Theoretical analysis of optical conveyor belt with plasmonic nanodisk array

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ABSTRACT

Plasmonic optical trapping allows trapping and manipulation of micro- and even nanometer-sized particles using localized and enhanced electric fields by plasmon resonance in metallic nanostructure. We consider an optical conveyor belt consisting of an array of nanodisks acting as optical tweezers with different sizes to implement a system to trap and manipulate particles through a laser-induced gradient force. An electric field induced and localized at each optical resonator is sensitive to the wavelength and polarization. The maximum electric field is enhanced at resonant wavelength depending on the shape and size of the plasmonic nanostructure used for light localization. By changing the light wavelength and polarization, the position of localized light induced in the disk can be determined and nanoparticles can be moved to a desired location through the variation of resonance conditions without any mechanical forces.

Keywords: Surface plasmon, Field localization, Optical trapping, Optical conveyor belt, Nanodisk array

1. INTRODUCTION

Optical trapping has been of tremendous interest since its introduction by Ashkin in 1970 and used in many applications [1]. Optical trapping is also known as optical tweezer since the gradient force induced by laser combined with scattering force is exerted on a dielectric particle for spatial localization and manipulation. The magnitude of the gradient force is proportional to the electric field intensity while it increases in proportion to the volume of a particle to be trapped. For this reason, trapping of nanoscale particles can be difficult, because trapping force can be very weak and a simple increase of light power may incur photodamage to the sample. Therefore, optical trapping techniques based on light localization to induce strong field strength has been closely investigated, in particular using surface plasmon (SP) localization among many approaches [2]. While SP localization has been employed extensively for biosensing [3-12] and imaging applications [13-18], use of tiny nanostructures to localize and amplify light fields allows an optical tweezer to trap nanoscale particles in a stable and controlled manner [19].

In this study, we have calculated the electric field localized by nanodisk arrays and the gradient force that is induced by the localized field. The results are expected to be crucial to producing an optimized design to implement an optical trap for capturing nanoscale particles with minimum incident light fields.

2. MODEL AND METHODS

Rigorous coupled-wave analysis (RCWA) has been used to calculate the localized near-field distribution and the induced gradient force on a periodic array of nanodisks of gold as the cross-section radius and the height were varied as the geometrical parameters. Incident light wavelength was also varied for p and s polarization. RCWA calculation for localized field intensity distribution was performed with 30 spatial harmonics for a wavelength range of $\lambda = 650 \sim 1100$ nm under normal incidence. Cylindrical nanodisks of $\phi = 100$, 150, and 200-nm diameter and 35-nm height were assumed to form a linear array on a BK7 glass substrate. Resonant wavelengths for each of the three nanodisks were selected so as to produce highest localization at the nanodisk. The gap distance (g) between nanodisks was g = 100 nm with a period of $\Lambda = 750$ nm, i.e., one period of the nanodisk array contains three nanodisks of varying diameter in an order of $\phi = 100$, 150, and 200 nm. Material optical constants were taken from [20]. Gradient force was calculated from the field distribution based on Maxwell stress tensor. Tensor differentiation was performed by finite difference method.

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3. RESULTS AND DISCUSSION

Resonant wavelength λ_{res}, which gives to the highest localization at the nanodisk of ϕ = 100, 150, and 200-nm diameter was, respectively, λ_{res} = 672, 815, and 910 nm. Figure 1 presents the light intensity distribution produced by the nanodisk array of ϕ = 100, 150, and 200-nm diameter (left to right) at the respective resonant wavelength λ_{res}. Figure 1 clearly shows localized light fields, in particular, at the rim of nanodisks. The light localization at each nanodisk can be controlled by changing light wavelength.

