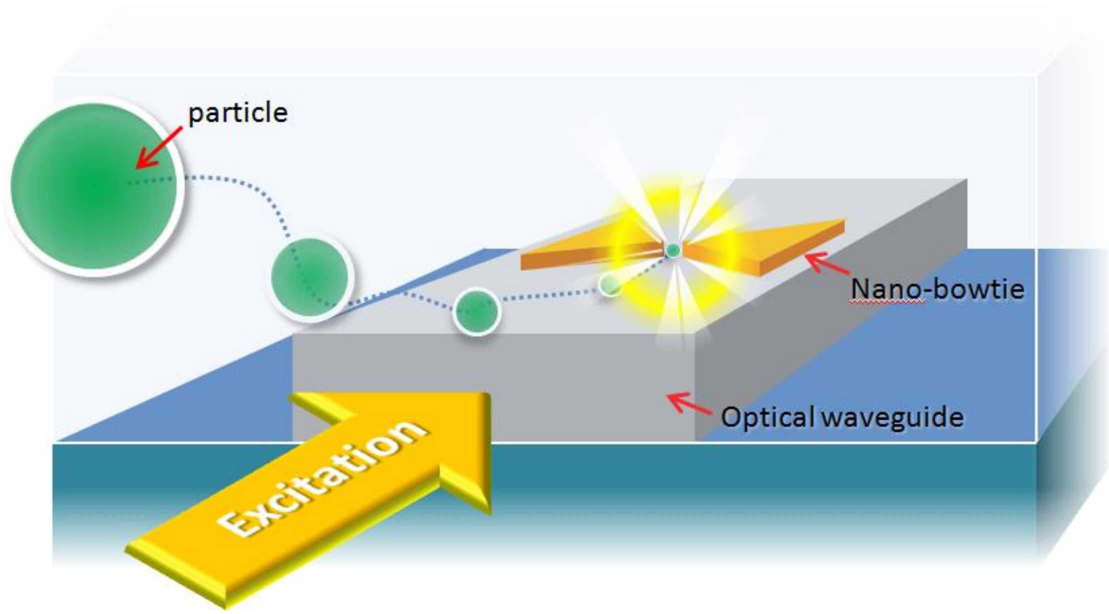

A compact plasmonic tweezers on optical waveguide is proposed and demonstrated with highly enhanced and concentrated field to trap particle precisely with very strong optical forces.

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ARTICLE TYPE

Trapping particle by waveguide-coupled gold bowtie plasmonic tweezers

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We propose and demonstrate a trapping configuration integrating coupling waveguide and gold bowtie structure to form a near-field plasmonic tweezers. Compared with excitation from the top, wave coupled through the waveguide can excite specific bowtie on the waveguide and trap particle precisely. Thus this scheme is more efficient, compact, and will ease the circuit design on a chip. With lightning rod effect and gap effect, the gold bowtie structure can generate highly concentrated resonant field and induce trapping force as strong as 652 pN/W on particle as small as 20 nm in diameter. This trapping capability is investigated numerically and verified experimentally with observation of transport, trapping, and release of particle in the system.

Introduction

Near-field optical tweezers as an important component in lab-on-chip system is more compact and robust comparing to the conventional counterparts based on massive and fragile focusing systems. Once the tweezers can be integrated into a chip, many applications in clinic, daily life, and even military can be realized [1, 2]. Recent development of nanophotonics allows us to tailor the optical modes approaching subwavelength size [3, 4]. The concentrated energy distributed with high gradient will induce strong optical force and lower the power consumption. Therefore particles of nanometer size can be trapped stably and precisely. This tweezing capability is difficult to be achieved by conventional optical tweezers because of the inherent diffraction limit [5]. For further miniaturization of the trapping site, one promising candidate, localized surface plasmon resonance (LSPR) of metallic structure, attracts intensive interests recently. In this scheme, plasmon resonance breaks the diffraction limit because the field is induced by resonance of electric carriers at metal surface instead of propagating electromagnetic waves. Therefore metallic structures, such as nano-rod [6] and nano-ring [7], can generate optical forces to trap particles or molecules down to a few tens of nanometers in size. Furthermore, the overall device footprints of these plasmonic tweezers are much smaller than nanophotonic tweezers consisted of dielectric structures. For example, tens of photonic crystal periods are needed to retain resonant mode for the most prominent nanophotonic design [8].

