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Parametric excitation of surface plasma waves by stimulated Compton scattering of laser beam at metal-free space interface

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Abstract

An obliquely incident high-power laser (ω_0, k_{0z}) on the metallic surface can resonantly excite a surface plasma wave (SPW) (ω_1, k_{1z}) and a quasi-electrostatic plasma wave (ω, k_z) inside the skin layer at the phase-matching conditions of frequency $\omega_1 = \omega - \omega_0$ and wave number $k_{1z} = k_z - k_{0z}$. The oscillating electrons in the skin layer couples with the seed SPW and exert non-linear ponderomotive force on electrons at the frequency of quasi-static mode. Density perturbations due to quasi-static mode and ponderomotive force associate with the motion of electrons (due to incident laser) and give rise to a non-linear current by feedback mechanism. At $\omega/k_z \sim v_F$ (where v_F is the Fermi velocity of metal) this non-linear current is responsible for the growth of SPW. The maximum growth of the present process ($\cong 1.5 \times 10^{12}$ s^{-1}) is achieved at incident angle $\theta = 42°$ for laser frequency $\omega_0 = 2 \times 10^{15}$ rad/s. Growth of SPW enhances from 1.62×10^{11} to $\cong 1.5 \times 10^{12}$ s^{-1} as the magnetic field changes from 12 to 24 MG. The excited SPW can be utilized for surface heating and diagnostics purpose.

Keywords: Surface plasma waves; Parametric excitation; Stimulated Compton scattering

1. INTRODUCTION

In recent years, considerable attention has been given to the study of parametric instabilities of surface plasma waves (SPWs) on bounded plasma systems due to vast applications in fast ignition fusion, high harmonic generation, ion acceleration, laser ablation of materials, etc. (Sajal & Tripathi, 2004; Baeva *et al.*, 2006; Sajal *et al.*, 2007; Verma & Sharma, 2009; Kumar *et al.*, 2010; Hao *et al.*, 2013). SPW is an electromagnetic wave that propagates at the boundary between two media with different conductivities and dielectric properties, such as a conductor-free space boundary and its amplitude falls off exponentially away from the interface in both media (Kretschmann & Reather, 1968; Lindgren *et al.*, 1982; Prakash *et al.*, 2013). Excitation of SPWs over the smooth surfaces by lasers is an issue of importance as the SPW wave number is greater than the component of the laser wave vector along the interface. At low laser powers, one cannot do it unless one creates a density ripple on the metal surface or employs ATR configuration (Otto and Kretschmann geometry) to attain phase-matching conditions (Reather, 1988). At high powers, non-linear effects open up new possibilities. The excitation of a SPW occurs at the interface of vacuum overdense plasma, which can be created during the interaction of an intense laser pulse with a solid metal target (Rozmus & Tikhonchuk, 1990; Price *et al.*, 1995; Shoucri *et al.*, 2010). The laser pulse can penetrate into the surface of overdense plasma up to a distance comparable with the skin depth. The surface-wave modes couple parametrically through the incident pump wave and decay instability of the surface waves is expected to occur under suitable conditions.

There have been growing efforts in the direction of parametric generation of a SPW by a laser pulse. Lee and Cho (1999) investigated the parametric decay of a high-frequency light wave into two daughter surface waves of low-frequency. They derived the mode-coupling equations and solved them in the parametric approximation to obtain the threshold and growth rate. Macchi *et al.* (2002) have proposed a non-linear mechanism of electron surface oscillations in overdense plasma using two-dimensional (2D) particle-in-cell simulations. The normally incident laser pulse interacts with the overdense plasma resulting in generation of two counter

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propagating SPWs in the plasma. The mechanism of SPW generation was termed as a two surface wave decay process (TSWD) in an analogy with the well-known process of two plasmon decay in laser–plasma interaction. Kumar and Tripathi (2007) used different field of the TSWD process to study the parametric decay of the light wave into two SPW by a high-power laser obliquely incident on a vacuum–plasma interface. The generation of SPW by the parametric process leads to the surface plasma oscillations or rippling at the laser frequency or half of it. The growth rate of the (TSWD) process is maximum for the normal incidence of the laser pulse. Goel *et al.* (2015) studied the stimulated Compton scattering of SPW excited over the metallic surface by a laser. Growth rate of the Compton process increases with the pump wave frequency, width of the metal layer, laser amplitude, and its spot size.

Early studies (Zoboronkova *et al.*, 1976; Lindgren *et al.*, 1982) suggest that surface waves can be excited by parametric decay of a laser into two surface waves. Also, the non-linear theories of SPW excitation in an unmagnetiszed as well as in magnetized plasma have been developed (Gradov & Stenflo, 1980; Stenflo, 1996; Parashar *et al.*, 1998).

