Front. Optoelectron. 2021, 14(4): 399–406
https://doi.org/10.1007/s12200-021-1134-3

RESEARCH ARTICLE

Optical trapping using transverse electromagnetic (TEM)-like mode in a coaxial nanowaveguide

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Abstract Optical traps have emerged as powerful tools for immobilizing and manipulating small particles in three dimensions. Fiber-based optical traps (FOTs) significantly simplify optical setup by creating trapping centers with single or multiple pieces of optical fibers. In addition, they inherit the flexibility and robustness of fiber-optic systems. However, trapping 10-nm-diameter nanoparticles (NPs) using FOTs remains challenging. In this study, we model a coaxial waveguide that works in the optical regime and supports a transverse electromagnetic (TEM)-like mode for NP trapping. Single NPs at waveguide front-end break the symmetry of TEM-like guided mode and lead to high transmission efficiency at far-field, thereby strongly altering light momentum and inducing a large-scale back-action on the particle. We demonstrate, via finite-difference time-domain (FDTD) simulations, that this FOT allows for trapping single 10-nm-diameter NPs at low power.

Keywords fiber-based optical trap (FOT), optical waveguides, optical apertures, metal nanophotonic structures, self-induced back-action, plasmonic optical trapping

1 Introduction

Optical force — arising from momentum exchange in light-matter interaction — was first harnessed for optical trapping by Ashkin in 1970 [1]. Optical traps were then developed by realizing a restoring optical force field. Optical traps have emerged as powerful tools with applications in numerous areas, such as force transducer [2,3], spectroscopy [4–6], optical sorting [7–10], and assembly [11,12]. Conventional optical setups require bulky optical elements, such as objectives, mirrors, and lenses, to form a tight focus [13,14], or to couple the laser beam to micro-/nano-optical structures [15]. Fiber-based optical traps (FOTs) use optical fibers to guide the trapping beam and create the trapping center. In addition, they benefit from the compact structure and compatibility with fiber-optic systems. Since their first demonstration in 1993 [16], FOTs have rapidly attracted substantial research attention [17].

FOTs can be realized at the end-face of a single piece of fiber [18], between the tips of two pieces of fiber with the end-faces facing each other [16], or even inside a hollow photonic crystal fiber [19,20], potentially ready for different applications [20–22]. FOT at a single fiber tip may suit the most basic and straightforward demand because it is directly analogous to tweezers or pipettes, and is potentially compatible with fiber-based endoscopes. Various solutions have been proposed to realize a high-numerical-aperture focusing and subsequent gradient trapping at a single fiber tip. Microsphere lens [23–25], etched notches [26,27], tapered fiber tips [28–30], and graded-index fibers [31–33] have been used to achieve tight focus, central to the working principle of a single beam tweezer. Despite these advances, stable trapping of nanoparticles (NPs) is still challenging due to optical fiber's small entrance pupil is unsuitable for lensing. Another approach is to use plasmonic metal nanostructures [34–39] at a fiber end-face to achieve sub-diffraction-limit focusing and a larger optical force in an FOT. Several studies have transferred the nanoapertures from the glass substrate to the facet of fibers and realized single sub-100 nm NP trapping [40–43]. However, these studies seem only to use fibers as light carriers and hardly considered mode property in fibers.

In this study, we propose an FOT setup with nanoobject trapping capability that relies on a metallic nanocoaxial optical waveguide and supports a transverse electromagnetic (TEM)-like mode similar to its macro-compartment coaxial cable, which supports a fundamental TEM mode in

Received December 22, 2020; accepted February 22, 2021

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radiofrequency. The radially symmetric electric field inside the waveguide severely mismatches with the outside homogenous space, and such mismatching condition distorts as the mode symmetry gets broken by a particle at the waveguide front-end. We modeled, via finite-difference time-domain (FDTD) simulations, magnificent back-action optical force exerted on a particle induced during the perturbation of light momentum in the symmetry-breaking process and demonstrated stable trapping of a 10-nm-diameter particle. In addition, we proposed a scheme for excitation of the TEM-like mode using a tapered fiber tip that can routinely be fabricated from an ordinary dielectric fiber. Optical trapping has been used to isolate single quantum dots (QDs) [35,36], showing significant potential in revealing heterogeneity of emitters [44] and fabricating non-classical optical sources [45]. The proposed FOT has potential in the fabrication of single-QD-based emitters for developing next-generation quantum communication. Therefore, we set a goal for the proposed FOT to stably trap single QDs.