It had been proposed that metallic nano-bowtie with sharp tips neighboring a central gap possesses lightning rod effect and gap effect to enhance the LSPR around the gap [9]. However the proposed configuration is excited from the top. A more efficient approach would be exciting the LSPR from a coupling optical waveguide [10], which has not been applied to the nano-bowtie structure. And the potential of this system on optical trapping has not been explored. In this report we integrate the metallic nano-bowtie with optical waveguide and further investigate the trapping capability of this compact plasmonic tweezers. Behavior of a particle in this system is illustrated in Fig. 1. When wave is excited into the optical waveguide, the extended evanescent field of the propagation mode will attract particle and transport it forward via the propagating nature. This phenomenon was first demonstrated by Kawata *et al.* [11] and had been thoroughly investigated in the work by Yang *et al.* [12]. The wave also excites LSPR mode of the nano-bowtie. And when the particle reaches vicinity of the resonant mode, the induced optical force will trap it stably unless the excitation is turned off. The trapping force is so strong that Brownian motion of the particle in fluidic surrounding can be ignored and the waveguide can no longer transport the particle. The system with simplicity in configuration and freedom in circuiting will ease the design of lab-on-chip system. Most importantly, the induced strong trapping force can lower the operating power. All of these features make this system very suitable and advantageous for trapping applications.

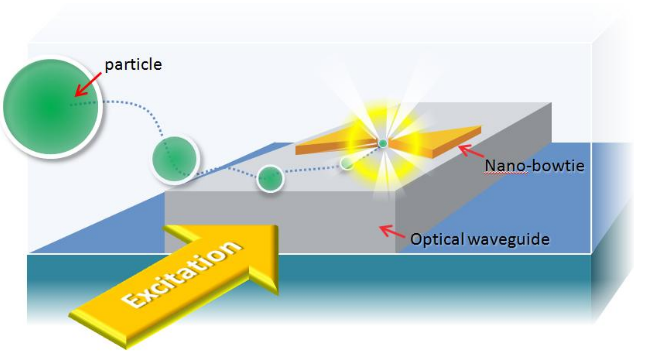

Fig. 1. Behavior illustration of a particle in a waveguide-coupled gold nano-bowtie trapping system.

Model description

The nano-bowtie structure with a small gap in between is made of

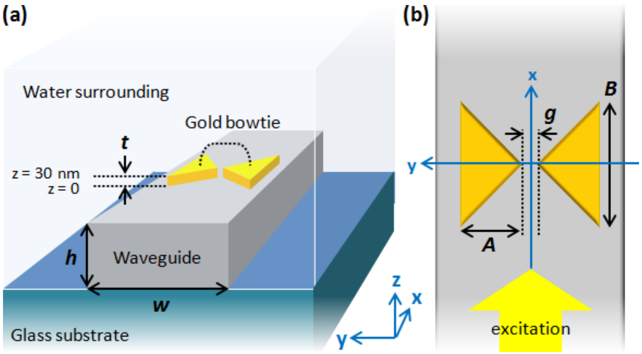

Fig. 2. Schematic illustrations of (a) three-dimensional view and (b) top view of the waveguide-coupled plasmonic tweezing system.

Table 1. Structure dimensions of the bowtie tweezing system.

Thickness (t)	Altitude (A)	Base (B)	WG height (h)	WG width (w)
30 nm	175 nm	350 nm	250 nm	800 nm

gold and illustrated in Fig. 2. The dielectric constant of gold is fitted by the Lorentz-Drude model [13]. The bowtie is on top of a coupling waveguide made of silicon nitride (refractive index n = 2.2) on glass substrate (n = 1.45). In the numerical analysis, the z axis (x = y = 0) is at center of the gap with plane of z = 0 on top surface of the waveguide, as indicated in Fig. 2. Dimensions of the bowtie and waveguide are listed in Table 1. We first investigate the tweezing capability of the bowtie plasmonic tweezers. For suspending particles as in real situation, the system is immersed in water surrounding (n = 1.33). The target particle we use for mimicking biological particles, such as proteins and viruses, is polystyrene sphere (n = 1.59) of 20 nm diameter, which is widely used in simulation works to evaluate the tweezing capability. The propagation of optical wave along the waveguide, coupling into the LSPR mode, and interacting with the particle are calculated using three-dimensional (3D) finite element method (Comsol multiphysics). Then we can obtain optical forces acting on the particle by integrating Maxwell stress tensor on external surface of the particle [12, 14, 15]. More details of the simulation method are provided in the supplementary information.

