Enabling Self-Induced Back-Action Trapping of Gold Nanoparticles in Metamaterial Plasmonic Tweezers

Theodoros D. Bouloumis,* Domna G. Kotsifaki, and Síle Nic Chormaic

ABSTRACT: The pursuit for efficient nanoparticle trapping with low powers has led to optical tweezers technology moving from the conventional free-space configuration to advanced plasmonic systems. However, trapping nanoparticles smaller than 10 nm still remains a challenge even for plasmonic tweezers. Proper nanocavity design and excitation has given rise to the self-induced back-action (SIBA) effect offering enhanced trap stiffness with decreased laser power. In this work, we investigate the SIBA effect in metamaterial tweezers and its synergy with the exhibited Fano resonance. We demonstrate stable trapping of 20 nm gold particles with trap stabilities as high as 4.18 ± 0.2 (fN/nm)/(mW/μm²) and very low excitation intensity. Simulations reveal the existence of two different groups of hotspots on the plasmonic array. The two hotspots exhibit tunable trap stiffnesses, a unique feature that can allow for sorting of particles and biological molecules based on their characteristics.

KEYWORDS: metamaterial tweezers, self-induced back-action, plasmonic tweezers, gold nanoparticle trapping, Fano resonance

Since the invention of optical tweezers by Arthur Ashkin,1,2 numerous trapping platforms have been studied and implemented for a variety of applications3–5 with specimens ranging from biological6–10 to quantum dots.11–17 One major direction in optical trapping is to develop a platform that can efficiently trap nanoparticles tens of nanometers or smaller in size, using as low light intensity as possible, thereby minimizing heating of the specimen.11–13 The most common configurations that meet these requirements are based on metallic nanostructures, where one exploits the strong near-field forces that arise due to the excitation of surface plasmons.14–17 The design of the nanostructure alone cannot improve the trap stiffness beyond a certain point. This led to the implementation of self-induced back-action (SIBA) trapping.18 In SIBA trapping, the plasmonic cavity resonance is tuned so that the particle, while trapped in the cavity, plays a dynamic role in the reconfiguration of the intracavity intensity.19 This optomechanical coupling facilitates trapping with lower light intensity, relaxing intensity requirements while providing a stable trap with less heating.20–23

Trapping gold nanoparticles (AuNPs) is of particular interest due to the versatility in their synthesis methods24,25 and their contribution to various fields.26 In 1908, rigorous theoretical work was done by Mie to describe the absorption of light by a subwavelength gold sphere.27 Owing to the great tunability of plasmon resonances and their unique properties, AuNPs have contributed to the development of fields within physics and material science such as surface-enhanced Raman scattering (SERS),28 enhanced photovoltaic conversion efficiency,29 and quantum nanophotonic systems coupled to single-photon emitters.30 There are numerous applications in other fields, too, such as chemistry for catalysis purposes31 and gas sensing,32 for computational methods with the newly established field of neuromorphic computing via AuNP cluster assemblies,33 and in biomedical research with applications in drug and gene delivery,34 cancer treatment,35 vaccine development,36 and many others.37,38 All these applications have triggered interest in trapping AuNPs and investigating their optomechanical properties.39–41

In our previous work,42 we demonstrated trapping of single 20 nm polystyrene particles using an array of metamolecules. The experimental trap stiffness was 8.65 fN/(nm·mW) and is the highest reported value.42 Implementing metamaterial structures in a plasmonic trap configuration offers the advantage of being able to excite and tune a very sharp Fano resonance, due to destructive interference between a broadband dipole resonance and a sharp quadrupole resonance.43 This leads to a nanocavity with ultrasmall mode volume, offering strong confinement of particles in the trap.43–45 A Fano resonator is also very sensitive to changes in the local

Received: November 15, 2022
Revised: May 11, 2023
Published: May 31, 2023

https://doi.org/10.1021/acs.nanolett.2c04492
Nano Lett. 2023, 23, 4723–4731
refractive index, making this platform an ideal candidate for combining with SIBA trapping. Proper structure design could foster a synergy between the Fano resonance and the SIBA effect, resulting in strong optomechanical responses that facilitate long duration trapping events with low laser power.

In this work, we trapped 20 nm AuNPs using the metamaterial tweezers introduced earlier. Simulations of the plasmonic hotspots revealed a wavelength-dependent trap stiffness per hotspot. This offers the ability to tune the hotspots’ strength, with applications in sorting nanoparticles of different sizes and refractive indices. Additionally, we investigated the synergy between the metamaterial tweezer’s and the SIBA effect and experimentally observed SIBA-assisted trapping. To the best of our knowledge, there is no prior reporting of this in the literature. A very high trap stiffness was obtained for on-resonant excitation (i.e., SIBA-assisted trapping) as well as for blue-detuned excitation, with the highest value being $4.18 \pm 0.2 (\text{fN/nm)}/(\text{mW/\mu m}^2)$. This is comparable with our previous work where the SIBA effect could not be implemented.

