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Parametric excitation of surface plasma waves over a metallic surface by laser in an external magnetic field

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Abstract

Effects of external static magnetic field (applied in $\hat{y}$-direction) on resonant excitation of surface plasma waves (SPW) have been investigated over the metal free space interface. The high power laser (ω_0, $\vec{k}_{0z}$) is incident over the metal surface and exerts a ponderomotive force on the metal electrons in the skin layer. The ponderomotive force disturbs the quasi-neutrality of plasma which results into the excitation of space charge field at the frequency $2\omega_0$. The electron density perturbation at frequency $2\omega_0$ driven by self-consistent space charge potential couples with the oscillatory velocity due to the seed SPW (ω, $\vec{k}_z$) and produces nonlinear current to drive another counter propagating SPW (ω_1, $\vec{k}_{1z}$) at the phase matching conditions of frequency $\omega = \omega_1 - 2\omega_0$ and wavenumber $\vec{k}_z = \vec{k}_{1z} - 2\vec{k}_{0z}$ (by feedback mechanism). The parametric process becomes resonant at $2\omega_0 \approx \omega_p$ and the maximum growth rate is achieved for an incidence angle of laser $\theta = 40°$. The growth rate of the process reduces to half on increasing the magnetic field from 0.49 to 2.45 MG. The present study may be significant to the laser absorption experiments where surface rippling can strongly affect the laser energy absorption.

Introduction

Surface plasma wave (SPW) is an electromagnetic wave that exists at the boundary between two media for example, metal–free space interface, its amplitude falls off exponentially in a direction perpendicular to the surface (Raether, 1988). The excitation of SPWs over smooth metal surfaces by lasers is not possible due to k-vector mismatch as the SPW wave number is greater than the component of the laser wave vector along the interface. Numerous techniques were utilized to increase the momentum of the light for the excitation of SPWs.

In recent years, extensive research has been done towards the excitation of SPW both experimentally and theoretically. With low laser powers, SPWs can be excited by attenuated total reflection configuration or by creating density ripple on the metal surface (Kretschmann & Reather, 1968). With high powers lasers, the excitation of a SPW occurs at the interface of vacuum over-dense plasma which can be created during the interaction of an intense laser pulse with a solid metal target (Brodin & Lundberg, 1991; Parashar *et al*., 1998; Macchi *et al*., 2002). The interaction of high power lasers with solid density targets leads to nonlinear phenomena having vast applications in high harmonic generation, ion acceleration, laser ablation of materials, and so on (Bulanov *et al*., 1994; Lee & Cho, 1999; Macchi *et al*., 2002; Baeva *et al*., 2006).

In view of the various applications, it would be interesting to consider wave-wave interactions involving SPWs. Yasumoto (1981) analyzed theoretically the decay instability of a high-frequency SPW and a low-frequency ion acoustic surface wave due to an intense electromagnetic plane wave incident perpendicularly on an unmagnetized semi-infinite plasma from a vacuum. He also investigated the parametric decay instability of two high frequency SPWs in semi-infinite plasma (Yasumoto & Noguchi Verma, 1982). The growth rate for the instability and the threshold amplitude of the incident wave are determined. The threshold amplitude of the order of 8.56×10^2 Vm^{-1} is obtained for an incident angle of the plane wave $(\theta) = 40°$. The process of two surface plasmon decay (TSWD) is similar to two-plasmon decay (TPD) in laser-produced plasma, though the former is primarily a surface phenomenon whereas the latter is a volume phenomenon. Macchi *et al.* (2001) observed a new electron parametric instability involving the decay of one-dimensional (1D) electrostatic oscillation of frequency 2ω into two surface waves each of ω frequency using particle-in-cell simulations (PIC). Later he discussed an analytical model involving the parametric excitation of electromagnetic surface waves in the interaction of an ultrashort, intense laser pulse with overdense plasma. The growth rate of the process is maximum for normal incidence of the laser (Macchi *et al*., 2002). Singh & Tripathi (2007) the explored the possibility of resonant SPW excitation by beating two laser beams, obliquely incident on a metal surface. The two lasers exert the ponderomotive force on free electrons at the beta frequency, producing a nonlinear current

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that resonantly derives the SPW. Kumar & Tripathi (2007) studied the resonant plasma oscillations at the second harmonic by obliquely incident high power laser on a vacuum plasma interface. The plasma oscillations parametrically excite a pair of counter-propagating SPWs. Recently, Goel *et al.* (2015) theoretically studied the stimulated Compton scattering of a SPW, excited on the metal–vacuum interface by a high-frequency laser. The parametric decay of the SPW into another surface wave can be realized via quasi-static plasma wave in metals. The growth rate of the Compton process increases with the pump wave frequency, the width of the metal layer, laser amplitude and its spot size.