Singh and Tripathi (2007) gave a theoretical model to excite SPW at frequency $\omega = \omega_1 - \omega_2$ by beating of two coplanar laser beams of frequencies ω_1 and ω_2 impinged on a metal surface. Brodin and Lundberg (1991) theoretically investigated the parametric excitation of surface waves in inhomogeneous plasma and calculated the growth rate and threshold value for the instability process.

The purpose of the present work is to study the effects of magnetic field on the parametric excitation of SPW by a laser incident on the metal-free space interface. The applied magnetic field is parallel to the surface and perpendicular to the SPW propagation vector. The laser field (ω_0, k_{0z}) inside the metal acts as a pump wave and excites a pair of waves, viz a quasi-electrostatic plasma wave of frequency (ω, k_z) having phase velocity v_F and a SPW (ω_1, k_{1z}) at the phase-matching conditions $\omega_1 = \omega - \omega_0$ and wave number $k_{1z} = k_z - k_{0z}$. The pump and the surface wave exert a beat-frequency ponderomotive force on the electrons at (ω, k_z) which drives a heavily damped quasi-mode inside the skin layer. The oscillating metal electrons under the influence of ponderomotive force and quasi-mode give rise to a non-linear density perturbation, which couples with the oscillatory motion of metal electrons due to the pump to produce a non-linear current that drives the surface wave. Growth rate equation is obtained on the basis of three wave parametric coupling at resonance. The parametric coupling of a pump wave, plasma wave, and SPW in the presence of external magnetic field is presented in Section 2. A discussion of results and conclusions are given in Section 3.

2. PARAMETRIC EXCITATION OF SPW

Consider the metal-free space interface at $x = 0$ with half-space $x < 0$ is the free space and $x > 0$ is the metal of equilibrium electron density n_0. The external magnetic field ($\vec{B}_s$) is applied in the $\hat{y}$-direction, that is, magnetic field is parallel to the surface and perpendicular to the SPW propagation. A high-power laser $(\omega_0, \vec{k}_0; \vec{k}_0 = k_{0x}\hat{x} + k_{0z}\hat{z})$ is obliquely incident on the interface from the free space at an angle of incidence θ as shown in Figure 1. The field of the incident laser is given by

$$\vec{E}_{0\mathrm{l}} = A\left(\hat{z} - \frac{k_{0z}}{k_{0x}}\hat{x}\right)e^{-i(\omega_0 t - k_{0z}z - k_{0x}x)}, \tag{1}$$

where $k_{0x} = \omega_0 \cos\theta/c$ and $k_{0z} = \omega_0 \sin\theta/c$

The electric field of the laser inside the metal can be written as follows (Jackson, 1975):

$$\vec{E}_0 = (E_{0x}\hat{x} + E_{0z}\hat{z})e^{\alpha_0 x}e^{-i(\omega_0 t - k_{0z}z)}. \tag{2}$$

Appling the condition $\nabla.\tilde{\varepsilon}E_0 = 0$ at the interface $x = 0$, we obtained

$$E_{0x} = \frac{ik_{0z}\varepsilon_{xx} - \alpha_0\varepsilon_{xz}}{\alpha_0\varepsilon_{xx} + ik_{0z}\varepsilon_{xz}}E_{0z},$$

where $\alpha_0^2 = k_{0z}^2 - (\omega_0^2/c^2)\varepsilon_v$, $\varepsilon_v = \varepsilon_{xx} + \varepsilon_{xz}^2/\varepsilon_{xx}$, $\varepsilon_{xx} = \varepsilon_L[1 - \omega_p^2/(\omega^2 - \omega_c^2)]$, and $\varepsilon_{xz} = -i\varepsilon_L\omega_c\omega_p^2/\omega(\omega^2 - \omega_c^2)\cdot\varepsilon_L$ is the lattice permittivity. $-e$, m, $\omega_p = \sqrt{n_0 e^2/m\varepsilon_0}$, and $\omega_c = eB_s/m$ are the charge, effective mass of electron, electron plasma frequency, and electron cyclotron frequency, respectively. The condition of continuity, that is, $\tilde{\varepsilon}E_{0x}$ and E_{0z} at $x = 0$, gives

$$E_{0z} = \frac{2A}{[(1 - (k_{0x}/k_{0z})(\varepsilon_{xx}(ik_{0z}\varepsilon_{xx} - \alpha_0\varepsilon_{xz})/(\alpha_0\varepsilon_{xx} + ik_{0z}\varepsilon_{xz}) + \varepsilon_{xz})]}.$$

On substituting the value from the above expression in Eq. (2), we obtained the transmitted field of laser inside the metal as

$$\vec{E}_0 = \frac{2A[\hat{x}(ik_{0z}\varepsilon_{xx} - \alpha_0\varepsilon_{xz})/(\alpha_0\varepsilon_{xx} + ik_{0z}\varepsilon_{xz}) + \hat{z}]}{[1 - k_{0x}/k_{0z}(\varepsilon_{xx}(ik_{0z}\varepsilon_{xx} - \alpha_0\varepsilon_{xz})/(\alpha_0\varepsilon_{xx} + ik_{0z}\varepsilon_{xz}) + \varepsilon_{xz})]} \times e^{\alpha_0 x}e^{-i(\omega_0 t - k_{0z}z)}. \tag{3}$$