A plasmonic metamaterial nanostructured device was used for the experiments. The device was fabricated using focused
ion beam milling (FIB) on a gold film, with the geometrical characteristics determined in advance through finite element method simulations. AuNPs with a diameter of 20 nm were dispersed in buffer solution diluted with heavy water to a certain concentration (see S1 Methods), and a small amount of surfactant was also used. The solution was placed onto the device, and the sample was mounted on a custom-made microscope setup. The excitation laser was incident from the glass side of the sample. A detailed description of the methods can be found in S1.

Figure 1a shows the simulated reflection, transmission, and absorption spectra of the metamaterial device (Figures 1b and S2a). The absorption peak at 928 nm indicates the resonance of the device, hence the incident wavelength required to excite the plasmonic field when the device is immersed in water solution. Microspectrophotometry measurements revealed that the experimental resonance peak was in perfect agreement with the simulations—since we cannot directly measure the absorption resonance, we calculated the experimental absorption resonance peak from the transmission spectrum (see Figure S2b). Figures 1c(i)−(iii) show the simulated empty-cavity electric (E-) field for 928 nm excitation light, propagating along the z-axis incident from the glass side and linearly polarized along the y-axis. Each unit cell has three hotspots where particles can be trapped: two symmetric and identical ones along the y-axis, referred to as Hotspot 1 (with no distinction between them), and one along the x-axis, referred to as Hotspot 2. We assume that a particle moving under Brownian motion in the solution has equal probabilities of being near either of the hotspots and subsequently trapped. In Figures 1c(iv)−(vi) we plot the E-field when a AuNP 20 nm in diameter is trapped at the equilibrium position of the hotspots (see S4 for details). Figures 1c(ii), (iii), (v), and (vi) depict the Hotspot 1 location. Note the concentration of the E-field around the AuNP, owing to the plasmonic field coupling between the particle and the cavity. Due to its metallic nature, the particle also has a plasmonic resonance and behaves like a trapped nanoantenna with a dipole emission, leading to significant field enhancement around it (Figure 1c(v),(vi)). The polarization of the excitation light affects accordingly the E-field distribution around the particle. In Figure S3, we also plot the field enhancement due to the presence of the particle, i.e., the E-field in the cavity when the particle is present, normalized to the empty cavity field. A field enhancement of more than five times external to the AuNP is observed.

A trapped particle inside the nanocavity not only creates an enhancement of the E-field but also results in a frequency shift of the cavity resonance

$$\Delta \omega = \frac{\alpha_d}{2V_m} f(r_p)$$

(1)

where \(\omega\) is the resonant frequency and the mode volume of the empty cavity, respectively; \(\alpha_d\) is the polarizability of the nanoparticle; \(\varepsilon_0\) is the vacuum permittivity; and \(f(r_p)\) is the cavity intensity profile. Using eq 1, we calculated the expected cavity shift to be about 4.34 nm (see S3). This shift compares well with the value obtained through simulations (Figure 2). For a particle trapped in either Hotspot 1 or Hotspot 2, the resulting cavity redshift is 6 nm and 5 nm, respectively, and for consecutive trapping events the cavity shifts by an additional step of 6 nm or 5 nm depending on where the particle is trapped. This small discrepancy between the analytical and numerical shift is attributed to the approximate formula used to calculate the mode volume.

To further map the optical forces on the nanoparticles around the hotspots and identify the equilibrium positions of trapped particles, extensive simulations were performed. In Figure 3a the normalized trap stiffnesses (i.e., trap stiffness divided by incident light intensity) for the two hotspots are
plotted as derived from the simulated optical forces (see S4). An interesting behavior is observed, where the trap stiffnesses around Hotspot 1 increases as we scan the excitation wavelength from 920–930 nm, but a decreasing trend is observed for the stiffnesses around Hotspot 2. Additionally, particles trapped at Hotspot 2 experience a higher stiffness, $k_2$, than particles trapped at Hotspot 1, $k_1$, for every wavelength. However, the two hotspots exhibit similar trap stiffnesses when excited with 930 nm light.