The motivation of the paper is to study the effect of the static magnetic field on the parametric excitation of two SPW by high-intensity laser over the surface of dense plasma, created by laser irradiation of a metallic target. The magnetic field is parallel to the surface and perpendicular to the SPW propagation. The transmitted field of the laser inside the metal acts as a pump wave of frequency (ω_0, k_{0z}) and exerts the ponderomotive force on the metal electrons resulting in resonantly driven plasma oscillations at the second harmonic when $2\omega_0 = \omega_p$ (where ω_p is the plasma frequency). The ponderomotive force displaces the electrons creating the self-consistent electrostatic potential. The potential couples with the oscillatory velocity due to one SPW and gives rise to a nonlinear density perturbation to drive other SPW. Growth rate equation is obtained on the basis of parametric coupling of a pump wave and two SPWs. This paper has been organized into four sections where introduction is presented as the first section. In the section Parametric growth of the SPW, the parametric coupling of a pump wave and two SPWs in the presence of external magnetic field is presented. A discussion of results and conclusions are given in the third and fourth section, respectively.

Parametric growth of the SPWs

Consider the metal–free space interface at $x = 0$ with half-space $x > 0$ is the free space and $x < 0$ is the plasma of equilibrium electron density n_0. The external constant magnetic field ($\vec{B}_s$) is applied in $\hat{y}$-direction that is, a magnetic field is parallel to the surface and perpendicular to the SPW propagation. A high power laser is obliquely incident on the interface from the free space at an angle of incidence θ as shown Figure 1. The field of the incident laser is

$$\vec{E}_I = A_I \cos\theta\left(\hat{z} + \frac{k_{0z}}{k_{0x}}\hat{x}\right)e^{-i(\omega_0 t - k_{0z}z + k_{0x}x)} \tag{1}$$

where $k_{0x} = \omega_0/c \cos\theta$ and $k_{0z} = \omega_0/c \sin\theta$. The reflected laser from the plasma surface is

$$\vec{E}_R = A_I \cos\theta\left(\hat{z} - \frac{k_{0z}}{k_{0x}}\hat{x}\right)e^{-i(\omega_0 t - k_{0z}z - k_{0x}x)} \tag{2}$$

The transmitted field inside the metal is

$$\vec{E}_T = \frac{2A_I\cos\theta(\hat{z} - \zeta_0\hat{x})}{1 + (k_{0x}/k_{0z})(-\varepsilon_{0xx}\zeta_0 + \varepsilon_{0xz})}e^{\alpha_0 x}e^{-i(\omega_0 t - k_{0z}z)} \tag{3}$$

Where $\zeta_0 = (ik_{0z}\varepsilon_{0xx} - \alpha_0\varepsilon_{0xz}/\alpha_0\varepsilon_{0xx} + ik_{0z}\varepsilon_{0xz})$, $\varepsilon_{0xx} = \varepsilon_L (1 - \omega_p^2/(\omega_0^2 - \omega_c^2))$, $\alpha_0^2 = k_{0z}^2 - (\omega_0^2/c^2)\varepsilon_{v0}$, $\varepsilon_{0xz} = i\omega_c\omega_p^2\varepsilon_L/\omega_0((\omega_0^2 - \omega_c^2)$, and $\varepsilon_{v0} = \varepsilon_{0xx} + \varepsilon_{0xz}^2/\varepsilon_{0xx}$. ε_L is the lattice permittivity. $\varepsilon_p = \sqrt{n_0 e^2/m\varepsilon_0}$ and $\omega_c = eB_s/m$ are the plasma and

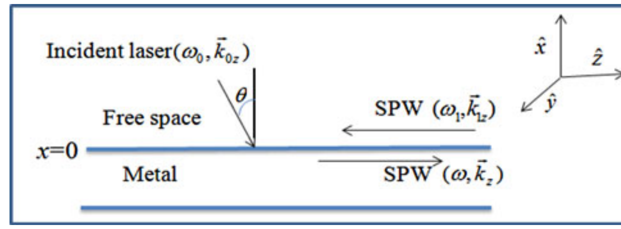

Fig. 1. Schematic of parametric excitation of SPW at the metal–free space interface.

cyclotron frequency respectively. $-e$ and m are the charge and effective mass of electron.

