Interaction of Bessel Light Beams with Epsilon-near-zero Metamaterials

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Abstract

The article explores possibilities and conditions of generation of a new type of diffraction-free needle-like field Bessel plasmon polaritons (BPPs) with super narrow cone angle in an epsilon-near-zero metamaterial, surrounded by semi-infinite dielectric media. Correct analytical expressions are obtained and analyzed in detail for the electric and magnetic fields of BPPs formed inside and outside the metamateral slab.

1. Introduction

Recent advances in nanofabrication and developments in the theory of light-matter interaction have brought to life a new class of composite media, known as metamaterials (MMs). MMs offer new avenues for manipulation of light, lithography, lifetime engineering, high-resolution imaging [1-3]. One subclass of metamaterials is hyperbolic metamaterials (HMMs) in which one of the diagonal permittivity tensor components is negative [4-6]. This results in a hyperbolic dispersion instead of elliptic one as in conventional dielectrics. The reason for HMMs widespread interest is due to relative ease of nanofabrication, broadband non-resonant response, wavelength tunability and high figure of merit [7]. Hyperbolic metamaterials can be used for a variety of applications from negative index waveguides to nanoscale resonators [6,7].

In the approximation of the effective medium theory hyperbolic metamaterial can be considered as an uniaxial uniform medium characterizing by the effective permittivities which are dependent on parameters of HMM. The conditions can be fulfilled when one of the effective permittivities is very small (≈ 0). As established earlier [8, 9], such metamaterials, named as epsilon-near-zero metamaterials (ENZMs), display unique properties by interaction with a plane wave, for example, the possibility of canalization of radiation. Recently such media were experimentally realized [10].

In 1987 Durnin suggested a new type of waves, the so-called Bessel light beams (BLBs); they are also referred to as diffraction-free beams [11- 18]. The transverse profile of the amplitude of these beams is described by a Bessel function of the first kind. In the domain of spatial frequencies BLBs are represented as a superposition of plane waves with wave vectors which are wrapped around a conical surface having the cone angle 2γ. The main properties of Bessel light beams are the ability to keep the transverse size of the central lobe unchanged much longer than the Rayleigh range and to restore the wave front behind an obstacle. Owing to these features BLBs are promising for a number of applications, for example, for optical trapping and manipulation of microparticles and atoms, and for technical diagnostics of subjects with a sub-wave resolution [19-22].

The authors of Ref. [23-27] theoretically and experimentally investigated evanescent BLBs formed in the condition of the internal total reflection in an optically less dense dielectric medium. 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 [28].

But the evanescent BLBs investigated before 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 plasmon polaritons (BPPs) [29, 30].

The present report considers the peculiarities of generation of Bessel plasmon polaritons in epsilon-near-zero metamaterials. Investigation of this problem attracts interest owing to a possibility to combine unusual features of BPPs and ENZMs.

The paper is structured as follows. In Section 2 the description is given of features of generation of Bessel plasmon polaritons in the symmetrical structure on the base of ENZM slab sandwiched between two semi-infinite dielectrics. The behavior of electric and magnetic vectors in the structure is analyzed in detail. A conclusion is given in Section 3.

2. Bessel plasmons in epsilon-near-zero metamaterials

We considered the hyperbolic metamaterial made of metallic nanocylinders periodically embedded in the dielectric template matrix, having the thickness h (Fig.1), surrounded by an external isotropic medium with the dielectric permittivity ε_1 (for example, by air with $\varepsilon_1 = 1$). This composite can be made electrochemically.

