International Journal of Engineering Research and General Science Volume 4, Issue 2, March-April, 2016
ISSN 2091-2730

Anomalous Absorption of Surface Plasma Wave over a Metal Surface Embedded With Carbon Nano-Tubes

Deepika Goel[#], Prashant Chauhan, Anshu Varshney
Department of Physics and Material Science & Engineering, Jaypee Institute of Information Technology, Noida-201307, UP, India.
Email: deepika7nov@yahoo.co.in

Abstract -The anomalous absorption of surface plasma wave (SPW) by two dimensional arrays of carbon nanotubes, embedded over a metal surface with their length along $\hat{x}$ direction is studied theoretically. As surface wave of frequency ω propagates through the nanotubes, electrons in the nanotubes start oscillating and dissipate their energy via collisions in the nanotubes resulting in resonant absorption of SPW energy at frequency $\omega \approx \omega_{pe}/\sqrt{2}$, where ω_{pe} is plasma frequency of electrons inside the nanotubes. The absorption of SPW by the nanotubes is enhanced and has a sharp peak at resonant frequency. Results revealed that absorption coefficient increases with the density of nanotubes. Effect of lattice permittivity variation on absorption coefficient is also studied

Keywords: Surface plasma waves, carbon nanotubes, Absorption, nanoparticles

INTRODUCTION

The interaction of electromagnetic radiations with carbon nanotubes (CNT) has been a very active area of research due to their outstanding mechanical, thermal, electrical, magnetic, and optical properties that make them an ideal material for optical switches, modulators and saturable absorbers [1-2]. Also, nanoscale dimensions and high carrier mobility makes them potential candidates for high performance electronics and sensing applications [3-5]. Smooth metal surface reradiates the electromagnetic wave energy in the surrounding medium due to high free electron density, resulting in poor absorption. Due to presence of CNT over the metal surface, the electromagnetic waves are absorbed at wave frequency close to the natural frequency of oscillations of the electron cloud [6]. Li et al. [7] have reported the optical absorption spectra of carbon nanotube array having electric field parallel to the tube direction and deduced the relationship between the absorption coefficient and the polarization angle of the array. Ahmed [8] reported the resonant absorption of laser light by two dimensional array of carbon nanotubes occurs at frequency $\omega \approx \omega_{pe}/\sqrt{2}$, where ω_{pe} is plasma frequency of electrons inside the nanotubes. Kumar and Tripathi [9] investigated linear and non linear interaction of laser with an array of carbon nanotubes and observed that surface plasmon resonance occurs at frequency $\omega \approx \omega_{pe}/\sqrt{2}$. The attenuation constant is also resonantly enhanced around these frequencies. The absorption of electromagnetic waves can be greatly enhanced when these waves gets mode converted into surface plasma wave (SPW) [10]. SPW are collective longitudinal oscillations of quasi-free electrons propagating along the interface of a metal and a dielectric medium (or free space). The electric field of these waves decays exponentially away from the interface in both media. The distance to which surface plasma wave lasts is called propagation length. The propagation length of the wave is of the order of 3900 A^o in free space and 240 A^o in the metal film [11]. The decay is rapid inside the metal as compared to dielectric. Surface plasma wave excites resonant plasma oscillations inside the nanotubes, embedded over the metal surface. At resonant frequency, the absorption constant rises sharply which corresponds to the strong dissipation of the surface wave energy via collisions of the free electrons of the nanotube [8]. Moradi [12] investigated the propagation of the coupled surface plasma waves in the metallic single-walled carbon nanotubes. Bliokh *et al.* [13] depicted both theoretically and experimentally that resonant excitation of surface plasma waves can achieve total absorption of electromagnetic waves in overdense plasmas. Kumar *et al.* [14] theoretically studied the absorption of SPW energy by metal nanoparticles embedded over the metal surface. Results indicate the increase in absorption coefficient at frequency $\omega_{sp}=\omega_p/\sqrt{3}$, where ω_p is the plasma frequency.