Under the influence of the transmitted laser field, plasma electrons oscillate in the presence of a static magnetic field. The oscillatory velocity of electrons is given by

$$v_{0x} = \frac{e}{m}\frac{(i\omega_0\zeta_0 + \omega_c)}{(\omega_0^2 - \omega_c^2)}E_{Tz} \tag{4}$$

$$v_{0z} = \frac{e}{m}\frac{(-i\omega_0 + \zeta_0\omega_c)}{(\omega_0^2 - \omega_c^2)}E_{Tz} \tag{5}$$

The laser exerts ponderomotive force on the electrons at frequency ω_0, given by

$$\vec{F}_p = -\frac{m}{2}[\vec{v}_0.\nabla\vec{v}_0] - \frac{e}{2}[\vec{v}_0 \times \vec{B}] \tag{6}$$

where $\vec{B} = i\vec{k}_0 \times \vec{E}_T/i\omega_0$ is the magnetic field of pump wave inside the overdense plasma. On substituting the values from Eqs. (4) and (5) into Eq. (6), we obtained

$$F_{px} = \frac{-e}{2}\frac{E_{Tz}}{(\omega_0^2 - \omega_c^2)}\frac{(-i\omega_0\varepsilon_{0xz} + \omega_c\varepsilon_{0xx})}{(\alpha_0\varepsilon_{0xx} + ik_{0z}\varepsilon_{0xz})}\nabla^2 v_{ox} - \frac{e}{2i\omega_0}\frac{(\varepsilon_{0xx}E_{Tz})}{(\alpha_0\varepsilon_{0xx} + ik_{0z}\varepsilon_{0xz})}\nabla^2 v_{oz} \tag{7}$$

$$F_{pz} = \frac{-e}{2}\frac{E_{Tz}}{(\omega_0^2 - \omega_c^2)}\frac{(-i\omega_0\varepsilon_{0xz} + \omega_c\varepsilon_{0xx})}{(\alpha_0\varepsilon_{0xx} + ik_{0z}\varepsilon_{0xz})}\nabla^2 v_{oz} + \frac{e^2}{2i\omega_0}\frac{(\varepsilon_{0xx}E_{Tz})}{(\alpha_0\varepsilon_{0xx} + ik_{0z}\varepsilon_{0xz})}\nabla^2 v_{ox} \tag{8}$$

Here, F_{px} and F_{pz} are the x and z components of ponderomotive force and $\nabla = i(k_{0z}\hat{z} - i\alpha_0\hat{x})$. The ponderomotive force displaces the electrons creating the space charge potential ($E_{2\omega_0} = -\nabla_{2\omega_0}\phi_{2\omega_0}$) where $\nabla_{2\omega_0} = 2i(k_{0z}\hat{z} - i\alpha_0\hat{x})$. On solving equation of motion and continuity equation, we obtain the density perturbation ($n_{2\omega_0}$) due to ponderomotive force and space charge potential as follows

$$n_{2\omega_0} = \frac{-\chi_e}{4\pi e}\nabla_{2\omega_0}^2\phi_{2\omega_0} + \frac{n_0}{4m\omega_0(\omega_0^2 - \omega_c^2)} \left[2\omega_0(\alpha_0 F_{px} + ik_{0z}F_{pz}) + 2i\omega_c(\alpha_0 F_{pz} - ik_{0z}F_{px})\right] = n_{2\omega_0}^{L} + n_{2\omega_0}^{NL} \tag{9}$$

where $n_{2\omega_0}^{L}$ and $n_{2\omega_0}^{NL}$ are the linear and nonlinear part of the

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electron density perturbation. $\chi_e = -\omega_p^2/4(\omega_0^2 - \omega_c^2)$ is the electron susceptibility. Using Eq. (9) in Poisson's equation $\nabla^2\phi = 4\pi n_{2\omega_0} e$, we get

$$\phi_{2\omega_0} = \frac{4\pi e n_{2\omega_0}^{NL}}{4(\alpha_0^2 - k_{0z}^2)\varepsilon} \tag{10}$$

where $\varepsilon = 1 + \chi_e$. Using Eq. (10) in Eq. (9), we get

$$n_{2\omega_0} = \left(1 - \frac{\chi_e}{\varepsilon}\right) n_{2\omega_0}^{NL} \tag{11}$$

