Resonant unidirectional and elastic scattering of surface plasmon polaritons by high-refractive index dielectric nanoparticles

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We consider scattering of surface plasmon polaritons (SPPs) and light by individual high-refractive-index dielectric nanoparticles (NPs) located on a metal (gold) substrate and supporting electric and magnetic dipole resonances in the visible spectral range. Numerical calculations are carried out by making use of the discrete dipole approximation including the multipole decomposition procedure. Extinction and scattering cross section spectra of spheroid silicon NPs in visible and near-infrared are presented and discussed. The roles of the in-plane and out-of-plane components of electric and magnetic dipoles in the scattering processes are clarified and demonstrated. It is revealed that, owing to the NP interaction with electromagnetic fields reflected from the substrate (that leads to biaxiality), the in-plane electric and magnetic dipoles can resonantly be excited at the same wavelength. Due to this effect, the resonant unidirectional (forward) and elastic (in-plane) scattering of SPPs by oblate spheroid NPs can be realized within a narrow spectral range. In the case of normal light incidence, the biaxiality effect can provide significant suppression of the SPP excitation because of the destructive interference between the SPP waves generated by induced electric and magnetic dipole moments. The results obtained open new possibilities for the development of SPP-based photonic components and metasurfaces, whose operation involves resonant excitations of dielectric NPs.

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I. INTRODUCTION

Surface optical electromagnetic waves can be excited at the interface between a dielectric and a metal and are called surface plasmon polaritons (SPPs). One of the most attractive properties of SPPs is the possibility to concentrate and channel electromagnetic radiation using subwavelength structures.\textsuperscript{1-6} Experimental studies demonstrated that ensembles of metal nanoparticles (NPs) arranged on metal surfaces can be used to realize efficient micro-optical elements for two-dimensional (2D) manipulation of SPP waves, such as mirrors, beam splitters and interferometers.\textsuperscript{7-11} Furthermore, periodic arrays of metal NPs have been shown to exhibit band gap properties for SPPs.\textsuperscript{11} If such an SPP band-gap structure has narrow channels free from NPs, then SPP waves can be confined to and guided along these channels.\textsuperscript{12}

From the theoretical point of view, the SPP scattering properties of individual metal NPs and NP ensembles mentioned above can efficiently be treated in the point-dipole approximation,\textsuperscript{13-15} with each NP being considered as an electric dipolar scatterer and the NP dipole moments being self-consistently determined by solving the couple-dipole equations.\textsuperscript{16-18} It has been shown that electric dipolar NPs scatter SPP waves mainly isotropically, with only small modulation in the forward and backward directions with respect to the incident SPP propagation.\textsuperscript{19} With increasing of NP sizes, higher multipole modes of NPs can be excited influencing and changing the SPP scattering diagrams,\textsuperscript{20} a feature that could be used for functional optimization of SPP-based components. It should, however, be borne in mind that metal NPs efficiently absorb the electromagnetic radiation at optical frequencies due to large Ohmic losses. This feature together with the (inelastic or out-of-plane) scattering SPP into light, propagating away from metal surface,\textsuperscript{21} can significantly restrict the application potential of metal NP structures in 2D SPP-optics.

It is possible overcome this principal drawback of metal NPs and nanostructures by employing an alternative approach based on high-refractive-index dielectric or semiconductor NPs. Due to Mie resonances, the dielectric NPs can strongly interact with both electric and magnetic field components of optical waves.\textsuperscript{22-25} Recently it has been shown both theoretically\textsuperscript{26-28} and experimentally\textsuperscript{29} that crystalline silicon NPs exhibit pronounced optical Mie resonances associated with the excitation of magnetic and electric dipole (MD and ED) modes in these NPs. Depending on NP sizes, the resonances can be realized within the visible or near-infrared spectral ranges, where the silicon dielectric permittivity has a very small imaginary part and the silicon NPs can be considered as high-refractive-index dielectric NPs. Because silicon NPs support resonant excitation of MD and ED modes, there appears a possibility to realize a strong unidirectional (forward) light scattering by satisfying the so-called Kerker condition.\textsuperscript{30-32} Importantly, the spectral separation between the ED and MD resonances can be controlled by NP shapes and irradiation conditions\textsuperscript{33} that gives a possibility to realize the resonant Kerker effect and to create novel metamaterials.\textsuperscript{34-36} Resonant optical properties of high-refractive dielectric NPs have been suggested for realization of new types of optical nanoantennas\textsuperscript{37-39} and ultra-high efficiency photovoltaic cells.\textsuperscript{40-42} However, resonant interaction of high-refractive index dielectric NPs with SPPs have not hith-
SPP-based photonic components and metasurfaces. The excitation of SPPs by spheroid silicon NPs can be realized within the resonant range. It is predicted and numerically demonstrated that dielectric permittivity \( \varepsilon_d \) of metal satisfies the conditions \(-Re(\varepsilon_s) > \varepsilon_d > 0\) and \(-Re(\varepsilon_s) \gg Im(\varepsilon_s)\) in the considered spectral range, where \( \varepsilon_s \) is the dielectric permittivity of a medium above the metal surface (in this paper \( \varepsilon_d = 1 \)). The last inequality guarantees that the SPP propagation length is larger than the SPP wavelength. Under these conditions, for the sake of simplicity, we can neglect the imaginary part of \( \varepsilon_s \) for calculations of extinction and scattering cross sections\(^{21,22}\).

