Non linear surface plasma wave assisted electron acceleration in metal structure

Kanwal Gurbakhsish Kaur¹, Pawan Kumar², Niti Kant¹ and Jyoti Rajput*¹

¹Department of Physics, Lovely Professional University, Phagwara, Punjab, India-144411
²Department of Physics, Raj Kumar Goel Institute of Technology, Ghaziabad, UP-201003, India

Corresponding Address: Email: jyoti_physics@yahoo.co.in (J Rajput)

Abstract:
The electron dynamics is realized by the field of surface plasma waves, which are created by the interaction of a femto-second laser and a metal sheet of finite thickness. The amplitude of surface plasma wave is maximum at the interface of two media and starts decays exponentially as we move far from the boundary. The applied magnetic field (along y-axis) is utilized to bend the trajectory of electron and helps the electron to gain energy by resonance between electron, magnetic and SPW fields and as a result, the electron gets accelerated.

Keywords: Surface Plasma wave, Electron acceleration, femto-second laser.

1. Introduction

Surface plasma waves (SPW) also known as surface plasmons [1], are electromagnetic modes (EM) restricted at the boundary of two different media, allows local field confinement and its enhancement. Surface plasmons have many applications ranging from biosensors [2] to concentration of light beyond diffraction limit and plasmonic chips [3]. The extension of plasmonics in the region of high fields in which relativistic and non-linear effects arise, is largely undetected. An example is given by multi terawatt laser-driven excitation of SPs by the separation of charges [4], along with an application in the generation of high intensity THz pulses, electron acceleration [5, 6]. The field of SPW decreases exponentially as we move far from the boundary in both the media. The SPW amplitude reaches maxima at the boundary and falloffs exponentially along the perpendicular direction within both the medium, with a decreasing length on the order of wavelength. The excitation of surface plasma wave is a resonant phenomenon, strongly dependent on the boundary conditions, SPW are probes of structural and optical properties of the boundary which allows by means of visible source of light, the detection of changes in sub-angstrom dimensions in thin films which covers the surface of metal. In last two decades, the intensive studies related to SPW largely focused on near-infrared and visible regions. The dispersion relation for Surface Plasma Wave in metal-dielectric boundary is given by

\[ k_z^2 = \frac{\omega^2}{c^2} \left( \frac{\varepsilon_m \varepsilon_g}{\varepsilon_m + \varepsilon_g} \right) \]  

where the effective relative permittivity of a metal at frequency \( \omega \) is given by

\[ \varepsilon_m = \varepsilon_L - \frac{\omega_p^2}{\omega^2}, \]
where $\varepsilon_L$ is lattice dielectric constant of metal, $\omega_p = (n_e e^2 / m_e \varepsilon_0)^{1/2}$, $m_e$ and $n_e$ are the effective mass, charge and density of free electrons, $\varepsilon_0$ is the permittivity of free space, $c$ is velocity of light in free space/vacuum and the collisions are ignored for the moment. The dispersion relation for SP at vacuum-metal boundary is

$$k_z^2 = \frac{\omega^2}{c^2} \left( \frac{\varepsilon_m}{\varepsilon_m + 1} \right).$$

Denton, et al. [7] have studied the SPW excitation from charged particles moving near the solid surface. The velocity of SPW is less than the velocity of light in vacuum or free space, so these can be excited by relativistic electron beams via Cerenkov interactions as done in a Smith-Purcell metal grating device or a travelling wave tube [8]. So, a coherent radiation is produced when the SPW passes over the surface ripple [9, 10]. Zwardzka et al. have observed electrons having energy 400 eV for $10^{13}$ W/cm$^2$ of laser intensity [11]. Irvine et al. have observed the similar accelerations in the experiments in which their energies are comparable to the energies of ponderomotive force by SPW also, the electrons move with much lesser velocity than the velocity of SPW [12]. Steinhauer et al. [13] have produced analytical formalism and its potential for acceleration of electron, for SPW which propagates on the inner sideline of hollow cylinder and on the two parallel conducting planes.

In the present paper, a scheme of acceleration of electron using resonant interaction of electrons with SPW is presented. We have plotted dispersion relation graph for the metal and vacuum interface. The present scheme can be used for the acceleration of electrons to higher orders of energies with their controlled paths.

2. The excitation of SPW in the metal surface

We consider a boundary which is separating the free space ($x>0$) from a silver metal of permittivity $\varepsilon = 4$, equation of permittivity of a metal at frequency $\omega$ is

$$\varepsilon = \varepsilon_L - \frac{\omega_p^2}{\omega^2},$$

(4)

Where $\varepsilon_L$ is lattice permittivity and $\omega_p$ is plasma frequency.

