Reactive optical matter: Light-induced motion

December 28 2018, by Thamarasee Jeewandara

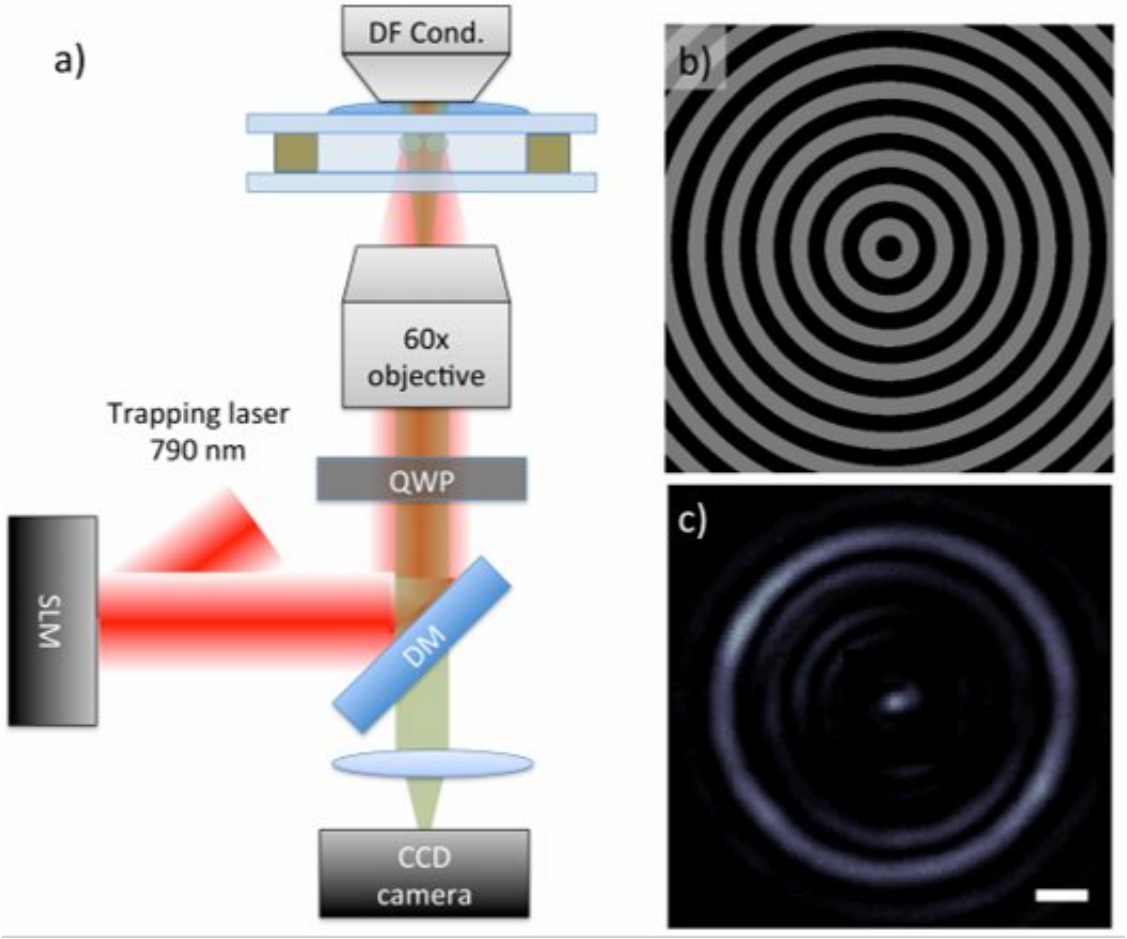


Diagram of the experimental optical trap described in the text. The setup contains a spatial light modulator (SLM), dark field condenser (DF Cond.), dichroic-mirror (DM) and quarter wave plate (QWP). The trapping laser is reflected from the SLM, which is used for beam shaping. Dark-field illumination that scatters from the Ag (silver) nanoparticles is collected by the

microscope objective, spectrally filtered and imaged to a sCMOS (scientific CMOS) array detector camera. b) Depicts the phase mask used to create the ring trap used in the experiments. c) Image of the ring trap on the sCMOS detector. The Gaussian spot in the center is the zero-order reflection of the trapping laser from the SLM. The spot did not affect the experiments since the trap had a larger diameter (scale bar 1 μm). Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-018-0105-y

