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Original article

# Simulation of Bessel plasmon polariton field formation in a dielectric-metal structure

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ABSTRACT We study the conditions for the formation and transformation of the Bessel plasmon-polariton field in a dielectric-metal structure excited by a Bessel light beam with arbitrary polarization. The effect of the metal layer thickness on the resulting plasmon field structure is investigated. The formation of Bessel plasmon-polaritons in a scheme consisting of a conical axicon with its base in contact with a silver layer of defined thickness is simulated.

KEYWORDS surface plasmons, Bessel light beam, surface Bessel plasmon-polariton, dielectric-metal structure.

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## 1. Introduction

Plasmonics, the study of surface plasmon polaritons (SPPs) generated at the interface between a dielectric and a metal, has seen remarkable interest in recent years [1–3]. This is due to the wide-ranging potential applications of SPPs in areas such as high-resolution microscopy, optical communication, and sensing technologies [4–6]. Surface plasmons, which are collective oscillations of free electrons at the metal surface, can confine light at sub-wavelength scales, making them particularly valuable for nanoscale optical applications. Traditional studies on SPP generation typically focus on plane waves or Gaussian beam excitation, which has been well-documented [7, 8]. However, more recent advancements have introduced alternative approaches to generating SPPs, including the use of non-diffracting beams like Bessel beams [9–11].

Bessel beams, known for their non-diffracting and self-reconstructing properties, have become a subject of interest in the plasmonics community. These beams offer unique advantages for plasmon generation, particularly for applications requiring high stability and precise control of field distributions [12–14]. In contrast to Gaussian beams, Bessel beams can form more localized plasmon fields, potentially enhancing the performance of optical devices . Recent studies have investigated the interaction between Bessel light beams (BLBs) and surface plasmon polaritons, specifically focusing on the generation of Bessel plasmon polaritons (BPs). These works suggest that BPs can be generated using Bessel beams with specific polarization, most notably transverse magnetic (TM) polarization [15, 16].

This paper builds upon these findings by exploring the generation of Bessel plasmon polaritons using arbitrarily polarized Bessel beams. While prior research has predominantly focused on TM-polarized Bessel beams, little attention has been given to the role of arbitrary polarizations in the formation of BPs. This aspect is critical for expanding the range of applications for Bessel plasmons in fields like optical communication and surface-enhanced spectroscopy, where control over beam polarization can enhance system functionality. In this study, we simulate the formation of Bessel plasmon polaritons in a dielectric-metal multilayer structure under excitation by arbitrarily polarized Bessel beams. By analyzing the impact of different polarizations on the generated plasmon field, we aim to provide new insights into the tunability and application potential of Bessel plasmons. This work not only contributes to the understanding of Bessel beam interactions with dielectric-metal interfaces but also opens up possibilities for further research into the practical applications of these unique plasmonic modes.

## 2. Bessel plasmon-polariton characterization in dielectric-metal structure

Let's consider a vector Bessel light beam

$$\vec{E}(R) = A^{TE}\vec{E}^{TE}(R) + A^{TH}\vec{E}^{TH}(R) \tag{1}$$

incident on the dielectric-metal interface. In expression (1), $R = (\rho, \varphi, z)$ are the cylindrical coordinates with the $Z$ axis orthogonal to the interface between the two media with corresponding dielectric permittivities of $\varepsilon_1$ and $\varepsilon_m$, $\vec{E}^{TE,TH}$ are

