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Edge scattering of surface plasmons excited by scanning tunneling microscopy

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Abstract: The scattering of electrically excited surface plasmon polaritons (SPPs) into photons at the edges of gold metal stripes is investigated. The SPPs are locally generated by the inelastic tunneling current of a scanning tunneling microscope (STM). The majority of the collected light arising from the scattering of SPPs at the stripe edges is emitted in the forward direction and is collected at large angle (close to the air-glass critical angle, θc). A much weaker isotropic component of the scattered light gives rise to an interference pattern in the Fourier plane images, demonstrating that plasmons may be scattered coherently. An analysis of the interference pattern as a function of excitation position on the stripe is used to determine a value of 1.42 ± 0.18 for the relative plasmon wave vector (kSPP/k0) of the corresponding SPPs. From these results, we interpret the directional, large angle (θ ~ θc) scattering to be mainly from plasmons on the air-gold interface, and the diffuse scattering forming interference fringes to be dominantly from plasmons on the gold-substrate interface.

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42. Theoretically it may be shown that by assuming that the scattered light is driven by a weighted coherent sum of SPP modes from both interfaces, the effectively observed $k_{e\text{ff}}/k_0$ determined from the above fringe shift method is neither that of the air/Au mode nor that of the Au/ITO/glass mode but a weighted average of the two. If both modes mix at the edge, there is some change in fringe visibility (due to partly constructive or destructive interference) and the fringes in the Fourier plane shift as if only one SPP with an effective $k_{e\text{ff}}$ is excited.

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1. Introduction

Propagating surface plasmon polaritons (SPPs) may be used to transfer information and energy in metallic nanostructures with spatial resolution below the diffraction limit [1, 2]. Plasmon-guiding structures, such as metal nanowires [3–9] and stripes [10–15], and their coupling to quantum emitters [16–18] have been extensively studied. However, there are comparatively few experimental reports on the scattering of plasmons into photons at nanostructure edges [8, 19–22], despite the fundamental and practical importance of this issue. One of the challenges of these studies is the separation of the light originating from the edge scattering of plasmons from the light due to the optical excitation.

We use a scanning tunneling microscope (STM) to electrically excite SPPs on electron beam-lithographed Au metal stripes and study the scattering behavior. STM-excitation of plasmons [23–26] has several advantages over the more common optical excitation, for example i) low energy electrical excitation (< 4 eV), which is compatible with current microelectronics, ii) very localized excitation (~10 nm) [27] and iii) the absence of background excitation light. Thanks to this local excitation and the absence of any background excitation light we have demonstrated a new method for measuring the relative wave vector of scattered SPPs.

In this article, we use real and Fourier plane measurements of the collected light from STM-excited plasmons to investigate their scattering properties. Both directional, large angle ($\theta \sim \theta_c$) and diffuse, isotropic contributions to the scattered light are observed. The diffuse emission, observed in the Fourier plane, is modulated by interference fringes. From the excitation point dependence of these interferences, the relative wave vector of the corresponding SPPs ($k_{SPP}/k_0$) is determined to be $1.42 \pm 0.18$. From these measurements it is proposed that the directional, large angle ($\theta \sim \theta_c$) scattering is mainly from plasmons on the air-gold interface, and the diffuse scattering is mostly due to plasmons on the gold-substrate interface.

2. Experiment

The experiment is shown schematically in Fig. 1(a). The experimental setup consists of a commercial STM (Veeco D3100 Nanoscope IVa) operated in air and mounted on an inverted optical microscope (Zeiss Axiovert 200) [25]. Typical tunnel current values are $I = 2-6$ nA and typical sample voltages are $V_s = 2.5 - 2.8$ V. These parameters lead to tip-sample separation distances typically on the order of ~1 nm [28]. Commercially cut Pt/Ir and sharp electrochemically etched W tips [29] are used for STM imaging and plasmon excitation. An air objective (63X, NA = 0.95) and oil immersion objective (100X, NA = 1.45) are used to obtain real and Fourier plane images of the light emitted through the transparent substrate and collected with a charge coupled device (CCD) camera (Roper Scientific). Emission spectra are obtained using a liquid nitrogen-cooled spectrometer (Jobin Yvon).