To interpret this behavior, we simulated the E-field magnitudes at the two hotspots for both cases of an empty cavity and with a trapped particle (Figure 3b). Despite the simulated absorption resonance being at 928 nm (Figure 2), Hotspot 1 exhibits a maximum E-field intensity at 930 nm, while Hotspot 2 has a maximum at 919 nm when the cavity is empty. Additionally, the maximum E-field intensity for both hotspots has a similar magnitude. However, the situation is different when a particle is trapped. The presence of the metallic particle in the plasmonic nanocavity creates an enhancement of the E-field by approximately 6 times (Figure 3b). The total E-field in the cavity is stronger for Hotspot 2 than for Hotspot 1 because the slot width at Hotspot 2 ($w_2 \approx 33$ nm) is narrower than the slot width at Hotspot 1 ($w_1 \approx 39$ nm) (see Figure S2a). This leads to a stronger E-field and better confinement of the nanoparticle at Hotspot 2.

The increasing and decreasing trends of the trap stiffnesses at Hotspots 1 and 2 (Figure 3a) also follow the E-field resonances, as indicated by the dashed lines in Figure 3b. This offers the ability to excite the hotspots with a different ratio of resulting stiffnesses, hence the possibility of sorting particles based on their size, shape, and refractive index at different hotspots; e.g., bigger particles could be trapped in the hotspot with the lowest trapping force and larger slot width, while smaller particles that need higher optical forces could be trapped in the other hotspot. The optical forces as a function of excitation wavelength are shown in Figure S6 and exhibit the same resonance features as the E-field.

Experimentally, we performed trapping with the same excitation wavelengths used in simulations, with incident powers ranging from 1.7 to 4.3 mW. For each wavelength, up to 10 experiments were performed for increasing incident laser power in steps of 0.5 mW with a total number of about 100 trapping events per wavelength. The trapping events were recorded and analyzed using trapping transient analysis,9,40 to derive the experimental trap stiffness, $k_{\text{exp}}$, as explained in S1. In Figure 4 we present the probability distribution histograms of the trap stiffnesses normalized to the incident laser intensity. Data were fitted with a normal distribution function, and for the wavelengths 920–928 nm, two distribution functions were required to fit the experimental results. This is in agreement with the simulations where particles trapped at Hotspot 1 (blue curves) experience a weaker trap stiffness compared with particles trapped at Hotspot 2 (orange curves). However, for trapping with 930 nm wavelength (Figure 4d), a single distribution function is sufficient since, at this wavelength, the two hotspots have a similar stiffness (see Figure 3a) and are indistinguishable. It is also worth noting that the probability of trapping at Hotspot 1 is higher than that at Hotspot 2; this is expected since each metamolecule is comprised of twice as many hotspots of type 1.

The averaged normalized stiffnesses, $k_{1,norm}$ and $k_{2,norm}$ (Figure 4e), although seeming to exhibit some similarities with the simulated values (Figure 3a), are approximately 5–8 times lower in magnitude. The maximum normalized trap stiffness obtained was 4.18 (fN/nm)/(mW/μm²) for excitation at 920 nm which is of the same order of magnitude as that reported for polystyrene trapping.42 However, the deviation from the simulated values indicates the existence of additional destabilization forces that were not considered in the simulations and may affect the trapping process.

The situation is different when trapping with the 930 nm excitation laser; the average trap stiffness, $k_{930,norm}$ significantly deviates from the simulated behavior, exhibiting the lowest value over all wavelengths (Figure 4e). To get a clearer view on the experimental findings, in Figure 5 we plotted the initial non-normalized trap stiffnesses as a function of the incident laser power and trapping wavelength. Although the behavior is quite complex, an increasing trend of the trap stiffness with increasing incident laser power is observed for the wavelengths 920–928 nm for both hotspots (Figure 5a,b). This trend is clearly not linear, as theoretically expected, and that is attributed to the collective effect of different forces acting on
the nanoparticles. Interestingly, the behavior at 930 nm is less complicated and in agreement with previous works where the SIBA effect was investigated.\textsuperscript{21}

As mentioned earlier, exciting the structure with 930 nm light is strongly desired because at this wavelength the SIBA contribution is enabled, resulting in a high trap stiffness with a low laser intensity. Indeed, as shown in Figure 5a,b, trapping with 930 nm light results in two distinct regimes of trap stiffness values. These are the result of a combination of the optical forces along with the SIBA effect acting on the nanoparticle. The highest normalized trap stiffness when trapping with 930 nm was measured to be 2.92 (fN/nm)/(mW/μm$^2$) (Figure 5c,d) for an incident intensity as low as 0.61 mW/μm$^2$. In the low power regime, the SIBA effect is the dominant mechanism keeping the particle trapped since the optical forces are not strong enough.\textsuperscript{19} As the incident power