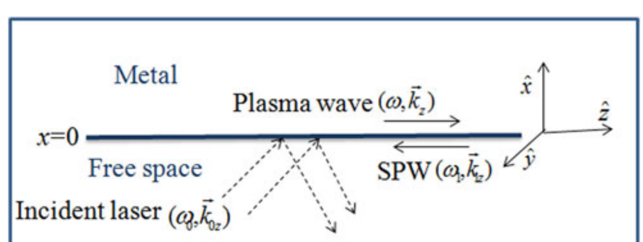

Fig. 1. Schematic diagram of parametric excitation of SPW at the metal-free space interface

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The transmitted laser field imparts oscillatory velocity to electrons in the skin layer

$$v_{0x} = \frac{e}{m}(i\omega_0 E_{0x} - \omega_c E_{0z})(\omega_c^2 - \omega_0^2)^{-1},$$

$$v_{0z} = \frac{e}{m}(\omega_c E_{0x} + i\omega_0 E_{0z})(\omega_c^2 - \omega_0^2)^{-1},$$

which parametrically excite a SPW ($\omega_1, \vec{k}_{1z}, \vec{k}_1, k_{1z}\hat{z} - i\alpha_1\hat{x}$) of the electric field

$$\vec{E}_1 = (E_{1x}\hat{x} + E_{1z}\hat{z})e^{-\alpha_1 x}e^{-(\omega_1 t - k_{1z}z)}, \tag{4}$$

and lower-frequency space charge quasi-mode (ω, $\vec{k}$) of potential of ϕ, given by

$$\phi = \phi(x)e^{-(\omega t - k_z z)}, \tag{5}$$

where $\alpha_1^2 = k_{1z}^2 - (\omega_1^2/c^2)\varepsilon_{1v}$, $\varepsilon_{1v} = \varepsilon_{1xx} + \varepsilon_{1xz}^2/\varepsilon_{1xx}$, $\varepsilon_{1xx} = \varepsilon_L[1 - \omega_p^2/({\omega_1}^2 - \omega_c^2)]$, and $\varepsilon_{1xz} = -i\varepsilon_L\omega_c\omega_p^2/\omega_1(\omega_1^2 - \omega_c^2)$. The phase-matching conditions for the parametric decay are $k_z = k_{0z} + k_{1z}$ and $\omega = \omega_0 + \omega_1$. The surface wave provides an oscillatory velocity to plasma electrons.

$$v_{1x} = \frac{e}{m}(i\omega_1 E_{1x} - \omega_c E_{1z})(\omega_c^2 - \omega_1^2)^{-1}, \tag{6a}$$

$$v_{1z} = \frac{e}{m}(\omega_c E_{1x} + i\omega_1 E_{1z})(\omega_c^2 - \omega_1^2)^{-1}. \tag{6b}$$

The pump and surface wave exert a ponderomotive force ($\vec{F}_p = F_{px}\hat{x} + F_{pz}\hat{z}$) on the electrons at frequency ω, which is obtained as follows:

$$\overrightarrow{F}_p = -m[\overrightarrow{v} \cdot \nabla\overrightarrow{v}] - e[\overrightarrow{v} \times \overrightarrow{B}]. \tag{7}$$

In the above equation, $\vec{v}$ and $\overrightarrow{B}$ are replaced by $\vec{v}_0 + \vec{v}_1$ and $\vec{B}_0 + \vec{B}_1$, respectively, due to the combined effect of the pump and the SPW. Here, $\vec{B}_0 = i\vec{k}_0 \times \vec{E}_0/i\omega_0$ and $\vec{B}_1 = i\vec{k}_1 \times \vec{E}_1/i\omega_1$ are the magnetic field for the pump and SPW, respectively. On substituting these values into Eq. (7), we obtained

$$\begin{aligned} F_{px} = \frac{-e^2}{2m}E_{0z}E_{1z}[&-(\alpha_0 + \alpha_1)c_1c_3 + ik_{0z}c_1c_4 \\ &+ ik_{1z}c_2c_3 + \frac{1}{i\omega_1}(-\alpha_1c_2 - ik_{1z}c_2d_1) \\ &+ \frac{1}{i\omega_0}(-\alpha_0c_4 - ik_{0z}c_4d_0)], \end{aligned} \tag{8}$$

$$\begin{aligned} F_{pz} = \frac{-e^2}{2m}E_{0z}E_{1z}[&-\alpha_0c_2c_3 - \alpha_1c_1c_4 \\ &+ (ik_{0z} + ik_{1z})c_2c_4 + \frac{1}{i\omega_1}(\alpha_1c_1 + ik_{1z}c_1d_1) \\ &+ \frac{1}{i\omega_0}(\alpha_0c_3 + ik_{0z}c_3d_0)], \end{aligned} \tag{9}$$

