Recent Progress in Optical-Resonance-Assisted Movement Control of Nanomotors

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Light exerts force or torque on objects through the momentum or angular momentum exchange between photons and the objects. For absorbing structures, light also induces a thermal gradient that can be used to power the object movement. The light-driven mechanism, with the advantages of wireless, versatile modulation, and excellent spatial and temporal resolution, is very attractive and triggers various studies on micro- and nanomotors controlled by light. However, when the size of the motor becomes smaller and reaches the nanoscale, their interaction with light decreases and therefore it is very challenging to overcome the random Brownian motions. Optically resonant nanomotors can break such limitations. Alternatively, one can use optically resonant structures that significantly confine the light energy to control the movements of nanoobjects. Herein, the recent research on state-of-the-art light resonant nanomotors, which includes both optically resonant nanomotors and nanomotors controlled by optically resonant nanostructures, is discussed. Their driving mechanisms, movement control, limitations, and possible improvements are introduced in detail. The exploration of the light resonant nanomotors in various applications is also introduced. Finally, an outlook on the future development of light resonant nanomotors is provided.

1. Introduction

Motors convert energies of different types to mechanical movement and are crucial for the development of all types of machines. Biological nanomotors enable thermodynamically unfavorable processes and are responsible for most forms of motion in all life forms. An example, flagellated cells, such as bacteria and the mammalian sperm cells, use their flagella to propel themselves. The flagella are powered by protein motors that are adenosine triphosphate (ATP) or proton-driven. Inspired by these natural nanometer-sized biomotors, researchers have developed various artificial nanomotors that are driven by self-propulsion or external fields. The self-propulsion is often realized by the mechanisms of self-electrophoresis, self-thermophoresis, self-diffusiophoresis, and chemical-reaction-generated bubbles. These nanomotors harvest energy from their surrounding environments and propel themselves. On the contrary, other nanomotors are driven by external fields, such as magnetic field, electric field, light, and ultrasound waves. In addition, substrates with patterned surfaces can be used to assist the propulsion of nanomotors.

The artificial nanomotors have shown promising potentials in addressing challenges in biomedical applications and environmental governance, such as drug delivery, cancer diagnosis, biochemical reagent degradation, chemical sensing, and remediation of oil-contaminated water. The development of nanomotors also provides new solutions for technologies in lab-on-a-chip and micro-electromechanical system (MEMS) devices, including the manipulation of micro/nanoscale objects or fluids, autonomous identification and repair of electronic systems, and manufacture of complex microstructures.

Light is one of the most efficient, flexible, and widely used driving stimuli to power the nanomotors. The optically propelled nanomotors can be tuned “on” or “off” readily on demand, which makes them greatly favored in practical applications. However, when the motor size reaches the nanoscale, the weakened light–matter interaction makes it difficult to overcome the random Brownian motions of the nanomotors. Optically resonant structures that strongly enhance their interaction with light are good candidates to enable the efficient propulsion of nanomotors by light. By using optically resonant structures, the Brownian movement of the nanomotors can be rectified or even completely constrained. The nanomotors have been powered to perform directional translational movements, rapid spinning, and circular rotations, by choosing the optically resonant structures and tuning the polarization, phase, and intensity of light.

There are two ways to construct light resonant nanomotors. One is to use nanostructures that support optical resonances,
such as plasmonic metal\textsuperscript{[13]} and high-refractive-index\textsuperscript{[34]} nanostructures, as the motors. The other way is to apply optically resonant structures/surfaces to generate optical potentials or other gradient forces that drive the movement of nanoobjects with or without optical resonance properties. In both methods, plasmonic metal nanostructures that support collective and coherent oscillations of conduction electrons are usually used because they have remarkable optical cross sections at their resonance wavelengths\textsuperscript{[15]} and support significantly enhanced optical forces\textsuperscript{[36]} in the last decade, many research efforts have been devoted to exploring the construction of light resonant nanomotors and their applications. In this progress report, we present an overview of representative light resonant nanomotors. We emphasize our discussion on driving mechanisms and movement control, including speed regulation, direction adjustment, and collective behavior modulation, of the nanomotors. The respective advantages and side effects of different light resonant nanomotors are also discussed. Finally, according to the motion characteristics of the nanomotors, we point out their applications in environmental sensing, biomedicine, physical chemistry, and other fields.

2. Nanomotor Movement Control Powered by Optical Resonances

2.1. Light-Driven Translational Movement of Plasmonic Nanomotors

Asymmetric fields are required to drive the directional translational movement of nanomotors. For light-driven nanomotors, the asymmetric fields can be achieved by using asymmetric nanostructures or introducing nonuniform illumination conditions. Janus nanostructures are the most commonly used asymmetric structures in the design of light-driven translational nanomotors. The two-faced Janus structures provide asymmetry and directionality. Asymmetric fields are therefore established by the different photochemical or photophysical effects of the two faces of the Janus nanostructures, which exhibit different surface properties. Janus nanostructures have been intensively explored as photochemically powered translational nanomotors. When one face of the nanomotors is photocatalytic, the translational motions will be powered by the solute concentration gradient or bubbles generated by the catalytic reaction of the fuel in the surrounding environment\textsuperscript{[29]} . The catalytic efficiency thus has a profound effect on the translational speed, which enables the control of the nanomotor translational motions by varying the environmental conditions. It has been reported that the velocity and efficiency of the nanomotors are significantly improved by increasing the solvent temperature\textsuperscript{[17]} or the fuel concentration.\textsuperscript{[18]} However, the excessive heating of the solvent or the overuse of the fuel are not suitable for some specific biological environments.

To prevent the unwanted solvent heating and minimize the use of chemical fuels, the introduction of optically resonant plasmonic materials on translational nanomotors has been demonstrated to achieve fuel-free propulsion and on/off control excited by the resonant light.

