

Dielectric and Plasmonic Hybrid Dimer Pair: Broadband Reversal of Optical Binding Force

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Abstract—Controlled mutual attraction or repulsion, by the aid of light beam, between two or more particles, is regarded as the reversal of optical binding force. It has emerged as an important tool in the area of optical manipulation, facilitating clustering or aggregating between homodimer and heterodimer arrangements of particles. Despite a vast array of works being done in this area, dielectric-plasmonic hybrid dimer pair has not received any attention yet. To the best of our knowledge, in this letter, we have provided the very first proposal of a generic way to attain the controlled broadband reversal of optical binding force between dielectric and plasmonic hybrid dimer pair. A simple optical setup consisting of a plasmonic substrate placed underneath the hybrid dimer pair has been proposed, where the reversal of optical binding force can be attained by the incidence of a non-structured laser beam in both near- and far-field regions. Furthermore, we have demonstrated that the magnitude of this binding force can be enhanced, simply by altering the angle of incidence of the source of illumination. The force reversal has been attained based on two physical phenomena — mutual attraction and repulsion between the charges formed within the hybrid pair and the reversal of current density in the plasmonic object.

1. INTRODUCTION

Since its first observation in 1989 [1], optical binding has become an important research area as it is completely different from other optical forces having gradient, scattering, and curl force. Optical binding has revealed some interesting aspects of multi-particle interactions like the mutual attraction and repulsion for crystallization, particle clustering, colloidal science, etc. [1] between different objects. One of the most fascinating aspects of optical binding force is that it does not need any high intensity light fields [2].

So far, most of the experiments on optical binding have been done for the far-field region [3,4], where the inter particle gap distance is generally several micrometers. On the other hand, only a few works have been done on near-field regions [5,6]. The very few works that have been done in the near-field region are mostly done on plasmonic objects. Among them, even fewer works have been done on the reversal of near-field binding force. The reversal of near-field binding force means the modification of mutual attraction and repulsion between nano-dimers. These very few works on the reversal of near-field optical binding force for plasmonic heterodimers have been experimented among plasmonic spherical heterodimers [5], plasmonic nanoparticle dimers [6], plasmonic disk-ring nanostructures which has important application in alternative (green) energy sources, plasmonic nanorod heterodimers, etc.

Till now, there is no generic way to control the reversal of optical binding force between dielectric and plasmonic hybrid dimer pairs for both near-field and far-field regions. The only report that has been found of controlling the reversal of optical binding force in the near-field region was for plasmonic

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cube-shaped homodimers, with the presence of a plasmonic substrate [5]. For dielectric particles, one of the works was done using optical tweezers at different angles (theta) to obtain optical binding force where nanoparticles of radius 150 nm and a gap distance smaller than wavelength (λ) were placed on a flat dielectric surface [7].

2. OPTICAL SETUP, METHOD AND FULL-WAVE SIMULATION RESULTS

In this letter, we propose a generic methodology for facilitating the reversal of optical binding force between dielectric-plasmonic hybrid dimer pair for both far-field and near-field regions. Two spherical objects having a radius of 30 nm have been modelled as the scatterers for our work, where the real part of the refractive index for the dielectric material has been set to $n = 1.45$, and we used the standard Palik's data for defining the real and imaginary portions of the refractive index of the plasmonic material. The background medium has been defined as that of air, being set to $n = 1$. Inter-particle gap of 100 nm and 200 nm has been regarded as near-field while a gap of 300 nm, 700 nm, and 1000 nm has been regarded as far-field region throughout our work. A plane-polarized time-harmonic laser beam, defined by $\mathbf{E} = E_0 e^{jkz} \hat{x}$ and $\mathbf{E} = E_0 e^{jk(\cos(45)x + \sin(45)z)} \hat{x}$, has been used as the source of illumination for the two cases demonstrated in this letter. For all the full-wave simulations demonstrated in this work, the magnitude of the incident beam (E_0) has been set to 1 V/m. Figs. 1(a)–(c) show the schematic view of the three different setups discussed in this letter, and the outcome of the full-wave simulations, on the said setups, are shown in Figs. 1(d)–(g).

