The surface plasmon polariton dispersion relations in a nonlinear-metal-nonlinear dielectric structure of arbitrary nonlinearity*

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The analytic surface plasmon polaritons (SPPs) dispersion relation is studied in a system consisting of a thin metallic film bounded by two sides media of nonlinear dielectric of arbitrary nonlinearity is studied by applying a generalised first integral approach. We consider both asymmetric and symmetric structures. Especially, in the symmetric system, two possible modes can exist: the odd mode and the even mode. The dispersion relations of the two modes are obtained. Due to the nonlinear dielectric, the magnitude of the electric field at the interface appears and alters the dispersion relations. The changes in SPPs dispersion relations depending on film thicknesses and nonlinearity are studied.

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1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic excitations propagating at the interface between a dielectric and a conductor (e.g. Au, Ag, Al), evanescently confined in the perpendicular direction, the electromagnetic surface waves arise via the coupling of the electromagnetic fields to oscillations of the conductor's electron.[1,2] Since the extraordinary optical transmission through a two-dimensional (2D) metallic hole array was first reported by Ebbesen *et al.*,[3] much interest in SPPs has been excited in subwavelength metallic structures.[4−10] SPP-based optical manipulations open up a new avenue for designing new types of nano-optic devices. Insulator–metal–insulator (IMI) and metal–insulator–metal (MIM) structures are two basic geometries. Especially, in IMI structure, the plasmon propagation distances increase substantially due to the coupling of plasmons at the neighbouring interfaces and the field concentration in dielectric rather than metal. Rigorous linear analyses of these structures have been studied in Refs. [11] and [12]. Recently, nonlinear optical devices based on subwavelength metallic structures have been proposed to actively control plasmonic signals by nonlinear material.[13,14] Compared with the usual all-optical devices based on various types of optical nonlinearities, these new nonlinear optical devices have the advantage of smaller size and stronger nonlinear effects because of electromagnetic field confinement and enhancement in metallic structures. Optical bistability in nonlinear surface-plasmon polaritonic crystals has been observed.[15] Full numerical simulations of the nonlinear SPP crystals in various geometries have recently been performed using finite-difference-time-domain method.[16,17]

Recently, Liaw and Wu studied the dispersion relation of SPPs propagating along a curved metal-dielectric interface.[18] Davoyan *et al.*[19] studied the dispersion relation of nonlinear plasmonic modes in metal-dielectric slot waveguide. Using a first integral approach, the dispersion relation at a metal/Kerr-type nonlinear interface was studied firstly by Mihalache *et al.*[20] Using the same method, Huang *et al.*[21] studied how Kerr nonlinearity affects the SPP frequency for large wave vectors. Yin *et al.*[22] studied the SPP dispersion relations of a thin slab of metal of thickness d separating an arbitrary nonlinear dielectric from a linear dielectric. We have studied the SPP dispersion relations analytically for a metallic thin film covered on two sides media of Kerr nonlinear dielectric.[23] In this paper, we study the SPP dispersion relations of a thin metal slab of thickness d bounded by two sides media of arbitrary nonlinear dielectric. Exact ana-

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lytic expressions for the SPP dispersion relations are derived using a generalised first integral approach.

2. Theory

Figure 1 shows the system studied in this paper, which consists of a thin metal slab of thickness d separating two sides media of two arbitrary nonlinear dielectrics that occupy the space of $z > d$ and $z < 0$, respectively. The nonlinear dielectric functions ε_1 and ε_3 can be written as follows:

$$\varepsilon_1 = \varepsilon_{1\mathrm{L}} + \alpha_1 |\boldsymbol{E}|^{\beta}, \quad \varepsilon_3 = \varepsilon_{3L} + \alpha_3 |\boldsymbol{E}|^{\beta}, \tag{1}$$

where $\varepsilon_{1,3\mathrm{L}}$ are the linear dielectric coefficients, $\alpha_{1,3}$ are the nonlinear susceptibilities respectively, and are frequency-dependent in general; β is the arbitrary nonlinearity. The nonlinear media is a Kerr type as a special case of $\beta = 2$.[23]

