Reconfigurable Size-Sorting of Micronanoparticles in Chalcogenide Waveguide Array

Meng Lian, Libang Mao, Zhe Li, Zeru Liu, Zhongming Wang, and Tun Cao*

Optical tweezers are considered as a revolution, allowing for manipulating particles ranging in scale from a few hundred nanometers (nm) to several micrometers (μm). Near-field optical force allows effective trapping of a broad range of entities, from atom to living cells. Yet, there are formidable challenges for existing on-chip photonic trapping techniques to simultaneously handle at will multiple entities with cross-scales (i.e., from nm to μm). Herein, optical transportation and trapping of polystyrene particles with the different diameters are demonstrated in optofluidic nanophotonic sawtooth waveguide array (ONSWA) made of chalcogenide alloys Sb$_2$Se$_3$. The chalcogenide ONSWA produces sawtooth-like light fields that can be actively modulated via the phase transition of Sb$_2$Se$_3$. Particularly, the chalcogenide ONSWA can stably trap the polystyrene particles with the diameters of 500 nm and 1 μm for both the amorphous and crystalline states, respectively. It is experimentally demonstrated that the phase transition of Sb$_2$Se$_3$ from amorphous to crystalline and vice versa can be achieved in nanoseconds. Using the technique of nanosecond laser-induced phase transition of Sb$_2$Se$_3$, a dynamically reconfigurable size-sorting of objects on the identical ONSWA is proposed.

1. Introduction

Since the experimental demonstration of optical tweezers in 1970s,[1] it has been rapidly developed into noninvasive and versatile tool to manipulate atoms[2] and biomolecules.[3,4] Particularly, the optical trapping is based upon the gradient force whose direction and magnitude are determined by the local field gradient.[5–7] In order to manipulate multiple entities with the different sizes (i.e., viruses and DNAs), the optical tweezers need to be assisted with the other forces.[8] For example, by combining the quasi-Bessel beam with the forces induced by both fluid and photore sist, sub-100 nm particles can be separated.[9] Other schemes, like acoustics[10,11] and microfluidics,[12–14] are also promising for separating biomolecules with diameter of ≈μm.[15] Ultimately, whereas, optical tweezers face two critical challenges: first, the diffraction limits how tightly the beam can be focused hence limiting the trapping strength; second, the short focal depth of trapping area forbids the continuously optical transportation of nanoparticles using free space light.[16,17] As such, the diffraction limit of optical tweezers restrains the manipulated particles’ size to be micrometer. Thus, optical trapping and long-distance transporting of particles with the size ranging from nanometer to micrometer by free-space beam is extremely formidable. To manipulate sub-wavelength particles, optical waveguides (WGs) confining light beam within solid structures have been intensively investigated. Such a light confinement can lead to a self-consistent beam that indefinitely transmits through the WG without loss or varying its form.[18,19] To this end, optical forces produced by the different kinds of dielectric nanostructures like channel WG,[20–22] WG loops,[23] rib WG,[24] and slot WG,[16,17] have attracted intense attentions. These structures produce E-field decaying exponentially within a region above the diffraction limits. They can trap nanometer-sized objects to WG’s surface and transport them by transmission fields. Most WG structures are often designed to manipulate the nanoparticles and employed rarely for microscale objects. In the meantime, the size of fluidic channels cannot diminish from nanoscale biomolecules (i.e., DNA and viruses) to microscale liquid droplets.[25] This issue has been somewhat resolved by manipulating and sorting microsphere that acts as carriers of biomolecules with a quantity of DNAs or proteins attaching on them.[26,27] The new-generation “lab-on-chip” sorting system[28,29] will merge optical manipulation, microfluidic, and some other techniques to obtain size-sorting of micronanoo objects over a single chip. Such a system entails tunable manipulation techniques that can convey and trap different sized particles freely between regimes.

