Surface Plasmon Polariton Generation on Metal Surface: From Nano-optical to Terahertz Frequency Regime

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Abstract— We investigate surface wave generation by a single slit, both in nano-optical and in terahertz regimes. The wave-front in optical regime separates itself into forward propagating wave and surface-bound 90-degree diffracted wave; while, no such clear separation of modes is not observed in terahertz regime. Excitation wavelength dependency is systematically studied.

I. Introduction And Background

Surface wave propagating on a conducting surface has been a fascinating issue in radio antenna community since Zenneck derived the surface bound wave solution which satisfies Maxwell's equation. Especially, experimental measurement of surface wave excluding diffracted wave which propagates into free space (space wave) has been a crucial problem for those who sought to use this surface wave in radio frequency applications[1].

Surface Zenneck wave in optical and terahertz regime, which is frequently denoted as the surface plasmon polariton (SPP), is also attracting research efforts, because it has a wide range of potential application such as subwavelength focusing, field amplification, or novel biological sensors. To utilize SPP effectively, discrimination of surface wave from space wave is important.

Here, we address this problem: discrimination of SPP from space wave in wide wavelength range. Near-fields of SPP generation are measured in nano-optical and terahertz regime respectively, which has both wide wavelength and conductivity gaps between them. Excitation wavelength dependent trends of modes discrimination are calculated between optical and terahertz frequency regimes.

II. Results

In THz regime, we measure the vectorial electric field around the single slit aperture perforated on an aluminum sheet (60 μm of width) using a polarization-resolved THz time-domain imaging[2]. Electro-optic crystals of different orientations provide images of different electric field vector components, and images at each frequency is generated through Fourier-transforming the original time-dependent images. Shown in fig 1. (a) is an intensity $E_x^2 + E_z^2$ plot at an arbitrary temporal phase at a frequency 1.2 THz. The emerging wave-fronts from the slit are continuous without break, without any signature of an apparently surface-bound mode.

In optical regime (wavelength=780 nm), we performed vector-field mapping[3] of light emerging from a single nano-slit (width=200 nm) using a gold-nano-particle functionalized tip, obtaining a time-averaged intensity $< E_x^2 + E_z^2 >$. In stark contrast to THz regime, upon exiting the slit, the wave-fronts are immediately separated into propagating and surface-bound SPP waves. Theoretical results in fig. 1 (c) and (d) show qualitative agreements with experimental near-field measurements especially in terms of the presence of surface-bound waves in the optical regime.

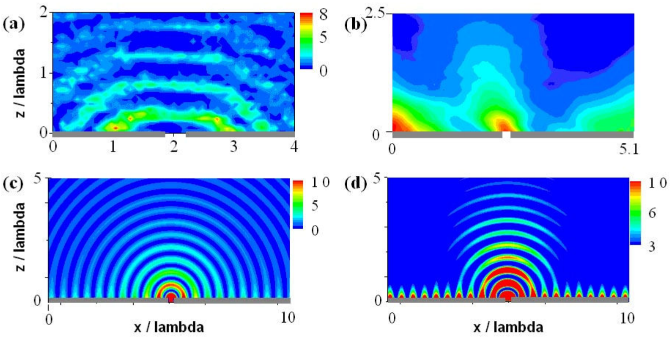

Figure 1. Experimental and theoretical near-field images of diffraction from a single slit aperture. (a) Experimentally measured near-field image at a chosen frequency of 1.2 THz and slit width 60 μm . (b) Experimental near-field image at wavelength 780 nm and slit width 200 nm. (c) Theoretically calculated near-field images of single slit diffraction from a perfect conductor. (d) Same as (c), except for using a real conductor parameter for gold at 780 nm.

The reason for separation of SPP from space wave in optical frequency is due to the finite conductivity of metal: $|\varepsilon|$ is in the range of 10-20. In contrast, metals in THz frequency act as perfect conductor, with the real part of the ε of the order of 10^4, and the imaginary part of the order of 10^5. Following the dispersion relation of SPP, SPP with such large ε is very akin to the propagating light in free space. As a result, it is widely accepted that SPP in THz frequency regime is not a useful concept, as the 2D raster scanned images of experimental and theoretical results in fig. 1 show. Here, an interesting question arises: from what ε value, can we be free of the SPP concept and consider the metal as *perfect*? To investigate this problem systematically, we perform finite-difference-time-domain (FDTD) simulation in wide frequency range between optical and THz frequencies. The model structure is a single slit aperture perforated on gold metal film, with the slit width scaling with the wavelength.

