

# Second Harmonic Generation Induced by Surface Plasma Wave on Metallic Surface in the Presence of Wiggler Magnetic Field

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## Research Article

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Second harmonic generation induced by surface plasma wave on metallic surface in the presence of wiggler magnetic field.

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#### Abstract

Under the influence of wiggler magnetic field, the phenomenon of second harmonic generation at the metal-semiconductor interface, induced by surface plasma wave (SPW) has been investigated. Metals like Cu, Ag and Al, each with a thin layer of n-InSb over it, are considered for our study. Laser light is incident on metal layered on glass prism in attenuated total reflection Kretschmann configuration (ATR) which generates SPW. The SPW further interacts nonlinearly with the electrons of n-type semiconductor layered over the metal, leading to second harmonic generation (SHG). The presence of an external wiggler magnetic field makes the process resonant and helps in phase matching. Relatively more enhancement in the amplitude of the second harmonic is observed for Cu-InSb as compared to Ag-InSb and Al-InSb. Numerical analysis shows that the enhancement in the amplitude of SHG increases with the wiggler magnetic field.

Keywords- Surface plasma waves, wiggler field, semiconductor, second harmonic generation.

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## Introduction

Surface plasma waves (SPW) are electromagnetic waves that are formed by the interaction of laser with metals. These waves propagate along the interface of two different media and have amplitude larger than the amplitude of the laser[1-2]. The nonlinear interaction of laser with the matter has gained much attention in the past few decades because of its unique applications like high harmonic generation, laser driven plasma based accelerators, sensors, photoelectron spectroscopy, etc.[3-7]. Harmonic generation on different materials and in the presence of external agents like wiggler field has been studied by many researchers. Jha *et. al.*[8] studied SHG with an intense laser beam in magnetized plasma and found high conversion efficiency in the presence of the transverse magnetic field. Rajput *et.al.*[9] investigated the generation of third harmonic by a short pulse laser in plasma and observed that the presence of the wiggler magnetic field makes the generation process resonant accompanied by the increase in the efficiency of harmonic generation. Vinay *et.al.*[10] investigated propagation of laser pulse through plasma and found that laser interacts nonlinearly with electrons exerting a ponderomotive force which in turn oscillates them. It results in the harmonic generation. Abedi-Varaki[11] investigated the acceleration of electrons of metal by SPW in the presence of a helical magnetostatic wiggler and observed that under the effect of both SPW and wiggler field the electrons can travel more distance in the direction of propagation of laser. Vij *et.al.*[12] studied the production of Terahertz (THz) radiation by carbon nanotubes in the presence of a wiggler magnetic field and observed that the presence of the wiggler field enhances the efficiency of the generation of THz radiation. Abedi-Varaki and Jafari[13] studied the generation of THz radiations by mixing two Cosh-Gaussian laser beams in the presence of a wiggler magnetic field and observed the increase in efficiency with the increase in wiggler frequency. Ghimire *et.al.*[14] had investigated harmonic generation in solids and reported that terahertz or infrared fields are suitable for metals and semiconductors due to their small band gap. The presence of external factors like wiggler magnetic field helps to make the process resonant. Singh *et. al.*[15] studied the acceleration of electrons by a laser pulse in the presence of magnetic wiggler, in vacuum and plasma. Their work showed that the suitably tapered magnetic wiggler can maintain electron-laser resonance conditions for a longer time and electrons can gain sufficient energy.

In the present manuscript, second harmonic generation induced by surface plasma wave at metal-semiconductor interface in the presence of wiggler magnetic field has been studied. The phase

matching condition is fulfilled by the application of the wiggler magnetic field. Here, in section 2, we have obtained the expression for normalized amplitude for second harmonic generation. Results are discussed and presented in graphical form in section 3 and conclusion is presented in section 4.

## 2. Theoretical considerations

A thin metal layer over a glass prism with a thin layer of semiconductor over it has been considered in Kretschmann ATR configuration as shown in Fig.1, where, laser light is incident at an acute angle on metal glass interface leading to SPW in metal[16]. The em fields of laser interact with electrons of metal and produce SPW of nearly the same frequency as laser but with higher amplitude. The component of the wave vector of the laser along the surface matches with the surface plasma wave number, leading to efficient coupling [17]. A thin layer of n-InSb with the thickness of a few nanometers is considered above the metal surface. The electromagnetic fields of SPW at the metal-semiconductor interface interact with electrons of n-InSb. The semiconductor can accumulate energetic electrons which can easily tunnel through plasmonic entities[18].

