Plasmon Optical Trapping in Silicon Nitride Trench Waveguide

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Abstract: Optical trapping by using bowtie antennas deposited on top of a microfluidic SiN trench waveguide is investigated. We show that the presence of plasmonic field enhancement boosts the vertical trapping force by 3 orders of magnitude.

1. Introduction

A novel approach of silicon nitride trench waveguide has been put forward recently with the ability to combine microfluidic channel and waveguide together [1]. Analyte, contained in the trapezoidal trench, interacts with the field tailing away from the trench waveguide, which can be enhanced by a plasmonic bowtie antenna. Plasmon enhanced field is widely used in optical tweezing such as nanoparticle trapping [2], molecules sensing [3] and bio cell control [4]. Here we investigate the optomechanical properties of a trench silicon nitride waveguide enhanced by gold bowtie antennas. The bowtie antenna leads to 60-fold enhancement of electric field in the antenna gap. With the help of scattering by the antenna, the optical trapping force on a 10 nm radius polystyrene nanoparticle is boosted by 3 orders of magnitude. Therefore the strong tendency of a nanoparticle to move to the high field intensity region is obtained, exhibiting the trapping capability of the antenna. The device is promising for particle sensing and sorting.

2. Waveguide and bowtie antenna design

The waveguide employed here is a trapezoidal silicon nitride trench waveguide with controllable depth and width and wide transparency window [1]. Fabrication of the waveguide is rather straight forward and does not require e-beam lithography to achieve submicron waveguide dimension, and merely relies of optical lithography followed by anisotropic potassium hydroxide. Detailed work on fabrication and characterization can be found in ref. [1].

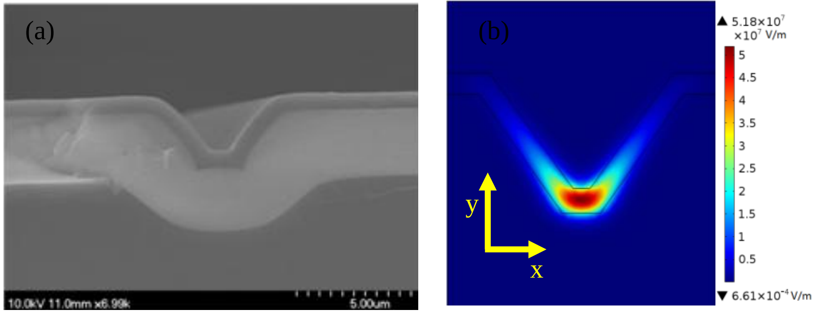
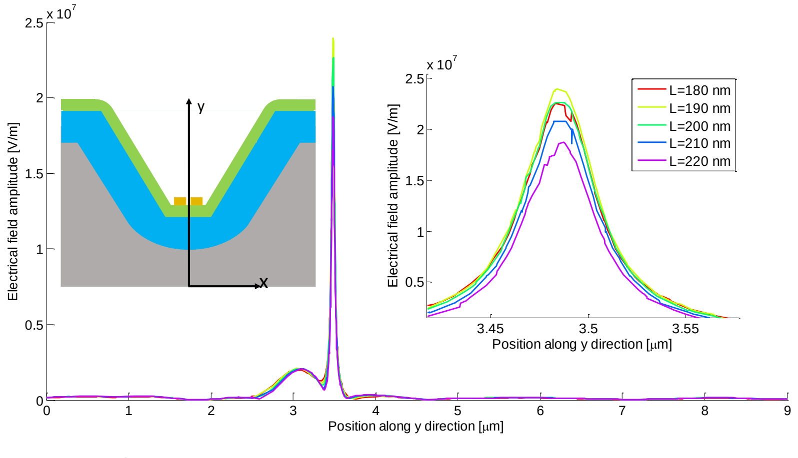
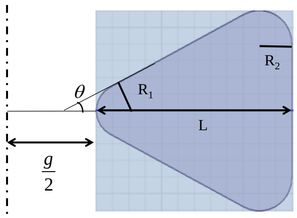


Figure 1. (a) shows an SEM image of fabricated trench waveguide. The top opening window is 6 µm and the waveguide upper width is 0.8 µm. (b) COMSOl mode analysis, at 1550 nm with 10 mW input power, of a similar structure with top opening 5.5 µm and waveguide upper width 0.5 µm. TE mode is simulated with electrical field vibrating along *x* direction.

In recent years, bowtie antenna arrays for particle manipulation in objective lens configuration have extensively been studied [5]. When incident light is linearly polarized across the gap of a bowtie antenna, capacitive effects lead to a confined and intense electric field spot in antenna near field particularly within the gap region [3]. However, to the author’s knowledge, the use of a waveguide combined with a bowtie antenna for optical manipulation has not been demonstrated yet. To facilitate coupling from a waveguide mode to the antennas, TE mode is preferred due to its significant tangential electric field with respect to the top surface of the waveguide. The waveguide that is studied here is designed to be 0.5 µm wide at the top, 1.15 µm wide at bottom and has a height of 725 nm in favor of TE mode, as shown in Fig 1a. A bowtie antenna, made of two equilateral triangle gold patches separated by a gap along the *x* direction, can be deposited using nanosphere lithography [6]. By manipulating the side length of the antennas shown in Fig.2 (b), resonance can be altered. Although smaller gap leads to stronger field, the gap of bow-tie antenna is set to be 30 nm for the sake of trapping particles and conforming to fabrication limitations. The metal thickness of the antennas is set to be 20 nm. In the simulation of 10 mW launched power at 1550 nm wavelength, the peak intensity, reported in Fig 2(a), in the antenna gap (10 nm above the waveguide) is 60 times larger than that in absence of the antenna, at the same location.