where $c_1 = i\omega_0d_0 - \omega_c/\omega_c^2 - \omega_0^2$, $c_2 = d_0\omega_c + i\omega_0/\omega_c^2 - \omega_0^2$, $c_3 = i\omega_1d_1 - \omega_c/\omega_c^2 - \omega_1^2$, $c_4 = d_1\omega_c + i\omega_1/\omega_c^2 - \omega_1^2$, $d_0 = -\alpha_0\varepsilon_{xz} + ik_{0z}\varepsilon_{xx}/\alpha_0\varepsilon_{xx} + ik_{0z}\varepsilon_{xz}$, and $d_1 = -\alpha_1\varepsilon_{1xz} + ik_{1z}\varepsilon_{1xx}/\alpha_1\varepsilon_{1xx} + ik_{1z}\varepsilon_{1xz}$.

Now, metal electrons oscillate under the influence of both ponderomotive force and self-consistent low-frequency field at frequency ω and causes perturbation in density. By solving equation of motion, the oscillatory velocity of the electron at frequency ω is obtained

$$\begin{aligned} v_{\omega x} = &\frac{1}{m(\omega^2 - \omega_c^2)} \\ &\times\left[i\omega F_{px} - (F_{pz} + e\nabla\phi - \frac{T_e}{n_0}\nabla n_{1e})\omega_c\right], \end{aligned} \tag{10}$$

$$\begin{aligned} v_{\omega z} = &\frac{1}{m(\omega^2 - \omega_c^2)} \\ &\times\left[\omega_c F_{px} + (F_{pz} + e\nabla\phi - \frac{T_e}{n_0}\nabla n_{1e})i\omega\right]. \end{aligned} \tag{11}$$

$v_F^2 = 2T_e/m$ is the electron Fermi velocity and Fermi temperature of electrons. Substituting the value of oscillatory velocity from Eqs (10) and (11) into continuity equation $[\partial n/\partial t + \nabla \cdot (n_0\vec{v}_\omega) = 0]$, we obtain the density perturbation (n) due to oscillatory motion of the metal electrons and ions, given by

$$\begin{aligned} n_{1e} = \frac{k_z^2\phi}{4\pi e}\chi_e + &\frac{n_0k_z}{m\omega(\omega^2 - \omega_c^2 - k_z^2v_F^2/2)} \\ &\times[F_{px}\omega_c + F_{pz}i\omega] = n_{1e}^L + n_{1e}^{NL} \end{aligned} \tag{12}$$

$$n_{1i} = \frac{k_z^2\phi}{4\pi e}\chi_i, \tag{13}$$

where n_{1e}^L and n_{1e}^{NL} are the linear and non-linear part of the electron density perturbation. $\chi_e = -\omega_p^2/[(\omega^2 - \omega_c^2) - k_z^2v_F^2/2]$ and $\chi_i = -\omega_{pi}^2/\omega^2$ are the electron and ion susceptibilities, respectively. ω_{pi} is the ion plasma frequency and n_0 is the equilibrium electron density inside the skin layer of the metal. Using the density perturbation (n) in Poisson's equation $\nabla^2\phi = 4\pi(n_{1e} - n_{1i})e$, we obtain

$$\phi = -4\pi e n_{1e}^{NL}/\varepsilon k_z^2, \tag{14}$$

$$\varepsilon\phi = \frac{\chi_e}{k_z}\left(\frac{\omega_c}{\omega}F_{px} + iF_{pz}\right), \tag{15}$$

where $\varepsilon = 1 + \chi_e + \chi_i$. On substituting Eq. (14) into Eq. (12), we obtain

$$n_{1e} = \left(1 - \frac{\chi_e}{\varepsilon}\right)n_{1e}^{NL}. \tag{16}$$

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The density perturbation couples with oscillatory movement of metal electrons at frequency (ω_0) and excites a non-linear current density ($\overrightarrow{J}_1^{\mathrm{NL}}$) at ($\omega_1$, k_{1z}), which is given by

$$\vec{J}_1^{\mathrm{NL}} = -\frac{1}{2} e n_{1\mathrm{e}} v_0^*$$

On substituting values of $n_{1\mathrm{e}}$ from Eq. (16), the non-linear current density is given by

$$\vec{J}_1^{\mathrm{NL}} = \frac{\varepsilon k_z^2}{8\pi}\left(1 - \frac{\chi_\mathrm{e}}{\varepsilon}\right) v_0^* \phi. \tag{17}$$

