Plasmonic nanograting tip design for high power throughput near-field scanning aperture probe

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Abstract: We design nanogratings consisting of concentric plasmonic resonance grooves on the metallic sidewalls of near-field scanning probe aperture to increase the power throughput without losing the imaging resolution. Nanograting tip design involves choosing the proper pitch length and the cut location of grooves. Four different nanograting designs are evaluated, as compared with standard single aperture pyramidal near-field scanning probe without grating patterns. We show that, by adding nano-grooves at the location of electromagnetic field intensity-maximum along interface and with the pitch period matching the surface plasmon wavelength, the power throughput can be greatly increased by at least a factor of 530 at 405nm UV wavelength with 100nm diameter aperture probe.

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References and links

1. H. Raether, Surface Plasmons on Smooth and Rough Surfaces and on Gratings, (Springer-Verlag, 1988).


1. Introduction

Periodically modulating metal surface is often used to support surface plasmonic polaritons (SPP) and enhance local focusing beyond the diffraction limit [1]. Effective electric or magnetic field concentration and delivery into or out from the sub wavelength spatial volume are extremely challenging for nano-optical imaging and diagnostics [2,3]. Various pursuits for effectively squeezing electromagnetic energy within near-field region have been studied, such as bull’s eye structure surrounding a cylindrical hole in a suspended silver film [4], convergent geometries of narrowed waveguides [5,6], air gap [7], and tapered conic metal rods [8–10]. Because surface plasmon wave along the metal and dielectric interface is sensitive to the surface periodical corrugations, one can use gratings to combine plasmonic resonance and diffraction to enhance apertureless probe with radially polarized incident light [8,10]. Similarly spherical rings have been fabricated on fiber probe apex to demonstrate power enhancement of 36 times with respect to the single aperture probe tip through photolithography [11]. Slits or rings on flat substrate have also been widely studied for collimation, interference [12] and concentration with shaped radially polarized beam [13].

Although studies on tapered fiber tip or conic metal point tip have brought extensive attentions for optimized nanofocusing [8–11,13,14] and spectrum modulation [15], the hollow-pyramid near-field probe, benefited from its hollow structure, looks more attractive as it can provide larger taper angle, higher power throughput [16], higher thermal threshold and mechanical robustness. Its negligible optical path distance helps avoid pulse chirping with ultrafast excitation [17]. As demonstrated in [18], the hollow pyramidal silicon dioxide probe coated with aluminum nanogratings increased power throughput over 10-fold by varying the nanograting period. A 35-fold second harmonic generation (SHG) intensity enhancement at near-infrared region has also been reported [19].

A proper nanograting design involves choosing the pitch length and its “cut location” (the distance from the center of groove to the apex), which are determined by many factors, including the tip geometric dimensions, material parameters, the operating wavelength and the electromagnetic field distribution. The nanogratings that have been studied in [9,11,18] often have very different pitch lengths and locations along the three dimensional probe sidewall surfaces. In this paper, we will explore how these design parameters will affect the divergence angle and transmission ability of light emitted from near-field scanning microscope (NSOM) aperture probe [20,21].

In general, we optimized the nanogratings on cantilever-based pyramidal aperture probe [16,22], whose structure is shown in Fig. 1, through a comparative study of four grating designs with various pitch lengths and cut locations. A finite-difference time-domain (FDTD)
Simulation shows that by properly choosing the pitch length and cut location, one can increase the power throughput of near-field scanning probe by a factor of 530 at UV wavelength as compared with a standard single aperture probe with the same aperture diameter of 100nm, while retaining the same scanning resolution. To be consistent with the later experiment where we plan to measure fluorescent power from quantum dots excited by the evanescent light from the probe, we choose 405nm wavelength in the simulation. However, the grating design principle is applicable to other wavelengths.

![Diagram of nanogratings on probe tip](image)

For the rest of the paper, we first illustrate the theoretical model and design considerations. The numerical simulation results are then presented and discussed, with emphasis on how to choose the proper parameters for optimized power throughput enhancement.

2. Theoretical model and design

NSOM system offers high resolution from the tip localized evanescent wave. It is the crux that the tip aperture diameter is smaller than the cut-off size of the lowest incident mode such that only the evanescent wave can contribute to the near-field scanning. The power leak is in general around $10^{-4}$ for a standard aperture probe. The incident field inside the aperture probe forms a standing wave pattern. This electromagnetic field distribution is only affected by the tip taper angle, structure material, incident field but not the aperture opening size, as long as all the modes are cut-off at the aperture.

We first illustrate several electromagnetic field distributions with different aperture size obtained by three dimensional FDTD simulations. In Fig. 2, (a) describes the cross section of the pyramidal tip with Cartesian coordinates and linear polarized illumination. The aperture is opened through Ag coatings. (b)-(f) demonstrate the average incident field intensity distribution with different aperture openings. The lowest square-shaped TE mode is picked as the source. These single apertures have diameters smaller than 137nm, the cut-off width of lowest mode TE$_{10}$ or TE$_{01}$ of the metal square waveguide cavity (TE mode referred to the near-field observation plane). The standing wave couples its intensity maxima into Ag coatings along the interface of Ag/SiO$_2$. Since the majority of the incident energy is concentrated inside the pyramidal tip, from perturbation theory the field distribution will not be disturbed significantly by the sub-wavelength tip opening or tip to sample interaction.