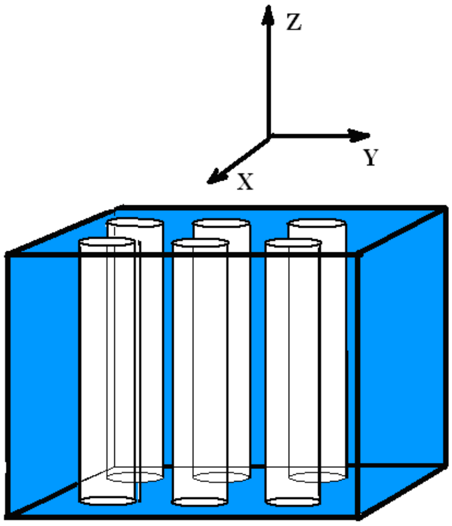

Figure 1: Metamaterial made of metallic nanocylinders periodically embedded in the dielectric template matrix.

At that, the controllable parameters are the metallic nanocylinder radius r, the metallic permittivity ε_m, the average distance between the centers of two adjacent cylinders D, and the membrane dielectric permittivity ε_d. It should be noted that permittivity of metallic nanocylinders is determined by the following correlation:

$$\varepsilon_m(\lambda) = \varepsilon_\infty - \lambda^2 / [\lambda_p^2 (1 + i\lambda\Gamma_1 / 2\pi c)], \quad (1)$$

where ε_∞ is the dielectric permittivity of the bulk metal, λ is the wavelength of optical radiation, λ_p is the plasma wavelength, $\Gamma_1 \approx \Gamma + V_F / 2r$, Γ is the damping constant, V_F is the Fermi velocity. For silver (Ag) nanocylinders, for example, we have $\varepsilon_\infty = 5$, $\lambda_p = 137\,nm$, $\Gamma = 32 \cdot 10^{12} s^{-1}$, $V_F = 1.4 \cdot 10^6 ms^{-1}$ [31].

In the approximation of the effective medium theory neglecting nonlocal spatial dispersion effects this metamaterial can be considered as a uniaxial uniform medium characterizing by the following main effective permittivities [32]:

$$\varepsilon_x = \varepsilon_y = \frac{\beta\varepsilon_m N + \varepsilon_d (1-N)}{\beta N + (1-N)}, \quad (2)$$

$$\varepsilon_z = \varepsilon_m N + \varepsilon_d (1-N),$$

where $N = \pi r^2 / D^2$ is the inclusion factor $\beta = 2\varepsilon_d / (\varepsilon_m + \varepsilon_d)$. At that, $N << 1$ and $D, r << \lambda$. As follows from Eq.(2), if the inclusion factor is fulfilled by the condition

$$N = N_0 = \varepsilon_d / (\varepsilon_d - \mathrm{Re}\,\varepsilon_m), \quad (3)$$

the real part of the component ε_z is equal to zero.

As it is known, the optical anisotropy of a uniaxial medium is characterized by the difference between two parameters: $\varepsilon_o = \varepsilon_x = \varepsilon_y$ and ε_e. At that:

$$\varepsilon_e = \frac{\varepsilon_o \varepsilon_z}{\varepsilon_o \sin^2\gamma_e + \varepsilon_z \cos^2\gamma_e}, \quad (4)$$

$$\gamma_e = \arcsin \frac{\sqrt{\varepsilon_1}\sin\gamma_{inc}}{\sqrt{\varepsilon_o + (1 - \frac{\varepsilon_o}{\varepsilon_z})\varepsilon_1 \sin^2\gamma_{inc}}}, \quad (5)$$

where γ_{inc} is the angle of incidence of light. It follows from Eq.(3) that if $\varepsilon_z = 0$, ε_e is not equal zero only for $\gamma_e = 0$. Moreover, from Eq. (5) one can see that for the case $\varepsilon_z = 0$ for the arbitrary γ_{inc} angle we have $\gamma_e = 0$.