At resonance, this non-linear current density ($\vec{J}_1^{\mathrm{NL}}$) is responsible for the growth of SPW whose characteristic equation can be derived by solving wave equation. The wave equation governing electric field of SPW at the frequency (ω_1) can be written as

$$\nabla^2 \vec{E}_1 - \nabla(\nabla \cdot \vec{E}_1) = \frac{4\pi}{c^2}\frac{\partial \vec{J}_1^{\mathrm{NL}}}{\partial t} + \frac{\varepsilon_1}{c^2}\frac{\partial^2 \vec{E}_1}{\partial t^2}. \tag{18}$$

The longitudinal and transverse components of the SPW are obtained by simplifying Eq. (18). Both components are correlated by the following equations:

$$\left(k_{1z}^2 - \frac{\omega_1^2}{c^2}\varepsilon_{1xx}\right) E_{1x} + \left(ik_{1z}\frac{\partial E_{1z}}{\partial x} - \frac{\omega_1^2}{c^2}\varepsilon_{1xz} E_{1z}\right) = \frac{4\pi i \omega_1}{c^2} J_{1x}^{\mathrm{NL}}, \tag{19}$$

$$\left(ik_{1z}\frac{\partial E_{1x}}{\partial x} + \frac{\omega_1^2}{c^2}\varepsilon_{1xz} E_{1x}\right) - \left(\frac{\partial^2 E_{1z}}{\partial x^2} + \frac{\omega_1^2}{c^2}\varepsilon_{1xx} E_{1z}\right) = \frac{4\pi i \omega_1}{c^2} J_{1z}^{\mathrm{NL}}. \tag{20}$$

On solving Eqs (19) and (20), we obtained

$$\frac{\partial^2 E_{1z}}{\partial x^2} - \alpha_1^2 E_{1z} = \frac{4\pi i}{\omega_1 \varepsilon_{1xx}}\left\{ J_{1z}^{\mathrm{NL}}\left(k_{1z}^2 - \frac{\omega_1^2}{c^2}\varepsilon_{1xx}\right)\right\} - \frac{\omega_1^2}{c^2}\varepsilon_{1xz} J_{1x}^{\mathrm{NL}}. \tag{21}$$

Equation (21) is linearized by substituting $\partial/\partial x = -\alpha_1$ to obtain the characteristic equation of SPW.

$$D' E_{1z} = \frac{4\pi i \omega_1}{c^2}\left[J_{1z}^{\mathrm{NL}}\left(k_{1z}^2 - \frac{\omega_1^2}{c^2}\varepsilon_{1xz}\right) - J_{1x}^{\mathrm{NL}}\left(ik_{1z}\alpha_1 + \frac{\omega_1^2}{c^2}\varepsilon_{1xz}\right)\right], \tag{22}$$

where

$$D' = \frac{\omega_1^4}{c^4}\varepsilon_{1xz}^2 + \frac{\omega_1^2}{c^2}\varepsilon_{1xz}\alpha_1^2 - \frac{\omega_1^2}{c^2}\varepsilon_{1xx}k_{1z}^2 + \frac{\omega_1^4}{c^4}\varepsilon_{1xz}\varepsilon_{1xx}.$$

In the absence of the non-linear coupling, the solution of Eq. (22) can be written as

$$E_1 = A_1 \psi_1,$$

$$\psi_1 = \left(\hat{z} + \frac{(-\alpha_1\varepsilon_{1xz} + ik_{1z}\varepsilon_{1xx})}{(\alpha_1\varepsilon_{1xx} + ik_{1z}\varepsilon_{1xz})}\hat{x}\right) e^{-\alpha_1 x}, \quad \text{for} \quad x > 0, \tag{23a}$$

$$\psi_1 = \left(\hat{z} - \frac{ik_{1z}}{\alpha_1'}\hat{x}\right) e^{\alpha_1' x}, \quad \text{for} \quad x < 0, \tag{23b}$$

where $\alpha_1^2 = k_{1z}^2 - (\omega_1^2/c^2)\varepsilon_{1v}$ and $\alpha_1'^2 = k_{1z}^2 - (\omega_1^2/c^2)$. The dispersion relation for the SPW in the presence of a magnetic field (Wallis *et al.*, 1974) is

$$\alpha_1 + \alpha'\varepsilon_{1v} + ik_{1z}\frac{\varepsilon_{1xz}}{\varepsilon_{1xx}} = 0. \tag{23c}$$

On multiply Eqs (15) and (22), we obtain the equation governing the stimulated Compton scattering.