The chalcogenide alloys, pioneered by Ovshinsky,[30] are well known for their successful applications in phase-change memory and rewritable optical discs due to the advantages of rapid switching speed, excellent scalability, high cyclability, and thermal stability.[31,32] In particular, the reversible and prompt phase change of chalcogenide semiconductor between amorphous (AM) and crystalline (CR)[33–35] enables the compounds to be an exceptional ingredient for fast tunable photonic devices.[36,37]
The phase transition significantly changes the permittivity of chalcogenide alloy that, in turn, leads to a massive shift of the working frequency of the devices and hence altering functionalities. Note that, the chalcogenide alloy has proved to be promising and useful for optical WGs,[38,39] fibers,[40] and photonics crystals devices.[42] Our study extends the above knowledge into the area of manipulation of micro–nanoparticles.

In this work, we demonstrate a reconfigurable size-sorting of micro–nanoparticles on the identical optofluidic nanophotonic sawtooth waveguide array (ONSWA) based on Sb2Se3, a family of chalcogenide phase-change materials.[42] Coupled hotspots array can be produced by the beam coupling between the paired WGs. We study theoretically the optical transporting and trapping of polystyrene particles of various sizes varying from nanoscale to microscale. By reversibly switching the structural state of Sb2Se3 between AM and CR, the coupling length between the hotspots can be engineered reconfigurably. This results in on-demand size-selective sieving of the micro–nanoparticles in the hotspots. Just as importantly, a variable angle spectroscopic ellipsometry (VASE) measurement presents that the Sb2Se3 layer has a radical variation of complex refractive index and a very fast phase transition of nanoseconds between AM and CR phases. This makes it possible to manipulate dynamically at will the multiple objects over the cross-scale between nanometer and micrometer. Our study may put one step forward for biomedical application in which an ultrafast and reconfigurable size sieving of micro–nanoobjects is a major concern.

