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Demultiplexing Surface Waves With Silicon Nanoantennas

I. Sinev[1,a)], A. Bogdanov[1], F. Komissarenko[1,2], M. Petrov[1], K. Frizyuk[1], S. Makarov[1], I. Mukhin[1,2], A. Samusev[1], A. Lavrinenko[3] and I. Iorsh[1]

[1]*ITMO University, Kronverksky pr. 49 197101 St. Petersburg, Russia*
[2]*St. Petersburg Academic University, Khlopina st. 8/3 194021 St. Petersburg, Russia*
[3]*Technical University of Denmark, 2800 Kongens Lyngby, Denmark*

[a)]Email: i.sinev@metalab.ifmo.ru

Abstract. We demonstrate directional launching of surface plasmon polaritons on thin gold film with a single silicon nanosphere. The directivity pattern of the excited surface waves exhibits rapid switching from forward to backward excitation within extremely narrow spectral band (¡ 50 nm), which is driven by the mutual interference of magnetic and electric dipole moments supported by the dielectric nanoantenna.

INTRODUCTION

With recent advances in surface photonics, researhcers are now exploring new types of materials and artificial structures which support surface waves with tailorable polarization states.[1, 2] One of the crucial building blocks for devices operating in 2D is an efficient source of surface waves. On the other hand, another important element is a spectral demultiplexer, which allow simultaneous operation at multiple wavelengths, thus dramatically accelerating the performance of the integrated photonic circuit. Usually, excitation of surface waves as well as their demultiplexing is performed using 1D and 2D structures like gratings [3], structured nanoslits[4], or arrays of nanoholes [5]. However, severely limited amount of space available on a modern integrated optical circuit calls for using more compact structures for surface waves excitation and routing.

In this work, we reveal that a very basic dielectric nanoantenna (silicon nanosphere) provides unmatched performance serving as a highly efficient source and spectral demultiplexer for surface plasmon polaritons (SPPs). The unique opportunities for manipulation of directivity pattern of SPP are delivered by mutual interference of inherently strong electric and magnetic dipole resonances of the dielectric nanoparticle. Using analytical approach based on Green function and leakage radiation microscopy measurements, we predict and demonstrate experimentally the rapid switching between directional forward and backward excitation of SPP by silicon nanosphere on gold substrate.

THEORETICAL MODEL

To study the excitation of SPPs by a silicon nanosphere, we employ the analytical model based on the Green function approach[6]. This model relies on calculation of the sphere electric and magnetic polarizabilities in the dipole approximation. Applicability of the dipole approximation for calculation of plasmon fields was discussed in Ref. 7. Due to the structure of SPP fields,[3] the only dipole component that does not couple to a SPP mode is the normal magnetic one. Therefore, for the s-polarized excitation the SPP directivity pattern is inherently symmetric. The p-polarized excitation, on the other hand, can provide directional excitation of a SPP due to interference between the induced dipole moments (see Fig. 1a). Using the Green function formalism, we obtain the expression for the intensity of SPP excited by the nanosphere in a given direction:

$$I_{SPP} \sim \frac{1}{\rho} \left| \cos \phi_0 (m_y - i\kappa p_x) - \tilde{k}_{SPP} p_z \right|^2 . \tag{1}$$

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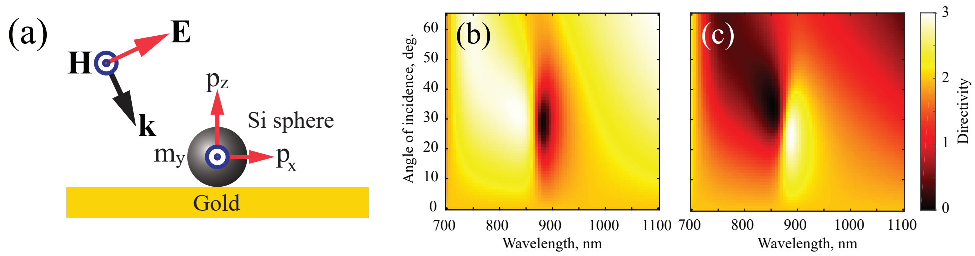

FIGURE 1. (a) Scheme of silicon nanoparticle excited by an obliquely incident p-polarized plane wave. Dipole moments induced in the nanoparticle are shown with arrows. (b,c) Analytically calculated maps of (b) forward and (c) backward directivity of surface plasmon polariton launched by a single 275 nm silicon nanosphere on gold substrate. The SPP direction is defined with respect to the direction of the in-plane component of the wavevector of the incident plane wave.

