PLASMONIC-ENHANCED FLOATING ELECTRODE OPTOELECTRONIC TWEEZERS (FEOET) FOR EFFECTIVE OPTICAL DROPLET MANIPULATION

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ABSTRACT

A plasmonic-enhanced floating electrode optoelectronic tweezers (FEOET) device is presented for effective optical droplet manipulation. Due to the importance of having a high-quality photoconductive layer, conventional FEOET devices face the issue between ineffective DEP performance and cost-ineffective fabrication. In this study, the use of metallic nanoparticles enables plasmonic light scattering to significantly enhance light absorption onto a photoconductive layer of the device, resulting in a largely improved dielectrophoretic (DEP) performance. Two numerical simulation studies have demonstrated the working principle of plasmonic-enhanced DEP and were further validated experimentally by an improved spectrophotometric light absorbance of the TiOPc layer, as well as demonstrating an 11-fold increase in light-actuated droplet speed. With much-improved DEP performance, this plasmonic-enhanced FEOET technology can provide a low-cost solution for various digital microfluidic (DMF) applications with the benefits of device simplicity.

KEYWORDS

Dielectrophoresis (DEP), optical droplet manipulation, floating electrode optoelectronic tweezers

INTRODUCTION

Optoelectronic tweezers (OET) have been developed as a powerful tool for light-driven dielectrophoretic (DEP) manipulation of microscopic particles [1]. Upon the light illumination onto a photoconductive layer, the rays are absorbed to generate electron-hole pairs and increase its photo-state conductivity. Consequently, the electric impedance was locally modified to create the non-uniformity of the electric field necessary for DEP manipulation. However, due to impedance matching issue, it was difficult to modulate the electric field in an electrically insulating medium such as oil commonly used for two-phase droplet-based microfluidic systems. To overcome this issue, Park *et al.* have presented a floating electrode optoelectronic tweezers (FEOET) mechanism for optical DEP manipulation of oil-immersed aqueous droplets [2]. Using FEOET, various droplet-based microfluidic functions (*e.g.* droplet transportation, merging, mixing, and parallel processing) have been demonstrated with the benefits of device simplicity [3].

For previous FEOET studies [2, 3], the rays passing through a photoconductive layer do not contribute to its photo-state conductivity. Due to this limited performance in photoconductivity, previous FEOET devices critically require high-quality photoconductive materials such as amorphous silicon (a-Si). However, it requires complex and expensive facilities such as CVD and PECVD for its thin-film layer fabrication, resulting in cost-ineffective devices. Alternatively, a polymer-based photoconductive material, titanium oxide phthalocyanine (TiOPc), has been experimentally used because it can be simply fabricated via a low-cost spin-coating method without the need of CVD and PECVD [4]. The main drawback of the TiOPc is, however, its photoconductivity much poorer than that of the a-Si by a few orders, resulting in a weak DEP force.

The study herein presents the plasmonic field enhancement to enlarge light absorption of the poor-quality TiOPc, leading to a strong DEP force for effective optical droplet manipulation. By using metallic nanoparticles as scattering elements on top of the TiOPc layer, the rays passing through the TiOPc undergo light scattering with an increased optical path length over a wide angular spread. As a result, more rays are re-directed onto the TiOPc and dramatically increase its light absorption and photoconductivity, resulting in a much stronger DEP force for effective optical droplet actuation. Two simulation studies have been implemented to demonstrate a working principle of the plasmonic-enhanced DEP on FEOET devices. A spectrophotometric measurement study experimentally determined a largely enhanced light absorption onto a TiOPc layer, while another experimental study on light-actuated droplet dynamics presented a maximum instantaneous droplet speed as fast as 1.69 mm/s (an 11-fold improvement) by using plasmonic nanoparticles. The use of metallic nanoparticles for plasmonic light scattering to enhance optical DEP performance can offer device effectiveness for a wide range of digital microfluidic (DMF) applications.

