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TRAPPING OF GOLD NANOPARTICLE AND POLYSTYRENE BEADS BY DYNAMIC OPTICAL TWEEZERS

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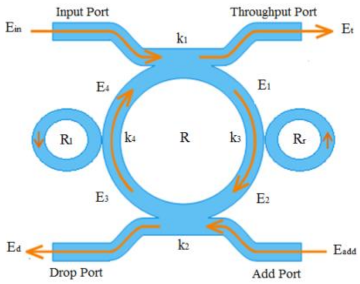
Graphical abstract



Abstract

Gold nanoparticles and polystyrene beads are very important to use in advanced nanoscopic optical trapping techniques to probe any biological system of interest. Multiple trapping of these particles with different diameters can be performed by an optical tweezers system employing dark soliton controlled by Gaussian pulse within a particular configuration of microring resonators. By controlling some parameters and input power of the system, dynamics of the tweezers can be tuned. Radiation pressure acting on the particles including gradient and scattering forces were theoretically measured as a function of normalized position from the center of the laser beam. In this work, the highest output signal in the form of potential well is recorded at 112.80 W corresponding to 1.6 µm wavelength. Sizes of the tweezers are found within the range of 20 nm and the highest value of the optical force is recorded at 895.70 pN. We have demonstrated that the gradient force component is dominant over particle size within Rayleigh regime, thus a good agreement with theory is found.

Keywords: Gold, polystyrene, optical tweezers

Abstrak

Nanopartikel emas dan manik polistirena adalah sangat penting untuk digunakan dalam teknik nanoscopic perangkap optik maju untuk menyiasat mana-mana sistem biologi. Perangkap zarah dengan diameter yang berbeza boleh dihasilkan oleh sistem optik menggunakan pinset soliton gelap dikawal oleh nadi Gaussian dalam konfigurasi tertentu cincin pengalun mikro. Dengan mengawal beberapa parameter dan kuasa input sistem, dinamik pinset boleh biubah. Tekanan radiasi yang bertindak ke atas zarah termasuk kecerunan dan kuasa-kuasa yang berselerak telah secara teori diukur sebagai fungsi kedudukan normal dari pusat pancaran laser. Dalam kajian ini, isyarat output yang tertinggi dalam bentuk perigi potensi telah direkodkan pada 112.80 W bersamaan dengan 1.6 µm panjang gelombang. Saiz pinset didapati dalam julat 20 nm dan nilai tertinggi kuasa optik direkodkan pada 895.70 pN. Kami telah menunjukkan bahawa komponen daya kecerunan adalah dominan atas saiz zarah dalam rejim Rayleigh, oleh itu suatu persetujuan yang baik dengan teori telah dibuktikan.

Kata kunci: Emas, polistirena, pinset optik

1.0 INTRODUCTION

Since the pioneering works of Ashkin on radiation pressure from a single beam laser, wide ranges of applications have been developed in various fields of studies [1-3]. One of the most important applications is the use of single-beam force to trap micro and nano-scale particles [4]. This phenomenon is known as optical tweezers, it refers to three-dimensional optical trap generated from a focused laser beam passing through a high numerical aperture lens by a specific geometry. This method has been applied on non-linear physics and biology to dynamically control and optically manipulate particle without leaving any damage to the sample [5, 6]. Optical forces produced from intense laser beam are very small and can be neglected on the scale of larger particles (few millimeters), but it is significant if we are dealing with living cells and single atom. Magnitude of the force in the pN range is sufficient to stretch or assembles macromolecules such as RNA and DNA [7]. In biological process such as macro and nano-molecular assemblies and transportation, the specimens are often attached to a small refractile sphere or dielectric particle which is known as handle or probe e.g. amine and carboxyl bind to proteins [8]. Recently, gold nano-particle (Au-Nps) offers important breakthrough applications in nano-biotechnology and medicine especially in cancer tumor targeting and cancer photo-therapy [9, 10]. The advantages are due to its properties such as easy conjugation with bio-molecules and strong absorbance [11]. On the other hand, polystyrene are widely used in biological experiments as a probe. This is because polystyrene beads usually provided in a variety of sizes and colors covering a wider ranges of optical trapping regime. Thus, in this research work, polystyrene and gold particle are being studied. The dynamics of the trapping can be controlled and the optical forces acting on different sizes of particles are measured.