When an NP is illuminated either by an SPP wave propagating along the substrate surface or a light wave incident on the substrate, there are two scattering channels: i) into SPPs and ii) into light propagating away from the metal surface (Fig. 1). The scattered electric field above the surface \( z > 0 \), Fig. 1 is

\[
E_{\text{scat}}(r) \approx \frac{k_0^2 e^{-i k_0 r_0}}{\varepsilon_0} S(r) \left\{ p - \frac{k}{\omega} [n \times m] \right. \\
\left. - i k \frac{2}{6} \hat{Q} \cdot \hat{O}(n) + \frac{k^2}{2 \omega} [n \times \hat{M}] \right\}.
\]

where \( k_0 \) is the wave number of light, \( \varepsilon_0 \) is the vacuum dielectric permittivity, \( p \) and \( m \) are the electric and MD moments of the scatterer, respectively, \( Q \) and \( M \) are the electric and magnetic quadrupole tensors of the scatterer, respectively, and \( O \) is the electric octupole tensor. The multipole moments are calculated (and consequently located) at the point \( r_0 \). The value \( k \), vector \( n \) and the tensor \( S(r) \) are determined by the scattered waves\(^{11}\).

For \( E_{\text{d}}(r) \): \( k = k_0 = k_0 \sqrt{\varepsilon_d}; \ n = r/|r| \).

For \( E_{\text{r}}(r) \): \( k = k_d = k_0 \sqrt{\varepsilon_d}; \ n = r'/|r'| \), where \( r' = (x, y, z) \).

For \( E_{\text{SPP}}(r) \): \( k = k_S = k_0 \sqrt{\varepsilon_s \varepsilon_d / (\varepsilon_s + \varepsilon_d)} ; \ n = (x/\rho, y/\rho, -i \alpha), \ \rho = \sqrt{x^2 + y^2}, \ \alpha = \sqrt{-\varepsilon_d/\varepsilon_s} \). The multipole moments of the NP are calculated using the induced polarization \( \mathbf{P}(r) = \varepsilon_0 (\varepsilon_p - \varepsilon_d) \mathbf{E}(r) \) inside the NP, where \( \mathbf{E}(r) \) is the total electric field inside the NP and \( \varepsilon_p \) is its dielectric permittivity.

\[
p = \int_{V_S} \mathbf{P}(r')dr'
\]

is the ED moment,

\[
\hat{Q} \equiv \hat{Q}(r_0) = 3 \int_{V_S} (\Delta r \mathbf{P}(r') + \mathbf{P}(r') \Delta r)dr',
\]

\[
\mathbf{m} \equiv \mathbf{m}(r_0) = -i \omega \int_{V_S} [\Delta r \times \mathbf{P}(r')]dr',
\]

are the electric quadrupole tensor, the MD moment, where \( V_S \) is the NP’s volume, \( \Delta r = r' - r_0 \) (it is convenient to choose the point \( r_0 \) at the NP’s center of mass\(^{22}\)). Note, that \( \mathbf{mm} \) and \( \Delta \mathbf{P} \) represent the dyadic (outer) products between the corresponding vectors. Expressions for higher-order multipole moments and electric fields generated (scattered) by the corresponding multipole moments can be found elsewhere\(^{22}\).
A. Scattering and extinction cross-sections

Let us first consider the scattering cross sections. Since scattered light waves propagate away from the metal surface, their interference with scattered SPP waves propagating along the surface is negligible weak in the far-filed zone. As a result the total scattering cross section $\sigma_{\text{scat}}$ can be represented as the sum of two parts $\sigma_{\text{SPP}}$ and $\sigma_{\text{Light}}$ corresponding to the scattering into SPP and into light propagating away from the surface, respectively:

$$\sigma_{\text{SPP}} = \frac{P_{\text{SPP}}}{P_{\text{in}}} \quad \text{and} \quad \sigma_{\text{Light}} = \frac{P_{\text{L}}}{P_{\text{in}}} \quad (6)$$

where $P_{\text{SPP}}$ and $P_{\text{L}}$ are the scattered powers into SPP and light, respectively, and $P_{\text{in}}$ is the incident wave power. For the incidence of a light plane wave: $P_{\text{in}} = \sqrt{\varepsilon_0\mu_0}|E_0|^2/2$, and in the case of incident SPP plane wave:

$$P_{\text{in}} = \frac{1}{2\varepsilon_0 k_0} \sqrt{\frac{\varepsilon_0 - 1 - a^2}{\mu_0}} (1 - a^4)|E_0^{\text{SPP}}|^2,$$

where $E_0$ and $E_0^{\text{SPP}}$ are the electric amplitudes of the incident light plane wave and the normal (out-of-plane) component of incident SPP plane wave, respectively. Note that, in the case of SPP incidence, $P_{\text{in}}$ is determined per unit length $\text{d}z$.

The power of scattered SPP propagating into an in-plane angle $[\varphi, \varphi + d\varphi]$ (the polar coordinate system) is given by the expression:

$$P(\varphi)d\varphi = \frac{\varepsilon_0 (1 - a^2)(1 - a^4)}{4\mu_0 a k_0} |E_{\text{SPP}}|^2 \rho d\varphi \quad (7)$$

where the z-component (out-of-plane) of the scattered SPP electric field $E_{\text{SPP}}$ is taken in the domain above metal surface just on metal surface ($z = 0$). Note that the expression (7) was obtained by neglecting the imaginary part of metal permittivity $\varepsilon_x$. The total SPP power can be written down as follows:

$$P_{\text{SPP}} = \int_0^{2\pi} P(\varphi)d\varphi = \int_{-\pi/2}^{\pi/2} P(\varphi)d\varphi + \int_{\pi/2}^{3\pi/2} P(\varphi)d\varphi \quad (8)$$

where the first and second integrals from the right hand side are the "Forward" $F_{\text{SPP}}$ and "Backward" $B_{\text{SPP}}$ scattering powers, respectively (here we suppose that the incident SPP plane wave propagates along the positive direction of $x$-axis as shown in Fig.1).