2. Results

2.1. Design of the Sb2Se3 ONSWA

Herein, we demonstrate by using a sawtooth WG array made of Sb2Se3, for the AM state optical gradient force can be exerted to polystyrene nanoparticle with a diameter of 500 nm to stably trap it inside one hotspot. As changing the phase of the Sb2Se3 from as-deposited (AD) AM to CR by heating the WG above the crystallization temperature of Sb2Se3 (Tc = 200 °C) but below its melting temperature (Tm = 610 °C), the gradient force can trap the microparticle with a diameter of 1 μm inside the hotspot. As backward transiting the structural state from CR to melt quenched (MQ) AM by heating the structure above Tm = 610 °C using nanosecond laser pulse excitation,[43,44] followed by a fast cooling, the gradient force can be turned into trapping the nanoparticle again. As shown in Figure 1a, the ONSWA is composed of Sb2Se3 photonic nanowaveguides array embedding into a SiO2 substrate. A microfluidic channel runs over the sawtooth WG conveying the particles to the trap. Thus, the top cladding is defined by the refractive index of water. The gap (G), thickness (T), and width (W) of the paired WG are G = 0.2, T = 0.22, and W = 0.35 μm, respectively. The polystyrene particles are chosen due to their low index contrast relative to water surroundings and low absorption cross sections. Moreover, the polystyrene particles roughly mimic the characteristic of biological and organic materials. The incident light has a power of 20 mW inside the WG and excitation wavelength of λ = 1.55 μm. In Figure 1b, a variable angle spectroscopic ellipsometry (VASE) measurement presents that the Sb2Se3 layer possesses a radical variation of complex refractive index (nse = nse + i × kse) and a very fast phase change time of nanoseconds (ns) between the AM and CR states, where nse and kse represent the real and imaginary components of Nse, respectively. We first sputter a 40 nm-thick Sb2Se3 film onto the substrate by a radio frequency (RF) magnetron sputtering system, where the substrate is a 200 μm-thick Si wafer. Before the deposition, the Si substrate was cleaned ultrasonically in acetone, isopropanol, and deionized water and dried via the dry nitrogen. We then sputter-deposited the 40 nm-thick Sb2Se3 laminate on the Si substrate. Detailed description of the fabrication processing can be found in Methods. The phase changes of amorphization and recrystallization occur at the different temperatures and on the different time scales.[43,44] For examples, we crystallize the AM-Sb2Se3 layer by heating it for 5 min at TC = 200 °C on a hot-plate in a flowing Ar gas. To reversibly change the phase from CR to MQ-AM, we melt the crystal lattice and quench it into the AM state (room temperature) under 102–103 K/sec rate, forbidding the recrystallization of atomic structure.[45] Such a high quench rate can be realized by employing either ultrashort laser or electrical Joule pulses.[46] In Figure 1b, we experimentally demonstrate Nse of the 40 nm-thick bare Sb2Se3 layer for the AD-AM (red line), CR (blue line), MQ-AM (pink line), and recrystallized (R-CR, cyan line) states. The VASE is employed to measure both nse (solid lines) and kse (dashed lines), which are fitted by a Tauc–Lorentz model. The vast alternation in nse between the two structural phases provides the tunable near-infrared (N-IR) resonances. The change in both nse and kse originates from a bonding change between predominantly covalent in the AM structural phase and resonant bonds in the CR structural phase.[47] Moreover in the N-IR spectra, the photon energy is lower than the photonic bandgap of both AM- and CR-Sb2Se3. This offers a very low extinction coefficient (κse) over the spectrum from 1000 to 1600 nm. The variation in nse controls the spectrum of the optical gradient force, and the very low kse contributes to small losses. In our proposed system, light at λ = 1.55 μm is chosen because both the AM- and CR-Sb2Se3 are transparent at that wavelength. The Nse spectra for the CR and R-CR Sb2Se3 films, as well as for the AD-AM and MQ-AM Sb2Se3 film, are nearly same, indicating that the Sb2Se3 layer can be reversible. The nonvolatile characteristic is another advantage of the Sb2Se3 phase change. The structural phases are steady under room temperature, and the thermal energy is needed only for the phase change process, not for upholding a particular state.[48,49] This enables the reconfigurable size sieving of micro–nanoparticles to be interesting from a green technology point of view. As presented in Figure 1c, the coupling length (C1) between the neighboring hotspots, which is associated with the structural state of the Sb2Se3 of the paired sawtooth WGs, is a crucial parameter for the particle manipulation in the ONSWA. The size sieving of the cross-scale particles (from nanoscale to microscale) can be achieved by adjusting the C1 between the hotspots. We employ the nanosphere with the diameter of d nano = 500 nm and the microparticle with the diameter of d micro = 1 μm, for instance. The refractive index of the polystyrene bead is n polystyrene = 1.59. Herein, the parameters of WG were determined to enable the WG to selectively trap the particles with the different sizes by controlling the C1 via phase transition of Sb2Se3.