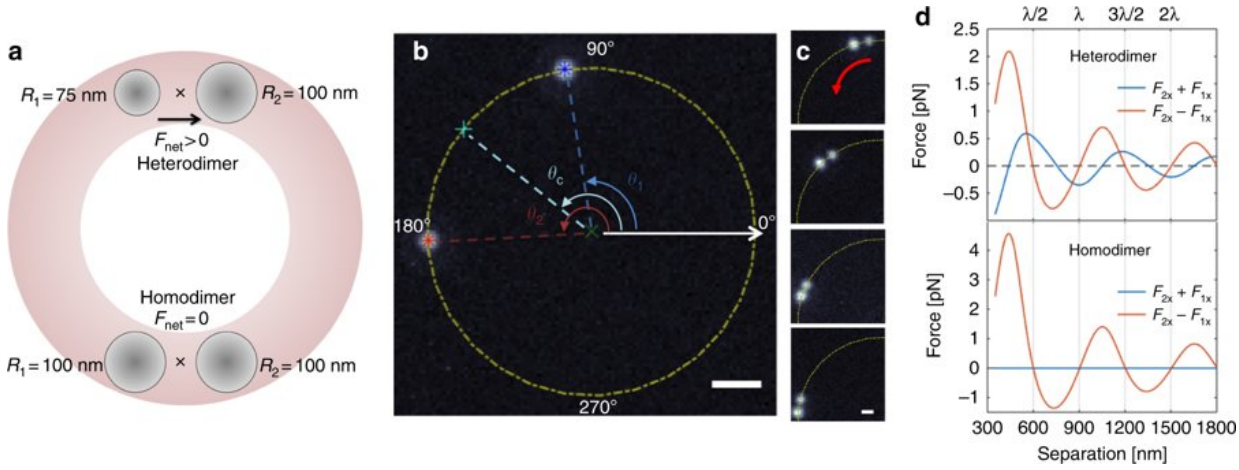
Newton's third law dictates that forces between interacting particles are equal and opposite for closed systems. In a non-equilibrium environment, the third law can be defied, giving rise to "nonreciprocal" forces. Theoretically, this was shown when dissimilar, optically trapped particles were mediated by an external field. In a recent study, Yuval Yifat and colleagues measured the net nonreciprocal forces in electrodynamically interacting, asymmetric nanoparticle dimers and nanoparticle aggregates. In the experiments, the nanoparticle structures were confined to pseudo one-dimensional geometries and illuminated by plane waves. The observed motion was due to the conservation of total momentum for particles and fields with broken mirror symmetry (represented by a changed direction of motion). The results are now published on *Light: Science & Applications*.

The ability to convert light energy into self-directed motion with light-driven nanomotors or micromachines has already attracted great interest. A variety of methods in optics can produce rotational motion or give rise to translational motion with photoreactive materials. The promise to engineer light-driven nanomotors arose from recent theoretical work, which predicted that dissimilar particles illuminated by an electromagnetic plane wave, will experience a nonreciprocal net force.

The predicted nonreciprocal forces were demonstrated with simulations to vary very little with interparticle separation. However, straightforward

experimental evidence on the phenomenon was not presented thus far. Exploring the reactive optical effects can open new possibilities of self-assembling, light-driven micromachines to herald a new field in optics and photonics.

To fill the experimental gap, in the present study, Yifat et al. demonstrated self-motility using optically bound dimers of disproportionate metallic nanoparticles (NPs). The experimental findings were also supported by quantitative electrodynamic simulations. Aside from dimers, the scientists similarly generated and measured the motion of asymmetric nanoparticle clusters or assemblies. To perform the experiments, Yifat et al. used a standard optical trapping setup with a Ti:Sapphire laser operating at a wavelength of 790 nm. A tightly focused, circularly polarized spatially phase-modulated beam of light formed an optical ring trap.