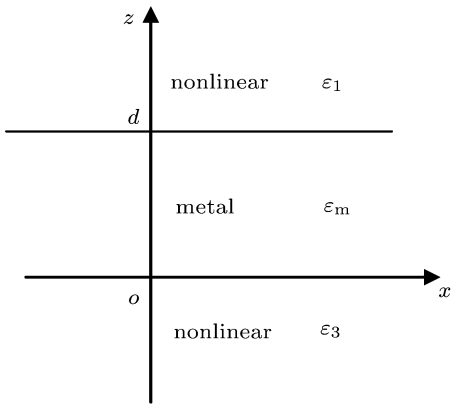


Fig. 1. The system consists of a metallic film separating two semi-infinite arbitrary nonlinear dielectric regions.

The metal has a Drude dielectric constant

$$\varepsilon_{\mathrm{m}}(\omega) = 1 - \omega_{\mathrm{p}}^2/\omega^2, \tag{2}$$

where ω_{p} is the bulk plasma frequency. In this paper, all media are assumed to be lossless and nonmagnetic.

Consider a TM-polarised wave with the $\boldsymbol{H}$ field having y-component only. The electric field at a location in the system can in general be written as

$$\boldsymbol{E}(\boldsymbol{r}, t) = \frac{1}{2}\{\mathrm{i}\, E_x(z)\hat{x} + E_z(z)\hat{z}\} \times \exp[\mathrm{i}(\boldsymbol{k}x - \omega t)] + \mathrm{c.c.}, \tag{3}$$

where $\boldsymbol{k}$ is the wave vector.

The equations for the field amplitudes $E_x(z)$, $E_z(z)$, and $H_y(z)$ obtained from Maxwell equations are in the form

$$\frac{\mathrm{d}E_x}{\mathrm{d}z} = \left(\boldsymbol{k} - \frac{\omega^2}{kc^2}\varepsilon_{\mathrm{i}}\right)E_z, \tag{4}$$

$$\frac{\mathrm{d}(\varepsilon_{\mathrm{i}}E_z)}{\mathrm{d}z} = \boldsymbol{k}\varepsilon_{\mathrm{i}}E_x, \tag{5}$$

$$H_y(z) = -\frac{\omega}{\boldsymbol{k}}\varepsilon_0\varepsilon_{\mathrm{i}}E_z. \tag{6}$$

Here, $\varepsilon_{\mathrm{i}} = \varepsilon_1$, ε_{m}, ε_3 depend on the location. In the metal, since ε_{m} is independent of z, Eq. (5) reduces to $\mathrm{d}E_z/\mathrm{d}z = \boldsymbol{k}E_x$. In the nonlinear region, however, ε_{i} cannot be cancelled in Eq. (5).

2.1. The asymmetric structure

In this case, ε_1 and ε_3 are different. In the metal, note that for a decaying wave, $\boldsymbol{k}^2$ should be greater than $\varepsilon_{\mathrm{m}}\frac{\omega^2}{c^2}$. $E_x(z)$ and $E_z(z)$ can be expressed as:

$$E_x = \{E_{dx}\sinh(q_2 z) + E_{0x}\sinh[q_2(d-z)]\}/\sinh(q_2 d), \quad 0 < z < d, \tag{7}$$

$$E_z = -k\{E_{dx}\cosh(q_2 z) + E_{0x}\cosh[q_2(d-z)]\}/q_2\sinh(q_2 d), \quad 0 < z < d, \tag{8}$$

where $q_2 = (k^2 - \frac{\omega^2}{c^2}\varepsilon_{\mathrm{m}})^{1/2}$.