The equation of SPW propagation over a metal surface is given as:

$$E = (\hat{z} + \frac{x-i k_x}{\alpha_l}) A e^{-\alpha_l x} e^{-i(\omega t - k_z z)} \text{ for } x>0$$

$$E = (\hat{z} - \frac{x-i k_x}{\alpha_l}) A e^{+\alpha_l x} e^{-i(\omega t - k_z z)} \text{ for } x<0,$$

(5)

$$k_z^2 = \frac{\omega^2}{c^2} \frac{\varepsilon}{1 + \varepsilon},$$

Where $\alpha_l = (k_z^2 - \frac{\omega_p^2}{c^2})^{1/2}$ and $\alpha_2 = (k_z^2 - \frac{\omega_p^2 \varepsilon}{c^2})^{1/2}$, so chosen $\nabla \cdot E = 0$ for $x>0$ and $x<0$.

The equation of magnetic field of plasma wave is calculated from Maxwell equation given by $B = (\nabla \times E) / i \omega$. Consider an electron beam propagating in the longitudinal direction to the metal surface. The initial velocity as assumed as $v_o$. The electrodynamics of motion of electron is administered by equation of motion.

$$\frac{d\vec{p}}{dt} = -e\vec{E} - e(\vec{v} \times \vec{B})$$

(6)

From the above equation the momentum components are resolved along $x$, $y$ and $z$ direction and can be calculated. Also, from the above equation of momentum, electron energy gain can be calculated from:
\[ \gamma = \sqrt{1 + \left( \frac{p_z^2}{m_0 c^4} \right)} \]  \hspace{1cm} (7)

The following set of parameters are employed to normalise all equations:

\[ a_0 = \frac{e A}{m_0 \omega c}, \quad t' = \omega t, \quad k' x' = \frac{k c}{\omega}, \quad v' = \frac{v_c}{c}, \quad \alpha'_t = \sqrt{k'^2 - \omega_L^2} \]

3. Results and Discussion

In the present manuscript, we numerically solved eqn. (8-10) to plot electron energy and momentum. We have shown the schematic and figures to explain the surface plasma wave, dispersion relation and electron energy by optimizing the laser and plasma parameters for higher electron energy gain.

**Figure 1.** Schematic of surface plasma wave excitation due to laser propagation in metal structure.

Figure 1 shows the schematic of surface plasma wave excitation due to laser propagation in metal structure. Here a SPW propagates through metal configuration with \( t, z \) variation. A laser is incident at an optimum angle on the metal interface resulting in the excitation of SPW as a space wave and a transmitted laser beam.

**Figure 2.** Variation of normalised frequency \( \frac{\omega}{\omega_p} \) and normalised wavenumber \( \frac{k c}{\omega_p} \) for surface plasma wave in free space and metal (silver) layer surface. Here \( \varepsilon_L = 4 \).

One may note that the SPW is excited due to laser beam falling on a metal-glass boundary if the frequency of laser beam equals the SPW frequency. The laser exerts a ponderomotive force on
electrons in the skin layer and drive the SPW at phase matching conditions. Due to the resonance established between the two frequencies, the amplitude of SPW enhances and saturates. In future, we will plot electron energy also due to SPW phenomenon.

4. Conclusion

Surface plasma waves can be amplified due to resonance due to frequency matching condition between the laser beam frequency and the SPW frequency. The surface plasma waves so excited can be utilized in the applications such as Surface plasma enhanced resonance sensors, sensors with high degree of sensitivity, generation of coherent radiations, greater removal of material, processing of materials, emission of electrons and plasma diagnostics. Also it is a key player in the advanced study of metamaterials.

References

[1] Otto, A. Z. Physik (1968) Zeitschrift fü r Physik 216, 398.
[2] Willingale, Barnes, Alain Dereux, and Ebbesen T W, 2003 Nature 424, pp. 824-830.
[3] Genet C and Ebbesen T W, 2007 Nature, 445, no. 7123, 39-46.
[4] Klimov V V, Ducloy M, and Letokhov V S, 2007 Nature, 450, 402–406.
[5] Rajput J, Kant N and Singh A, 2019 AIP conf. Proceedings, 2136(1) 060012
[6] Kant N, Rajput J and Singh A, 2019 Optik 182, 858-865
[7] Denton C, Gervasoni J L, Barchina, R O and Arista N R, 1998, Phys. Rev. A 57, 4498.
[8] Kumar A. Verma A, 2011 Laser Part Beams, 29, 333-338.
[9] Liu C S, Kumar G, 2007 J. Appl. Phys., 102, issue 11 113301.
[10] P Rajeev, Ayyub P, Bagchi S, Kumar G, 2004 Opt. Letts, 29, 2662-2664.
[11] Zawadzka J, Jaroszynski D, Carey J J, and Wynne K, 2001 Appl. Phys. Lett. 79, 2130.
[12] Irvine S E and Elezzabi A Y, 2005 Appl. Phys. Lett. 86, 264102.
[13] Steinhauer L C and Kimura W D, 2003 Phys. Rev. ST Accel. Beams 6, 061302.