2 Results and discussion

Coaxial cable is widely used as transmission lines for radio and microwave technology, but its nanooptic compartment has rarely been reported. Figure 1(a) shows a typical coaxial nanowaveguide (CNWG) consisting of a gold core with a radius, $r = 50$ nm, a gold annular cladding with inner radius, $R = 70$ nm, and thickness, $h = 130$ nm. The 20-nm gap between the gold cladding and core was filled with silica. A commercial FDTD software package (FDTD Solutions, Lumerical Inc., Canada) was used to simulate possible mode in coaxial waveguide under 976-nm-laser excitation. The refractive index (RI) of gold was obtained from the research of Johnson and Christy [46], and the RI of silica was set to 1.46. Figures 1(b), 1(c), 1(e), and 1(f) demonstrate a radially symmetric transverse electric field and annularly symmetric transverse magnetic field — indicators of a typical TEM mode. Figures 1(d) and 1(g) show finite longitudinal elements — magnified by ten times — of the electromagnetic fields due to the excitation of surface plasmon mode. In such a regime, the TEM-like mode has a cutoff at a finite but very long and irrelevant wavelength [47].

Figure 2(a) shows an almost flat, non-resonant out-transmission spectral feature of light through the CNWG end-face when the CNWG guides a TEM-like mode, which is different from resonant electromagnetic modes in previous studies using coaxial apertures with other modes excited [48–51]. In comparison, when the CNWG guides a linearly polarized (LP) mode without the axial symmetry as shown in Fig. 2(b), the out-transmission spectrum shows stronger wavelength-dependence. The axially symmetric TEM-like mode severely mismatches with the outside homogeneous medium at the waveguide end-face, which causes a low outward coupling efficiency and transmission intensity. After loading a 20-nm-diameter dielectric NP (RI, $n_p = 3$), the symmetry of the mode is broken, and it enhances transmitted power (normalized to the maximum transmission for the case with a particle), as shown in Fig. 2(a). By contrast, a negligible change occurs to the