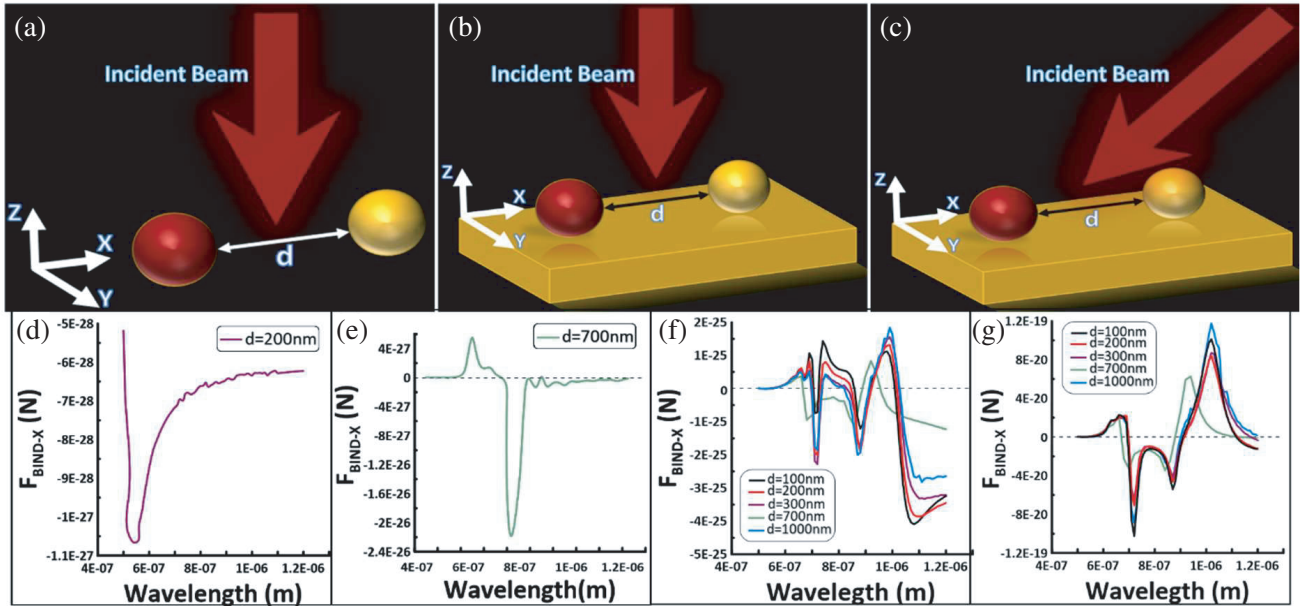


Figure 1. (a) Shows the schematic of a dielectric (left nanosphere) plasmonic (right nanosphere) hybrid dimer pair placed in air and incident beam is travelling from “+z” to “-z” direction. (b) Shows the same setup placed over a plasmonic substrate. (c) Shows the same setup placed over a plasmonic substrate having an oblique incidence of linearly polarized laser beam at 45degree with the normal. (d) and (e) Shows the outcome of the Full-wave simulation for the setup in (a) for near and far-field respectively. (f) Shows the outcome of the Full-wave simulation for near and far-field region for the setup in (b). (g) Shows the same for the setup shown in (c).