Using the electric field $E_{\text{SPP}}$, as a superposition of multipole fields, the contribution of different multipoles in the scattered SPP power can be evaluated. In the electric and MD approximation one can write:

$$E_{\text{SPP}} \sim p_z + iap \rho - (1 - a^2)\sqrt{\mu_0\varepsilon_0} \frac{k_0}{R_0} m_{\varphi} \quad (9)$$

where $p_z$ and $p_{\rho\varphi}$ are the out-of-plane and in-plane components of ED moment $p$, respectively, and $m_{\varphi}$ is the in-plane component of the MD moment $m$. The in-plane components are connected with the Cartesian component of the corresponding dipole moments: $p_\rho = p_x \cos \varphi + p_y \sin \varphi$ and $m_{\varphi} = -m_x \sin \varphi + m_y \cos \varphi$. It is important to note that i) the contribution of the in-plane component of ED moment $p_\rho$ is proportional to the parameter $a$, which is very small ($a << 1$) in the spectral region where SPPs can be excited and ii) the out-of-plane component $m_x$ of MD does not excite SPP on metal surfaces.

The scattered power into the light waves propagating away from the metal surface can be calculated from:

$$P_{\text{L}} = \frac{1}{2} \sqrt{\varepsilon_0\mu_0} \int_{0}^{\pi/2} \int_{0}^{2\pi} |E_d + E_r|^2 r^2 \sin \theta d\theta d\varphi \quad (10)$$

where $\varphi$ and $\theta$ are the azimuthal and polar angles of the spherical coordinate system, respectively. Note that the expression

$$\sigma(\varphi, \theta) = \frac{1}{2P_{\text{in}}} \sqrt{\varepsilon_0\mu_0} |E_d + E_r|^2 r^2 \quad (11)$$

is the differential cross section of the scattering into the light propagating away from the substrate surface. This value describes the angular distribution of the scattered light. In the electric and MD approximation one can write:

$$(E_d + E_r)_{\varphi} \sim [r(\rho) e^{ik \rho z \cos \theta} + 1] \times (p_\rho + \sqrt{\mu_0\varepsilon_0\mu} m_\varphi \sin \theta)$$

$$+ [r(\rho) e^{ik \rho z \cos \theta} - 1] \sqrt{\mu_0\varepsilon_0\mu} m_\rho \cos \theta \quad (12)$$

and

$$(E_d + E_r)_\theta \sim [r(\rho) e^{ik \rho z \cos \theta} + 1] \times (\sqrt{\mu_0\varepsilon_0\mu} m_\varphi - p_\rho \sin \theta)$$

$$+ [1 - r(\rho) e^{ik \rho z \cos \theta}] p_\rho \cos \theta \quad (13)$$

where $r(\rho)$ and $r(\rho)$ are the reflection coefficients for $s$- and $p$-polarized waves, respectively. $z_0$ is the position of the dipole moments, $p_\rho$ and $p_\varphi = -p_\rho \sin \varphi + p_\rho \cos \varphi$ are the in-plane components of the particle ED moment, $m_\varphi = m_x \cos \varphi + m_y \sin \varphi$. In contrast to (10) contributions of the ED in-plane components in electric field (12) and (13) are not proportional to the small parameter $a$.

The extinction (scattering+absorption) cross-section $\sigma_{\text{ext}}$ can be evaluated by:

$$\sigma_{\text{ext}} = \frac{P_{\text{ext}}}{P_{\text{in}}} = \frac{\omega}{2P_{\text{in}}} \text{Im} \int_{V_S} E_0^*(r) \cdot P(r) dr \quad (14)$$

where $P_{\text{ext}}$ is the extinction power, $E_0(r)$ is the electric field of the incident (external) electromagnetic waves (the field that we would have if the scattering object was not there). The multipole decomposition of the extinction cross section is presented elsewhere. In the case of SPP plane wave incidence (Fig.1):}

$$E_0(r) = E^{\text{SPP}} e^{ik_x x - a k_z z}(-ia\hat{z}, 0, \hat{z}), \quad z > 0,$$
where $E^{\text{SPP}}$ is the amplitude magnitude of electric field. In the case of light plane wave incidence

$$E_0^{\text{in}}(r) = e^{ik_d z \sin \beta} \left( E_0^{\text{in}} e^{-ik_d z \cos \beta} + R E_0^{\text{ref}} e^{ik_d z \cos \beta} \right),$$

where $\beta$ is the incident angle, $E_0^{\text{in}}$ and $E_0^{\text{ref}}$ are the amplitude vectors of the incident and reflected waves, respectively, $R$ is the reflection coefficient depending on the wave polarization. Here we suppose that the light incident plane is the $x_2$-plane (Fig. 1b). In the case of $TE$-polarization $E_0^{\text{in}} = E_0^{\text{ref}}$ and

$$R = \frac{\cos \beta - \sqrt{(\varepsilon_s / \varepsilon_d) - \sin^2 \beta}}{\cos \beta + \sqrt{(\varepsilon_s / \varepsilon_d) - \sin^2 \beta}}.$$

In the case of $TM$-polarization $E_0^{\text{in}} = -E_0^{\text{ref}}$ and $E_0^{\text{in}} = E_0^{\text{ref}}$, and

$$R = \frac{\varepsilon_s \cos \beta - \varepsilon_d \sqrt{(\varepsilon_s / \varepsilon_d) - \sin^2 \beta}}{\varepsilon_s \cos \beta + \varepsilon_d \sqrt{(\varepsilon_s / \varepsilon_d) - \sin^2 \beta}}.$$

The magnetic field $H_0$ can be found using the Maxweel equation $\nabla \times E_0 = ik_0 \sqrt{\mu_0 / \varepsilon_0} H_0$.