The density perturbation couples with plasma oscillations and excites the two counter propagating SPWs of frequency ω and ω_1, in the plasma. The wave equation governing electric fields of two SPWs can be written as

$$\nabla^2\vec{E}_\omega - \nabla(\nabla.\vec{E}_\omega) = \frac{4\pi}{c^2}\frac{\partial \vec{J}_\omega^{NL}}{\partial t} + \frac{\tilde{\varepsilon}}{c^2}\frac{\partial^2 \vec{E}_\omega}{\partial t^2} \tag{12}$$

$$\nabla^2\vec{E}_{\omega_1} - \nabla(\nabla.\vec{E}_{\omega_1}) = \frac{4\pi}{c^2}\frac{\partial \vec{J}_{\omega_1}^{NL}}{\partial t} + \frac{\tilde{\varepsilon}_1}{c^2}\frac{\partial^2 \vec{E}_{\omega_1}}{\partial t^2} \tag{13}$$

In the absence of nonlinear coupling, Eqs. (12) and (13) yield the field structure of the SPWs as

$$E_{\omega z} = a\psi(x, z) \tag{14}$$

where $\psi(x, z) = \begin{cases} e^{-\alpha' x} e^{-i(\omega t - k_z z)} & \text{for } x > 0 \\ e^{\alpha x} e^{-i(\omega t - k_z z)} & \text{for } x < 0 \end{cases}$ and

$$E_{\omega_1 z} = a_1 \psi_1(x, z) \tag{15}$$

where

$$\psi_1(x, z) = \begin{cases} e^{-\alpha'_1 x} e^{-i(\omega_1 t - k_{1z} z)} & \text{for } x > 0 \\ e^{\alpha_1 x} e^{-i(\omega_1 t - k_{1z} z)} & \text{for } x < 0 \end{cases}$$

where $\alpha'^2 = k_z^2 - \omega^2/c^2$, $\alpha^2 = k_z^2 - \omega^2\varepsilon_v/c^2$, $\alpha_1'^2 = k_z^2 - \omega_1^2/c^2$, and $\alpha_1^2 = k_z^2 - \omega_1^2\varepsilon_{v1}/c^2$. The dispersion relation of these SPWs is given by

$$\alpha + \alpha'\varepsilon_v + ik_z\frac{\varepsilon_{xz}}{\varepsilon_{xx}} = 0 \text{ and } \alpha_1 + \alpha_1'\varepsilon_{v1} + ik_{1z}\frac{\varepsilon_{1xz}}{\varepsilon_{1xx}} = 0$$

where $\varepsilon_v = \varepsilon_{xx} + (\varepsilon_{xz}^2/\varepsilon_{xx})$ and $\varepsilon_{v1} = \varepsilon_{1xx} + (\varepsilon_{1xz}^2/\varepsilon_{1xx})$ The phase matching conditions for the parametric decay are $k_z = k_{1z} - 2k_{0z}$ and $\omega = \omega_1 - 2\omega_0$. On replacing $\nabla = (\partial\hat{x}/\partial x) + (\partial\hat{z}/\partial z)$ in Eqs. (12) and (13) and simplification yields the following set of equations.

$$\frac{\omega^2}{c^2}\varepsilon_{xx}\left[\frac{\partial^2 E_z}{\partial x^2} - \left(k_z^2 - \frac{\omega^2}{c^2}\left(\varepsilon_{xx} + \frac{\varepsilon_{xz}^2}{\varepsilon_{xx}}\right)\right)E_z\right] = \frac{4\pi i\omega}{c^2}\left[J_{\omega z}^{NL}\left(k_z^2 - \frac{\omega^2}{c^2}\varepsilon_{xx}\right) - J_{\omega x}^{NL}\left(ik_z - \frac{\omega^2}{c^2}\varepsilon_{xz}\right)\right] \tag{16}$$

$$\frac{\omega_1^2}{c^2}\varepsilon_{1xx}\left[\frac{\partial^2 E_{1z}}{\partial x^2} - \left(k_{1z}^2 - \frac{\omega_1^2}{c^2}\left(\varepsilon_{1xx} + \frac{\varepsilon_{1xz}^2}{\varepsilon_{1xx}}\right)\right)E_{1z}\right] = \frac{4\pi i\omega_1}{c^2}\left[J_{\omega_1 z}^{NL}\left(k_{1z}^2 - \frac{\omega_1^2}{c^2}\varepsilon_{1xx}\right) - J_{\omega_1 x}^{NL}\left(ik_{1z} - \frac{\omega_1^2}{c^2}\varepsilon_{1xz}\right)\right] \tag{17}$$

