Research Article

Generation of Bessel Surface Plasmon Polaritons in a Finite-Thickness Metal Film

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Received 9 January 2013; Revised 11 March 2013; Accepted 23 March 2013

Academic Editor: Yu S. Kivshar

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A theory of generation of low- and high-index Bessel surface plasmon polaritons and their superposition in a metal film of a finite thickness is developed. Correct analytical expressions are obtained for the field of two families of Bessel surface plasmon polariton modes formed inside and outside the metal layer. The intensity distribution near the boundary of the layer has been calculated and analyzed. A scheme for the experimental realization of a superposition of Bessel surface plasmon polaritons is suggested. Our study demonstrates that it is feasible to use the superposition of Bessel surface plasmon polaritons as a virtual tip for near-field optical microscopy with a nanoscale resolution.

1. Introduction

Surface plasmon polaritons (SPPs) are surface electromagnetic waves related to collective electron oscillations near the metal surface excited by light [1–3]. These fields arise under the resonance condition, and due to such nature of excitation, they are attractive in the context of enhancing the resolution of imaging systems substantially by increasing the amplitude of evanescent waves [4–6].

In 1987, Durnin et al. suggested a new type of waves, namely, Bessel light beams (BLBs), that kept the transverse spot size unchanged much longer than the Rayleigh range [7, 8]. Such a localized radiation mode was called the nondiffracting beam (or the diffraction-free beam). The transverse profile of the amplitude of this beam is described by a Bessel function of the first kind. In the domain of spatial frequencies, BLB is represented as a superposition of plane waves which are wrapped around a conical surface. Within the last decades, an intensive study of the scalar and vector BLBs has been made theoretically and experimentally (see, e.g., [9–18]). Bessel light beams are used in numerous applications, such as the optical manipulation of micro-sized particles [19], the fabrication of long polymer fiber induced by the photopolymerization [20] and microchanneling by

structural modification in glass materials [21] the enhancement of energy gain in inverse-free electron lasers and inverse Cherenkov accelerators [22].

The authors of [23] pioneered in obtaining solutions of Maxwell's equations which correspond to evanescent BLBs formed in the condition of the internal total reflection in an optically less dense dielectric medium. A more detailed theory of evanescent Bessel beams is presented in [24–29]. These beams exponentially decay while moving off the surface but retain their original transversal shape. In those investigations, of particular interest was the structure of the central lobe of evanescent BLBs. It is established that its diameter can be reduced to a nanosize value. This makes it possible to use evanescent Bessel beams in optical microscopy [30].

But the evanescent BLBs investigated before [24–29] possess an essential disadvantage, namely, they are weak, which causes the necessity of application of strong laser fields for their generation. One of the ways of taking Bessel light field advantages for microscopy is the formation of Bessel surface plasmon polaritons (BSPPs). Kano et al. [31] reported the first experimental result concerning an efficient excitation of surface plasmon polaritons by using the zeroth-order BLBs. More recently, radially polarized BLBs have been

demonstrated to provide the TM polarization required for an effective coupling to the SPPs, which can be used as a virtual probe for the two-photon fluorescence microscopy [32]. In paper [33], the authors have demonstrated the existence of SPP in a multilayered metal-dielectric structure that evolves without distortion within an energy attenuation length and whose in-plane profile traces a Bessel function along the transverse direction relative to the beam axis.

However, despite of intensive theoretical and experimental investigations up to now there is no detailed analysis of the problem of generation of different types of Bessel surface plasmon polaritons in the structure including a metallic absorbing layer separating a substrate and targeted (dielectric) medium. Also of great interest is the study of the intensity distribution in the structure containing a thin metal film. An exact solution of these problems is presented in this paper.

The study of the superposition of two vortex Bessel surface plasmon polaritons with opposite topological charges (J_m and J_{-m}) is undoubtedly beneficial in practical terms. Such superposed beams are promising for creating near the interface an array of diffraction-free nanoscale light needles. At the same time, we attach importance to the development of a scheme for experimental realization of a superposition of Bessel surface plasmon polaritons. And the theory developed ought to be best suited to experiment. This practical motivation necessitates a more detailed description of the field which is a superposition of Bessel surface plasmon polaritons.

The paper is structured as follows. In Section 2, the description of features of generation of different types of Bessel surface plasmon polaritons in layered metal-dielectric structure is presented. The intensity distribution in the structure is analyzed in details analytically and numerically in Section 3. The possibility of the use of a superposition of Bessel surface plasmon polaritons is considered in Section 4. A conclusion is given in Section 5.

2. Description of Bessel Surface Plasmon Polaritons Generation in a Metal-Dielectric Layered Structure

2.1. Formation of Bessel Surface Plasmon Polaritons in a Finite-Thickness Metal Film. Let us consider a vector TM-polarized high-order ($m \neq 0$) Bessel light beam J_m (BLB) incident onto the boundary of two semi-infinite media. We use the cylindrical coordinate system with the unit vectors $\vec{e}_\rho$, $\vec{e}_\varphi$, and $\vec{e}_z$ ($\vec{e}_z$ is collinear to the propagation direction). It is known (see, e.g., [10, 17, 18]) that the electric $\vec{E}(R)$ and magnetic $\vec{H}(R)$ vectors of BLB, propagating normally (in z -direction) in a medium with the refractive index n_i , can be represented as

$$\begin{aligned}\vec{E}(R) &= A\vec{E}^{\text{TM}}(\rho) \exp i(k_{zi}z + m\varphi), \\ \vec{H}(R) &= A\vec{H}^{\text{TM}}(\rho) \exp i(k_{zi}z + m\varphi),\end{aligned}\quad (1)$$

where $R = (\rho, \varphi, z)$ are the cylindrical coordinates, m is an integer, k_{zi} is the z -component of the wave vector, A is a complex constant, the common phase multiplier $\exp[i(qx - \omega t)]$ is omitted, and $q = \sqrt{k_0^2 n_i^2 - k_{zi}^2}$ is the transversal component of the wave vector.