### III. RESULTS AND DISCUSSIONS

Our numerical calculations are carried out using the discrete dipole approximation (DDA) including the procedure of the multipole decomposition. We consider first a spherical 95-nm-radius silicon NP placed near a gold surface (the space gap between the NP and the substrate is equal to 5 nm). The studied system together with the chosen coordinate system are shown in Fig. 1a. Dielectric constant for gold and crystalline silicon are taken from the tables in Refs. JC1972 and Palik, respectively. Importantly, for gold $\Re a >> \Im a$ and $a \approx \Re a \leq 0.3$ and $k_d / k_0 \approx \Re k_d / k_0 \approx 1$ in the considered optical range. This will be used in the following when conducting estimations.

#### A. SPP scattering

Scattering and extinction cross-sections for the case of SPP scattering by the spherical silicon NP are shown in Fig. 2a. Small differences between the scattering and extinction cross sections indicate on very weak absorption of electromagnetic energy by the NP. The partial scattering cross-sections for the two scattering channels are also presented in Fig. 2b. In the whole considered spectral range, the (elastic) SPP scattering into SPPs is more efficient than the (inelastic) SPP scattering into light. Especially, this concerns the spectral vicinity of the wavelength of 645 nm, at which the ratio between $\sigma_{\text{SPP}}$ and $\sigma_{\text{Light}}$ is at its maximum and equals to 4 (blue curve in Fig. 2b). Note that this maximum of the elastic SPP scattering is realized outside the resonance of the total scattering cross-section and outside the spectral region, within which the forward SPP-into-SPP scattering dominates over the backward one resulting in the unidirectional SPP scattering (red curve in Fig. 2b). For physical clarification of these scattering features, we employ a multipole analysis of SPP scattering by NPs on a plane surface. From the multipole decomposition presented in Fig. 3 one can see that the extinction is basically determined by contributions of the out-of-plane ED ($p_z$) and in-plane MD ($m_y$) moments of the NP. Contributions of the in-plane ED ($p_z$) and electric quadrupole moments in the extinction cross-section are weak. The broad peak is associated with resonant excitation of $m_y$ at the wavelength of 670 nm and the nonresonant contribution from $p_z$. So that the resonant forward (unidirectional) scattering of the incident SPP into SPPs (Fig. 2a) is explained by interference effect between electromagnetic fields generated by $m_y$ and $p_z$. From 4 neglecting contribution of...
\[ \lambda = 650 \text{ nm} \] is due to the bianisotropic effect, where the ED response is induced mainly by the electric field generated by the MD and reflected from the metal substrate surface. This is a reason why this antiresonance is appeared at the condition of the MD resonance and the induced in-plane ED moment is out of the phase with external incident electric field. Generally, the bianisotropic effect can be perceived as an excitation of the in-plane electric (magnetic) dipole moment by the magnetic (electric) field of incident electromagnetic waves. In this case the in-plane components of electric \( \mathbf{p}_\parallel = (p_x, p_y) \) and magnetic \( \mathbf{m}_\parallel = (m_x, m_y) \) dipole moments are determined by the expressions

\[
\mathbf{p}_\parallel = \hat{\alpha}_e \mathbf{E}_0 + \hat{\alpha}_{eh} \mathbf{H}_0, \\
\mathbf{m}_\parallel = \hat{\alpha}_h \mathbf{H}_0 + \hat{\alpha}_{he} \mathbf{E}_0, 
\]

where the tensors \( \hat{\alpha}_e \), \( \hat{\alpha}_{eh} \), \( \hat{\alpha}_h \), \( \hat{\alpha}_{he} \) are determined by the electromagnetic interaction between the NP and substrate. Moreover \( \hat{\alpha}_{eh} = \mu_0 \hat{\alpha}_{he} \).

In the spectral region corresponding to the \( p_x \) antiresonance the magnitudes of \( p_x \) and \( p_z \) are close to each other (Fig. 3). Therefore both ED components and the MD will determine the scattered light waves (22) and (13). However, due to the bianisotropic effect, the scattered electric field generated by \( p_x \) will be out of phase with respect to the electric field generated by \( m_y \). As a result the scattered light waves propagating away from the surface will be partially suppressed providing the minimum of \( \sigma_{\text{Light}} \) (Fig. 2a) and the maximum for the ratio \( \sigma_{\text{SPP}}/\sigma_{\text{Light}} \) (Fig. 2b). Thus the spectral difference between the two resonances presented in Fig. 2b is explained i) by different importance of the in-plane component \( p_x \) in the two scattering channels and ii) by the bianisotropic effect.

In order to realize the resonant unidirectional and elastic SPP scattering within the same spectral region, one

\[ p_x \text{ and taking into account that } a^2 \ll 1 \text{ and } k_S/k_0 \approx 1 \text{ one can write} \]

\[ E_{\text{SPP}} \sim p_z - \sqrt{\mu_0 \varepsilon_0} m_y \cos \varphi, \]

At the condition of the forward (backward) scattering (with respect to the direction of incident SPP) \( \varphi = 0(\pi) \). Therefore the ratio between the elastic forward and backward SPP scattering can be estimated as

\[ \frac{|p_z - \sqrt{\mu_0 \varepsilon_0} m_y|^2}{|p_z + \sqrt{\mu_0 \varepsilon_0} m_y|^2}. \]

The spectral maximum of the ratio (18) shown in Fig. 4 is in agreement with the corresponding maximum for \( F_{\text{SPP}}/B_{\text{SPP}} \) in Fig. 2a, confirming a very small role of the \( p_z \) component in the unidirectional SPP scattering.

