Silver-Nanowire-Based Interferometric Optical Tweezers for Enhanced Optical Trapping and Binding of Nanoparticles

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Light-induced self-assembly offers a new route to build mesoscale optical matter arrays from nanoparticles (NPs), yet the low stability of optical matter systems limits the assembly of large-scale NP arrays. Here it is shown that the interferometric optical fields created by illuminating a single Ag nanowire deposited on a coverslip can enhance the electrodynamic interactions among NPs. The Ag nanowire serves as a plasmonic antenna to shape the incident laser beam and guide the optical assembly of colloidal metal (Ag and Au) and dielectric (polystyrene) NPs in solution. By controlling the laser polarization direction, both the mesoscale interactions among multiple NPs and the near-field coupling between the NPs and nanowire can be tuned, leading to large-scale and stable optical matter arrays consisting of up to 60 NPs. These results demonstrate that single Ag nanowires can serve as multifunctional antennas to guide the optical trapping and binding of multiple NPs and provide a new strategy to control electrodynamic interactions using hybrid nanostructures.

1. Introduction

Optical tweezers have been widely used in materials science and life science since Ashkin first demonstrated a single-beam gradient force optical trap for dielectric particles. Optical tweezers are generally applied to manipulate individual particles, but they are also capable of assembling multiple particles into ordered arrays via optical trapping and/or optical binding. Optical trapping forces can be applied to simultaneously trap several colloidal particles in structured optical fields created by holographic beam shaping or interferometry techniques. However, the former method is generally limited to assembling microparticle structures with minimum interparticle separations of several micrometers, and the latter requires precise alignment of two or more coherent laser beams. Interferometric optical tweezers, however, allow the creation of particle arrays with sub-micrometer lattice constants defined by the wavelengths and angles of incident laser beams. For arrays consisting of plasmonic metal nanoparticles (NPs), the mesoscale sub-micrometer lattice constants are of particular interest as they allow coupled photonic–plasmonic interactions.

The coupled interactions can lead to novel phenomena in plasmonic NP arrays, such as lattice plasmon modes, plasmonic lasing, terahertz generation, and nonlinear chiro-optical amplification. Optical binding forces are interparticle forces arising from electrodynamic interactions between two or more polarizable particles illuminated by light, which lead to self-arrangement of the particles into ordered structures (i.e., optical matter). For example, plasmonic NPs can self-assemble into optical matter chains and arrays with sub-micrometer interparticle separations and high precision, but generally only a few NPs can form stable structures while an assembly of many NPs becomes unstable. Very recently, we found that a large number of Ag NPs illuminated by a linearly polarized laser beam could self-assemble into partially ordered arrays, but they exhibited frequent structure transition among dimer chains, hexagonal NP lattice, and disordered structures. A similar study also found that a large assembly of Au NPs dynamically fluctuated in a focused laser beam with linear polarization. This dynamic behavior of light-induced self-assembly limits the fabrication of large-scale optical matter with NPs. So far stable NP chains or arrays have only been made with fewer than 20 NPs by optical binding.

One way to improve the optical binding interactions is by combining optical trapping and optical binding, that is, guiding the light-induced self-assembly in shaped, especially interferometric, optical fields. For example, ultrastrong optical binding of Au NPs was observed in a standing wave optical line trap created over a reflecting coverslip surface. Later, Au nanoplates have been used as mirrors to create similar interferometric optical traps for enhancing optical binding interactions between Ag NPs. However, due to the compensation of radiation pressure in a standing wave along the beam propagation direction, NPs could hardly enter the trapping fields and thus assembly of large-scale optical matter remains a significant challenge.
Here we report a new type of nanowire-based interferometric optical tweezers for enhanced optical trapping and binding of colloidal NPs. A single Ag nanowire can create a 3D interferometric optical field, especially in the cross-section of a laser beam, leading to light-induced self-assembly of NPs into stable optical matter arrays. NPs can easily enter the lateral trapping field where the radiation pressure is not compensated. The nanowire-guided self-assembly can be controlled by tuning the direction of linear polarization relative to the long-axis of a nanowire. The plasmonic nanowire can enhance the optical binding of NPs both along and perpendicular to the laser polarization when the polarization is aligned at a specific angle (30°) to the long-axis of the nanowire. Stable optical matter arrays with up to 60 Au NPs have been demonstrated, which is the largest NP-based optical matter assembly reported so far. The multifunctional roles of single Ag nanowires are well studied by finite-difference time-domain (FDTD) simulations and experimentally confirmed by probing the intensity profile of the electric field around the nanowires: i) far-field scattering from the Ag nanowire antenna can shape the incident field and improve the optical binding strength of nearby NPs; ii) near-field electromagnetic hotspots from the Ag nanowire can act as a plasmonic template to trap NPs along the wire, then a hexagonal lattice grows up from the nucleus of these NPs by optical binding interactions. We demonstrate that the silver nanowire-based interferometric optical tweezers can work for metal (Au and Ag) and dielectric (polystyrene, PS) NPs with different sizes and shapes. Our work thus provides a general strategy for optical assembly of colloidal NPs, and more importantly, it reveals the perspective of tuning electrodynamic interactions using a hybrid nanostructure system.