Simulation is conducted using the finite-difference time-domain (FDTD) method solver within Lumerical Solution. The electric (\(E\)) field distribution in the paired sawtooth WGs is calculated by solving Maxwell’s equations for the WG geometry, including the upper (water) and lower (SiO\(_2\)) cladding areas. The mesh size is set at 3 nm along all Cartesian axes (\(\Delta x = \Delta y = \Delta z = 3\) nm) to diminish the numerical errors. The perfect matched layer (PML) boundary conditions are used along the \(x\), \(y\), and \(z\) axes. The \(E\)-field intensity distribution for the transverse electric (TE) mode that is 10 nm above the top surface is presented at \(\lambda = 1.55\) \(\mu\)m. The region with the maximum \(E\)-field intensity above the WG can form the “hotspot” to trap the particles in the \(x\)–\(y\) plane. For the AM state, the \(C_L\) is around 7 \(\mu\)m as shown in the left column of Figure 1c. In this case, the effect of the hotspots on the nanosphere is not dependent with the lower and upper WGs. The nanoparticle can be trapped stably in the hotspots via the optical gradient force (\(F_g\)). The trapping potential well (\(U\)) exerted to the nanoparticle in the \(x\)–\(y\) plane 10 nm above the top surface of ONSWA possesses a valley-like energy shape, presenting stable trapping (the central column of Figure 1c). However, the diameter of microsphere is close to the center-to-center distance between two WG modes; the microsphere that is momentarily trapped in the lower hotspot is influenced by the upper hotspot, resulting in an unstable trapping condition. It is easy for the microparticle to jump from the WG with weak \(E\)-field to that with strong \(E\)-field. The \(F_g\) from the upper hotspot attracts the microsphere and causes it to rotate by generating a torque \(M_z\). The \(M_z\) can be calculated by integrating...
Minkowski stress tensor \( \mathbf{T} \) on the surface of the microsphere, which is described as \( M_z = \int r \times (\mathbf{T} \cdot \mathbf{n}) \, dS \), where \( r \) represents the position vector of the point on surface \( S \); \( S \) is an arbitrary surface that encloses the sphere and Minkowski stress tensor, respectively.\(^{[50-52]}\) We have shown the detailed analysis in Methods. Due to the slight rotation, the part of the microsphere temporarily trapped in the lower hotspot can shift into the upper hotspot. This causes the microsphere to escape eventually because the stable trapping location is absent in the upper WG. Moreover, the microsphere in the upper WG is drawn to the next paired WGs owing to the narrow pitch of 1 \( \mu \)m between each paired WGs. Thereby, the energy shape of the \( U \) shows that there is no trapping location for the larger microsphere (see the right column of Figure 1c). Namely, although the \( U \) for the microsphere along the \( y \)-axis possesses a valley-like energy shape, the \( U \) along the \( x \)-axis cannot trap the microsphere. Herein, the optical scattering force \( F_s \) dominates the gradient force \( F_g \) and the resultant force can convey the microsphere to the microchannel edge, where the flow stream flushes the microsphere away. Note that the Rayleigh approximation of \( F_s \) was only accurate when the radii of target objects were smaller than 1/10 of the operating wavelength.\(^{[53,54]}\) The radii of our two target spheres are 250 and 500 nm, respectively, which were much larger than the 1/10 of the operating wavelength (\( \lambda = 1550 \) nm). Thus, the \( F_s \) was not theoretically calculated. As switching the structural state from AM to CR, the \( C_1 \) between the adjacent hotspots becomes \( \approx 25 \mu \)m, which is much larger than the diameter of the microsphere (\( d_{\text{micro}} = 1 \mu \)m) as presented in the left column of Figure 1d. The microsphere can be trapped in the hotspots because this particle is only influenced by one hotspot and does not interfere with the coupling hotspot. In this case, the \( U \) acting on the microparticle is above 10kBT in the \( x \)-\( y \) plane and thus stably trapping the microsphere as shown in the right column of Figure 1d. In the meanwhile, the small nanoparticle (\( d_{\text{nano}} = 500 \) nm) runs away from the paired WGs because the \( U \) acting on the particle is lower than 10kBT as presented in the central column of Figure 1d. In summary, when the structural state of Sb\(_2\)Se\(_3\) is AM, the paired WGs can efficiently catch the nanoparticle inside a single hotspot while releasing the microparticle. Yet, this size sieving of the particles is reversed by crystallizing the Sb\(_2\)Se\(_3\) WGs. The bandgaps of Sb\(_2\)Se\(_3\) with the different structural states are almost same around a wavelength of 1.1 \( \mu \)m,\(^{[55]}\) which was shorter compared to \( \lambda = 1.55 \mu \)m. Therefore, the bandgap of the Sb\(_2\)Se\(_3\) may not affect the capturing process.