First, the plasmon resonance helps to boost the catalytic reactions. The plasmon resonance allows the strong confinement of light energy in the surrounding of the plasmonic nanostructures and therefore improves the light harvesting efficiencies of the catalyst structures.\textsuperscript{[39]} High-energy electrons generated from the decay of surface plasmons will additionally facilitate the catalytic reactions even when the photon energy is below the bandgap of semiconductor catalysts.\textsuperscript{[40]} For example, Janus nanocaps, composed of Au and TiO\textsubscript{2} layers, have been shown to act as a plasmon-enhanced photocatalytic nanomotors (Figure 1a–d) driven by the catalysis of water oxidation.\textsuperscript{[41]} Under the illumination of light at the nanocaps resonance wavelength of about 700 nm, the electromagnetic energy is mostly confined at the TiO\textsubscript{2}/environment and Au/TiO\textsubscript{2} interfaces (Figure 1b) because of the excitation of the localized surface plasmons. The 700 nm photons cannot excite electron–hole pairs in TiO\textsubscript{2}, but some high-energy electrons in the Au nanostructure generated from the decay of surface plasmons can transfer to TiO\textsubscript{2} conduction band and produce a charge separation (Figure 1c)\textsuperscript{[40,42]} . Water is believed to be oxidized at the Au layer by the holes left in Au. The generated protons flow to the TiO\textsubscript{2} surface and get reduced by the injected electrons. The resultant asymmetric distribution of ions produces a self-generated electric field, which propels the nanomotors to move through a self-electrophoresis mechanism. An enhanced Brownian motion of the nanocaps is therefore observed (Figure 1d). Ag/AgCl Janus particles have been reported to work as translational nanomotors that are believed to be propelled by a similar mechanism as well. The surface plasmon resonance on Ag nanostructure largely
Figure 1. Optically propelled translational nanomotors. a–d) Janus Au/TiO$_2$ nanocaps that are driven to move translationally by self-electrophoresis caused by plasmon-enhanced photocatalytic reactions.$^{[49]}$ Using polystyrene particles as sacrificial template, Au core/TiO$_2$ shell nanocaps (a) that support plasmon resonances (b) are prepared by combining plasma etching, physical vapor deposition, and annealing processes. The photocatalytic effect is enhanced by surface plasmons (c). The nanocap motors therefore show the resulting enhanced self-diffusiophoresis motion (d). Adapted with permission.$^{[45]}$ Copyright 2018, Wiley-VCH. e–h) Janus nanostructures as nanomotors driven by self-thermophoresis. The Janus nanomotors are obtained by coating half of mesoporous silica nanoparticle surface with Au layer (e). Under the excitation of NIR irradiation, the plasmonic Janus nanomotors exhibit an anisotropic temperature distribution (f), leading to imbalanced collisions of water molecules along the nanomotor (g). As a result, the nanomotors were pushed to the cold side (h). Reproduced with permission.$^{[45]}$ Copyright 2016, American Chemical Society. (g) Reproduced with permission.$^{[47]}$ Copyright 2016, Tsinghua University Press and Springer Nature.

enhances the utilization of blue light. Because of the photocatalysis by AgCl, the Ag/AgCl Janus particles generate strong chemical gradients. The Janus particles therefore perform self-diffusiophoresis motion that is strong enough to exclude surrounding obstacles. The self-propelled motion can be further enhanced by the agglomeration of the Ag/AgCl Janus particles.$^{[43]}$ The nanomotors driven by plasmonically powered or enhanced catalysis exhibit an enhanced Brownian motion under the illumination of a visible or ultraviolet light, but they might fail to show good directional movement.

Second, Janus nanostructures with plasmon resonances or other types of optical resonances exhibit light-triggered self-thermophoresis because of the inhomogeneous temperature distribution photothermally generated on the nanostructure surface.$^{[44]}$ These nanomotors are usually composed of materials with very different thermal conductivities. The metallic layer with plasmonic resonance, converting light energy into heat efficiently, has been widely used in the light-driven self-thermophoresis nanomotors. For example, Janus mesoporous silica nanoparticles, half of which are covered with a 10 nm Au layer, produce an apparent thermal difference between the silica and the gold under the illumination of near-infrared (NIR) light because of the plasmonic photothermal conversion of Au half-shells in the NIR region (Figure 1e–h).$^{[45]}$ Self-thermophoresis is then induced owing to the imbalanced collisions of water molecules along the nanomotors, driving them to move along the direction of the laser irradiation (Figure 1g,h). Up to 950 body lengths $\mu$m s$^{-1}$ of the 50 nm nanomotors has been recorded under the NIR laser power of 70.3 W cm$^{-2}$, demonstrating the ultrafast movement based on self-thermophoresis. In addition to the Janus nanostructures, multilayer capsules, made from layer-by-layer self-assembly of chitosan and alginate, have been used as self-propelled nanomotors when Au nanorods were deposited on one side of the capsules for the generation of thermal gradient under the NIR irradiation.$^{[46]}$ These nanomotors' on/off motions and speeds can be easily controlled by adjusting the power of the NIR laser. Under the NIR irradiation, the translational speed reaches up to 23.27 $\mu$m s$^{-1}$. However, it is still challenging to maintain a good directionality during the translational movement of the nanomotors.