$$\begin{aligned} \varepsilon D' = {} & \frac{ie\omega_1 k_z}{4mc^2}\chi_\mathrm{e}(1+\chi_\mathrm{i})\left(\frac{\omega_\mathrm{c}}{\omega}F_{\mathrm{p}x}' + iF_{\mathrm{p}z}'\right) \\ & \times \left(v_{0z}^*\left(k_{1z}^2 - \frac{\omega_1^2}{c^2}\varepsilon_{1xz}\right) - v_{0x}^*\left(-ik_{1z}\alpha_1 + \frac{\omega_1^2}{c^2}\varepsilon_{1xz}\right)\right), \end{aligned} \tag{24}$$

where

$$\begin{aligned} F_{\mathrm{p}x}' = {} & -(\alpha_0 + \alpha_1)c_1c_3 + ik_{0z}c_1c_4 + ik_{1z}c_2c_3 \\ & + \frac{1}{i\omega_1}(-\alpha_1 c_2 - ik_{1z}c_2 d_1) \\ & + \frac{1}{i\omega_0}(-\alpha_0 c_4 - ik_{0z}c_4 d_0), \end{aligned}$$

$$\begin{aligned} F_{\mathrm{p}z}' = {} & -\alpha_0 c_2 c_3 - \alpha_1 c_1 c_4 + (ik_{0z} + ik_{1z})c_2c_4 \\ & + \frac{1}{i\omega_1}(\alpha_1 c_1 + ik_{1z}c_1 d_1) \\ & + \frac{1}{i\omega_0}(\alpha_0 c_3 + ik_{0z}c_3 d_0). \end{aligned}$$

In the absence of non-linear coupling, frequency of the plasma wave and the SPW are $\omega \cong k_z v_\mathrm{F} = \omega_\mathrm{r}$ and $\omega_1 \cong \omega_{1\mathrm{r}}$, respectively, which are obtained by $\varepsilon = 0$ and $D' = 0$. In the presence of non-linear coupling (i.e., $v_{0x}^* \neq 0$ and $v_{0z}^* \neq 0$), frequencies are modified and given by $\omega = \omega_\mathrm{r} + i\gamma$, $\omega_1 = \omega_{1\mathrm{r}} + i\gamma$, where γ is the growth rate of the stimulated Compton process. By using Taylor expansion ε and D' are expanded around ω_r and $\omega_{1\mathrm{r}}$, respectively and Eq. (24) is solved numerically to calculate the growth rate of the Compton process for different values of incident angle θ, pump wave frequency ω_0, and magnetic field B_s. Variation of SPW frequency ($\omega_1/\omega_\mathrm{p}$) is plotted with angle of incidence (θ) and normalized frequency ($\omega_0/\omega_\mathrm{p}$) of pump laser in Figures 2a, 2b, respectively. The SPW frequency increases with θ and $\omega_0/\omega_\mathrm{p}$. Normalized growth rate (γ/ω_p) of the Compton process is plotted as a function of incident laser frequency ($\omega_0/\omega_\mathrm{p}$) and angle of incidence (θ) for different values normalized cyclotron frequency ($\omega_\mathrm{c}/\omega_\mathrm{p}$) in Figures 3 and 4, respectively. The applied magnetic field turns out to

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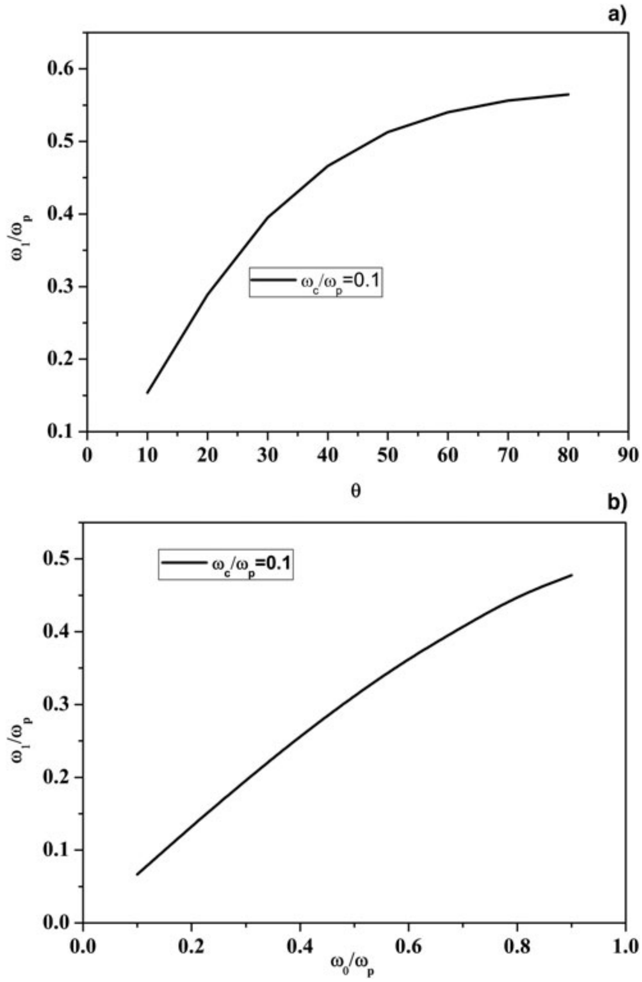

Fig. 2. Variation of the normalized frequency of SPW (ω_1/ω_p) with (a) the angle of incidence of laser at $(\omega_0/\omega_p) = 0.9$ and $(\omega_c/\omega_p) = 0.1$ and (b) normalized pump wave frequency (ω_0/ω_p) for $\theta = 42°$ and $(\omega_c/\omega_p) = 0.1$.