2. Results and Discussion

Figure 1 shows the schematic of using a single Ag nanowire to tailor the optical manipulation of colloidal NPs. An aqueous droplet of the Ag nanowires was spin coated on a coverslip. This Ag nanowire-coated coverslip was then used to build a sample cell containing an aqueous solution of colloidal NPs. The experiments were conducted with an optical trapping apparatus using a linearly polarized laser with wavelength $\lambda = 800$ nm. The diameter of the laser spot (≈13 µm) is much larger than the length of the Ag nanowire and could confine multiple NPs near the coverslip surface by laser radiation pressure (along $z$-direction). The position of the nanowire is adjusted by an x–y translational stage.

The dark-field image of Figure 1b-I shows the anisotropic dimer chain structures formed by laser-induced self-assembly of fluctuating Au NPs (150 nm dia.) in the absence of Ag nanowire, which is similar to what we observed in previous work. However, in the presence of a single Ag nanowire, the...
same Au NPs could form stable and ordered hexagonal structures with an optimized laser polarization direction, as shown in Figure 1b-II. In this work, we always define the polarization direction by the angle $\theta_p$ between that and the long-axis of a nanowire, where the optimized direction is $\theta_p = 30^\circ$. The optical assembly can be further enhanced by using two parallel Ag nanowires (Figure 1b-III, also see Video S1, Supporting Information). Other types of NPs, e.g., Ag NPs (150 nm in dia.), can also form stable hexagonal arrays with the guidance of a Ag nanowire (Figure 1b-IV).

To quantify the perfection and stability of the assembled optical matter arrays, a local orientational bond order parameter is used. For a given particle $n$, the local hexagonal order parameter $\psi_6(n)$ is defined as

$$
\psi_6(n) = \frac{1}{M} \sum_{m=1}^{M} \exp \left( 6i\theta_p^m \right)
$$

where $M$ is the total number of nearest neighbors of particle $n$ and $\theta_p^m$ is the angle between a fixed axis (here the $x$-axis) and the bond joining the particle $n$ with another particle $m$. For a single monolayer particle assembly, the hexagonal order parameter ($\psi_6$) is treated as the average of the local parameters of all the particles

$$
\psi_6 = \frac{1}{N} \sum_{n=1}^{N} \psi_6(n)
$$

where $N$ is the total number of particles. This $\psi_6$ parameter has been widely used by the colloidal science community to evaluate the perfection of a hexagonal lattice, where $\psi_6 = 1$ for a perfect 2D hexagonal crystal.[33,34] In our experiments, the trajectories of the particles were obtained by tracking the acquired videos (300 fps) using TrackMate in ImageJ. We could then calculate the hexagonal order parameter $\psi_6$ of the assembled NPs in each video frame and plot histograms with different experimental conditions.

Figure 1c shows the measured hexagonal order parameter of the trapped 150 nm Au NPs as a function of time with different trapping conditions (e.g., without nanowire (Figure 1b-I), with a single nanowire (Figure 1b-II), and with two nanowires (Figure 1b-III)). The corresponding hexagonal order parameter $\psi_6$ distributions are shown in Figure 1d. It can be seen that in the absence of any Ag nanowire (b-I), the average value of $\psi_6$ is $\approx 0.5$ and the data curve suffers from a low signal-to-noise ratio (broad distribution of the histogram) due to the poor stability of the NP system. However, both the average value and signal-to-noise ratio of $\psi_6$ significantly increase ($\psi_6$ exceeds 0.8 with a much narrower distribution) in the presence of Ag nanowires, demonstrating the formation of ordered and stable NP arrays (b-II and b-III). These results clearly reveal the critical role of nanowire on the formation of large-scale optical matter arrays.