Several efforts have been devoted to overcoming the difficulty in controlling the directionality of the translational nanomotors. By using a nanoporous polycarbonate membrane template, a tubular structure has been fabricated by layer-by-layer assembling negatively charged poly(styrenesulfonic acid) (PSS) and positively charged poly(allylamine hydrochloride) (PAH) into the inner walls of the template. Au nanoparticles stabilized by citrate are deposited onto the outer or inner surface of the conical tubular structure via electrostatic interactions (Figure 2a).$^{[48]}$ The strong absorption of plasmonic Au nanoparticles under the illumination of NIR light produces local temperature gradients, which results in the thermophoretic forces along the elongated axis of the tubular structures. The conical structure further makes the tubular nanomotors move directly toward the direction of the front small opening with a speed of up to 160 $\mu$m s$^{-1}$. Scientists have further developed more sophisticated nanomotors to achieve a better control of the directionality of their movement. For example, an asymmetric nanomotor with different materials deposited on its surface has been demonstrated to move bidirectionally with the movement direction tuned by changing the incident light wavelength (Figure 2b).$^{[49]}$
Figure 2. Direction control of optically propelled translational nanomotors. a) Directional nanomotors driven by self-thermophoresis. The nanomotors are fabricated by layer-by-layer assembled PSS and PAH with Au nanoparticles in them. The conical structure will make the nanomotors move to the direction of the front small opening when the motors are irradiated by light.[30,48] a) Top: Reproduced with permission.[30] Copyright 2014, American Chemical Society. Bottom: Reproduced with permission.[48] Copyright 2015, Wiley-VCH. b) An asymmetric nanomotor consisting of a dielectric core, a titanium-nitride cap (A) and an Au cap (B) on each side. The coating materials enable wavelength-selective optical absorption so the nanomotor direction can be controlled by changing the wavelength of the incident light.[49] Reproduced with permission.[49] Copyright 2016, American Chemical Society.

A polystyrene bead, half covered by gold and half covered by titanium-nitride, has been designed to preferentially absorb light with wavelengths at 500 and 800 nm, respectively. By switching the wavelength of the actuating light, the difference of the two materials in optical absorption creates a switchable thermal gradient, finally leading to the transport of the nanomotor along a desired route. In addition to the light wavelength, the polarization of light can also be applied to modulate the directionality of the nanomotors’ movement if the motor material and structure are properly designed.[50]

2.2. Plasmonic Nanostructures as Rotary Nanomotors

Rotary nanomotors are another important category of nanomotors. Most of the reported works have demonstrated the rotation of these nanomotors at a fixed location. Optical tweezers have been a useful implement for achieving rotation of trapped micron-sized particles because of its advantages of strong confinement and efficient light—matter momentum and angular momentum exchange.[51] Because of their strong interaction with light, plasmonic nanocrystals can be tightly trapped in optical tweezers.[52] Under their resonance wavelength, the plasmonic nanocrystal motors in the optical tweezers feel maximized optical rotational torque and achieve fast and stable rotations.[8] The rotation of the plasmonic nanomotors can be driven by laser light with zero photon angular momentum (linear polarization), photon spin angular momentum, and photon orbital angular momentum, respectively.

First, the plasmonic nanomotors can be rotated by linearly polarized laser light. For anisotropic plasmonic nanocrystal structures, such as nanorods, nanodimers, and nanowires trapped by optical tweezers with linear polarization, the oscillating electric field of the laser light induces an electric dipole moment, which generally points in a different direction than the polarization direction of the trapping light. An optical torque is therefore generated, trying to align the plasmonic nanostructure to minimize the optical potential energy (Figure 3a).[53] For example, Ag nanorods are aligned with their long axis parallel to the laser polarization, while Ag nanowires are aligned perpendicularly to the laser polarization (Figure 3b).[15] Rotating the laser polarization, which is often achieved by using a half waveplate (Figure 3c) or an optoelectronic device, as a result enables the continuous rotation of the trapped plasmonic anisotropic nanostructures. As an experimental demonstration, rapid rotation of the incident linear polarization has been shown to drive the Ag nanowire to spin (Figure 3d).[53] The optical aligning torque is balanced by the friction torque that is proportional to the rotational frequency, resulting in a constant spinning frequency of the nanowire at around 0.8 Hz.

In addition to rotating the light polarization, an alternative way to achieve the propulsion of rotary nanomotors is to use specific nanostructures that are directly driven by linearly polarized light. For instance, a planar gammadion-shaped Au nanostructure has been experimentally demonstrated to serve as a plasmonic nanomotor (Figure 3e).[18] Although the incident photons do not carry any angular momentum, the scattered light of the plasmonic gammadion nanostructure gains some angular momentum. The nanomotor therefore can be rotated by the angular momentum transfer mediated by the scattering processes. A close look at the near field in the surrounding of the plasmonic nanostructure and the electromagnetic analysis show that the Poynting vector generates forces at the gammadion arms, providing optical torques to rotate the nanostructure (Figure 3f). The magnitude and direction of the optical torque depend on the wavelength sensitively. At the plasmon resonance wavelengths (810 and 1700 nm), the magnitude of the optical torque is maximized. Calculation results reveal that the Poynting vector generates tangential forces at the gammadion arms to provide a positive (anticlockwise) torque at 810 nm, and mainly concentrates in the gaps between the metallic arms to cause a negative (clockwise) torque at 1700 nm (Figure 3g), respectively. The optical torque on the gammadion nanomotor will be large enough to propel the rotation of microsilica disk in water when the incident light has a power of several megawatts.[18]