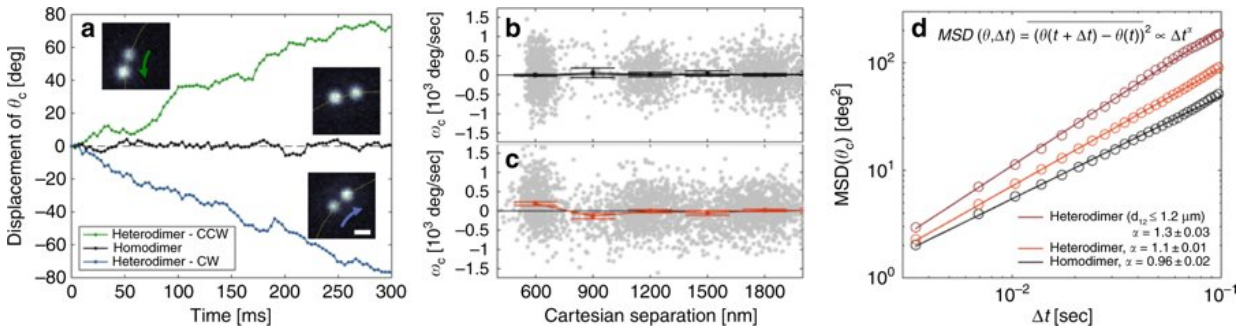


A schematic diagram of the experiment: a) Example trajectories for a homodimer (black) and a heterodimer (color) that are moving in counterclockwise (green) and clockwise (blue) directions. Distribution of instantaneous angular velocities (gray dots) and the mean angular velocities of the homodimers (b, black) and heterodimers (c, orange) as a function of interparticle separation. The bin size is 300 nm. The mean angular velocity value

was calculated by fitting a Gaussian function to the instantaneous velocity distribution. The error bars are the 3σ confidence intervals for fitted means of the distribution. Positive velocity is defined as motion of the heterodimer toward the larger NP. d) The calculated mean square displacement (MSD) values for the homodimer data that are shown in (b) (black), the heterodimer data that are shown in (c) (orange), and the subset of the heterodimer data where the interparticle separation was ≤1.2 μm (red). Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-018-0105-y

In the study, the motion of a trapped mixture of silver (Ag) nanoparticles with 150 nm – 200 nm diameter were measured using dark-field microscopy at a high frame rate of 290 fps. The particles were tracked, and their precise position used to calculate the angular position (θi) on the ring. The scientists conducted particle imaging and tracking using the mosaic particle tracking toolbox available via Image J software.

Yifat et al. observed a "heterodimer" of dissimilar particles in which the directed motion of electrodynamically interacting pairs were toward the larger particle. Conversely, when two particles of the same size, termed a "homodimer" came into close proximity, directed motion was not observed. The results were in agreement with the forces calculated using the generalized Mie theory (GMT). The scientists did not observe full or free rotation in the experiment – the manifested torque and its effect will be investigated further in future work.