Using the solution of Maxwell's equations for the components of the vector amplitudes $\vec{E}^{\text{TM}}(\rho)$, $\vec{H}^{\text{TM}}(\rho)$, the problem of transmission and reflection of vector Bessel beams at the boundary of two dielectrics has been solved (see [17, 18]). Following [17, 18], in the case of TM-polarized BLB with an amplitude A_{inc} incident on the interface between two media characterized by refractive indices n_i and n_j , the electric $\vec{E}_t(R)$ and magnetic $\vec{H}_t(R)$ vectors of the refracted Bessel beam (symbol "t" denotes refracted BLB) can be represented in the form

$$\begin{aligned}\vec{E}_t(R) &= \vec{E}_t^{\text{tr}}(R) + \vec{E}_t^{\text{l}}(R), \\ \vec{E}_t^{\text{l}}(R) &= A_{\text{inc}} t_{ij}^{\text{TM}} \exp i[m\varphi + k_{zj}z] \sin \gamma_j J_m(q\rho) \vec{e}_z, \\ \vec{E}_t^{\text{tr}}(R) &= \frac{iA_{\text{inc}}}{\sqrt{2}} \exp i[(m-1)\varphi + k_{zj}z] t_{ij}^{\text{TM}} \\ &\quad \times \cos \gamma_j [J_{m-1}(q\rho) \vec{e}_+ - J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-], \\ \vec{H}_t(R) &= \frac{n_j A_{\text{inc}}}{\sqrt{2}} \exp i[(m-1)\varphi + k_{zj}z] t_{ij}^{\text{TM}} \\ &\quad \times [J_{m-1}(q\rho) \vec{e}_+ + J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-].\end{aligned}\quad (2)$$

Here $\cos \gamma_j = k_{zj}/k_0 n_j$, $k_0 = \omega/c$, ω is the frequency of the Bessel beam, c is the light velocity in vacuum, $J_m(q\rho)$ is the m -order Bessel function; symbols "tr," "l" denote the transversal and longitudinal component of the electric (magnetic) vector, respectively; $t_{ij}^{\text{TM}} = A_t^{\text{TM}}/A_{\text{inc}}$ is the amplitude transmission coefficient; A_t^{TM} is the amplitude factor for TM BLB; $\vec{e}_\pm = (\vec{e}_1 \pm i\vec{e}_2)/\sqrt{2}$ are the unit circular vectors which are orthogonal to the $\vec{e}_z$ vector.

In a similar manner, for the reflected field (it is marked with the symbol "r"), we obtain

$$\begin{aligned}\vec{E}_r(R) &= \vec{E}_r^{\text{tr}}(R) + \vec{E}_r^{\text{l}}(R), \\ \vec{E}_r^{\text{l}}(R) &= A_{\text{inc}} r_{ij}^{\text{TM}} \exp i[m\varphi - k_{zi}z] \sin \gamma_i J_m(q\rho) \vec{e}_z, \\ \vec{E}_r^{\text{tr}}(R) &= -\frac{iA_{\text{inc}}}{\sqrt{2}} \exp i[(m-1)\varphi - k_{zi}z] r_{ij}^{\text{TM}} \\ &\quad \times \cos \gamma_i [J_{m-1}(q\rho) \vec{e}_+ - J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-], \\ \vec{H}_r(R) &= \frac{n_i A_{\text{inc}}}{\sqrt{2}} \exp i[(m-1)\varphi - k_{zi}z] r_{ij}^{\text{TM}} \\ &\quad \times [J_{m-1}(q\rho) \vec{e}_+ + J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-].\end{aligned}\quad (3)$$

FIGURE 1: Schematic representation of the structure including a metallic layer (ϵ_1), a substrate (ϵ_0), and a targeted (ϵ_2) medium.

Here $r_{ij}^{\text{TM}} = A_r^{\text{TM}}/A_{\text{inc}}$ is the amplitude reflection coefficient; A_r^{TM} is the amplitude factor for TM BLB. The amplitude refraction and reflection coefficients are

$$\begin{aligned} t_{ij}^{\text{TM}} &= \frac{2n_i \cos \gamma_i}{n_i \cos \gamma_j + n_j \cos \gamma_i}, \\ r_{ij}^{\text{TM}} &= \frac{n_j \cos \gamma_i - n_i \cos \gamma_j}{n_j \cos \gamma_i + n_i \cos \gamma_j}. \end{aligned} \quad (6)$$

Equations (6) can be used for the description of the transformation of BLB at the boundary between dielectric with the real refractive index n_i and metal having the complex refractive index $n_j = n'_j + in''_j$, where $n'_j = \text{Re}(n_j)$, $n''_j = \text{Im}(n_j)$.

Using (2), (3), and (6), let us consider now the formation of Bessel surface plasmon polaritons in a layered structure containing a metal film with the dielectric constant $\epsilon_1 = n_1^2$ and thickness h between two semi-infinite dielectric media with dielectric constants $\epsilon_0 = n_0^2$, $\epsilon_2 = n_2^2$ (Figure 1). The origin of the coordinated system $z = 0$ is assumed to be chosen at the interface between the dielectric substrate and the layer ϵ_1 (Figure 1).