---

**Figure 4.** Probability distribution histograms of the normalized experimental trap stiffnesses for the excitation wavelengths (a) 920 nm, (b) 925 nm, (c) 928 nm, and (d) 930 nm, with the Gaussian fits corresponding to trapping events at Hotspot 1 (blue curves) and Hotspot 2 (orange curves). (e) The average normalized experimental trap stiffnesses per excitation wavelength for the two hotspots and linear fits indicating the ascending and descending trends of trap stiffness for Hotspot 1 and 2, respectively. The error bars are calculated from the standard deviation of the mean stiffness values.
increases, the optical forces play a more dominant role, and the trap stiffness decreases because the scaling between laser power and particle confinement, upon which the SIBA is based, becomes less efficient. After a certain power threshold, which in our experiment is at 2.82 mW (1 mW/μm² intensity), the SIBA effect vanishes, and the optical forces linearly increase with power. No trapping was observed for powers lower than 1.9 mW, due to the optical forces being very weak, and thus the performance of the SIBA cannot be evaluated for such low powers. We conclude that, in principle, based on Figure 5c,d, low optical intensities result in higher trap stiffnesses when exciting on-resonance for the SIBA (930 nm); however, for higher intensities the blue-detuned excitation of the cavity provides stiffer traps.

At Hotspot 2, due to better confinement of the E-field, the resulting plasmonic field was stronger than at Hotspot 1. Even for low powers and off-resonant conditions, high optical forces were exerted on the nanoparticles (Figure 5b,d). Despite the slightly higher trap stiffnesses that were obtained when exciting at off-resonant conditions (920–928 nm), trapping with SIBA is still favorable due to the dynamic reconfiguration of the trap that allows the particle to be trapped in low intracavity intensity.

An interesting observation in Figure 5a,b is the fluctuations in the trap stiffness with increasing incident power and the deviation from the linear increase that is theoretically predicted. The fluctuations are more intense in the case of trapping at Hotspot 1, where the optical forces are weaker. This may be due to additional forces, such as thermal and fluid-related forces, competing against the optical trapping ones.

**Thermal Forces.** According to the literature, with similar size plasmonic structures, the photoinduced temperature rise in the solution was about 20–40°C, for illumination with approximately 2 mW/μm², and thus we assume that in our experiments we have a similar rise. This heating, resulting from intrinsic losses of the metallic nanostructures, generates thermal convection currents and thermophoresis that could influence trapping. Specifically, as the laser trapping intensity increases, the optically generated temperature gradients could induce fluid flows that quickly deliver the nanoparticles above the nanostructures. To maximize trapping probabilities, the nanoparticle should be delivered with low fluid velocity to

---

**Figure 5.** Experimental trap stiffness as a function of incident laser power for particles trapped at (a) Hotspot 1 and (b) Hotspot 2 and normalized trap stiffness as a function of the excitation wavelength, respectively, (c) and (d).
the hotspot where it could be trapped under the short-range plasmonic fields. When the height of the solution’s microwell is larger than 20 μm the fluid velocity is large, thereby preventing stable trapping.\textsuperscript{8,57} In addition, thermophoresis could alter thermophoretic migration of particles.\textsuperscript{59} For temperatures higher than a critical temperature, the Soret coefficient sign changes,\textsuperscript{58} and thermophoresis repels particles away from a high-temperature location,\textsuperscript{13} hindering trapping stability.

**Fluid-Related Forces.** An important factor that may impact the trapping performance is the role of the Triton X-100 in the liquid solution. It has been reported that a small amount of nonionic surfactant generates thermodiffusion with opposite sign to the optical force, leading to fluctuations of the particle’s position inside the trap and a lower trap stiffness magnitude.\textsuperscript{12} This also depends on the interaction of the surfactants with the surface of the particle itself, which may make the particle thermophobic or thermophilic.\textsuperscript{56} In our study, the AuNPs were successfully trapped using Triton X-100. It is worth noting that, when using no surfactant or using an ionic surfactant (sodium dodecyl sulfate), we failed to observe stable trapping. Since we used a range of incident intensities, it is possible that beyond a certain intensity (leading to increased heating) the Soret coefficient sign also changes, resulting in a complicated trapping mechanism. The role of the surfactant in the trapping performance is a subject of future research.

**Electrostatic and Scattering Forces.** An additional effect may be present due to electrostatic repulsive forces as the AuNPs (−24 mV zeta potential) approach the gold surface, with both being negatively charged.\textsuperscript{59} This can result in a decreased measured trap stiffness since our evaluation method is based on the motion of the particle as it enters the trap. Finally, upon illumination of the gold structure, light scattering may contribute to destabilization of the particle and the deviation from the linear increase of the trap stiffness.