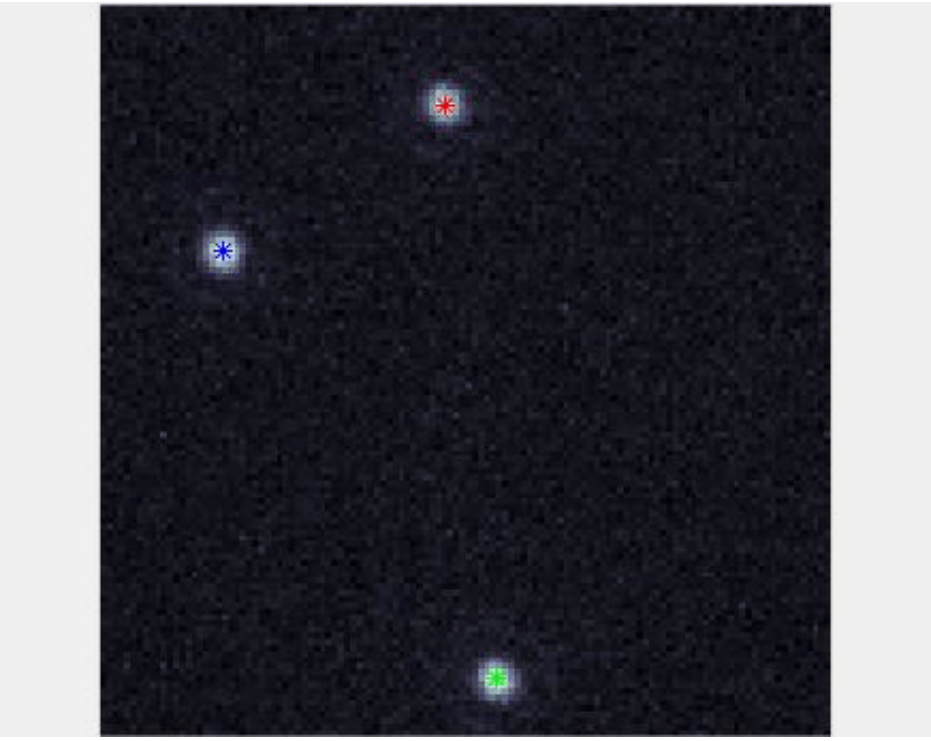


"Nonreciprocal" force-induced dynamics. a) Example trajectories for a homodimer (black) and a heterodimer (color) that are moving in counterclockwise (green) and clockwise (blue) directions. Distribution of instantaneous angular velocities (gray dots) and the mean angular velocities of the homodimers (b, black) and heterodimers (c, orange) as a function of interparticle separation. The bin size is 300 nm. The mean angular velocity value was calculated by fitting a Gaussian function to the instantaneous velocity distribution. The error bars are the 3σ confidence intervals for fitted means of the distribution. Positive velocity is defined as motion of the heterodimer toward the larger NP. d) The calculated mean square displacement (MSD) values for the homodimer data that are shown in (b) (black), the heterodimer data that are shown in (c) (orange), and the subset of the heterodimer data where the interparticle separation was ≤1.2 μm (red). Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-018-0105-y

Thereafter, Yifat et al. imaged the representative time trajectories of θ_c (the central angle of the pair) for the heterodimers and homodimers. In the heterodimers, motion of the pair was directed toward the larger particle and therefore could move clockwise or counterclockwise, around the ring depending on its orientation. The scientists repeated the experiments and combined the results. In the combined data with different heterodimer orientations, positive velocity was defined as the vector from the smaller sample toward the larger particle.

For instance, the heterodimers exhibited a positive mean angular velocity at an optical binding separation of 600 ± 150 nm and a negative mean angular velocity when the separation was larger at 900 ± 150 nm. In contrast, the mean angular velocity for a homodimer was zero for all separations. The change in mean velocity and the motion of the heterodimer pair toward the larger, thermally hotter particle was due to