In view of (2), (4), the electric vector of the field inside the metal layer and outside it is expressed as

$$\begin{aligned} \vec{E}_0(R) &= \vec{E}_0^{\text{tr}}(R) + \vec{E}_0^{\text{l}}(R), \\ \vec{E}_0^{\text{l}}(R) &= A_{\text{inc}} \frac{q}{k_0 n_0} \exp i[m\varphi - k_{z0}z] J_m(q\rho) \vec{e}_z, \\ \vec{E}_0^{\text{tr}}(R) &= -\frac{iA_{\text{inc}}}{\sqrt{2}} \exp i[(m-1)\varphi - k_{z0}z] \\ &\times \sqrt{1 - \left(\frac{q}{k_0 n_0}\right)^2} [J_{m-1}(q\rho) \vec{e}_+ - J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-], \\ \vec{E}_2(R) &= \vec{E}_2^{\text{tr}}(R) + \vec{E}_2^{\text{l}}(R), \\ \vec{E}_2^{\text{l}}(R) &= A_{\text{inc}} \frac{q}{k_0 n_2} t \exp i[m\varphi + k_{z2}(z-h)] J_m(q\rho) \vec{e}_z, \end{aligned}$$

$$\begin{aligned} \vec{E}_2^{\text{tr}}(R) &= \frac{iA_{\text{inc}}}{\sqrt{2}} \exp i[(m-1)\varphi + k_{z2}(z-h)] t \\ &\times \sqrt{1 - \left(\frac{q}{k_0 n_2}\right)^2} [J_{m-1}(q\rho) \vec{e}_+ - J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-], \end{aligned} \quad (7a)$$

$$\vec{E}_1(R) = \vec{E}_1^{\text{tr}}(R) + \vec{E}_1^{\text{l}}(R),$$

$$\vec{E}_1^{\text{l}}(R) = (\vec{E}_1^{\text{l}})^f + (\vec{E}_1^{\text{l}})^b,$$

$$\vec{E}_1^{\text{tr}}(R) = (\vec{E}_1^{\text{tr}})^f + (\vec{E}_1^{\text{tr}})^b,$$

$$(\vec{E}_1^{\text{l}})^{f,b} = A_{\text{inc}} \frac{q}{k_0 n_1} s^{f,b} \exp i[m\varphi \pm k_{z1}z] J_m(q\rho) \vec{e}_z,$$

$$\begin{aligned} (\vec{E}_1^{\text{tr}})^{f,b} &= \pm \frac{iA_{\text{inc}}}{\sqrt{2}} s^{f,b} \exp i[(m-1)\varphi \pm k_{z1}z] \\ &\times \sqrt{1 - \left(\frac{q}{k_0 n_1}\right)^2} [J_{m-1}(q\rho) \vec{e}_+ - J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-]. \end{aligned} \quad (7b)$$

Here, symbols “0”, “1”, and “2” denote the substrate, metal layer, and targeted medium, respectively. Similarly, for the magnetic vector we have

$$\begin{aligned} \vec{H}_0(R) &= \frac{n_0 A_{\text{inc}}}{\sqrt{2}} \exp i[(m-1)\varphi - k_{z0}z] \\ &\times [J_{m-1}(q\rho) \vec{e}_+ + J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-], \end{aligned}$$

$$\begin{aligned}\vec{H}_2(R) &= \frac{n_2 A_{\text{inc}}}{\sqrt{2}} \exp i[(m-1)\varphi + k_{z2}(z-h)] \\ &\times t [J_{m-1}(q\rho) \vec{e}_+ + J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-],\end{aligned}\quad (8a)$$

$$\vec{H}_1(R) = (\vec{H}_1(R))^f + (\vec{H}_1(R))^b,$$

$$\begin{aligned}(\vec{H}_1(R))^{f,b} &= \frac{n_1 A_{\text{inc}}}{\sqrt{2}} s^{f,b} \exp i[(m-1)\varphi \pm k_{z1}z] \\ &\times [J_{m-1}(q\rho) \vec{e}_+ + J_{m+1}(q\rho) \exp(2i\varphi) \vec{e}_-].\end{aligned}\quad (8b)$$

Here, $t = A_2/A_{\text{inc}}$, $s^f = A_f/A_{\text{inc}}$, $s^b = A_b/A_{\text{inc}}$ are the amplitude coefficients for the forward and backward Bessel fields inside the metal film, respectively; $A_{f,b}$ are the amplitude factors inside the metal layer.

Using the boundary conditions of continuity of the tangential components of the electric and magnetic fields, which have to be satisfied at the planes $z = 0$ and $z = h$, as well as (7a), (7b), (8a), (8b), and (6), we obtain the system of equations for the coefficients t , $s^{f,b}$. As a result of its solution, one can find the dispersion equation determining the existence of Bessel surface plasmon polaritons in the structure shown in Figure 1:

$$1 + r_{01}^{\text{TM}} r_{12}^{\text{TM}} \exp 2i(k_{z1}h) = 0. \quad (9)$$

As known (see [34]), the amplitude reflection coefficient of the layer is

$$r = \frac{r_{01}^{\text{TM}} + r_{12}^{\text{TM}} \exp 2i(k_{z1}h)}{1 + r_{01}^{\text{TM}} r_{12}^{\text{TM}} \exp 2i(k_{z1}h)}. \quad (10)$$

Then, (9) determines the poles of the reflection coefficient r of the metal layer. Taking into account (6), this expression can be transformed to the form

$$F = -itg(k_{z1}h) \left(1 + \frac{k_{z1}^2 \varepsilon_0 \varepsilon_2}{k_{z0} k_{z2} \varepsilon_1^2} \right) + \frac{k_{z1} \varepsilon_0}{k_{z0} \varepsilon_1} + \frac{k_{z1} \varepsilon_2}{k_{z2} \varepsilon_1} = 0. \quad (11)$$

Here, k_{zi} is the z -component of the wave vector, and the index i refers to the medium number. As seen from (11), unlike plane waves, the dispersion equation relates the frequency with the transversal component $q = \sqrt{k_0^2 n_j^2 - k_{zi}^2}$ of a Bessel surface plasmon polariton. Due to complexity of the metal refractive index, q is a complex quantity. Here, $\text{Re } q$ determines the radius of rings of the excited Bessel surface plasmon polariton.

