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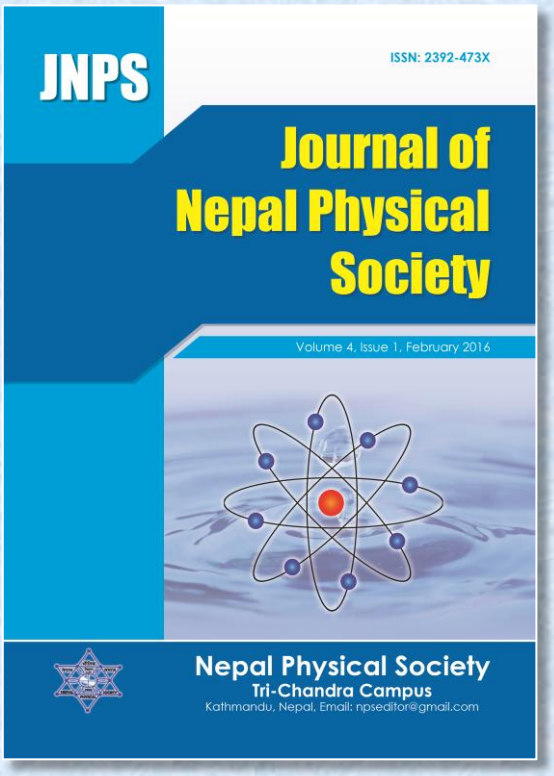

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Research Article

Study of Signal Transmission through different Array of Cu, Au and Ag Nanospheres

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ABSTRACT

Twenty first century is the age of Information Technology and we always look for faster information transport and processing capabilities. Data can be moved by transistors and optical fibers. Transistors carry small amount of data and are small in size while optical fibers can carry huge amount of data but are much bigger in size. Metal nanostructures may possess right combination of electric and optical properties to tackle the issues outlined above and realized the dream of significantly faster processing speeds. In this work, dispersion relation in Plasmon modes in linear chain and alternated chain of nanoparticles like silver-gold, silver-copper and gold-copper were studied. Expressions of angular frequency of Plasmon modes, group-velocity and extinction-coefficient were derived by solving equation of motion of Plasmon oscillation on the single kind of nanoparticle and that on different alternated chain of nanoparticles. Expressions of angular frequency of Plasmon modes, group velocity and extinction coefficient were tested for specific linear chain of nanoparticles. Extinction coefficients for the linear chain of Copper, gold and silver nanoparticles were found to be less and group velocities higher than that of alternated silver-gold and alternated gold-copper at their respective resonance frequencies.

Keywords: Surface Plasmon Polariton, Point Dipole Approximation, Nanospheres, Signal Transmission.

INTRODUCTION

Quantum of collective longitudinal excitation of conduction electron on the surface is called Surface plasmon (Kittle, 2004). This excitation of conduction electron on the metal surface can be achieved using beam of accelerated electron and electromagnetic (EM) radiation as well. In 1957, Refuse Ritchie (Ritchie *et al.*, 1957) published a finding on electron energy losses in thin films, in which it was shown that plasmon modes can exist near the surface of metals. This was the first theoretical description of surface plasmons. In 1970 Uwe Keribig and Peter Zacharias (Kreibig and Zacharias, 1970), performed a study in which they compare the electronic and optical responses of gold and silver nanoparticles. For the first time they described the optical properties of metal nanoparticles in terms of surface plasmon. In case of noble metal nanospheres, this exciting EM radiation lies in the range of the visible and near-infrared energy range. Excited plasmon by the interaction of light radiation with electron cloud is called plasmon polariton (Barner *et al.*, 2003 *and* Brongersma *et al.*, 2007). At first glance, the use of metallic structures to transmit light signals seems impractical, because metals are known for high optical losses. But from the simulation data, it has been shown that electromagnetic radiation can transmitted through the array of closely spaced metallic nanospheres (Quintin *et al.*, 1998 and Atwater *et al.*, 2007). Using the Silver nanospheres chain below the diffraction limit of visible range light, possibility of transportation and extinction of signal had been studied by the Brongersma, Hartman, and Atwater (Brongersma *et al.*, 2000) using point dipole approximation. They showed that signal can be transmitted using such an array of metallic nanospheres even at the speed of 0.1c.

At the early stage, information transporting devices used to be bulky and slow in performance. Discovery of semiconductor followed by the transistor greatly increased speed of propagation of signal and hence tuned new era in information transportation technology. In this process not only speed was greatly increased, as illustrated in the figure 1, but also there was reduction in size of device using present advance nanotechnology. These semiconductor and transistor based devices

let us to design circuit that can transport signal in terms of electric current.