But it is very difficult to realize in practice the condition when ε_z is exactly equal to zero. Fixing the value of permittivity ε_z to a nonzero but low value, let us study the interaction of TH polarized Bessel light beams having the wavelength λ and the half-cone angle γ_{inc} with ENZM. From the Maxwell's equations for a uniaxial crystal in the cylinder 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) and $z = 0$ at the entrance face of the metamaterial, one can obtain the formula for the longitudinal (z), radial (ρ) and azimuthal (φ) components of the electric $\vec{E}$ and magnetic $\vec{H}$ fields for extraordinary (e) type Bessel beams excited inside semi-infinite ENZM :

$$E_\rho^e = i\frac{k_{ze}}{\varepsilon_o} J'_m(q\rho), \quad H_\rho^e = k_0 \frac{m}{q\rho} J_m(q\rho),$$

$$E_\varphi^e = -\frac{k_{ze}}{\varepsilon_o} k_{ze} \frac{m}{q\rho} J_m(q\rho), \quad H_\varphi^e = ik_0 J'_m(q\rho), \quad (6)$$

$$E_z^e = q\frac{1}{\varepsilon_z} J_m(q\rho), \quad H_z^e = 0.$$

Here the phase multiplier $\exp[i(k_e z + m\varphi)]$ is omitted; $k_0 = 2\pi/\lambda$; q and k_{ze} are transversal and longitudinal (in general case, complex) components of wave vectors forming BLB in the domain of spatial frequencies, respectively; $J_m(q\rho), J'_m(q\rho) = \partial J_m(q\rho)/\partial(q\rho)$ are the m-order Bessel functions and their derivatives, m is the integer. At that

$$k_{ze} = [k_0^2 \varepsilon_o - (\varepsilon_o / \varepsilon_z) q^2]^{1/2}. \quad (7)$$

Note that the formula for TH BLB inside the semi-infinite isotropic medium ε_1 can be obtained from Eqs.(6) where it should be replaced $\varepsilon_z \to \varepsilon_1$, $k_{ze} \to k_{z1} = [k_0^2 \varepsilon_1 - q^2]^{1/2}$.

The electric and magnetic vectors of the field inside the ENZM slab (it is denoted by the symbol "2") of finite thickness h and outside it in our case are expressed as

$$\vec{E}_{1,3}(R)=\vec{E}_{1,3}^{tr}(R)+\vec{E}_{1,3}^{l}(R),$$

$$\vec{E}_1^{l}(R)=A_{inc}\frac{q}{\varepsilon_1}\exp i\left[m\varphi-k_{z1}z\right]J_m(q\rho)\vec{e}_z,$$

$$\vec{E}_1^{tr}(R)=-\frac{iA_{inc}k_{z1}}{\varepsilon_1\sqrt{2}}\exp i[(m-1)\varphi-k_{z1}z]\vec{F}_m^{-}, \quad (8)$$

$$\vec{E}_3^{l}(R)=A_{inc}\frac{q}{\varepsilon_1}t\exp i\left[m\varphi+k_{z3}(z-h)\right]J_m(q\rho)\vec{e}_z,$$

$$\vec{E}_3^{tr}(R)=\frac{iA_{inc}k_{z1}}{\varepsilon_1\sqrt{2}}\exp i[(m-1)\varphi+k_{z1}(z-h)]t\vec{F}_m^{-}.$$

$$\vec{H}_1(R)=\frac{k_0A_{inc}}{\sqrt{2}}\exp i[(m-1)\varphi-k_{z1}z]\vec{F}_m^{+},$$

$$\vec{H}_3(R)=\frac{k_0A_{inc}}{\sqrt{2}}\exp i[(m-1)\varphi+k_{z3}(z-h)]t\vec{F}_m^{+}. \quad (9)$$

$$\vec{E}_2(R)=\vec{E}_2^{tr}(R)+\vec{E}_2^{l}(R),$$

$$\vec{E}_2^{l,tr}(R)=(\vec{E}_2^{l,tr})^{f}+(\vec{E}_2^{l,tr})^{b},$$

$$(\vec{E}_2^{l})^{f,b}=A_{inc}q\frac{1}{\varepsilon_z}s^{f,b}\exp i[m\varphi\pm$$