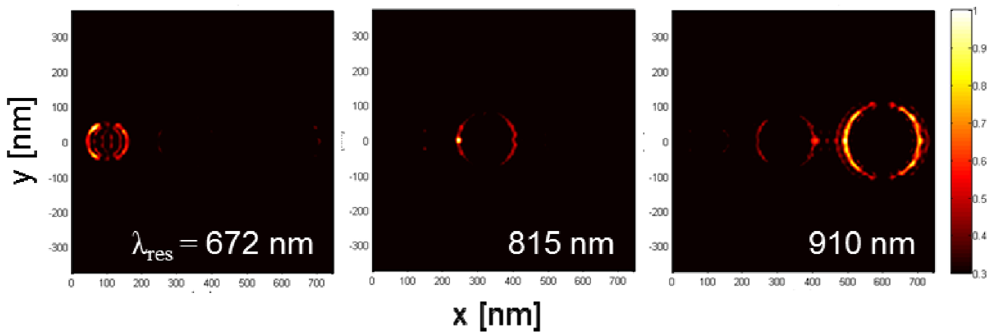

Figure 1. Near-field distribution of the nanodisk array at the resonant wavelength. Color bar represents normalized light intensity. Incident light is *p*-polarized (along the x-axis).

At the resonant wavelength of each nanodisk, the gradient force that is induced by the field localization at the nanodisk can be clearly distinguished from those at the other two nanodisks, as shown in Figure 2. The strong spike of gradient force at the edges of a nanodisk indicates the trapping force acting toward the rim, regardless of the sign. This suggests that gradient force induced at the nanodisks can be switched and tuned by adjusting light wavelengths.

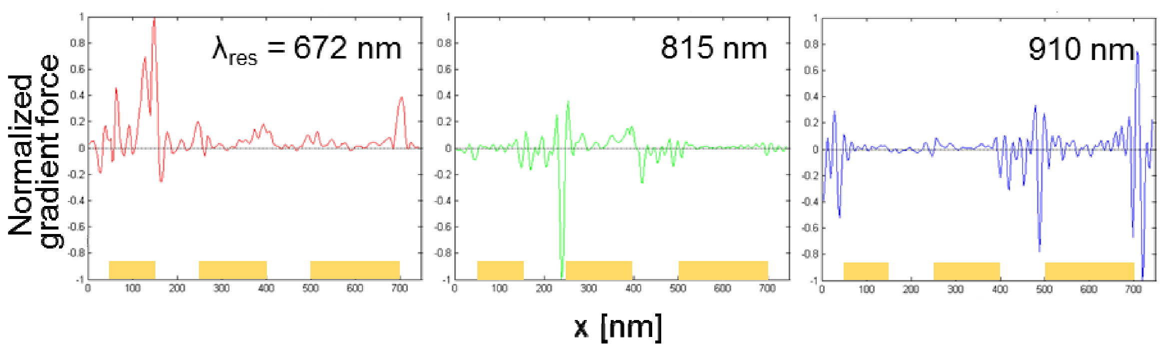

Figure 2. Normalized gradient force calculated from the localized light field for the nanodisk array at the resonant wavelength. It is clear shown that a smaller disk is associated with the highest gradient force at a shorter wavelength.

4. CONCLUDING REMARKS

In summary, we have investigated light localization and induced gradient force by linear nanodisk arrays for potential optical trapping applications. The results confirm that near-field distribution is localized and that nanodisks can be designed so that the localized field as well as the gradient force can be switched among nanodisks by light wavelength and polarization. The results suggest that continuous switching of light wavelengths and polarization in the resonance waveband may allow nanoscale optical trapping at a desired location on a nanostructure and thereby an optical conveyor belt in effect. The possibility may be applied to nanoscale synthesis of novel materials and can be useful for lab-on-a-chip applications.