The full-wave simulations have been carried out using COMSOL Multiphysics numerical solver where successful convergence of all the simulations was attained. The wavelength (λ) has been varied from 500 nm to 1200 nm, and the optical force for every iteration has been obtained. The total optical force has been calculated by the integration of time-averaged Minkowski stress tensor at $r = a +$

employing the background fields of the scatterer of radius a [8, 9]:

$$\langle F_{Total}^{out} \rangle = \oint \left[\langle \bar{\mathbf{T}}^{out} \rangle \right] \cdot ds \quad (1)$$

$$\langle \bar{\mathbf{T}}^{out} \rangle = \frac{1}{2} \text{Re} \left[\mathbf{D}_{out} \mathbf{E}_{out}^* + \mathbf{B}_{out} \mathbf{H}_{out}^* - \frac{1}{2} \bar{\mathbf{I}} (\mathbf{E}_{out}^* \cdot \mathbf{D}_{out} + \mathbf{H}_{out}^* \cdot \mathbf{B}_{out}) \right] \quad (2)$$

Here, ‘out’ represents the exterior total field of the scatterer; \mathbf{E} , \mathbf{D} , \mathbf{H} and \mathbf{B} are the electric fields, displacement vector, magnetic field, and induction vectors respectively; $\langle \rangle$ represents the time average; and $\bar{\mathbf{I}}$ is the unity tensor.

Next, using the “ x ” values of the optical force obtained using Eq. (1), we have calculated the lateral binding force between the particles, which is defined as $F_{Bind-x} = F_1(x) - F_2(x)$, where (1), (2) indicates “+ x ” direction, left sphere (dielectric particle), right sphere (plasmonic particle), respectively. From the equation, it can be seen that a positive binding force would yield attractive binding force between the nanoparticles, while a negative force would give a repulsive binding force between the nanoparticles.

Usually, the reversal in near-field optical binding force for plasmonic homodimers [6, 10, 11] is highly dependent on Fano resonance, which, however, completely vanishes when the particle distance exceeds 100 nm [11]. But it does not work for dielectric homodimers, and did not occur in our setups as well. So, we have ignored it as Fano resonance is not a generic feature for our work.

3. DIELECTRIC PLASMONIC HYBRID DIMER WITHOUT SUBSTRATE: NO REVERSAL OF OPTICAL BINDING FORCE

We initiate our investigation by placing the said hybrid dimer pair in an air medium and shine light from above (Fig. 1(a)) to find out how the hybrid pair behaves in the near-field and far-field regions, where $d = 200$ nm has been set for the former and $d = 700$ nm for the latter. As shown in Fig. 1(d), the force is negative, which means that the two nanospheres are fully repelling each other, and no reversal of binding force is occurring. In the case of far-field region, as depicted in Fig. 1(e), we observe that the nanodimer pair experiences a weak attractive force from a wavelength of 620 nm to 720 nm, following which, reversal of optical binding force takes place, and the two nanodimers start to repel each other. Although the graph clearly exhibits the reversal of optical binding force within the aforementioned ranges, it does not suffice the goal of our study as for higher wavelengths (which is attaining broadband reversal of optical binding force); no apparent reversal of binding force can be seen; and the attractive force attained in the 620 nm–720 nm range is very weak. In both the near- and far-field regions, the repulsive behavior can be directly attributed to the interaction between the charges formed within the hybrid dimer pair. As shown in Fig. 2(a), we observe the formation of like charges within the nanodimer pair facing each other, and as per Columb’s law, like charges repel whereas unlike charges attract. Thus, both the objects experience repulsive binding force as the orientation of the charges formed remains same for the wavelength range of 500 nm–1200 nm. Since the force experienced by the plasmonic scatterer plays a pivotal role in our work, we tried to identify the physical phenomenon that leads towards the change in the direction of force exerted on a plasmonic scatterer. As reported in [12], the direction of induced current is one of the primary aspects that governs the direction of exerted force on a plasmonic scatterer. As shown in Fig. 2(b), the induced current density of the plasmonic scatterer remains unchanged. Next, in the case of far-field region, the magnitude of repulsive force is found considerably higher than that in near-field region. Here, we observe that the orientation of charges are quite similar in both attractive and repulsive cases, as depicted in Figs. 2(c), (d) for attractive and repulsive cases. Based on the orientation, it seems that they should attract. However, in this case, due to the large interparticle gap, coupling between the nanodimer pair is weaker, and the magnitude of force is fully dependent upon the current density distribution within the plasmonic object, as shown in Fig. 2(e). In fact, the magnitude of current density increases as the repulsive binding force between the hybrid dimer pair increases. Furthermore, comparing Fig. 2(b) and Fig. 2(e), we observe that the direction of current density remains the same for both the near-field and far-field cases, where the objects experience repulsive force.