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We investigate the height dependent electric field intensity at various x-positions from the slit. SPP can be discriminated from space wave by their z-axis decay lengths, because SPP has its characteristic exponential decay length determined by metal permittivity while space wave doesn't. FDTD results show that whether we can distinguish SPP from space wave, and vice versa, is determined by two factors: wavelength and distance from the slit aperture. As shown in fig. 2(a), the height dependence shows single exponentially decaying curve only close to the surface when the detecting position is at the distance of one wavelength away from the slit: SPP is buried into the space wave. As we move farther away from the slit, the single exponentially decaying behavior begins to show up at higher height, and it survives over a SPP decay length at a distance of five wavelengths from the slit. In contrast to the 700 nm wavelength case, height dependent curve slowly approach the single exponentially decaying curve (dash), and it should move over 10 wavelengths away from the slit to make SPP decaying curve survive over its characteristic decay length when the incident wavelength is 3 μm, as shown in fig. 2(b).

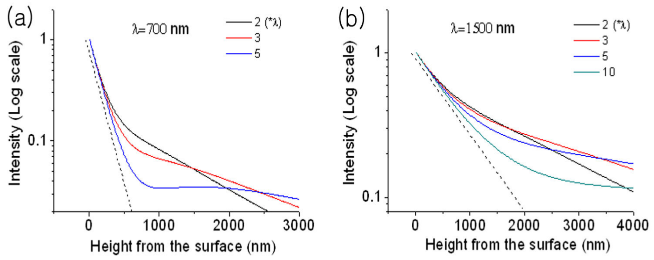

Figure 2. FDTD results of height dependent intensity at various distances away from the slit aperture along x-axis. (a) Height dependent plot with incident beam wavelength of 700 nm. (b) Height dependent near-field plot with incident beam wavelength of 1.5 μm. (dash) log plot of single exponentially decaying SPP.

To evaluate the SPP separation positions where SPP begins to be distinguished from space wave, we define the criteria for SPP separation as follows: SPP is considered separated from space wave when the initial decay behavior follows that of SPP. Shown in fig. 3 is the SPP separation position evaluated from FDTD simulation. This result is consistent with our expectation that longer incident wavelength requires farther SPP detecting position away from the slit to discriminate SPP from space wave.

We model SPP separation from space wave in single slit aperture using semi-analytic solution with surface impedance boundary condition [4]. The z-axis polarized electric field of the diffracted light from single slit aperture in real metal case with permittivity ε is written as,

$$E_z(x,z) \sim \int_{-\infty}^{\infty} \frac{k_x}{\sqrt{k_0^2-k_x^2}+k_0 W} \exp i(k_x x+\sqrt{k_0^2-k_x^2}\,z)\ \ dk_x, \qquad (1)$$

where surface impedance term W is $(1+\varepsilon)^{-1/2}$ and k_0 is momentum vector of incident light. Keeping only the non-evanescent terms, we arrive at the following approximation for space wave intensity at (x, z), with the slit aperture located at (0, 0):

$$I_{z,space} = | A_{space} \frac{x}{z+W\sqrt{x^2+z^2}} (x^2+z^2)^{-1/2} |^2 . \qquad (2)$$

In equation (2), if W is very small, we are dominated by space wave in all regions of interest. Therefore, we can derive the criteria for having significant SPP features as $\delta_z = | W\sqrt{x^2+\delta_z{}^2} |$, where δ_z is the evanescent decay length of SPP. Equivalently, the separation position is given: $x_d = \varepsilon\lambda / 4\pi$.

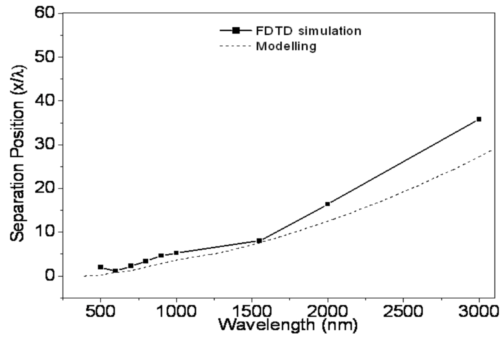

Figure 3. Incident wavelength dependent SPP discrimination position defined as a distance along x-axis away from the slit aperture, where SPP begins to be discriminated from a space wave.

In conclusion, we experimentally measure the diffracted light from the subwavelength single slit both in optical and THz frequency regimes. SPP in optical frequency regime is well discriminated from space wave, while it isn't in THz frequency regime. Based on FDTD simulations, we reveal that as wavelength becomes longer and therefore dielectric constant larger, the SPP separation position becomes farther and farther away from the slit. Finally in THz regime, the separation position is too far away to be realistically detectable. We believe our result will be beneficial to SPP application engineering in various wavelengths.

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