Applying the continuity of E_x and D_z across $z = 0$ and $z = d$ yields

$$q_2 E_{0z}^{-}[\varepsilon_{3L} + \alpha_3(E_{0z}^{-})^{\beta} + \alpha_3(E_{0x})^{\beta}]\sinh(q_2 d) = -k\varepsilon_{\mathrm{m}}[E_{dx} - E_{0x}\cosh(q_2 d)], \tag{9}$$

$$q_2 E_{dz}^{+}[\varepsilon_{1\mathrm{L}} + \alpha_1(E_{dz}^{+})^{\beta} + \alpha_1(E_{dx})^{\beta}]\sinh(q_2 d) = -k\varepsilon_{\mathrm{m}}[E_{dx}\cosh(q_2 d) - E_{0x}], \tag{10}$$

where $E_{0z}^{\pm} = E_z(0^{\pm})$; $E_{dz}^{\pm} = E_z(d^{\pm})$; $E_{0x}^{+} = E_{0x}^{-} = E_{0x}$; $E_{dx}^{+} = E_{dx}^{-} = E_{dx}$.

A standard treatment of the nonlinear region 1 and region 3 invokes a 'first integral'[14−16] to obtain an equation for $\mathrm{d}E_x/\mathrm{d}z$. Differentiating Eq. (4) with respect to z, using Eq. (5) and multiplying by $\mathrm{d}E_x/\mathrm{d}z$, we have in region 1 and region 3

$$\frac{\mathrm{d}E_{x1,3}}{\mathrm{d}z}\frac{\mathrm{d}^2E_{x1,3}}{\mathrm{d}z^2} = k\frac{\mathrm{d}E_{x1,3}}{\mathrm{d}z}\frac{\mathrm{d}E_{z1,3}}{\mathrm{d}z} - \frac{\omega^2}{c^2}\varepsilon_{1,3}E_{x1,3}\frac{\mathrm{d}E_{x1,3}}{\mathrm{d}z}. \tag{11}$$

Integrating with respect to z, and substituting Eq. (4) in Eq. (11), yield

$$\frac{\omega^2}{c^2}(E_{0z}^{-})^2[\varepsilon_{3L} + \alpha_3(E_{0z}^{-})^{\beta} + \alpha_3(E_{0x})^{\beta}]^2$$

$$= k^2\left\{\varepsilon_{3L}(E_{0z}^-)^2 - \varepsilon_{3L}(E_{0x})^2 + 2\alpha_3(E_{0z}^-)^{\beta+2} + 2\alpha_3(E_{0x})^\beta(E_{0z}^-)^2 - \frac{2\alpha_3}{\beta+2}[(E_{0x})^2 + (E_{0z}^-)^2]^{\beta+2/2}\right\}, \quad (12)$$

in region 3; and

$$\frac{\omega^2}{c^2}(E_{dz}^+)^2[\varepsilon_{1\mathrm{L}} + \alpha_1(E_{dz}^+)^\beta + \alpha_1(E_{dx})^\beta]^2$$
$$= k^2\left\{\varepsilon_{1\mathrm{L}}(E_{dz}^+)^2 - \varepsilon_{1\mathrm{L}}(E_{dx})^2 + 2\alpha_1(E_{dz}^+)^{\beta+2} + 2\alpha_1(E_{dx})^\beta(E_{dz}^+)^2 - \frac{2\alpha_1}{\beta+2}[(E_{dx})^2 + (E_{dz}^+)^2]^{\beta+2/2}\right\}, \quad (13)$$

in region 1. Here we have set the integration constant $C = 0$ for $E_{x1,3}$, $E_{z1,3}$, and $\mathrm{d}E_{x1,3}/\mathrm{d}z$ must vanish as $z \to \pm\infty$.

There are five unknown quantities in Eqs. (9), (10), and (12), (13). Given one of these, we can obtain the dispersion relations in the asymmetric structure by solving the four equations. By comparing these with the results in Ref. [22], it is clear that the model in Ref. [22] is a special case at $\alpha_1 = 0$. However, that model is not a symmetric structure and hence cannot support two kinds of special modes: odd and even modes, as we will define in the next section.

