transport of 1 μm silica spheres along a reconfigurable trajectory given by an analytical function $(\mathbf{R}(t), \xi(t))$ or as a combination of Bézier curves. The propelling forces are strong enough to overcome radiation pressure and allow the motion along the 3D curve **[1,3]**.
- Dynamic morphing: programmable, smooth and rapid transformation in time of the 2D or 3D curved laser trap's shape into another one. This allows to make versatile manoeuvres required in complex optical transport, like avoiding suddenly appearing obstacles, delivering particles towards a moving target or adapting the trajectory to the outline shape of an object **[1]**.
- Dynamic routing. Multiparticle transport along trajectories composed of many crossing paths is a difficult task. This technique consists on a temporal reconfiguration of the curve by switching on or off crucial chunks of the curve to enable the particle circulation in such complex systems, handling traffic jams and making possible the particle separation and re-distribution across the knot circuit **[2].**

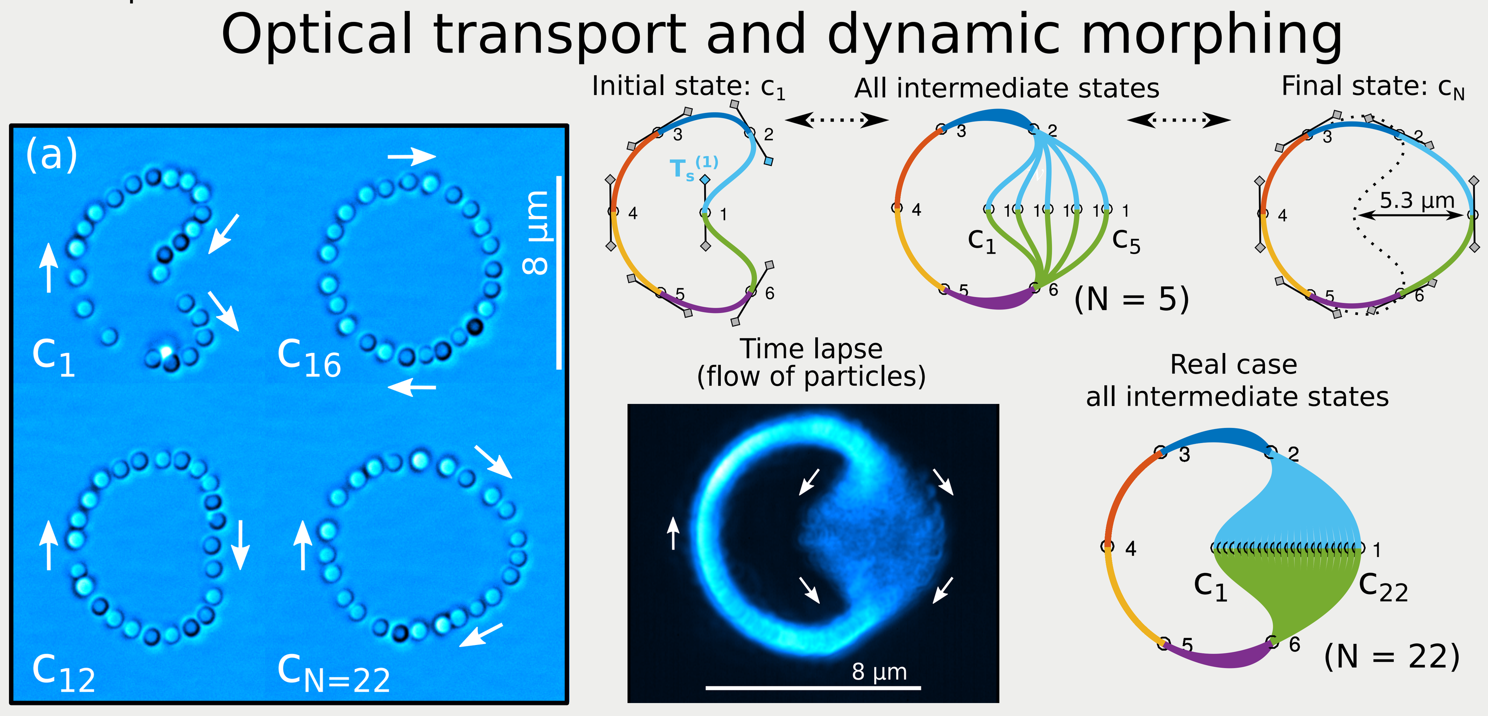
Applications

- Complex light-driven rotating colloidal motors; Study of multi-particle dynamics; Rheology; Microfluidics; Targeted photothermal therapy: transport with simultaneous heating of resonant plasmonic NPs; Dynamic morphing and routing are crucial functionalities for robotic motion planning in optical transport problems; etc