(a)



(b)

Figure 2. (a) Electrical field profile along the y direction. The left inset shows the cutline in the structure. The right inset shows the maximum electric field for different antenna lengths. (b) Half structure of a bowtie antenna. *g* = 30 nm in our case.

3. Optical force simulation

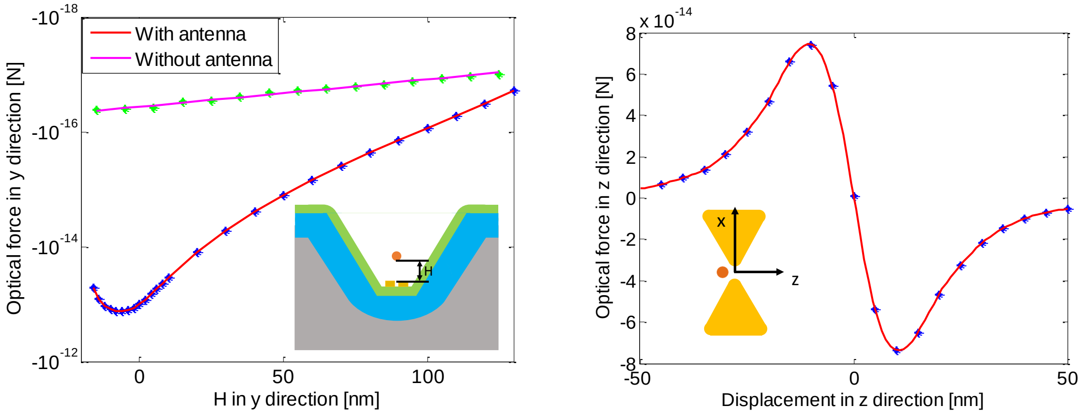


Figure 3 (a) Vertical optical force (y component) with respect to the gap *H* between particle and waveguide. Red curve indicates the case with antenna enhancement, while the magenta curse shows optical force without antenna. (b) Longitudinal optical force (z component) with respect to the displacement of particle to the antenna center in x direction.

A polystyrene particle with 10 nm radius immersed in water is placed in the gap of bowtie antennas. Optical force is calculated by integration of Maxwell stress tensor over the particle surface. As shown in Figure 3 (a), the vertical optical force magnitude increases first and then decreases as the nanoparticle is elevated away from the waveguide. Maximum force occurs when the particle bottom surface is 14 nm away from the waveguide, at which position the trapping force is boosted by 3 orders of magnitude compared to that occurring without antenna enhancement. The peak vertical optical force is estimated to be 6.8 $\times 10^8$ times larger than the net gravitational and buoyancy force. Figure 3 (b) illustrates that the longitudinal optical force (*z* component) tends to attract the nanoparticle back when it is aberrant to the antenna center. The simulation was carried out when the particle is partially immersed in the antenna gap ($H = -6$ nm). The force is positive when the particle is in negative position, and vice versa. The maximum force occurs when the particle is 10 nm away from the center. The trapped particle can be optically detected by nonlinear optical response such as two-photon fluorescence (TPF) and second harmonic generation [7].

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4. References

[1] Y. Huang, et.al, “Sub-micron silicon nitride waveguide fabrication using conventional optical lithography,” in *Advanced Photonics for Communications*, 2014.

[2] W. Zhang, et.al, “Trapping and Sensing 10 nm Metal Nanoparticles Using Plasmonic Dipole Antennas,” *Nano Lett.*, 2010.

[3] M. L. Juan, et.al, “Plasmon nano-optical tweezers,” *Nat. Photonics*, 2011.

[4] M. Righini, et.al, “Nano-optical Trapping of Rayleigh Particles and Escherichia coli Bacteria with Resonant Optical Antennas,” *Nano Lett.*, 2009.

[5] B. J. Roxworthy, et.al, “Application of Plasmonic Bowtie Nanoantenna Arrays for Optical Trapping, Stacking, and Sorting,” *Nano Lett.*, 2011.

[6] T. R. Jensen, et.al, “Nanosphere Lithography: Tunable Localized Surface Plasmon Resonance Spectra of Silver Nanoparticles,” *J. Phys. Chem. B*, 2000.

[7] K. C. Toussaint and B. J. Roxworthy, “Plasmonic nanotweezers based on Au bowtie nanoantenna arrays for manipulation of nano-to-macroscopic objects,” 2013, vol. 8810, p. 88100U–88100U–7.