Near-field optical trapping with an ultrashort pulsed laser beam

Smitha Kuriakose,[1] Dru Morrish,[1] Xiaosong Gan,[1] James W. M. Chon,[1] Kishan Dholakia,[2] and Min Gu[1,a)]
[1]*Centre for Micro-Photonics, Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Victoria 3122, Australia*
[2]*SUPA, School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS, Scotland*

(Received 15 August 2007; accepted 31 January 2008; published online 28 February 2008)

We report the focused evanescent optical trapping of nonfluorescent and fluorescent dielectric microspheres using a femtosecond laser. The experiment confirms that the trapping efficiency increases with the size of the particles. As a result, a pulsed laser has been used to trap particles in the Mie regime and to excite whispering gallery modes in them. The excitation of whispering gallery modes in a near-field femtosecond trap shows a significant suppression of the two-photon fluorescence background with an improvement of the photon storage factor by 46%, as compared to far-field two-photon excitation. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2888771]

Optical tweezers, which are powerful and versatile tools for optical micromanipulation, have emerged as a discipline in itself and provide a great range of flexibility and accuracy for all optical micromanipulation. Near-field optical tweezers, which adopt an evanescent wave rather than a propagating wave to trap and manipulate samples within dimensions well below the diffraction limit, are a recent important advancement in the optical tweezing methodology.[1–4] The evanescent wave generated on a prism surface under the total internal reflection condition has been used for particle guiding over extended areas,[3] where such guiding confines the particles along a surface, due to the confinement of the evanescent wave within a distance of the order of $\lambda/10$ from the interface. To make near-field tweezing possible, we have previously demonstrated the focused evanescent wave geometry.[4] In this case, the axial and transverse trapping dimensions of the focused evanescent trap are both confined.

One of the main features of this trapping geometry is that the strength of the focused evanescent wave[4] is so strong that nonlinear excitation becomes possible. It has been demonstrated previously that such an evanescent field could be used to excite two-photon absorption in semiconductor quantum dots[5] as well as in fluorescent microparticles, if an ultrashort pulsed laser beam is applied.[6] Recently, we have demonstrated that due to the confined excitation volume, the morphology-dependent resonance (MDR) or whispering gallery mode (WGM) coupling under two-photon excitation in a microcavity is significantly enhanced.[7] Therefore, using a pulsed laser beam to perform focused evanescent trapping of fluorescent polymer microspheres should enable simultaneous nonlinear excitations in the near-field tweezed sample. Such functionality can be potentially useful to manipulate, diagnose, and sort samples of interest with increased detectability in micromanipulation and sensing.[8] The aim of this paper is to demonstrate focused evanescent trapping using a femtosecond laser and the subsequent excitation of MDR.

The experimental setup for pulsed focused evanescent trapping is represented schematically in Fig. 1, where a femtosecond Ti-sapphire laser at a wavelength of 780 nm and at a repetition rate of 80 MHz is used to generate the focused evanescent field. The generated focused evanescent field is used to trap nonfluorescent polystyrene microspheres and fluorescent microspheres (Polysciences, Inc.). The latter have an absorption peak at 486 nm that is suitable for inducing two-photon absorption. A high numerical aperture (NA) objective (NA=1.65) is used to focus the laser beams onto the interface between the cover glass and water of refractive indices 1.78 and 1.33, respectively, generating the focused evanescent field by total internal reflection (TIR).[4] The back aperture of the high NA objective is apodized using an obstruction disk of suitable size ε, normalized with respect to the entrance aperture of the objective. For $\varepsilon \geqslant \varepsilon_c$, (where $\varepsilon_c = 0.806$ corresponds to the TIR condition for the cover glass-water interface), the disk selectively blocks all the propagating components that would have been reaching the interface. The microspheres are suspended in a glass cell of thickness of approximately 600 μm, which is scanned transversely in directions either parallel (p) or perpendicular (s) to the laser polarization direction while a microsphere of interest is trapped using the focused evanescent field. The maximum scanning speed at which the particle falls out of the trap is determined, which is used to calculate the trapping force using the drag force method, in accordance with Faxen's law for the approximate drag on a spherical particle near an interface.[9] The trapping efficiency η is calculated from the drag force F as