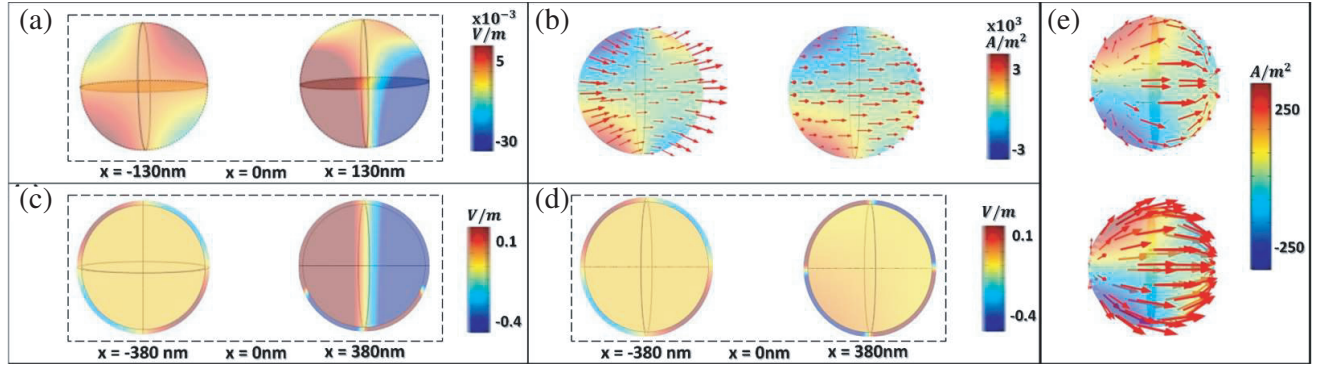


Figure 2. (a) Shows the induced charges (E_z) within the hybrid dimer pair in near-field region. (b) Shows the distribution and direction of induced current density (J_y) in the plasmonic scatterer at a wavelength of 540nm (left scatterer) and 960 nm (right scatterer). (c) Shows the induced charges (E_z) within the hybrid dimer pair in far-field region where the particles are getting attractive binding force and (d) shows the same when the two particles are getting repulsive binding force. (e) Shows the distribution and direction of induced current density (J_y) in the plasmonic scatterer in the attractive region (top scatterer) and repulsive region (bottom scatterer).

4. DIELECTRIC-PLASMONIC HYBRID DIMER PAIR PLACED OVER PLASMONIC SUBSTRATE: REVERSAL OF BINDING FORCE ATTAINED

Next, we investigated the optical binding force by placing the dielectric-plasmonic hybrid dimer pair over a plasmonic substrate having a thickness of 50 nm, as shown in Fig. 1(b). A plasmonic substrate has been chosen due to its ability to enhance coupling between the nanodimer pair. As shown in Fig. 1(f), we observe multiple points where the reversal of optical binding force is taking place in both the near- and far-field regions. Furthermore, the magnitude of attractive and repulsive forces is higher in this case due to the enhanced coupling between the hybrid dimer pair, aided by the plasmonic substrate. As shown in Figs. 3(a), (b) for near-field region and Figs. 3(d), (e) for far-field region, we observe that the induced charges flip in attractive and repulsive regions. When the binding force reverses from attractive to repulsive or vice-versa, we observe that the direction of induced current in the plasmonic nanoparticle also reverses, as shown in Fig. 3(c) for near-field and Fig. 3(f) for far-field region.