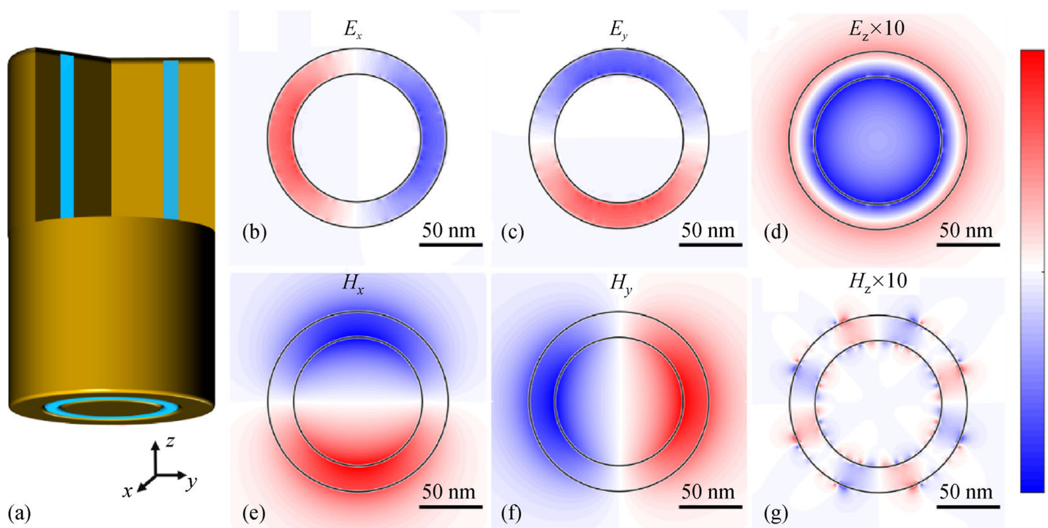

Fig. 1 (a) Schematic diagram of coaxial nanowaveguide (CNWG) for optical trapping. Light propagates along the *z*-axis and would be scattered by the trapped nanoparticle (NP). (b)–(d) *x*-, *y*-, and *z*-component of electric field of the transverse electromagnetic (TEM)-like mode, respectively. (e)–(g) *x*-, *y*-, and *z*-component of magnetic field of TEM-like mode, respectively. The value of the *z*-component is magnified ten times. Large positive and negative values are shown as dark-red and dark-blue regions, respectively, whereas white areas represent regions of zero values of the field

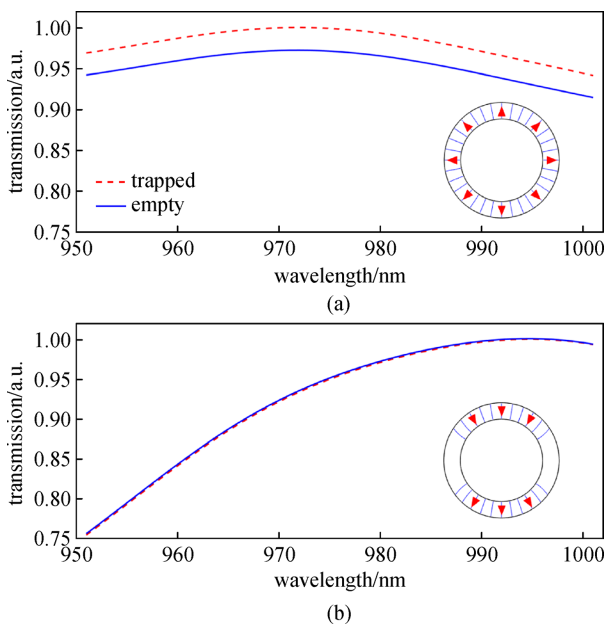

Fig. 2 Transmission intensity of (a) TEM-like and (b) LP modes, respectively, from the waveguide at different wavelengths. Inset declares the polarization direction. The blue solid line represents the transmission intensity when the trapping spot is empty, and the red dashed line represents a particle centered at 14 nm before the waveguide end-face was trapped. The results were normalized to the intensity with a trapped particle

transmission with the same particle placed at the end-face of a CNWG guiding an LP mode.

We now analyze how a NP near the end-face, by symmetry breaking, can enhance the waveguide-surrounding coupling and increase the transmission intensity. Figure 3(a) shows that the localized electric field significantly changed with placing a NP near the waveguide end-face. To demonstrate that the increase in the waveguide transmission stems from the NP-induced radial mode symmetry breaking, we compare with the case of an LP mode supported by the same CNWG. Figure 3(b) illustrates a slight difference with and without the particle.

The far-field radiation pattern of propagating field scattered from the CNWG can illustrate the NP-induced symmetry breaking. First, we examined the longitudinal Poynting vector ($\boldsymbol{P}_z$) at the transverse plane across the center of the trapped particle and plotted the difference computed without and with the trapped particle (Fig. 3). The particle significantly changes $\boldsymbol{P}_z$ in the TEM-like mode (Fig. 3(c)). It is interesting to notice how a local dielectric loading (by a particle of a larger RI) resulted in a Poynting vector change over the entire waveguide cross-section. By contrast, under the excitation of LP mode, the trapped particle represented only influence on the local region (Fig. 3(d)). This phenomenon was also observed in the comparison of the waveguide out-coupling directivity patterns when they transmit either the TEM-like or LP mode. Both cases exhibited symmetric main lobes without particles (blue solid lines in Fig. 4). With a particle placed at the end-face, the radiation directivities of both cases skew, with apparently much larger extent for the TEM-like mode case (red dashed lines).