Second, plasmonic nanomotors can be driven by light with spin or orbital angular momentum. The angular momentum carried by photons can be transferred to the plasmonic nanostructure through both absorption and scattering. Circularly polarized laser beams, with each photon carrying an inherent spin angular momentum of $\pm \hbar$, have been used to rotate plasmonic nanomotors trapped in an optical tweezers.[54,55] Absorbed photons will transfer its angular momentum completely to the nanomotor, generating the absorption torque,[54] while the scattering torque results from the change of polarization states of the scattered photons.[56] In most cases, both absorption and scattering torques reach their maximum at the plasmon resonance wavelengths. It is worth noting that a circularly symmetric particle cannot produce scattering torques under the illumination of circularly polarized light (Figure 4a top). A symmetric Au nanosphere with a diameter of around 400 nm can be driven to rotate by the absorption of circularly polarized photons, leading to a rotation frequency of 0.6 kHz.
in an 830 nm laser focus with an intensity of around 10 mW μm⁻² (Figure 4b). Faster rotation of the plasmonic nanosphere motors requires higher laser powers, which unfortunately bring problematic strong photothermal heating side effects. In contrast, the scattering torque is introduced for asymmetric nanomotors. For a Au nanorod with a length of 173 nm and a width of 65 nm, the scattering contribution to the optical torque reaches over 85% at the longitudinal plasmon resonance wavelength of the nanorod (Figure 4a bottom). Under the propulsion of the same laser beam (830 nm, 10 mW μm⁻²), the Au nanorod is speeded up to 42 kHz (Figure 4b), which is the fastest artificial rotary motors in aqueous solutions recorded to date. The Au nanorod motors therefore are much more efficient in converting light energy into motor mechanical rotation, and as a result remarkably reduce the photothermal side effect. The circularly polarized laser focus is perfect for the control and analysis of individual plasmonic rotary nanomotors. The rotational dynamics of the plasmonic nanomotors can be fully modulated by varying the laser intensity or by creating specific optical rotational potential energy landscapes when one uses light of different polarization states. However, it is challenging to achieve a good control of simultaneously rotating multiple nanomotors within the same laser focus. The optical binding effects, which strongly depend on the particle spacing and the particle number, cannot be neglected and result in complex motions. For example, it has been theoretically predicted that a plasmonic dimer composed of two Au nanospheres undergoes interparticle-distance-dependent movement when trapped by a focused Gaussian beam with circular polarizations. Light carrying orbital angular momentum has been shown to rotate the plasmonic nanomotors as well. Higher order Laguerre–Gaussian beams, with an annular intensity distribution and a phase dependence of \( e^{i\lambda} \) (\( \lambda \) is the topological charge), have an orbital angular momentum of \( l \) per photon. Plasmonic nanomotors can be captured in the bright ring or confined to the dark center of the focused optical vortex beam. The orbital angular momentum of photons are transferred by absorption and scattering, driving the nanomotors to rotate or spin according to the relative size between the nanomotor and the light spot. For example, an Au nanosphere with a diameter of 400 nm has been shown to be trapped in the bright ring of an optical vortex beam (830 nm, 73 mW) with \( l = 8 \) and rotate at a frequency of 86 Hz (Figure 4c). An Ag nanowire with a length of around 10 μm, on the contrary, can be trapped in the laser center and spin (Figure 4d). Furthermore, the direction and magnitude

**Figure 3.** Rotary nanomotors driven by linearly polarized light. a) Schematic of an anisotropic plasmonic nanostructure optically trapped against a glass substrate. An optical torque \( M_{\text{opt}} \) is generated by the interaction between the electric field \( E \) of the incident light and the induced nanostructure dipole \( p \). b) Experiments showing that the optical torque tends to align an Ag nanowire perpendicular to the laser polarization (red arrows) when one of its ends is trapped by the light (red spot). Schematic illustrating the rotation of a plasmonic nanorod propelled by consistently rotating the laser polarization through a half-waveplate. Reproduced with permission. Copyright 2018, Wiley-VCH. d) Experimental results showing the continuous rotation of a Ag nanowire at around 0.8 Hz driven by rotating the laser polarization. (b,d) Adapted with permission. Copyright 2010, American Chemical Society. e–g) Rotation of a gammadion plasmonic nanostructure embedded in a silica microdisk driven by linearly polarized light. At the plasmon resonance wavelengths of 810 and 1700 nm, the induced electric field (color map) and Poynting vector (red arrows) have been calculated (f). The absorbed or scattered Poynting vector at the outside of the arm (810 nm) and in the elbow (1700 nm) provides the largest positive and negative optical torques, respectively. The optical torque exhibits a strong dependence on the excitation wavelength and therefore anticlockwise (green area) and clockwise (purple area) rotation of the nanomotors can be achieved (g). Adapted with permission. Copyright 2010, Springer Nature.
of optical torques exerted on the nanostructure by an optical vortex beam can be tuned by varying the topological charge and the laser intensity. For instance, the rotation of the Ag nanowire can be switched from clockwise to counterclockwise by changing \( l \) from +20 to −20 (Figure 4e).\(^{[63]}\)

### 2.3. Movement Control of Nanomotors by Plasmonic Nanostructures

Plasmonic nanocrystals or other optically resonant nanostructures suspended in liquid are promising nanomotors that can be used as sensors for biomedical environment probing,\(^{[55]}\) or external photothermal spots for nanosurgery. However, introducing these foreign particles may increase the complexity and result in unwanted side effects. For example, automation of microfluidic chips requires the manipulation of biological samples, such as large molecules, cells, and viruses. The optically resonant nanomotors can act as handles to help deliver the cells or biomolecules, but they will possibly bring in unexpected pollution to the biological sample. One solution to avoid this disadvantage is to immobilize the optically resonant nanostructures on the substrate. Optical potential energy landscapes with certain properties can be formed by designing the resonant nanostructures, allowing the conversion of optical energy into the mechanical energy of nonresonant small objects (nanomotors).