Trapping characterization

Assume that the target particle is attracted above the gap with a 2 nm separation from the bowtie top surface (centered at coordinate of (0, 0, 42 nm)), we examine spectrum of the vertical trapping force (F_z, optical force component in z direction) acting on the particle. Four different gap sizes (30, 20, 10, and 5 nm) are studied and each bowtie is on an individual waveguide. Fundamental transverse-electric-like (TE-like) waveguide mode (electric field (E) mainly points in y direction) is launched into these waveguides and coupled with the bowtie tweezers. The vertical force spectra for different gap sizes show similar distributions with negative value representing trapping phenomenon toward the gap, as shown in Fig. 3(a). Comparison among these distributions revels that shrinking the gap size will lead to red-shift of the spectral peak with significantly enhanced peak force value. The red-shift phenomenon had been

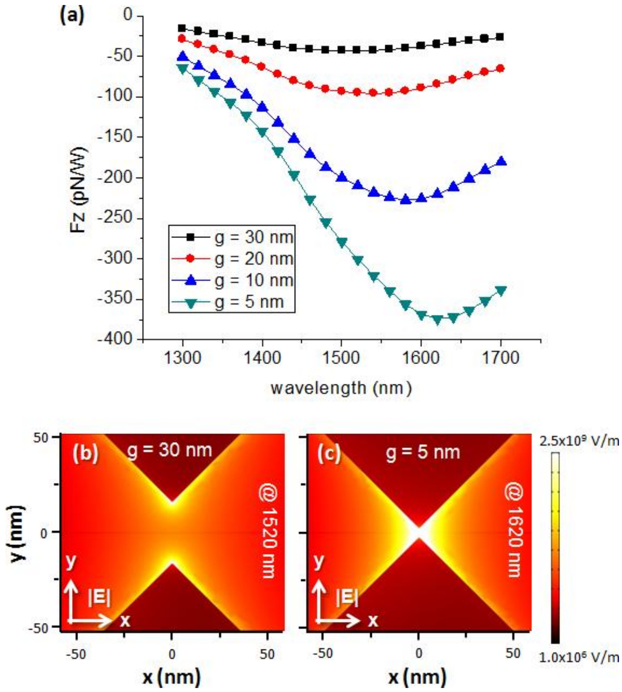

Fig. 3. (a) Spectra of vertical optical force on 20 nm particle trapped by waveguide-coupled gold bowtie with 5, 10, 20, and 30 nm gap sizes. Field distributions of the LSPR modes around the bowtie gaps of (b) 30 nm and (c) 5 nm, respectively, at plane z = 30 nm.

investigated and attributed to lowering electrostatic energy of the mode [16]. And the force enhancement is resulted from the better electric coupling across the gap, which can be verified by comparing LSPR field distributions of the bowtie tweezers with 30 nm and 5 nm gap sizes, as shown in Figs. 3(b) and (c), respectively. At centre of the 5 nm gap, the electric field can be enhanced to 2.50×10^9 V/m. However it is only 4.06×10^7 V/m on a bare waveguide. More details of comparison between the LSPR modes corresponding to bowties with 30 nm and 5 nm gap sizes are provided in the supplementary information. At this position the strongest vertical trapping force induced by the bowtie tweezers of 5 nm gap size is 374 pN/W, which is large compared to most results reported in prior works utilizing nanophotonic tweezers with particles of similar index and size [3, 4, 8, 17]. Therefore, the waveguide-coupled gold nano-bowtie tweezers can be an efficient trapping system. Besides, the device is very compact with length of only 350 nm in longitudinal direction.