We expect the NP-induced perturbation to the symmetry of the TEM-like mode to exert magnificent back-action onto the particle, and we proceeded to the computation of the optical force exerted on the NP. The Maxwell stress tensor analysis was employed for quantitative

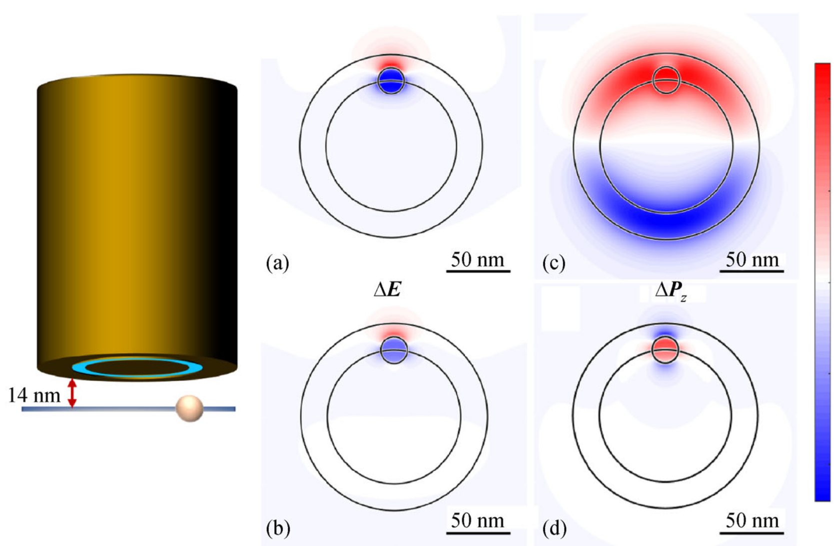

Fig. 3 Difference in localized electric field for (a) TEM and (b) LP modes, respectively. Change ratio of longitudinal Poynting vector ($\boldsymbol{P}_z$) for (c) TEM-like and (d) LP modes, respectively. Data were obtained from the transverse plane 14 nm below the waveguide

calculation [52]:

$$\boldsymbol{F} = -\frac{1}{4}\varepsilon_0\left(\int_V \boldsymbol{E}^*\boldsymbol{E}\nabla\varepsilon_r \mathrm{d}\boldsymbol{V}\right), \tag{1}$$

where $\boldsymbol{F}$ denotes optical force, $\boldsymbol{E}$ denotes the electric field, the asterisk (*) implies complex conjugation, while ε_0 and ε_r represent the free-space and relative permittivity, respectively.

Here, we calculate the optical force generated on a 10-nm-diameter particle suspended in water ($n_b = 1.33$). The RI of the particle (n_p) was set to 2, which is close to light-emitting nanocrystals, such as QDs and upconversion NPs [48]. The center of the particle was located at 14 nm below the waveguide. We placed the particle at various points along the fiber end-face and axis and pictured a force map (Figs. 5(a) and 5(c)). The maximum force obtained using TEM-like mode excitation was 7.78 pN/mW. Figure 5(b) shows a transverse potential well obtained by

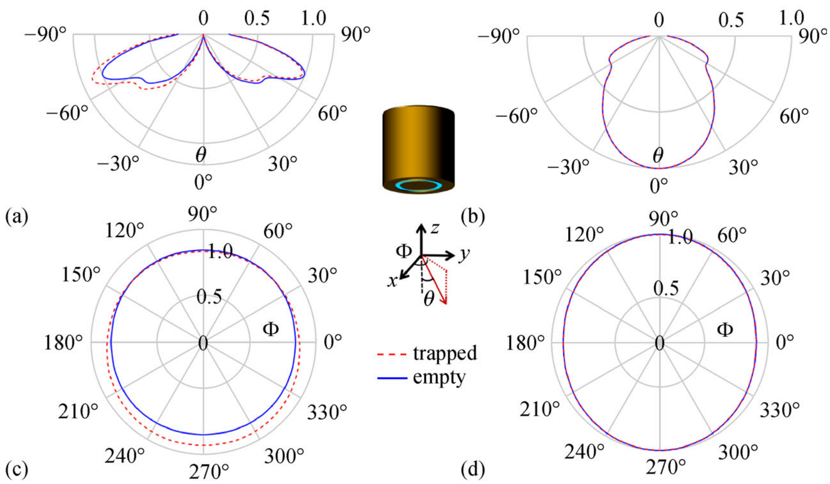

Fig. 4 Angular far-field radiation pattern in polar angle θ ((a) and (b)) and azimuth angle Φ ((c) and (d)) for TEM and LP mode, respectively