Weak negative (antiresonant) contribution of the in-plane ED \( p_x \) into the extinction cross section (Fig. 4)

\[ \sigma_{\text{ext}}(nm) \]

\[ \lambda \text{ (nm)} \]

\[ \text{Scattering ratio} \]

\[ \text{DM (arb.units)} \]

\[ \lambda \text{ (nm)} \]
FIG. 6: The magnitudes of the (a) out-of-plane \( p_z \) and (b) in-plane \( p_x \) components of the ED moment and (c) the in-plane \( m_y \) component of the MD moment of spheroid silicon NPs irradiated by a SPP plane wave. \( q \) is the NP aspect ratio. The volume of the NPs are corresponded to a spherical NP with the radius of 95 nm.

has to increase the contribution of the in-plane component \( p_z \) into the elastic SPP scattering. Here, we suggest to achieve this effect by reshaping spherical particles into oblate spheroids. It is seen (Fig. 6b) that different aspect ratios \( q \) (\( q = 1 \) corresponds to spherical shape, for oblate spheroids \( q > 1 \)) result in different magnitudes of the dipole components \( p_z, p_x \), and \( m_y \) excited by SPP plane waves in silicon oblate spheroids. Note that the considered NPs have the same volume, corresponding to a sphere with the radius of 95 nm. With increasing of the oblation parameters \( q \) the magnitude of the in-plane dipole component \( p_z \) grows including the two resonances (Fig. 6b). The other (out-of-plane) dipole component \( p_x \) is decreased with increasing \( q \) (Fig. 6a) providing more important influence of \( p_x \) on the SPP scattering in the case of oblate NPs. Note that the two resonances of \( p_x \) (\( q = 1.8 \)) are appeared at the spectral regions where the corresponding resonances of \( m_y \) are also excited (Fig. 6b and c). This correlation is a result of the bianisotropy effect connecting the electric and MD resonances. The spectral shifts of the \( p_x \) and \( m_y \) resonances with changing of \( q \) are a result of complex combination of the bianisotropy and dressing effects. The latter can be illustrated using the image theory. For more oblate spheroid NPs the distance between induced dipoles and their images (with respect to metal-mirror surface) is decreased providing more strong interaction between them. As a result the in-plane MD (ED) resonance could have blue (red) shift because the MD (ED) and its image are directed in the same (opposite) directions.

Thus the two resonances and the spectral difference between them shown in Fig. 6b and c for the oblate spheroid NP with \( q = 1.8 \) explain the spectral features of the extinction and scattering cross sections presented in Fig. 7. The multipole decomposition in Fig. 7 confirms that the extinction and scattering cross section are determined by the electric and MD modes excited by SPP waves inside the oblate NP. In contrast to the results shown in Fig. 6a for the spherical NP the negative contribution of \( p_x \)-term into the short-wavelength resonance of the total extinction cross section in Fig. 7 is increased indicating on importance of the in-plane \( p_x \) component in the SPP scattering. As a result the elastic SPP scattering maximum (\( \sigma_{\text{SPP}}/\sigma_{\text{Light}} \)) and the maximum of the SPP forward scattering (\( S_{\text{SPP}}/S_{\text{B}} \)) are realized at the narrow spectral region around \( \lambda = 610 \) nm (Fig. 8). It is seen from the figure that under these conditions the SPP forward (SPP elastic) scattering is ten (five) times more effective than the SPP backward (SPP into light) scattering. The more broad resonance of \( S_{\text{SPP}}/S_{\text{B}} \) at \( \lambda = 790 \) nm in Fig. 8 is realized when \( \sigma_{\text{SPP}}/\sigma_{\text{Light}} \approx 1 \).

For the explicit demonstration of the SPP backward scattering suppression, we calculated the SPP intensity distribution in a plane located in near-field zone above the metal substrate surface with the oblate NP (\( q = 1.8 \)) illuminated by an incident SPP wave corresponding to the resonant wavelength \( \lambda = 614 \) nm.

The spatial intensity distribution of scattered SPP demonstrates close to complete suppression of the SPP backward scattering (Fig. 9). Moreover, the SPP-into-light scattering is also significantly weakened at this resonant wavelength (Fig. 10). Concluding this subsection, we note that, if a space gap between the oblate NPs and metal substrate surface increases, the spectral distribution of the SPP scattering cross section begins to look like that of the scattering cross section for spherical NPs located on the substrate.
FIG. 7: (a) Extinction cross-section spectra of an oblate spheroid silicon NP (the aspect ratio $q = 1.8$, the volume corresponds to a spherical NP with radius of 95 nm) located on a gold surface and irradiated by a SPP plane wave. The plot shows different multipole contributions to the total extinction cross section: ED electric dipole; MD magnetic dipole; EQ electric quadrupole. (b) Scattering cross-section spectra of this spheroid silicon NP. SPP (Light) corresponds to $\sigma_{\text{SPP}}$ ($\sigma_{\text{Light}}$).

FIG. 8: Spectral dependence of the ratios $\sigma_{\text{SPP}}/\sigma_{\text{Light}}$ and $F_{\text{SPP}}/F_{\text{Light}}$ for the spheroid silicon NP irradiated by a SPP plane wave. The parameters are as in Fig. 9.