In order to achieve a stable 3 dimensional trapping, laser beam need to be focused down to a tiny spot in a range of few microns in diameter. This will create the most intense part of the beam along the propagation direction and generates enormous local fluxes and high intensity gradient on the specific region. This phenomenon is crucial to produce a large enough optical forces to confined any particle of interest. In this paper, a combination of optical add-drop filter incorporating two nanoring resonators (PANDA configuration) are used. By controlling or tuning some important parameters on the system such as input power, control signals and coupling coefficients, a very high/intense optical field can be formed and propagates within the microring resonators system. Thus, the concept of optical trapping by intensity gradient can be utilized from the proposed system.

2.0 EXPERIMENTAL

During simulation, dark soliton has been used as input signal fed into the system via input port. The signal propagates within PANDA ring resonator and controlled by Gaussian pulse from drop port. Electric fields interaction within the ring resonator produced intense output signal from the small cross section area of the waveguides. The potential well formed between the gaps of two intensities from the output signal produce forces to confine atoms/molecules, which imply the same concept as single-beam optical tweezers [12]. The dynamics of the optical tweezers are tuned and controlled by changing some important parameters and input power of the system according to Figure 1.

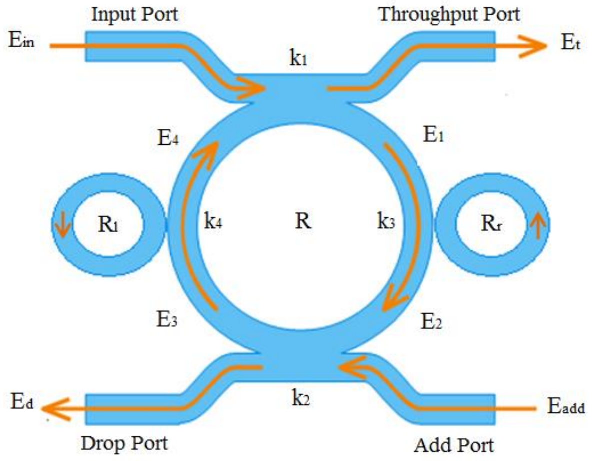


Figure 1 Panda ring resonator configuration consisting add-drop multiplexer and nano-ring on both sides

Output field at throughput port, E_t is given by:

$$E_t = E_{in} x_1 y_1 + j\sqrt{\kappa_1}\, x_1 x_2 y_2 E_L E_R E_1 \exp(\varphi) - \sqrt{\kappa_1 \kappa_2}\, x_1 x_2 E_L E_{Add} \exp(\varphi/2) \qquad (1)$$

Output field at drop port, E_d is given by:

$$E_d = j\sqrt{\kappa_2}\, x_2 E_1 E_R \exp(\varphi/2) + E_{Add} y_2 x_2 \qquad (2)$$

The circulated field, E_1 is given by:

$$E_1 = \frac{j\sqrt{\kappa_1}\, x_1 E_{in} + j\sqrt{\kappa_2}\, y_1 x_1 x_2 E_L E_{Add} \exp(\varphi/2)}{1 - E_R E_L y_1 y_2 \exp(\varphi\ )} \qquad (3)$$

Where $y_1 = \sqrt{1-\kappa_1}$, $y_2 = \sqrt{1-\kappa_2}$, $x_1 = \sqrt{1-\gamma_1}$, $x_2 = \sqrt{1-\gamma_2}$, $\varphi = -(\alpha L/2) - jK_n L$. L is the circumference of the ring which is given by L=2πR, R is the radius of the ring measured from the center of the ring to the center of the waveguide. γ is a coupling intensity loss for the field amplitude (for lossless coupling, γ is equal to 0) [13]. The coupler parameterκ is the power coupling coefficient of the coupler and it is assume to be wavelength independent. κ is associated with each transmission field that passes through the coupler. Transmission for one complete roundtrip is represented by $\exp(\frac{-\alpha L}{2} - jk_n L)$ while $k_n = \frac{2\pi}{\lambda} n_{eff}$ is the propagation constant. λ is the wavelength and n_{eff} is the effective index of the waveguide. Roundtrip loss inside ring is given by $\exp(\frac{-\alpha L}{2})$. α referred to intensity attenuation coefficient, which includes propagation loss, losses resulting from transitions in the curvature of the ring, and bending losses. Value of α is dependent on the properties of the material and waveguide in used. E_L and E_R are the fields that propagate within the nanorings on the left and right hand sides of the add-drop filter. E_{in} and E_{add} on the equation refer to input and control optical fields fed into the system.

