УДК 535.3
DOI 10.18413/2075-4639-2019-51-1-115-120

OPTICAL FORCE NEAR THE LASER ILLUMINATED TAPERED TIP

ОПТИЧЕСКАЯ СИЛА ВБЛИЗИ ЛАЗЕРНОЙ ПОДСВЕТКИ КОНИЧЕСКОГО НАКОНЕЧНИКА

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Abstract
Optical near-fields are localized to the source region of optical radiation or to the surfaces of materials interacting with free radiation. Due to the high field gradients of evanescent waves, strong forces are predicted in optical near-fields. In this paper, by solving Maxwell's equations with Finite difference Time Domain (FDTD) simulation based on the numerical software, the effect of changing the period of grating on the optical force around tapered tip with 90 degree laser beam incident angle was studied. The optimization results show that optimum value for period of circular gratings in order to achieve maximum optical force enhancement 208 nm was obtained. This maximum optical force is $1.4 \times 10^{-14} \frac{\mathrm{N}}{\mathrm{W}}$ and occurs when laser wavelength is 655 nm.

Аннотация
Оптические ближние поля локализуются в области источника оптического излучения или на поверхностях материалов, взаимодействующих со свободным излучением. Из-за высоких градиентов поля затухающих волн сильные силы предсказываются в оптических ближних полях. В данной работе, решая уравнения Максвелла с помощью метода конечных разностей во временной области (FDTD) на основе числового программного обеспечения, изучалось влияние изменения периода решетки на оптическую силу вокруг конического наконечника с углом падения лазерного луча 90 градусов. Результаты оптимизации показывают, что было получено оптимальное значение для периода круглых решеток для достижения максимального увеличения оптической силы 208 нм. Эта максимальная оптическая сила составляет $1.4 \times 10^{-14} \frac{\mathrm{Н}}{\mathrm{В}}$ и возникает, когда длина волны лазера составляет 655 нм.

Keywords: Optical antenna, Surface Plasmon, Optical force, Tapered tip, Finite difference Time Domain (FDTD).
Ключевые слова: оптическая антенна, поверхностный плазмон, оптическая сила, наконечник конуса, метод конечных разностей во временной области (FDTD).

Introduction

In many situations, optical near-fields are explored for their ability to localize optical energy to longitudinal scales smaller than the roughly diffraction limit of half-wavelength of incident light. Discrete momentum transfer between photons and electrons was shown experimentally by Compton in 1923. It results in a decrease in energy (increase in wavelength) of the photon (which may be an X-ray or gamma ray photon), called the Compton Effect. Part of the energy of the photon is transferred to the recoiling electron. Inverse Compton scattering occurs when a charged particle transfers part of its energy to a photon. Also the recoil momentum transferred from photons to atoms was observed by Frisch in 1933 [Frisch, 1993].

The mechanical force in laser trapping and cooling experiments can be understood on a semi classical basis where the electromagnetic field is treated classically and the particle being trapped as a quantized two-level system [Shimizu & Sasada, 1998]. In the semi-classical approach atoms are classical and the photons are quantum studied [Mohebbifar et al., 2015]. However, the quantum theory of photons is used to interpret the results correctly [Stenholm, 1986]. Furthermore, according to the photon concept, there are quanta of energy and momentum transfer between the radiation field and the atom. In order to derive the conservation law for linear momentum in an optical field classical electrodynamics was used. In the small object limit, a familiar expression was obtained for gradient and scattering forces. It is possible to derive the forces exerting on atoms and molecules in optical traps. This theory is applied to calculate the trapping forces near a laser illuminated metal tip. The net force exerted on an arbitrary object is determined by Maxwell's stress tensor [Novotny et al., 1998; Larsen, Metiu, 2001; Martin et al., 2001; Krug et al. 2002; Novotny, Hecht, 2006; Novotny et al., 2009; Kharintsev et al., 2013; Zohrabi, Mohebbifar, 2015; Kharintsev et al., 2017].

Field enhancement near metallic nanoparticles structures plays a major role in optical phenomena such as second harmonic generation (SHG) surface enhanced Raman scattering and near-field microscopy. The enhancement originates from the combination of the electrostatic lightning-rod effect, due to the geometric singularity of sharply pointed structures, and localized Surface plasmon resonance (SPR) which depends sensitively on the excitation wavelength. Indeed Surface plasmon resonance is the resonant oscillation of conduction electrons at the interface between negative and positive permittivity material stimulated by incident light. SPR is the basis of many standard tools for measuring adsorption of material onto planar metal (typically gold or silver) surfaces or onto the surface of metal nanoparticles. On the other hand Strong evanescent waves are excited preferentially (although not exclusively) at the boundary of two different media, for example by total internal reflection (TIR), light interaction with sub-wavelength period gratings or small micro/nano-objects (particles, tips, apertures, etc.) whose sizes are comparable to the incident wavelength. Evanescent waves are undamped electromagnetic modes at two dielectric media interfaces. Unlike dielectrics, the free electron gas of metals can sustain surface and volume charge density oscillations (i.e. plasmonic resonance wave, leading to the absorption and scattering of laser light in an unusual way compared to dielectrics [Wang et al., 2004]). The plasmonic waves are damping electromagnetic modes due to the high dissipative factor of metals and can only propagate a limited short distance (typically several tens of micrometers) along the surface. Despite the slightly different physical natures of evanescent waves and plasmonic waves, both waves are near-field limited and are able to confine light into a subdiffraction-limited spot, which is important for laser nanofabrication [Wang et al., 2009].