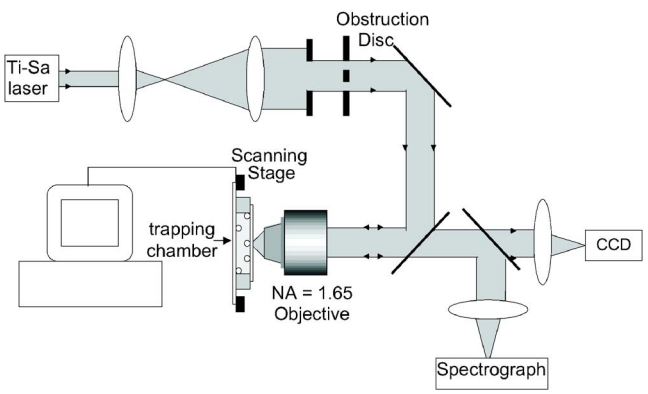

FIG. 1. (Color online) The schematic diagram of the experimental setup used to perform focused evanescent trapping using a pulsed laser.

a)Electronic mail: mgu@swin.edu.au.

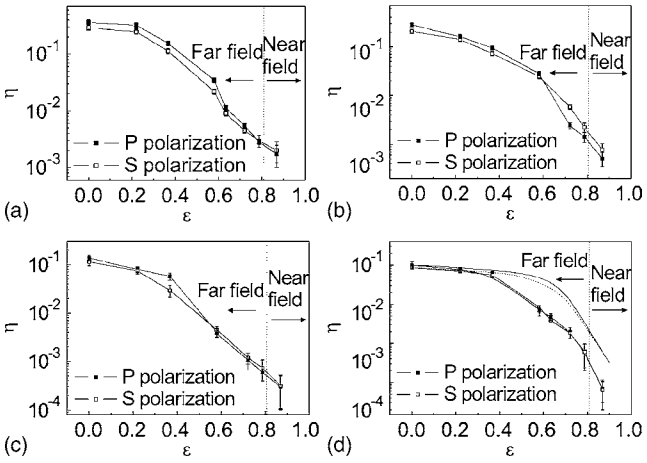

FIG. 2. The logarithmic values of the maximum transverse trapping efficiency η measured as a function of ε for femtosecond laser trapping (λ=780 nm), for (a) ϕ=3.2 μm, (b) ϕ=2 μm, (c) ϕ=1.5 μm, and (d) ϕ=1 μm. (d) Shows the theoretical plot of trapping efficiency values computed using vectorial model.

$$\eta = \frac{Fc}{nP},$$

where c is the speed of light in vacuum, P the power employed to trap the particle, and n the refractive index of the surrounding medium.

In order to determine the maximum near-field transverse trapping efficiency (η) using the femtosecond laser beam, nonfluorescent polystyrene microspheres of diameters (ϕ) ranging from 1 to 3.2 μm are used. As the sizes of the particles decrease, it becomes increasingly difficult to trap them as the Brownian force increases with the particle size. The size of the obstruction disk has been changed for values of $0 \leqslant \varepsilon \leqslant 0.86$ so that the relative evanescent contribution to the total trapping illumination is gradually increased until it is all evanescent for ε_c=0.86 for the given cover glass-water interface.

Figures 2(a)–2(d) show the dependence of η on ε in trapping polystyrene microspheres with ϕ ranging from 1 to 3.2 μm using pulsed illumination. In general, η decreases with ε as is expected.[10] For a given size of the microsphere, the maximum trapping efficiencies along the s (perpendicular) direction η_s is smaller than that in the p (parallel) direction η_p for ε=0, while $\eta_s > \eta_p$ for ε=0.86. The trapping performance for ε=0 is similar to that reported elsewhere.[10,11] According to the dependence of η on the particle size for near-field trapping, we observe that

$$\eta_s > \eta_p \quad \text{for } \phi \gg \lambda,$$

$$\eta_s \approx \eta_p \quad \text{for } \phi \leqslant \lambda. \tag{1}$$

A theoretical model for calculating the near-field trapping efficiency under continuous wave illumination has been developed.[12,13] To calculate the near-field trapping efficiency under femtosecond illumination, it is necessary to develop the diffraction theory for a high NA objective under femtosecond illumination, which is beyond the scope of this paper. However, the model has been used to calculate the change in trapping efficiency as a function of ε, as shown in Fig. 2(d), which qualitatively confirms the observed change in the values of trapping efficiency with ε. The experimentally measured values of near-field trapping efficiency are lower than