3.0 RESULTS AND DISCUSSION

3.1 Optical Forces Components

In this study, dark soliton is generated at peak power 5 w and pulse width 1.20 ns. Gaussian pulse as a control signal is introduced into the system via the add port. Radius of the center add-drop multiplexer is set to be 50 μm and the sizes of nanorings on both sides are R_r=100 nm and R_l=100 nm respectively. Effective core area, A_{eff} of the add-drop and nanoring are 4 μm² and 1 μm² respectively. Values of coupling coefficients are $\kappa_1 = 0.16$, $\kappa_2 = 0.66$, $\kappa_3 = 0.10$, and $\kappa_4 = 0.10$. Waveguide losses coefficient, α is 0.25 and coupling loss, γ is assumed to be 0.01. Dynamics tweezers are generated at three different center wavelengths which are 1.5, 1.6 and 1.7 μm as can be seen in Figure 2. E_1, E_2, E_3 and E_4 shows the profiles of optical fields circulated within the system. E_t and E_d are output field at throughput port and drop port respectively. Different center wavelengths show different properties of tweezers, which comprises different peak powers and trap sizes. By tuning some important parameters on the system, required dynamics behavior of the tweezers can be achieved, thus providing different activity of trapping for different applications. Based on the generated results, tweezers with the center wavelength of 1.6 μm will produce the highest output signals at drop port with magnitude 112.80 W.