The boundary conditions allow one to determine the quantities t , s^f , and s^b entering into (7a), (7b), (8a), and (8b):

$$\begin{aligned}t &= \frac{t_{01}^{\text{TM}} t_{12}^{\text{TM}} \exp(ik_{z1}h)}{1 + r_{01}^{\text{TM}} r_{12}^{\text{TM}} \exp(2ik_{z1}h)}, \\ s^f &= \frac{t_{01}^{\text{TM}}}{1 + r_{01}^{\text{TM}} r_{12}^{\text{TM}} \exp(2ik_{z1}h)}, \\ s^b &= \frac{t_{01}^{\text{TM}} r_{12}^{\text{TM}} \exp(2ik_{z1}h)}{1 + r_{01}^{\text{TM}} r_{12}^{\text{TM}} \exp(2ik_{z1}h)}.\end{aligned}\quad (12)$$

Here, the coefficients t_{ij}^{TM} , r_{ij}^{TM} are determined by (6).

Then, (7a), (7b), (8a), (8b), and (12) at q , which meets condition (11), describe Bessel surface plasmon polaritons formed in the structure “dielectric substrate metal layer dielectric.” The field of a superposition of Bessel surface plasmon polaritons can be defined as a sum of the beams with the electric (magnetic) vector in the form (7a), (7b) ((8a), and (8b)).

It would be interesting to give a physical interpretation of the Bessel SPPs being localized and to compare them with traditional surface plasmon polaritons. It is well-known that the traditional SPPs are associated with the propagating wave process on metal/dielectric surface. In contrast to this, according to (7a), (7b), (8a), and (8b), the Bessel SPP is excited by an incident BLB, which can be considered as a superposition of p -polarized plane monochromatic waves having frequency ω and wave vectors lying on the surface of a cone.

The SPP propagating in the metal film is excited by every p -polarized plane-wave component of the incident BLB in conditions of the plasmon resonance. Here, the phase of every SPP is determined by the phase of the plane-wave component of the incident BLB. Thus, in the metal film, an array of propagating SPPs arises, wave vectors of which are being oriented in the direction of the center determining the intersection of the incident BLB axis with the surface of the metal film. As a result, there occurs the generation of pairs of two counter-propagating SPP waves with the wave vectors $\pm \vec{q}$. The generated SPPs will propagate in all the possible radial directions to form a localized SPP field. This results in a complex high-symmetric interference light structure emerging in sections parallel to the metal-dielectric surface.

For the case where the longitudinal components of the electric field $\vec{E}_1^l$ for every radially propagating SPP has the same phase, in the center of such a standing light structure a maximum appears, that is, the shape of the $\vec{E}_1^l$ component of localized Bessel SPP is described by zero-order Bessel function $J_0(q\rho)$. In a special case, each pair of counter-propagating SPPs is in counter-phase and the local plasmonic field appears with a minimum in the center, that is, the so-called vortex localized Bessel SPP is formed. In this case, the electric field $\vec{E}_1^l$ of vortex Bessel SPP is described by $J_m(q\rho)$ Bessel function (see (7b)).

The problem should be studied now of attenuation of the Bessel SPP inside the metal layer. With this aim, the limited narrow Bessel light beam of radius r_0 in the

FIGURE 2: The phase of F function (a) and the derivative of the phase of F function (b) versus the real part of the Bessel surface plasmon polariton mode effective index.

transversal section should be considered. Such an apertured beam excites Bessel SSP in a cylindrical region limited by r_0 . As follows from (7a), (7b), the transversal distribution of the longitudinal component of the electric field of Bessel SPP is determined by $J_m(q\rho)$ Bessel function which can be represented as a sum of the cylindrical Hankel functions of the first $H_m^{(1)}(q\rho)$ (outgoing) and second $H_m^{(2)}(q\rho)$ (incoming) kinds [35]:

$$J_m(q\rho) = \frac{(H_m^{(1)}(q\rho) + H_m^{(2)}(q\rho))}{2}. \quad (13)$$

According to (13), in the region $\rho < r_0$, the Bessel SPPs are formed by converging and diverging conical beams described by appropriate Hankel functions. Outside the area $\rho > r_0$ there exists only a diverging conical beam, and that is why in the decomposition (13) it is supposed that $H_m^{(2)} = 0$. Using the asymptotic approximation of Hankel function [36], we obtain that the intensity of the longitudinal component of Bessel SPP electric vector $|\vec{E}^l|^2 \sim |J_m^2(q\rho)|^2$ is determined by the expression

$$|\vec{E}^l|^2 \sim \frac{1}{|q|^2 \rho^2} \exp[-2(\text{Im } q)\rho]. \quad (14)$$

Thus, from (14), it follows that beyond the boundary of the exciting source the Bessel SPP decays exponentially in the radial direction. The $1/e$ energy-attenuation radius R_{BSSP} is determined by the imaginary part of the SPP wave number and given by the expression

$$R_{\text{BSSP}} = \frac{1}{2 \text{Im } q}. \quad (15)$$

Thus, the energy-attenuation radius of Bessel SPP, generated by limited narrow Bessel beam, coincides with the decay length L_{SP} of propagating surface plasmon. From the physical

point of view, it is explained by the fact that the Bessel SPP (outside the area of excitation) can be represented by the superposition of radially propagating plane wave SPPs.