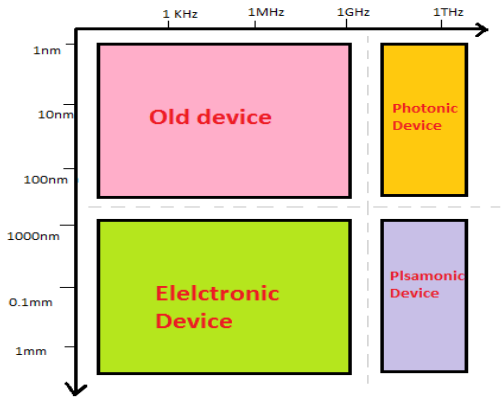

Fig.1. Progress in signal transporting device speed and dimension.

Nano-scale study of matter has allowed us to design transistor even within 50nm (Ozbay *et al.*, 2007). But their efficiency is bounded by the velocity of electron flow through the wire. Optical signal carrying devices, like optical fiber can carry signal with efficiency > 1000 (Ozbay *et al.*, 2007), is desirable to find out structures that can interconnect optical signal carrying device and electric signal carrying bulky device (example: optical fibers that are bulky size in compare to that of present very tiny nanoscale level chips and circuit elements like transistor, capacitor, etc). Metallic nanospheres can interact with electromagnetic radiation and excites LSPP on it that oscillates at the frequency many times greater that of incident radiation (Barnes *et. al.*, 2003). This compresses signal many times to very short wavelength range so that signal can pass below its diffraction limit. Thus, the scarcity of efficient and fast interconnector can be fulfilled by the nano-spheres array of metal, as nanospheres array of metal can provide guide to light signal by the mean of electron cloud oscillation on its surface, and hence allows signal to propagate through it. This permits us to design whole ultrafast signal processing circuit within a nano-scale range with ultrafast speed (Atwater *et al.*, 2007).

METHODOLOGY

In this presented work, it is tried to describe attenuation coefficients and signal propagation velocity, signal that lies within visible and red infrared region, through array of linear and alternated nanospheres of Copper (Cu), Gold (Au) and Silver (Ag) based on point dipole approximation. In this analytical method of investigation, we have used classical electrodynamics' concept that can deal with even oscillating dipole and their interactions.

Under the incident monochromatic EM radiation of wavelength, λ, very greater than that of radius, R, and inter-particle spacing between neighboring nanospheres, d, there is homogenous polarization of nanospheres in the array and get polarized long the direction of incident electric field that gives Longitudinal mode (L-mode) and Transverse mode (T-mode) of polarization depending upon the polarization of nanopsheres along the axis and perpendicular to the axis of nanospheres array respectively. Electric field by an individual oscillating dipole $\boldsymbol{P}_{i,m,j}$, due to j^{th} types of material located at m^{th} position in i^{th} mode of polarization, at the neighboring nanospheres of k^{th} types of material located at $(m+1)$ and $(m-1)$ position, depends upon the polarization dependent constant γ_i, is given by an equation (Brongersma *et al.*, 2000),

$$\boldsymbol{E}_{i,jm,} = \frac{\gamma_i \boldsymbol{P}_{i,m,j}}{4\pi\epsilon_0 d^3}. \qquad (1)$$

Electric field is dependent of d^{-3} and hence there is significance of near field rather than far field in coupling phenomena. Here we have used ϵ_0 for dielectric constant of free space, $i = L$ and $i = T$ for L-mode and T-mode respectively such that $\gamma_L = -2$ and $\gamma_T = 1$. $j,k = 1,2,3$ stands for Cu, Au and Ag respectively. Dipole on Localized Surface Plasmon (LSPP) at j^{th} type of nanosphere material oscillates with frequency $\omega_{0,j}$, can be obtained in terms of bulk plasma frequency $\omega_{p,j}$ of j^{th} types of material given by Drude model of metal. Due to oscillation of dipole with Eigen frequency of oscillation, $\omega_{0,j}$, there is radiation loss and its affect can be expressed in term of relaxation frequency, $\Gamma_{R,j} = \omega_{0,j}^2 \tau_j$, with $\tau_j = \frac{2e}{3m_j^* c^3}$ (Jackson, 1999) such that e, m_j^*, and c are representing electric charge, optical effective mass of an electron and, velocity of light respectively. Oscillating LSPP also suffers damping due to non radiative loss like electron hole formation, hot electron formation, and phonon excitation, that depends on the Fermi velocity, $V_{F,j}$, bulk mean free path, $\lambda_{B,j}$, and radius of nanosphere, R, and hence give heating effect. This gives relaxation frequency for j^{th} type of material, $\Gamma_{l,j}$, given by the relation (Kreibig and Genzel, 1985),

$$\Gamma_{l,j} = \frac{V_{F,j}}{\lambda_{B,j}} + \frac{V_{F,j}}{R}. \qquad (2)$$

There is coupling between nearby nanospheres through the electric field interaction between oscillating dipoles, and hence give rise coupling frequency of j^{th} types of nanospheres, $\omega_{1,j}$, depends upon the dipole charge, q_j, as well as center to center spacing between nanospheres, d, and optical effective mass of electron, m_j^*, as given by equation (Brongersma *et al.*, 2000),