In a linearly polarized optical field, Ag NPs prefer to form linear chains with orientation perpendicular to the light polarization in the absence of Ag nanowires (see Figure S1, Supporting Information). However, in the presence of a Ag nanowire, by simply controlling the laser beam polarization, the NPs exhibit totally different self-assembly behaviors. The column I in Figure 2a–d plots the calculated electric-field intensity distributions around a single Ag nanowire (5.9 μm in length and 80 nm in diameter) with linearly polarized light of different polarization angles. When the light polarization is parallel with the Ag nanowire, longitudinal surface plasmon modes are excited along the nanowire in the near field and interference fringes are created in the far field (Figure 2d-I). The distance between the antinodes of the interference fringes is $\approx 600$ nm, which matches well with the interparticle separation of optically bound metal NPs.[21,22,25,26] However, with perpendicular polarization, the intensity of far-field scattering along the $y$-axis decays much faster (Figure 2a-I). In the near field, the electric fields are strongly confined near the surface of the nanowire with all polarization directions. To verify the near and far fields of Ag nanowire antennas, we have used a single trapped Ag NP to probe the intensity distribution of the electric field around a nanowire and further studied the electrodynamic interactions between the nanowires and two NPs. The results agree well with our simulations (see Note S1 and Figures S2–S7, Supporting Information).

The representative dark-field images and trajectories of the trapped Ag NPs with different polarization directions are shown in columns II and III of Figure 2a–d. When the longitudinal plasmon modes are not excited ($\theta_p = 90^\circ$), chain structures involving NP dimers will form (Figure 2a-II). The enhanced electric field near the nanowire does not contribute to the trapping of a NP because repulsive near-field electrodynamic interaction exists between them at this polarization direction. The Brownian fluctuations of the NPs in the $x$- and $y$-directions are nearly the same as shown by their trajectories (Figure 2a-III). However, when the longitudinal plasmon modes of the nanowire are weakly excited ($\theta_p = 60^\circ$), the NPs near the nanowire gain additional stability along the $y$-axis while fluctuations along the $x$-axis are still the same (Figure 2b-III). The most interesting observation is that the strongly radiating nanowire antenna could largely improve the stability of the trapped NPs and promote the formation of stable hexagonal lattice structures especially at $\theta_p = 30^\circ$ (Figure 2c-II), while stable dimer chains can form at $\theta_p = 0^\circ$ (Figure 2d-II). In both cases, fluctuations along the $y$-axis have been strongly suppressed (Figure 2c,d-III). Additionally, it is worth noting that Ag NPs could be in close proximity to the nanowire (separation much smaller than traditional optical binding separations) due to the strong near-field coupling, leading to tighter confinement than that of other interference fringes in the optical field. As a result, optical binding interactions are greatly enhanced when one NP couples to the nanowire and other NPs are trapped in the second interference fringes of the scattered field.

The column IV of Figure 2a–d shows the measured $\psi_6$ distributions of the NP assemblies. The average value of $\psi_6$ increases as $\theta_p$ decreases from $90^\circ$ to $30^\circ$, indicating the tendency to form hexagonal structures (see Figure S8, Supporting Information, for the measured spatial arrangements of the multi-NP system), while it significantly decreases at $\theta_p = 0^\circ$ due to the formation of dimer chains. These results reveal that: i) the scattering interference fringes provide additional spatial gradients in the field that guides the self-assembly of NPs; ii) the spatiotemporal stability of Ag NPs assembly could be controlled and improved by tuning the radiating behaviors of Ag nanowire antennas; iii) there is a competition between the formation of Ag dimer chains and hexagonal lattices.
Recently we found that ordered hexagonal lattice structures may temporarily form during light-induced self-assembly, but they suffer from poor stability and would easily collapse into dimer chain structures due to the anisotropic optical binding strength.\[30\] The structure transition between dimer chains and disordered structures occurs frequently especially when the number of trapped NPs is over 30.\[30\] The optical binding strength is much weaker along the linear polarization direction compared to the perpendicular direction, preventing the assembly of isotropic hexagonal lattice structures. Mesoscale NP arrays can support coupled photonic–plasmonic resonances with tunable optical response that would benefit light-harvesting and biosensing,\[35\] yet assembly of such ordered plasmonic lattice structure with linearly polarized light is still a big challenge. Here, the use of Ag nanowire antennas provides a novel strategy to solve this problem. The nanowire provides a plasmonic template to attract several NPs along the wire due to near-field coupling of the NPs and nanowire, as illustrated by the red circles in Figure 3a (assuming a nanowire is fixed along the y-axis). To grow a hexagonal lattice from the nucleus of these NPs by optical binding, the polarization direction is important. Since the long-range optical binding interaction is the strongest in the direction perpendicular to the light polarization (indicated by the dashed lines), the interparticle separation along that direction must match the optical binding separation to achieve a stable structure. This occurs when the polarization is at $\theta_p = 30^\circ$ (Figure 3a-I) or $90^\circ$. However, the far-field scattering of the nanowire is the weakest with polarization at $90^\circ$ (Figure 2a-I), which cannot prevent the collapse of the hexagonal structure along this direction and dimer structures will form (Figure 2a-II). Similarly, the interparticle separation along the dashed lines at $\theta_p = 60^\circ$ is $\sqrt{3}s$ where $s$ is the optical binding separation (Figure 3a-II), which will decrease the optical binding strength to form dimer structures.