DEVICE FABRICATION AND ITS WORKING PRINCIPLE

Fig. 1 shows a schematic of the FEOET device that enables plasmonic-enhanced DEP performance for effective optical droplet manipulation. The device is first fabricated by patterning indium tin oxide (ITO) electrodes at both edges of a glass substrate with a 20 mm gap. To provide a photoconductive property, a solution of titanium oxide phthalocyanine (TiOPc) was firstly prepared by dissolving TiOPc powder in a chlorobenzene solvent (1.0 wt%) at 80 ºC for 2 hours. The TiOPc solution was drop-casted and cured at room temperature for another 2 hours to obtain an 8 μm thick TiOPc layer on top of the ITO electrodes. Then, another 2 wt% solution of aluminum (Al) nanoparticles sizing ∼50 nm was subsequently spun-

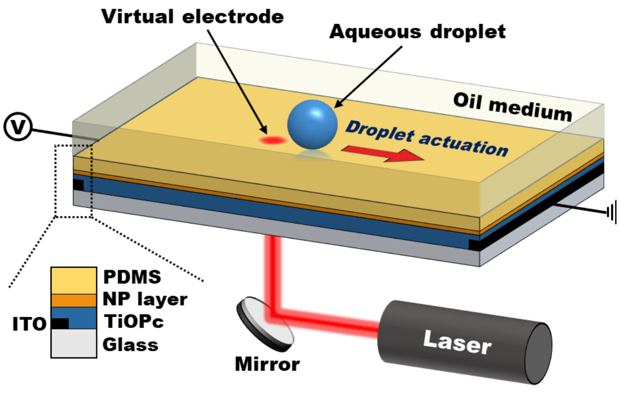

Figure 1: A schematic of the plasmonic-enhanced FEOET device.

coated, and the nanoparticles were randomly dispersed on top of the TiOPc layer with the 2-µm layer thickness. An open polydimethylsiloxane (PDMS) chamber in 12.5-µm thickness is placed on top of the nanoparticle layer to house oil-immersed aqueous droplets.

When a dc bias voltage is applied between two ITO electrodes placed at the edges of the device, a uniform electric field is created in a lateral direction. At the absence of light illumination, the originally created uniform field distribution remains without any disturbance (i.e. no DEP force is induced). When a light beam illuminates onto the photoconductive layer, photogenerated electron-hole pairs are created and locally modify its photoconductivity. Thus, the uniform electric field is strongly perturbed near the illuminated area and penetrates to the oil layer, which creates non-uniformity of the electric field necessary for DEP manipulation in the electrically insulating oil. To achieve optical droplet actuation, a light beam illuminates nearby the droplet and the field non-uniformity strongly disrupts the original field pattern around the droplet. This results in a net positive DEP force to drive it away from the light pattern towards the strong electric field region. 3D simulation studies will be discussed later to verify the working principle of the light-induced DEP in Fig. 3(a).

Although a thin layer of the TiOPc can be simply fabricated via a low-cost, drop-casting method, its photoconductive performance is very limited (a few orders lower than semiconductors such as the a-Si), resulting in a weak DEP force. To further enhance light-induced DEP performance even with the poor-quality TiOPc, this study proposes the plasmonic effect for effective optical droplet actuation. By using a layer of metallic nanoparticles as scattering elements on the surface of the TiOPc layer, incident light rays undergo plasmonic light scattering to increase their effective optical path length over an angular spread. Thus, more light rays are re-directed onto the TiOPc layer and contribute to increasing light absorption. This improved photoconductive performance can create a much larger non-uniformity in the field pattern near the droplet, resulting in a stronger DEP force for effective optical droplet actuation.

NUMERICAL SIMULATIONS

Three-dimensional (3D) numerical simulations using finite-element software (COMSOL Multiphysics 5.5) were conducted to verify plasmonic-enhanced DEP performance. The first study on plasmonic light scattering of nanoparticles helps understand the effect of nanoparticles on improving light absorption onto the photoconductive layer. Another simulation on electric field distribution qualitatively demonstrates enhanced DEP performance for effective droplet manipulation.