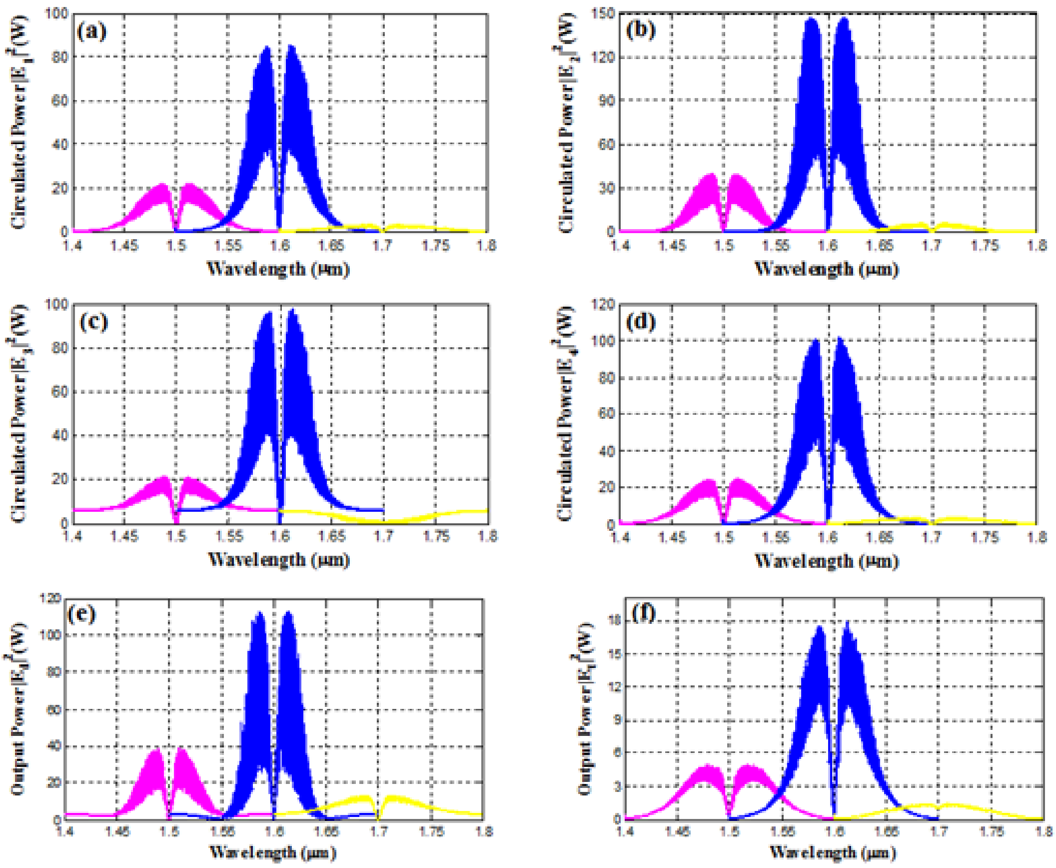


Figure 2 Results of optical tweezers generated at three different wavelengths which are 1.5 μm, 1.6 μm and 1.7 μm. (a), (b), (c) and (d) are circulated fields within the system. Output signals at drop and throughput port shown in (d) and (e) respectively

The underlying physics for optical trapping mechanism originates from momentum transfer associated with bending of intense light when it passes through particle [14, 15]. A quantum of light known as photons carries energy with the magnitude proportional to its momentum and in the same direction of the light propagation. When light passes through an object, it will refract and changing direction, thus results in momentum exchange of the light-particle system. To conserve the total momentum, an object itself acquires momentum equal to that lost by the photons and provides radiation pressure [16, 17]. In this work, a dipole or Rayleigh approximation are applied to describe the behavior of particle in intense electromagnetic wave because the size/radius of particle is much smaller than the wavelength of laser beam (r << λ). Under this limiting circumstance, dielectric sphere are treated as induced point dipole. Radiation forces on this particle can be assigned into two components which are known as scattering force F_s and gradient force F_g. Expressions for both forces are given in terms of electric field and intensity of the laser beam:

$$F_{scatt} = n_m \frac{\langle S\rangle \sigma}{c}, \tag{4}$$

where

$$\sigma = \frac{8}{3}\pi (kr)^4 r^2 \left(\frac{m^2-1}{m^2+2} \right)^2 \tag{5}$$

and

$$F_{grad} = \frac{\alpha}{2} \nabla \langle E^2 \rangle, \tag{6}$$

where

$$\alpha = n_m^2 r^3 \left(\frac{m^2-1}{m^2+2} \right) \tag{7}$$

σ is known as the scattering cross section of a Rayleigh sphere with radius r and a is the polarizability of the particle. $\langle S\rangle$ is the time averaged pointing vector, n and nm are known as the refractive index of the particle and surrounding medium respectively. $m=n/n_m$ is the relative index, and $k=2\pi n_m/\lambda$ is the wave number of the light. Scattering force pointing in the same direction of laser beam propagation and its magnitude is proportional to the energy flux. The gradient force is proportional and parallel to the gradient in energy density, it is also recognized as Lorentz force acting on the dipole induced by the electromagnetic field.

3.2 Optical Trapping

Optical trapping phenomenon is said to be stable when the magnitude of gradient force is sufficient to overcome the scattering force on the particle. In Figure 3 and 4, components of F_g and F_s as a function of normalized position z (from the center of the beam) are calculated and graphically compared for both gold and polystyrene sphere. Radii of the particles increase within the range of 5 to 20 nm.