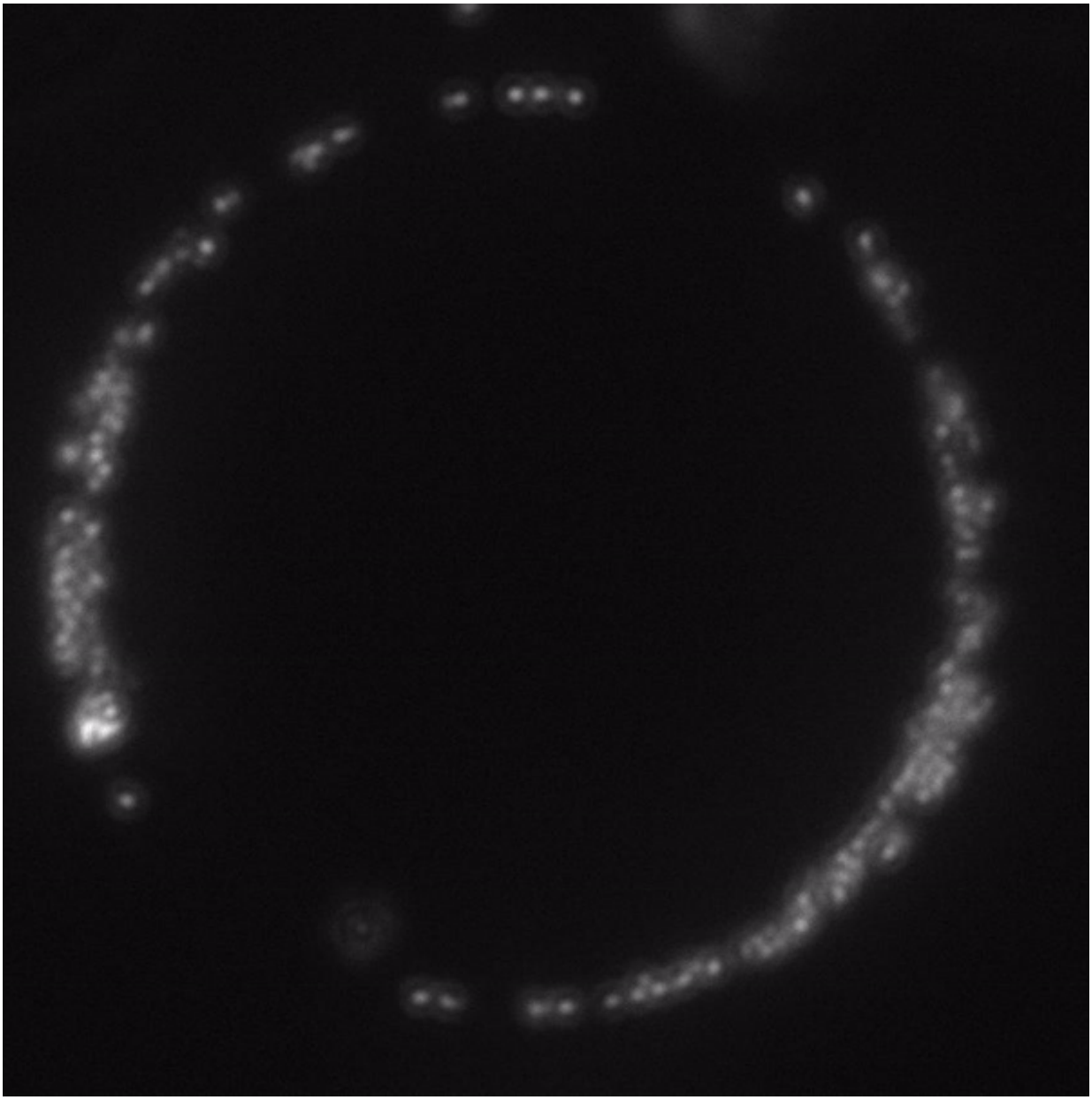
the electromagnetic field and not due to heat-induced self-thermophoresis (i.e. local temperature gradient generated due to laser adsorption by the metal-coated particles).



Video of the silver (Ag) heterodimer in a ring trap – motion in a counter-clockwise direction. Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-018-0105-y

The findings agreed with previous publications on the asymmetry of light scattered by optically trapped objects. The simulated motion was similarly directed from the small particle to the larger particle. The scientists observed a separation-dependent imbalance of angular scattering (where more light was scattered in one direction than another). The asymmetry in far-field scattering created a force on the dimer, setting it in motion as observed. Similar asymmetric scattering was

previously observed for plasmonic nanoantenna. Yifat et al. used the same experimental approach to study gold (Au) nanostar dimers and large asymmetric aggregates of gold nanoparticles.



Video of gold (Au) nanoparticle clusters in the ring trap. Credit: Light: Science & Applications, doi: https://doi.org/10.1038/s41377-018-0105-y

In this way, the scientists experimentally demonstrated light-driven motion of heterodimers and asymmetric scatterers in optical ring traps to quantify net nonreciprocal forces in one-dimensional plane wave-fields. Although the experiments were confined to a ring trap in this study, the strategy is transferable to any optically trapped matter structure that exhibits electromagnetic asymmetry. The optical trapping used in the study offered solutions to the experimental challenge of generating directed motion at the nanoscale. Nonreciprocal forces in the study created the self-motile particles without the use of chemical environments, chemical fuels or complex structures.

The electrodynamic theory and simulations that were simultaneously conducted in the study also showed that interparticle interactions caused asymmetric scattering in the heterodimers. The work thus fundamentally followed Noether's theorem (the symmetry of the action of a physical system contains a corresponding conservation law). Accordingly, Yuvat et al. rationalize that the observed self-motility and the quantified nonreciprocal forces followed from the conservation of total momentum of particles and fields, for systems with broken symmetry. The scientists envision the use of such light-driven asymmetric nanoparticle assemblies as active colloids with artificial chemotactic systems, and as fully operational "nanoswimmers" for research in soft condensed matter and biophysics.

More information: Yuval Yifat et al. Reactive optical matter: light-induced motility in electrodynamically asymmetric nanoscale scatterers, *Light: Science & Applications* (2018). DOI: 10.1038/s41377-018-0105-y

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