In this study, at first effect of changing the period of grating on the field enhancement around tip apex was studied by solving Maxwell's equations with Finite difference Time Domain (FDTD) simulation numerical software. Then optical force near a laser-illuminated tapered Tip was studied and optimum value of circular gratings in order to achieve maximum output electric field intensity and maximum optical force enhancement were obtained.

Method and simulation results

The Finite-Difference Time-Domain method (FDTD) is today's one of the most popular technique for the solution of the Maxwell's equations with complex geometries [Taflove, Hagness, 2000; Galarreta et al., 2011]. It has been successfully applied to an extremely wide variety of problems, such as scattering from metal objects and dielectrics, antennas, micro strip circuits, and electromagnetic absorption in the human body exposed to radiation. The main reason of the success of the FDTD method resides in the fact that the method itself is extremely simple, even for programming a three dimensional code. The technique was first proposed by K. Yee, and then improved by others in the early 70s.

In FDTD, the electromagnetic field and structural materials of interest are described on a discrete mesh composed of so-called Yee cells. Maxwell's equations are solved discretely in time, where the time step used is related to the mesh size through the stability criterion. The Lumerical software, based on the FDTD method, is utilized. The FDTD approach has rapidly become to one of the most important computational methods in Electromagnetics since Yee proposed it in 1966 [Novotny, 2008]. In other words FDTD (finite-difference time-domain) approach is one of the most commonly used techniques for solving the complex Maxwell's equation [Elsherbeni et al., 2003; Mulyanti et al., 2018; Sadeghi, Hamidi, 2018]. The commercial software has been developed based on FDTD approach such as XFDTD software, SEMCAD software and Lumerical software. Lumerical has been at the forefront of developing powerful simulation technology for photonic designers which was released in 2003 in two sections FDTD solutions and MODE solutions. In fact Lumerical develops photonic simulation software – tools which enable product designers to understand light, and predict how it behaves within complex structures, circuits, and systems. These tools allow scientists and engineers to exploit recent advances to photonic science and material processing to develop high impact technologies across exciting fields including augmented reality, digital imaging, solar energy, and quantum computing. FDTD can easily handle a variety of geometric shapes consisting of various types of materials, including dielectric, magnetic, frequency-dependent, nonlinear, and anisotropic materials. Features in electromagnetic computational technique of FDTD are very attractive to solve various applications, such as microwave devices, antennas, radar cross section, wave propagation, waveguide, and optical devices.

To generate a strong field enhancement at the tip, the electric field of the exciting laser beam needs to be polarized along the tip axis. The influence of tip shape and material on the field enhancement has been discussed in a series of publications with the aim of discovering the optimum tip [Martin et al., 2001; Gerton et al., 2004]. The electric field around the optical antenna is calculated and simulated based on Maxwell's equations (Eq. 1 and 2).

$$\mathrm{E(r)} = E_0 + \mathrm{i}\omega\mu\mu_0 \int_v \bar{G}(r, r') j(r')\, dV' \tag{1}$$

$$\mathrm{H(r)} = H_0 + \int_v \{\nabla \times \bar{G}(r, r')\} j(r')\, dV' \tag{2}$$

Where E_0 is the initial electric field of the plane wave laser, H_0 initial Hamiltonian, ω Angular frequency of incident field and $\bar{G}$ is the dyadic Green's function. The enhanced field at the tip results from an increase in the surface charge density. The incident laser beam drives the free electrons in the metal along the direction of polarization. While the charge density is zero inside the metal at any instant of time ($\nabla.\boldsymbol{E} = \boldsymbol{0}$), charges accumulate on the metal surface. When the incidence polarization is perpendicular to the tip axis, completely opposed points on the tip surface have opposite charges. As a consequence, the foremost end of the tip remains unchanged. On the other hand, when the incidence polarization is parallel to the tip axis the induced surface charge density is rotationally symmetric and has the highest amplitude at the tip apex. The enhanced field is confined to the tip apex in all three dimensions. Thus the illuminated tip represents a Nano-scale light source.