### 2.2. Optical Force Acting on the Micro–Nanoparticles Above the Sb\(_2\)Se\(_3\) ONSWA

The force exerted to polystyrene particle positioned in time harmonic electromagnetic (EM) fields can be achieved via a linear momentum conservation. This linear momentum can be either field or mechanical momentum. The sum of these two momentums is maintained. By illuminating the particle, we can transfer the momentum from the optical to mechanical, leading to an optical force acting on the particle. Thus, the optical force is associated with the change of mechanical momentum \( (p) \) with time \( (dp/dt) \). The EM-field momentum flux in the linear medium of permeability \( \mu \) and permittivity \( e \) is shown by the time-averaged Maxwell stress tensor \( \left\langle \mathbf{T} \right\rangle \).\(^{[56,57]}\)

\[
\left\langle \mathbf{T} \right\rangle = \frac{1}{2} \sum_i \left[ i \mathbf{E}^* \times \mathbf{H}^* + \mathbf{E} \times \mathbf{H}^* \right] \left( 1 + \mu \right) \mathbf{I}
\]

where \( \left\langle \right\rangle \) is the time-average operation and \( \mathbf{E}, \mathbf{H} \) are the electric and magnetic fields, respectively. Here, \( \mathbf{I} \) is the matrix of identity, and \( \hat{n} \) is the vector perpendicular to the surface and \( s \) is the integration calculated on a closed surface that surrounds the sphere. The EM fields are calculated at the surface of a square box surrounding the polystyrene particle. An optical force map in the \( x \)-\( y \) plane 10 nm above the Sb\(_2\)Se\(_3\) ONSWA is numerically calculated to determine the trapping locations of both nanoparticle and microparticle. In Figure 2a, we demonstrate the 2D force map of \( F_x \) acting on the nanoparticle (\( d_{\text{nano}} = 500 \) nm) above the paired WG with the AM state. The \( F_x \) switches between the repelling and dragging forces in each WG along the light propagation direction. In the figure, the green region and black lines represent the nearly zero \( F_x \) and contour of \( F_x = 0 \), respectively. Figure 2b shows the force map of the force along the \( y \)-direction \( F_y \) composed of the fluidic drag force \( F_y^{\text{drag}} \) and optical force \( F_y^{\text{opt}} \), where the force map of \( F_y^{\text{opt}} \) is presented in Figure S1a, Supporting Information. The drag force can be expressed as\(^{[58]}\)

\[
F_y^{\text{drag}} = 3\pi d \eta v
\]

where \( \eta \) is the viscosity of the buffer, \( v \) the velocity of the flow, and \( d \) the diameter of sphere, respectively. Herein, the trapping positions are close to the WG edge where \( F_x = F_y = 0 \). This is different from the single WG trapping systems in which the particles are trapped at the locations along the central axis of the WG. To stably trap the particles, the restoring optical forces are required on both sides of the trapping position (\( F_x = F_y = 0 \)). The detailed description can be found in Figure S2, Supporting Information. In Figure 2c, the stable trapping positions of \( F_x = 0 \) and \( F_y = 0 \) are demonstrated in red and blue lines, respectively. The black dot at the cross of the red and blue lines is the final trapping place for the nanoparticle (see the central column of Figure 1c). On the contrary, the AM ONSWA cannot offer stable trapping positions for the microsphere. In Figure 2d,e, we numerically demonstrate the 2D force maps of \( F_x \) and \( F_y \) for the microsphere while showing the contours of \( F_x = 0 \) (red lines) and \( F_y = 0 \) (blue lines) in Figure 2f. The \( F_y^{\text{opt}} \) exerted to the microsphere with a diameter of \( d_{\text{micro}} = 1 \mu \)m is shown in Figure S1b, Supporting Information. The \( F_y^{\text{drag}} \) acting on the microsphere is around 0.04 pN when the flow velocity is 5 \( \mu \)m s\(^{-1}\). The smaller flow velocity may reduce the trapping performance due to the less momentum that suppresses the pulling well of the evanescent field.\(^{[59,60]}\) As was observed, the contour of \( F_x = 0 \) does not intersect the contour
of $F_y = 0$. This indicates that the AM ONSWA cannot provide the stable trapping places for the microparticles (see the right column of Figure 1c). As transiting the structural state of Sb$_2$Se$_3$ from AM to CR, in Figure 2g,h we have numerically simulated the 2D force maps of $F_x$ and $F_y$ acting on the microparticle ($d_{\text{micro}} = 1$ μm) that is 10 nm above the Sb$_2$Se$_3$-ONSWA with AM state. Distributions of g) $F_x$, h) $F_y$, and i) the contours of $F_x = 0$ (red lines) and $F_y = 0$ (blue lines) acting on the microparticle ($d_{\text{micro}} = 1$ μm) that is 10 nm above the Sb$_2$Se$_3$-ONSWA with CR state. In Figure S3, Supporting Information, we have investigated the effect of the flow rate on the trapping position of the target particle ($d_{\text{nano}} = 500$ nm) above the ONSWA with AM state. It was shown that the particle was stably trapped at the flow velocity of 5 μm s$^{-1}$ (see Figure S3a, Supporting Information). As increasing the flow velocity to 8 μm s$^{-1}$, the stable trapping position was changed from (−37, 0.3 μm) to (−38, 0.1 μm) (see Figure S3b, Supporting Information). It was because that the higher flow velocity could induce a larger Stokes drag force which counteracted the optical force that, in turn, affected the stable trapping location. However, the stable trapping position was absent when the flow velocity was above 12 μm s$^{-1}$ (see Figure S3c, Supporting Information).
2.3. Optical Force Acting on the Micro–Nanoparticles Above the Sb$_2$Se$_3$-ONSWA