The samples are electron beam-lithographed Au stripes deposited on a 30 nm-thick indium tin oxide (ITO) film on a glass substrate (refractive index $n_{glass} = 1.52$). The ITO layer is necessary since the surface must be conducting for STM measurements, yet transparent so that the scattered light may be collected through the substrate. The length and width of the Au stripes used are $5 \pm 0.05$ μm and $2 \pm 0.05$ μm respectively. Their thickness is chosen to be 100 nm in order to suppress SPP leakage radiation and thus enable us to concentrate on SPP edge scattering. The experiment is repeated using several different tips and stripes (>20).
3. Results and discussion

Fig. 1. (a) Schematic of the experiment: the STM excites SPPs (red arrows) which propagate radially on an Au stripe (5 μm × 2 μm × 100 nm) on an ITO/glass substrate. Inset: the edge scattered light is collected through the transparent substrate by the objective below the sample. (b) and (c) Real plane emission patterns from an Au stripe excited by STM, as collected with an oil objective (NA = 1.45) and an air objective (NA = 0.95), respectively. The yellow dotted lines indicate the Au stripe edges. The green spot indicates the STM tip position. The STM excitation parameters are V_s = 2.5 V, I = 2 nA, Pt/Ir tip, accumulation time t = 30 s in (b) and V_s = 2.8 V, I = 6 nA, accumulation time t = 120 s in (c).

Figure 1(b) shows the real plane image of the light generated when STM-excited SPPs are scattered at the edges of an Au stripe. For this image, the oil immersion objective was used so that light emitted at angles of up to almost 72° was collected (n_{glass} = 1.52). The STM tip position is in the center of the stripe (green dot) and the scattered light is seen along all four edges. STM excitation of SPPs on flat Au films has been shown to produce 2D outgoing circular waves [25, 26]. As the dimensions of the Au stripe are larger than the SPP wavelength in the visible spectrum range (i.e., for \lambda_0 = 700 nm, \lambda_{SPP} \sim 680 nm for air-Au interface SPPs), an outgoing circular wave is also expected in this case (see Fig. 1(a)). Thus it is plausible that SPP scattering into light is observed on all edges of the Au stripe in the real plane image. Note that no leakage radiation through the Au stripe is observed since the stripe is relatively thick (100 nm) [30]. The fringe structures seen outside the stripe are believed to be due to optical aberrations from the imaging system.

Figure 1(c) shows the real plane image for the same STM-surface plasmon excitation experiment, but this time for collection the air objective is used (maximum collection angle is about 39°). In this case, only four light emission spots are observed, located at the edges on the tip-stripe axes. The differences between the real plane images recorded with the oil and air objectives (Figs. 1(b) and 1(c)) are understood by considering the conservation of the k_{SPP} component parallel to the edge of the stripe, as detailed in the appendix.

The real plane and Fourier plane images in Fig. 2 were obtained with the oil objective and with a polarizer before the CCD camera, using the same stripe and same STM tip. The polarizer axis was oriented either perpendicular (Figs. 2(a), 2(c) and 2(e)) or parallel (Figs. 2(b), 2(d) and 2(f)) to the long axis of the stripe. In the real plane images of Figs. 2(a) and 2(b), we see that there is little scattered light detected from SPPs which propagates in a direction perpendicular to the polarizer axis. Thus it appears that the scattered light from SPPs incident on a stripe edge maintains its initial polarization (i.e. TM with respect to the SPP propagation direction) [32].

Figures 2(c)-2(f) show the corresponding Fourier plane images and their cross-sections. From this data it may be estimated that more than 60% of the collected light is emitted into a narrow θ angle range (FWHM \approx 6°) with a maximum at an angle of θ = 41.3° ± 0.6°. This angle is close to the critical angle of the air-glass interface \theta_c = \arcsin(1/n_{glass}) = 41.1° (n_{glass} = 1.52). This result shows that the majority of the scattered light is emitted at large angles.
Fig. 2. Real and Fourier plane images of the light generated when STM-excited SPPs are scattered at the edges of an Au stripe, obtained with the oil objective (NA = 1.45) and a polarizer before the CCD camera. (a) Real plane image, polarizer axis perpendicular to the Au stripe long axis. (b) Real plane image, polarizer axis parallel to the Au stripe long axis. Red double arrows indicate the polarizer orientation. Yellow dashed lines show the position of the Au stripe and the green dot represents the STM tip position. (c) and (d) The corresponding Fourier plane images. (e) and (f) Normalized cross sections of the Fourier plane images along the white dashed lines in (c) and (d) respectively. $\sin \theta = \sin \theta$ corresponds to the air-glass interface critical angle (the angle $\theta$ is measured with respect to the optical axis, see also Fig. 3(a)). The STM excitation is carried out with a Pt/Ir tip ($V_s = 2.5 \text{ V}, I = 2 \text{ nA}$, accumulation time $t = 60 \text{ s}$). As the usable wavelength range of the polarizer is 380 - 780 nm, a 775nm short pass filter is also used during these measurements. The Fourier plane measurements obtained with the oil immersion objective were calibrated from molecular fluorescence data by assigning the critical angle to the inflection point, i.e., where the intensity increases rapidly [25, 31].