Immobilized plasmonic nanostructures can work as plasmonic nanotweezers to confine and manipulate small objects because of the strong optical field gradient generated in the surrounding of these nanostructures when they are excited at their resonance wavelengths.\(^{[36,64]}\) In many applications, photothermal effect will influence the trapping stability and has to be taken into account.\(^{[65]}\) For example, Au nanopillars for plasmonic near-field trapping are integrated with a heat sink composed of Au film deposited on Si substrate-supported Cu film (Figure 5a) to achieve a stable trapping and controllable rotation of nanomotors.\(^{[66]}\) Heat dissipates from the nanopillar to the substrate to minimize the solution heating. Under the illumination of a 974 nm linearly polarized laser, the dipolar plasmon resonance of the nanopillar is excited, generating two electromagnetic hot spots at the two top corners that are aligned along the laser polarization direction (Figure 5a, right). The plasmonic hot spots, which have greatly enhanced local electric fields, provide a trapping optical potential to confine dielectric nanoparticles in solution. The trapped polystyrene bead nanomotor therefore can be rotated by rotating the polarization of the incident linearly polarized light (Figure 5b), as confirmed by the measured trajectory of the trapped bead centroid (Figure 5c). Under the illumination intensity of 5 mW \( \mu \text{m}^{-2} \), the trajectory of the trapped nanosphere centroid is a circle with a diameter of around 500 nm, roughly the sum of the nanosphere diameter (200 nm) and the nanopillar diameter (280 nm). In addition, the polystyrene...
bead can also be rotated under circularly polarized illumination. The photon spin angular momentum is transferred to the nanomotor through the plasmonic near-field, leading to the rotation of the trapped particles. The clockwise and anticlockwise rotation of a 340 nm-diameter particle has been achieved by using right- and left-handed circularly polarized illumination (974 nm, 5 mW/μm²), with the rotation frequency at 5.7 and 4.3 Hz, respectively.

The periodic arrangement of various plasmonic nanostructures, including nanoholes, nanoapertures, and nanorod dimer antennas, enables the excitation of a 2D array of electromagnetic field hot spots on the substrate, which helps to achieve the simultaneous trapping of multiple nanoobjects in solution. As a result, many nanomotors can be trapped and rotated on the substrate in parallel, which are superior for the applications of light energy harvesting and parallel sensing.

Moreover, in an array of plasmonic nanostructures, if each plasmonic near-field optical trap is independently controlled, one can turn on and off the traps, and thus rapidly trap and release the nanomotors. As a result, it is possible to translationally transport the nanomotors suspended in solution by sequentially activating the optical traps formed by adjacent plasmonic nanostructures. A nanooptical conveyor belt has been proposed based on this idea. C-shaped nanoapertures on a gold film generate electromagnetic hot spots that can create optical trapping potentials for small particles. The trapping potential is highly dependent on the wavelength and polarization of the incident light. As a result, arrangement of the properly aligned nanoapertures with different sizes (and thus different resonance wavelengths) can be used to transport a trapped polystyrene bead in different manners, with the help of sequentially switching the wavelength and/or polarization of the incident light. The periodically arranged apertures with gradually varying orientations have experimentally demonstrated to transport a 390 nm polystyrene bead by continuously changing the polarization of the incident linearly polarized light. (d,e) Reproduced with permission. Copyright 2014, American Chemical Society. (f) Reproduced with permission. Copyright 2014, American Chemical Society.
polarization of the incident light, proper arrangement of the nanoapertures with different sizes and orientations can be used to achieve the delivery of a trapped polystyrene bead in different manners, by sequentially varying the wavelength and/or polarization of the incident light (Figure 5e,f).[70,71]

The plasmonic tweezers utilizing the enhanced near field can only manipulate nanoparticles in solution that are very close to the plasmonic hot spots because of the fast decay of the local electromagnetic fields. This technique therefore suffers from the limited working area. In addition, the photothermal heating of the plasmonic nanostructure is usually a hindrance to the stable trapping and movement control of the nanomotors driven by plasmonic tweezers.[65]

Despite its negative effects in plasmonic tweezing, the photothermal heating of plasmonic nanostructures can generate thermal gradients, which offer additional opportunities, such as thermophoresis,[72] natural convection,[73] and Marangoni convection, for powering nanomotors. The presence of a thermal gradient will force objects to move along or against the gradient, which is called thermophoresis.[74,75] The photothermal heating of plasmonic nanostructures provides a convenient way to achieve the temporal and spatial control of the environmental temperature, and therefore enables various thermodiffusive movements of different nanomotors. For example, a hexagonal array of triangular Au patches, when illuminated by a 532 nm laser, induces a thermal profile with a low temperature in the hexagon’s center and the highest temperature in the Au area (Figure 6a).[72] The thermal profile has been used to confine and transport Brownian nanomotors and biomolecules.[72,76] The photothermal heating has also been demonstrated to trigger the reversible assembly of metal nanoparticles in aqueous solution.[77] When an Au film is illuminated by a 532 nm laser, the cetyltrimethylammonium chloride (CTAC)-coated Au nanoparticles in solution will be transported by thermophoresis forces from cold to photothermally heated region of the Au film and assemble together (Figure 6b). The assembled colloidal Au nanoparticles will be separated by the electrostatic repulsion when the laser is turned off. It is worth mentioning that thermophoresis can even perform complex and accurate operations on biomolecules, including the migration and extension of DNA molecules through the optical heating of a plasmonic nanopore.[78–80]

In addition to the thermophoresis, optical heating-induced natural convection can also power the movement of nanomotors. For most Newtonian liquids, the density decreases linearly with the increasing temperature. A temperature gradient thus produces a density gradient inside the fluid, resulting in the external buoyancy force that drives the natural convection (Figure 6c).[73] It has been proved by theory that plasmonic heating of individual metal nanostructures generates a low velocity of the natural convection, which is not suitable for microscale mass exchange in microfluidic chips.[73] On the contrary, the collective heating of periodic plasmonic nanostructures induces a much faster natural convection, which can further be accelerated to a flow rate of up to 46 μm s⁻¹ when the optical plasmonic heating is combined with an AC electric field-induced electrothermal effect (Figure 6d).[81] The natural convection drives the nanomotors