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REFERENCES

[1] Ashkin, A., "Acceleration and trapping of particles by radiation pressure," Phys. Rev. Lett. 24, 156-159 (1970).
[2] Juan, M. L., Righini, M. and Quidant, R., "Plasmon nano-optical tweezers," Nature Photon. 5, 349-356 (2011).
[3] Byun, K. M., Yoon, S. J., Kim, D. and Kim, S. J., "Experimental study of sensitivity enhancement in surface plasmon resonance biosensors by use of periodic metallic nanowires," Opt. Lett. 32(13), 1902–1904 (2007).
[4] Kim, K., Kim, D. J., Moon, S., Kim, D. and Byun, K. M., "Localized surface plasmon resonance detection of layered biointeractions on metallic subwavelength nanogratings," Nanotechnology 20(31), 315501 (2009).
[5] Moon, S., Kim, D. J., Kim, K., Kim, D., Lee, H., Lee, K. and Haam, S., "Surface-enhanced plasmon resonance detection of nanoparticle-conjugated DNA hybridization," Appl. Opt. 49(3), 484–491 (2010).
[6] Oh, J., Chang, Y. W., Kim, H. J., Yoo, S., Kim, D. J., Im, S., Park, Y. J., Kim, D. and Yoo, K. H., "Carbon nanotube based dual-mode biosensor for electrical and surface plasmon resonance measurements," Nano Lett. 10(8), 2755–2760 (2010).
[7] Halpern, A. R., Chen, Y., Corn, R. M. and Kim, D., "Surface plasmon resonance phase imaging measurements of patterned monolayers and DNA adsorption onto microarrays," Anal. Chem. 83(7), 2801–2806 (2011).
[8] Oh, Y., Lee, W. and Kim, D., "Colocalization of gold nanoparticle-conjugated DNA hybridization for enhanced surface plasmon detection using nanograting antennas," Opt. Lett. 36(8), 1353–1355 (2011).
[9] Kim, Y., Chung, K., Lee, W., Kim, D. H. and Kim, D., "Nanogap-based dielectric-specific colocalization for highly sensitive surface plasmon resonance detection of biotin-streptavidin interactions," Appl. Phys. Lett. 101(23), 233701 (2012).
[10] Moon, S., Kim, Y., Oh, Y., Lee, H., Kim, H. C., Lee, K. and Kim, D., "Grating-based surface plasmon resonance detection of core-shell nanoparticle mediated DNA hybridization," Biosens. Bioelectron. 32(1), 141–147 (2012).
[11] Yu, H., Kim, K., Ma, K., Lee, W., Choi, J.-W., Yun, C.-O. and Kim, D. , "Enhanced detection of virus particles by nanoisland-based localized surface plasmon resonance," Biosens. Bioelectron. 41, 249-255 (2013).
[12] Oh, Y., Lee, W., Kim, Y. and Kim, D., "Self-aligned colocalization of 3D plasmonic nanogap arrays for ultrasensitive surface plasmon resonance detection," Biosens. Bioelectron. 51, 401–407 (2014).
[13] Kim, K., Oh, Y., Lee, W. and Kim, D., "Plasmonics-based spatially activated light microscopy for super-resolution imaging of molecular fluorescence," Opt. Lett. 35(20), 3501-3503 (2010).
[14] Kim, K., Choi, J.-W., Ma, K., Lee, R., Yoo, K.-H., Yun, C.-O. and Kim, D., "Nanoisland-based random activation of fluorescence for visualizing endocytotic internalization of adenovirus," Small 6(12), 1293–1299 (2010).
[15] Kim, K., Yajima, J., Oh, Y., Lee, W., Oowada, S., Nishizaka, T. and Kim, D., "Nanoscale localization sampling based on nanoantenna arrays for super-resolution imaging of fluorescent monomers on sliding microtubules," Small 8(6), 892–900, 786 (2012).
[16] Choi, J., Kim, K., Oh, Y., Kim, A. L., Kim, S. Y., Shin, J.-S. and Kim, D., "Extraordinary transmission based plasmonic nanoarrays for axially super-resolved cell imaging," Adv. Opt. Mater. 2(1), 48–55 (2014).
[17] Oh, Y., Son, T., Kim, S. Y., Lee, W., Yang, H., Choi, J., Shin, J.-S. and Kim, D., "Surface plasmon-enhanced nanoscopy of intracellular cytoskeletal actin filaments using random nanodot arrays," Opt. Express 22, 27695-27706 (2014).
[18] Lee, W., Kinosita, Y., Oh, Y., Mikami, N., Yang, H., Miyata, M., Nishizaka, T. and Kim, D., "Three-dimensional superlocalization imaging of gliding Mycoplasma mobile by extraordinary light transmission through arrayed nanoholes," ACS Nano 9(11), 10896–10908 (2015).
[19] Kang, Z., Lu, H., Chen, J., Chen, K., Xu, F. and Ho, H. P., "Plasmonic graded nano-disks as nano-optical conveyor belt," Opt. Express 22, 19567-19572 (2014).
[20] Palik, E. D., [Handbook of Optical Constants of Solids], Academic Press (1985).