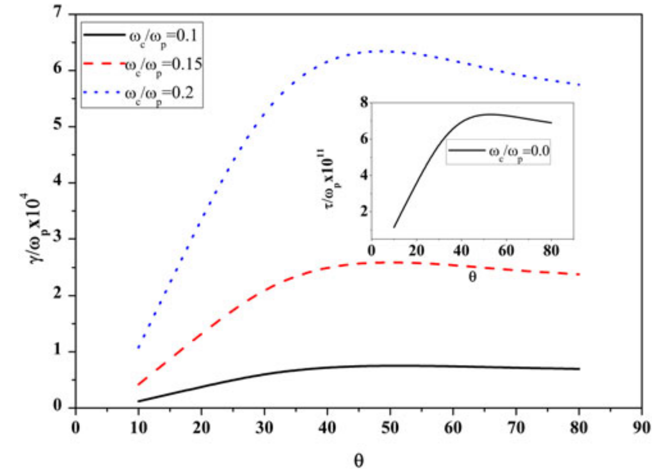

Fig. 4. Plot of normalized growth rate (γ/ω_p) with the angle of incidence of laser on varying normalized cyclotron frequency (ω_c/ω_p) for $(\omega_0/\omega_p) = 0.9$. Subplot shows the variation of (γ/ω_p) verses angle for $(\omega_c/\omega_p) = 0$.

be 12, 18, and 24 MG corresponding to $\omega_c/\omega_p = 0.1$, 0.15, and 0.2 respectively, using $\omega_c = eB_s/m$. The magnetic field strength of the order of 100 **T** has been observed experimentally by using pulsed magnet technology (Lagutin *et al.*, 2003; Zherlitsyn *et al.*, 2010). The other parameters are $\varepsilon_L = 1$, $T_e = 300$ K and $\omega_p = 2.17 \times 10^{15}$ rad/s. For fixed (ω_c/ω_p), growth rate of the Compton process first increases with the incident laser frequency upto a particular value and saturates at higher values of incident laser frequency. To study the effect of incident angle variation on growth rate, normalized transmitted field of the laser and normalized ponderomotive force is plotted with angle of incidence of the laser in Figures 5 and 6, respectively. The maximum growth rate is achieved ~42° angle.

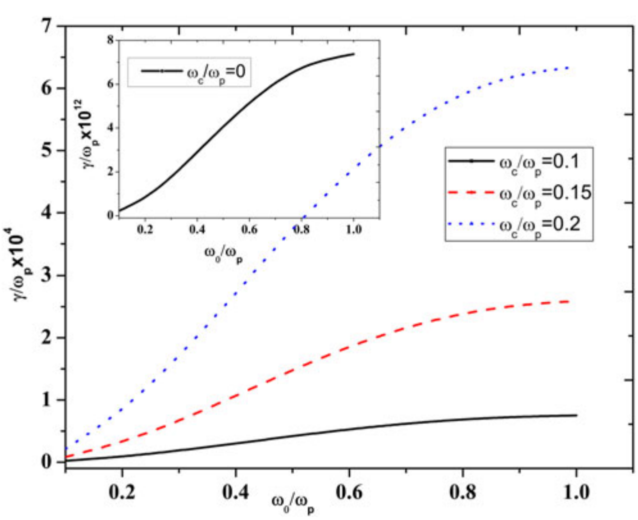

Fig. 3. Plot of normalized growth rate (γ/ω_p) with the frequency of incidence laser on varying normalized cyclotron frequency (ω_c/ω_p) for $\theta = 42°$. Subplot shows the variation of (γ/ω_p) verses frequency for $(\omega_c/\omega_p) = 0$.

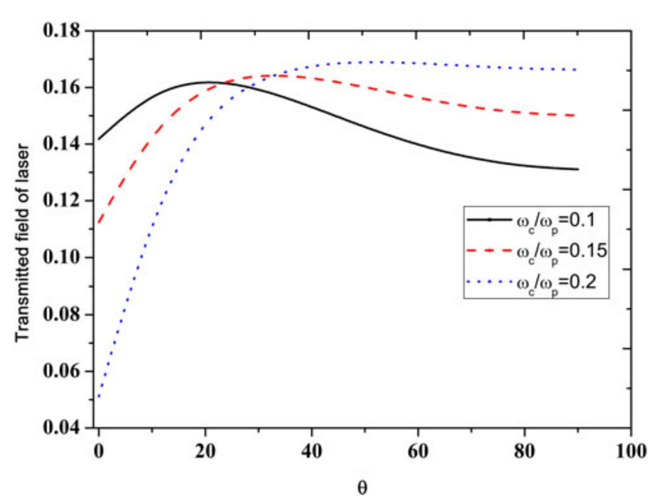

Fig. 5. Normalized transmitted field of laser verses angle of incidence of laser for $(\omega_0/\omega_p) = 0.9$.