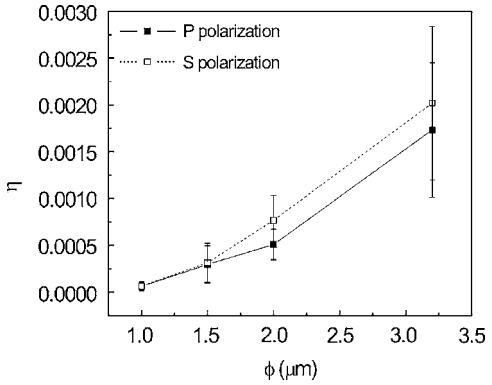

FIG. 3. Maximum near-field trapping efficiency η as a function of the particle diameter ϕ for femtosecond laser illumination (λ=780 nm, ε=0.86).

that predicted by the theory, which could be attributed to the increased Brownian motion for smaller particles and also due to the strong axial trapping force[12] and multiple scattering from the interface.

In the case of near-field trapping, i.e., for ε=0.86, the dependence of the maximum transverse trapping efficiency on the particle size along the s and p directions is shown Fig. 3(a), confirming the observation shown in Eq. (1). The values of η_p for ϕ=1, 1.5, 2, and 3.2 μm are 6.43×10^{-5}, 2.98×10^{-4}, 5.11×10^{-4}, and 1.73×10^{-3}, respectively, while the values of η_s are 6.77×10^{-5}, 3.16×10^{-4}, 7.7×10^{-4}, and 2.02×10^{-3}, respectively. Defining $\beta = \eta_s - \eta_p$, the value of β increases with ϕ and is equal to 0.5 for ϕ=2 μm.

Based on the observed trapping performance under pulsed illumination, fluorescent polystyrene microspheres with ϕ=6 μm and ϕ=10 μm have been used to study the excitation of WGMs in such near-field tweezed microspheres. The successive frames of a movie showing the focused evanescent trapping of a fluorescent microsphere of ϕ=6 μm are shown in Figs. 4(a)–4(c). The near-field tweezed particle is shown as marked by a box while the neighboring particle is scanned along the s direction at a speed $v = 1 \pm 0.05$ μm/s. The maximum near-field trapping efficiency has been calculated to be 1.04×10^{-3}, which corresponds to a trapping force of approximately 1 fN at a power of 10 mW in the trapping plane. The trapping efficiency value calculated for a microsphere of ϕ=6 μm from the size dependence graph in Fig. 3 is 6.25×10^{-3}. It is seen that from Figs. 4(a)–4(c) that there appears a bright ring around the surface of the trapped fluorescent particle. Using the spectral measurement method,[14] we have observed that the fluorescence spectra in the bright region shows a quadratic dependence on the excitation power [see Fig. 4(d)], confirming the two-photon excitation under femtosecond illumination. Further, the spectra exhibited the excitation of WGMs which became pronounced for larger microsphere diameters.

The two-photon fluorescence emission from a microsphere of ϕ=10 μm is analyzed using a spectrograph (Acton Research Corp.) of resolution 0.1 nm at a power of 9.15 mW and at ε=0.86, and is shown in Fig. 4(e). The visibility of the spectra[14] is calculated to be 0.45, which is facilitated by the strong suppression of the background intensity. This visibility value is four times higher than that of the spectrum acquired using two-photon excitation in far-field tweezed microspheres at a scanning velocity of 4 μm/s and also higher