In this paper, we study the absorption of surface plasma waves (SPW) by two dimensional array of carbon nanotubes embedded over the metal surface with their length along $\hat{x}$ direction. The surface plasma wave is propagating over the metal surface in $\hat{z}$ -direction and can be excited by using an attenuated total reflection configuration. It excites resonant plasma oscillations in the nanotubes incurring attenuation of the SPW due to absorption of energy by the nanotubes. Also, we analyse the effect on varying the density of nanotubes and lattice permittivity. This paper has been organised into three sections where introduction is presented as section 1. The propagation of SPW over the metal-vacuum interface and mathematical formalism for absorption of SPW by nanotubes is developed in section 2. Finally, results and conclusions are discussed in section 3.

ABSORPTION OF SURFACE PLASMA WAVES

Consider the metal free-space interface at $x=0$. The metal occupies the half space for $(x<0)$ and free space is for $(x>0)$ as shown in Fig. 1.

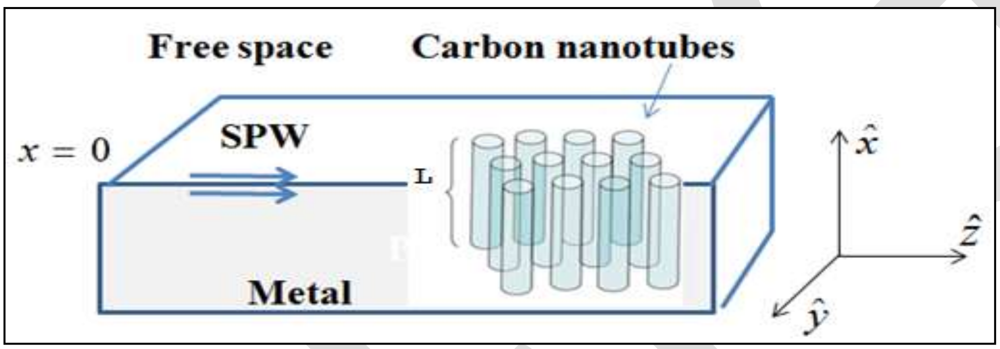

Fig. 10 Schematic of surface plasma wave propagation on metal free space interface embedded with carbon nanotubes.

The metal is characterized by lattice permittivity ε_L . The effective permittivity ε of metal is given by [8]

$$\varepsilon=\varepsilon_L-\frac{N\pi r_0^2\omega_p^2}{(\omega^2-\omega_{pe}^2/2+i\nu\omega)}$$

ω is the incident surface plasma wave frequency. N is the number of nanotubes per unit area and r_0 is the radius of nanotubes. ν is the electron phonon collision frequency in the metal particle with $\nu^2 \ll \omega^2$ and $\omega_p^2=4\pi ne^2/m$ is the plasma frequency. Here, $-e$ and m are the charge and effective mass of electron. n is the electron density at the metal surface. Suppose the SPW propagates along $\hat{z}$ having electric field components in $\hat{x}$ and $\hat{z}$ directions given by

$$E_1=\left[\frac{ik_z}{\alpha_1}\hat{x}+\hat{z}\right]Ae^{-\alpha_1 x}.e^{-i(\omega t-k_z z)} \qquad \text{for} \qquad x>0 \qquad 2(a)$$

$$E_2=\left[-\frac{ik_z}{\alpha_2}\hat{x}+\hat{z}\right]A_1e^{\alpha_2 x}e^{-i(\omega t-k_z z)} \qquad \text{for} \qquad x<0 \qquad 2(b)$$

where $\alpha_1=(k_z^2-\omega^2/c^2)^{1/2}$ and $\alpha_2=(k_z^2-\omega^2\varepsilon/c^2)^{1/2}$. A and A_1 are constants.

Using the boundary conditions i.e. the normal component of $\vec{D}$ and the tangential component of $\vec{E}$ are continuous at the interface $x=0$, the dispersion relation of surface plasma wave is

$$k_z = \frac{\omega}{c}\left(\frac{\varepsilon}{1+\varepsilon}\right)^{1/2} \tag{3}$$

The dispersion relation is dervied for low areal density of the nanotubes, so that the SPW field is not modified due to the presence of naotubes. Consider two dimensional array of carbon nanotubes embedded over the metal surface with their length along $\hat{x}$ direction. The SPW field [Eq. 2(a)] in the free space region $(x>0)$ interacts with the nanotubes. Under the influence of this field, electrons of the nanotube execute oscillations with displacement $\vec{s}$ and their response is governed by the equation of motion, given by [15]

$$m\frac{d^2\vec{s}}{dt^2} + m\nu\frac{d\vec{s}}{dt} + m\frac{\omega_{pe}^2\vec{s}}{2} = -e\vec{E}_1 \tag{4}$$