In Fig. 2 we note that the intensities are asymmetric in opposite directions. Such an asymmetry is common for the STM-excitation of plasmons on metal structures [33]. An artifact from the imaging system may be ruled out as the source of the observed asymmetry as it is not always in the same direction. While local roughness may play a role, it is unlikely to be the main cause of the asymmetry since the same phenomenon is seen to vary with time on thin gold films [33]. Thus we conclude that the observed asymmetry arises from a local asymmetry of the STM tip.

The data of Fig. 2 was acquired using the same tip and no evolution of the tip was observed during the experiment. From the Fourier plane cross-sections of Figs. 2(e) and 2(f), we see that the highest intensity arc is in the same direction as the brightest edge in the real plane images of Figs. 2(a) and 2(b) respectively. This observation implies that SPPs are mainly scattered in the forward direction at stripe edges. This result is similar to the unidirectionalmetry of light emitted from laser-excited metal nanowires of large diameter (> 300 nm) [8] and to the theoretical studies of SPP scattering on a metal wedge [34]. Thus SPPs excited by STM are shown to scatter principally in the forward direction at large angle $\theta$ (collected light observed close to the critical angle) when scattered at stripe edges.

If the grayscale is changed in Figs. 2(c) and 2(d), fringes are seen in the center of the image, i.e. for angles $\theta$ less than the air-glass critical angle, as shown in Figs. 3(c) and 3(g), (Fig. 3 data is obtained with the air objective in order to avoid collecting as much as possible the light emitted at large angle, thus increasing the signal-to-noise ratio for the data at small angle). The fringe period is inversely proportional to the distance between the opposite edges (width or length). This strongly suggests that the fringes are the result of the interference of...
the scattered light from each edge (labeled A and B in Fig. 3(a)). This implies that at least part of the STM-excited plasmon wave scatters coherently. Note that two perpendicular sets of fringes are superimposed when Fourier plane images are collected without a polarizer.

Fig. 3. Fringes observed in the Fourier plane. (a) Schematic of the experiment: a sharp tungsten STM tip is placed above the center of the stripe and launches SPPs. SPPs at both the air/Au (dark blue curve) and Au/substrate interface (red curve) are excited. The radiative scattering at opposite edges (A and B) is collected using an air objective (NA = 0.95) and a polarizer. The distance (L) between opposite edges is either the width or length of the stripe. The STM tip, located initially at d = 0, is then displaced by an amount Δd along the width or length of the stripe and the experiment is repeated. (b) and (f) Real plane images recorded with the polarizer axis perpendicular or parallel to the stripe long axis respectively. Yellow dashed lines indicate the profile of the stripe, and green dots indicate the STM tip excitation position. The excitation conditions are Vs = 2.5 V, I = 6 nA, and the accumulation time is t = 120 s (W tip). (c)-(e) and (g)-(i) Fourier plane images recorded with a polarizer perpendicular or parallel to the Au stripe long axis respectively, when the STM tip is displaced from the center by different values of Δd. The excitation conditions are Vs = 2.8 V, I = 6 nA, and the accumulation time t = 600 s (W tip). The dashed lines in (c)-(e) and (g)-(i), as well as j) and k) indicate the central fringe. (j) and (k) Cross sections of the Fourier plane images (vertical lines in (c)-(e) and (g)-(i)) are plotted together (raw data and smoothed curves). The red • are for Δd = 0, the blue ◦ for Δd = 100 nm, and the green ▲ for Δd = 200 nm. Curves in (j) and (k) are shifted vertically for clarity. The Fourier plane images obtained with the air objective were calibrated using the fringe pattern spacing from a known laser-illuminated diffraction grating. The fringes in (d) and (e) are seen to curve slightly due to the fact that phase difference between the light scattered from each edge depends on the incident angle of the SPP when the tip is not in the center of the stripe.