![Image](image-url)

**Figure 6.** Movement control of nanomotors by constructing temperature gradient with plasmonic nanostructures. a) Thermophoretic trapping of polystyrene beads. A hexagonal lattice of triangular Au patches is used to produce a temperature distribution (a, top).[72] Brownian polystyrene beads are trapped by the thermophoretic forces. Reproduced with permission.[72] Copyright 2013, American Chemical Society. b) Reversible assembly of plasmonic nanomotors on Au film modulated by thermophoresis.[77] When the Au film is illuminated by a 532 nm laser, the CTAC-coated Au nanotriangles will be transported by thermophoresis forces from cold to photothermally heated region and assemble together. The assembled Au nanotriangles will be separated by the electrostatic repulsion when the laser is turned off. Reproduced with permission.[77] Copyright 2016, American Chemical Society. c) Transport of nanomotors driven by natural convection induced by plasmonic photothermal heating.[73] Reproduced with permission.[73] Copyright 2011, American Chemical Society. (d) Transport of nanomotors driven by plasmonic heating-assisted electrothermal flow.[81] The plasmonic photothermal heating of a Au nanodisk array facilitates the electrothermal flow, enabling the dynamic manipulation of nanomotors. Reproduced with permission.[81] Copyright 2014, American Chemical Society.
to move following the same velocity profiles. It is therefore very powerful in delivering nanomotors over long distances.

2.4. Dielectric Resonant Nanomotors and Movement Control of Nanomotors by Dielectric Resonant Nanostructures

Plasmonic metal nanostructures can greatly enhance the light–matter interaction and are promising for light resonant nanomotors, but they always suffer from strong photothermal heating effect. High-refractive-index dielectric nanostructures support optical resonances as well and have much smaller light energy losses.[34] The dielectric nanoresonators therefore are also good candidates for achieving light-driven nanomotors.

High-refractive-index nanoparticles, such as Si nanorods, have been reported to work as dielectric resonant nanomotors. Like Au nanorods, Si nanorods with small length-to-width aspect ratio can be stably trapped in an optical tweezers with linear laser polarization. A rod-shaped anisotropic Si nanoparticle with its optical resonance at visible wavelength range has been stably trapped in a focused 1064 nm laser beam and aligned along the laser polarization direction (Figure 7a).[82] In addition, when a much longer Si nanowire is trapped by a tightly focused 830 nm linearly polarized laser tweezers, the Si nanowire will perform orbital rotation about the optical trap axis (the z-axis) (Figure 7b).[83] The nanowire rotation is driven by the optical torque arising from the transverse components of the radiation pressure when the nanowire is misaligned from the z-axis because of thermal fluctuations. The magnitude of the optical torque along the z-axis, \( \Gamma_{NC,z} \), and the resulting rotational frequency in the x–y plane, \( \Omega_{xy} \), scale with \( L^{-1} \) and \( L^{-2} \), with \( L \) the nanowire length, respectively (Figure 7c).

Dielectric nanoparticles have several advantages compared with their plasmonic nanocrystal counterparts in serving as rotary nanomotors. They are easier and more stable to be trapped by optical tweezers because they have much weaker photothermal heating effects. The reduced heating effect also enables the trapping of these nanoparticles in vacuum with laser beams of very high power. An up-to-megahertz rotation frequency has thus been achieved for a Si nanorod trapped and levitated in vacuum.[84] The fast rotation of the Si nanorod is driven by the photon angular momentum transfer from the circularly/elliptically polarized trapping light (Figure 7d).

Figure 7. Dielectric resonant nanostructures as rotary motors driven by light. a) Schematic showing that an elongated Si nanoparticle trapped by a linearly polarized laser tweezers (wavelength: 1064 nm) will be aligned along the laser polarization direction.[82] Reproduced with permission.[82] Copyright 2016, American Chemical Society. b,c) Orbital rotation of a Si nanowire trapped in a tightly focused, 830 nm linearly polarized laser tweezers.[83] The nanowire rotational motion is about the optical trap axis (the z-axis) and driven by the optical torque arising from the transverse components of the radiation pressure when the nanowire is misaligned from the z-axis because of thermal fluctuations (b). The magnitude of the optical torque along the z-axis, \( \Gamma_{NC,z} \), and the resulting rotational frequency in the x–y plane, \( \Omega_{xy} \), scale with \( L^{-1} \) and \( L^{-2} \), with \( L \) the nanowire length, respectively (c). Reproduced with permission.[83] Copyright 2016, American Chemical Society. d–g) Si rotary nanomotors in vacuum driven by circularly polarized laser light.[84,85] An individual Si nanorod motor is trapped in vacuum by the standing light wave formed by two counterpropagating 1550 nm laser beams (d). The rotational frequency of the nanomotor is modulated by the e) laser power as well as f) the pressure in the vacuum chamber.[84] Usually the distribution of the rotational frequency is broad because the collision between the nanomotor and the gas molecules pushes the nanomotor to regions of different light intensities. g) The rotation frequency stability can be improved by periodically switching the laser polarization between linear and circular.[85] (d–f) Reproduced with permission.[84] Copyright 2016, American Chemical Society. (g) Reproduced with permission.[85] Copyright 2017, Springer Nature.
frequency highly depends on the laser power and the pressure in the vacuum chamber (Figure 7e,f). Because of the collision with the gas molecules in the vacuum chamber, the Si nanorod motor is pushed to regions of different light intensities in the laser trap from time to time, resulting in a very broad distribution of its rotational frequency. One can improve the rotation frequency stability by periodically switching the laser polarization between linear and circular. With this configuration, researchers have achieved the stable trapping and rotation of a Si nanorod over 4 continuous days with the locked frequency at 1.11 MHz and the full width at half maximum (FWHM) at 1.3 μHz according to the power spectral density measurement (Figure 7g). Such unique advantages of dielectric nanomotors working in vacuum with precise frequency control capability make them a novel sensor for the research related to vacuum dynamics and quantum coherent rotational dynamics.

