Optical force mapping of plasmonic modes generated by a nanoantenna

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Abstract: We present experimental spatial mapping of optical force generated by the plasmonic mode confinement of a nanoantenna at 1550 nm. Maxwell's stress tensor method is used to simulate the force map and it agrees well with the experimental data.

Radiation pressure and optical force originate from the elastic scattering of photons with a momentum of h/λ. It has been shown that if light is focused by traditional lens optics, a force large enough to measure with a probe particle is possible [1]. Optical trapping, as this phenomenon is called, has been well developed by the far field optics community. More recently, a lot of interest has been generated to use the near field region to generate an optical force to trap smaller particles or molecules. In this case, one may use a nanoantenna to focus the light to a spot smaller than the incoming wavelength, and a force in the piconewton range may be expected, as shown by simulation [2]. One can then even use these local trapping forces to build a biosensor based on surface plasmon resonance[3]. So far, there has been little experimental work in measuring these near field forces with high spatial resolution. Here we present an experimental method to accurately map this force.

A plasmonic nanoantenna can be used to focus light down to a spot orders of magnitude smaller than the incoming incident wavelength [4]. Here we have chosen a metal-dielectric-metal (MDM) bow-tie antenna design, due to its capability to generate higher field enhancement [4]. Because optical force is based on the divergence of electromagnetic energy density, such a strong electric field concentration created by this bow-tie design can lead to a very large force density. We have chosen a lock-in atomic force microscope method to map this optical force, and the minimum force sensitivity of our system can be given by[5] $F_{\min} = \sqrt{4k_B TkB/\omega_0 Q}$, where k_B is the Boltzmann constant, T is room temperature, k is the spring constant of the cantilever (3 N/m), B is the bandwidth of measurement (set by lock-in amplifier) used in the force measurement (7.8 Hz), ω_0 is the resonant frequency of the AFM tip (~101 kHz), and Q is the quality factor of the cantilever (~160). This leads to a force sensitivity on the order of ~40 fN in our setup. Thus, measuring optical force on the order of a fraction of a piconewton is not limited by the thermal sensitivity of our system.

We have used FDTD software to simulate the bow-tie structure to find the resonant length at our operating wavelength of 1550 nm. We have then used Maxwell's stress tensor method to calculate the optical force intensity on the AFM tip and the results are shown in Figure 2d. After optimizing our design, we fabricated our devices on the end of a cleaved 125 μm Corning SMF-28E+ optical fiber. The fiber end was coated with $Au/SiO_2/Au$ by electron beam evaporation. The bow-tie antenna was then fabricated on the surface of the coated fiber using focused ion beam (FIB) milling. The SEM micrograph of the fiber and bow-tie is shown in Figure 1.

We have experimentally measured the near-field using apertureless near-field scanning optical microscopy (a-NSOM) and the optical force intensity using non-contact atomic force microscopy. Our a-NSOM setup has been previously characterized in [4], but this setup is fiber-based. To measure the optical force, we operate the laser at 4 mW at 50% duty cycle at 1 kHz. We need to modulate the laser at low frequency because it takes some time (~1ms) for an external force to change the amplitude or phase of the AFM tip[6]. We then connect the trigger of the laser to the reference of the lock-in and the cantilever deflection signal to the signal input of the lock-in. We then map the output of the lock-in to the position of the AFM tip, giving a map of how the laser signal has affected the amplitude of the AFM tip. The result is shown in Figure 2c.

The AFM output and the simulated force map both show a central peak with two lobes at the end of the bow-tie, where the signal is diminished compared to the central peak. The AFM output shows a

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larger central peak because in the simulation we considered only a sphere instead of the entire AFM tip and also our AFM tip likely has a larger radius than the sphere we used in the simulation.

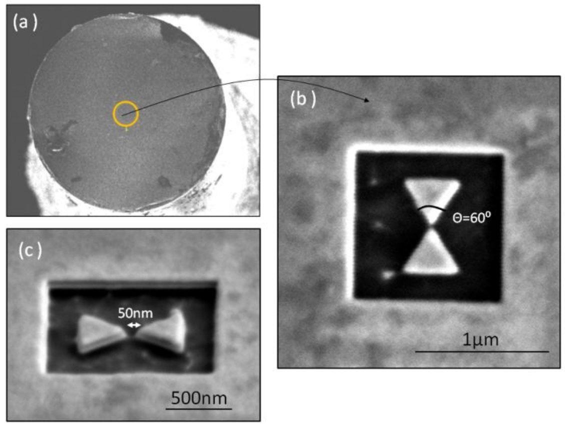

Figure 1 - SEM micrograph showing end of fiber (a), bow-tie antenna (b), and oblique angle of bow tie (c)

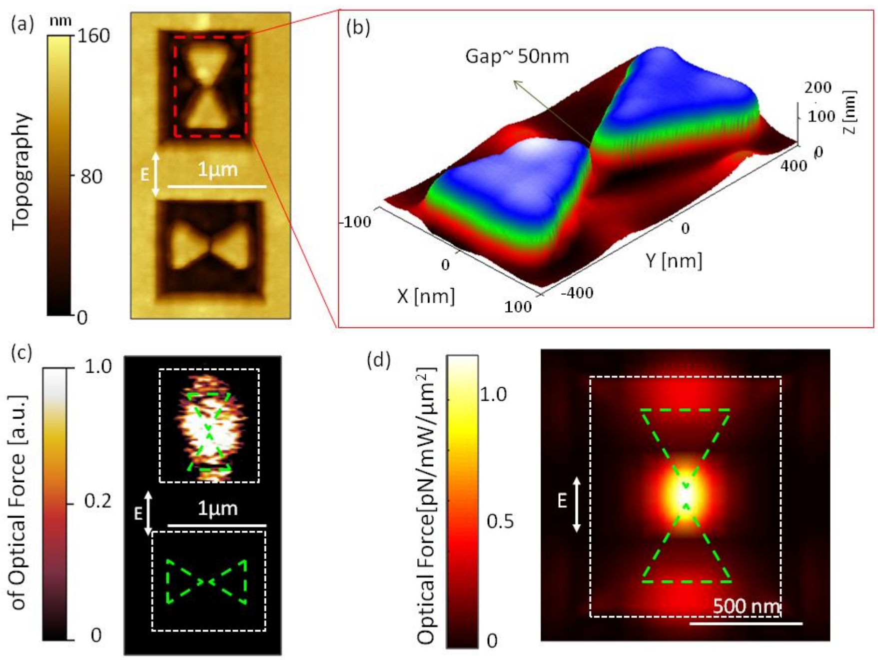

Figure 2 - Topography of bow-tie antennas (a), 3-d view (b), AFM lock-in map of optical force signal (c), simulation map of optical force (d)

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