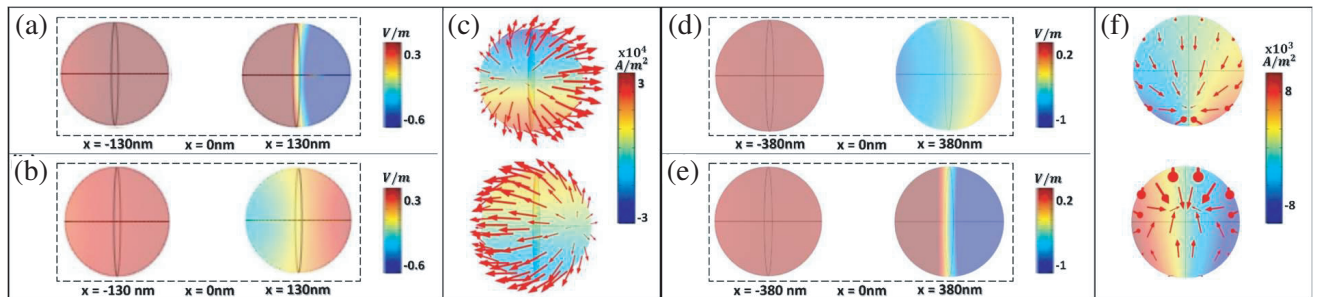


Figure 3. (a) Shows the induced charges (E_z) within the hybrid dimer pair (placed over a plasmonic substrate) in near-field region for repulsive case. (b) Shows the same for attractive case. (c) Shows the distribution and direction of induced current density (J_y) in the plasmonic scatterer for repulsive (top object) and attractive (bottom object) case. (d) Shows the induced charges (E_z) within the hybrid dimer pair (placed over a plasmonic substrate) in far-field region for attractive case. (e) Shows the same for repulsive case. (f) Shows the distribution and direction of induced current density (J_y) in the plasmonic scatterer for attractive (top object) and repulsive (bottom object) case.

5. ORIGIN OF THE REVERSAL OF OPTICAL BINDING FORCE: FOR PLASMONIC PARTICLE

Typically, reversal of optical force exerted on a plasmonic object can be explained based on the Lorentz force distribution inside a plasmonic (a lossy non-magnetic) particle [13]:

$$\oint \left[\langle \bar{\mathbf{T}}^{out} \rangle \right] \cdot d\mathbf{s} = \langle \mathbf{F}^{total} \rangle = \langle \mathbf{F}_{Mink.}^{Surface} \rangle + \langle \mathbf{F}_{Mink.}^{Bulk} \rangle \quad (3)$$

Here, the second term refers to the bulk force of Minkowski, which can be expressed as $\langle \mathbf{F}_{Mink.}^{Bulk} \rangle = \frac{1}{2} \text{Re}[\int [\rho_{\text{free}} \mathbf{E}_{in} + \mathbf{J}_{\text{free}}(in) \times \mu_0 \mathbf{H}_{in}] dv]$, which is found zero only for the lossless dielectric objects due to the absence of free charge densities (ρ_{free}) and free current densities ($\mathbf{J}_{\text{free}}(in)$) inside the particle. For an isolated dielectric particle, the full force arises from the first term (surface force of Minkowski), which can be expressed as $\langle \mathbf{F}_{Mink.}^{Surface} \rangle = \frac{1}{2} \text{Re}[\oint [-\frac{1}{2} |\mathbf{E}_{\text{Surf}}|^2 \nabla \epsilon] ds]$, also known as the Helmholtz force [14]. For a lossless object, this force can be made negative in various ways [14]. In contrast, for absorbing objects, such as plasmonic particles, both the terms at the right side in Eq. (3) play vital roles. The force density on free current usually leads to a positive bulk force for the lossy objects [15]; however, based on some recent reports [12–14, 16], it is possible to achieve overall pulling force on a lossy object by manipulating both the terms in Eq. (3). This reversal of force occurs at the point where the reversal of current density of the plasmonic scatterer takes place. Due to this reversal, the orientation of induced charges within the plasmonic nanodimer gets reversed [12] along with the force exerted on it. The reversal of induced charges within the plasmonic scatterer thus leads toward the generation of attractive or repulsive force between the hybrid dimer pair, based on the Columb's law.