2.2. The symmetric structure

In this case, region 1 and region 3 are the same nonlinear dielectric, i.e., $\varepsilon_1 = \varepsilon_3$, then two possible modes can exist: the odd mode and the even mode. In this paper, we define that a mode is odd one when $E_x(z)$ is an odd function, and a mode is even one when $E_x(z)$ is an even function.

2.2.1. The odd TM mode

In the metal, $E_x(z)$ and $E_z(z)$ can be expressed as

$$E_x = E_{dx}\sinh[q_2(z - d/2)]/\sinh(q_2 d/2), \quad 0 < z < d, \quad (14)$$

$$E_z = -\frac{kE_{dx}\cosh[q_2(z - d/2)]}{q_2\sinh(q_2 d/2)}, \quad 0 < z < d. \quad (15)$$

The continuity of E_x and D_z across $z = d$ then yields

$$q_2\tanh(q_2 d/2)E_{dz}^+[\varepsilon_{1\mathrm{L}} + \alpha_1(E_{dz}^+)^\beta + \alpha_1(E_{dx})^\beta] = -k\varepsilon_{\mathrm{m}}E_{dx}. \quad (16)$$

In a similar way with Eq. (13), we have

$$\frac{\omega^2}{c^2}(E_{dz}^+)^2[\varepsilon_{1\mathrm{L}} + \alpha_1(E_{dz}^+)^\beta + \alpha_1(E_{dx})^\beta]^2$$
$$= k^2\left\{\varepsilon_{1\mathrm{L}}(E_{dz}^+)^2 - \varepsilon_{1\mathrm{L}}(E_{dx})^2 + 2\alpha_1(E_{dz}^+)^{\beta+2} + 2\alpha_1(E_{dx})^\beta(E_{dz}^+)^2 - \frac{2\alpha_1}{\beta+2}[(E_{dx})^2 + (E_{dz}^+)^2]^{\beta+2/2}\right\}. \quad (17)$$

Rewrite Eq. (17) as

$$\left(\frac{\omega^2\varepsilon_1^2}{k^2c^2} - 2\varepsilon_1\right)E_{dz}^{+2} + \varepsilon_{1\mathrm{L}}E_d^2 + \frac{2\alpha_1}{\beta+2}E_d^{\beta+2} = 0, \quad (18)$$

where $E_d^2 = E_{dx}^2 + E_{dz}^{+2}$ is the squared magnitude of the electric field at the interface between regions 1 and 2. The relation between E_{dz}^{+2} and E_d^2 is given by Eq. (16):

$$(E_{dz}^+)^2 = \frac{k^2\varepsilon_{\mathrm{m}}^2}{k^2\varepsilon_{\mathrm{m}}^2 + [q_2\tanh(q_2 d/2)\varepsilon_1]^2}E_d^2. \quad (19)$$

Substituting Eq. (19) into Eq. (18), we obtain

$$\left(\frac{\omega^2\varepsilon_1^2}{k^2c^2} - 2\varepsilon_1\right)\frac{k^2\varepsilon_{\mathrm{m}}^2}{k^2\varepsilon_{\mathrm{m}}^2 + [q_2\tanh(q_2 d/2)\varepsilon_1]^2} + \varepsilon_{1\mathrm{L}} + \frac{2\alpha_1}{\beta+2}E_d^\beta = 0. \quad (20)$$

Rewrite Eq. (20) as

$$\tanh(q_2 d/2) = -\frac{\left[k^2 - \frac{\omega^2}{c^2}\varepsilon_1 + k^2\alpha_1\left(1 - \frac{2}{\beta+2}\right)\frac{E_d^\beta}{\varepsilon_1}\right]^{1/2}\varepsilon_{\mathrm{m}}}{q_2\varepsilon_1}\frac{1}{\left[1 - \alpha_1\left(1 - \frac{2}{\beta+2}\right)\frac{E_d^\beta}{\varepsilon_1}\right]^{1/2}}. \quad (21)$$

This is the dispersion relation of the odd TM mode.