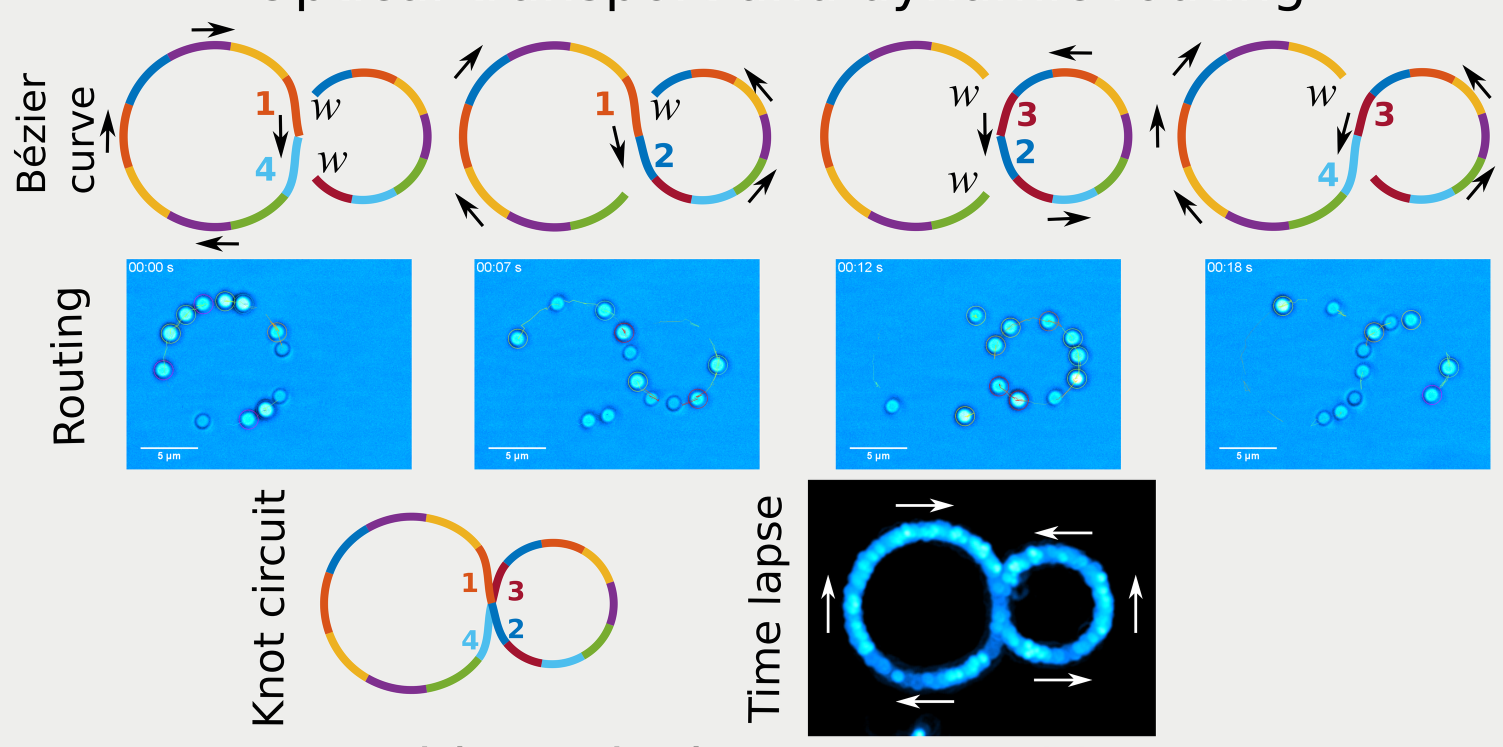
Optical transport of silica 1µm particles along 2D and 3D freestyle traps