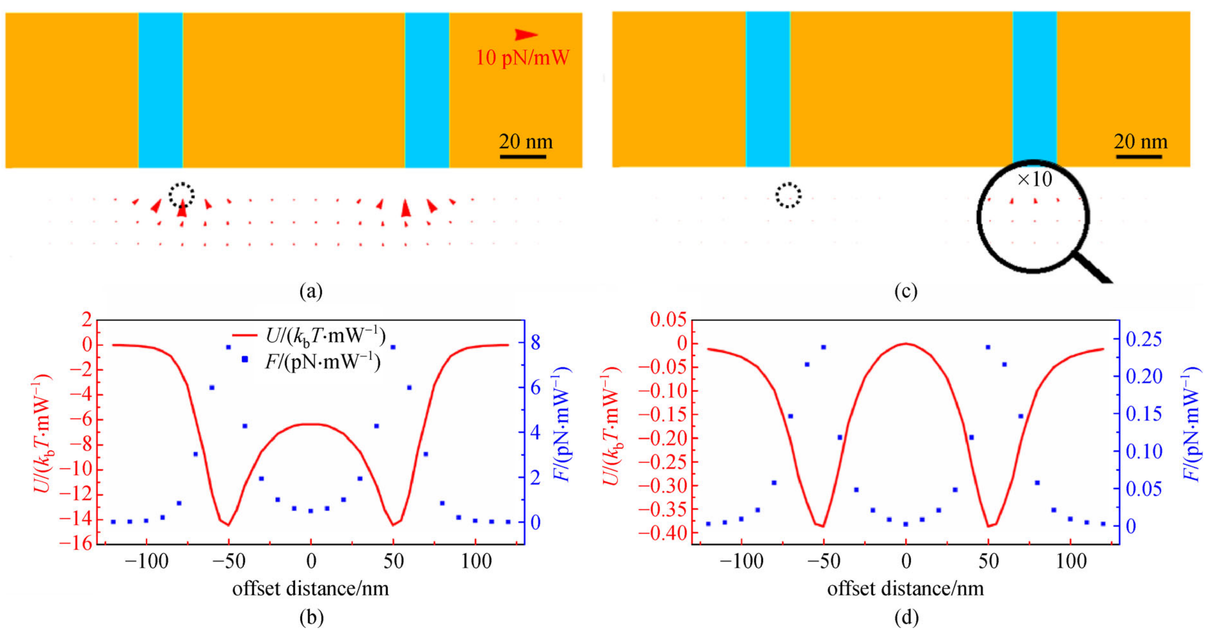

Fig. 5 (a) and (c) Optical force map in y–z plane. (b) and (d) Depth of optical potential well in the y-direction of TEM-like and LP modes, respectively. Scatterplots demonstrate optical force magnitude normalized to the total transmitted power. The dashed black circles in (a) and (c) represents a 10-nm particle