2.2.2. The even TM mode

$E_x(z)$ and $E_z(z)$ can be expressed as

$$E_x = E_{dx}\cosh[q_2(z-d/2)]/\cosh(q_2 d), \quad 0<z<d, \tag{22}$$

$$E_z = \frac{-kE_{dx}\sinh[q_2(z-d/2)]}{q_2\cosh(q_2 d)}, \quad 0<z<d. \tag{23}$$

In a similar way with Eqs. (16) and (17), we obtain

$$-q_2\coth(q_2 d/2)E_{dz}^{+}[\varepsilon_{1\mathrm{L}}+\alpha_1(E_{dz}^{+})^{\beta}+\alpha_1(E_{dx})^{\beta}] = k\varepsilon_{\mathrm{m}}E_{dx}, \tag{24}$$

$$\begin{aligned}&\frac{\omega^2}{c^2}(E_{dz}^{+})^2[\varepsilon_{1\mathrm{L}}+\alpha_1(E_{dz}^{+})^{\beta}+\alpha_1(E_{dx})^{\beta}]^2\\ &= k^2\left\{\varepsilon_{1\mathrm{L}}(E_{dz}^{+})^2-\varepsilon_{1\mathrm{L}}(E_{dx})^2+2\alpha_1(E_{dz}^{+})^{\beta+2}+2\alpha_1(E_{dx})^{\beta}(E_{dz}^{+})^2-\frac{2\alpha_1}{\beta+2}[(E_{dx})^2+(E_{dz}^{+})^2]^{\beta+2/2}\right\}.\end{aligned} \tag{25}$$

Substituting Eq. (24) into Eq. (25) yields the following relation

$$\left(\frac{\omega^2\varepsilon_1^2}{k^2c^2}-2\varepsilon_1\right)\frac{k^2\varepsilon_{\mathrm{m}}^2}{k^2\varepsilon_{\mathrm{m}}^2+[q_2\coth(q_2 d/2)\varepsilon_1]^2}+\varepsilon_{1\mathrm{L}}+\frac{2\alpha_1}{\beta+2}E_d^{\beta}=0. \tag{26}$$

Rewrite Eq. (26) as

$$\coth(q_2 d/2) = -\frac{\left[k^2-\dfrac{\omega^2}{c^2}\varepsilon_1+k^2\alpha_1\left(1-\dfrac{2}{\beta+2}\right)\dfrac{E_d^{\beta}}{\varepsilon_1}\right]^{1/2}\varepsilon_{\mathrm{m}}}{q_2\varepsilon_1}\frac{1}{\left[1-\alpha_1\left(1-\dfrac{2}{\beta+2}\right)\dfrac{E_d^{\beta}}{\varepsilon_1}\right]^{1/2}}. \tag{27}$$

It is the dispersion relation of the even TM mode.

3. Discussion

Equations (21) and (27) are the main results in this paper. Due to the nonlinearity, the strength E_d at the interface appears in the dispersion relations. When $\alpha_1 = 0$, Eqs. (21) and (27) can reduce back to the linear case,[2] i.e. $\tanh(q_2 d/2) = -q_1\varepsilon_{\mathrm{m}}/q_2\varepsilon_1$ and $\coth(q_2 d/2) = -q_1\varepsilon_{\mathrm{m}}/q_2\varepsilon_1$, where ε_1 is the dielectric of the linear media; $q_1 = (k^2-\frac{\omega^2}{c^2}\varepsilon_1)^{1/2}$ and $q_2 = (k^2-\frac{\omega^2}{c^2}\varepsilon_{\mathrm{m}})^{1/2}$. When $d\to\infty$, the left-hand side of Eq. (21) equals to 1, and can be rewritten as

$$k^2 = \frac{\omega^2}{c^2}\frac{\varepsilon_{\mathrm{m}}^2\varepsilon_1^2-\varepsilon_{\mathrm{m}}\varepsilon_1^2\left[\varepsilon_1-\left(1-\dfrac{2}{\beta+2}\right)\alpha_1 E_d^{\beta}\right]}{\varepsilon_{\mathrm{m}}^2\varepsilon_1+\left(1-\dfrac{2}{\beta+2}\right)\alpha_1 E_d^{\beta}\varepsilon_{\mathrm{m}}^2-\left[\varepsilon_1-\left(1-\dfrac{2}{\beta+2}\right)\alpha_1 E_d^{\beta}\right]\varepsilon_1^2}. \tag{28}$$