Two representative optical assembly processes with $\theta_p = 30^\circ$ and $60^\circ$ are shown in Figure 3b for comparison. Once several Ag

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**Figure 2.** Polarization controlled optical assembly of 150 nm Ag NPs with a single Ag nanowire. The polarization angle is $\theta_p = 90^\circ$ in (a), $60^\circ$ in (b), $30^\circ$ in (c), and $0^\circ$ in (d). Column I: Calculated intensity distribution of the electric field around a Ag nanowire (diameter of 80 nm and length of 5.9 $\mu$m) immersed in water and illuminated by a plane wave of $\lambda = 800$ nm. Column II: Dark-field images of the assembled Ag NPs. Column III: The corresponding trajectories of the NPs. Column IV: Histograms of the hexagonal order parameter $\psi_6$ of the NP assemblies. The laser power is fixed at 350 mW and the scale bars are 1 $\mu$m.
NPs are coupled to (fixed by) the nanowire (6.2 µm in length), a stable NP array forms at θp = 30° (Figure 3b-I). On the contrary, with θp = 60°, the assembled structure undergoes structural fluctuations between dimer chains and hexagonal lattice structures, and the whole particle system suffers from poor stability (Figure 3b-II). These results show that 30° is the most suitable polarization angle for assembling stable hexagonal structures. Large-scale optical matter can be assembled with this polarization-nanowire configuration; for example, Figure 3c shows the dark-field images of stable optical matter arrays consisting of up to 60 Au NPs (also see Video S2, Supporting Information).

Figures 3a and 3b show the schematics and optical images, respectively, of the assembly process. Figure 3a-a illustrates a hexagonal NP lattice where the polarization direction (the red arrow) is at I) 30° and II) 60° to the long axis of a Ag nanowire that is along y-direction (near the red circles but not drawn). The dashed lines indicate the directions perpendicular to the polarization directions where the optical binding strengths are the strongest. Figure 3a-b shows the structural differences between the two polarization angles. In Figure 3b-I, stable hexagonal lattice structures form when the laser polarization is at 30°. In Figure 3b-II, structure fluctuation occurs when the laser polarization is at 60°. Figure 3c shows the assembly of stable and large-scale Au NP arrays at θp = 30°. The scale bars are 1 µm.

The nanowire-based interferometric optical tweezers provide a general approach to assemble NPs, including metal (Ag, Au) and dielectric (polystyrene) NPs. Figure 4a shows the measured ψ6 distributions of polystyrene bead (490 nm in dia.) arrays with and without the guidance of a Ag nanowire. The dark-field images in the insets show that the polystyrene beads are loosely confined in the optical field with large interparticle separations, but when a nanowire is present, they show a tighter spatial confinement with ordered hexagonal structure. Optical binding interactions of dielectric NPs are generally much weaker compared to that of metal NPs with the same size. The optical binding forces are determined by the scattering cross-sections of particles. The plasmonic properties of Ag and Au give rise to large scattering cross-sections, so strong optical binding interactions can occur even at small sizes. For example, the average ψ6 of 150 nm Ag NP arrays (Figure 2c) is even larger than that of 490 nm polystyrene particle arrays (Figure 4a).