A detailed analysis of the simulation result shows that the intensity peak inside the inner Ag coating surface does not match the surface plasmonic wavelength of Ag/SiO$_2$ interface ($\lambda_{\text{pp,Ag/SiO}_2} = 192.9$nm) with 405nm source. Here, we use $\varepsilon_{\text{SiO}_2} = 2.1596$ and $\varepsilon_{\text{Ag}} = -4.0218 + \ldots$
0.69593i respectively in the simulation [23]. Those intensity maxima along Ag/SiO$_2$ interface directly come from the evanescent wave induced from incident field distribution. Each of them will transfer along the Ag inner surface with $\lambda_{spp, Ag/SiO_2}$ wavelength. From the analysis of the single aperture pyramidal probe as shown in Fig. 2, it is clear that we should cut the grating at locations where it could maximize the power coupling from incident field intensity, instead of etching the nanograting on the tip with pitch length as $\lambda_{spp, Ag/SiO_2}$ or the interference length of Ag/SiO$_2$ SPP wave and incident wave as shown in previous approaches [11,18].

![Fig. 2. Incident electrical field intensity distributions for a standard single aperture probe without grating. (a) Schematic configuration of the NSOM aperture probe tip. (b)-(f) Average intensity distributions in logarithm for 405nm wavelength source on the x-z plane of the probe tip with aperture diameter of 10nm in (b), 30nm in (c), 50nm in (d), 80nm in (e), and 100nm in (f). The mode source is linear polarized TE wave along x direction, and matches the simulation source plane structure. The dark outline marks the boundary of metal coating. (b) Shows the scale bar and x-z dimension with unit of nanometer, which is used for (c)-(f). The dashed line marks the first intensity-maximum location close to the apex along Ag/SiO$_2$ interface.](image)

Four types of nanograting probe tip are simulated based on the basic probe structure as shown in Fig. 1. Considering the metal for supporting SPP wave, Ag is a good candidate in visible range with small loss, compared with Au that is suitable for IR range, and with Al that has large loss in visible and grainy coating profile. We chose Ag as the coating material for 405nm excitation. The structure material is SiO$_2$ with thickness of 1.4µm. In the simulation (Fig. 2), the center aperture goes through the Ag layer for achieving sub-wavelength aperture dimension. The cylindrical symmetry nanogratings can be fabricated around the aperture with the compensation of the pyramidal shape sidewalls. Focus ion beam (FIB) can be used to fabricate the nanograting, and by controlling milling time for half cut through the Ag layer without breaking the thin SiO$_2$ structure layer, as shown in Fig. 3. We use cutting depth of 150nm and width of 50nm consistently for 4 types of nanograting with design parameters listed in Table 1.

![Fig. 3. (a) Nanograting designed on pyramidal-shape tip. The nanograting is etched along z direction. On the lateral x-y plane, the focus ion beam milling patterns illustrate the sidewall](image)
compensation. (b) Schematic drawings of the probe apex with nanograting. The distance from groove to tip apex is defined as pitch length or cut location of the designed nanograting.

Table 1. First 6 Nanograting Radius for Four Designs with 405 nm Excitation

<table>
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<tr>
<th>Type</th>
<th>Grating Radius [nm]</th>
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<td>A</td>
<td>210</td>
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<tr>
<td>B</td>
<td>210</td>
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<tr>
<td>C</td>
<td>210</td>
</tr>
<tr>
<td>D</td>
<td>345</td>
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Before diving into the detail of the four nanograting designs, we compare the four designs briefly. The design A and B has the same inner groove but with different grating period, where A has the pitch length matches SPP wavelength of Ag/air interface and B matches interference condition of wave inside the tip and SPP wave along the Ag/SiO$_2$ interface. Design C and D do not have fixed pitch lengths, while the grooves are cut according to electrical field intensity distribution inside the tip.

In our design, the incident light has certain field distribution pattern according to the source wavelength, structure materials and probe pyramidal shape. The intensity maximum of the lowest transmitted mode before cut-off is the closest “hot spot” for surface polariton transporting to the tip apex. This position is chosen as the 1st groove location, denotes with radius of $R_0$. The groove design A has period fixed with half of $\lambda_{\text{SPP, Ag/air}}$, which is 176.5nm. The radius of $n$th groove $R_n$ is calculated as in Eq. (1),

$$R_n = R_0 + \frac{n}{2} \cdot \lambda_{\text{SPP, Ag/air}}.$$  

Groove B is designed with phase matching between probe inside transmission wave and Ag/SiO$_2$ interface surface plasmonic wave, which has been developed in [11]. The radius of $n$th groove $R_n$ is calculated as Eq. (2),

$$R_n = \frac{n}{\lambda_{\text{SPP, Ag/SiO2}}^{-1} \sin(\phi)},$$

where $\phi$ is 54.7°. Design C is cutting the grooves at the intensity maxima along the Ag/SiO$_2$ interface, and design D is at the minima. The center aperture size is fixed as 10nm, 30nm, 50nm, 80nm and 100nm in simulation, which are all smaller than 137nm to ensure that only the SPP wave contributes to the probing light.

