Long-range optical pulling force device based on vortex beams and transformation optics

Shahin Firuzi and Shengping Gong

School of Aerospace Engineering, Tsinghua University, Qinghua West Road, Beijing, 100084, People’s Republic of China

E-mail: xiah16@mails.tsinghua.edu.cn and gongsp@tsinghua.edu.cn

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Abstract

In this work, a method for generating a long-range optical pulling force is presented which is realized by utilizing a vortex beam and a device designed based on transformation optics through conformal mapping. The device works by transforming an input perfect vortex beam into an almost paraxial plane wave, and generates a pulling force by maximizing the forward momentum of the beam. A three-dimensional full-wave analysis of the device is performed and the optical force is computed by the Maxwell stress tensor method. The simulation results show a very good agreement with the theoretical calculations.

Keywords: optical pulling force, negative radiation pressure, vortex beam, transformation optics, photonic propulsion

1. Introduction

Optical forces including conservative gradient forces which are the case in optical traps [1], and optical conveyors [2], as well as non-conservative forces applied to an object through radiation pressure [3], are caused by the interaction of electromagnetic (EM) field with matter. The EM field naturally applies a pushing force to the object in the direction of propagation, which has been the foundation of operation of solar sails and laser-pushed sails as in-space propulsion [4]. However, the negative radiation pressure or optical pulling force has been also realized [5]. In the case of a non-conservative optical force, according to the law of conservation of momentum, the fundamental requirement of realizing a negative radiation pressure (pulling force) is to increase the momentum of the scattered EM field in the direction of the propagation [6–8]. This condition can be achieved either by modifying the environment [9–16], utilizing the properties of the objects [17–20], applying specifically generated beams [6, 21–26], or by employing a combination of these conditions [8, 19, 20].

The environment can be modified by utilizing negative refractive index media which results in a negative radiation pressure applied to the particles [10, 11]. It has been also shown that the momentum of light can be increased by scattering into a medium with higher refractive index, which can be utilized to apply a pulling force to a non-absorbing arbitrary dielectric object [9]. However, a pulling force can also be applied to light-absorbing particles in a gaseous medium through photophoretic forces [12]. The concepts of using hyperbolic metamaterials [13, 14], and metasurfaces [14, 15], as well as photonic crystals [16, 17] as the environment around the object, have been also proposed to modify the interaction of the EM field with the object which can be used to generate a pulling force.

Increasing the forward momentum of the scattered field can be also achieved by using an already excited gain medium [18, 19]. However, the gain medium needs to be in a populated state to be able to generate a pulling force, and by considering a single source for populating and pulling the object, according to the law of conservation of momentum, it does not generate any total negative force. It has been shown that optical pulling forces can be also induced in dipole and
multipole chiral particles through coupling of angular momentum to linear momentum [20, 21]. However, structured fields are required to realize such negative forces [3].

Structured fields can be utilized as non-paraxial impact beams (with a non-zero Poynting vector component perpendicular to the propagation direction) which input less momentum in the direction of propagation. Increasing the forward momentum of such beams through scattering by an object (decreasing the non-paraxiality of the beam), applies a force to the object which is opposite to the propagation direction [6–8, 22, 23, 27]. The proposed methods operate by transforming a radially-directed Poynting vector component (generated by interference of multiple plane waves), to the propagation direction. However, the magnitude of this radial component such as in Bessel beams, depends on the size of the aperture relative to the distance to the object (focal distance), and vanishes for long-distance targets. In addition to the non-paraxial beams, several unconventional beams have been also shown to trap microscopic particles and pull them against the propagation direction, such as super-oscillating rotating beams [24], and solenoid beam [25, 26]. Apart from the optical pulling forces, their acoustic counterparts have been also realized on rigid [28], and elastic spherical particles [29], as well as spheroids [30], through high-order acoustic Bessel beams.