Subsequently, we focus on the bowtie tweezers of 5 nm gap size while the excitation wavelength is fixed at 1620 nm. Assuming the particle is originally far away and is attracted toward the gap along the z axis (x = y = 0), the evolution of F_z as a function of z position is shown in Fig. 4(a). The exponential distribution reveals that the trapping force will become much stronger when the particle gets closer to the gap and overlaps more with the LSPR field. The force value will far exceed 374 pN/W when separation between the particle and the bowtie top surface is less than 2 nm.

Except being trapped at the top, the particle is more likely to be trapped at sides of the bowtie because of the notch shape. Compared to the slot structure in one-dimensional photonic crystal cavity [3], the notch region of bowtie is more accessible

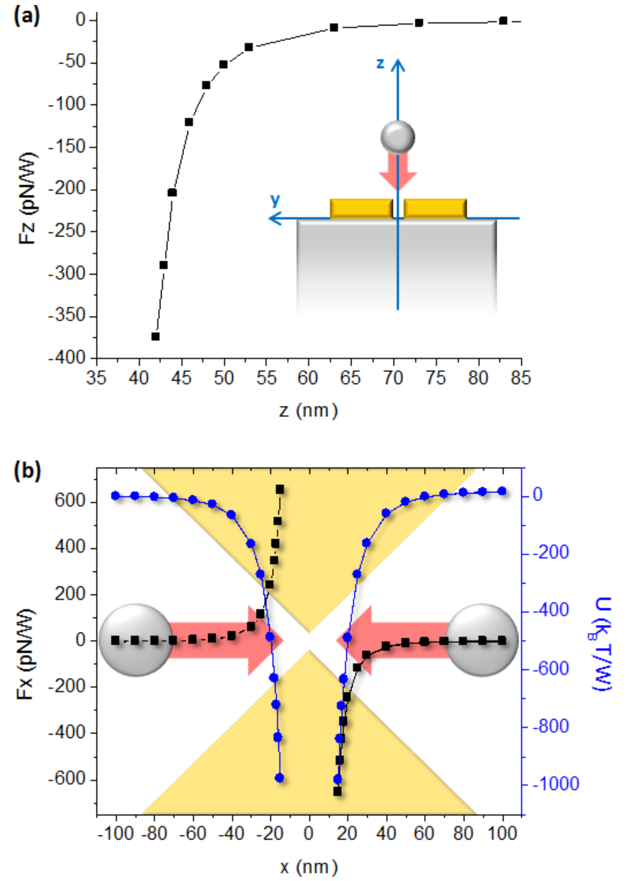

Fig. 4. (a) Evolution of vertical trapping force F_z on the particle of 20 nm diameter as a function of z position when x = y = 0. The inset illustrates the movement of particle as a result of F_z. (b) Evolution of longitudinal trapping force F_x on the particle of 20 nm diameter as a function of x position when y = 0 and z = 15 nm. The inset illustrates the movement of particle as a result of F_x.