Plasmonic Light Scattering

For the simulation study on plasmonic light scattering, a single metal nanoparticle (50 nm in diameter) was first modelled with a circular light beam illuminated from the bottom. Fig. 2(a) shows a cross-sectional view of the input rays (indicated as blue) and the rays scattered out from the nanoparticle (red). This study illustrates how incoming light rays are scattered by the nanoparticle with an increased optical path length over a wide angular spread. Next, to demonstrate plasmonic light scattering by arrays of the nanoparticles, 3 layers of the nanoparticles (50 nm in diameter) were modelled with 20 nm apart from each other laterally and a vertical height of 25 nm between the layers. Fig. 2(b) shows a side view of 20,000 input rays (blue) illuminated from the bottom. With 3 layers of the arrayed nanoparticles, 72.69% of the input rays are scattered out from the arrayed nanoparticles with an increased optical path length over a wide angular spread (red). Rest of the rays are emerging from the top layer as transmitted rays. It is importantly noted that the more numbers of layers and the denser layer, the more scattered rays. This simulation study has clearly shown that the use of nanoparticles can contribute to more light rays being scattered back onto the

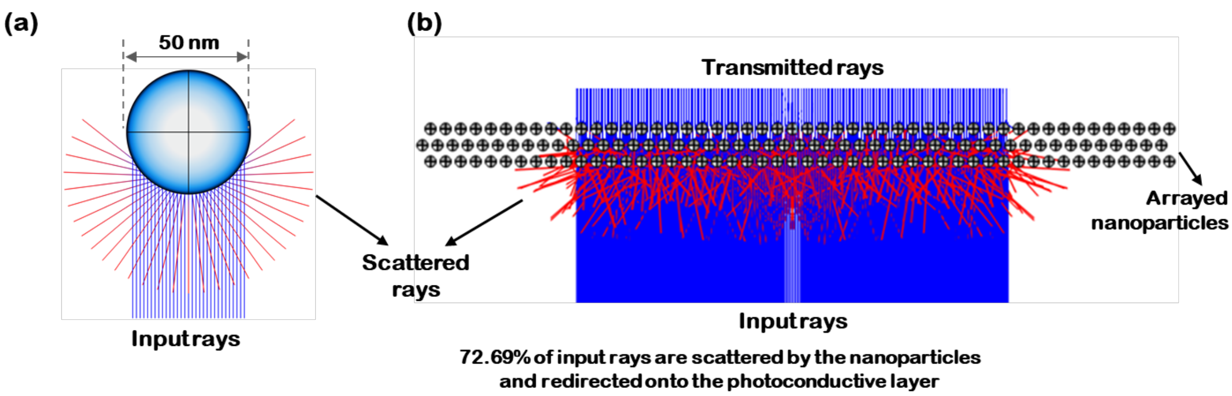

Figure 2: Plasmonic light scattering simulations by (a) a single spherical nanoparticle and (b) 3 layers of uniformly distributed nanoparticle arrays.

photoconductive layer beneath to enlarge its light absorption, which resulted in an enhanced DEP performance of the FEOET device.

Electric Field Distribution

For the simulation study on electric field distribution, the device was simply modelled to the following layers for concept understanding and reduce computational time: A 8.0 µm thick photoconductive layer was constructed as the bottom layer. Its conductivities were assumed as $\sigma_{photo} = 2 \times 10^{-8}$ S/m at photo state and $\sigma_{dark} = 1 \times 10^{-8}$ S/m at dark state, where the conductivity ratio is only 2-fold (*i.e.* $b = \sigma_{photo} / \sigma_{dark} = 2$) to represent a low-quality photoconductive property of the TiOPc. Next, 3 layers of uniformly distributed spherical nanoparticle arrays (50 nm in diameter, 20 nm away from each other) were modelled above the photoconductive layer, and finally covered with a 12.5 µm thick dielectric layer and a 500 µm oil medium. A 100 V dc bias voltage is then applied across both ends of the device with a 1.0 mm gap to creates a lateral electric field. A circular light beam (200 µm in diameter) illuminates in the middle of the FEOET device.