3. Numerical results

A 3D FDTD simulation is applied to solve the electromagnetic field distribution at near-field using commercial software from Lumerical Solution® [24]. The simulation volume was a cubic with the dimension of 2.5µm by 2.5µm by 2.7µm, which was modeled into 662 by 662 by 667 Yee cells [25]. The mesh size is 1% of the source wavelength.

During the simulation, the hollow side of the tip was irradiated with linear TE-polarized light beam (regarding to the observing near-field sample plane). Data are evaluated at tip exit media (air). Power enhancement and beam size (the beam size is defined as the cross-section area at the half of the maximum peak intensity) at different near-field distance are compared with the standard single aperture probe, as shown in Fig. 4. One can see that the power of light from probe with nanograting design A was boosted more than 530X compared with single aperture probe at near-field region. And the power enhancement is considerably affected by different grating designs. Design A is the best of the four designs. The average power throughput of design A achieves 1030X than reference probe with 80nm diameter aperture. Furthermore, the beam size of design A is close to single aperture probe and the average size...
ratio ranges from 0.7X to 1.1X with varied center aperture. Design B generally has larger beam size of 0.8X-1.3X. Throughput of design C is 1.7 times of design D, which means it is better to cut grooves at intensity maxima locations to achieve maximum power coupling.

4. Discussions

The comparative study of four nanogratings reveals many interesting facts. First by comparing design A and B, matching the SPP wavelength of Ag and exit media (air) is more effective to increase power throughput. The fixed pitches of design A and B resemble to adding a brag reflector for the probing light, which provides one freedom of engineering the probe for specific frequency source. The emitting SPP probing light can be effectively tuned to match the metal/exit medium surface-plasmon wave momentum along the pyramidal sidewalls. By comparing design C and D, periodically phase matching is more effective than just coupling power into exit medium. The larger enhancement of design C versus D indicates that the location of groove should meet the condition of maximum power coupling for power enhancement.

Secondly, the beam size for all four probes with nanogratings is comparable to standard single aperture probe within the near-field distance. This result is promising since the power enhancement can be decoupled from beam resolution. Meanwhile, the beam size is not sensitive to the center aperture size. Simulation indicates that without the center aperture, the probe provides similar resolution and a slightly reduced power throughput due to the dominant Ag/air SPP mode. Among the four types of nanograting designs, probe with nanograting D achieves the smallest resolution comparing with other probes. This is probably because the grooves are cut at the intensity minima and less power is coupled out along the direction of cut edges (direction z in Fig. 3(a)) to diverge the beam. Most of the energy is transmitted along the sidewall then decays into the air at the apex.
Fig. 4. Electromagnetic power throughput and beam size (beam cross section area at its intensity half maximum) from the probes within near-field range. (a) The center aperture of the probe has a diameter of 100nm. Compared four nanograting designs and the single aperture probe [20], the average power enhancement of design A is 530X compared with single aperture, and average beam size is the 0.7X within 1000nm range. (b)- (e) Probes with aperture size of 80nm, 50nm, 30nm, and 10nm. The power enhancement ratio and beam size ratio of design A to reference are indicated respectively.

Fig. 5. FDTD simulation electromagnetic field distribution around the probe and near-field space. The 100nm diameter aperture probes are simulated with (a) single aperture probe, (b) nanograting design A, (c) nanograting design B, (d) nanograting design C, and (e) nanograting design D. The same dimension and color bar in logarithm are used for plotting (b)-(e).
Overall, using the new purposed design principle, type A nanograting outperforms the other three designs. Figure 5 is x-z plane electric field intensity distribution of the four probes with 100nm aperture. The intensity mapping helps demonstrate our observations.

Finally, in this study we decide to choose linear polarized incident light simply because the radial polarization converter is not available for the experimental setup. The symmetrical probe structure favors a radially polarization light source, which excites the SPP eigen mode (lowest TM mode) [26]. With radially polarized illumination, a nondiffracting Bessel beam can be tightly focused into the probe tip by precisely selecting input wave spatial frequencies [27] and thus more energy can be fed into the Ag/air SPP wave. An ideal case would be to combine nanogratings, nanowire on tip, and nondiffracting Bessel beam for tight focusing to achieve better power enhancement and fine resolution.

5. Conclusions

In summary, we propose a novel approach of designing nanograting on NSOM aperture probe. The performance of four types of nanograting aperture probe has been studied. The results show that grating pitch should matches plasmon polarity phase change along probe metal/exit medium interface, instead of the metal/inner dielectric interface. The internal field distribution considerably affects the power coupling efficiency. The nanograting should be cut at intensity maxima locations. Numerical study shows that the power throughput is 530X compared with a standard single aperture probe at 405nm excitation while retaining comparable full width of half maximum. Finally it is interested to notice that the beam size of all four designs remain roughly the same with about 3 order of magnitude power enhancement. Thus one can improve the power throughput by nanogratings without compromising the probe resolution within near-field region.

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