Figures 3(c)-3(e) and Figs. 3(g)-3(i) show how the fringe pattern shifts as a function of STM tip excitation position. This fringe shift indicates that the SPPs which give rise to the Fourier plane interference pattern are not standing waves, since the phase difference between the scattered light from the opposite edges would be independent of the STM tip excitation position in that case. SPP standing waves in this system would give rise to interference oscillations in the emission spectrum [6] but these are not seen (see Fig. 4). This suggests that...
losses are too high and/or the reflectivity of the plasmons at the edges is too low, resulting in standing waves that are too weak to be detected.

The fringe patterns and related shifts with STM tip excitation position may be well explained using a Young’s double-slit model [35–37]. The radiation from the stripe edges (A and B) may be considered as two light sources. The electric field from the stripe edge at point A may be written as 

\[ E_A = E_{A0} \exp[i(\omega t - \Phi_A - \mu_A)], \]

where \( E_{A0} \) is the electric field amplitude, \( \omega \) is the angular frequency of the scattered light (corresponding to wavelength \( \lambda_0 \) in air), \( \Phi_A \) is the phase delay due to the propagation of SPPs from the STM tip to the point A, and \( \mu_A \) is an additional phase delay due to scattering at the stripe edge at point A. An analogous expression is found for the electric field from the stripe edge at point B.

If only scattering perpendicular to the edge is considered for simplicity, the intensity of the interference pattern in the Fourier plane is equal to:

\[
I = I_A + I_B + 2\sqrt{I_A \cdot I_B} \cos(\Phi_A - \Phi_B + \mu_A - \mu_B + \delta_A - \delta_B)
\]

where \( I_A = |E_A|^2 \), \( I_B = |E_B|^2 \), \( \delta_A(\delta_B) \) is the phase delay due to the light propagation from A(B) to the Fourier plane. The position of the STM tip is \( d \) (\( d = 0 \) in the middle of the stripe).

With \( k_{SPP} \) the wave vector of the propagating surface plasmons, we have \( \Phi_A - \Phi_B = 2k_{SPP} \cdot d \). We assume that the phase difference due to scattering at the stripe edges is independent of the tip excitation position, i.e., \( \mu_A - \mu_B \) does not depend on \( d \). The phase difference from the optical path difference is: \( \delta_A - \delta_B = k_0 \cdot L \cdot n_{\text{glass}} \cdot \sin \theta \) (see Fig. 3(a)), where \( k_0 = 2\pi / \lambda_0 \) is the wave vector of the emitted light in air.

Bright fringes appear if the total phase difference is:

\[
\Phi_A - \Phi_B = \mu_A - \mu_B + \delta_A - \delta_B = 2m\pi,
\]

where \( m \) is an integer. Thus, the position of a bright fringe in the Fourier plane is:

\[
\lambda_{\text{bright}} = \frac{\lambda_0}{L} \cdot m - \frac{2d}{L} \frac{k_{SPP}}{k_0} - \frac{\mu_A - \mu_B}{k_0 \cdot L},
\]

From the Fourier plane data in Fig. 3 we measure the separation between bright fringes to be 0.347 (\( L = 2 \mu m \)) or 0.142 (\( L = 5 \mu m \)). The spacing between fringes in the Fourier plane is equal to \( \Delta(n_{\text{glass}} \cdot \sin \theta)_{\text{bright}} = \lambda_{\text{bright}} / L \), as may be seen from Eq. (2). Thus from these measurements we determine values of 694 nm (\( L = 2 \mu m \)) or 710 nm (\( L = 5 \mu m \)) for the wavelength of the emitted light. From Fig. 4, we see that the light emitted from an STM-
excited gold stripe has a central wavelength at about 700 nm and a FWHM of ~150 nm. The photon wavelengths determined from Eq. (2) are thus in agreement with our broad emission spectra measurements.