ω_{pe} is the plasma frequency associated with free electrons in nanotube. Taking $\partial/\partial t = -i\omega$, $\hat{x}$ and $\hat{z}$ components of electron velocity are obtained by solving equation (4). These are given by

$$V_x = \frac{Ae\omega}{m(\omega^2 - \omega_{pe}^2/2 + i\nu\omega)}\left(\frac{k_z}{\alpha_1}\right)e^{-i\omega t} \qquad 5(a)$$

$$V_z = \frac{-ieA\omega}{m(\omega^2 - \omega_{pe}^2/2 + i\nu\omega)}e^{-i\omega t} \qquad 5(b)$$

The part of $\vec{V}$ in phase with the electric field of SPW gives rise to time average power absorption per electron

$$\varepsilon_{abs} = \frac{1}{2}\mathrm{Re}[-e\vec{E}^* \cdot \vec{V}] \tag{6}$$

where $\vec{E}^*$ is the complex conjugate of the SPW electric field in the free space. Substituting the values from equations 2(a), 5(a) and 5(b) in equation (6), we get

$$\varepsilon_{abs} = \frac{1}{2}\left(\frac{e^2A^2\omega^2\nu(1+k_z^2/\alpha_1^2)}{m((\omega^2-\omega_{pe}^2/2)^2+\nu^2\omega^2)}\right) \tag{7}$$

Suppose the electron density in nanotube is n_e. The effective electron density n_{eff} in the region occupied by the array is $n_{eff} = Nn_e\pi r_0^2$ [8]. Then, energy absorbed by n_{eff} nanotubes in distance dz is $dP = -\varepsilon_{abs}n_{eff}dz$

$$dP = -\frac{\omega_{pe}^2A^2\nu\omega^2(1+k_z^2/\alpha_1^2)Nr_0^2}{8((\omega^2-\omega_{pe}^2/2)^2+\nu^2\omega^2)}dz \tag{8}$$

Using Poynting theorem, the energy flow for surface plasma wave over the metal surface is given by

$$P = -\frac{A^2c^2k_z}{16\pi\alpha_1^2\omega}\left(\frac{k_z^2}{\alpha_1} - \alpha_1\right) \tag{9}$$

As the SPW propagates, the decay in energy of a beam propagating across a medium is given by $P = P_0e^{-k_{ip}z}$, k_{ip} is absorption constant. On differentiating this equation w.r.t *z* and dividing the two equations, we get

$$\int_{P_0}^{P} \frac{dP}{P} = \int_{0}^{z} k_{ip} dz + C \qquad (10)$$

where P_0 is the power at $z = 0$, while P is the power of SPW after the absorption length z. Substituting values of dP and P from eqns. (8) and (9) respectively in equation (10), we get the absorption constant k_{ip}, given as

$$k_{ip} = \frac{2N\pi r_0^2 \alpha_1^2 \omega_{pe}^2 \nu \omega^3 (1 + k_z^2 / \alpha_1^2)}{k_z c^2 ((\omega^2 - \omega_{pe}^2 / 2)^2 + \nu^2 \omega^2)(k_z^2 / \alpha_1 - \alpha_1)} \qquad (11)$$

Equation (11) is normalized and solved numerically for the parameters, $\omega_{pe} = 4.079 \times 10^{15}$ rad/s and $\nu / \omega_p = 1.5 \times 10^{-2}$.