Patterned dielectric nanostructures that support optical resonances are also available for the precise manipulation of nanomotors. Photonic crystal resonators with periodically arranged nanocavities on a dielectric substrate can confine light strongly in the nanocavity with large near-field electric field enhancement at the resonance wavelength, resulting in an optical potential well for the particle trapping. For example, a polystyrene particle is trapped by a circular defect cavity in a triangular photonic crystal lattice on a silicon membrane (Figure 8a). The polystyrene particles are confined by a self-induced trapping effect when the hollow photonic crystal cavity is resonantly excited by a coupling silicon waveguide nearby. A symmetric optical trapping potential is created, and a 500 nm fluorescent particle has been shown to be resonantly trapped with the waveguide power lower than 120 μW.

By breaking the symmetry of the dielectric nanostructures, an asymmetric optical potential well is produced. The periodic switching of such asymmetric trapping potential allows the long-distance transport of the Brownian nanomotors. Such asymmetric dielectric resonant nanostructures are named as Brownian ratchets. For example, the rectification of the motor Brownian motion along a certain direction is obtained by periodically switching on and off the asymmetric external trapping potential provided by asymmetric triangular nanoholes in a...
photonic crystal slab (Figure 8b).[31] When the laser with a wavelength resonant with the photonic crystal (1550 nm) is on, the particles are confined in the bottom of the asymmetric potential well. The trapped particles could diffuse freely when the trapping potential is turned off, and then have a chance to be captured again by the right neighboring potential well when laser is turned on. The transportation along a certain direction is accordingly realized. Under the modulation frequency at 10 Hz, the average speed of the Brownian particles toward the designed direction reaches 0.93 ± 0.14 μm s⁻¹ in experiments (Figure 8b).[31]

In addition to the modulation of optical trapping potentials constructed by patterned dielectric nanostructures, optical waveguides themselves are also able to achieve long-distance directional delivery of nanomotors. Slot waveguides,[88] micro/nanoscale fibers,[89] and hybrid waveguides[90] have been reported to transport the trapped small objects along the light propagation direction. However, high laser powers are required to generate large enough optical attractive force to confine the objects. For example, over 100 mW of laser power is required to transport dielectric nanomotors by a subwavelength slot waveguide.[88] The requirement of the laser power can be lowered by integrating the waveguide with photonic crystal cavities because the cavities can largely confine the energy of the electromagnetic fields and thus enhance the optical forces. For example, a silicon microring resonator (diameter: 10 μm) coupled with a bus waveguide[91,92] enables an electric field enhancement of 1.5 and is able to stably trap 1.1 μm-diameter polystyrene beads with a guided power as low as 0.67 mW (Figure 9a).[91] Under the guided optical power of 9 mW, the polystyrene particles have been propelled to revolve along the microring with the rotation frequency of 3.4 Hz (corresponding to velocities of 110 μm s⁻¹) (Figure 9b).[91]

3. Conclusions

Nanostructures supporting optical resonances have greatly facilitated the movement control of light-driven nanomotors. One can either simply use these resonant nanostructures as nanomotors or immobilize them on substrates to drive other nanoobjects. The former type of nanomotors has more flexibilities and has been used in many applications, which will be discussed in detail in the following. The latter offers the possibility of all-optical control of biological entities in an optofluidic chip. Plasmonic and dielectric resonant nanostructures can be chosen according to different requirements in the real applications. We have discussed the complexity, efficiency, speed of the movement, advantages, and limitations of the aforementioned nanomotors, as are summarized and compared in Table 1 and 2.

The optically resonant nanomotors, especially plasmonic nanomotors, are designed to yield the translational and rotational movements, which can be further used in performing programmed tasks in biosystems and MEMS. We here highlight some of their applications and discuss possible improvements.

The translational nanomotors, which are composed of plasmonic materials and other biocompatible materials, have demonstrated their capability of active movement and being remotely controlled under light illumination. The translational nanomotors driven by self-thermophoresis do not require any fuels or ultraviolet irradiation. They therefore have the application prospects in biopharmaceutical systems. For example, the Janus mesoporous silica nanoparticles (Figure 1e–h) can serve as efficient carriers for drug delivery with high loading capacity.[45] The Janus nanomotors can be integrated with a variety of biomolecules including DNA, protein, and antibody molecules, showing excellent application prospects in pharmaceuticals.[93] As a substitute for organic tissues, polymers have been widely applied in clinical medicine. The diversity of polymers makes it possible to prepare nanomotors with better biocompatibility. The combination of plasmonic structures and polymer capsules can be applied as photothermal therapy agents. These nanomotors (Figure 2a) have been driven to attach to the cells by the low-power NIR light, and then released at temperatures high enough for protein degradation and cancer cell apoptosis under the illumination of high-power NIR light.[30,47,48] The movement of nanomotors powered by self-thermophoresis mainly relies on the generation of high temperature, which will damage the normal cells around the nanomotors. The controllable injection of nanomotors and reagents into target cells will be a more efficient strategy to avoid the side effect of heating. The nanomotors with the functions of active tracing, membrane perforation and photothermal therapy, are very promising for the application in clinical trials.