Most of the methods have been mentioned above are either limited by the environment [9–17], the distance to the object [6, 8, 22, 23, 27], or the size of the object [6, 7, 23, 24, 26]. However, the idea of manipulating large objects at long distances by a single source, which can be used as a means of propulsion, such as pulling a laser-driven sail in space towards the source of light, is intensely appealing and seems to lie in the realm of science fiction. In this paper, we demonstrate how by designing both the beam and the device, such a desirable long-range pulling force can be achieved by designing both the beam and the device, according to the law of momentum to linear momentum

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around it which shape helical trajectories. The Poynting vector makes an angle with the propagation axis which theoretically can be designed by a desired value. We consider a perfect vortex beam [34], which has a ring diameter independent of its topological charge. Although other types of beam carrying OAM can be considered as a long-range non-paraxial beam, considering a perfect vortex beam enables the design of an arbitrary-sized device independent of the chosen topological charge. The field amplitude of a perfect vortex beam at the beam waist, in the cylindrical coordinates \((\rho, \phi, z)\), can be expressed as [34]

\[
E(\rho, \phi) = A_0(-1)^l \exp\left(-\frac{\rho^2 + \rho_0^2}{2}\right) I_l\left(\frac{2\rho}{\rho_0}\right) \times \exp(i l \phi + i k z),
\]

(1)

where \(A_0\) is a tunable constant, \(l\) is the topological charge, \(k\) is the axial wave vector, and \(I_l\) is an \(l\)th order modified Bessel function of first kind. This beam has a ring width and radius of \(2\rho_0\) and \(r_\rho\), respectively. The time-averaged Poynting vector \(S\) makes a \(\theta_l\) = \(\tan^{-1}(l/k)\) angle with the propagation axis. The direction of flow of the energy can be expressed by a unit vector given by cylindrical unit vectors \((\hat{\rho}, \hat{\phi}, \hat{z})\) as

\[
\hat{S} = \frac{l}{\sqrt{l^2 + k^2}} \hat{\phi} + \frac{kr}{\sqrt{l^2 + k^2}} \hat{z}.
\]

(2)

Therefore, the time-averaged Poynting vector of the beam in vacuum can be given as

\[
S = \frac{E_0}{2} \lVert E(\rho, \phi) \lVert^2 \hat{S},
\]

(3)

where \(c\) is the speed of light in vacuum, \(\varepsilon_0\) is the vacuum permittivity, and the notation \(\lVert \cdot \lVert\) represents the magnitude of a function. Therefore, the momentum flux vector of the beam can be given by

\[
P_{\text{beam}} = \frac{1}{c} \int_0^{2\pi} \int_{\rho = \rho_0}^{\rho + \rho_0} S \rho \, d\rho \, d\phi.
\]

(4)

From equation (3), it can be seen that the magnitude of \(S\) is independent of its direction. Therefore, the direction of \(S\), which is defined by \(\hat{S}\), can be modified by a passive device without necessarily changing the energy content of the beam. Any changes of this kind will alter the direction of \(P_{\text{beam}}\) without changing its magnitude. By considering a system consisting of the beam and the device, according to the law of conservation of momentum, the changes in the momentum flux vector of the beam and the device, are equal and in the opposite direction (i.e. \(\Delta P_{\text{device}} = -\Delta P_{\text{beam}}\)). According to equation (2), decreasing \(\hat{\phi}_l\) component of the Poynting vector (decreasing the non-paraxiality of the beam), increases its \(\hat{z}\) component, which consequently increases \(P_{\text{beam}}\) along the propagation direction. This change, therefore, applies a force to the device in the direction opposite to the propagation direction of light (i.e. optical pulling force). By considering a device composed of non-absorbing materials (e.g. SiO\(_2\)) in the operating wavelengths, the optical pulling force can be