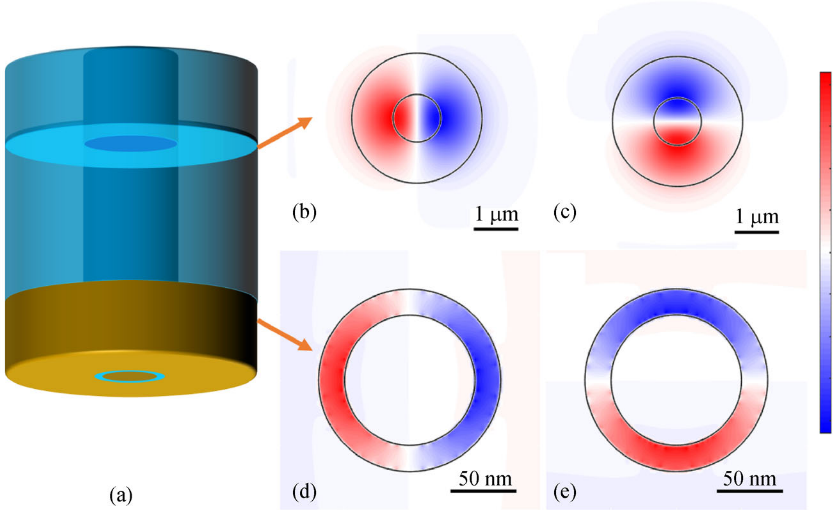

Fig. 6 (a) Schematic diagram of fiber-based CNWG traps. The dielectric fiber has a 1.1-μm-diameter core and 3-μm-diameter cladding. Their RIs were set to 1.56 and 1.46, respectively. (b) and (c) *x*- and *y*-component of electric field of TM mode in dielectric fiber. (d) and (e) *x*- and *y*-component of electric field in coaxial waveguide

integrating optical force with respect to a path. The depth of the potential well was calculated to be 14 times higher than the thermal energy, k_bT (where k_b is the Boltzmann constant and T = 300 K, room temperature) in the *y*-direction, thereby assuring stable optical trapping. In comparison, the LP-excited CNWG only resulted in a maximum optical force of 0.24 pN/mW and a potential well of 0.384 k_bT (Figs. 5(c) and 5(d)).

An optically guided mode with an axial symmetry, such as the proposed TEM-like mode, is notoriously difficult to excite by coupling from a homogeneous space for the same reason of the mismatch. This might explain why TEM-like modes — supported in coaxial nanowaveguides or nanoapertures — are rarely demonstrated and discussed in the optical regime. Several previous studies excited coaxial apertures using linear polarized light for NP trapping with both theoretical and experimental tools [48–50]. The parameters of coaxial apertures need to be well designed to match the excitation laser with the Fabry–Pérot resonant wavelength. Xiao et al. reported optical trapping using a resonant quadrupole-bonded radial breathing mode [51], but exciting this mode requires complicated control of the incident optical field.

We propose a possible excitation method using TM mode in dielectric optical fibers. Figure 6(a) shows a dielectric fiber tip to excite TEM-like modes of CNWG etched with a gold layer deposited on the tip. Although conventional dielectric optical fiber could not directly support the TEM mode, Figs. 6(b) and 6(c) indicate that the TM_{01} mode has a similar radially polarized electric field. As expected, a TEM-like mode with a radially symmetric electric field, as shown in Figs. 6(d) and 6(e), was successfully excited in CNWG. Fabricating the CNWG with an excitation fiber taper is straightforward: several previous studies have shown multiple methods to fabricate nanostructures on fiber tips [40–42]. CNWG has a higher tolerance for fabrication error than those of resonant structures, which is beneficial for its application.

CNWG FOT has potential applications in information science and technology as well as in biology. Recently, nanotweezers have been proposed for single-emitter spectrum research [36–38]. The ability to isolate and manipulate single nanocrystal emitters is paramount for fabricating single-emitter devices, which require assembling emitters with optical cavities precisely. Moreover, plasmonic cavities provide a flexible platform to control the spontaneous emission of emitters [53].

3 Conclusions

In summary, we have theoretically demonstrated self-induced back-action optical trapping using TEM-like mode in coaxial waveguides. CNWG transmitting a TEM-like mode allows for stable trapping of a 10-nm dielectric particle. This phenomenon is attributable to back-action force from transmission enhancement when the particle approaches. The radially symmetric profile of TEM-like mode — mismatching with the outside homogenous medium — was weakened by the particle and scattered more light to far-field. The excitation of the TEM-like mode in CNWG is possible using TM mode with a radially polarized electric field guided in an ordinary dielectric core-cladding fiber. It is feasible to fabricate such an assembled dielectric fiber-CNWG optical trap using an existing fabrication method. The proposed optical trapping scheme offers a simple technique to manipulate single NPs, and it has application potential in single-emitter research.

Acknowledgements This work was funded by the National Natural Science Foundation of China (Grant No. 11874164), the Innovation Fund of Wuhan National Laboratory for Optoelectronics and 1000 Talent Youth Program. The authors declare no conflicts of interest.

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