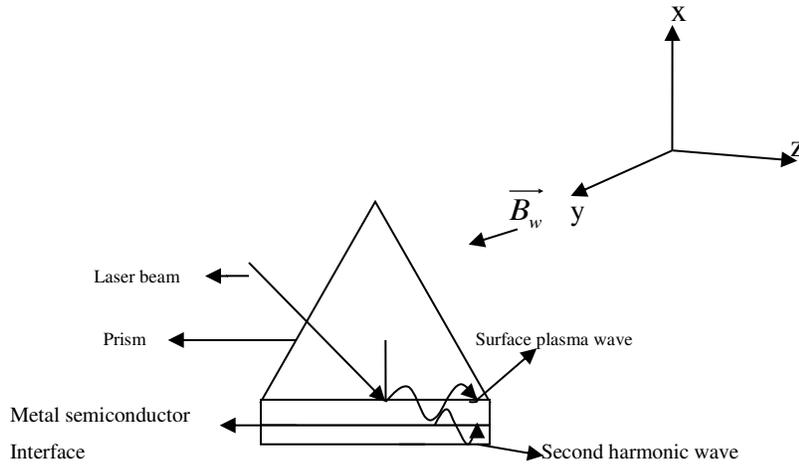


Fig.1. Kretschmann configuration with thin layer of a metal and a semiconductor

Electric and magnetic fields of laser are considered as  $\vec{E} = \hat{x}A(z, t)e^{-i(\omega t - k_1 z)}$  and  $\vec{B} = (\hat{k}_1 \times \vec{E}) / \omega$

where,  $A$  is the amplitude of field of laser,  $\omega$  is the frequency of laser and  $k_1$  is the propagation constant. These fields interact with electrons of metal and produces surface plasma waves  $\vec{E}_s = \hat{x}A_s e^{-i(\omega t - k_s z)}$  where,  $k_s$  is the propagation constant such that,  $k_s = (\omega_s / c)(\epsilon_s \epsilon_m / (\epsilon_s + \epsilon_m))^{1/2}$  with  $\epsilon_m$  and  $\epsilon_s$  as the permittivity of metal and semiconductor respectively and  $\omega_s$  is the frequency of surface plasma wave. The frequency of SPW is nearly same as the frequency of the laser, so  $\omega_s = \omega$  [16]. Amplitude of surface plasma wave  $A_s$  depends on amplitude of incident laser  $A$  with  $A_s = f(A)$ . Following [19],  $A_s / A$  can be considered as a normalized quantity with  $A_s = nA$  where,  $n$  is a positive real number. Fields of surface plasma waves interacts with electrons of semiconductor and accelerates them. Acceleration so produced is calculated using equation of motion,

$$m \frac{d\vec{v}_1}{dt} = -e\vec{E}_s - e\vec{E} \quad (1)$$

The velocity gained by electrons is,

$$\vec{v}_1 = \left[ \frac{-eAn' e^{-i(\omega t - k_s z)}}{m(-i\omega)} \right] \hat{x} \quad (2)$$

As the wave vector increases more than linearly with incident frequency, the momentum is not conserved, i.e. the momentum of second harmonic is more than two times the momentum of incident photon. Here,  $n' = 1 + n$  which is a positive real number. Wiggler magnetic field is applied in transverse direction given by,  $\vec{B}_w = B_0 e^{ik_0 z} \hat{y}$  where,  $B_0$  is the amplitude of wiggler field and  $k_0$  is the wiggler wave number. The presence of wiggler field helps to achieve the phase matching condition by providing additional momentum to the photons of second harmonic. The velocity  $\vec{v}_1$  beats with wiggler magnetic field of laser and generates ponderomotive force  $\vec{F}$ , where,  $\vec{F} = -e(\vec{v}_1 \times \vec{B}_w)$  due to this force velocity of electrons changes and it is taken as  $\vec{v}_1$  such that

(3)

$$\vec{v}_1 = \left[ \frac{-e^2 n' A B_0 e^{-i(\omega t - (k_1 + k_0) z)}}{m^2 \omega^2} \right] \hat{z}$$

It will induce density perturbation at  $(\omega_1, k_1 + k_0)$  in agreement with the equation of continuity,

$$n_1 = (k_1 + k_0) n_0 v_1 / \omega_1 \quad (4)$$

To exert ponderomotive force on electrons at  $(2\omega, 2k_1 + k_0)$   $v_1$  beats with  $B_1$  and imparts velocity,  $v_2^{NL}$  to electrons given as,

$$v_2^{NL} = \left[ \frac{-ie^3 n' A^2 k_1 B_0 e^{-i(2\omega t - (2k_1 + k_0)z)}}{2m^3 \omega^4} \right] \hat{x} \quad (5)$$