The particle locomotion, random Brownian motion, and optical forces from neighboring potential wells cause the microsphere ($d_{\text{micro}} = 1 \mu m$) to rotate in the Sb$_2$Se$_3$-ONSWA. In Figure 3a, b, we studied the rotation-induced force $F_y$ and $M_z$ by placing microsphere at the central line of the bottom WG ($y = 0$) but at various locations along the x-axis. For $x < 2 \mu m$ and $\theta < 0^\circ$, the $F_y$ is negative because the upper hotspot does not affect the microsphere. Nevertheless, when $x > 2 \mu m$ and $\theta > 0^\circ$, the upper hotspot start affecting the microsphere. Thus, a slight rotation may produce a giant positive force from the upper WG (Figure 3d). For $30^\circ < \theta < 90^\circ$, the microsphere rotates anticlockwise owing to the dragging gradient optical force pulls the microsphere particle and lines up the target particles at the different locations along the upper hotspot to the upper one. Such a rotation releases the microsphere from the AM Sb$_2$Se$_3$-based ONSWA. The simulated a) $F_y$ and b) $M_z$ acting on the microsphere positioned at the central line of the bottom WG but at various locations along the x-axis. c-f) Illustration $M_z$ on the microsphere in the various positions of the hotspot and with the various rotation angles of (c) $-90^\circ < \theta \leq 0^\circ$, (d) $0^\circ < \theta < 30^\circ$, (e) $30^\circ \leq \theta < 90^\circ$, and (f) $\theta = 90^\circ$.

$$dF = \langle T \rangle \cdot \hat{n} \, ds$$

(4)

The $M_z$ can be subsequently derived from the cross product between $dF$ and vector $r$

$$M_z = \int r \times dF$$

(5)

The surface integral of the $dF$ gives rise to a resultant force ($F_{\text{sum}}$) between $F_x$ and $F_y$ on the edge of the microsphere. The $F_{\text{sum}}$ around the border can be mimicked by the force with the identical magnitude at the center of sphere together with the $M_z$. Thereby, the dynamics of the microsphere in the complex light field can be decomposed into a conversion of the center of mass under the $F_{\text{sum}}$ and a self-rotation under the $M_z$. In Figure S4, Supporting Information, we studied the rotation-induced force $F_x$ by placing the microsphere at $x = 0$ while changing the position along the y-axis. It shows that the magnitude of $F_x$ is one order weaker than $F_y$. Thus, the effect of $F_y$ on the microsphere is ignored. In Figure 3c–f, we demonstrate the four typical actions of the microsphere in the twisted light (light coupling between the two neighboring WGs). For $-90^\circ < \theta < 0^\circ$ and $x < 3 \mu m$, the $M_z$ is positive (anticlockwise) because the gradient optical force pulls the microsphere particle and lines up the molecule to the WG (Figure 3c). For $0^\circ < \theta < 30^\circ$ and $x > 3 \mu m$, the microsphere rotates anticlockwise owing to the dragging gradient force from the upper WG (Figure 3d). For $30^\circ \leq \theta < 90^\circ$ and $x > 3 \mu m$, the microsphere rotates clockwise that is obtained by the dragging force of the upper WG (Figure 3e). Finally for $\theta = 90^\circ$, the microsphere can propagate through the gaps between the coupling hotspots, where both the $F_y$ and $M_z$ are weak (Figure 3f). We have explicitly described the simulation of the optical force and torque in Methods. The evanescent $E$-field appeared in the top surface of the paired Sb$_2$Se$_3$ WGs. The target particles at the different locations along the z-axis can be attracted to the surface of the structure by the $F_y$. Thus, the optical forces was only simulated in the x–y plane.