$$\pm k_{ze}|z-ph|]J_m(q\rho)\vec{e}_z, \quad (10)$$

$$(\vec{E}_2^{tr}(R))^{f,b}=\pm\frac{iA_{inc}k_{ze}}{\varepsilon_o\sqrt{2}}s^{f,b}\exp i[(m-1)\varphi\pm$$

$$\pm k_{ze}|z-ph|]\vec{F}_m^{-}.$$

$$\vec{H}_2(R)=(\vec{H}_2(R))^{f}+(\vec{H}_2(R))^{b},$$

$$(\vec{H}_2(R))^{f,b}=\frac{k_0A_{inc}}{\sqrt{2}}s^{f,b}\exp i[(m-1)\varphi\pm \quad (11)$$

$$\pm k_{ze}|z-ph|]\vec{F}_m^{+}.$$

Here $R=(\rho,\varphi,z)$ are the cylindrical coordinates; t is amplitude transmission coefficient of the slab, s^f, s^b are the amplitude coefficients for the forward and backward Bessel fields inside the ENZM slab, respectively; $\vec{F}^{\pm}=J_{m-1}(q\rho)\vec{e}_{+}\pm J_{m+1}(q\rho)\exp(2i\varphi)\vec{e}_{-}$; $\vec{e}_{\pm}=(\vec{e}_1\pm i\vec{e}_2)/\sqrt{2}$ are the unit circular vectors which are orthogonal to the $\vec{e}_z$ vector; $p=0$ for s^f and $p=1$ for s^b; symbols "*tr*", "*l*" denote the transver sal and l ongitudinal component of the electric (magnetic) vector, respectively; symbols "1" and "3" denote the media adjacent to the input and output surfaces of ENZM slab, respectively.

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 Eq s. (8), (9), (10), (11), we obtain the system of equations for the coefficients t, $s^{f,b}$ from which i t follows:

$$t=\left[\cos(k_{ze}h)-i\sin c(k_{ze}h)\frac{(\varepsilon_o^2k_{z1}^2+\varepsilon_1^2k_{ze}^2)h}{2\varepsilon_o\varepsilon_1k_{z1}}\right]^{-1}, \quad (12)$$

$$s^f=\frac{k_{z1}\varepsilon_o t\exp(-ik_{ze}h)}{\varepsilon_1k_{ze}(1+\vartheta)}, \quad (13)$$

$$s^b=-\frac{k_{z1}\varepsilon_o t\vartheta}{\varepsilon_1k_{ze}(1+\vartheta)}. \quad (14)$$

Here $\sin c(k_{ze}h)=\sin(k_{ze}h)/(k_{ze}h)$,

$\vartheta=\left[(k_{z1}/\varepsilon_1)-(k_{ze}/\varepsilon_o)\right]/\left[(k_{z1}/\varepsilon_1)+(k_{ze}/\varepsilon_o)\right]$.

From the boundary conditions for Eqs.(8), (9), (10), (11) one can find the dispersion equation determining the existence of Bessel surface p lasmon polaritons in the structure shown in Fig. 1.

$$\exp(ik_{ze}h)=\pm 1/\vartheta \quad . \quad (15)$$

Note that Eq.(15) coincides with the condition of determining the poles of reflection coefficient:

$$r=\frac{\vartheta(1-\exp(2ik_{ze}h))}{1-\vartheta^2\exp(2ik_{ze}h)}. \quad (16)$$

It is con veniently to rewrite Eq.(15) as a n equation for the unknown complex value k_{ze} taking into account that $k_{z1}^2=k_0^2(\varepsilon_1-\varepsilon_z)+(\varepsilon_z/\varepsilon_o)k_{ze}^2$. One ca n obtain from Eq. (15) that the condition of Bessel plasmon polariton generation in ENZM is fulfilled for $k_{ze}\approx 0$.