As the combination of the above effects strongly depends on the particle and solution properties, as well as local temperature effects, the trapping landscape can be quite complicated, and an optimized trapping scheme is required that would take advantage of all the positive phenomena and minimize the negative ones. However, this is beyond the scope of this paper and will constitute future work.

Trapping of gold nanoparticles was performed via metamaterial plasmonic tweezers. The investigated trapping conditions were for on-resonant and blue-detuned wavelengths to enable the SIBA effect. Very high experimental trap stiffness values were observed, with on-resonant trapping exhibiting the highest value at 2.92 ± 0.42 (N/nm)/(mW/μm\(^2\)) for an excitation laser intensity as low as 0.61 mW/μm\(^2\). For the blue-detuned excitation, the highest value was 4.18 ± 0.2 (N/nm)/(mW/μm\(^2\)) but for an intensity about 62% higher. The experimental results had the characteristic feature of SIBA-assisted trapping, where the maximum trap stiffness is exhibited for the lowest excitation intensity. For the SIBA-resonant wavelength of 930 nm, two distinct regimes were observed: the low-intensity regime where SIBA was the main mechanism contributing to the trap and the high-intensity regime where SIBA vanished and the optical forces dominated the trapping mechanism, in agreement with theory. Blue-detuned trapping exhibited a complex behavior that deviated from the linear increase of the trap stiffness with increased excitation intensity. Additional forces, such as thermal, fluid, and electrostatic forces, may have contributed to this deviation.

Extensive simulations were also performed and revealed the existence of two groups of hotspots per unit cell of the array. With varying excitation wavelength, a different ratio of E-field intensities could be excited at each hotspot, thus resulting in traps of different strengths with the ability to tailor the hotspots based on the desired application. This could prove extremely useful in biological applications where precise tuning of the force is required, for example in trapping and studying intracellular molecules through the cell’s membrane\textsuperscript{60} or exploring the interactions of viruses with their environment,\textsuperscript{61} thus opening new avenues in the development of next-generation drug delivery systems.\textsuperscript{52}

**ASSOCIATED CONTENT**

**Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.2c04492.

Details on the sample fabrication, solution preparation, and simulations can be found in the Methods section. Additional simulation figures and analytical calculations of the cavity shift and the optomechanical coupling constant are also included. S1: Methods. S2: Experimental and simulated structure. S3: Cavity shift and optomechanical coupling constant analytical calculations. S4: Simulated optical forces and potentials (PDF)

**AUTHOR INFORMATION**

**Corresponding Author**

Theodoros D. Bouloumis — Okinawa Institute of Science and Technology Graduate University, Onna, Okinawa 904-0495, Japan; orcid.org/0000-0002-5264-7338; Email: theodoros.bouloumis@oist.jp

**Authors**

Donna G. Kotsifaki — Okinawa Institute of Science and Technology Graduate University, Onna, Okinawa 904-0495, Japan; Natural and Applied Sciences, Duke Kunshan University, Kunshan, Jiangsu Province 215316, China; orcid.org/0000-0002-2023-8345

Síle Nic Chormaic — Okinawa Institute of Science and Technology Graduate University, Onna, Okinawa 904-0495, Japan; orcid.org/0000-0003-4276-2014

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.nanolett.2c04492

**Author Contributions**

T.D.B. and D.G.K. conceived the idea of this work; D.G.K. prepared the solutions; T.D.B. performed the experiments, simulations, and analyzed the data; and S.N.C. supervised all stages of the work. All authors contributed to writing the paper.

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

The authors thank M. Ozer for technical support, J. Keloth for useful discussions, and N. Kokkinidis for discussions regarding the simulations. They also acknowledge P. Puchenkov and J. Moren from the Scientific Computing and Data Analysis Section and the Engineering Section at OIST. This work was partially supported by the Okinawa Institute of Science and Technology Graduate University. T.D.B. acknowledges fund-
REFERENCES