FIG. 9: Scattered SPP electric field intensity (arb. units) calculated 150 nm above the air-gold interface for the SPP plane wave (light wavelength 614 nm) being incident on the oblate spheroid silicon NP ($q = 1.8$). The black circles indicate the NP position.

FIG. 10: Differential scattering cross-sections (scattering diagrams) of SPP-into-light scattering by the oblate spheroid silicon NP ($q = 1.8$) calculated in the $xz$-plane.

B. Light scattering

Let us consider the reciprocal light scattering from silicon NPs located on a gold surface and having parameters as in the previous subsection. Here we assume a normal incidence of linear-polarized light plane waves as it is shown in Fig. 1b. The spectra of extinction cross sections for spherical and oblate spheroid NPs are presented in Fig. 11. From the multipole decompositions included there it is clear that the optical properties of the NPs are determined by solely their electric and MD moments. Due to the byanisotropy effect the both resonant peaks of the extinction cross sections in Fig. 11a,b are corresponded to the simultaneous resonant excitation of the electric and MD moments. In contrast to the case of the SPP scattering here the partial negative contribution in total extinction cross sections is corresponded to...
FIG. 11: Extinction cross-section spectra of (a) spherical and (b) oblate spheroid silicon NPs ($q$ is the aspect ratio, the volumes correspond to a spherical NP with radius of 95 nm) located on a gold surface and irradiated by a normally incident light plane waves. The plot shows different multipole contributions to the total extinction cross section. (c) Scattering cross-section spectra of the same spheroid silicon NP. SPP (Light) corresponds to $\sigma_{SPP}$ ($\sigma_{Light}$).

FIG. 12: Spectral dependence of the function $f = |(iap_x - (1 - a^2)\sqrt{\mu_0\varepsilon_0 m_y})|^2$ for the spherical and oblate spheroid silicon NPs, Eq. (21).

FIG. 13: Spectral dependence of $\frac{\sigma_{SPP}}{\sigma_{Light}}$ calculated for the spherical and oblate spheroid silicon NPs irradiated by normal-incident light plane waves.

MD contribution in the extinction cross section is negative. Another important difference from the case of SPP scattering is the absence of the out-of-plane component $p_z$ under the condition of normal light incidence. Consequently, Eq. (9) reduces to the following one:

$$E_{SPP_z} \sim (iap_x - (1 - a^2)\sqrt{\mu_0\varepsilon_0 m_y}) \cos \varphi$$

for the incident light polarized along the $x$-axis. As a result, we obtain the condition for the suppression of SPP excitation in the system

$$p_x \approx -\sqrt{\frac{\mu_0\varepsilon_0\varepsilon_s}{\varepsilon_d}} m_y,$$

where $\varepsilon_s$ is the complex number and one takes $\sqrt{-1} = i$.

Owing to the bianisotropy interaction existing only between the in-plane ED and MD components, the condition could be satisfied in the spectral region, where
resonances of the ED and MD contributions in the extinction spectrum have opposite signs. Indeed, one notices (Fig. 11) that the scattering of light into SPP is significantly suppressed in the spectral region below \( \lambda = 600 \text{ nm} \). Figure 12 demonstrates the spectral dependence of the expression \( f = |(i\alpha_{p_e} - (1 - \alpha^2)\sqrt{\mu_0\varepsilon_0 m_p})|^2 \) from (21) for the spherical and spheroid NPs. In both cases the minimum (maximum) of excited SPPs in the considered systems is realized at the condition of the short-wavelength (long-wavelength) resonance of the total extinction and scattering cross sections (Fig. 11). Importantly the SPP suppression is realized for silicon nanospheroids with different aspect ratios at the condition of the short-wavelength resonance because the NP electric and MD resonances are automatically adjusted to each other due to the strong bianisotropy effect. Changing the NP shape is possible to shift the spectral point where the SPP excitation is suppressed (Fig. 13). Similar behavior can be also realized by changing the NP sizes at the fixed shape.

Concluding this section let us briefly discuss the scattering of incline-incident light plane waves. Figure 14 demonstrates the scattering cross sections calculated for the 70° incidence of light waves with TM- and TE-polarization. In the case of the TM-polarization light (Fig. 14 a) the partial scattering cross section \( \sigma_{\text{SPP}} \) exceeds the section \( \sigma_{\text{Light}} \) because of the contribution of the large out-of-plane ED component \( p_z \) excited by the electric field of the incident light wave. Partially the situation reminds the SPP scattering (Fig. 4 a) where the out-of-plane ED component \( p_z \) plays a principal role. In the case of the TE-polarization light (Fig. 14 b) the efficiency of scattering into light exceeds the scattering into SPPs as it is realized in the case of the normal-incident light. Additional resonant peak at \( \lambda = 710 \text{ nm} \) in Fig. 14 b corresponds to resonant excitation of the out-of-plane MD component \( m_z \). However, as already has been indicated above, this component does not participate in the SPP excitation and can increase the only light-into-light scattering cross section.