This give rise to second harmonic nonlinear current density at metal semiconductor interface,

$$J_2^{NL} = -n_0 e v_2^{NL} - n_1 e v_1 / 2 \quad (6)$$

The linear current density due to self consistent second harmonic field  $E_2 = A_2 e^{-i(2\omega t - k_2 z)}$  at  $(2\omega, k_2)$  is  $J_2^L = n_0 e v_2$  where,  $v_2$  is obtained using equation of motion  $m(dv_2/dt) = -eE_2$ .

The amplitude  $A_2$  for second harmonic is calculated by using equation,

$$\nabla^2 \vec{E}_2 = \frac{4\pi(\epsilon_m + \epsilon_s) \partial \vec{J}}{c^2(\epsilon_m \epsilon_s) \partial t} + \frac{\partial^2 \vec{E}_2}{c^2 \partial t^2} \quad (7)$$

By taking the laser profile to be Gaussian as  $A^2 = [F(z - v_{g1}t)]^2$  and  $F(z - v_{g1}t) = A_0 e^{-\left(\frac{z - v_{g1}t}{\tau v_{g1}}\right)^2}$  with  $v_{g1} = c\sqrt{1 - (\omega_p^2 / \omega^2)}$ ,  $v_{g2} = k_2(c^2 / 2\omega)\sqrt{1 - (1/4)(\omega_p^2 / \omega^2)(\epsilon_m + \epsilon_s) / \epsilon_m \epsilon_s}$  and  $\tau$  is laser pulse width. Using a new set of variables  $z - v_{g1}t = \Omega$ ,  $z = \eta$ ,  $\Omega_0 = \tau v_{g1}$ ,  $\beta' = (1 - v_{g1} / v_{g2})$ ,  $z' = z\Omega_0$  and  $t' = v_{g1}t / \Omega_0$ , we get normalized second harmonic amplitude as,

$$\left| \frac{A_2}{A_0} \right| = \left\{ \left( 1 - \frac{\omega_p^2}{\omega^2} \right)^{1/2} \left( \frac{\epsilon_m + \epsilon_s}{\epsilon_m \epsilon_s} \right) \left( \frac{\omega_p^2}{\omega^2} \right) \left( \frac{eB_0}{m\omega} \right) \left( \frac{eA_0}{mc\omega} \right) \times \right. \\ \left. \left[ \left( \frac{k_1 \Omega_0 \sqrt{\pi} n'}{8\beta'} \right) + \left( \frac{(k_1 + k_0) \Omega_0 \sqrt{\pi} n'^2}{4\beta'} \right) \right] \times \right. \\ \left. \left[ \text{Erf}(z' - t') - \text{Erf}\{(1 - \beta')z' - t'\} \right] \right\} \quad (8)$$

### 3. Results and discussion

Eq.(8) has been solved numerically for Nd:YAG laser with wavelength 1064nm. Effective permittivity are taken as 57.909 for Ag, 49.58 for Cu, 106.82 for Al and 19.5 for InSb at 1064nm[20]. Here, the layers of metal and semiconductor are considered to be of few nano-meters and doping level of n-InSb is adjusted to have  $\omega_p / \omega < 1$  for semiconductor. The graphical relationship for normalized second harmonic amplitude with normalized propagation distance has been presented for different metal-semiconductor interfaces at different values of time and wiggler field. The other parameters of Eq.(8) are taken as  $\omega_p / \omega_1 = 0.9$ ,  $n' = 2.5$ ,  $eA_0 / mc\omega_1 = 9$ ,  $(k_1 + k_0) \Omega_0 \sqrt{\pi} / 8\beta' = 0.23$ ,  $eB_0 / m\omega = 0.01, 0.02$  and  $0.03$ ,  $k_1 \Omega_0 \sqrt{\pi} / 8\beta' = 0.2$  and  $\beta' = 0.3$ .