It follows from Eq.(7) that it is realized if the following condition is fulfilled:

$$q=k_0\sqrt{\varepsilon_z} \ . \quad (17)$$

At that,

$$\mathrm{Re}\,q=\frac{k_0}{\sqrt{2}}\left[\mathrm{Re}\,\varepsilon_z+\sqrt{(\mathrm{Re}\,\varepsilon_z)^2+(\mathrm{Im}\,\varepsilon_z)^2}\right]^{1/2}, \quad (18)$$

$$\mathrm{Im}\,q=\frac{k_0\,\mathrm{Im}\,\varepsilon_z}{\sqrt{2}}\left[\mathrm{Re}\,\varepsilon_z+\sqrt{(\mathrm{Re}\,\varepsilon_z)^2+(\mathrm{Im}\,\varepsilon_z)^2}\right]^{-1/2} \quad (19).$$

If $\mathrm{Re}\,\varepsilon_z\to 0$ we have $\mathrm{Re}\,q\approx\mathrm{Im}\,q=k_0\sqrt{\mathrm{Im}\,\varepsilon_z}/\sqrt{2}$. Then, if th e absorption of m etal component of ENZM, determining the v alue of $\mathrm{Im}\,\varepsilon_z$, decreases, the parameter $\mathrm{Re}\,q$ decreases too. Note that $\mathrm{Re}\,q$ characterizes the half-cone angle of wave vectors γ_{inc} forming incident BLB in the domain of spatial frequencies.

If the condition $\mathrm{Im}\,\varepsilon_z\to 0$ is fulfilled, the generation of BPPs is observed at incidence on ENZM slab of Bessel light beam with the half-cone angle $\gamma_{inc}=\arcsin(\mathrm{Re}\,q/(k_0\sqrt{\varepsilon_1}))\to 0$.

We can represent dielectric permittivity ε_z in the form

$$\varepsilon_z=(\mathrm{Re}\,\varepsilon_m-\varepsilon_d)\alpha N_0+i\,\mathrm{Im}\,\varepsilon_m(1+\alpha)N_0, \quad (20)$$

where $\alpha=\Delta N/N_0$, ΔN is deviation of inclusion factor from N_0. As follows from Eqs. (17), (20), parameter $\mathrm{Re}\,q$ is dependent on the deviation of inclusion factor ΔN. The $\gamma_{inc}(\Delta N)$ for the case of ENZM slab made on the base of alumina oxide with p eriodically embedded silver nanocylinders is represented in Fig.2 It is seen that in real situation (when $\mathrm{Im}\,\varepsilon_z\neq 0$) the value of γ_{inc} is not equal zero too and decreases with increasing ΔN.

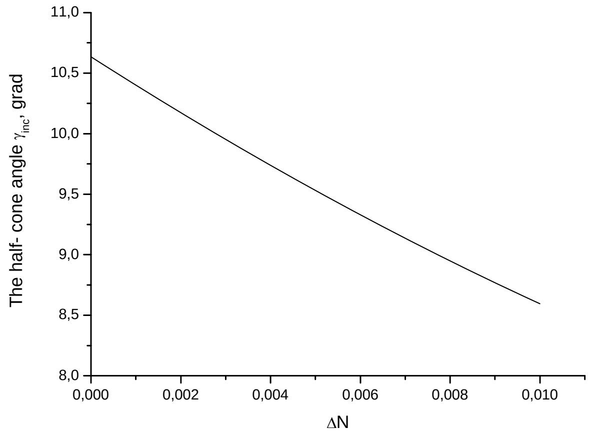

Figure 2: The dependence on the deviation of inclusion factor ΔN of the half-cone angle of incident Bessel light beam for which Bessel plasmon polariton is excited in ENZM slab made of alumina oxide with periodically embedded silver nanocylinders ($r = 25$ nm) and surrounded by air. Here $\lambda = 633$ nm.