2.4. The Trajectory of Polystyrene Micro–Nanoparticle Above the Sb$_2$Se$_3$-Based ONSWA

Taking into account the arbitrary Brownian motion of micro–nanoparticles in water, the stability of a particle must be studied. The movement of polystyrene particle is modeled by the Langevin Equation

$$\frac{d^2x(t)}{dt^2} = - \frac{\alpha}{m} \frac{dx(t)}{dt} + \frac{\gamma}{m} N_x(t) + \frac{F_x(x,y)}{m}$$

(6)

$$\frac{d^2y(t)}{dt^2} = - \frac{\alpha}{m} \frac{dy(t)}{dt} + \frac{\gamma}{m} N_y(t) + \frac{F_y(x,y)}{m}$$

(7)

where $x(t)$ and $y(t)$ are the positions of the particle, $F_x(x,y)$ and $F_y(x,y)$ are the transverse forces, $N_x(t)$ and $N_y(t)$ are the stochastic

---

**Figure 3.** Dynamics of microsphere ($d_{\text{micro}} = 1 \mu m$) positioned 10 nm above the AM Sb$_2$Se$_3$-based ONSWA. The simulated a) $F_y$ and b) $M_z$ acting on the microsphere positioned at the central line of the bottom WG but at various locations along the x-axis. c-f) Illustration $M_z$ on the microsphere in the various positions of the hotspot and with the various rotation angles of (c) $-90^\circ < \theta \leq 0^\circ$, (d) $0^\circ < \theta < 30^\circ$, (e) $30^\circ \leq \theta < 90^\circ$, and (f) $\theta = 90^\circ$. 

---
Figure 4. Observation of the stability of polystyrene micro- and nanospheres under the sawtooth-like light fields. The white lines present the 100 ms trajectories of the polystyrene spheres of a) $d_{nano} = 500$ nm, b) $d_{micro} = 1$ μm placed 10 nm above the ONSWA for the AM Sb$_2$Se$_3$, as well as c) $d_{nano} = 500$ nm d) $d_{micro} = 1$ μm placed 10 nm above the ONSWA for the CR Sb$_2$Se$_3$. The pink dotted line indicates the initial location of the particle.

noise terms that simulate arbitrary collisions from fluid molecules along both the x- and y-axes, respectively, $m$ is the mass of sphere, $\alpha = 3\eta$ ($d_{sphere}$) is the drag coefficient (from Stoke’s law for a spherical particle), and the viscosity of water is $\eta = 0.89$ mpa s. $d_{sphere}$ is the diameter of polystyrene particle. The scaling constant for the stochastic noise term is given by $y = \frac{2\pi k_B T}{d_{nano}}$, where $T = 300$ K and $k_B$ is Boltzmann’s constant. The simulation algorithm is performed for 10 000 times steps with a time step of 10 μs. To simplify the model, we did not consider the influence of optical force along the z-axis ($F_z$) on the movement of the particle. In Figure 4a,b, we modeled the stabilities of both polystyrene nanosphere ($d_{nano} = 500$ nm) and microsphere ($d_{micro} = 1$ μm), respectively, by observing time sequences of the motions of the spheres that are placed 10 nm above the ONSWA with the AM Sb$_2$Se$_3$. The spheres in the x-y plane are traced with nanometer accuracy. In Figure 4a, a 100 ms trajectory of the nanoparticle above the AM ONSWA is presented by the white solid line. Due to the positions of the hot spots in the ONSWA (see Figure 1c), the gradient force is generated along the +y axis ($F_y > 0$; see Figure 2b) and thus conveys the nanosphere toward the hot spot. The particle is stably trapped at the place of pink circle at the end of 100 ms (Movie S1, Supporting Information). Yet, for the microsphere, as shown in Figure 4b, the optical scattering force is much larger than the gradient force, enabling the microsphere to pass through the surface of the ONSWA (Movie S2, Supporting Information). As transiting the structural state of the Sb$_2$Se$_3$ from AM to CR, the nanoparticle ($d_{nano} = 500$ nm) passed through the top surface of the CR ONSWA (see white solid line). This is because the $U$ exerting to the nanoparticle is smaller than 10$k_B T$, thus cannot stably trap it (Movie S3, Supporting Information). On the contrary, in Figure 4d the ONSWA can trap the microparticle (Movie S4, Supporting Information). Our proposed strategy may also be applicable for other active materials like graphene. 