Fig. 2 shows the variation of normalized second harmonic amplitude  $A_2/A_0$  with normalized propagation distance  $z'$  for metals like Cu, Ag and Al with thin layer of n-InSb at time  $t' = 4$  in the presence of wiggler magnetic field. It has been observed that as the strength of magnetic field increases, amplitude of second harmonic increases. In Fig. 2(a), a sharp increase in amplitude has been observed at  $z' = 5$  for all three metal-semiconductor interfaces at  $eB_0 / m\omega = 0.01$  and increase in amplitude is more for Cu-InSb interface. The presence of wiggler field helps to attain phase matching conditions by providing additional momentum to the second harmonic photon. The electromagnetic fields of laser interact with electrons of metal and excite them. The excited electrons beat with magnetic field of laser and wiggler field, leading to resonant SPW. These waves with high amplitude interact nonlinearly with electrons of n-InSb, leading to second harmonic. Fig. 2(b) and 2(c) show the variation of normalized second harmonic amplitude  $A_2/A_0$  with normalized propagation distance  $z'$  for all three metal-semiconductor interfaces at  $eB_0 / m\omega = 0.02$

and  $eB_0/m\omega = 0.03$  respectively. The values of other parameters for Fig.2(b) and Fig.2(c) are same as for Fig.2(a). As observed graphically under given conditions, increase in amplitude of SHG has been found more for Cu-InSb than for Ag-InSb and Al-InSb. The reason for this observation can be understood as the value of the conduction electron density for Cu is more as compared to Ag and Al so the fields of SPW of Cu are expected to be comparatively stronger and can efficiently interact with electrons of n-type semiconductor. As per the study by Takagi *et al.*[21] surface plasma waves in Kretschmann geometry shows good agreement with bulk dielectric function for Cu than Ag. Similarly in our work, we have seen better enhancement in the amplitude of second harmonic for Cu. Sharma *et al.*[22] studied SHG of cosh-Gaussian laser beam in magnetized plasma and found enhancement in efficiency in the presence of wiggler field. Similarly, in the present work good enhancement in amplitude of second harmonic has been observed in the presence of wiggler field.

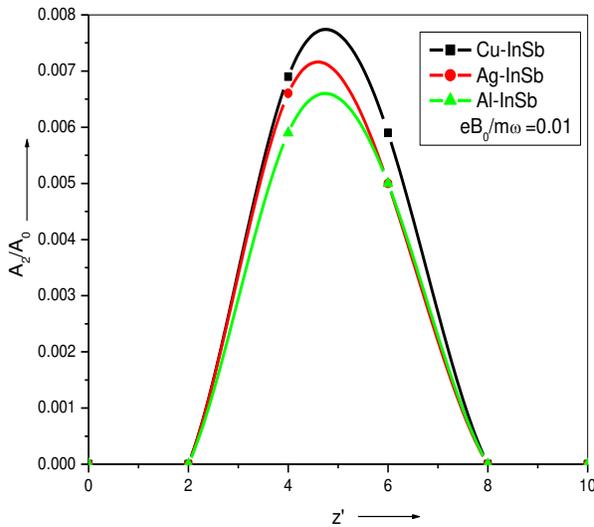


Fig. 2(a)

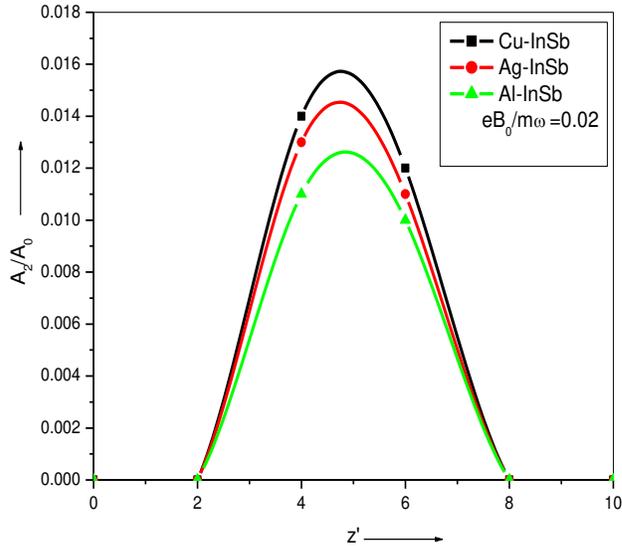


Fig. 2(b)