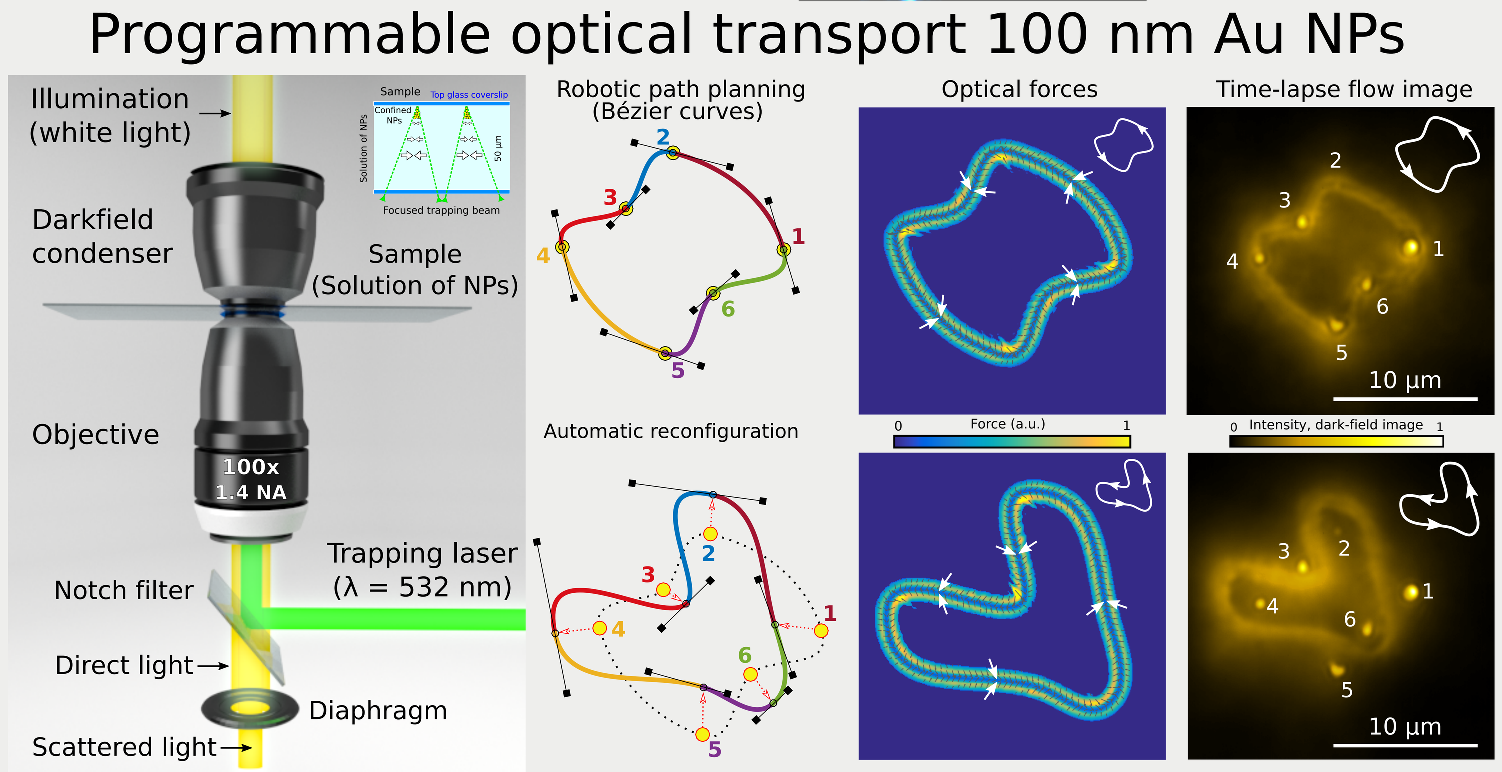
Optical transport and dynamic morphing



Optical transport and dynamic routing



Programmable optical transport 100 nm Au NPs



References and links

[1] J. A. Rodrigo, M. Angulo, and T. Alieva, "Dynamic morphing of 3D curved laser traps for all-optical manipulation of particles," Opt. Express **26**, 18608-18620 (2018)
[2] J. A. Rodrigo and T. Alieva, "Freestyle 3D laser traps: tools for studying light-driven particle dynamics and beyond," Optica **2**, 812 (2015).
[3] J. A. Rodrigo, M. Angulo, and T. Alieva,"Programmable optical transport of particles in knot circuits and networks," Opt. Lett. **43**, 4244-4247 (2018).

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