The coupling of SPWs with plasma oscillations excites non-linear current densities $\vec{J}_\omega^{NL} = -en_{2\omega_0}^* v_{\omega_1}/2$ and $\vec{J}_{\omega_1}^{NL} = -en_{2\omega_0}^* v_\omega/2$ at a frequency ω and ω_1 respectively. $\tilde{\varepsilon} = 1$ and $\tilde{\varepsilon}_1 = 1$ for free space and in the metal are the dielectric tensors due to the presence of the external magnetic field, given by

$$\tilde{\varepsilon} = \begin{pmatrix} \varepsilon_L\left(1 - \frac{\omega_p^2(\omega + iv)}{\omega((\omega + iv)^2 - \omega_c^2)}\right) & 0 & \frac{-i\omega_c}{\omega}\frac{\varepsilon_L\omega_p^2}{((\omega + iv)^2 - \omega_c^2)} \\ 0 & \varepsilon_L\left(1 - \frac{\omega_p^2}{\omega(\omega + vi)}\right) & 0 \\ \frac{i\omega_c}{\omega}\frac{\varepsilon_L\omega_p^2}{((\omega + iv)^2 - \omega_c^2)} & 0 & \varepsilon_L\left(1 - \frac{\omega_p^2(\omega + iv)}{\omega((\omega + iv)^2 - \omega_c^2)}\right) \end{pmatrix}$$

and

$$\tilde{\varepsilon}_1 = \begin{pmatrix} \varepsilon_L\left(1 - \frac{\omega_p^2(\omega_1 + iv)}{\omega_1((\omega_1 + iv)^2 - \omega_c^2)}\right) & 0 & \frac{-i\omega_c}{\omega_1}\frac{\varepsilon_L\omega_p^2}{((\omega_1 + iv)^2 - \omega_c^2)} \\ 0 & \varepsilon_L\left(1 - \frac{\omega_p^2}{\omega_1(\omega_1 + vi)}\right) & 0 \\ \frac{i\omega_c}{\omega_1}\frac{\varepsilon_L\omega_p^2}{((\omega_1 + iv)^2 - \omega_c^2)} & 0 & \varepsilon_L\left(1 - \frac{\omega_p^2(\omega + iv)}{\omega_1((\omega_1 + iv)^2 - \omega_c^2)}\right) \end{pmatrix}$$

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The SPWs impart oscillatory velocities to the electrons. The x and z components of the velocity at frequency ω and ω_1 are given by

$$v_x = \frac{e}{m}\frac{(-i\omega E_x + \omega_c E_z)}{(\omega^2 - \omega_c^2)} \text{ and } v_z = \frac{-e}{m}\frac{(\omega_c E_x + i\omega E_z)}{(\omega^2 - \omega_c^2)}$$

$$v_{1x} = \frac{e}{m}\frac{(-i\omega_1 E_{1x} + \omega_c E_{1z})}{(\omega_1^2 - \omega_c^2)} \text{ and } v_{1z} = \frac{-e}{m}\frac{(\omega_c E_{1x} + i\omega_1 E_{1z})}{(\omega_1^2 - \omega_c^2)}$$

where

$$E_{1x} = \frac{-ik_{1z}\varepsilon_{1xx} + \alpha_1\varepsilon_{1xz}}{ik_{1z}\varepsilon_{1xz} + \alpha_1\varepsilon_{1xx}}E_{1z} = \zeta_1 E_{1z}$$

$$E_x = \frac{-ik_z\varepsilon_{xx} + \alpha\varepsilon_{xz}}{ik_z\varepsilon_{xz} + \alpha\varepsilon_{xx}}E_z = \zeta E_z$$

Substituting the values from Eqs. (14) and (15) and the corresponding nonlinear current at frequency ω and ω_1 in Eqs. (16) and (17), respectively. On multiplying the resultant equations by ψ^* and ψ_1^* respectively and integrating them from $-\infty$ to ∞ yields