2.2. Formation of Bessel Surface Plasmon Polaritons in a Symmetric Metal-Dielectric Layered Structure. Finding the roots of the complex equation (11) is numerically challenging. The reflection pole method (RPM) provides the phase of F as a function of the real part of the Bessel surface plasmon polariton mode effective index $n^* = q/k_0$. The Bessel surface plasmon polaritons correspond to the rapid changes of the phase of F function. According to the Bode plot theory [37], a peak of the derivative of the phase of F function corresponds to the real part of the Bessel surface plasmon polariton mode effective index, and the full width at the half maximum of the phase derivative curve is the imaginary part of the Bessel surface plasmon polariton mode effective index.

Using the reflection pole method, we searched the Bessel surface plasmon polaritons for a gold (Au) metal film ($\epsilon_1 = -11.679 + 1.181i$ at the 0.633 micron wavelength [38]) of 50 nm thickness embedded in SF10 glass ($\epsilon_0 = \epsilon_2 = (1.723)^2$). Figures 2(a) and 2(b) are the plots of the phase of F function and its derivative versus the real part of the Bessel surface plasmon polariton mode effective index. From Figures 2(a) and 2(b), we see two rapid changes of the phase of F which correspond to two Bessel surface plasmon polariton modes. The complex Bessel surface plasmon polariton mode effective indices we found are $n_1^* = 1.874 + 0.012i$ and $n_2^* = 2.179 + 0.073i$.

The first (so-called low-index Bessel surface plasmon polariton (LIBSPP)) and the second (high-index Bessel surface plasmon polariton (HIBSPP)) BSPs are characterized by the first ring radius $R_1 \approx 2.4/(k_0 \text{Re } n^*)$ equal to 129 nm and 110 nm, respectively.

It is interesting to consider the symmetry of the longitudinal ($\vec{E}_1^l = E_1^l \vec{e}_z$) and transversal, for example, radial (E_1^p)

FIGURE 3: The normalized real part of the longitudinal E_1^l (a) and radial E_1^ρ (b) components of the electric vector for low-index (1) and high-index (2) TM-polarized zero-order Bessel surface plasmon polaritons versus the distance inside the gold film of 50 nm thickness embedded in SF10 glass. The distance from the Bessel surface plasmon polariton axis is $\rho = 0.05 \mu\text{m}$, and the wavelength is $\lambda = 0.633 \mu\text{m}$.

FIGURE 4: 2D pattern of normalized intensity distribution $|E_2^l|^2 / |E_2^l|_{\text{max}}^2$ for low- (a) and high-index (b) zero-order Bessel surface plasmon polaritons outside the gold layer of 50 nm thickness embedded in SF10 glass. BSPPs are generated by a purely radially polarized Bessel beam having a wavelength of 633 nm. The distance from the entrance surface of the metal layer is $z = \lambda/3$.

components of the BSPP electric vector inside the metal layer. Note that the equation for E_1^ρ can be obtained from (7b). As calculation shows, the symmetry of real and imaginary parts of longitudinal (as well as transversal) components of electric vector of Bessel SPP inside the metal layer is the same. Figure 3 illustrates the dependence of the function $\text{Re } E_1^l$ normalized to the amplitude factor A_{inc} (at the center $\rho = 0$ of Bessel surface plasmon polariton) on the distance z in a 50 nm thickness gold film surrounded by dielectric media for low- and high-index zero-order BSPPs. It is seen that for the low-index Bessel SPP with the topological charge $m = 0$, the distribution of E_1^l (E_1^ρ) turns out to be symmetrical (antisymmetrical) (Figure 3) with respect to the middle plane

of the metal film. For the high-index Bessel SPP, it is antisymmetrical (symmetrical).

Figure 4 demonstrates a 2D-pattern of the normalized intensity distribution $|E_2^l|^2 / |E_2^l|_{\text{max}}^2$ for low- and high-index Bessel surface plasmon polaritons formed outside the gold layer of 50 nm thickness embedded in SF10 glass. This is the most interesting case where BSPPs are generated by a purely radially polarized Bessel beam. The results of calculations presented in Figure 4 prove that the widths of the central maximum in the transverse distribution, which can be estimated approximately by the ratio $D_1 = 2R_1 = 4.8/(k_0 \text{Re}(n^*))$, for LIBSPP as well as for HIBSPP, turn out to be less than the wavelength. It should be noted that as

FIGURE 5: The derivative of the phase of F function versus the real part of Bessel surface plasmon polariton mode effective index for gold film of 100 nm (—), 80 nm (---), 60 nm (···), and 50 nm (— · —) embedded in SF10 glass.

follows from (7a) while increasing the distance from the surface of the metal layer, the central peak of BSPP, generated in the structure, decays as $\exp(-\text{Im } k_{zi}z)$ ($i = 1, 2$), but its transversal size D_1 does not change practically.

Let us investigate now how the conditions of excitation of Bessel surface plasmon polaritons depend on the thickness of the metal layer. Figure 5 shows the dependence of the derivative of the phase of F function versus the real part of the Bessel surface plasmon polariton mode effective index at various thicknesses of the gold film. It is seen that at an increase in the metal layer thickness two maxima of the curve merge into one, which testifies the degeneration of Bessel surface plasmon polariton modes. Here, the Bessel surface plasmon polariton mode effective index approaches the n_{free}^* for the case of BSPP excitation at the boundary of two semi-infinite media—dielectric and metal [38]:

$$n_{\text{free}}^* = \sqrt{\varepsilon_2 \frac{\varepsilon_1'(\varepsilon_1' + \varepsilon_2) + \varepsilon_1''^2 + i[\varepsilon_1''(\varepsilon_1' + \varepsilon_2) - \varepsilon_1'\varepsilon_1'']}{(\varepsilon_1' + \varepsilon_2)^2 + \varepsilon_1''^2}}, \quad (16)$$

where $\varepsilon_1' = n_1'^2 - n_1''^2$, $\varepsilon_1'' = 2n_1'n_1''$. Equation (16) can be obtained from dispersion equation (11) at $h = 0$.