When the excitation position of the STM tip is displaced by $\Delta d$ the bright fringe shift is equal to:

$$\Delta(n_{\text{glass}} \cdot \sin \theta)_{\text{height}} \bigg|_{\text{shift}} = \frac{2 \cdot \Delta d}{L} \cdot \frac{k_{\text{SPP}}}{k_0}$$  (3)

Rearranging Eq. (3) we get

$$\frac{k_{\text{SPP}}}{k_0} = \frac{L}{2 \cdot \Delta d} \cdot \Delta(n \cdot \sin \theta)_{\text{height}} \bigg|_{\text{shift}}$$  (4)

Thus from Eq. (4), the $k_{\text{SPP}}/k_0$ value can be deduced from the fringe shift for a displacement $\Delta d$ of the STM tip excitation position. The obtained $k_{\text{SPP}}/k_0$ values are $1.37 \pm 0.16$ for $L = 2 \ \mu m$ and $1.49 \pm 0.20$ for $L = 5 \ \mu m$. Combining these two sets of measurements gives us an average value of $1.42 \pm 0.18$. This value is large compared to the $k_{\text{SPP}}/k_0$ value measured previously for stripes [22]. Sources of error include thermal drift of the STM tip with respect to the sample, as we are working in air at room temperature, and the fact that the precise fringe positions are difficult to determine due to the broadband nature of STM excitation (see Fig. 4) and the low signal-to-noise ratio.

In order to verify the validity of our experimental method for the determination of the plasmon relative wave vector $k_{\text{SPP}}/k_0$, we perform similar fringe shift measurements on a 200 nm thick Au film perforated with two 250 nm-diameter holes [33], see Fig. 5. The center-to-center distance between the holes is 2 $\mu$m and the same experimental setup is used. By measuring the shift of the center fringe as a function of STM tip excitation position between the holes, $k_{\text{SPP}}/k_0$ is determined to be about $1.06 \pm 0.08$ from Eq. (4). This value agrees to within experimental uncertainty with the theoretical value of $k_{\text{SPP}}/k_0 = 1.03$ [38] estimated for a gold film. ($\varepsilon_{\text{Au}} = -16.78 + 1.317i$ [39], $\lambda_0 = 700$ nm), thus confirming the validity of the method.
From these results we propose that there are two main contributions to the scattered light observed when SPPs are excited on gold stripes. From previous experiments [25, 26], it is known that the STM can excite SPPs on the air/metal interface of a gold film, and the same is expected on a gold stripe. The major contribution (more than 80%) to the collected light is thus assigned predominantly to SPPs on the air/gold interface which are forward scattered and collected at angles larger than the air/glass critical angle, $\theta_c$. In other words, when the SPPs on the “top” surface (air/gold interface) are scattered into photons at the stripe edge, there is little change in the direction of propagation. Here, for the first time for STM experiments, a second, much smaller contribution (0.5 – 2% of the collected light, as estimated by integrating the Fourier plane data for $n_{\text{glass}} \cdot \sin \theta \leq 0.5$) is attributed to the SPPs excited on the Au/ITO/glass interface (see Fig. 4(a)). The value of $k_{\text{SPP}}/k_0 = 1.42 \pm 0.18$ determined from the fringe pattern shift with STM tip excitation position is in agreement (to within the uncertainty of the experimental measurement) with the expected value of 1.57 calculated for SPPs excited on the Au/ITO/glass interface (i.e., the “bottom” of the stripe, see Fig. 3(a)). This theoretical value was obtained using the optical transfer function method [40, 41], ($k_\circ = 2\pi/\lambda_\circ, \lambda_\circ = 700 \text{ nm}$). This suggests that the major component of the coherent light giving rise to fringes is from Au/ITO/glass interface plasmons, but the fact that the measured value is somewhat lower than the calculated $k_{\text{SPP}}/k_0$ value suggests that diffusely scattered light from air/Au interface plasmons may also contribute [42].

Other possible explanations for this surprisingly large value of $k_{\text{SPP}}/k_0$ should be considered. The STM tip and the localized plasmons located beneath it might contribute to the scattered light in the case where the tip radius of curvature is large compared to the stripe width. However, in our case the STM tip radius is less than 100 nm, an order of magnitude smaller than the stripe width. Another possibility might be the influence of corner modes. SPP modes on Au stripes are hybrid due to the coupling of SPPs on the Au/air interface with corner modes which are highly confined at Au stripe edges [10]. This hybridization leads to a modification of the $k_{\text{SPP}}$ [22, 43]. However, changes in $k_{\text{SPP}}$ due to corner plasmons are small for $L = 2 \mu \text{m}$ ($\Delta k_{\text{SPP}}/k_0 < 0.1$) and cannot completely account for the large value of $k_{\text{SPP}}$ measured here. Thus the idea that the fringes arise from light scattered from plasmons on the gold-substrate interface appears to be the most probable.