2. Theoretical basis

The Poynting vector of a vortex beam carrying orbital angular momentum (OAM) [33], can be understood by imagining the photons move along the propagation axis while rotating
where the superscripts \( i \) and \( o \) correspond to the device’s input and output beams, respectively. The maximum magnitude of the optical pulling force can be achieved by transforming the vortex input beam into a paraxial output beam (i.e. \( \delta_{io} = 0, \delta_{oi} = 1 \)). Such a device transforms the perfect vortex beam into an annular shaped Gaussian beam, and consequently maximizes the momentum of the beam along its propagation direction. In this case, by assuming \( r_r \gg w_0 \), and by having the total power \( (P_{\text{total}}) \) of the vortex beam, the maximum pulling force for a given \( \theta_i \) can be expressed as

\[
F_z = \frac{\varepsilon_0 r_r}{2} \int_{0}^{2\pi} \int_{r_r-w_0}^{r_r+w_0} |E(\rho, \phi)|^2 (\hat{s}_{\theta} - \hat{s}_{\phi}) \rho d\rho d\phi. \tag{5}
\]

Since \( r_r \gg w_0 \), then \( \theta_i \) can be given by \( \theta_i = \tan^{-1}(l/r_r k) \).

3. Design of the device

The device used for generating the optical pulling force, needs to guide the EM wave in a reflection-less fashion to avoid the back scattering of the beam which may reduce the pulling force. TO [31, 32] is a great candidate for the design of such a device. TO techniques have been utilized to design optical devices which can control the behavior of EM field, such as waveguides and wave shifters/splitters/combiners, invisibility and illusion devices, flat lenses, low-profile highly directive antennas, and many other remarkable devices [35, 36]. TO has been used to generate optical forces in subwavelength particles [37]. The analysis and design of optical forces in graded-index media operating in geometrical optics regime, have been done through force tracing method [38, 39]. TO devices have been also used to generate vortex beams [40, 41], the design of which, however, needs anisotropic materials [41]. For such designs, due to azimuthally varying refractive index at the input/output ports of the device [40, 41], index matching cannot be applied, which may result in reflections and backscattering of the light on the input/output boundaries.

In this section, we show that a device designed based on TO using conformal mapping [32], can be utilized to modify the Poynting vector of a perfect vortex beam in a desired manner, while minimizing the reflections on the input/output boundaries. The reflections on the boundaries are minimized using an index-matched layer, by matching the refractive index of the device and the surrounding environment on the input/output boundaries. A TO device can be realized by using metamaterials. However, metal-dielectric metamaterials have large losses in optical wavelengths, which may influence the generation of the pulling force by decreasing the forward momentum of the output beam. Therefore, implementing a low-loss all-dielectric design based on conformal mapping techniques [32, 42], is necessary.

The conformal mapping can be applied to a two-dimensional device, by solving the Laplace’s equation over certain boundary conditions [42]. However, this technique has been also applied to three-dimensional devices which are identical along the third dimension [35]. From equation (2), it can be seen that the unit vector \( \hat{\delta} \) depends on \( \rho \), which implies that the Poynting vector of a vortex beam is not identical along \( \hat{\varepsilon}_{\rho} \). However, by considering a perfect vortex beam which its ring radius is so much larger than the ring width \( (r_r \gg w_0) \), the dependency of \( \hat{\delta} \) on \( \rho \) can be minimized, and the device can be considered as identical along \( \hat{\varepsilon}_{\rho} \). Therefore, a two-dimensional conformal mapping can be applied to the \( \hat{\varepsilon}_{\rho} \) surface corresponding to \( \rho = r_r \), and the results can then be extruded along \( \hat{\varepsilon}_{\phi} \).