IV. CONCLUSION

The multipole analysis of SPP and light scattering by arbitrary-shaped NPs located on a plane surface has been applied to study the optical response of individual spheroidal silicon NPs with sizes of the order of 200 nm being placed near a gold surface. Using numerical calculations by the DDA method together with the multipole decomposition procedure, we showed that the extinction and scattering cross sections of the silicon NPs have two resonances (in the spectral range of \( \lambda \in [575 – 825] \text{ nm} \) corresponding to the resonant excitations of their ED and MD moments. Due to the bianisotropy effect, the in-plane ED and MD components are excited by both electric and magnetic fields of incident electromagnetic waves. As a result, the resonant peaks of the extinction cross sections can include both ED and MD resonant contributions. It was found that, in the case of SPP scattering by oblate spheroidal silicon NPs, the ED and MD resonant excitations can ensure resonant unidirectional and elastic SPP scattering within the spectral range that is determined by the NP aspect ratio. For NPs with the aspect ratio of 1.8, it was obtained that at the wavelength \( \lambda = 610 \text{ nm} \) the SPP forward (elastic)scattering is ten (five) times more effective than the SPP backward (SPP into light) scattering. The suppression of SPP scattering into light is connected with the destructive interference between light waves radiated by the induced ED and MD moments of NP.

We have also discussed a role of the bianisotropy effect in the realization of the efficient elastic SPP scattering. It was shown that due to the bianisotropy effect the contributions of the in-plane ED and MD components to the extinction cross section can be of opposite signs. In this case, the destructive interference between the waves generated by these dipole components can suppress the considered scattering channel. In the case of SPP incidence, this destructive interference practically eliminates
of normally incident light, this ensures efficient suppression of SPP excitation in the system. The appropriate analytical condition for the suppression of the SPP excitation has been obtained. Difference in SPP and light scattering by NPs is connected with different spatial distributions of the electric and magnetic fields created in these two cases near a gold surface. In the case of normally incident light waves, the induced ED $\mathbf{p}$ exceeds the induced MD $\sqrt{\mu_0\varepsilon_0}\mathbf{m}$ (where $\sqrt{\mu_0\varepsilon_0}$ is the dimension factor) within the considered spectral range (Fig. 15 a). As a result, only the SPP scattering suppression can be realized in the system at the short-wavelength resonance (Fig. 15 a). In the case of SPP scattering, the corresponding magnitudes of $\mathbf{p}$ and $\sqrt{\mu_0\varepsilon_0}\mathbf{m}$ can be equal to each other at the short-wavelength resonance (Fig. 15 b), providing the possibility of suppression of SPP-into-light scattering (Fig. 8). Additionally, it was shown that, in the case of oblique light incidence, the scattering cross sections for scattering into light and SPP excitation are strongly dependent on the light polarization.

Summarizing, the results obtained demonstrate directly that high-refractive-index dielectric NPs (for example, crystalline silicon NPs), supporting resonant excitation of the MD and ED modes and being located on metal (gold, silver) substrates, can be used for the realization of unidirectional and elastic SPP scattering as well as for the suppression of SPP scattering when illuminated by light. We believe that these unique optical properties are very important for designing SPP-based photonic components and metasurfaces for control and manipulation of SPP and light waves.

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1. S. A. Maier, *Plasmonics: Fundamentals and Application*, (Springer, Berlin, 2007).
2. M. I. Stockman, *Nanoplasmonics: past, present, and glimpse into future*, Opt. Express 19, 22029 (2011).
3. S. I. Bozhevolnyi and F. A. Pudonin, *Two-dimensional micro-optics of surface plasmons*, Phys. Rev. Lett. 78, 2823 (1997).
4. H. Ditlbacher, J.R. Krenn, G. Schider, A. Leitner, and F.R. Aussenegg, *Two-dimensional optics with surface plasmon polaritons*, Appl. Phys. Lett. 81, 1762 (2002).
5. J.R. Krenn, H. Ditlbacher, G. Schider, A. Hohenau, A. Leitner, and F.R. Aussenegg, *Surface plasmon microand nano-optics*, J. Microsc. 209, 167 (2003).
6. A.L. Stepanov, J.R. Krenn, H. Ditlbacher, A. Hohenau, A. Drezet, B. Steinberger, A. Leitner, and F.R. Aussenegg, *Quantitative analysis of surface plasmon interaction with silver nanoparticles*, Opt. Lett. 30, 1524 (2005).
7. A.B. Evlyukhin, S. I. Bozhevolnyi, A.L. Stepanov, R. Kiyano, C. Reinhardt, S. Passinger, and B.N. Chichkov, *Focusing and directing of surface plasmon polaritons by curved chains of nanoparticles*, Opt. Express 15, 16667, 2007.
8. I.P. Radko, S. I. Bozhevolnyi, A. B. Evlyukhin, and A. Boltasseva, *Surface plasmon polariton beam focusing with parabolic nanoparticle chains*, Opt. Express 15, 6576 (2007).
9. I.P. Radko, V.S. Volkov, J. Beermann, A.B. Evlyukhin, T. Sondergaard, A. Boltasseva, and S.I. Bozhevolnyi, *Plasmonic metasurfaces for waveguiding and field enhancement*, Laser & Photon. Rev. 3, 575 (2009).
10. T. Sondergaard and S.I. Bozhevolnyi, *Surface plasmon polariton scattering by a small particle placed near a metal surface: An analytical study*, Phys. Rev. B 69, 045422 (2004).
11. A.B. Evlyukhin and S.I. Bozhevolnyi, *Point-dipole approximation for surface plasmon polariton scattering: Implications and limitations*, Phys. Rev. B 71, 134304 (2005).
12. T. Sondergaard and S.I. Bozhevolnyi, *Vectorial model...
for multiple scattering by surface nanoparticles via surface polariton-to-polariton interactions, Phys. Rev. B 67, 165405 (2003).