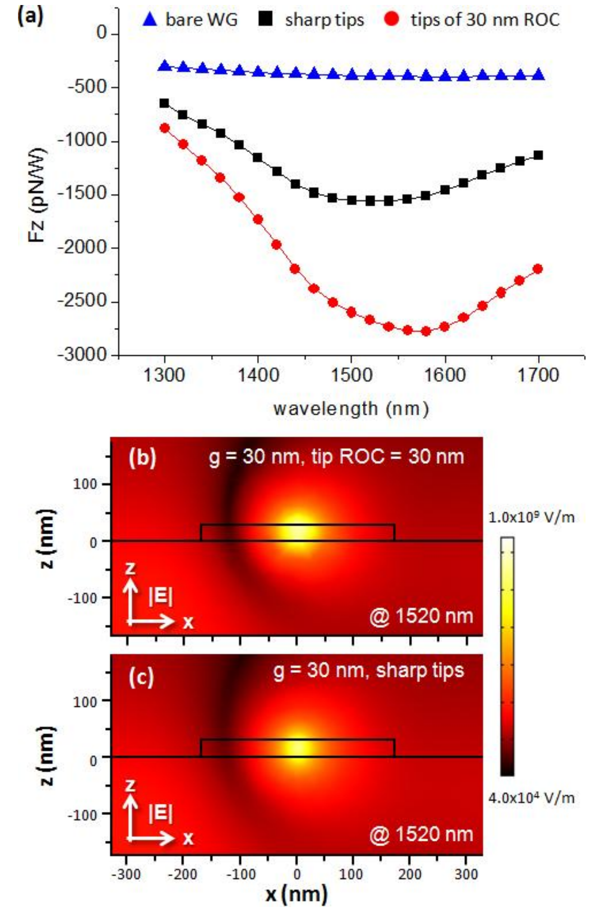

Fig. 5. (a) Spectra of vertical optical force on 1 µm particle trapped by a bare waveguide and the waveguide-coupled gold bowtie tweezers with 30 nm gap and either sharp tips or tips of 30 nm ROC. Field distributions of the LSPR modes for the 30 nm gap bowtie with (b) tips of 30 nm ROC and (c) sharp tips, respectively, at the plane of $y = 0$.

for trapping and the particle size is not limited. Assuming the particle is attracted from either side of the bowtie tweezers (along the path in x direction with $y = 0$ and $z = 15$ nm), the longitudinal optical force (F_x) experienced by the particle distributes as restoring force in a spring system, as shown in Fig. 4(b). When the particle is at negative x side of the bowtie, F_x is positive. And when it is at positive x side of the bowtie, F_x is negative even the guided wave along the waveguide naturally pushes the particle forward. Finally it will be trapped at either side of the bowtie tweezers. In our simulation the strongest retainable F_x is 652 pN/W (limited by mesh production). Again, the exponential distribution reveals that the force can be much stronger when the particle can approach closer to the LSPR field around the gap. For comparison, the propulsion force provided by the guided wave along the waveguide is only 0.0052 pN/W. Thus, we can claim that stopping of particle around the bowtie must be a result of plasmonic trapping. By integrating the trapping force along the path, we can obtain the potential (U) experienced by the particle. In simulation, a widely used criterion for stable trapping requires that the depth of potential must be larger than $10k_BT$ for suppressing Brownian motion caused by thermal perturbation [3, 18, 19], where k_B is the Boltzmann constant and T is the environmental temperature in unit of K. In a trapping system, the lowest power sufficient for generating $10k_BT$ potential depth is defined as the threshold power. Here we set T as 300K at room temperature. Assume that 1 W power is launched into the waveguide, the resulting potential depth of $979k_BT$ is about two orders deeper than the requirement. Based on the criterion, a threshold power as low as 10.2 mW is sufficient to produce $10k_BT$ potential depth for stable trapping of the particle as small as 20 nm in diameter. The threshold power can be even lower for trapping larger particles because the induced optical force will be stronger [4, 19, 20]. At this low power level, thermal problem is insignificant and will not disturb trapping phenomenon. From the potential distribution, it is also obvious that trapping particle by the bowtie tweezers is very precise within only a few tens of nanometers in the vicinity of the bowtie gap. On the other hand, position of particle in the trap has some uncertainty with multiple trapping sites for many other trapping schemes [19, 21].

From the above investigations, we show that waveguide-coupled bowtie tweezers with small gap is indeed an efficient trapping configuration. Since a 5 nm gap with sharp neighbouring tips is difficult to be realized in experiment even using expensive and sophisticated facilities (*ex.* focused ion beam milling) [22], a wider gap with round tips is more practical and easier to be fabricated. To support the experimental results, we investigate the waveguide-coupled bowtie tweezers with 30 nm gap size and either sharp tips or round tips of 30 nm radius of curvature (ROC).