The desired trajectory of a photon on the \( \hat{\varepsilon}_{\rho} \) surface as controlled by the device, is shown in figure 1(a) by the dashed curve. It can be seen that the Poynting vector is modified along this curve and redirected towards the \( z \) axis. As shown in figure 1(b), a two-dimensional waveguide is formed by cutting the cylindrical \( \hat{\varepsilon}_{\rho} \) surface along this curve, and spreading it on a plane. The conformal mapping is applied to the region surrounded by lines \( \Gamma_1 \) to \( \Gamma_8 \), which is shown in...
where \( \mu \) is the refractive index of the surrounding environment, and the subscripts \( x \) and \( y \) show the partial derivatives with respect to \( x \) and \( y \), respectively. The conformal mapping is applied to the region surrounded by \( \Gamma_1 \) to \( \Gamma_8 \) (figure 1(b)), by solving the Laplace’s equation considering the Dirichlet boundary conditions on \( \Gamma_1 \) and \( \Gamma_8 \) lines, and the Neumann boundary conditions on \( \Gamma_2, \Gamma_3, \Gamma_4, \Gamma_6, \) and \( \Gamma_7 \) and \( \Gamma_8 \) curves as

\[
\zeta|_{\Gamma_1} = 0, \quad \zeta|_{\Gamma_8} = a, \quad N_{\Gamma_i} \cdot \nabla \zeta|_{\Gamma_i} = 0 \quad \text{for} \quad i = 2, 4 \quad \text{and} \quad i = 6, 8, \tag{10}
\]

where \( N_{\Gamma_i} \) is the unit normal vector to the curve \( \Gamma_i \). In order to guarantee the all-dielectric structure of the waveguide, the constant \( a \) is defined in such a way to realize \( n_{\min} \geq 1 \), where \( n_{\min} \) is the minimum refractive index of the waveguide.

In order to apply index matching to the input/output ports of the device, it is necessary to achieve a nearly uniform refractive index on the \( \Gamma_1 \) and \( \Gamma_8 \) boundaries. Since the alteration of the propagation path of the beam in the waveguide (figure 1(b)) occurs mostly in the curved region between \( \Gamma_3 \) and \( \Gamma_7 \), the refractive index has a large variation in this region. However, it does not become uniform instantly outside this region, and by increasing the length of \( \Gamma_2, \Gamma_4, \Gamma_6, \) and \( \Gamma_8 \), the refractive index becomes more uniform on \( \Gamma_1 \) and \( \Gamma_8 \). Therefore, the length of the device needs to be long enough to be able to get a desirably uniform refractive index at the ports of the waveguide. This may result in a very long device compared to its width, which increases the mass-illuminated-surface ratio of the device, and consequently reduces the resultant acceleration and the effectiveness of the optical pulling force. The thickness of conventional devices used in photonic propulsion such as solar sails can be made as thin as 50 nm or less for different sail materials [43]. In the case of the pulling force device, reducing the thickness can be realized by dividing the \( \partial_{\phi} \partial_{\rho} \) surface of the device into multiple (\( m \) number of) waveguides, as shown in figure 1(c). In this way, the length of the waveguides can be reduced, which results in a shorter and lighter device. Therefore, by keeping the size of every waveguide \( (2\pi r/m) \) in the geometric optics regime, the length of the device can be reduced to as small as tens of the wavelength of the beam. In this way, designing thin and light devices will become possible. At the ports of the waveguide an index matching layer (figure 1(b)) is applied to minimize the reflections. The index matching layers, however, can be omitted by a modification method proposed in [44]. By applying this method, the index matching can be applied within the conformal mapping boundaries without the need for index matching layers. The modified index may be beneficial for fabrication purposes due to a simpler distribution compared to the original CM generated index.