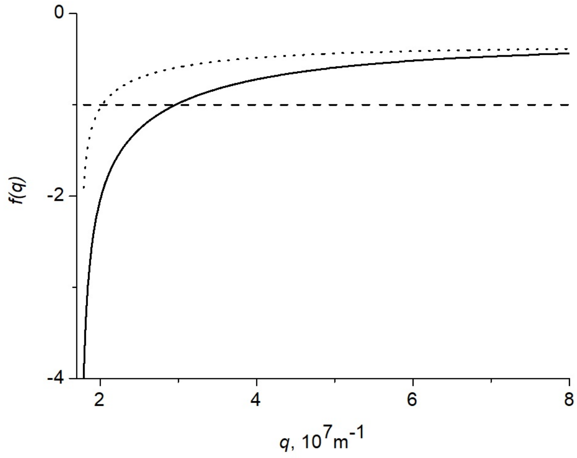

FIG. 1. Dependence $f(q)$ for the structure "optical glass ($n = 1.52$) – silver – air". The thickness of the silver layer is 16,5 nm (solid line) and 150 nm (dashed line). $\lambda = 550$ nm

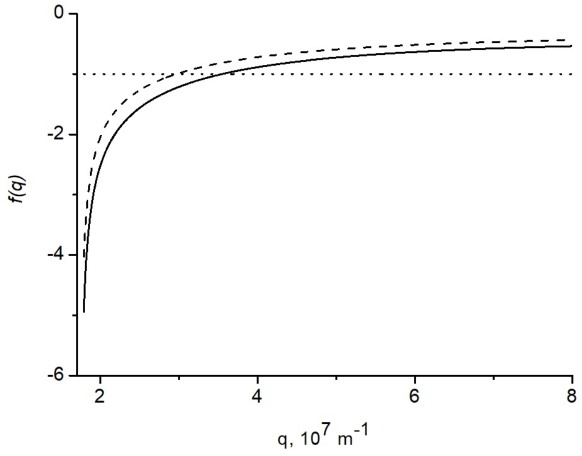

FIG. 2. Dependence $f(q)$ for the structure "optical glass ($n = 1.52$) – metal layer (Na (solid line), Ag (dashed line)) with a thickness of 16.5 nm – air". $\lambda = 550$ nm

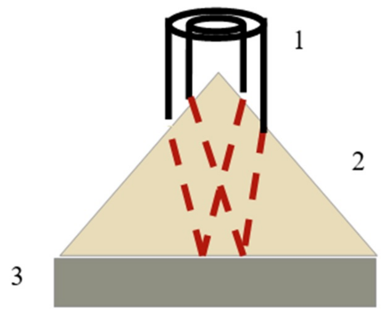

FIG. 3. Bessel plasmon excitation scheme. 1 – ring beam, 2 – axicon, 3 – metal layer

the electric field intensity vector of the TE ($E_z = 0$) and TH ($H_z = 0$) Bessel modes, $A^{TE,TH}$ are the complex constants. In this case, it is possible to generate a surface field for which

$$E^{TH}_{z1,m} = qJ_m(q\rho)/(k_0 n_{1,m}) \exp[\pm\chi_{1,m}(q)z + im\varphi],$$

$$H^{TE}_{z1,m} = -iqJ_m(q\rho)/(k_0) \exp[\pm\chi_{1,m}(q)z + im\varphi], \tag{2}$$

where $q$ is the conicity parameter (the transverse component of the wave vector), $q^2 - \chi^2_{1,m} = k_0^2\varepsilon_{1,m}$, $\varepsilon_{1,m} = n^2_{1,m}$, $k_0 = \omega/c$, $J_m(q\rho)$ is the Bessel function of the m-th order. From the solutions of Maxwell's equations it follows that the transverse component of the formed surface Bessel beam is determined by the following expression:

$$\begin{gathered}
\vec{E}_{\perp 1,m}(R) = \frac{i}{\sqrt{2}} \exp\{i(m-1)\varphi \pm \chi_{1,m}(q)z]\\
\times \left\{ A^{TE}_{1,2}\left[J_{m-1}(q\rho)\vec{e}_+ + J_{m+1}(q\rho)\exp(2i\varphi)\vec{e}_-\right] \mp iA^{TH}_{1,2}\frac{\chi_{1,m}}{k_0 n_{1,m}}\left[J_{m-1}(q\rho)\vec{e}_+ - J_{m+1}(q\rho)\exp(2i\varphi)\vec{e}_-\right]\right\},\\
\vec{H}_{\perp 1,m}(R) = -\frac{n_{1,m}}{\sqrt{2}} \exp\{i(m-1)\varphi \pm \chi_{1,m}(q)z]\\
\times \left\{ A^{TH}_{1,2}\left[J_{m-1}(q\rho)\vec{e}_+ + J_{m+1}(q\rho)\exp(2i\varphi)\vec{e}_-\right] \mp iA^{TE}_{1,2}\frac{\chi_{1,m}}{k_0 n_{1,m}}\left[J_{m-1}(q\rho)\vec{e}_+ - J_{m+1}(q\rho)\exp(2i\varphi)\vec{e}_-\right]\right\},
\end{gathered} \tag{3}$$

where $\vec{e}_\pm = (\vec{e}_1 \pm i\vec{e}_2)/\sqrt{2}$. As follows from (3), taking into account the boundary conditions, it is possible to excite only TH polarized surface Bessel modes, the dispersion equation for which has the form:

$$1 + \frac{\chi_1(q)\,\varepsilon_m(\omega)}{\chi_m(q)\,\varepsilon_1} = 0. \tag{4}$$