$$a\left[\left(\alpha^2 - k_z^2 + \frac{\omega^2}{c^2}\varepsilon_v\right)\frac{1}{2\alpha} + \left(\alpha'^2 - k_z^2 + \frac{\omega^2}{c^2}\right)\frac{1}{2\alpha'}\right]$$
$$= \frac{n^*_{2\omega_0}a_1e^2}{4m}\frac{4\pi i}{\omega(\omega_1^2 - \omega_c^2)\varepsilon_{xx}}\frac{1}{(2\alpha_0 + \alpha_1 + \alpha)}$$
$$\times\left[\left(k_z^2 - \frac{\omega^2}{c^2}\varepsilon_{xx}\right)(\omega_c\zeta_1 + i\omega_1) + \left(ik_z\alpha - \frac{\omega^2}{c^2}\varepsilon_{xz}\right)(-i\omega_1\zeta_1 + \omega_c)\right] \quad (18)$$

$$a_1\left[\left(\alpha_1^2 - k_{1z}^2 + \frac{\omega_1^2}{c^2}\varepsilon_{v1}\right)\frac{1}{2\alpha_1} + \left(\alpha_1'^2 - k_{1z}^2 + \frac{\omega_1^2}{c^2}\right)\frac{1}{2\alpha'_1}\right]$$
$$= \frac{n^*_{2\omega_0}ae^2}{4m}\frac{4\pi i}{\omega_1(\omega^2 - \omega_c^2)\varepsilon_{1xx}}\frac{1}{(2\alpha_0 + \alpha_1 + \alpha)}\times$$
$$\left[\left(k_{1z}^2 - \frac{\omega_1^2}{c^2}\varepsilon_{1xx}\right)(\omega_c\zeta + i\omega) + \left(ik_{1z}\alpha_1 - \frac{\omega_1^2}{c^2}\varepsilon_{1xz}\right)(-i\omega\zeta + \omega_c)\right] \quad (19)$$

where

$$n^*_{2\omega_0} = \frac{n_0}{4m\omega_0(\omega_0^2 - \omega_c^2)}$$
$$\left[2\omega_0(\alpha_0F^*_{px} - ik_{0z}F^*_{pz}) - 2i\omega_c(\alpha_0F^*_{pz} + ik_{0z}F^*_{px})\right]\left(1 - \frac{\chi_e}{\varepsilon}\right)$$

F^*_{px} and F^*_{pz} are the complex conjugate of the x and z components of ponderomotive force. In the absence of nonlinear coupling (i.e., with zero RHS of Eqs. (16) and (17)), these equations give eigen functions (14) and (15) and frequencies of two surface plasma waves as $\omega \cong \omega_r$ and $\omega_1 \cong \omega_{1r}$ respectively. These frequencies are modified in the presence of nonlinear coupling [i.e., $v_\omega \neq 0$ and $v_{\omega_1} \neq 0$] and are given by $\omega = \omega_r + i\gamma$ and $\omega_1 = \omega_{1r} + i\gamma$, where γ is the growth rate of the two surface wave decay obtained under the influence of external magnetic field numerical values of the growth rate can be calculated by solving Eqs. (18) and (19) for different values of normalized cyclotron frequency (ω_c/ω_p), incident laser angle (θ), and amplitude $(a_0 = eA_I/m\omega_pc)$. The other parameters are $\omega_p = 2\omega_0$, $a_0 = 0.05$, and $\nu/\omega_p = 0.01$. The normalized frequency (ω/ω_p) and normalized growth rate (γ/ω_p) of SPW is plotted as a function of laser incidence angle (θ) for different values of ω_c/ω_p in Figures 2 and 3, respectively. The frequency of the SPW (ω_c/ω_p) increases with θ and ω_c/ω_p and saturates at its higher values. At $\omega_p = 2\omega_0$, the frequency of other SPW can be calculated using the phase matching conditions $\omega = \omega_1 - 2\omega_0$. The growth rate (γ/ω_p) of the process reduces to half on increasing $\omega_c/\omega_p = 0.004$ to $\omega_c/\omega_p = 0.02$. At fixed ω_c/ω_p, the maximum growth rate is obtained around θ = 40°. In Figures 4(a) and 4(b), the transmitted field of incident laser and ponderomotive force are plotted with ω_c/ω_p. Figure 5 shows the normalized growth rate (γ/ω_p) for different values of laser amplitude (a_0). Growth rate increases with the amplitude of the incident laser.