Here, m_y, p_z, p_x are magnetic and electric polarizabilities of the silicon nanosphere on gold substrate, ρ is the distance from the sphere within the substrate plane, $\tilde{k}_{SPP} = k_{SPP}/k_0$ is the normalized SPP wavevector, and $\kappa = -i\tilde{k}_z$, where $\tilde{k}_z = \sqrt{1 - \tilde{k}_{SPP}^2}$.

The calculated maps of forward and backward directivity of SPP from 275 nm silicon nanosphere calculated via this expression are shown in Fig. 1b,c. The maps demonstrate resonant switching between forward and backward SPP excitation at 870 nm, with forward directivity reaching zero near the angle of incidence of approximately 25 degrees.

EXPERIMENTAL RESULTS

To demonstrate the effect of SPP directivity switching experimentally, we realized the setup for leakage radiation microscopy combined with Fourier plane imaging optics[8]. A series of silicon nanospheres with a diameters ranging from 240 to 300 nm obtained with fs laser ablation was transferred to 40 nm gold layer on glass substrate via nanomanipulations under electron beam. SPP was launched from the sphere by exciting it with a TM-polarized beam incident at ≈30 degrees to the substrate normal and mildly focused with a achromatic doublet lens. The SPP radiation leaking through thin gold film was collected from the bottom with an oil immersion objective (Zeiss 100x, NA=1.46). In the Fourier imaging optical channel, the incident beam was filtered with a beamstop to avoid camera overexposure.

Figure 2a and b show the Fourier plane images and directivity patterns of SPP from 275 nm nanosphere for three distinctively different regimes at three wavelengths: highly directional forward excitation (750 nm), inversion of the directivity pattern at 875 nm, and recovery of forward excitation regime at 1000 nm. The resonant behavior of the switching process predicted by the analytical model is best illustrated in Fig. 2c, where the spectral dependence of SPP leakage radiation intensity in forward and backward half-planes is shown. In full agreement with the analytical model, the backward SPP excitation regime manifests itself only within an extremely narrow band of about 30 nm.

CONCLUSION

In summary, we have demonstrated spectral demultiplexing of surface plasmon polaritons with a single high-index dielectric nanoparticle. We showed that for particular angle of incidence, mutual interference of electric and magnetic dipole moments of the nanoparticle provides total suppression of the surface wave launched in either forward or backward direction. The experimental demonstration of rapid switching between these regimes was carried out via leakage radiation microscopy combined with Fourier plane imaging optics, which allowed to reconstruct full spectral dependence of the SPP directivity pattern. Our findings have important practical implications for on-chip optical communications and surface photonics.

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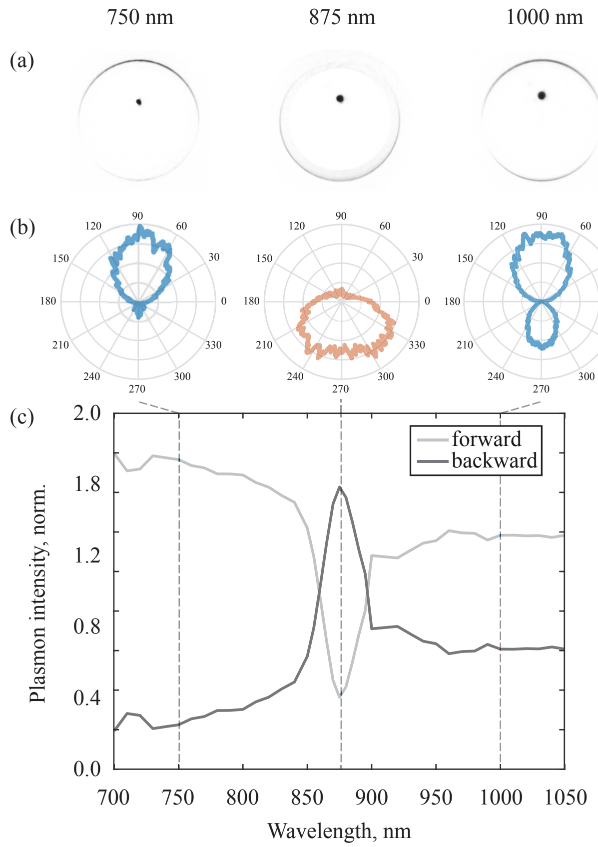

FIGURE 2. (a) (False color) Fourier plane images of SPP excited by a 275 nm silicon nanosphere on 40 nm gold layer at 750, 875 and 1000 nm wavelengths. (b) SPP directivity patterns reconstructed from the measured Fourier images. (c) Spectral dependence of forward and backward SPP intensity demonstrating fast switching between SPP excitation directions. The wavelengths corresponding to data presented in (a,b) are marked with dashed lines.

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