At a decrease in thickness of the metal film, the difference between the Bessel surface plasmon polariton mode effective indices increases. So, for example, in the structure containing gold (Au) metal film of 20 nm thickness embedded in SF10 glass, the effective indices take on the values $n_1^* = 1.759 + 0.0018i$ and $n_2^* = 3.212 + 0.234i$. At a metal film thickness of 15 nm, we have $n_1^* = 1.744 + 0.0009i$ and $n_2^* = 3.940 + 0.331i$. As is seen, in the first case the generated high-index Bessel surface plasmon polariton has the first ring radius R_1 equal to 75 nm. In the second case, while decreasing the thickness of metal film by 15 nm, it is possible to obtain HIBSPP with $R_1 \approx 61$ nm.

Taking into account that ε_1'' is significantly less than $|\varepsilon_1'|$, (16) enables one to get the expressions for the real (n_{free}^*) and

FIGURE 6: The derivative of the phase of F function versus the real part of Bessel surface plasmon polariton mode effective index for the gold film of 50 nm (—), 30 nm (---), and 20 nm (···) embedded in ZrO_2 .

imaginary ($n_{\text{free}}^{*'}$) parts of the effective index n_{free}^* for Bessel surface plasmon polariton mode excited at the boundary of two semi-infinite media—dielectric and metal:

$$n_{\text{free}}^{*'} = \sqrt{\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1' + \varepsilon_2}}, \quad n_{\text{free}}^{*''} = \sqrt{\left(\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1' + \varepsilon_2}\right)^3 \frac{\varepsilon_1''}{2\varepsilon_1'^2}}. \quad (17)$$

The calculation, made according to (17), shows that for Bessel surface plasmon polariton, formed at the boundary of two semi-infinite media “gold-SF10 glass,” $n_{\text{free}}^{*''} = 0.034$. As established above, for the structure containing the 50 nm thickness gold film embedded in SF10 glass, $\text{Im}(n_1^*) = 0.012$. Thus, in a thin metal film immersed in a dielectric, there may be the generation of a low-index Bessel surface plasmon polariton, for which the imaging part of the Bessel surface plasmon polariton mode effective index appears to be lower than that for BSPP excited at the boundary of semi-infinite media “metal-dielectric.”

As it is mentioned above, in the z -direction, the electric field of the Bessel surface plasmon polariton decays as $\propto \exp(-\text{Im } k_{zi}z)$ ($i = 0, 1, 2$). The penetration depth of the field in the medium is determined by the expression $d = 1/\text{Im } k_{zi}$. As the calculation shows, for the LIBSPP penetration depth d_{LIBSPP} into the targeted medium turns out to be larger than d_{free} for the case of the plasmon formation at the “metal-dielectric” boundary. So, in the case under study $d_{\text{LIBSPP}} = 137$ nm, $d_{\text{free}} = 75$ nm.

Now using the reflection pole method, we consider the Bessel surface plasmon polaritons generation for a gold film of 50 nm thickness embedded in material for which the difference $|\varepsilon_1| - \varepsilon_0$ is lower than that in the case studied earlier. Such parameters belong, for example, to ZrO_2 ($\varepsilon_0 = \varepsilon_2 = 4$). Figure 6 is the derivative of the phase of F function versus the real part of the Bessel surface plasmon polariton mode effective index for this case. We see that there are two fast changes of the phase of F corresponding to two Bessel surface plasmon polariton modes with the effective indices

FIGURE 7: Dependence of the first ring radius of Bessel surface plasmon polariton on the thickness of Au layer embedded in ZrO_2 for high-index BSPP.

dependent on the thickness h of the metal layer. As it follows from Figure 7, for $h = 50$ nm, we have $n_1^* = 2.270 + 0.027i$ and $n_2^* = 2.732 + 0.120i$; for $h = 30$ nm, we obtain $n_1^* = 2.1320 + 0.0097i$ and $n_2^* = 3.312 + 0.217i$; for $h = 20$ nm, we find $n_1^* = 2.065 + 0.004i$ and $n_2^* = 4.235 + 0.351i$. It is seen that if the difference between the dielectric constants of a targeted medium (substrate) and metal decreases, the Bessel surface plasmon polariton mode effective indices increase. Moreover, if h decreases, the difference $\Delta n^* = n_2^* - n_1^*$ increases. Thus, in a thin metal layer with a symmetric dielectric surrounding, the generation of a Bessel surface plasmon polariton with the first ring radius of several tens of nanometers is possible (see Figure 7).

2.3. Formation of Bessel Surface Plasmon Polaritons in Metal Film with Asymmetric Dielectric Surrounding. The asymmetric configuration leads to more interesting phenomena. Using the reflection pole method for solving dispersion equation (11), we searched the Bessel surface plasmon polaritons for a gold metal film of 50 nm thickness separating SF10 glass and air. The complex Bessel surface plasmon polariton mode effective indices are found to be $n_1^* = 1.0480 + 0.0001i$ and $n_2^* = 2.022 + 0.043i$. Here, the profile of $E_1^l(z)$ changes essentially inside the metal film for both generated types of TM_0 Bessel surface plasmon polaritons (Figure 8), that is, it loses symmetry with respect to the middle plane of the metal layer. Moreover, Figure 8 shows that there is a certain value z_e on the BSPP axis ($\rho = 0$), for which the longitudinal component of electrical vector $\vec{E}_1^l$ of high-index BSPP is equal to zero, in this concrete case $z_e = 45$ nm.