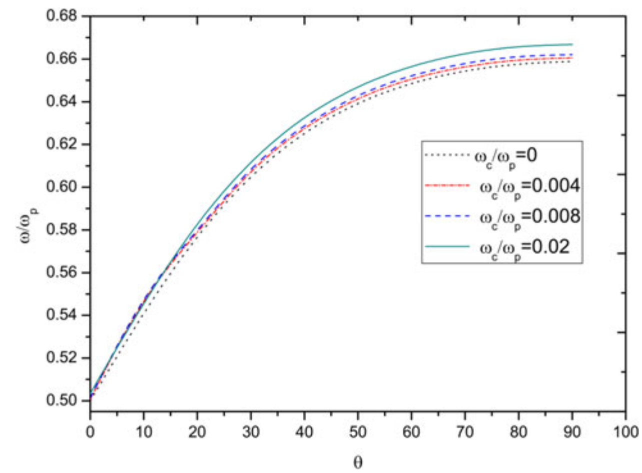

Fig. 2. Variation of the normalized frequency of surface plasma wave (ω/ω_p) with the angle of incidence of the laser pulse at $(\omega_0/\omega_p) = 0.5$.

Discussion

In the present work, effects of static magnetic field ($\omega_c = eB_s/m$, where B_s is the external magnetic field) are examined on the parametric excitation of a pair of SPW over the metal surface by a

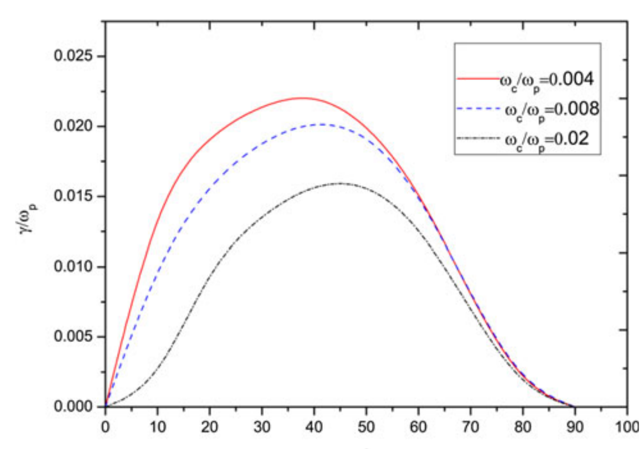

Fig. 3. The plot of normalized growth rate (γ/ω_p) with the angle of incidence of the laser pulse on varying normalized cyclotron frequency (ω_c/ω_p) for $(\omega_0/\omega_p) = 0.5$.

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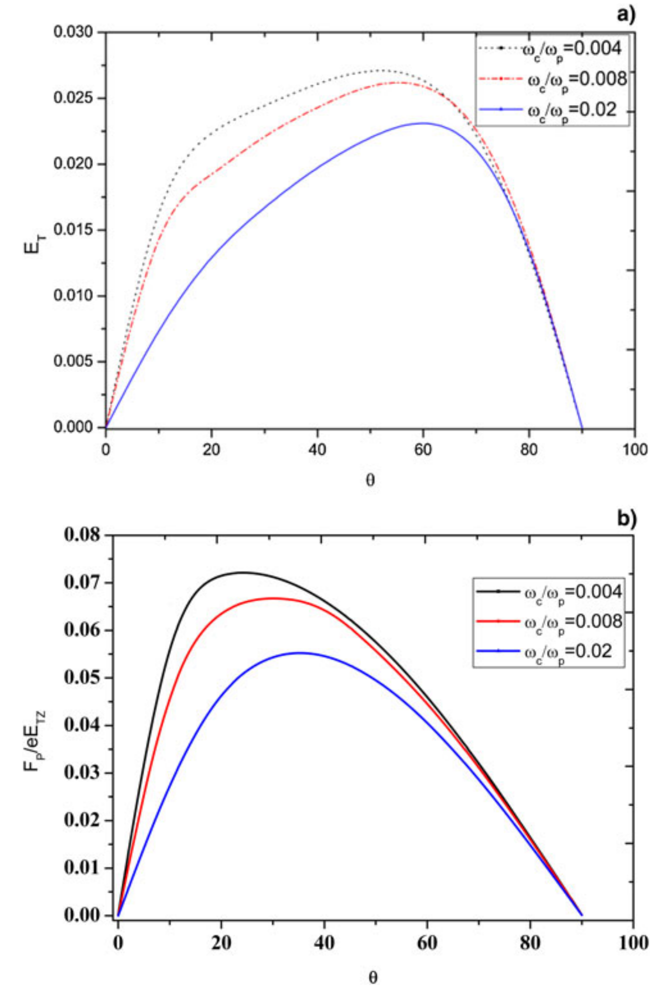

Fig. 4. (a) Variation of laser transmitted field in the metal and (b) ponderomotive force on the metal electrons as a function of the incidence angle of laser for different values of the normalized magnetic field.