Here the effect of changing the antenna geometry on the field enhancement and then on the optical force enhancement was studied. A golden tip with a 30^0 Cone angle, a 10 nm radius of apex, 1200 nm distance of the last circular grating from tip apex, 30 nm depth of etched grating and some proposed period of grating were considered. A plane wave of laser beam was considered in the visible spectral range. For mentioned geometry of golden tip and three period of grating 200, 250 and 300 nm enhancement of electric field was simulated and then light intensity as the square of electric field was calculated and illustrated in figures 1(a), 1(b) and 1(c) respectively. These results confirm that there are significant changes in the distribution of intensity in the x-y plane around apex by changing the period of grating. The optimization results show that the highest light intensity near tip occurs for period of grating 208 nm and these results presented in figure 1(d).

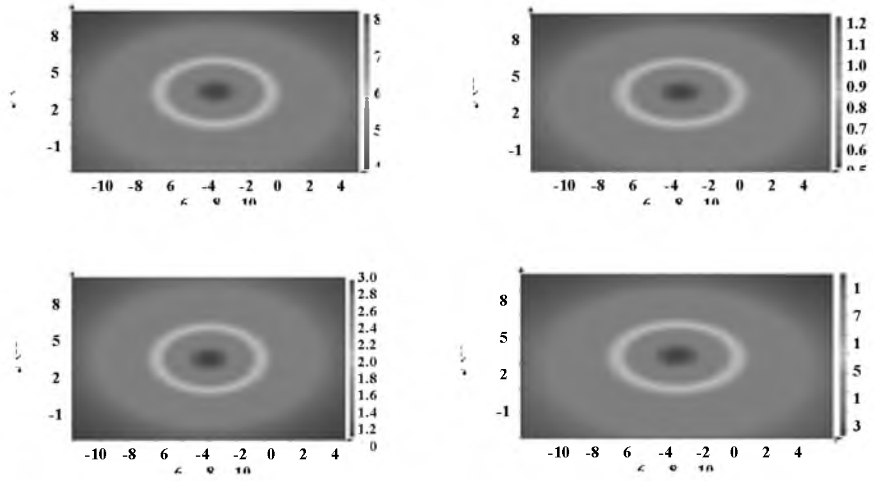

Fig.1. Electric field enhancement in the xy plane near the tip when the period of the grating is (a) 200 nm, (b) 250 nm, (c) 300 nm and (d) 208 nm (optimized) with 90 degree laser beam incident angle.

In the next step, the optical force near a laser-illuminated tapered tip for three period of grating 200, 250 and 300 nm and then for optimum value of circular gratings 208 nm was obtained. The results of these simulations are shown in figures 2 (a), 2 (b), 2 (c) and 2 (d) respectively.

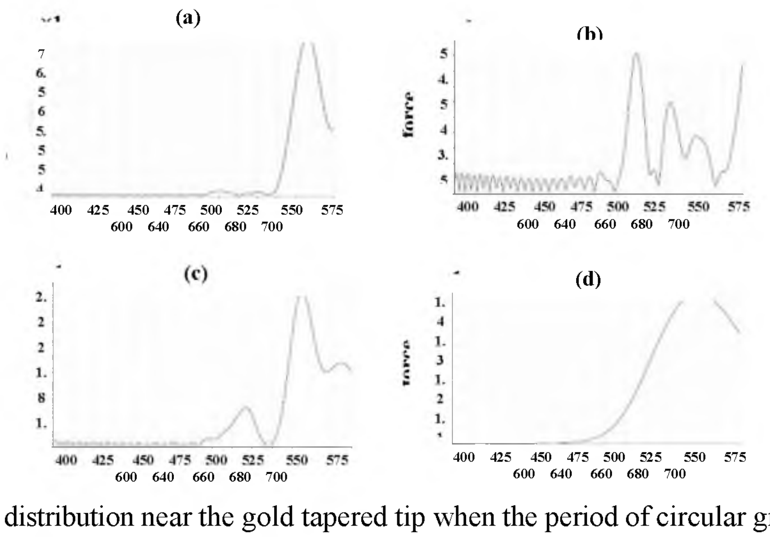

Fig. 2. Optical force distribution near the gold tapered tip when the period of circular grating is (a) 200 nm, (b) 250 nm, (c) 300 nm and (d) 208 nm (optimized antenna)

From these figures it is clear that by changing the geometry of the antenna, the optical force near the gold tip also changes. Also these figures show that for optimum value of circular gratings 208 nm both maximum light intensity and maximum optical force near the gold tip occurs. This maximum optical force is $1.4\times10^{-14}\frac{N}{W}$ and occurs when laser wavelength is 655 nm. One of the most important applications of this approach are increasing the resolution of microscopic photographs in tip-enhancement near field optical microscopy and decreasing of background signal.

Conclusion

In this theoretical work, the effect of antenna geometry on the electric field enhancement and optical force around gold tapered tip was investigated. The Maxwell's equations with Finite difference Time Domain (FDTD) simulation Lumerical Software were solved. The simulation results show that changing the period of gratings, electric field distribution and optical force around gold tapered tip changes. The optimization results show that tapered tip with period of gratings 208 nm has maximum optical force enhancement ($1.4\times10^{-14}\frac{N}{W}$) at 655 nm laser wavelength incident.

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