As a result of the calculation performed with the help of the reflection pole method for solving dispersion equation (11), it is revealed that at an increase in the refraction index of the targeted medium Bessel surface plasmon polariton mode effective indices increase too, but their difference is determined, mainly, by the thickness of the metal film. And the value z_e decreases.

3. Intensity Distribution of Superposition of Bessel Surface Plasmon Polaritons in Layered Metal-Dielectric Structure

Let us consider now the intensity distribution of the superposition of two TM_m Bessel surface plasmon polaritons with different topological charges ($m_1 \neq m_2$) and phase changes ($\Delta_1 \neq \Delta_2$) inside the targeted medium:

$$\begin{aligned}
 I &\sim |\vec{E}^l(R)|^2, \\
 \vec{E}^l(R) &= \frac{A_{\text{inc}}}{k_0 n_2} \\
 &\times [q_1 t_1 \exp i \\
 &\times [m_1 \varphi + k_{z2}^{(1)}(z - h_1) + \Delta_1] J_{m_1}(q_1 \rho) \\
 &+ q_2 t_2 \exp i [m_2 \varphi + k_{z2}^{(2)}(z - h_1) + \Delta_2] \\
 &\times J_{m_2}(q_2 \rho)] \vec{e}_z.
 \end{aligned} \tag{18}$$

Here, parameters t_1, t_2 determine the amplitudes of interfering plasmons and can be calculated from (12), $k_{z2}^{(1,2)} = \sqrt{k_0^2 n_2^2 - q_{1,2}^2}$. We will consider in more detail the case of practical interest where Bessel surface plasmon polaritons are generated in a Au film separating SF10 glass and air. This case is described in Section 2.3. Two different variants are realizable: case 1 where BSPPs with different n^* (and hence, q) interfere; case 2 when BSPPs with equal n^* (and hence, q) but different topological charges and/or phase changes interfere. Now consider one more important case where interfering Bessel surface plasmon polaritons with the same mode effective indices have topological charges equal in value but different in sign. In this case, the superposition of two BSPPs J_m and J_{-m} , leads to the excitation of Bessel surface multiplasmon polariton for which, as it follows from (18), the azimuthal modulation of intensity is brought about. Owing to this, the interference structure being a set of annular maxima is separated into substructures at a nanoscale transverse size. Figure 9 illustrates the 2D distribution of normalized intensity in the air at the distance $z = \lambda/3 \mu\text{m}$ from the boundary with metal layer. Here, the plasmon polariton field is a superposition of J_3 and J_{-3} low-index (a) and high-index (b) BSPPs. Figures 9(c) and 9(d) show that the field formed by two interfering high-index Bessel surface plasmon polaritons is characterized by more narrow near-axial maxima and essential suppression of lateral maxima while moving off the field axis to its periphery. The above-mentioned interference patterns are rather stable when moving off the interface of metal film. In Figure 10, as an example, the 2D normalized intensity distribution of the field formed by J_3 and J_{-3} low-index BSPPs is given at various distances from the “metal-air” boundary.

Thus, the superposition of two oppositely charged Bessel surface plasmon polaritons allows one to form near the interface of metal an array of quasi-nondiffracting nanoscale spots.

FIGURE 8: The normalized real part of the longitudinal component E_1^l of electric vector of low-index (1) and high-index (2) TM0 Bessel surface plasmon polariton versus the distance inside the 50 nm gold film separating the SF10 glass and air (a) or fluid with refractive index 1.33 (b). The distance from the Bessel surface plasmon polariton axis is $\rho = 0$, and the wavelength is $\lambda = 0.633 \mu\text{m}$.

4. Possible Applications of a Superposition of Bessel Surface Plasmon Polaritons

Thus, the established property of a superposition of Bessel surface plasmon polaritons is applicable to the creation of a virtual multitip for near-field optics. A conceptual sketch of formation of such a multitip, the so-called virtual Bessel surface multiplasmon polariton tip, is illustrated in Figures 11 and 12.

As is seen from Figure 11, the lateral surface of conical lens 2 is illuminated by two conical beams (their extreme rays 1 and 1' are presented in Figure 11) having the same half-cone angles. These beams are necessary for further exiting BSPPs. One of the pointed conical beams is obtained from the TM_m Bessel mode, and another conical beam is formed from the TM_{-m} BLB using a scheme represented in Figure 12 [39] and composed of a reflective conical lens (RCL) and conical mirror (CM). Both conical beams incident on the conical lens 2 perturb Bessel surface plasmon polaritons in metallic film 3. In the region of overlapping of conical beams (shaded area in Figure 11), a superposition of two Bessel surface plasmon polaritons is generated. In turn, in the air near the base surface of the conical lens covered by metal layer 3, a Bessel surface multiplasmon polariton is formed. If the tested surface is placed at the distance $z \leq \lambda$ from the metal layer, the forming exponentially decaying field penetrates into the surface. Thus, the superposition of Bessel surface plasmon polaritons can be used for testing the surfaces of various specimens.

The first crucial advantage of the near-field technique based on a superposition of Bessel surface plasmon polaritons is related to the nondiffractive nature of these fields. Namely, the virtual Bessel surface multiplasmon polariton tip is characterized by the constant size of a probing beam while increasing the probe-to-sample distance which can vary from zero up to $\sim \lambda$. Thus, the use of the virtual Bessel surface

multiplasmon polariton tip allows one to extend potentially the working distance between an object and apparatus.