It is interesting to physically interpret Bessel plasmon polariton. As it mentioned above, Bessel beam can be considered as a superposition of *p*-polarized plane monochromatic waves having the wavelength λ and wave vectors lying on the surface of a cone. Every *p*-polarized plane-wave component of the incident BLB in conditions of the plasmon resonance excites the surface plasmon polariton (SPP) propagating along the interface of external medium and ENZM slab. Here the phase of every SPP is determined by the phase of the plane-wave component of the incident BLB. Thus, in the ENZM slab 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 epsilon-near-zero metamaterial. 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 dielectric-metamaterial surface.

For the case where the longitudinal components of the electric field $\vec{E}$ for every radially propagating SPP has the same phase, in the center of such a standing light structure a maximum appears, i.e. the shape of the $\vec{E}$ component of localized Bessel plasmon polariton 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, i.e. the so-called vortex localized BPP is formed. In this case the electric field $\vec{E}$ of vortex BPP is described by $J_m(q\rho)$ Bessel function.

One of most important characteristics of Bessel plasmon polariton is the first ring radius $R_1 \approx 2.4/(\mathrm{Re}\,q)$ in transversal section of intensity distribution. It follows from Eq.(18) that if $\mathrm{Im}\,\varepsilon_z \to 0$ then $R_1 \to \infty$. But existence of absorption of metal component of ENZM limits the value of R_1.

The problem of attenuation of the BPP should be studied now. Let us consider this field outside the ENZM layer (at the interface between air and ENZM). With this aim the limited narrow Bessel light beam of radius r_0 in the transversal section should be considered. As follows from Eq. (8), the transversal distribution of the longitudinal component of the electric field of Bessel SPP is determined by the $J_m(q\rho)$ 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 [33]:

$$J_m(q\rho) = \left(H_m^{(1)}(q\rho) + H_m^{(2)}(q\rho)\right)/2\,. \qquad (21)$$

According to Eq.(21), in the region $\rho < r_0$ the BPPs 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 Eq. (21) it is supposed that $H_m^{(2)} = 0$. Using the asymptotic approximation of Hankel function [34], we obtain that the intensity of the longitudinal component of Bessel SPP electric vector $\left|\vec{E}^l\right|^2 \sim \left|J_m(q\rho)\right|^2$ is determined by the expression:

$$\left|\vec{E}^l\right|^2 \sim \frac{1}{|q|^2\rho^2}\exp[-2(\mathrm{Im}\,\mathrm{q})\rho]. \qquad (22)$$

Thus, from Eq. (22) it follows that beyond the boundary of the exciting source the BPP decays exponentially in the radial direction. The 1/e energy-attenuation radius R_{BSSP} is determined by the expression

$$R_{BSSP} = 1/(2\,\mathrm{Im}\,q)\,. \qquad (23)$$

Let us analyze in detail the features of Bessel plasmon polariton generating in the structure represented in Fig.1. As it follows from Eq. (8) the electric (magnetic) vector of the field of BPP in dielectric medium near the exit surface of ENZM slab is dependent on the transmission coefficient t determining by the following expression at $k_{ze} \approx 0$:

$$t = \left[1 - i\frac{\varepsilon_o k_{z1} h}{2\varepsilon_1}\right]^{-1}. \qquad (24)$$

It is evident from Eq. (24) that the value t (and hence, the longitudinal and transversal components of electric vector of BPP inside the external medium "3") is not equal to zero and dependent on the optical properties of ENZM and its thickness.

Much interest is attracted to investigate the features of BPP inside the ENZM slab. As it follows from Eqs. (10), (13), (14) in the conditions of plasmon resonance $k_{ze} \approx 0$

the longitudinal component of electric vector of BPP inside the ENZM slab is determined by the expression:

$$\vec{E}_2^l(R) \approx iA_{inc}\frac{q}{\varepsilon_z}\frac{k_{z1}\varepsilon_o t}{\varepsilon_1}(z-h)\times$$
$$\times \sin c[k_{ze}(z-h)]\exp i[m\varphi]J_m(q\rho)\vec{e}_z \approx \quad (25)$$
$$\approx (-1+i)A_{inc}\frac{k_0}{\sqrt{2\,\mathrm{Im}\,\varepsilon_z}}\frac{k_{z1}\varepsilon_o t}{\varepsilon_1}(z-h)J_m(q\rho)\vec{e}_z.$$