(1) Ashkin, A. Acceleration and trapping of particles by radiation pressure. Phys. Rev. Lett. 1970, 24, 156−159.
(2) Ashkin, A.; Dziedzic, J. M.; Bjorkholm, J. E.; Chu, S. Observation of a single-beam gradient force optical trap for dielectric particles. Opt. Lett. 1986, 11, 288−290.
(3) Polimeni, P.; Magazzù, A.; Iati, M. A.; Patti, F.; Saija, R.; Esposito Boschi, C. D.; Donato, M. G.; Gucchiardi, P. G.; Jones, P. H.; Volpe, G.; Maragò, O. M. Optical tweezers and their applications. J. Quant. Spectrosc. Radiat. Transfer 2018, 218, 131−150.
(4) Bouloumis, T. D.; Nic Chormaic, S. From far-field to near-field micro- and Nanoparticle optical trapping. Appl. Sci. 2020, 10, 1375.
(5) Righini, M.; Ghenuche, P.; Cherukulappurath, S.; Myrosenychenko, V.; de abajo, F. J. G.; Quidant, R. Nano-optical trapping of Rayleigh particles and Escherichia coli bacteria with resonant optical antennas. Nano Lett. 2009, 9, 3387−3391.
(6) Verschuren, D.; Shi, X.; Dekker, C. Nano-optical tweezing of single proteins in plasmonic nanopores. Small Methods 2019, 3, 1800465.
(7) Peng, X.; Kotnala, A.; Rajeeva, B. B.; Wang, M.; Yao, K.; Bhatt, N.; Penley, D.; Zheng, Y. Plasmonic nanotweezers and nanosensors for Point-of-Care Applications. Adv. Opt. Mater. 2021, 9, 2100050.
(8) Xu, Z.; Crozier, K. B. All-dielectric nanotweezers for trapping and observation of a single quantum dot. Opt. Express 2019, 27, 40344−4045.
(9) Hong, C.; Yang, S.; Kravchenko, I. L.; Ndukaife, J. C. Electrothermoplasmonic trapping and dynamic manipulation of single colloidal nanodiamond. Nano Lett. 2021, 21, 4921−4927.
(10) Jiang, Q.; Roy, P.; Claude, J.-B.; Wenger, J. Single photon source from a nanoantenna-trapped single quantum dot. Nano Lett. 2021, 21, 7030−7036.
(11) Roxworthy, B. J.; Ko, K. D.; Kumar, A.; Fung, K. H.; Chow, E. K. C.; Liu, G. L.; Fang, N. X.; Toussaint, K. C. Application of plasmonic bowtie nanoantenna arrays for optical trapping, stacking, and sorting. Nano Lett. 2012, 12, 796−801.
(12) Jiang, Q.; Rogez, B.; Claude, J.-B.; Baffou, G.; Wenger, J. Quantifying the role of the surfactant and the thermophoretic force in plasmonic nano-optical trapping. Nano Lett. 2020, 20, 8811−8817.
(13) Kotsifaki, D. G.; Nic Chormaic, S. The role of temperature-induced effects generated by plasmonic nanostructures on particle delivery and manipulation: a review. Nanophotonics 2022, 11, 2199−2218.
(14) Juan, M. L.; Righini, M.; Quidant, R. Plasmon nano-optical tweezers. Nat. Photonics 2011, 5, 349−356.
(15) Saleh, A. A. E.; Dione, J. A. Toward efficient optical trapping of sub-10-nm particles with coaxial plasmonic apertures. Nano Lett. 2012, 12, 5581−6.
(16) Kotsifaki, D. G.; Nic Chormaic, S. Plasmonic optical tweezers based on nanostructures: fundamentals, advances and prospects. Nanophotonics 2019, 8, 1227−1245.
(17) Bouloumis, T. D.; Kotsifaki, D. G.; Han, X.; Nic Chormaic, S.; Truong, V. G. Fast and efficient nanoparticle trapping using plasmonic connected nanoring apertures. Nanotechnology 2021, 32, 025507.
(18) Juan, M. L.; Gordon, R.; Pang, Y.; Efekharhi, F.; Quidant, R. Self-induced back-action optical trapping of dielectric nanoparticles. Nat. Phys. 2009, 5, 915−919.
(19) Neumeier, L.; Quidant, R.; Chang, D. E. Self-induced back-action optical trapping in nanopophonic systems. New J. Phys. 2015, 17, 123008.
(20) Descharmes, N.; Dharanipathy, U. P.; Diao, Z.; Tonin, M.; Houdré, R. Observation of backaction and self-induced trapping in a planar hollow photonic crystal cavity. Phys. Rev. Lett. 2013, 110, 123601.
(21) Mestres, P.; Berthelot, J.; Acimovic, S. S.; Quidant, R. Unraveling the optomechanical nature of plasmonic trapping. Light Sci. App. 2016, 5, No. e16092.