Besides, particle of 20 nm in diameter is too small to be observed even by microscope of high magnification owing to the diffraction limit. For easy observation and demonstration in experiment, particles of 1 μm in diameter are used. Black curve in Fig. 5(a) shows the simulated spectrum of vertical trapping force experienced by a 1 μm particle when it is above the gap of sharp tips and separated from the bowtie top surface by 5 nm. Since larger particle experiences stronger optical force, the vertical trapping force on the 1 μm particle is much stronger than those in the previous cases even the bowtie gap used here is larger. The peak value of vertical trapping force in this case is 1560 pN/W. Moreover, when the tips become round, the trapping force can be further enhanced to a peak value of 2776 pN/W, shown as the red curve in Fig. 5(a), 1.8 times stronger than that in the case for sharp tips. This enhancement can be understood firstly from the better coupling of waveguide mode into the LSPR mode which is more extended in the case of round tips comparing to that in the counterpart of sharp tips, as shown in Figs. 5(b) and (c). Second, the extension of mode distribution results in better overlap between the particle and the resonant mode, which in turn increases the trapping force. Thus a better performance can be provided by a more practical structure including fabrication consideration. On the other hand, the peak value of trapping force induced by a bare waveguide (without bowtie) only reaches 396 pN/W when the 1 μm particle is separated from the waveguide surface by 5 nm, shown as the blue curve in Fig. 5(a). This comparison again shows the merit provided by the integrated bowtie structure. Therefore, the threshold power for stable trapping can be reduced significantly.

Fabrication

In fabrication, a 250 nm-thick silicon nitride layer on glass substrate is prepared. The bowtie structure is defined on a polymethylmethacrylate (PMMA) layer using electron beam lithography (EBL). Gold of 30 nm thickness is deposited by thermal evaporator and then stripped off by lift-off process, leaving gold in bowtie shape on the sample to form the tweezers. Subsequently, EBL is used again to define the coupling waveguide. Then reactive ion etching (RIE) is utilized to form the silicon nitride waveguide. Scanning electron microscopic (SEM) images of the fabricated structure are shown in Figs. 6(a) and (b). A gold bowtie of 30 nm gap size is located not at the center but on the upper side of the coupling waveguide. This can help prove the trapping phenomenon, as discussed in the following.

Measurement

For coupling light into the waveguide, the sample is cut and polished until entrance of the waveguide appears at the sample edge. Then we mount the sample in a fluid chamber and probe it by a tapered lens fiber as illustrated in Fig. 6(c). The chamber must be thin for preventing thermal convection flow. We use fiber sections of 250 μm diameter as the spacer between glass substrate and the covering glass to form the chamber. Capillary effect will keep fluid in the chamber automatically. The whole system is observed through a 20X objective lens. As mentioned, the particles we use for observation are 1 μm in diameter. They are dispersed in aqueous solution with 0.05% wt/vol

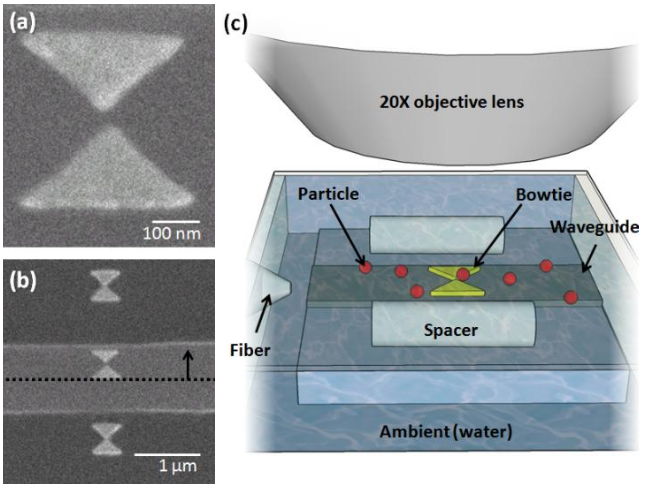

Fig. 6. (a) and (b) are SEM images of the fabricated gold bowtie tweezers on coupling waveguide. (c) Schematic illustration of the measurement setup. The relative sizes are adapted for better understanding.

concentration containing 1% surfactant to prevent aggregation.