4. Simulation, results, and discussion

In order to prove the existence of a negative radiation pressure, performing a three-dimensional full-wave analysis of the device is necessary. Since the device is divided into multiple identical waveguides with completely identical conditions, performing the simulation on a single waveguide is sufficient to show the performance of the whole device. The device is considered to be an annular cylinder divided into 90 waveguides (\( m = 90 \)). The source is a perfect vortex beam with \( r_v = 170 \mu \text{m}, \quad w_\theta = 9.5 \mu \text{m}, \quad l = 180 \), a wavelength of \( \lambda = 1.064 \mu \text{m} \), and a total power of 90 watts, which results in 1 watt power on a single waveguide. However, for large topological charges, equation (1) results in slightly different ring radius coinciding with the maximum intensity of the beam. Therefore, the ring radius of the device is calculated as \( r_v \) = 176.047 \( \mu \text{m} \). The ring width and the length of the device are \( 2w_\theta = 19 \mu \text{m} \) and \( h = 70 \mu \text{m} \), respectively.
The two-dimensional refractive index distribution is derived by performing the conformal mapping through solving the Laplace’s equation numerically, which is then extruded along the third dimension (\(\hat{e}_z\)) to generate the three-dimensional refractive index of the waveguide. The two- and three-dimensional refractive index distributions are shown in figures 2(a) and (b), respectively.

The performance of the three-dimensional waveguide is simulated by finite-difference time-domain (FDTD) simulations with commercial software (Lumerical FDTD Solutions), and the EM fields are computed. The optical forces are computed using Maxwell stress tensor method, by a surface integral of the time-averaged Maxwell stress tensor over the three-dimensional waveguide’s surface. The phase of the perfect vortex beam at the entrance port of the device is shown in figure 3(a), and the phase of the output beam is shown in figure 3(b). It can be seen that the phase of the output beam is almost uniform, which indicates that the wavefront is almost flat and perpendicular to the propagation direction (paraxial beam). The distribution of the magnitude of the electric field is shown in figure 3(c). It can be seen that, as the wave propagates in the device, the direction of the power flow changes towards the z axis. From figure 3(d) it can be seen that the x component of electric field (\(E_x\)) also follows the same path. It also shows that the structure of the electric field is maintained along the propagation in the device. The time-averaged azimuthal component of the Poynting vector which is shown in figure 3(e), vanishes with the propagation of the beam in the device. It shows that the direction of the energy flow is altered, and the azimuthal component of the Poynting vector is transferred to the axial Poynting vector component.

Maxwell stress tensor results show a pulling force of \(F_z^{\text{sim}} = -5.0616 \times 10^{-11} \text{ N}\) per unit power is applied to the waveguide. The forces along x and y axes are computed as \(F_x^{\text{sim}} = -2.3338 \times 10^{-11} \text{ N}\) and \(F_y^{\text{sim}} = 5.9191 \times 10^{-10} \text{ N}\), respectively. The torque generated by \(F_x^{\text{sim}}\) and \(F_y^{\text{sim}}\) can be estimated as \(T_x^{\text{sim}} = 1.0429 \times 10^{-13} \text{ N m}\). The theoretical optical forces applied to the device is calculated by equation (5) as \(F_x^{\text{theory}} = -5.2915 \times 10^{-11} \text{ N}\), \(F_y^{\text{theory}} = -2.1474 \times 10^{-11} \text{ N}\), and \(T_y^{\text{theory}} = 6.1493 \times 10^{-10} \text{ N m}\), which results in a theoretical torque of \(T_z^{\text{theory}} = 1.046 \times 10^{-13} \text{ N m}\). It can be seen that there is a good agreement between the theoretical and simulation results. However, the theoretical optical forces are calculated under ideal conditions, which the reflections on boundaries and the imperfections of the gradient refractive index have not been considered. Therefore, these imperfections result in small differences between the simulation and theoretical results. It needs to be mentioned that, the x and y components of the force applied to a single waveguide (\(F_x\) and \(F_y\)) will be canceled out throughout the cylindrical device consisting of the whole number of waveguides, and consequently a single pulling force (\(F_z\)) and a single torque (\(T_z\)) will be applied to the whole structure of the cylindrical device.
As mentioned previously, an essential requirement for the device’s material is to be low-loss in the operating wavelength. Therefore, for the devices designed for the visual and near-IR spectrum, applying an all-dielectric structure by the use of materials such as SiO$_2$ is highly favorable. The gradient refractive index can be implemented using non-resonant bulk metamaterials [45], by providing an effective refractive index which can be controlled by tuning the filling factor of the building blocks [46]. By considering the range of the effective refractive index in our design shown in figure 2 (1 < n < 1.2), the index distribution can be implemented by considering the building blocks composed of SiO$_2$ and air (or vacuum), which can be in the shape of radial cylindrical pillars of SiO$_2$ [46–48] or the holes drilled radially into the SiO$_2$ slab [49–52]. The circular holes arrangement, however, may not be able to provide very low effective indices near to unity, as required by the design (figure 2). The cylindrical pillars, on the other hand, can be arranged to reconstruct very low index values [46], which may provide the proper basis for realization of our index design. Since the refractive index distribution of the device is invariant along $\hat{r}$, by considering a radially polarized beam, the cylindrical pillars with their circular base on $\hat{r}$, surface which is extruded along $\hat{r}$, can be utilized to realize the three-dimensional index. According to the wavelength of the beam considered in this simulation ($\lambda = 1.064 \mu$), the diameter of the cylinders can be considered in the range of hundreds of nanometers. However, in order to fabricate the waveguides with the desired thickness (along $\hat{r}$), the nanopillars need to be long enough which is indicated by the aspect ratio of nanopillars.