Here $0 < z < h$. It follows from Eq. (25) that the longitudinal component of electric vector of Bessel plasmon polariton decreases linearly with increasing the distance inside the slab. The intensity of longitudinal component is found from the expression

$$I^l \sim \frac{k_0^2}{\mathrm{Im}\,\varepsilon_z}\frac{k_{z1}^2\varepsilon_o^2\,|\,t\,|^2}{\varepsilon_1^2}(h-z)^2\,|\,J_m(q\rho)\,|^2 . \quad (26)$$

The value I^l is equal to zero at $z = h$. Note that I^l is greater for the case of ENZM with small absorption (small value of $\mathrm{Im}\,\varepsilon_z$) of the metal nanocylinders.

One can see from Eq. (26) that the transversal distribution of I^l is described by the Bessel function. Then the size of the central lobe of intensity pattern is not changed moving off the entrance surface of the ENZM slab.

The transversal component of the electric vector of BPP inside the ENZM slab is given by

$$\vec{E}_2^{tr}(R) \approx -A_{inc}\frac{k_{z1}t}{\sqrt{2}\varepsilon_1}\sin[k_{ze}(z-h)]\exp i[(m-1)\varphi]\vec{F}_m^-, \quad (27)$$

and it is very small.

As it follows from Eq. (11), the transversal component of magnetic vector can be expressed as

$$\vec{H}_2(R) \approx \frac{ik_0A_{inc}k_{z1}\varepsilon_o t(z-h)}{\sqrt{2}\varepsilon_1}\times$$
$$\times \sin c[k_{ze}(z-h)]\exp i[(m-1)\varphi]\vec{F}_m^+ \approx \quad (28)$$
$$\approx \frac{ik_0A_{inc}k_{z1}\varepsilon_o t(z-h)}{\sqrt{2}\varepsilon_1}\exp i[(m-1)\varphi]\vec{F}_m^+.$$

One can see from Eq. (28) that $\vec{H}_2(R)$ has essential value.

It is important to emphasize that in opposite to the case of generation of Bessel plasmon polariton in metal film [35] in considered case only single BPP is formed inside the ENZM slab. The full field of Bessel plasmon polariton inside and outside the ENZM slab is described by the Eqs. (8), (9), (26), (27), (28).

3. Conclusions

Thus, in this paper a theory is developed of generation of Bessel plasmon polaritons in the structure including a epsilon-near-zero metamaterial layer separating semi-infinite dielectrics.

The comparison was made of Bessel plasmon polaritons investigated in this paper and traditional surface plasmon polaritons. The traditional SPP is a propagating wave on the ENZM/dielectric surface. Unlike it, BPP 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 ENZM/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 plasmon polariton excited by a limited narrow Bessel beam. It is shown that outside the region of the exciting source the BPP decays exponentially in the radial direction.

We have analyzed the cases of symmetric "dielectric – ENZM slab – dielectric" structure. A dispersion equation has been derived and analyzed for this case. The possibility is shown of excitation of the single type of Bessel plasmon polariton independently on the thickness of the ENZM slab. It is established that this BPP is characterized by essential transversal component of magnetic vector and longitudinal component of electric vector. The magnitude of the latter component is substantially dependent on the absorption in the metal nanocylinders.

The intensity distribution of the longitudinal component of the electric vector of Bessel plasmon polariton inside the ENZM layer is analyzed. It is shown that the large central lobe of the intensity pattern is not changed in its transversal size when moving off the entrance surface of the epsilon-near-zero metamaterial slab. So, it is established the possibility to form the diffraction-free needle-like standing plasmon field inside the ENZM layer.

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 plasmon polaritons.

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