laser. The equation of motion of the metal electrons is solved along with continuity equation to study the effect of the externally applied magnetic field. The applied magnetic field induces changes in the dispersion relation of the SPWs and a complex mathematical expression for the growth rate of the SPW is obtained which reduces to the expression obtained by Kumar & Tripathi (2007) in the absence of magnetic field ($\omega_c/\omega_p = 0$). Macchi *et al.* (2002) studied the process of SPW excitation using 2D particle in cell simulation and postulated that growth rate is maximum for normal incidence of the laser on the metal surface. Kumar & Tripathi (2007) theoretically verified the results. However, in the presence of the external magnetic field, the growth rate increases with the angle of incidence reaches a maximum value at $\theta = 40°$ and starts decreasing afterwards as observed in Figure 3. The transmitted field of the laser [Eq. (3)] is modified due to the applied magnetic field and not maximum for normal incidence of the laser as observed in Figure 4(a). It decreases with further increase in magnetic field. Also, the ponderomotive force experienced by the metal electrons decreases with the magnetic field as shown in Figure 4(b). The growth rate decreases with the applied magnetic field due to the decrease in transmitted field of the laser in metal and ponderomotive force with the applied magnetic field. It is clear from Eqs. (18) and (19), that growth rate is directly proportional to the amplitude of the laser and increases significantly with the laser amplitude as observed in Figure 5. The parametrically excited SPW may be useful for heating of plasma ions. In relativistic case (laser intensity $I \geq 10^{19}$ W/cm^2) the plasma electrons become highly energetic and their mass modify by Lorentz factor. In this situation, the resonance condition $W_p = 2W_0$, may be change due to relativistic effect.

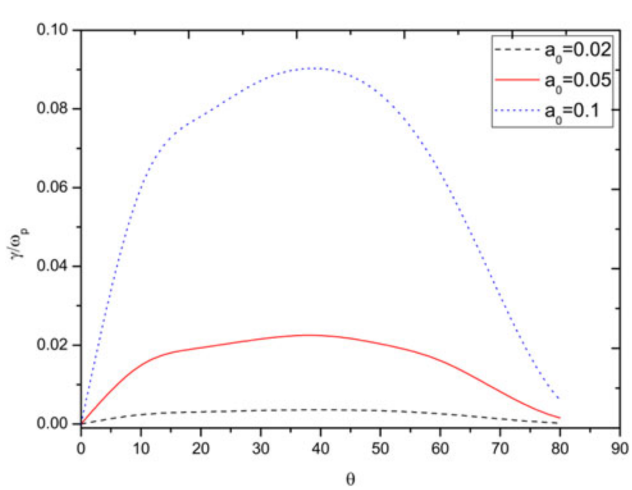

Fig. 5. The plot of normalized growth rate (γ/ω_p) with the angle of incidence of the laser pulse on varying the normalized amplitude of the laser pulse.

In mild relativistic case, electron mass is modified by relativistic mass, and it affects the resonance condition as well as the growth rate of the SPW. While in strong relativistic case, SPW excitation process becomes more complicated due to other effects like hole boring, particle acceleration etc, during ultra-high laser interaction with mater.

In the present analysis, we have considered very high magnetic, that is, like a few tens or Tesla. Hosokai *et al.* (2006), observed the effect of external static magnetic in on electron bean generation in their setup. Although they have applied less than 1 T, now a days one can get the pulsed magnetic field up to 70 T (Lagutin *et al.*, 2003). Nalini *et al.* (2010), also proposed a scheme through which they generated hundreds of Tesla in inertial magnets. The strength of external magnetic field can also be optimized with laser intensity. At low laser intensity, the optimum values of the magnetic field are very high; however, it decreases with high laser intensity. If such a strong magnetic field is not available at a laboratory, then the experiment can be carried out at high laser intensity, but in that case, the relativistic effect should also be considered.

Conclusions

In this work, we discussed two surface wave decay of the high power laser obliquely incident at the metal–free space interface in the presence of an external magnetic field. The decay is possible due to plasma density perturbations at the second harmonic when $\omega_p = 2\omega_0$. The growth rate of the process increases with the angle of incidence of laser upto a particular value and decreases at higher angles. With the increase in magnetic field strength, growth rate decreases from $\simeq 0.022\omega_p$ to $\simeq 0.013\omega_p$. Thus, the applied magnetic field can be optimized for efficient growth of the SPW.

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