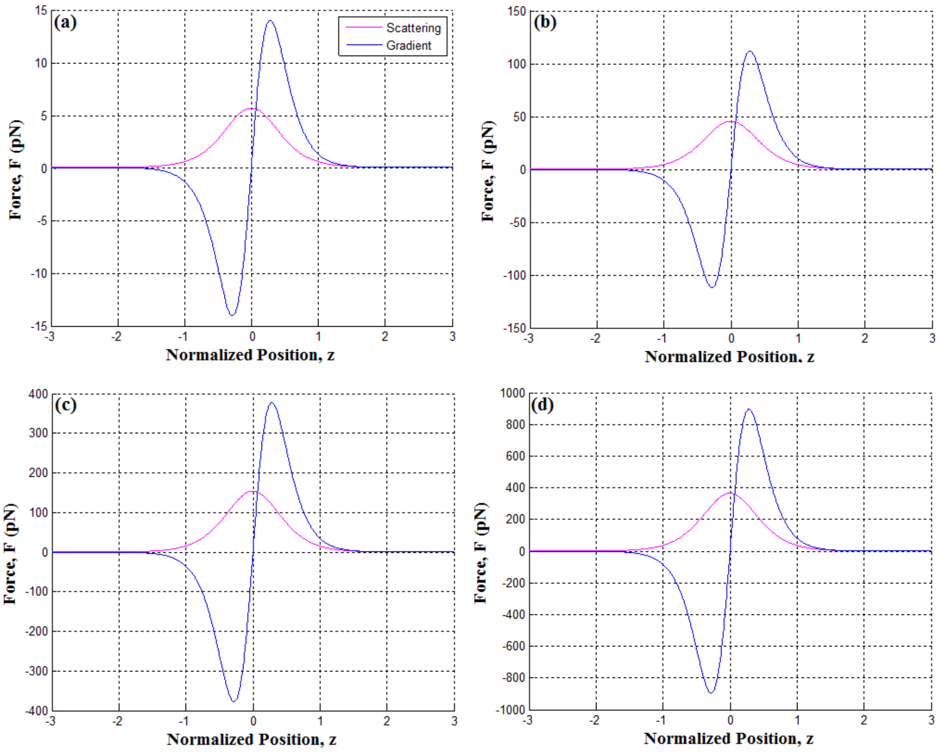


Figure 3 Scattering and gradient force components against axial normalized position of four different diameter of gold nanoparticles where (a) 5 nm, (b) 10 nm, (c) 15 nm and (d) 20 nm

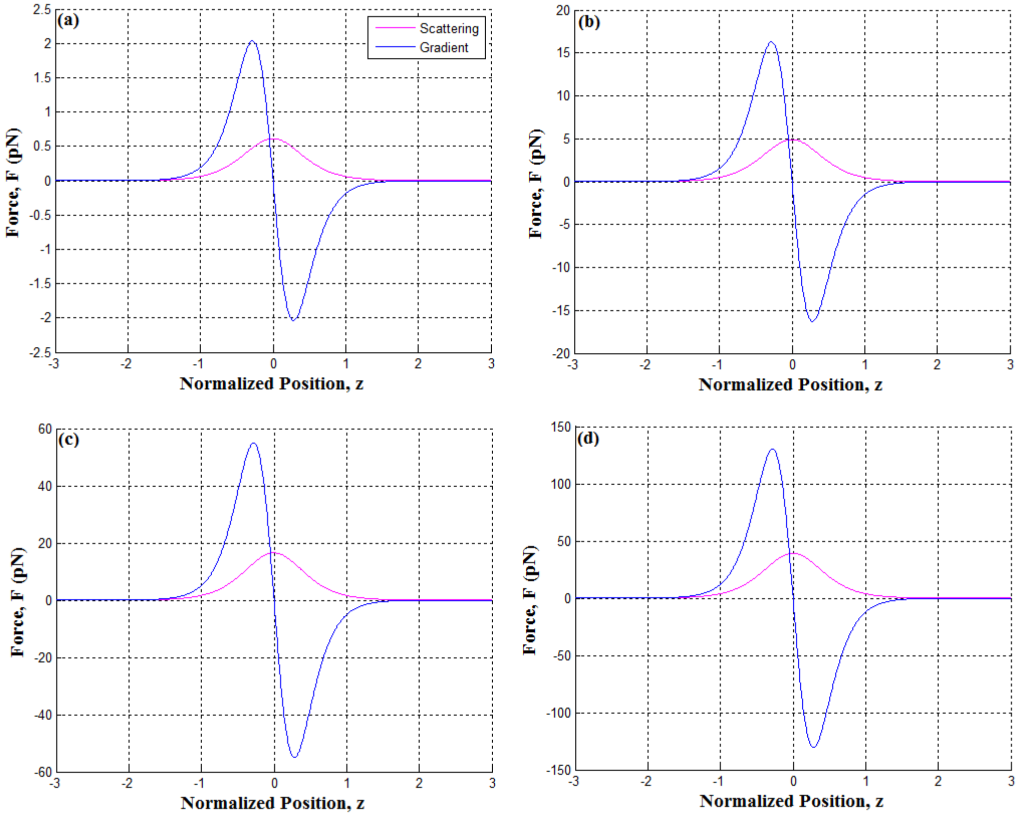


Figure 4 Scattering and gradient force components against axial normalized position of four different diameter of polystyrene beads where (a) 5 nm, (b) 10 nm, (c) 15 nm and (d) 20 nm