13. A. I. Kuznetsov, A. B. Evlyukhin, C. Reinhardt, A. Seidel, R. Kiyani, W. Cheng, A. Ovsyannikov, and Boris N. Chichkov, Laser-induced transfer of metallic nanodroplets for plasmonics and metamaterial applications, J. Opt. Soc. Am. B 26, B130 (2009).

14. A. V. Shchegrov, I. V. Novikov, and A. A. Maradudin, Scattering of surface plasmon polaritons by a circularly symmetric surface defect, Phys. Rev. Lett. 78, 4269 (1997).

15. C. F. Bohren and D. R. Huffman, Absorption and scattering of light by small particles, (Wiley-Vch, 2008).

16. A. B. Evlyukhin, C. Reinhardt, A. Seidel, B. S. Luk’yanchuk, and B. N. Chichkov, Optical response features of Si-nanoparticle arrays, Phys. Rev. B 82, 045404 (2010).

17. A. Garcia-Etxarri, R. Gomez-Medina, L. S. Froufe-Perez, C. Lopez, L. Chantada, F. Scheffold, J. Aizpurua, M. Nieto-Vesperinas, J. J. Saenz, Strong magnetic response of submicron silicon particles in the infrared, Opt. Express 19, 4815 (2011).

18. A. B. Evlyukhin, S. M. Novikov, U. Zyvietz, R. L. Eriksen, C. Reinhardt, S. I. Bozhevolnyi, and B. N. Chichkov, Demonstration of magnetic dipole resonances of dielectric nanospheres in the visible region, Nano Lett. 12, 3749 (2012).

19. A. I. Kuznetsov, A. E. Miroshnichenko, Y. H. Fu, J. Zhang, and B. Luk’yanchuk, Magnetic light, Sci. Rep. 2, 492 (2012).

20. M. Kerker, D.-S. Wang, C. Giles, Electromagnetic scattering by magnetic spheres, J. Opt. Soc. Am. 73, 765 (1983).

21. Y. H. Fu, A. I. Kuznetsov, A. E. Miroshnichenko, Y. F. Yu, and B. Luk’yanchuk, Directional visible light scattering by silicon nanoparticles, Nature Commun. 4, 1527 (2013).

22. A. B. Evlyukhin, C. Reinhardt, and B. N. Chichkov, Multipole light scattering by nonspherical nanoparticles in the discrete dipole approximation, Phys. Rev. B 84, 235429 (2011).

23. I. Staude, A. E. Miroshnichenko, M. Decker, N. T. Fofang, S. Liu, E. Gonzales, J. Domínguez, T. S. Luk, D. N. Neshev, I. Brener, and Y. S. Kivshar, Tailoring directional scattering through magnetic and electric resonances in subwavelength silicon nanodisks, ACS Nano 7, 7824 (2013).

24. Y. F. Yu, A. Y. Zhu, R. Paniagua-Domínguez, Y. H. Fu, B. Luk’yanchuk, and A. I. Kuznetsov, High-transmission dielectric metasurface with 2π phase control at visible wavelengths, Laser Photon. Rev. 9, 412 (2015).

25. M. Decker, I. Staude, M. Falkner, J. Domínguez, D. N. Neshev, I. Brener, T. Persch, and Y. S. Kivshar, High-Efficiency Dielectric Huygens Surfaces, Adv. Opt. Mater. 3, 813 (2015).

26. A. E. Krasnok, A. E. Miroshnichenko, P. A. Belov, and Y. S. Kivshar, All-dielectric optical nanoantennas, Opt. Express 20, 20599 (2012).

27. B. Rolly, B. Stout, and N. Bonod, Boosting the directivity of optical antennas with magnetic and electric dipolar resonant particles, Opt. Express 20, 20376 (2012).

28. M. K. Schmidt, R. Esteban, J. J. Saenz, I. Suarez-Lacalle, S Mackowski, and J. Aizpurua, Dielectric antennas - a suitable platform for controlling magnetic dipolar emission, Opt. Express 20, 13636 (2012).

29. P. Spinelli, M. A. Verschuuren, and A. Polman, Broadband omnidirectional antireflection coating based on subwavelength surface Mie resonators, Nature Commun. 3, 692 (2012).

30. M. L. Brongersma, Y. Cui, S. Fan, Light management for photovoltaics using high-index nanostructures, Nature Mater. 13, 451-460 (2014).

31. A. B. Evlyukhin, G. Brucoli, L. Martín-Moreno, S. I. Bozhevolnyi, and F. J. García-Vidal, Surface plasmon polarization scattering by finite-size nanoparticles, Phys. Rev. B 76, 075426 (2007).

32. A. B. Evlyukhin, C. Reinhardt, E. Evlyukhin, and B. N. Chichkov, Multipole analysis of the light scattering by arbitrary-shaped nanoparticles on a plane surface, J. Opt. Sc. Am. B 30, 2589 (2013).

33. B. T. Draine, the discrete-dipole approximation and its application to interstellar graphite grains, Astrophys. J. 333, 848 (1988).

34. P. B. Johnson and R. W. Christy, Optical constants of the noble metals, Phys. Rev. B 6, 4370 (1972).

35. E. Palik, Handbook of Optical Constant of Solids (Academic: San Diego, CA, 1985).

36. A. E. Miroshnichenko, A. B. Evlyukhin, Y. S. Kivshar, and B. N. Chichkov, Substrate-induced resonant magneto-electric effects for dielectric nanoparticles, ACS Photonics (submitted).

37. E. Xifré-Pérez, L. Shi, U. Tuzer, F. Ramírez-Manzano, R. Quidant, and F. Meseguer, Mirror-Image-Induced Magnetic Modes, ACS Nano 7, 664 (2013).
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