The scattering cross-sections of plasmonic NPs depend on their sizes and shapes. Generally, larger particles can lead to stronger optical binding interactions, so it is easier to form stable assemblies, e.g., from 200 nm Au NPs compared to 150 nm Au NPs as shown in Figure 4b. Additionally, the optical binding force is linearly proportional to the laser intensity, so more stable and ordered hexagonal particle arrays would form at a higher laser power, e.g., at 365 mW rather than 150 mW (Figure 4b). The shape also matters. For example, the scattering cross-section of a 110 nm Ag nanocube (5.0 × 10^4 nm^2) is close to that of a 150 nm Ag sphere (4.3 × 10^4 nm^2) at λ = 800 nm, so the smaller nanocubes should be able to form optical matter arrays near a Ag nanowire with similar stability as the 150 nm Ag nanospheres. We have experimentally verified that and the results are shown in Figure 4c.

Moreover, we find that a thick (large diameter) Ag nanowire can largely improve the stability of the assembled NP arrays (Figure 4d) because it can generate a much stronger scattering...
field than a thin nanowire (Figure S9, Supporting Information). The calculated thermal energies of trapped NPs are \( \approx k_B T \) where \( k_B \) is the Boltzmann constant and \( T = 300 \) K, which are small compared to the depths of the optical binding potentials (Figure S10, Supporting Information). The temperature increases for the 150 nm Au and 490 nm polystyrene beads are 12.6 and 0.01 K, respectively, which are negligible.

Recently, colloidal Ag nanowires have been applied as plasmonic tweezers, where propagating surface plasmons were excited in single Ag nanowires by illuminating one end of a Ag nanowire with a laser or using a Ag-nanowire-embedded polymer fiber.\(^\text{[36,37]}\) Optical forces induced by the surface plasmons could be applied for optical trapping and transport of one to two dielectric (TiO\(_2\) or polystyrene) NPs.\(^\text{[36,37]}\) We find that the enhanced optical trapping of NPs can also occur along a Ag nanowire fully illuminated by a laser beam (e.g., Figure 1b). Figure 5a shows the calculated intensity distribution of the electric field around a single Ag nanowire in different planes. The electric field is strongly confined near the nanowire and nearly periodically spaced in the \( z \)-direction (\( x-z \) plane, where \( x = 0 \)). The first interference fringe contains discrete electromagnetic hotspots along the nanowire that provide modulated trapping potentials (\( x-y \) plane, where \( z = 130 \) nm). However, when the light polarization direction is perpendicular to the nanowire, no electromagnetic hotspot is generated (Figure S11, Supporting Information). Figure 5b shows a single, two, and three Ag NPs that are trapped by the hotspots when the light polarization is parallel to the nanowire (Video S3, Supporting Information).

Note that optically bound NP dimers or trimers prefer to align perpendicular to the light polarization direction due to the anisotropic optical binding interactions,\(^\text{[22,27]}\) but here they align parallel to the polarization due to the plasmonic confinement by the nanowire. The corresponding probability density distributions of the NPs along (\( x \)) and perpendicular (\( y \)) to the nanowire are shown in Figure 5c,d, respectively. Movements of the NP along the nanowire are not continuous: the separation of the adjacent peak position is \( \approx 450 \) nm, which matches well with the separation between the antinodes of the plasmon standing wave intensity profiles (Figure 5a). Most interestingly, the \( y \)-positions of the NPs are tightly confined within \( \approx 40 \) nm (strong spatial confinement). When using the standard deviation of fluctuations to evaluate the stability of the NP along the \( y \)-direction, these electromagnetic hotspots can lead to a more than 20-fold suppression of the Brownian fluctuation (see Figures S12 and S13, Supporting Information, for the trapping of a single NP with a Ag nanowire located at different positions).

Different from the near-field hotspots generated in a plasmonic nanogap or rough surface, what we observed here clearly reveal that the electromagnetic hotspots created by plasmonic scattering can generate strong spatial confinement hundreds of nanometers away from the metallic structure, which may enable new types of noncontact plasmon-enhanced spectroscopies. These hotspots are similar to the ones generated by 1D optical matter chains,\(^\text{[27]}\) where localized electromagnetic hotspots via coherent scattering from Ag NPs allow cotrapping of
less polarizable particles (e.g., semiconductor quantum dots) in an optical line trap.