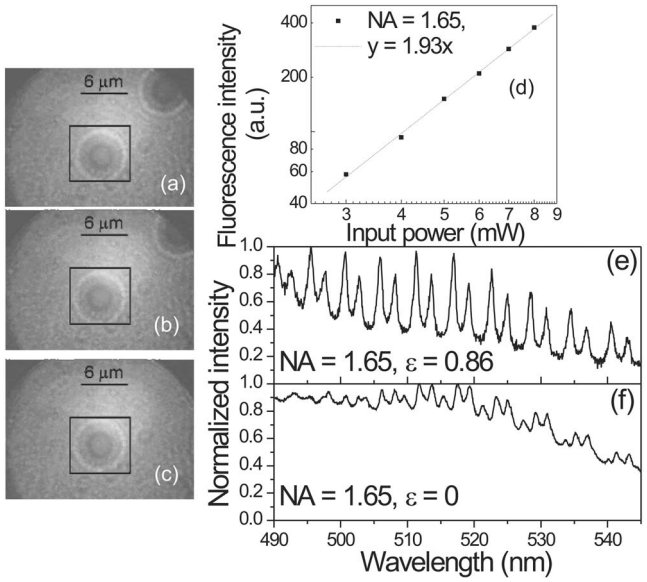

FIG. 4. [(a)–(c)] Successive frames taken from the movie showing femtosecond near-field trapping (ε=0.86) of a microsphere of ϕ=6 μm. The trapped microsphere is marked by a black box. (d) The logarithmic plot of the fluorescence peak intensity as a function of the logarithm of the input power for ϕ=6 μm microsphere, for a scanning speed of ν=0. [(e) and (f)] The two-photon fluorescence spectra obtained from the microsphere of ϕ=10 μm excited using by near-field (ε=0.86) and far-field traps (ε=0), respectively.

by 18% than that of the highest visibility achieved at a maximum translational speed of 29 μm/s.[14]

It is shown that the resonance under the near-field trapping is significantly stronger compared with the far-field case. The calculated mode photon storage factor, defined as $Q=\nu/\Delta\nu$, for one of the dominant resonant peaks at 511 nm is 706, which is 46% high compared to the photon storage factor of 483 for a resonant spectra from a microsphere excited by a far-field trap. Though the photon storage factor of a microsphere is improved in near-field trapping, the absolute value is not so high. The factors contributing towards the lower photon storage factor could be the small size of the cavity resulting in radiation losses,[15] coupling losses due to the presence of the dielectric substrate,[16] and the lower refractive index contrast available, as the microsphere is suspended in water.[17]

To summarize, we have demonstrated that Mie particles can be trapped in a focused evanescent field under pulsed illumination. It has been found that the near-field maximum transverse trapping efficiency η increases with the particle size. As such, Mie particles could be trapped in a focused evanescent field under femtosecond illumination. It has been observed that the maximum near-field trapping efficiency η is higher along the s scanning direction for Mie particles. WGMs can be excited in the microsphere in a near-field femtosecond laser trap, showing an increase of the photon storage factor by 46% and the visibility by four times, as compared to far-field two-photon coupling. Such a mechanism could be used for simultaneous tweezing and nonlinear excitation, for the development of accurate sensing techniques.

The authors thank the Australian Research Council for its support.

[1]S. Kawata and T. Sugiura, Opt. Lett. **17**, 11 (1992).
[2]L. Novotny, R. X. Bian, and X. S. Xie, Phys. Rev. Lett. **79**, 645 (1997).
[3]V. Garcés-Chávez, K. Dholakia, and G. C. Spalding, Appl. Phys. Lett. **86**, 031106 (2005).
[4]M. Gu, J.-B. Haumonte, Y. Micheau, J. W. M. Chon, and X. Gan, Appl. Phys. Lett. **84**, 4236 (2004).
[5]J. W. M. Chon, M. Gu, C. Bullen, and P. Mulvaney, Opt. Lett. **28**, 1930 (2003).
[6]J. W. M. Chon and M. Gu, Appl. Opt. **43**, 1063 (2004).
[7]S. Kuriakose, D. Morrish, X. Gan, J. W. M. Chon, and M. Gu, Appl. Phys. Lett. **89**, 211125 (2006).
[8]D. Morrish, X. Gan, and M. Gu, Appl. Phys. Lett. **88**, 141103 (2006).
[9]K. Svoboda and S. M. Block, Annu. Rev. Biophys. Biomol. Struct. **23**, 247 (1994).
[10]D. Ganic, X. Gan, and M. Gu, Opt. Express **12**, 5533 (2004).
[11]B. Agate, C. T. A. Brown, W. Sibbett, and K. Dholakia, Opt. Express **12**, 3011 (2004).
[12]D. Ganic, X. Gan, and M. Gu, Opt. Express **12**, 2670 (2004).
[13]M. Gu, *Advanced Optical Imaging Theory* (Springer, Heidelberg, 2000).
[14]D. Morrish, X. Gan, and M. Gu, Opt. Express **12**, 4198 (2004).
[15]J. R. Buck and H. J. Kimble, Phys. Rev. A **67**, 033806 (2003).
[16]H. Ishikawa, H. Tamaru, and K. Miyano, J. Opt. Soc. Am. A **17**, 802 (2000).
[17]P. Chylek, J. T. Kiehl, and M. K. W. Ko, Phys. Rev. A **18**, 2229 (1978).