There have been different methods employed to fabricate the dielectric nanopillars using the bottom-up approaches such as chemical vapor deposition and pulsed laser deposition [53], as well as the top-down techniques including laser interference lithography [54], electron beam lithography [55], focused ion beam lithography [56], reactive ion etching (RIE) [57–60], and metal-assisted chemical etching (MacEtch) [61]. Among them, RIE and MacEtch have been used to fabricate the nanopillars with very high aspect ratios of above 60:1 and 160:1 [57, 61], respectively, which can be great approaches for implementation of our index design.

5. Conclusion

This paper demonstrated a device for generation of non-conservative optical pulling force (negative radiation pressure), by transforming a vortex beam into an almost paraxial beam. Since the non-paraxiality of a vortex beam is caused by the azimuthal component of the Poynting vector which is independent of the focal distance, the pulling force can be realized at very long distances. The device which is designed based on TO, transforms the waveform of an input perfect vortex beam to an annular plane wave, and thereby maximizes the forward momentum of the output beam, which consequently generates an optical pulling force. The magnitude of the pulling force per unit power for a certain wavelength has a direct relationship with the topological-charge-to-ring-radius ratio. Accordingly, for the large values of this ratio, the magnitude of the pulling force per unit power approaches the value of the maximum pushing force per unit power by absorption (i.e. half of the optical force due to complete specular reflection). We also proposed the potential techniques which may be used for the fabrication of such a device by the use of bulk metamaterials made of nanopillars of SiO$_2$. The presented device may have applications in long-range optical manipulation of large objects such as in-space photonic propulsion.