The rotary nanomotors driven by light with rotating linear polarization or circular polarization are another important type...
of nanomotors. Their rotational motion, Brownian dynamics, and optical resonance characteristics are strongly associated with the surrounding environment. These nanomotors are therefore prospective sensors with high sensitivity and accuracy to probe the local environmental parameters in the surrounding media, including temperature, viscosity, viscoelasticity, and the surrounding biochemical molecules.\[^8\]\ The attachment of chemical or biological molecules on the nanomotor surface leads to changes in friction and impedes the motor’s movement. The rotation frequency and the fluctuation have been proved to be closely related to the thickness of the adhesive layer, indicating a novel method of measuring the thickness of an adsorbed molecular layer.\[^55\]\ With the help of the photothermal effect, it was also possible to explore and quantify the kinetics and thermodynamics of the release of DNA molecules with high temporal and spatial resolutions.\[^9\]\ Plasmonic nanocrystals have been explored much as rotary nanomotors. In comparison, dielectric rotary nanomotors still require further development. The dielectric nanomotors suffer from much less photothermal heating effect and can be manipulated by lasers with higher power densities. Dielectric nanomotors illuminated by lasers have been shown to achieve a rotation frequency higher than 1 MHz in vacuum. Further experiments are needed to explore the applications of such a fast nanomotor, for example, in

| Nanomotor structure | Driving light source | Driving mechanism | Movement | Speed | Complexity | Disadvantage |
|---------------------|----------------------|------------------|----------|-------|------------|--------------|
| \(\text{Au/TiO}_2\) nanocaps\[^41\] | LCD lamp, 100 mW cm\(^{-2}\) | Plasmonically enhanced catalysis, self-electrophoresis | Enhanced Brownian motion | 1.87 ± 0.5 \(\mu\)m s\(^{-1}\) | Low | Poor directionality |
| Janus silica nanoparticles\[^45\] | NIR laser, 70.3 W cm\(^{-2}\) | Self-thermophoresis | Translational movement | 950 body lengths s\(^{-1}\) | Low | Poor directionality |
| Polymeric tubular rocket\[^48\] | NIR laser, 20 mW \(\mu\)m\(^{-2}\) | Self-thermophoresis | Translational movement | 160 \(\mu\)m s\(^{-1}\) | High | Large size |
| Ag nanowire\[^53\] | 830 nm laser, 100 mW, LP\[^1\] | Aligning by linear polarization | Rotation (spinning) | 0.8 Hz | Low | Low rotation speed |
| Gammadion Au nanostructure\[^18\] | 810 nm laser, 1 mW, LP | Optical torque by phase retardation | Rotation (spinning) | 0.3 Hz | High | Complex fabrication |
| \(\text{400 nm Au sphere}\)^[^54\] | 830 nm laser, 10 mW \(\mu\)m\(^{-2}\), CP\[^1\] | Photon spin angular momentum transfer | Rotation (spinning) | 0.6 kHz | Low | Severe optical heating |
| \(\text{Au nanorod}\)^[^55\] | 830 nm laser, 10 mW \(\mu\)m\(^{-2}\), CP | Photon spin angular momentum transfer | Rotation (spinning) | 42 kHz | Low | Photothermal side effect |
| \(\text{400 nm Au sphere}\)^[^62\] | 830 nm laser, 73 mW, LG\[^1\] | Photon orbital angular momentum transfer | Rotation | 86 Hz | Low | Low speed |
| Si nanorod\[^65\] | 1550 nm laser, 1.35 W, LP/CP | Photon spin angular momentum transfer | Rotation (spinning) | 1.11 MHz (in vacuum) | Low | High laser power needed |

\[^1\]Linearly polarized (LP); \[^2\]Circularly polarized (CP); \[^3\]Laguerre–Gaussian (LG) beam.

Table 2. Comparison of performance of the nanomotors controlled by optically resonant nanostructures.

| Nanomotor/resonant structure | Driving light source | Driving mechanism | Movement | Speed | Complexity | Disadvantage |
|-----------------------------|----------------------|------------------|----------|-------|------------|--------------|
| Polystyrene bead/\(\text{Au nanopillars}\)^[^66\] | 974 nm laser, 5 mW \(\mu\)m\(^{-2}\), CP | Photon spin angular momentum transfer | Rotation | 4.3–5.7 Hz | Low | Limited working region |
| Polystyrene bead/\(\text{C-shaped Au apertures}\)^[^71\] | 1064 nm laser, 3.8 mW \(\mu\)m\(^{-2}\) | Switching optical traps | Directional translation | – | High | Limited working region |
| Polystyrene bead/\(\text{Au disk array}\)^[^81\] | 1064 nm laser, 17 mW, \(\mu\)W | Plasmonic heating, electrothermal flow (external AC source) | Translational movement | 46 \(\mu\)m s\(^{-1}\) | Low | High temperature |
| Polystyrene bead/\(\text{triangular nanoholes}\)^[^31\] | 1550 nm laser, 100 mW, 10 Hz on/off | Rectified Brownian movement | Directional translation | 0.93 ± 0.14 \(\mu\)m s\(^{-1}\) | High | Low precision |
| Polystyrene bead/\(\text{Si ring resonator}\)^[^91\] | 1550 nm laser, 9 mW | Optical trapping potential | Rotation | 3.4 Hz | Low | Individual control |
vacuum dynamics and quantum coherent rotational dynamics.[35] When immersed in liquid, the dielectric nanomotor systems can eliminate the influence of photothermal effect if the light absorption by the liquid is negligible, which is of great importance for the biological applications because it will not cause thermal damage to biological samples.

In conclusion, a lot of research efforts are still required for developing novel light resonant nanomotors and exploring their applications. It is expected that the light resonant nanomotors will be able to provide many new possibilities and boost the application in areas such as clinical medicine, environmental science, and sensor development.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

nanomotors, optical manipulation, optical resonances, surface plasmons, thermophoresis

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