The development of colloidal synthesis has largely increased the availability of nanocrystals with well-controlled sizes and shapes, yet it is still a fundamental challenge to precisely control and assemble those nanocrystals. In particular, there is an increasing interest in the union of photonic and plasmonic effects from discrete NP arrays and superlattices with inter-particle separations of hundreds of nanometers. Unlike other assembly methods that generally lead to closely packed structures, light-driven self-organization naturally creates discrete photonic lattices, which are good candidates for exploring the new science of coupled photonic-plasmonic interactions. Our work reveals a new way to direct the self-assembly of NPs into mesoscale arrays by tuning their electrodynamic interactions using a hybrid nanostructure system. Since metal nanostructures (e.g., wires, spheroids, bipyramids, rods, etc.) can strongly scatter light near their surface plasmon resonances, many of them should lead to similar (but size and shape-dependent) effects involving the interference of incident and scattered light, which can create modulated optical fields in the far field and strong gradients in the near field. These modulated fields, in turn, allow guiding the spatial distribution of other NPs in solution. Compared to other plasmonic nanostructures, Ag nanowires are of particular interest because they can be easily synthesized by low-cost and high-throughput chemical methods. Additionally, these anisotropic nanowires with microscale length could produce much stronger scattering fields in a larger space, which can benefit the optical assembly of a large number of NPs. Several aspects can be further explored to fulfill the potential of nanowire-based interferometric optical tweezers. In the current study, we have focused on the influence of a single Ag nanowire on the trapping and assembly of NPs. It will be interesting to explore the properties of multiple (e.g., Figure 1b) and well-arranged Ag nanowires (e.g., with rational patterning) on a substrate and use them to assemble more functionalized structures with other plasmonic nanostructures.

3. Conclusion

In summary, we have used a single Ag nanowire to construct interferometric optical tweezers. We show that the plasmonic nanowire antenna allows tight spatial confinement of colloidal NPs in the near field and enhanced optical binding of multiple colloidal metal (Ag and Au) and dielectric (polystyrene) NPs in the far field. Furthermore, by tuning the light polarization directions, the intensity distribution of the electric field around the nanowire can be engineered to tailor the spatial arrangement of optical matter structures. In particular, controlled mesoscale self-assembly of large-scale hexagonal lattices consisting of up to 60 Au NPs in linearly polarized light has been achieved. Using plasmonic nanowire antennas to enhance and guide the electrodynamic interactions of metal NPs provides a new strategy to build novel architectures with colloidal nanostructures, and the polarization-controlled optical assembly will
benefit on-demand construction of reconfigurable photonic devices with nanoscale building blocks.

4. Experimental Section

Materials: The silver nanowires were purchased from Sigma-Aldrich with diameters of 60–90 nm and lengths up to 10 µm. The silver NPs (150 ± 13 nm dia.) were purchased from nanoComposix, Inc. Both the Ag nanowires and NPs were coated by polyvinylpyrrolidone with negative surface charges. The Au NPs were purchased from Sigma-Aldrich. The polystyrene beads were purchased from Ted Pella Inc. The microscope cover slips were purchased from Fisher Scientific. To prevent the NPs from being stuck on the glass surface, UV/Ozone was used to make the surface of coverslips negatively charged.

Optical Setup: A Gaussian beam with wavelength of 800 nm was generated by a continuous wave Ti:Sapphire laser (Spectra-Physics 3900S). The laser beam was collimated and focused to the back aperture of an objective (Olympus UPLSAP0 60XW, numerical aperture (NA) 1.2), creating an expanded and relatively flat optical field on a coverslip surface. The NPs were trapped near the upper glass surface of an aqueous sample cell placed on an inverted microscope (Olympus IX71). The NPs were visualized by dark-field microscopy with a high NA dark-field condenser and their motions were recorded by a COMOS camera (Point Grey Grasshopper3) with flame rate of 300 fps. The trajectories of the particles in the videos were obtained using TrackMate in ImageJ. Note that in this paper, the probability distributions of the data (e.g., positions, separations, angles, etc.) are plotted as the normalized frequency (i.e., probability density) distributions of the variables. The integration of a probability density distribution equals to 1 and various lengths as specified in the main text) illuminated by a linearly polarized plane wave (vacuum wavelength of 800 nm) in water. The refractive index of Ag and water are 0.036 and 1.33, respectively.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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