Fig. 3(a) and (b) show the cross-sectional view of the electric field distribution along a lateral direction for the devices without and with the layers of nanoparticle arrays, respectively. As discussed in the previous section, the illumination of a light beam onto the photoconductive layer creates photogenerated electron-hole pairs and increases the photoconductivity only at the illuminated area. As a result, two strong electric field regions are created near the two edges of the illuminated area parallel to the field direction and a weak field region in the middle of the illuminated area. This electric field distribution is similarly observed in both Fig. 3(a) and (b). However, a stronger electric field gradient can be seen with the use of the nanoparticle arrays (see Fig. 3b). To demonstrate the enhancement in field gradient near the edge of a circular light beam due to plasmonic light scattering of the nanoparticles, the field strengths are extracted right above the dielectric layer of Fig. 3(a) and (b) and plotted in Fig. 3(c). By referring to Fig. 3(c), without the presence of nanoparticles, the field gradient near the edges of the circular light beam is seen to be small (see a red curve). However, with the presence of plasmonic nanoparticles in the device, a much stronger field gradient can be observed at the edges of the light beam (see a blue curve). Consequently, such an enhanced field gradient strongly perturbs the originally balanced electric field pattern around the droplet, resulting in a much-improved DEP force for effective optical droplet manipulation.

EXPERIMENTAL RESULTS

Two experimental studies were conducted to validate the simulation results discussed in the previous section.

Light absorbance study

Firstly, a spectrophotometer was used to measure the absorption spectrum of a 1.0 µm thick pure TiOPc layer (*i.e.* without nanoparticles). The measurement was repeated with another TiOPc sample coated with an additional 2.0 µm thick layer of Al nanoparticles. The absorption spectra of both samples were plotted in Fig. 4, where light absorption is significantly enlarged with the TiOPc sample coated with the nanoparticles. This enhanced light absorbance can be attributed to the plasmonic light scattering by the nanoparticles, which increased their optical path length within the TiOPc layer.

Droplet dynamics study

Next, we demonstrated the enhancement of DEP performance with the use of plasmonic light scattering of nanoparticles by investigating droplet dynamics during a light-driven droplet actuation. For this study, a 1.5 µL de-ionized water droplet was placed on the surface of the FEOET device, which is filled with mineral oil. To actuate the water droplet, an electric field of 150 V/mm is applied across the device, while a laser beam (4 mW, 635 nm) with a 0.9 mm output spot size was directed onto the device at a position adjacent to the droplet. A high-speed camera (Fastcam Mini AX200, Photron, Japan) was used to capture the droplet's movement after being repelled by the laser beam, with its instantaneous actuation speed being calculated at various positions. Then, the study was repeated on a FEOET device without the presence of nanoparticles with the same applied lateral electric field. The droplet dynamics study in Fig. 5 presents the

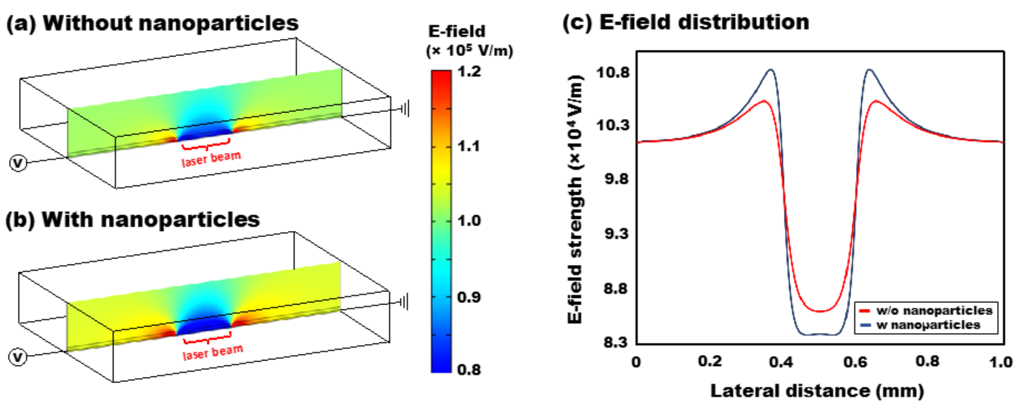

Figure 3: Simulations showing electric field (e-field) distributions along a device. Cross-sectional views of the e-field distribution along the lateral direction when a 200 µm circular light beam illuminates in the middle of the device (a) without and (b) with nanoparticles. (c) E-field strengths along the surface of the dielectric layer extracted from each device in (a) and (b). The e-field strength generated at the edges of the light beam can be observed to be stronger in the device with nanoparticles, demonstrating plasmonic-enhanced DEP performance for effective optical droplet manipulation.