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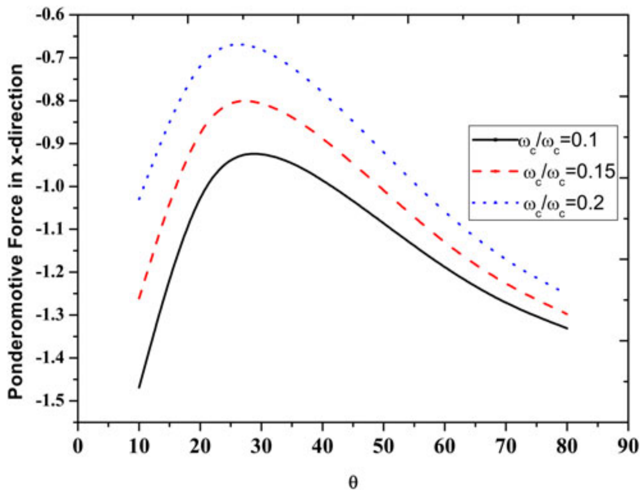

Fig. 6. Plot of normalized ponderomotive force along the $-\hat{x}$ direction (F_{px}) with the angle of incidence of laser for $(\omega_c/\omega_p) = 0.9$.

3. DISCUSSION

SPW may be parametrically excited by a laser beam incident obliquely on the metal free-space interface via the stimulated Compton process. The parametric decay of the laser into SPW may be realized via quasi-static mode in metals. This process takes place at resonance given by phase-matching conditions. Figure 2 shows that the frequency of the SPW (ω_1/ω_p) increases with both the frequency (ω_0/ω_p) and angle (θ) of the incident laser corresponding to phase-matching conditions $\omega = \omega_0 + \omega_1$ and $k_z = k_{0z} + k_{1z}$ (where $k_z = \omega/v_F$). Here, v_F is the Fermi velocity of the metal.

Figure 3 shows that the growth rate of the SPW increases with the laser frequency due to enhanced skin depth and higher magnitude of the transmitted field of laser in the metal. In the absence of magnetic field, the obtained results are in agreement with the results obtained by Lee and Cho (1999) and Drake *et al.* (1990) theoretically as well as experimentally.

Apart from this, the skin depth and transmitted field of the laser at metal-free space interface further increase by applying a transverse static magnetic field, which results in higher growth rate as shown in Figure 3. In the static magnetic field, the oscillatory motion of metal electrons is superimposed with cyclotron motion, which imparts an extra transverse component of the non-linear ponderomotive force along with longitudinal component of the ponderomotive force. Due to this, the characteristic equation for SPW [Eq. (22)] gets modified in the presence of an applied magnetic field, resulting in growth of transverse and longitudinal components of the nonlinear currents that further enhances the growth rate of the SPW in the presence of the magnetic field. The growth rate saturates at higher values of (ω_0/ω_p).

Figure 4 shows that the growth rate of the SPW first increases with the angle of incidence maximizes at ~42° and then starts decreasing at higher angles. This result can be explained in the light of Figures 5 and 6, which exhibit that the transmitted field of the laser and the inward ($-\hat{x}$ direction) ponderomotive force (F_{px}) at the metal-free space interface also increases linearly for lower values of incidence angle (θ), maximizes at a particular value of θ and then starts decreasing. The maximum growth of the present process ($\cong 1.5 \times 10^{12}$ s^{-1}) is achieved at incident angle θ = 42° for laser frequency $\omega_0 = 2 \times 10^{15}$ rad/s. Growth of SPW enhances from 1.62×10^{11} to $\cong 1.5 \times 10^{12}$ s^{-1} as the magnetic field changes from 12 to 24 MG.

In conclusion, the excitation of SPWs via stimulated Compton scattering of laser is sensitive to angle and frequency of the incidence laser, along with magnetic field strength. One can obtain the efficient growth of SPWs by optimizing these parameters. In this work, growth rate of the order of $\cong 10^{12}$ s^{-1} is obtained by using Nd: glass laser of intensity $\cong 10^{16}$ W/cm^2. The Compton process can produce energetic electrons traveling along the plasma boundary. Zhaoquan *et al.* (2012) diagnosed the plasma parameters of SPWs by resonant excitation of surface plasmon polaritons. The measured experimental results show that the plasma near the heating layer is excited by surface waves and electron beams of energy about 10 eV can be obtained. Giulietti and Gizzi (1998) discussed the laser interaction with matter and reported that the laser energy can be converted into hot electrons. As the laser intensity is varied from 10^{15} to 10^{19} W/cm^2, electrons of energy 200 eV–0.6 MeV can be produced (Giulietti & Gizzi, 1998). These electrons in turn can give rise to stronger X-ray emission, which can be utilized for various purposes along with the plasma diagnostics.

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