When $\beta = 2$, from Eq. (28), we can obtain

$$k^2 = \frac{\omega^2}{c^2}\frac{\varepsilon_1^2\varepsilon_{\mathrm{m}}(\varepsilon_1+\varepsilon_{1\mathrm{L}}-2\varepsilon_{\mathrm{m}})}{(\varepsilon_1+\varepsilon_{1\mathrm{L}})\varepsilon_1^2-3\alpha_1 E_d^2\varepsilon_{\mathrm{m}}^2-2\varepsilon_{1\mathrm{L}}\varepsilon_{\mathrm{m}}^2}. \tag{29}$$

This result is the same as the dispersion relation at the single interface between metal and Kerr-type nonlinear medium in Ref. [21].

Figure 2 shows the dispersion relations of odd and even modes for a NL–M–NL geometry for three different thicknesses of the silver thin film. The values for the relevant parameters involve[21] $\alpha_1 = 6.397\times10^{-12}$ m$^2\cdot$V^{-2}, $\omega_{\mathrm{p}} = 1.36\times10^{16}$ rad/s, $\varepsilon_{1\mathrm{L}} = 2.405$, a field $E_d = 2.5\times10^5$ V/m, $\beta = 2$, $d = 40$, 50, and 70 nm for our computations. Figure 2 shows that the wave vector k of even mode is always larger than that of odd mode. It can be seen clearly that the difference between odd and even modes grows steadily with decreasing thickness d.

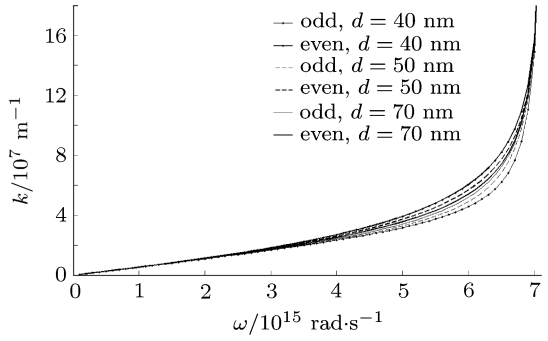


Fig. 2. The dispersion relations of the odd and even modes in the symmetric system.

The dispersion relations are plotted in Fig. 3 for different nonlinearity β for the thickness $d = 40$ nm. In Fig. 3, the wave vector $\boldsymbol{k}$ comes to different asymptotic lines with different β. The asymptotic line can be obtained from Eq. (28).

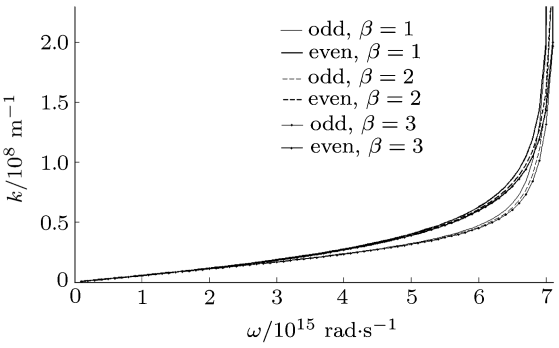


Fig. 3. The dispersion relations of the odd and even modes with different nonlinearities.

Figure 4 plots the dispersion relation as a function of the thickness d for different nonlinearity β at $\omega = 4 \times 10^{15}$ rad/s. These curves show that the larger the thickness d, the smaller the wave vector $\boldsymbol{k}$ for the even case, and the larger the value of $\boldsymbol{k}$ for the odd case.