(22) Zhang, C.; Li, J.; Park, J. G.; Su, Y.; Goddard, R. E.; Gelfand, R. M. Optimization of metallic nanoapertures at short-wave infrared wavelengths for self-induced back-action trapping. Appl. Opt. 2019, 58, 9498−9504.
(23) Zhu, T.; Cao, Y.; Wang, L.; Nie, Z.; Cao, T.; Sun, F.; Jiang, Z.; Nieto-Vesperinas, M.; Liu, Y.; Qu, C.-W.; Ding, W. Self-induced backaction optical pulling force. Phys. Rev. Lett. 2018, 120, 123901.
(24) Daniel, M.-C.; Astruc, D. Gold nanoparticles: Assembly, supramolecular chemistry, quantum-size-related properties, and applications toward biology, catalysis, and nanotechnology. Chem. Rev. 2004, 104, 293−346.
(25) Grammatikopoulos, P.; Steinhauer, S.; Vernieres, J.; Singh, V.; Sowman, M. Nanoparticle design by gas-phase synthesis. Adv. Phys. - X 2016, 1, 81−100.
(26) Halas, N. J.; Lal, S.; Chang, W.-S.; Link, S.; Nordlander, P. Plasmons in strongly coupled metallic nanostructures. Chem. Rev. 2011, 111, 3913−3961.
(27) Mie, G. Beiträge zur optik trüber medien, speziell kolloidaler metallosungen. Ann. Phys. (Berlin, Ger.) 1908, 330, 377−445.
(28) Jeanmaire, D. L.; Van Duyne, R. P. Surface Raman spectroelectrochemistry: Part I. Heterocyclic, aromatic, and aliphatic amines adsorbed on the anodized silver electrode. J. Electroanal. Chem. Interfacial Electrochem. 1977, 84, 1−20.
(29) Notarianni, M.; Vernon, K.; Chou, A.; Aljada, M.; Liu, J.; Motta, N. Plasmonic effect of gold nanoparticles in organic solar cells. Sol. Energy 2014, 106, 23−37.
(30) Nguyen, M. A. P.; Kim, S.; Tran, T. T.; Xu, Z.; Kinania, M.; Toth, M.; Abaronovich, I. Nanoassembly of quantum emitters in hexagonal boron nitride and gold nanospheres. Nanoscale 2018, 10, 2267−2274.
(31) Liu, L.; Corma, A. Metal catalysts for heterogeneous catalysis: From single atoms to nanoclusters and nanoparticles. Chem. Rev. 2018, 118, 4981−5079.
(32) Wueneschell, J.; Jee, Y.; Buric, M.; Chorpening, B. Gold nanoparticle incorporated oxide thin films for gas sensing at high temperature. MRS Commun. 2022, 12, 308−314.
(33) Mirigliano, M.; Paroli, B.; Martini, G.; Fedrizzi, M.; Falqui, A.; Casu, A.; Milan, P. A binary classifier based on a reconfigurable dense network of metallic nanojunctions. Neuromorphic Comput. Eng. 2021, 1, 024007.
(34) Ghosh, P. S.; Han, G.; De, M.; Kim, C.; Rotello, V. M. Gold nanoparticles in delivery applications. Adv. Drug Deliv. Rev. 2008, 60, 1307−15.
(35) Vines, J. B.; Yoon, J.-H.; Ryu, N.-E.; Lim, D.-J.; Park, H. Gold nanoparticles for photothermal cancer therapy. Front. Chem. 2019, 7, 167.
(36) Carabineiro, S. A. Applications of gold nanoparticles in nanomedicine: Recent advances in vaccines. Molecules 2017, 22, 857.
(37) Daraee, H.; Etemadmi, A.; Abbasi, E.; Aval, S. F.; Kouhi, M.; Akbarzadeh, A. Application of gold nanoparticles in biomedical and drug delivery. Artif. Cells Nanomed. Biotechnol. 2016, 44, 410−422.
(38) Nejati, K.; Dadashpour, M.; Gharibi, T.; Mellatyar, H.; Akbarzadeh, A. Biomedical applications of functionalized gold nanoparticles: A review. J. Clust. Sci. 2022, 33, 1−16.
(39) Wang, K.; Schonbrun, E.; Crozier, K. B. Propulsion of gold nanoparticles with surface plasmon polaritons: Evidence of enhanced optical force from near-field coupling between gold particle and gold film. Nano Lett. 2009, 9, 2623−2629.
(40) Zhang, W.; Huang, L.; Santschi, C.; Martin, O. J. F. Trapping and sensing 10 nm metal nanoparticles using plasmonic dipole antennas. Nano Lett. 2010, 10, 1006−1011.
(41) Min, C.; Shen, Z.; Shen, J.; Zhang, Y.; Fang, H.; Yuan, G.; Du, L.; Zhu, S.; Lei, T.; Yuan, X. Focused plasmonic trapping of metallic particles. Nat. Commun. 2013, 4, 2891.
(42) Kotsifaki, D. G.; Truong, V. G.; Nic Chormaic, S. Fano-resonant, asymmetric, metamaterial-assisted tweezers for single nanoparticle trapping. *Nano Lett.* 2020, 20, 3388–3395.