6. DIELECTRIC-PLASMONIC HYBRID DIMER PAIR PLACED OVER PLASMONIC SUBSTRATE WITH OBLIQUE INCIDENCE: STRONGER REVERSAL ATTAINED

In our final setup, we simply shined the substrate-scatterer system by the oblique incidence of the same laser beam used throughout our work, as shown in Fig. 1(c). As depicted in Fig. 1(g), the magnitude of attractive and repulsive force encountered a substantial gain (10^5 times higher). The field profiles for attractive and repulsive cases in this setup have been found to be in full agreement with our earlier mentioned finding, where the reversal of current density alters the distribution of induced charges within the plasmonic scatterer, causing the hybrid dimer pair to exert attractive and repulsive binding force on each other, undergoing multiple reversals of optical binding force bin the 500 nm–1200 nm range. In the following section of this letter, we have explored the reason contributing towards this immense rise in force.

7. ENHANCEMENT OF INDUCED CURRENT IN THE SUBSTRATE IN CASE OF OBLIQUE INCIDENCE

In order to delve deeper, we examined how the induced current in the plasmonic substrate varied in the case of an oblique incidence of the same time-harmonic plane-polarized beam. We find that in the case of oblique incidence, the magnitude of current density over the plasmonic substrate rises significantly shown in Fig. 4(b) as compared to the case of vertically travelling beam, shown in Fig. 4(a). Here, oblique incidence of the same beam causes the excitation of surface plasmons at a higher degree, leading towards the generation of stronger induced current in the plasmonic substrate, which contributes to this immense rise in the magnitude of optical binding force between the said hybrid dimer pair. Based on the works in [17], it has been found that varying the incident angle of the beam affects the degree of surface plasmon excitation in plasmonic material. Similarly, in our work, it has been found that the induced current gets higher when the incident beam is at an angle of 45 degrees with the normal than the one propagating vertically from “+z” to “-z”.

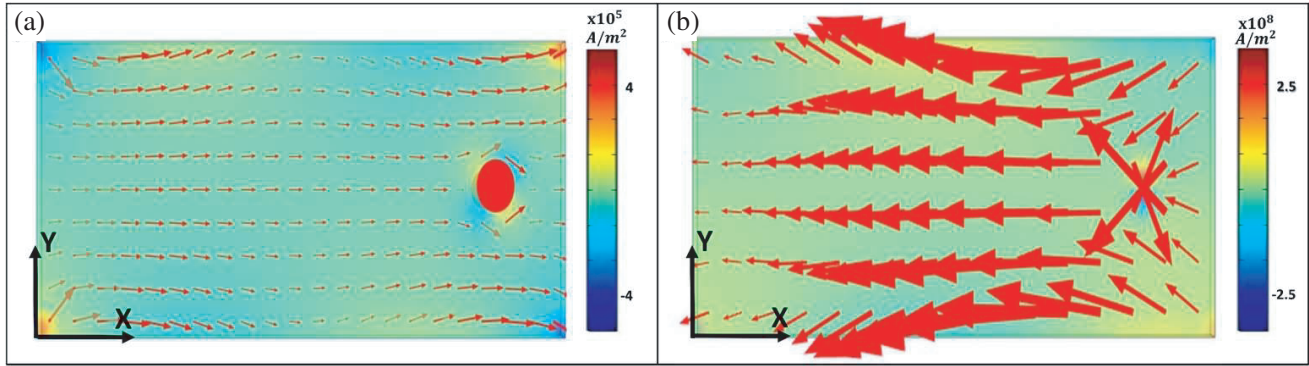


Figure 4. (a) Shows the current density (J_y) distribution over the plasmonic substrate in the x - y plane at a wavelength of 700 nm. (b) Shows the same for oblique incidence of a time-harmonic plane-polarized laser beam at 700 nm wavelength.