The question of how these Au/ITO/glass interface plasmons are excited is an interesting one. It is known that the inelastic tunnel current of an STM excites both localized and propagating surface plasmons on air-gold film [25, 26]. The localized plasmons might in turn excite the “bottom” interface plasmons. Another possibility might be that the scattered light from the top interface is the excitation source. This last possibility may be ruled out, as the measured fringe shift as a function of the STM tip excitation position would not reflect the relative $k_{\text{SPP}}$ value of the Au/substrate plasmon. We thus propose that it is the localized surface plasmons directly beneath the STM tip that excite the Au/substrate plasmons which lead to the observed fringe shift.

Since the contribution from these SPPs on the gold-substrate interface is expected to be small due to the thickness of the gold stripe (100 nm), it appears that the majority of the scattered light from this lower interface is coherently and diffusely scattered, and is thus quite different from the mainly directional forward scattering from the upper interface. If the plasmons from the two interfaces scattered in a similar fashion, we would expect that the relative $k$-vector measured by the fringe shift method would be closest to the value for the air/gold interface plasmons, which is not the case. (It is assumed that the air/gold interface plasmons are more efficiently excited by STM). Thus, in this way we have identified two different scattering regimes for SPPs on gold stripes, depending on from which interface the SPPs originate.

4. Conclusion

We have investigated the scattering of electrically exited SPPs on a gold stripe. Two different scattering components have been identified: a strong directional contribution that is scattered...
at large angle (i.e., 60% in a 6° range around the air/glass critical angle and more than 80% at angles above \( \theta_c \)) and a weaker (\( \gtrsim 0.5\% \)) contribution that is diffusely, yet coherently scattered, and observed at low angle (\( n_{\text{glass}} \cdot \sin \theta \leq 0.5 \)). Using an original method to determine the wave vector of SPPs, we attribute the weak, small \( \theta \) angle scattering primarily to light from SPPs on the Au/substrate interface and the directional, large \( \theta \) angle scattering to light principally from SPPs on the Au/air interface. This knowledge of how SPPs are scattered at edges is important in the context of coupling plasmonic stripes with other plasmonic nanostructures or with quantum emitters.

**Appendix: Real plane images recorded using the air and oil immersion objectives**

In order to satisfy the boundary conditions of Maxwell's equations and conserve momentum, the \( x \) components of the SPP and scattered light wave vectors must be equal, i.e., \( k_{x,\text{glass}} = k_{\text{SPP}} \cdot \sin \alpha \) (see Fig. 6(b), \( k_{\text{SPP}} \) is the SPP wave vector, \( \alpha \) the SPP incident angle and \( k_{x,\text{glass}} \) the \( x \) component of the scattered light wave vector in glass). In order to see how the SPP incident angle \( \alpha \) relates to the collection angle \( \theta \) (i.e., the angle the scattered light makes with the optical axis, see Fig. 6(a)) we consider \( k_{xy,\text{glass}} \), the component of the scattered light wave vector in the glass substrate that lies in the \( xy \) plane (\( k_{xy,\text{glass}} = k_{\text{glass}} \cdot \sin \theta \), see Fig. 6).

Since by definition, \( k_{xy,\text{glass}} \) is equal to \( k_{xy,\text{glass}} = |\vec{k}_{x,\text{glass}} + \vec{k}_{y,\text{glass}}| \), it is always larger or equal to \( k_{x,\text{glass}} \), or in other words, \( k_{\text{glass}} \cdot \sin \theta \geq k_{\text{SPP}} \cdot \sin \alpha \). With \( k_{\text{glass}} = n_{\text{glass}} \cdot k_0 \), we get:

\[
\theta \geq \arcsin(\frac{1}{n_{\text{glass}}} \cdot \frac{k_{\text{SPP}} \cdot \sin \alpha}{k_0})
\]

The maximum angle \( \theta_{\text{max}} \) at which the scattered light may be detected is limited by the objective numerical aperture \( NA \), \( \theta_{\text{max}} = \arcsin(NA / n_{\text{glass}}) \).

Thus, when SPPs hit the stripe edge at a large incident angle \( \alpha \), the scattered photons emitted at a large \( \theta \) angle may be collected with the oil objective (\( NA = 1.45 \)) but not with the air objective (\( NA = 0.95 \)). Thus in this way we can explain the difference between the real plane images recorded with the oil (see Fig. 1(b)) and air objectives (see Fig. 1(c)).
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