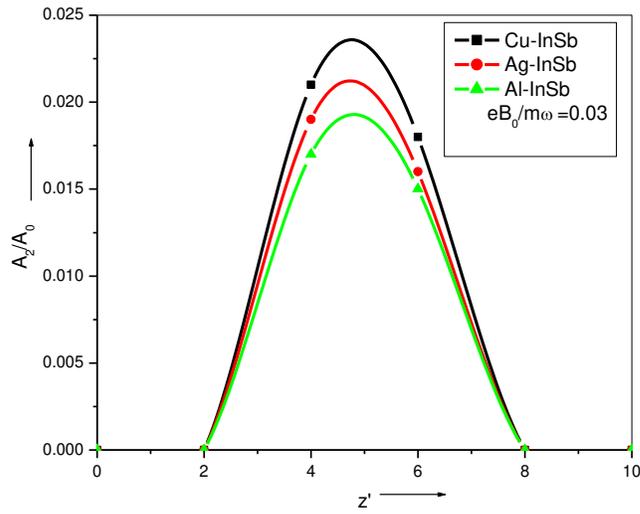


Fig. 2(c)

Fig.2. Variation of normalized second harmonic amplitude  $A_2/A_0$  with normalized propagation distance  $z'$  for metals Cu, Ag and Al with layer of n-InSb for different values of wiggler field at time  $t' = 4$ .

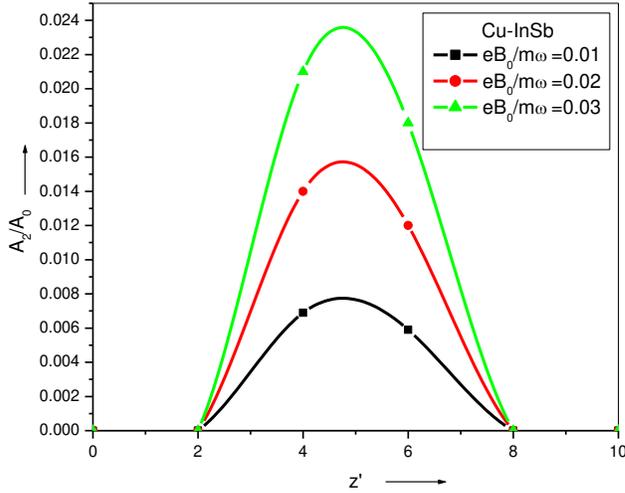


Fig. 3

Fig.3. Variation of normalized second harmonic amplitude  $A_2/A_0$  with normalized propagation distance  $z'$  for Cu-InSb interface for different values of wiggler field at time  $t' = 4$ .

Fig. 3 shows the variation of the normalized amplitude of second harmonic,  $A_2/A_0$  with normalized propagation distance  $z'$  at different values of wiggler field with  $eB_0/m\omega = 0.01, 0.02$  and  $0.03$  for Cu-InSb interface. The values of other parameters have been taken same as taken in Fig. 2. It is clear from Fig. 3 that with the slight increase in wiggler field strength, the amplitude of second harmonic enhances rapidly. Aggarwal *et al.*[23] studied second harmonic generation in atomic clusters in the presence of wiggler magnetic field and they found increase in amplitude of second harmonic with the wiggler field strength. As per their work amplitude of second harmonic shows enhancement in the region where  $13 < z' < 16$ , for different values of wiggler frequency. In the present work, we have used same values for wiggler frequency and have observed sharp increase in amplitude at  $z' = 5$ , for Cu-InSb interface. Fig.2 reveals that enhancement in amplitude is more for Cu-InSb as compared to Ag-InSb and Al-InSb interfaces. Our work shows that metallic surface like Cu-InSb interface would be a better choice to study the second harmonic generation and its applications.

#### 4. Conclusion

The electromagnetic fields of laser interact with electrons of metal and generate SPW, which are electromagnetic waves with higher amplitude. The SPW of different metals like Cu, Ag and Al interact nonlinearly with electrons of n-InSb, leading to second harmonic generation. The interaction has been studied in the presence of wiggler field with different amplitudes. It has been observed that amplitude increases sharply at the Cu-InSb interface as compared to Ag-InSb and Al-InSb. The enhancement in second harmonic amplitude has been observed with the increase in wiggler field strength. Presence of wiggler field helps in phase matching and resonates the process of second harmonic generation.