The important feasible application of beams under consideration is also creating multiple optical traps when using two interfering high-order Bessel surface plasmon polaritons.

5. Conclusion

In this paper, a theory is developed of the generation of single Bessel SPPs and their superposition in the structure including a metal layer separating two semi-infinite dielectrics.

The comparison was made of Bessel surface plasmon polaritons investigated in this paper and traditional surface plasmon polaritons. The traditional SPP is a propagating wave process on the metal/dielectric surface. Unlike it, Bessel SPP is a superposition of counter propagating SPPs in all the possible radial directions. It is a complex high-symmetric interference light structure in sections parallel to the metal/dielectric interface. It should be noted as opposed to the propagating surface plasmon polariton, the Bessel one is a standing light structure.

The problem is studied of attenuation of the Bessel SPP excited by a limited narrow Bessel beam. It is shown that outside the region of the exciting source the Bessel SPP decays exponentially in the radial direction. It is established that the $1/e$ energy-attenuation radius of Bessel SPP, generated by the limited narrow Bessel beam, coincides with the decay length of the propagating surface plasmon.

We have analyzed the cases of symmetric and asymmetric "dielectric-metal-dielectric" structures. A dispersion equation has been derived and numerically analyzed for these cases. The possibility is shown of excitation of two types (low- and high-index) of Bessel surface plasmon polaritons characterized by various profiles of longitudinal component $E_1^l(z)$ of electric vector inside the metal film. It has been

FIGURE 9: 2D and 3D normalized intensity distribution $|E_2^l|^2/|E_2^l|_{\max}^2$ of Bessel multiplasmon in the air at the distance $z = \lambda/3 \mu\text{m}$ from the interface of 50 nm thickness gold film of “SF10 glass—Au layer—air” structure. Bessel surface multiplasmon polariton is a superposition of J_3 and J_{-3} low-index (a, c) and high-index (b, d) BSPPs with wavelength $\lambda = 0.633 \mu\text{m}$.

established that in a symmetric “dielectric-metal-dielectric” structure, the profile of $E^l(z)$ for low-index Bessel surface plasmon polaritons turns out to be a symmetric relatively medium plane of the metal film. For high-index Bessel surface plasmon polariton mode it is antisymmetric. In an asymmetric “dielectric-metal-dielectric” structure, the distribution of $E^l(z)$ inside metal film losses symmetry with respect to the medium plane of the metal layer for both generated plasmon polaritons. Moreover, there is a definite value z_e of the longitudinal coordinate inside the layer, for which the longitudinal component of the electric vector $\vec{E}^l$ for high-index Bessel SPP is equal to zero. It is shown that if the difference between the refraction indices of adjoining

dielectrics and a metal layer decreases, the position z_e shifts toward the medium plane of metal film.

The dependence has been investigated of conditions of excitation of Bessel surface plasmon polaritons on the metal layer thickness h . It has been shown that if h increases, the degeneration of Bessel plasmon modes occur. Here, the Bessel surface plasmon polariton mode effective index approaches the one for the case of excitation of Bessel SPP at the boundary of two semi-infinite media, that is, dielectric and metal.

The intensity distribution of low- and high-index Bessel surface plasmon polaritons inside and outside the metal layer have been calculated and analyzed. A two- and three-dimensional pattern of the intensity for the single Bessel SPPs as well as for a superposition of two Bessel SPPs with opposite

FIGURE 10: 2D normalized intensity distribution $|E_2^i|^2/|E_2^i|_{\max}^2$ of Bessel surface multiplasmon polariton in the air at the distance $z = \lambda/3 \mu\text{m}$ (a), $z = \lambda/2 \mu\text{m}$ (b), and $z = \lambda \mu\text{m}$ (c) from the interface of 50 nm thickness gold film of “SF10 glass—Au layer—air” structure. Bessel surface multiplasmon polariton is a superposition of J_3 and J_{-3} low-index BSPPs with wavelength $\lambda = 0.633 \mu\text{m}$.

topological charges has been calculated. It is shown that while increasing the distance from the surface of the metal layer, the central peak of Bessel SPP generated in the structure decays exponentially, but its transversal size does not change.

It is established that the plasmon polariton field, excited by the superposition of two Bessel beams with opposite topological charges, is characterized by the azimuthal modulation of intensity. Owing to it, the intensity pattern is separated into substructures of a nanoscale transverse size. It is shown that the above-mentioned substructures are rather stable when moving off the interface. Thus, using the superposition of two opposite charged vortex Bessel SPPs, which keeps their transversal size at any distance ranging from zero up to about the wavelength, one can form near the interface an

array of diffraction-free nanoscale light “needles.” This field is associated with creating a Bessel surface plasmon polariton multitip which is perspective for probing the surface simultaneously through several channels. An experimental set-up is proposed for producing such a Bessel surface plasmon polariton multitip.

The results obtained can be used for the development and optimization of techniques and devices for testing the quality of the surface of various substrates by Bessel surface plasmon polaritons; for creating Bessel surface plasmon polariton-based optical tweezing systems; and for the capturing and manipulating of nanoparticles; applications are expected to be found in near-field optical microscopy with a nanoscale resolution.

FIGURE 11: Schematic set-up for excitation of Bessel surface multi-plasmon polariton. 1 and 1' are extreme rays of conical beams excited Bessel surface plasmon polaritons, and 2 is conical lens on the basic surface of which metal film 3 is plotted.

FIGURE 12: Basic scheme of obtaining of conical beams. RCL is a reflective conical lens, CM is a conical mirror, 1 and 1' are extreme rays of the formed conical beam.

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