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Modeling and analysis of surface plasmon microscopy with radial polarization

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ABSTRACT

This paper is to present a model of surface plasmon microscopy (SPM) with radial polarization and numerically examine its far-field imaging performance. More preciously, we analyze the SP distribution on the back focal plane (BFP) of an immersion objective lens and explore how it is focused on the far-field image plane. We show that many of the effects of large angles are eliminated since the image plane is magnified many times with normal *NA* lens. Specifically, we show that the strong longitude component in focal plane vanishes in image plane and the calculations of transverse component distributions of the two planes are also different. We establish the model which gives the mathematical model on SPM imaging area and shows great potentials in relevant field such as confocal configuration or interferometric SPM.

1. Introduction

Surface plasmon (SP) is a powerful surface-sensitive metrology for measurement of sub-nanoscale films thickness and refractive index indication. It propagates along a thin metal layer between two dielectrics [1]. The excellent sensitivity to tiny variations of dielectrics on the metal surface makes SP widely applied in biomedical, chemical and life science related fields. However SP suffers from poor lateral resolution due to the long propagation length in prism based configuration. To optimize this problem, Kano proposed a high numerical aperture (NA) objective excited SP configuration [2] and restricted the propagation length of SP wave within the diffraction localized region, which made the lateral resolution fantastically enhanced. More recently, radial polarization has been introduced to the SP field, aiming to firstly achieve higher signal to noise ratio (SNR) since all the incident is TM polarized and thus available to be converted to SP; secondly to ensure that the well confined SP focus with circularly symmetry [3,4]. The modeling of surface plasmon microscopy (SPM) has drawn much attention since the concept of objective excited configuration was proposed. As for the linearly polarized case, previous work [5] applied Richards & Wolf diffraction [6] theory and explained the focusing property and the imaging performance of SP focusing model. In this paper, we discuss the radial polarization case. Youngworth and Brown studied the focusing properties of cylindrical-vortex beam [7]. Later Yuan [8] and Zhan [9] et al. extended the idea to the plasmonic case and proposed the SP focusing model which revealed the excitation of SP using an immersion objective in radial polarized mode. In previous works [10–12], the distribution of the captured electric intensity on the image plane was taken the same as that on the focal plane. In this paper, we claim that in a reflecting SPM, the two distributions are different for the reason that the image plane is magnified many times that many of the effects of large angles are eliminated. More precisely, the strong longitude component on the focal plane is nearly eliminated when the reflecting beam is focused onto the image plane, and the captured focus is almost composed of transverse component. Based on that, we establish the model of a reflecting SPM when it is in radial polarization mode. We firstly examine the distribution of the back focal plane (BFP) reflected from a high NA objective lens, secondly investigate how it contributes to the electric field distribution on the detected image plane and then discuss how it affects the behavior of image plane through a normal NA lens. We also prove that the distribution of the image plane is Hankel Transform of the field on the BFP. The established model of SPM with radial polarization gives the mathematical model on SPM imaging area and corrects the misunderstanding of the image field distribution in relevant fields. Besides, it shows great potential applications when captured distribution is required such as the confocal configuration [13,14] or interferometric optical *V(z)* field [15]. Furthermore, the proposed model also works for non-plasmonic cases with radial symmetry.

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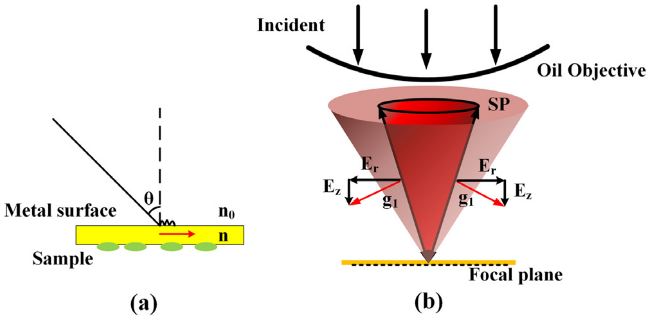

Fig. 1. (a) Schematic diagram showing the Kretschmann configuration for SP excitation. (b) Diagram that showing surface plasmons excitation with immersion objective lens.

2. Excitation of surface plasmons

In this section we make a brief introduction of the SP excitation using objective lens. The excitation of SP with Kretschmann configuration is shown in Fig. 1(a). When the incident beam is focused to the metal surface on the focal plane, SP is excited when the wave vector of the evanescent wave k_x matches with that of the SP which is solved by the Maxwell's theory [2,4]:

$$k_x = \frac{w}{c}\sqrt{\varepsilon}\sin\theta_{sp} = k_{sp} \tag{1}$$

where ω is the plasmon frequency, c is the speed of light in vacuum, ε is the dielectric constant of the targeted metal medium and k_{sp} is the wave vector of SP. θ_{sp}, the optimal resonance angle, is thus acquired by Eq. (1). SP phenomenon features on a sharp amplitude drop and phase variation of 2π around the SP optimal excitation angle. The geometry of SP excitation with an immersion objective lens (NA = 1.25 in this paper) is shown in Fig. 1(b). In the geometry, only the TM polarized beam incident on the sensor chip is able to excite SP which demonstrates the superiority of the radial illumination system since all the incident light is TM polarized and thus available to be converted to SP. It indicates that the SP signal is enhanced in radial polarized SPM. When the light is incident to the sample surface, the k-vectors of the illumination $\mathbf{g_1}$, which is perpendicular to the rays, have a superposition on z-axis when focusing as shown in Fig. 1(b). In this case the electrical field on the focal plane possesses a very strong E_z component when focused on the sensor-chip surface which is introduced in details in [9]. The electric field in the vicinity of the focus through a high NA objective lens can be calculated with Richards–Wolf diffraction theory [6] and the transverse focal plane intensity distribution E_r and longitude distribution E_z, as shown in Fig. 2, along the cylindrical coordinate (ρ_1, z_1) can be expressed as [4,9]:

$$\begin{cases} E_r = A\displaystyle\int_0^{\theta_{\max}} P(\theta)\cos^{1/2}(\theta)\sin\theta\cos\theta t_p(\theta)J_1(k_c\rho_1\sin\theta)\exp(ik_z z_1)d\theta \\ E_z = iA\displaystyle\int_0^{\theta_{\max}} P(\theta)\cos^{1/2}(\theta)\sin^2\theta t_p(\theta)J_1(k_c\rho_1\sin\theta)\exp(ik_z z_1)d\theta \end{cases} \tag{2}$$

where θ is the incident angle of objective and equals to $\arcsin(k_r)$. $P(\theta)$ refers to pupil function of the objective. $t_p(\theta)$ represents the transmission coefficient. k_z equals to $\sqrt{k_c^2 - k_r^2}$, where k_c is $2\pi n_0/\lambda$ and n_0 is the refractive index of the couplant and also that of the substrate. $J_n(x)$ refers to the nth-order Bessel function of the first kind. For an aplanatic system in Richards–Wolf model, an additional factor of $\cos^{1/2}(\theta)$ should be incorporated to account for an amplitude variation of the electric field in object space when the beam is focused. Readers can find more details of the focusing properties in the focal space of radial SPM in [3,8,9].

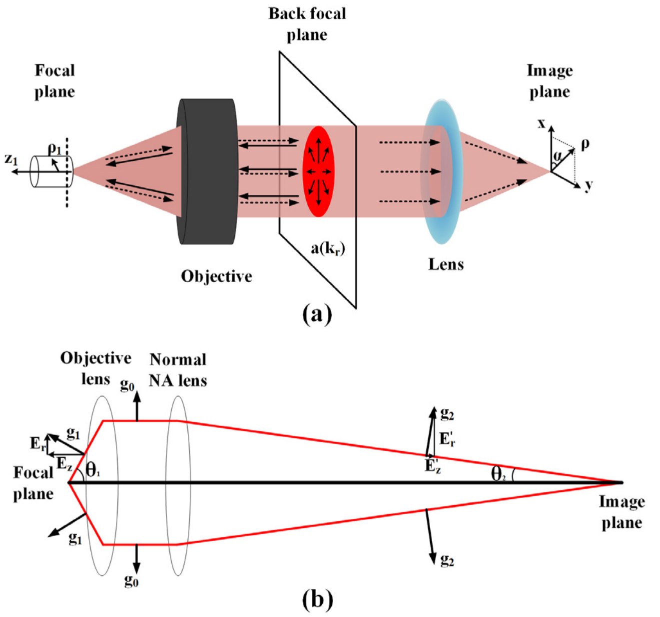

Fig. 2. (a) Geometry of reflecting SPM; a(k_r) refers to the incident wave; the beam reflects back through the BFP and focuses on the image plane; (b) The meridional plane of the beam in SPM system.

3. Modeling of SPM

In this section, we aim to derive the actual distribution that we capture in image plane and model the SPM system with radial illumination. Fig. 2(a) illustrates the SP excitation in a commonly used surface plasmon microscopy configuration with radial polarization. In this configuration, we regard the BFP $a(k_r)$ as the incident plane and assume a planar phase front and constant amplitude, in which k_r is the k vector component parallel to the entrance plane. In this radial SPM system, the arrows on BFP image illustrate the radially polarized direction. The solid arrows are the beam incident to the sample, and the dash arrows refer to the reflective beam. The incident beam is focused onto the sample by an immersion objective with high NA on the focal plane and then reflected back to the system. The excited SP field in focal plane was generally taken the same as the field in the image plane in previous literatures [10,11]. To better explain the focusing in reflecting SPM and reveal how the two electric fields distribute, we give a meridional plane of the beam propagation in Fig. 2(b). The vector $\mathbf{g_0}$ indicates the wave polarized vector on the pupil plane, which is perpendicular to the rays in object space. The reflected distribution with the SP excitation signal passes through the BFP and is focused on the image plane through a normal lens and captured by the detector. The distributions of E_r and E_z on focal plane have been discussed in Section 2. To get the output distribution of the SPM, two procedures are carried out as described in Sections 3.1 and 3.2 respectively.

3.1. From the focal plane to BFP

As shown in Fig. 2(b), when the beam is reflected back and focused on the image plane, the incident angle θ_2 to the detector is nearly zero since the beam is magnified many times and the propagating beam is nearly parallel. The longitude component E'_z in this field at each direction is calculated as $\mathbf{g_2}$ $\sin\theta_2$, which almost equals to zero. It indicates that in this condition only the transverse component should be considered for the captured intensity, and the strong longitude component vanishes. Besides, the E'_r distribution should also be calculated