#### References

- [1] P. Kumar and V. K. Tripathi, "Surface plasma wave excitation via laser irradiated overdense plasma foil," *Appl. Phys. Lett.*, vol. 100, no. 15, p. 151605, 2012.
- [2] P. Kumar, V. K. Tripathi, and C. S. Liu, "A surface plasmon laser," *J. Appl. Phys.*, vol. 104, no. 3, p. 033306, 2008.
- [3] P. Englebienne, A. V. Hoonacker, and M. Verhas, "Surface plasmon resonance: principles, methods and applications in biomedical sciences," *Spectroscopy*, vol. 17, 1970.
- [4] H. H. Nguyen, J. Park, S. Kang, and M. Kim, "Surface plasmon resonance: a versatile technique for biosensor applications," *Sensors*, vol. 15, no. 5, p. 10481–10510, 2015.
- [5] D. Umstadter, "Review of physics and applications of relativistic plasmas driven by ultra-intense lasers," *Phys. Plasmas*, vol. 8, no. 5, p. 1774–1785, 2001.
- [6] S. Zeng, D. Baillargeat, H.-P. Ho, and K.-T. Yong, "Nanomaterials enhanced surface plasmon resonance for biological and chemical sensing applications," *Chem. Soc. Rev.*, vol. 43, no. 10, p. 3426–3452, 2014.
- [7] J. Zhang, L. Zhang, and W. Xu, "Surface plasmon polaritons: physics and applications," *J. Phys. Appl. Phys.*, vol. 45, no. 11, p. 113001, 2012.
- [8] P. Jha, R. K. Mishra, A. K. Upadhyaya, and G. Raj, "Self-focusing of intense laser beam in magnetized plasma," *Phys. Plasmas*, vol. 13, no. 10, p. 103102, 2006.
- [9] J. Rajput, N. Kant, H. Singh, and V. Nanda, "Resonant third harmonic generation of a short pulse laser in plasma by applying a wiggler magnetic field," *Opt. Commun.*, vol. 282, no. 23, p. 4614–4617, 2009.

- [10] V. Sharma, V. Thakur, and N. Kant, "Third harmonic generation of a relativistic self-focusing laser in plasma in the presence of wiggler magnetic field," *High Energy Density Phys.*, vol. 32, p. 51–55, 2019.
- [11] M. Abedi-Varaki, "Electron acceleration of a surface wave propagating in wiggler-assisted plasma," *Mod. Phys. Lett. B*, vol. 33, no. 23, p. 1950267, 2019.
- [12] S. Vij, N. Kant, and V. Thakur, "Resonant enhancement of THz radiation through vertically aligned carbon nanotubes array by applying wiggler magnetic field," *Plasmonics*, vol. 14, no. 5, p. 1051–1056, 2019.
- [13] M. Abedi-Varaki and S. Jafari, "Enhanced THz radiation from beating of two Cosh–Gaussian laser beams in a wiggler-assisted collisional magnetized plasma," *JOSA B*, vol. 35, no. 5, p. 1165–1172, 2018.
- [14] S. Ghimire and D. A. Reis, "High-harmonic generation from solids," *Nat. Phys.*, vol. 15, no. 1, p. 10–16, 2019.
- [15] K. P. Singh and V. K. Tripathi, "Laser induced electron acceleration in a tapered magnetic wiggler," *Phys. Plasmas*, vol. 11, no. 2, p. 743–746, 2004.
- [16] S. Chauhan and J. Parashar, "Surface plasma wave assisted second harmonic generation of laser over a metal film," *Phys. Plasmas*, vol. 22, no. 1, p. 013111, 2015.
- [17] C. S. Liu and V. K. Tripathi, "Excitation of surface plasma waves over metallic surfaces by lasers and electron beams," *IEEE Trans. Plasma Sci.*, vol. 28, no. 2, p. 353–358, 2000.
- [18] J. Huang, W. Guo, Y. Hu, and W. D. Wei, "Plasmonic metal–semiconductor heterostructures for hot-electron-driven photochemistry," *MRS Bull.*, vol. 45, no. 1, p. 37–42, 2020.
- [19] C. S. Liu, G. Kumar, and V. K. Tripathi, "Laser mode conversion into a surface plasma wave in a metal coated optical fiber," *J. Appl. Phys.*, vol. 100, no. 1, p. 013304, 2006.
- [20] "Refractive index of Ag (Silver) - Johnson." <https://refractiveindex.info/?shelf=main&book=Ag&page=Johnson> (accessed May 16, 2021).
- [21] K. Takagi, S. V. Nair, R. Watanabe, K. Seto, T. Kobayashi, and E. Tokunaga, "Surface plasmon polariton resonance of gold, silver, and copper studied in the kretschmann geometry: Dependence on wavelength, angle of incidence, and film thickness," *J. Phys. Soc. Jpn.*, vol. 86, no. 12, p. 124721, 2017.