RESULTS AND DISCUSSION

The resonant absorption of SPW propagating on the metal free space interface embedded with nanotubes is studied. In figure 2, graph is plotted between normalized absorption constant $(k_{ip} c / \omega_p)$ verses normalized frequency of SPW (ω / ω_{pe}) for $\varepsilon_L = 1$. The absorption constant increases from 0.18 to 0.7 as $N\pi r_0^2$ is increased from 0.005 to 0.015. Resonance is sharply peaked at SPW frequency close to $\omega_{pe} / \sqrt{2}$. Ahmad [8] reported enhanced absorption of laser light by two dimensional arrays of nanotubes and it is sharply peaked around resonance frequency. Nurbek Kakenov *et al.* [16] experimentally studied the reflection spectra from the gold surface with increasing carbon nanotube densities using surface plasmon resonance. The absorption of SPW by nanotubes is facilitated by resonant plasma oscillations inside the nanotubes. The electrons inside the nanotube resonantly absorb SPW energy when the SPW frequency resonates with the surface charge oscillations of the nanotubes i.e. at $\omega = \omega_{pe} / \sqrt{2}$, where ω is the frequency of the SPW. At this frequency, there is sharp increase in absorption constant which corresponds to the strong dissipation of the surface wave energy via collisions of the free electrons of the tube. Absorption constant reduces sharply as one move away from the resonance point. The SPW propagating at the interface is influenced by the properties of the medium. In figures 3, normalized absorption constant $(k_{ip} c / \omega_p)$ is plotted on varying lattice permittivity of metals. The plasmon field of the SPW is distorted when the lattice permittivity of the medium is changed [15]. It is observed that for particular value of $N\pi r_0^2 = 0.015$, the absorption constant decreases from 0.7 to 0.36 and resonance peak shifts towards smaller frequencies for variation of ε_L from 1 to 9.

International Journal of Engineering Research and General Science Volume 4, Issue 2, March-April, 2016
ISSN 2091-2730

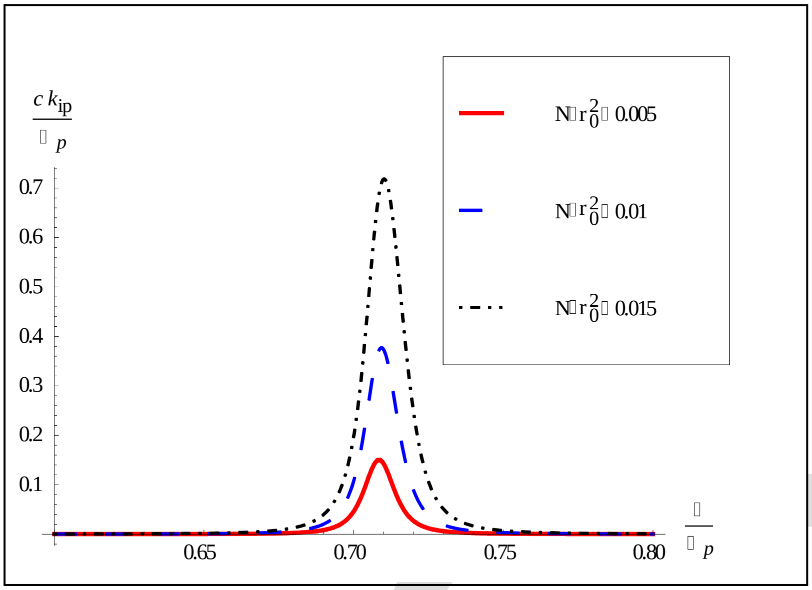

Fig. 2 Variation of normalized absorption constant $(k_{ip}c/\omega_{pe})$ *verses normalized frequency* (ω/ω_{pe}) *for* $\varepsilon_L = 1$.

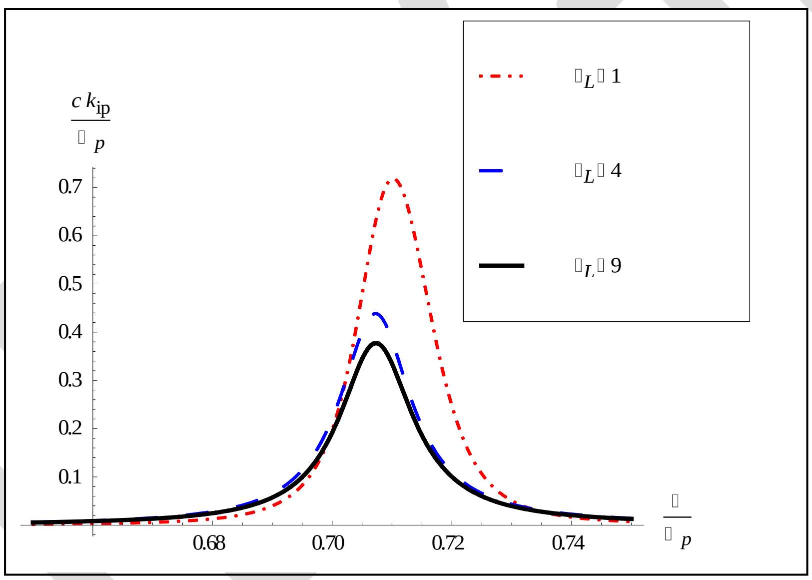

Fig. 3 Plot of normalized absorption constant $(k_{ip}c/\omega_{pe})$ *verses normalized frequency* (ω/ω_{pe}) *on varying* ε_L.