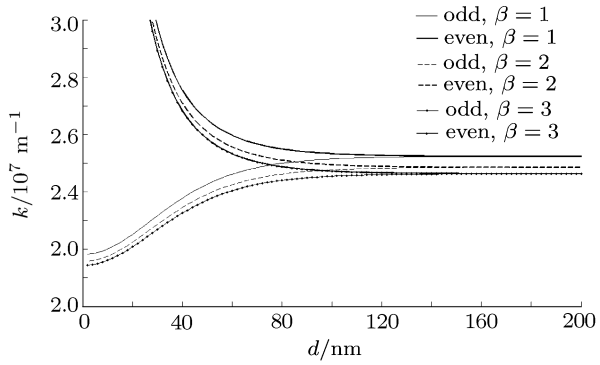


Fig. 4. The dispersion relation as a function of the thickness d.

However, the value of $\boldsymbol{k}$ of the odd and even cases will approach the same value as the thickness of the metal increases. The reason is that the SPPs in the two interfaces between the nonlinear and metal cannot couple to each other when the thickness d becomes larger.

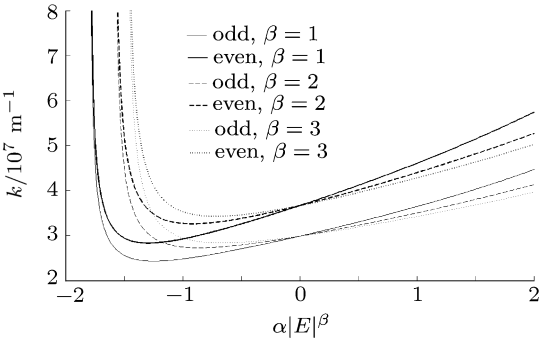


Fig. 5. The dispersion relation as a function of $\alpha\,|E|^\beta$.

Furthermore, the curves of the dispersion relation $\boldsymbol{k}$ versus the nonlinear term $\alpha\,|E|^\beta$ are plotted in Fig. 5 for different β at $d = 40$ nm and $\omega = 5 \times 10^{15}$ rad/s. For $\alpha > 0$, k increases monotonically with $\alpha\,|E|^\beta$. For $\alpha < 0$, k decreases with the absolute value of $\alpha\,|E|^\beta$ at the beginning; however, there is a rapid change as the absolute value of $\alpha\,|E|^\beta$ increases further, and a cutoff value of $\alpha\,|E|^\beta$ exists. The wave vector $\boldsymbol{k}$ becomes very large at the cutoff value of $\alpha\,|E|^\beta$. The cutoff value of $\alpha\,|E|^\beta$ can be obtained as follows. When $\boldsymbol{k} \to \infty$, the left-hand side of Eq. (21) equals to 1, and can be rewritten as

$$1 = -\frac{\left[1+\alpha_1\left(1-\dfrac{2}{\beta+2}\right)\dfrac{E_d^\beta}{\varepsilon_1}\right]^{1/2}\varepsilon_{\rm m}}{\varepsilon_1} \times \frac{1}{\left[1-\alpha_1\left(1-\dfrac{2}{\beta+2}\right)\dfrac{E_d^\beta}{\varepsilon_1}\right]^{1/2}}. \tag{30}$$

Solving Eq. (30), we can obtain the cutoff value of $\alpha\,|E|^\beta$.

4. Conclusion

In summary, we have derived the SPP dispersion relations analytically for a metallic thin film bounded by two sides media of nonlinear dielectric of arbitrary nonlinearity by introducing a generalised first integral approach. The dispersion relations of the odd mode and the even mode are obtained in the symmetric structure. Due to the nonlinearity of dielectric, the strength E_d at the interface appears and can alter the

dispersion relations. The dispersion relations can reduce to the linear case as nonlinear coefficient $\alpha_1 = 0$, and the Kerr nonlinear case can be obtained for the arbitrary nonlinearity $\beta = 2$. The numerical result shows how the metal film thickness, the magnitude of the electric field and nonlinearity β affect the SPP frequency.

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