- [22] V. Sharma, V. Thakur, and N. Kant, "Second harmonic generation of cosh-Gaussian laser beam in magnetized plasma," *Opt. Quantum Electron.*, vol. 52, no. 10, pp. 1–9, 2020.
- [23] M. Aggarwal, S. Vij, and N. Kant, "Wiggler magnetic field assisted second harmonic generation in clusters," *Eur. Phys. J. D*, vol. 69, no. 6, pp. 1–5, 2015.

# Figures

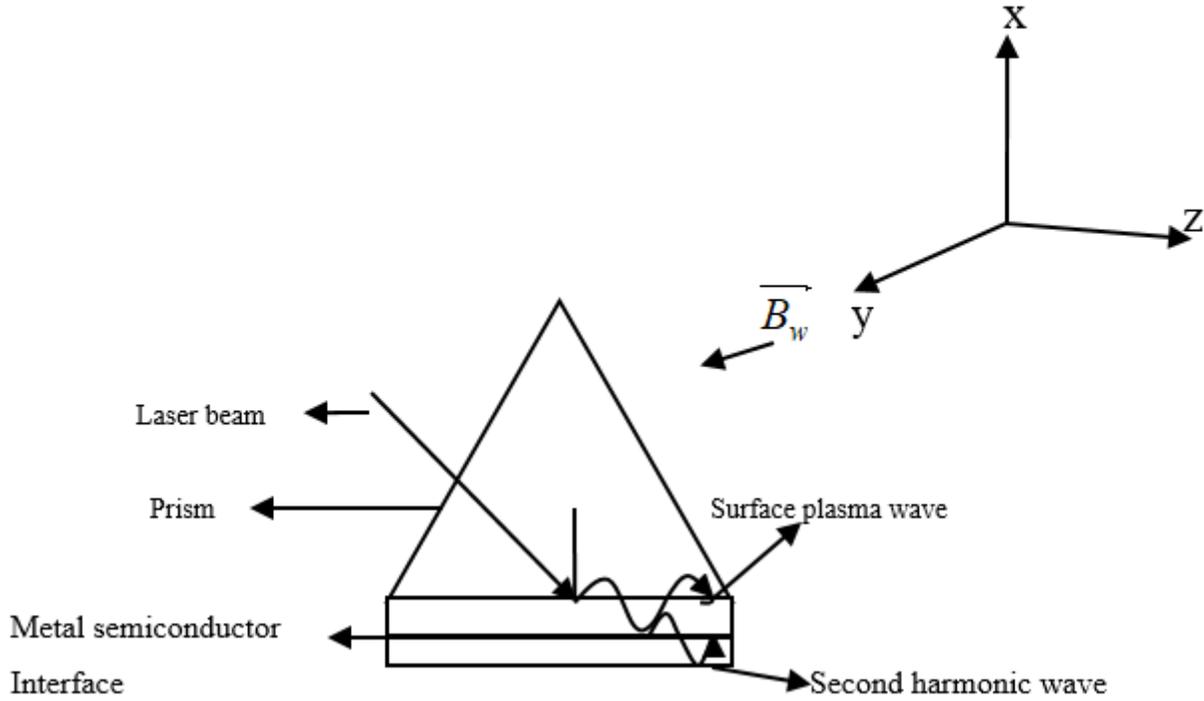


Figure 1

Kretschmann configuration with thin layer of a metal and a semiconductor

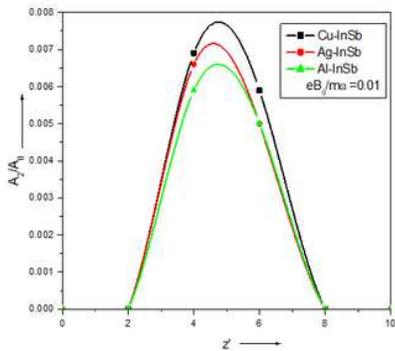


Fig. 2(a)

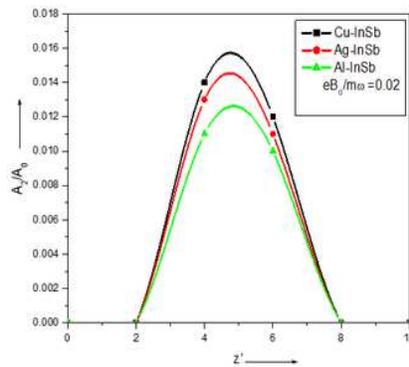


Fig. 2(b)

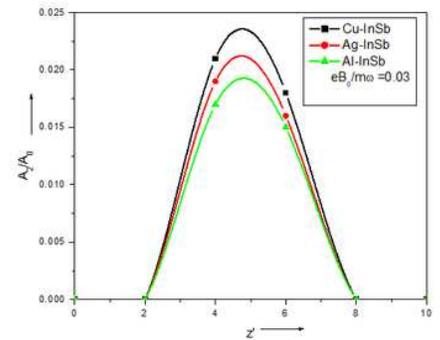


Fig. 2(c)

Figure 2

Variation of normalized second harmonic amplitude with normalized propagation distance for metals Cu, Ag and Al with layer of n-InSb for different values of wiggler field at time .