CONCLUSION

In conclusion, absorption of SPW by carbon nanotubes embedded over the metal surface occurs when SPW frequency becomes $1/\sqrt{2}$ times the plasma frequency associated with free electrons in nanotube. At this frequency, SPW induces a huge localized electric field inside the nanotubes and electrons dissipate their energy via collisions in the nanotubes. The absorption constant rises sharply and increases with the density of the nanotubes. The absorption coefficient is also influenced by the properties of the medium. This could be a good scheme to measure the surface plasma frequency in nanotube.

REFERENCES:

1) Dresselhaus M S, Dresselhaus G and Eklund P C 1996 Science of Fullerenes and Carbon Nanotubes, Academic Press, New York.
2) Wang C, Badmaev A, Jooyaie A, Bao M Q, Wang K L, Galatsis K and Zhou C W 2011 Radio frequency and linearity performance of transistors using high purity semiconducting carbon nanotubes *ACS Nano* 5, 4169-4176.
3) Kakenov N, Balci O, Balci S and Kocabas C 2012 Probing molecular interactions on carbon nanotube surfaces using surface plasmon resonance sensors *Applied Phy. Lett.* 101, 223114.
4) Schedin F, Geim A K, Morozov S V, Hill E W, Blake P, Katsnelson M I and Novoselov K S 2007 Detection of individual gas molecules adsorbed on graphene *Nature Mater* 6, 652-655.
5) Barone P W, Baik S, Heller D A and Strano M S 2005 Near infrared optical sensors based on single walled carbon nanotubes. *Nature Mater* 4, 86-92.
6) Haque M S, Marinelli C, Udrea F and Milne W I 2006 Absorption Characteristics of Single Wall Carbon Nanotubes *NSTI Nanotech, Boston.*
7) Li Z M, Tang Z K, Liu H J, Wang N, Chan C T, Saito R, Okada S, Li G D, Chen J S, Nagasawa N and Tsuda S 2001 Polarized Absorption Spectra of Single-Walled 4 Å Carbon Nanotubes Aligned in Channels of an AlPO4-5 Single Crystal. *Phys. Rev. lett.*, 87, 127401.
8) Ahmad A 2006 Parametric instabilities and plasma effects in nanotubes and nanoparticles. PhD Dissertation, Department of Physics, Indian Institute of technology Delhi, India.
9) Kumar M and Tripathi V K 2013 High power laser coupling to carbon nano-tubes and ion Coulomb explosion *Phy. of Plasma* 20, 092103.
10) Jonsson G E, Fredriksson H, Sellappan R and Chakarov D 2011 Nanostructures for enhanced light absorption in solar energy devices. *International Journal of Photoenergy* 11, 939807.
11) Raether H 1988 Surface plasmons on smooth and rough and on gratings. Springer Tracts in Modern Physics Vol. 111 *Springer*, *New York*.
12) Moradi A 2013 Coupled Surface plasmon-polariton modes of metallic single-walled carbon nanotubes *Plasmonics* 8, 1509-1513 (2013).
13) Bliokh Y P, Felsteiner J and Slutsker Y Z 2005 Total absorption of an electromagnetic wave by an overdense plasma *Phys. Rev. Lett 9*5, 165003.
14) Kumar G and Tripathi V K 2007 Anomalous absorption of surface plasma wave by particles adsorbed on metal surface *Appl. Phys. Lett.* 91,161503.
15) Chen F F Introduction to plasma physics and controlled fusion. Vol. 1. *New York: Plenum.*
16) Kakenov N, Balci O, Balci S and Kocabas C 2012 Surface Plasmons in metallic nanoparticles: Probing molecular interactions on carbon nanotube surfaces using surface plasmon resonance sensors. *Appl. Phys. Lett.* 101, 223114.