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ORCID iDs

Shahin Firuzi @ https://orcid.org/0000-0002-9385-1255

References

[1] Ashkin A 1970 Acceleration and trapping of particles by radiation pressure Phys. Rev. Lett. 24 156–9
[2] Ruffner D B and Grier D G 2012 Optical conveyors: a class of active tractor beams Phys. Rev. Lett. 109 163903
[3] Sukhov S and Dogariu A 2017 Non-conservative optical forces Rep. Prog. Phys. 80 112001
[4] Levchenko I, Bazaka K, Mazouffre S and Xu S 2018 Prospects and physical mechanisms for photonic space propulsion Nat. Photon. 12 649–57
[5] Dogariu A, Sukhov S and Sáenz J 2013 Optically induced negative forces Nat. Photon. 7 24–7
[6] Chen J, Ng J, Lin Z and Chan C T 2011 Optical pulling force Nat. Photon. 5 531–4
[7] Sáenz J J 2011 Laser tractor beams Nat. Photon. 5 514–5
[8] Sukhov S and Dogariu A 2011 Negative nonconservative forces: optical ‘tractor beams’ for arbitrary objects Phys. Rev. Lett. 107 203602
[9] Kajomdejnikul V, Ding W, Sukhov S, Qiu C-W and Dogariu A 2013 Linear momentum increase and negative optical forces at dielectric interface Nat. Photon. 7 787–90
[10] Salandrino A and Christodoulides D N 2011 Reverse optical forces in negative index dielectric waveguide arrays Opt. Lett. 36 3103
[11] Nemirovsky J, Rechtsman M C and Segev M 2012 Negative radiation pressure and negative effective refractive index via dielectric birefringence Opt. Express 20 8907
[12] Shvedov V, Davoyan A R, Hnatovsky C, Engheta N and Krolickowski W 2014 A long-range polarization-controlled optical tractor beam Nat. Photon. 8 846–50
[13] Shalim A S, Sukhov S V, Bogdanov A A, Belov P A and Ginzburg P 2015 Optical pulling forces in hyperbolic metamaterials Phys. Rev. A 91 063830
[14] Iviniskaya A et al 2018 Tractor beams at metamaterial substrates J. Phys.: Cond. Mat. 1092 012132
[15] Iviniskaya A et al 2018 Optomechanical manipulation with hyperbolic metasurfaces ACS Photonics 5 4371–7
[16] Zhu T et al 2017 Mode conversion enables optical pulling force in photonic crystal waveguides Appl. Phys. Lett. 111 061105
[17] Zhu T et al 2018 Self-induced backaction optical pulling force Phys. Rev. Lett. 120 123901
[18] Mizrahi A and Fainman Y 2010 Negative radiation pressure on gain medium structures Opt. Lett. 35 3405
[19] Webb K J and Shivanand 2011 Negative electromagnetic plane-wave force in gain media Phys. Rev. E 84 057602
[20] Ding K, Ng J, Zhou L and Chan C T 2014 Realization of optical pulling forces using chirality Phys. Rev. A 89 063825
[21] Canaguier-Durand A and Genet C 2015 Chiral route to pulling light beam drags particles as tractor beams Phys. Rev. Lett. 107 203601
[22] Sukhov S and Dogaru A 2010 On the concept of ‘tractor beams’ Opt. Lett. 35 3847
[23] Lee S-H, Roichman Y and Grier D G 2010 Optical solenoid beams Opt. Express 18 6988
[24] Novitsky A, Qiu C-W and Wang H 2011 Single gradientless light beam drags particles as tractor beams Phys. Rev. Lett. 107 203601
[25] Firuzi S and Gong S 2019 All-dielectric tailored-index index-matched optical tractor beams based on transformation optics arXiv:1903.04398
[26] Akbarzadeh A, Koschty N, Kafesaki M, Economou E N and Soukoulis C M 2016 Graded-index optical dimer formed by optical force Opt. Express 24 269002
[27] Shu W et al 2012 Generation of optical beams with desirable orbital angular momenta by transformational media Phys. Rev. A 85 063840
[28] Zhang C et al 2016 Three-dimensional simultaneous arbitrary-way orbital angular momentum generator based on transformation optics Sci. Rep. 6 38667
[29] Ma Y G, Wang N and Ong C K 2010 Application of inverse, strict conformal transformation to design waveguide devices J. Opt. Soc. Am. A. 27 968
[30] Kezerashvili R Y 2008 Thickness requirement for solar sail foils Acta Astronaut. 65 507–18
[31] Akbarzadeh A et al 2014 Tracing optical force fields within graded-index media New J. Phys. 16 053035
[32] Akbarzadeh A, Koschty N, Kafesaki M, Economou E N and Soukoulis C M 2016 A graded-index optical dimer formed by optical force Opt. Express 24 269002