3. Conclusions

Herein, we have expanded the possibility of using Sb$_2$Se$_3$-based ONSWA to develop an optical sieving technique for multiple particles with a cross-scale ranging from 500 nm to 1 μm. By changing the structural state between AM and CR, our proposed ONSWA can actively modulate the sawtooth-like light fields. For the AM state, the ONSWA can capture the nanoparticle in each single hotspot. However, the microsphere is twisted into the other hotspots owing to the microsphere movement and the Brownian motion-induced rotation, in which the giant optical force and torque are generated to drag the microsphere away from the original hotspot, leading to an escape. For the CR state, the ONSWA can trap the microparticle inside a single hotspot due to the increasing coupling length between the neighboring hotspots. Yet, an unstable trapping of the nanoparticle is induced because the force balance location of nanoparticle inside one hotspot along the x-axis is suppressed by the force along the y-axis from the other coupled hotspot. Note that, our experimental measurement illustrates that the Sb$_2$Se$_3$ planar film is dynamically reconfigurable. This builds up the solid basis for making the ONSWA selectively trap the particles between nanoscale and microscale in 100 ms by transiting the Sb$_2$Se$_3$ phase between AM and CR. Flexible manipulation of the interactions of the coupled hotspots opens the avenue for observing collective phenomena of cross-scale entities and may be harnessed to provide a new twist of multifunctional object manipulation optofluidic chips based upon chalcogenide phase-change material.

Supporting Information

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

Acknowledgements

M.L., L.M., and T.C. contributed equally to this work. T.C. acknowledges support from the National Key Research and Development Program of China (grant nos. 2019YFA0709100 and 2020YFA0714504) and LiaoNing Revitalization Talents Program with grant number (grant no. XLYC1807237).

Conflict of Interest

The authors declare no conflict of interest.
[58] M. J. CASARELLA, P. A. LAURA, J. Hydronautics 1969, 3, 180.
[59] B. S. Schmidt, A. H. Yang, D. Erickson, M. Lipson, Opt. Express 2007, 15, 14322.
[60] S.-K. Hoi, C. Udalagama, C.-H. Sow, F. Watt, A. Bettiol, Appl. Phys. B 2009, 97, 859.
[61] H. Zhao, L. K. Chin, Y. Shi, K. T. Nguyen, P. Y. Liu, Y. Zhang, M. Zhang, J. Zhang, H. Cai, E. P. H. Yap, W. Ser, A.-Q. Liu, Sens. Actuators, B 2020, 306, 127562.
[62] Z. Li, S. Zhang, L. Tong, P. Wang, B. Dong, H. Xu, ACS Nano 2014, 8, 701.
[63] H. Chen, S. Liu, J. Zi, Z. Lin, ACS Nano 2015, 9, 1926.
[64] H. Xu, P. Alvaro, Y. Xiang, T. S. Kelly, Y.-X. Ren, C. Zhang, Z. Chen, Photonics Res. 2019, 7, 28.
[65] P. Hansen, Y. Zheng, J. Ryan, L. Hesselink, Nano Lett. 2014, 14, 2965.
[66] M. Danesh, M. J. Zadeh, T. Zhang, X. Zhang, B. Gu, J. S. Lu, T. Cao, Z. Liu, A. T. Wee, M. J. L. Qiu, Laser Photonics Rev. 2020, 14, 2000030.