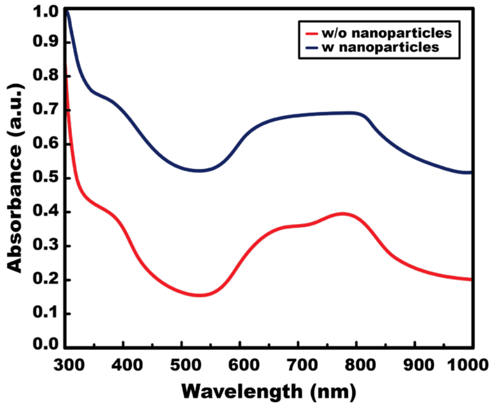

Figure 4: Light absorption spectra of the TiOPc layers, with and without plasmonic nanoparticles, were measured by a spectrometer. In contrast to the absorbance spectrum of a pure TiOPc layer (red curve), the significantly enlarged light absorbance observed with the plasmonic-enhanced TiOPc layer (blue curve) is attributed to the plasmonic light scattering by the nanoparticles, thus increasing the optical path length of light within the TiOPc layer.

experimental instantaneous speed profiles of the droplet at its corresponding positions for the device enhanced with nanoparticles (see blue curve) and without any nanoparticles (see red curve). The droplet's instantaneous speed peaked at 0.152 mm/s after being actuated 0.84 mm from its original location on the device without nanoparticles. However, due to plasmonic light scattering from the nanoparticles on the FEOET device, the water droplet achieved a peak instantaneous speed of 1.69 mm/s after being actuated 2.91 mm away from its origin.

Herein, this droplet dynamics study has experimentally verified the significant enhancement in DEP-based droplet actuation with the use of plasmonic nanoparticles. Even with the same electric field applied and light intensity, plasmonic light scattering of nanoparticles in the FEOET device has enabled a water droplet to have an 11-fold faster instantaneous actuation speed than in a FEOET device without any nanoparticles.

CONCLUSION

We developed a plasmonic-enhanced FEOET device for effective light-driven DEP droplet manipulations. We have conducted numerical simulation studies to understand how incoming rays are scattered by plasmonic nanoparticles as well as the effects of plasmonic light scattering on enhancing DEP performance. Furthermore, simulation results were validated by experimental demonstrations of both TiOPc light absorbance and light-driven droplet dynamics studies. The use of a polymer-based TiOPc as a low-quality photoconductive material helps us clearly understand the effects of plasmonic nanoparticles on significant enhancements in light absorption onto the TiOPc layer and optical DEP droplet actuation performance on the FEOET device. Notably, a maximum instantaneous speed of 1.69 mm/s can be achieved by the adding a layer of plasmonic nanoparticles in the FEOET device, which shows 11-fold improvement in speed as compared to that without the nanoparticle layer.

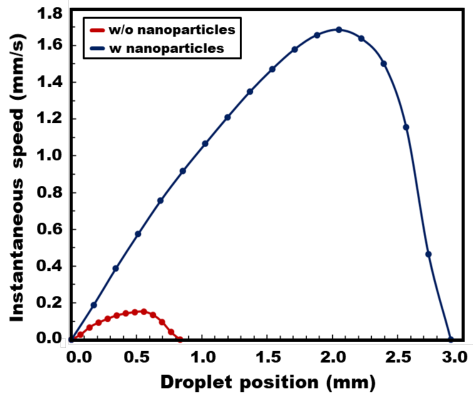

Figure 5: Experimental demonstration of light-driven droplet actuation enhanced by using the plasmonic nanoparticles. A laser beam (4 mW, 635 nm) is illuminated onto the FEOET device under the application of electric field at 150 V/mm. The instantaneous speeds of a 1.5 µL water droplet were measured at its various positions. On the FEOET device without nanoparticles, the instantaneous speed of the droplet reached a peak of 0.152 mm/s, while with the presence of nanoparticles, a peak instantaneous speed of 1.69 mm/s (11-fold increase) is attained.

Both simulation and experimental studies have demonstrated large enhancement in optical DEP performance. In addition, the single-sided open configuration of the plasmonic-enhanced FEOET device provides a flexible interface for easy integration with other microfluidic components such as reservoir and optical detectors, thus promising extensive functionality and vast potential applications with a low-cost, simple fabrication process.

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