(43) Fedotov, V. A.; Rose, M.; Prosvirnin, S. L.; Papasimakis, N.; Zholudev, N. I. Sharp trapped-mode resonances in planar metamaterials with a broken structural symmetry. *Phys. Rev. Lett.* 2007, 99, 147401.

(44) Papasimakis, N.; Zholudev, N. I. Metamaterial-induced transparency: Sharp Fano resonances and slow light. *Opt. and Photonics News* 2009, 20, 22–27.

(45) Tanaka, K.; Plum, E.; Ou, J. Y.; Uchino, T.; Zholudev, N. I. Multifold enhancement of quantum dot luminescence in plasmonic metamaterials. *Phys. Rev. Lett.* 2010, 105, 227403.

(46) Luk'yanchuk, B.; Zholudev, N. I.; Maier, S. A.; Halas, N. J.; Nordlander, P.; Giessen, H.; Chong, T. C. The Fano resonance in plasmonic nanostructures and metamaterials. *Nat. Mater.* 2010, 9, 707–715.

(47) Thijssen, R.; Kippenberg, T. J.; Polman, A.; Verhagen, E. Plasmomechanical resonators based on dimer nanoantennas. *Nano Lett.* 2015, 15, 3971–3976.

(48) Aspelmeyer, M.; Kippenberg, T. J.; Marquardt, F. Cavity optomechanics. *Rev. Mod. Phys.* 2014, 86, 1391–1452.

(49) Simmons, R.; Finer, J.; Chu, S.; Spudich, J. Quantitative measurements of force and displacement using an optical trap. *Biophys. J.* 1996, 70, 1813–1822.

(50) Kotnala, A.; Gordon, R. Quantification of high-efficiency trapping of nanoparticles in a double nanohole optical tweezer. *Nano Lett.* 2014, 14, 853–856.

(51) Baffou, G.; Berto, P.; Bermúdez Ureña, E.; Quidant, R.; Monneret, S.; Polleux, J.; Rigneault, H. Photoinduced heating of nanoparticle arrays. *ACS Nano* 2013, 7, 6478–6488.

(52) Roxworthy, B. J.; Bhuiya, A. M.; Vanka, S. P.; Toussaint, K. C. Understanding and controlling plasmon-induced convection. *Nat. Commun.* 2014, 5, 3173.

(53) Ndukaife, J. C.; Mishra, A.; Guler, U.; Nnanna, A. G. A.; Wereley, S. T.; Boltaševa, A. Photothermal heating enabled by plasmonic nanostructures for electokinetic manipulation and sorting of particles. *ACS Nano* 2014, 8, 9035–9043.

(54) Ndukaife, J. C.; Kädishev, A. V.; Nnanna, A. G. A.; Shalaev, V. M.; Wereley, S. T.; Boltaševa, A. Long-range and rapid transport of individual nano-objects by a hybrid electrothermoplasmonic nanotweezer. *Nat. Nanotechnol.* 2016, 11, 53–59.

(55) Xu, Z.; Song, W.; Crozier, K. B. Direct particle tracking observation and Brownian dynamics simulations of a single nanoparticle optically trapped by a plasmonic nanoaperture. *ACS Photonics* 2018, 5, 2850–2859.

(56) Fränzl, M.; Cichos, F. Hydrodynamic manipulation of nano-objects by optically induced thermo-osmotic flows. *Nat. Commun.* 2022, 13, 656.

(57) Braibanti, M.; Vigolo, D.; Piazza, R. Does thermophoretic mobility depend on particle size? *Phys. Rev. Lett.* 2008, 100, 108303.

(58) Würger, A. Thermal non-equilibrium transport in colloids. *Rep. Prog. Phys.* 2010, 73, 126601.

(59) Rodríguez-Sevilla, P.; Prorok, K.; Bednarkiewicz, A.; Marques, M. I.; García-Martín, A.; García Sole, J.; Haro-González, P.; Jaque, D. Optical forces at the nanoscale: Size and electrostatic effects. *Nano Lett.* 2018, 18, 602–609.

(60) Zhang, Y.; Min, C.; Dou, X.; Wang, X.; Urbach, H. P.; Somekh, M. G.; Yuan, X. Plasmonic tweezers: for nanoscale optical trapping and beyond. *Light Sci. Appl.* 2021, 10, 59.

(61) Popovic, M. Beyond COVID-19: Do biothermodynamic properties allow predicting the future evolution of SARS-CoV-2 variants? *Microb. Risk Anal.* 2022, 22, 100232.

(62) Amako, Y.; Woo, C. M. A chiral trick to map protein ligandability. *Nat. Chem.* 2019, 11, 1080–1082.