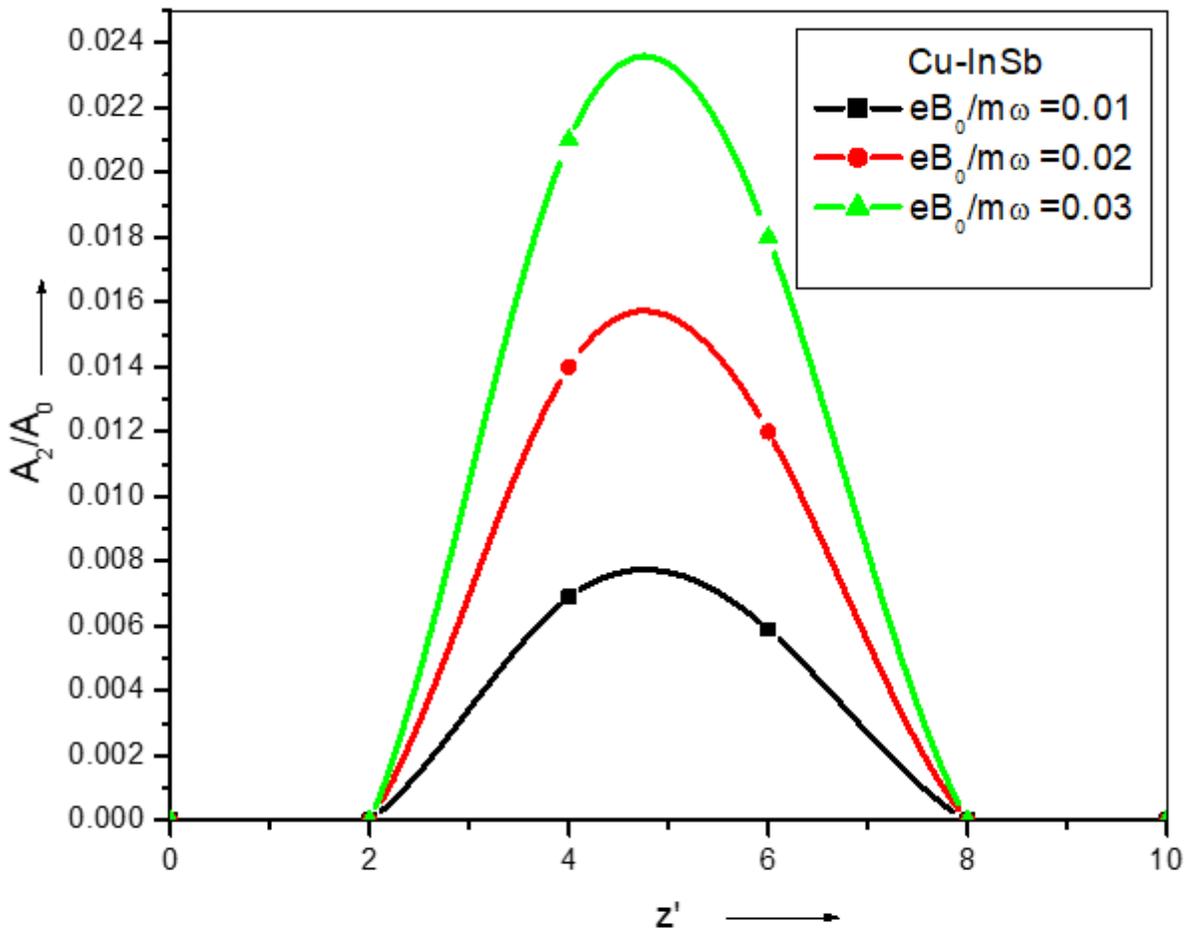


Fig. 3

Figure 3

Variation of normalized second harmonic amplitude with normalized propagation distance for Cu-InSb interface for different values of wiggler field at time