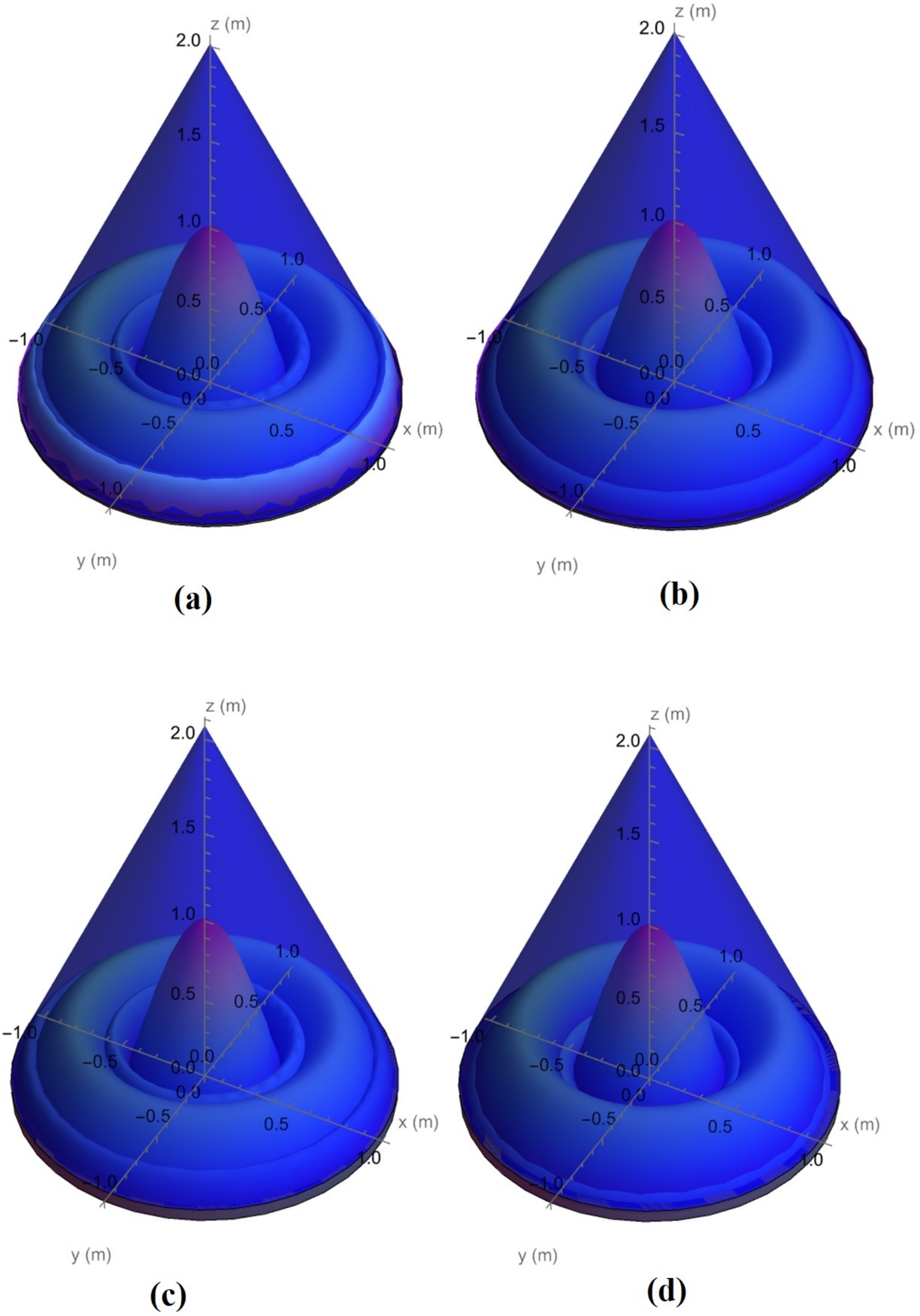

FIG. 4. The formation of the Bessel plasmon-polaritons in the scheme of “axicon-silver layer with a thickness of 16.5 nm (a,b), 70 nm (c,d)” on the surface of the silver layer (a,c), at a depth of 12 nm from the surface of the metal layer (b,d)

From the equation (4), we obtain the following expression:

$$\chi_{1,m} = \sqrt{\frac{\varepsilon_{1,m}^2(\varepsilon_m - \varepsilon_1)}{\varepsilon_1^2 - \varepsilon_m^2}}. \tag{5}$$

As can be seen from (5), the surface Bessel beam exists under the conditions

$$\frac{\varepsilon_m(\omega)}{\varepsilon_1} < 0, \quad |\varepsilon_m| > \varepsilon_1. \tag{6}$$

The dispersion equation (5) coincides in form with the corresponding expression for surface waves in the plane-wave approximation. However, unlike plane waves, this dispersion equation relates the frequency to the conicity parameter of the Bessel light beam:

$$q = k_0\sqrt{\frac{\varepsilon_1\varepsilon_m}{\varepsilon_1 + \varepsilon_m}}. \tag{7}$$

Let us now consider the structure "dielectric 1 ($\varepsilon_1$) – metal ($\varepsilon_m$) – dielectric 2 ($\varepsilon_2$)". As follows from the boundary conditions for fields of type (3), in this case, it is also possible to have only TH- polarized surface Bessel beams (Bessel plasmon-polaritons), the dispersion equation for which has the form:

$$f(q) = \frac{\chi_m^2(q)\varepsilon_1(\omega)\varepsilon_2(\omega)}{\chi_1(q)\chi_2(q)\varepsilon_m^2} + \mathrm{cth}(\chi_m d)\left(\frac{\chi_m^2(q)\varepsilon_2(\omega)}{\chi_2(q)\varepsilon_m} + \frac{\chi_m(q)\varepsilon_1(\omega)}{\chi_1(q)\varepsilon_m}\right) = -1. \tag{8}$$

Here $d$ is the thickness of the metal layer. As the calculation performed in accordance with (7) shows, the radius of the first ring $R_1 = 2,4/q$ of the Bessel plasmon-polariton generated on the surface of a metal film of thickness $d \geq 0,1\lambda$ coincides with that of the Bessel plasmon-polariton generated at the interface of semi-infinite media "dielectric - metal". The radius of the first ring of the Bessel plasmon-polariton generated in the structure "dielectric - metal layer - dielectric" can be reduced by reducing the thickness of the metal layer (Fig. 1), as well as by using media with permittivities close in absolute value in the structure (Fig. 2). For example, in the structure "optical glass – sodium layer with a thickness of 16,5 nm - air" at a wavelength of 550 nm, a Bessel plasmon with a first ring radius of 65 nm is formed, which allows us to conclude that Bessel plasmon can be used for probing surfaces with subwavelength resolution.