In the beginning, particles all move randomly in Brownian motion. When laser at wavelength of 1500 nm is coupled into the waveguide through the probing fibre, motion of particles around the sample starts to be influenced. There is an overall rightward motion which is caused by the inevitable scattering of laser wave from the coupling interface (see ESI†). However the particles away from the excited waveguide still move leftward in some instant owing to the effect of Brownian motion. Once a particle is attracted on the excited waveguide, the optical force induced by the guided wave will hold it and transport it along the waveguide. As shown in Fig. 7, at time (*t*) of 20 sec, a particle transported by the guided wave comes into the scope of observation. The existence of particle can be clearly seen as a dark spot on the waveguide. It is transported forward progressively. Only this particle stably moves without leftward motion. This is evidence that the additional optical force induced by the guided wave is significant, which can suppress the Brownian motion and transport the particle along the waveguide. Then after t = 80 sec, the particle is completely stopped right at the point where the bowtie tweezers is located. As shown in the supporting video, transport of the particle is not smooth and stops occasionally. This is due to fabrication imperfections that scatter the guided wave and disturb the propagation. However, the stopping phenomenon at the bowtie is very obvious and the motion of the particle is suddenly suppressed. At the same time, other particles away from the bowtie still move around under effects of Brownian perturbation and the scattered waves. This stopping phenomenon at the bowtie sustains until the laser source is turned off at t = 140 sec. After then, the particle drifts away very quickly in the way of Brownian motion, which manifests the fact that stopping is a result of trapping caused by the waveguide-coupled LSPR mode. It is worthy to note that when being transported, the particle is always on the center of waveguide and appears as a solid spot. But when it is about to stop, it moves to the upper side of the waveguide and appears as a half spot. This observation further proves that the particle is indeed trapped by the bowtie since the fabricated bowtie is actually located on the upper side of the waveguide, as indicated in Fig. 6(b). Therefore, we

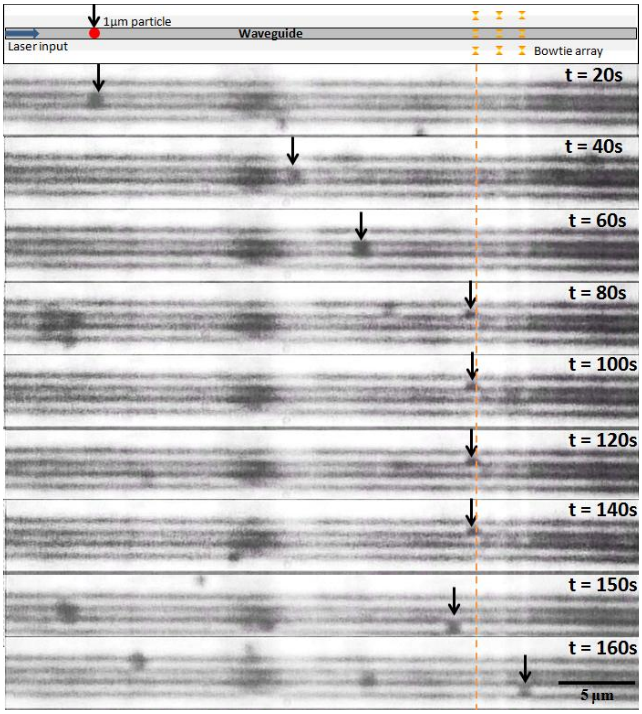

Fig. 7. Captured movement of particles as time evolves. Orange dash line indicates location of the gold bowtie.

successfully demonstrate waveguide-coupled gold bowtie plasmonic tweezers with compact device footprint, and observe particle transport by the waveguide and precise and stable trapping by the bowtie structure experimentally.

Conclusions

In conclusion, we propose a waveguide-coupled bowtie plasmonic tweezers, in which the LSPR mode of gold bowtie structure is utilized with strong field enhancement around the gap. For polystyrene particle as small as 20 nm in diameter, the simulated maximum vertical and longitudinal trapping forces induced by the LSPR mode with gap size of 5 nm are 374 and 652 pN/W, respectively. Compared with most nanophotonic tweezers, this plasmonic trapping is much stronger and more precise. More importantly, the device is very compact, with only 350 nm in length. The trapping capability of the waveguide-coupled gold bowtie with a feasible gap size of 30 nm and round tips of 30 nm ROC is also investigated. For 1 μm polystyrene particle, the trapping is demonstrated both in simulation and experiment. The results show clear and undoubted stopping phenomenon of the particle stably trapped by the gold bowtie structure, which is further verified by precise trapping of the particle on the upper side of the waveguide. We believe such a compact, efficient and simple tweezing configuration will be an important building block for lab-on-chip development.

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