8. CONCLUSION

In summary, we have devised a generic methodology for facilitating the complete control over the laterally attractive or repulsive binding force between dielectric-plasmonic hybrid dimer pair over a wide range of wavelength, which is regarded as the broadband spectrum. Using this same simple setup, the reversal of optical binding force can be attained for both near- and far-field regions. Notably, the setup with the oblique incidence of light can be experimentally verified by imposing simple laser beam. Our proposed generic methodology can pave the path towards future research works in the fields of engineering, bio-medicine, nano-technology, nano-science [18], etc.

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REFERENCES

1. Burns, M. M., J.-M. Fournier, and J. A. Golovchenko, "Optical binding," *Physical Review Letters*, Vol. 63, No. 12, 1233, 1989.
2. Neuman, K. C., et al., "Characterization of photodamage to Escherichia coli in optical traps," *Biophysical Journal*, Vol. 77, No. 5, 2856–2863, 1999.
3. Demergis, V. and E.-L. Florin, "Ultrastrong optical binding of metallic nanoparticles," *Nano Letters*, Vol. 12, No. 11, 5756–5760, 2012.
4. Brzobohatý, O., et al., "Experimental and theoretical determination of optical binding forces," *Optics Express*, Vol. 18, No. 24, 25389–25402, 2010.
5. Mahdy, M. R. C., et al., "Substrate and Fano resonance effects on the reversal of optical binding force between plasmonic cube dimers," *Scientific Reports*, Vol. 7, No. 1, 1–11, 2017.
6. Mahdy, M. R. C., et al., "Plasmonic spherical heterodimers, reversal of optical binding force based on the forced breaking of symmetry," *Scientific Reports*, Vol. 8, No. 1, 1–12, 2018.
7. Chaumet, P. C. and M. Nieto-Vesperinas, "Optical binding of particles with or without the presence of a flat dielectric surface," *Physical Review B*, Vol. 64, No. 3, 035422, 2001.
8. Qiu, C.-W., et al., "Photon momentum transfer in inhomogeneous dielectric mixtures and induced tractor beams," *Light, Science & Applications*, Vol. 4, No. 4, e278–e278, 2015.

9. Zhu, T., et al., "Optical pulling using evanescent mode in sub-wavelength channels," *Optics Express*, Vol. 24, No. 16, 18436–18444, 2016.
10. Ng, J., R. Tang, and C. T. Chan, "Electrodynamics study of plasmonic bonding and antibonding forces in a bisphere," *Physical Review B*, Vol. 77, No. 19, 195407, 2008.
11. Miljkovic, V. D., et al., "Optical forces in plasmonic nanoparticle dimers," *The Journal of Physical Chemistry C*, Vol. 114, No. 16, 7472–7479, 2010.
12. Gao, D., et al., "Fano-enhanced pulling and pushing optical force on active plasmonic nanoparticles," *Physical Review A*, Vol. 96, No. 4, 043826, 2017.
13. Rahaman, M. H. and B. A. Kemp, "Negative force on free carriers in positive index nanoparticles," *APL Photonics*, Vol. 2, No. 10, 101301, 2017.
14. Mahdy, M. R. C., et al., "Dielectric or plasmonic Mie object at air-liquid interface, The transferred and the traveling momenta of photon," *Chinese Physics B*, Vol. 29, No. 1, 014211, 2020.
15. Kemp, B. A., J. A. Kong, and T. M. Grzegorzczuk, "Reversal of wave momentum in isotropic left-handed media," *Physical Review A*, Vol. 75, No. 5, 053810, 2007.
16. Jones, C., B. A. Kemp, and C. J. Sheppard, "Enhanced radiation pressure reversal on free carriers in nanoparticles and polarization dependence in the Rayleigh regime," *Optical Engineering*, Vol. 60, No. 2, 027104, 2021.
17. Kriesch, A., "Oblique-incidence excitation of surface plasmon polaritons on small metal wires," *arXiv preprint arXiv:0906.2089*, 2009.
18. Gao, D., et al., "Enhanced spin Hall effect of light in spheres with dual symmetry," *Laser & Photonics Reviews*, Vol. 12, No. 11, 1800130, 2018.