Using (3), it is possible to determine the energy characteristics of the surface Bessel plasmon-polaritons formed in the layered structure. Calculations show that both inside and outside the metal layer, the only non-zero component of the Umov-Poynting vector is the azimuthal component

$$S_{\varphi 1,2} \sim \frac{m}{k_0\rho}J_m^2(q\rho)\exp(\pm 2\chi_{1,2}z), \quad S_\varphi \sim \frac{m}{k_0\rho}J_m^2(q\rho)\mathrm{ch}(2\chi_m z). \tag{9}$$

In this case, as follows from (9), the directions of rotation of energy inside the layer and outside it coincide.

## 3. Simulation of the Bessel plasmon-polariton excitation system in the metallic layer

The excitation scheme for the Bessel plasmon-polaritons is illustrated in Fig. 3. A ring-shaped beam (1) is incident on the axicon (2), which has a metal film (3) applied to its lower edge.

In order to simulate the formation of Bessel plasmon-polaritons within the experimental setup consisting of an axicon cone and a silver layer at its base, we employ Wolfram Mathematica 13.1. This software allows us to model the complex interactions and wave dynamics accurately, providing valuable insights into the behavior of plasmon-polaritons under these specific conditions.

Fig. 4 describes the formation of the Bessel plasmon-polaritons in a scheme excited by a zero-order Bessel beam with a wavelength of 550 nm directly incident on a conial axicon with a base radius of 1 $\mu$m and a height of 2 $\mu$m, adjacent to the silver metal layer. As shown in Fig. 4a,b, the intensity distribution of the Bessel plasmon-polaritons shows a central peak with concentric rings radiating outward. This pattern is characteristic of the Bessel functions. Fig. 4a represents the Bessel plasmon-polariton structure at the surface of the metallic layer ($z = 0$), while Fig. 4b shows the structure at a depth of 12 nm from the surface. At the surface, the intensity distribution is more pronounced with sharper peaks and well-defined concentric rings. This indicates stronger plasmonic interactions at the interface. As we move 12 nm below the surface, the intensity of the plasmon-polaritons decreases. The concentric rings become less distinct, suggesting a damping effect as the plasmonic waves penetrate deeper into the metallic layer. The overall structure of the plasmon-polaritons becomes more diffuse at the 12 nm depth, indicating that the energy is spreading out and the coherence of the plasmonic waves is reducing with depth. At the surface of the metallic layer, the Bessel plasmon-polariton field shows a well-defined pattern with sharp intensity peaks. This is consistent for both 16,5 nm and 70 nm thicknesses.

At a depth of 12 nm, the intensity of the plasmon-polariton field decreases for both thicknesses. However, the field structure for the 70 nm thick layer shows a more pronounced damping effect compared to the 16.5 nm layer. The thicker metallic layer (70 nm) results in a more diffuse plasmon-polariton field at depth, indicating that the energy spreads out more and the coherence of the plasmonic waves reduces more significantly compared to the thinner layer (16,5 nm). The thinner metallic layer (16.5 nm) maintains a relatively higher energy confinement at depth compared to the thicker layer (70 nm), which could be beneficial for applications requiring strong plasmonic interactions close to the surface.

## 4. Conclusion

In this paper, we have investigated the features of the Bessel plasmon generation at the dielectric-metal interface when excited by beams of arbitrary polarization. The possibility and conditions for obtaining quasi-diffraction-free surface fields with a submicron-sized central maximum are demonstrated. We have proposed and simulated a model for exciting Bessel-plasmon polaritons on the surface of a metal layer. This scheme is significant for applications in plasmonic devices and sensors, where precise control over light-matter interactions is crucial.

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