As shown from Figures 3 and 4, gradient force tends to push back the particle toward the center of the beam where z=0. Scattering force demonstrates the highest values at this point. As the radius of the particle increases, magnitude of both forces increase with the highest value is recorded at 895.7 pN. The highest value of radiation pressure is measured at the region near to the center of the beam. It is clearly shown that the magnitude of the gradient force is sufficient to overcome the scattering force components acting on the particle. Thus, stable optical trap is allowed.

4.0 CONCLUSION

In this work, we have developed a concept of optical tweezers system employing a dark soliton controlled by Gaussian pulse within a particular configuration of microring resonators (PANDA). Values of trapping force including Fg and Fs have been recorded for both dielectric gold nano-particle and polystyrene bead. Radiation pressures acting on those particles are compared graphically. Our simulation results quantitatively verify that trapping force for gold was higher than the corresponding polystyrene for the same radius of particle, thus demonstrated that gold nano-particle possess higher optical trapping efficiency within Rayleigh regime.

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References

[1] R. D. Leonardo, G. Rucco, J. Leach, M. J. Padget, A. J. Wright, J. M. Girkin, D. R. Burnham and D. MacGloin. 2007. *Phys. Rev. Lett.* 99: 010601.
[2] A. R. Zakharian, P. Polynkin, M. Mansuripur and J. V. Moloney. 2006. *Opt. Express.* 14: 3660.
[3] T. A. Nieminen, V. L. Y. Loke, A. B. Stilgoe, G. Knoner, A. M. Branczyk, N. R. Heckenberg and H. R. Dunlop. 2007. *J. Opt A.* 9: S196.
[4] A. Ashkin and J. M. Dziedzic. 1989. *Berichte der Bunsen Gesellschaft fur Physikalische Chemie.* 9(3): 254.
[5] R. A. Sperling, P. R. Gil, F. Zhang, M. Zanella and W. J. Parak. 2008. *Chem. Soc. Rev.* 37: 1896.
[6] M. P. MacDonald, G. C. Spalding and K. Dholkia. 2003. *Nature.* 426: 421.
[7] K. Svoboda and S. M. Block. 1994. Annu. Rev. *Biophys. Biomol. Struct.* 23: 247.
[8] W. Cai, T. Gao, H. Hong, J. Sun. 2008. *Nanotechnology Science and Applications.* 1: 17.

[9] M. R. Choi, K. J. Stanton-Maxey, J. K. Stanley. 2007. *Nano Lett.* 7: 3759.

[10] J. M. Fucntc, C. C. Berry and M. O. Richle. 2006. *Langmuir.* 22: 3286.

[11] B. D. Chithrani and W. C. W. Chan. 2007. *Nano Lett.* 7: 1542.

[12] C. Teeka, M. A. Jalil, P. P. Yupapin, J. Ali. 2010. *IEEE Transactions on Nanobioscience*. 9: 4.

[13] N. Suwanpayak, M. A. Jalil, C. Teeka, J. Ali and P. P. Yupapin. 2011. *Biomed. Opt. Express.* 2: 159.

[14] L. Wilson, R. Besseling, J. Arlt, W. C. K. Poon, K. Dholakia, G. C. Spalding. 2005. *SPIE.* 5930: 593016.

[15] R. L. Eriksen, V. R. Daria and J. Gluckstad. 2002. *Opt Express.* 10: 597.

[16] J. Guck, R. Ananthakrishnan, H. Mahmood, T. J. Moon, C. C. Cunningham and J. Kas. *Biophysics.* J. 81: 767.

[17] Moffitt, J. R., Chemla, Y. R., Izhaky, D., Bustamante, C. 2006. *Proc. Natl. Acad. Sci.* U.S.A. 103: 9006.