$$\omega_{1,j} = \frac{q_j\, e}{4\pi m_j^* \epsilon_0 d^3}\,. \tag{3}$$

With above consideration, equation of oscillation of nanospheres array, made by two different material of types j and k, is given by the relation,

$$\ddot{\boldsymbol{P}}_{i,j,m} = -\omega_{0,j}^2 \boldsymbol{P} - \Gamma_{l,j}\dot{\boldsymbol{P}}_{i,j,m} + \frac{\Gamma_{Rj}}{\omega_{0,1}^2}\dddot{\boldsymbol{P}}_{i,j,m} + \gamma_i \omega_{1,j}^2\left(\boldsymbol{P}_{i,k,m+1} + \boldsymbol{P}_{i,k,m-1}\right). \tag{4}$$

This is equation of damped harmonic oscillator giving resultant acceleration of LSPP located at j^{th} types of material. First term on right side is arising from the Eigen frequency oscillation of nanosphere, considered at center in the array of nanospheres. Second and third terms give acceleration arising from non-radiative and radiative energy loss. The last term is giving effect of coupling between nanospheres, of j^{th} type and k^{th} of materials, on the array. As this equation is representing damped harmonic oscillator, it is desirable to introduce solution of above equation in the form of,

$$\boldsymbol{P}_{i,j,m} = \boldsymbol{P}_{i,j,0} e^{i(\omega t - Kmd)} e^{-\alpha_i md}$$

and

$$\boldsymbol{P}_{i,k,m} = \boldsymbol{P}_{i,k,0} e^{i(\omega t - Kmd)} e^{-\alpha_i md}\,. \tag{5}$$

$\boldsymbol{P}_{i,j,0}$ and $\boldsymbol{P}_{i,k,0}$ are dipole moments of LSPPs on nanospheres of j^{th} and k^{th} type of material located as the first nanospheres being excited by the radiation respectively. Exponential terms with attenuation coefficient, α_i, give damping on the oscillation and other exponentials without α_i give Plasmon oscillation without damping. Solving above equations we get real part and imaginary part. Real part gives dispersion equation,

$$\omega^2 = 0.5\left(\omega_{0,j}^2 + \omega_{0.k}^2 + \Gamma_{l,j}\Gamma_{l,k}\right) + 0.5\sqrt{\left(\omega_{o,j}^2 - \omega_{0,k}^2\right)^2 + 8\gamma_i^2\omega_{1,j}^2\omega_{1,k}^2\{1+\cos(2Kd)\}}\,. \tag{6}$$

Using the group velocity relation, $V_{g,i} = \frac{\partial\omega}{\partial K}$ and approximating $\cos h(\alpha_i d) \approx 1$, $\sinh(\alpha_i d) \approx (\alpha_i d) \ll 1$ for very small damping, we get group velocity at i^{th} mode of polarization,

$$V_{g,i} = \frac{4\gamma_i^2\, d\, \omega_{1,j}^2\, \omega_{1,k}^2 \sin(2\mathrm{Kd})}{\left[2\omega\left(\omega_{0,j}^2+\omega_{0,k}^2+\Gamma_{l,j}\Gamma_{l,k}\right) - 4\omega^3\left[1-\frac{\Gamma_{R,j}\Gamma_{l,k}}{\omega_{0,j}^2}+\frac{\Gamma_{R,k}\Gamma_{l,j}}{\omega_{0,k}^2}\right]\right]}\,. \tag{7}$$

Imaginary part of the solution gives attenuation coefficient, α_i gives the energy loss of signal on passing through the signal carrier, in terms of group velocity, damping frequencies, etc as,

$$\alpha_i = \frac{\omega^3\left[\left\{\Gamma_{R,k}\frac{\omega_{0,j}^2}{\omega_{0,k}^2}+\Gamma_{R,j}\frac{\omega_{0,k}^2}{\omega_{0,j}^2}\right\} - \left(\Gamma_{l,j}+\Gamma_{l,k}\right)\right] + \omega\left[\Gamma_{l,k}\omega_{0,j}^2 + \Gamma_{l,j}\omega_{0,k}^2\right] - \omega^5\left[\frac{\Gamma_{R,j}}{\omega_{0,j}^2}+\frac{\Gamma_{R,k}}{\omega_{0,k}^2}\right]}{V_{g,i}\left[2\omega\left(\omega_{0,j}^2+\omega_{0,k}^2+\Gamma_{l,j}\Gamma_{l,k}\right) - 4\omega^3\left\{1-\left(\frac{\Gamma_{R,j}\Gamma_{l,k}}{\omega_{0,j}^2}+\frac{\Gamma_{R,k}\Gamma_{l,j}}{\omega_{0,k}^2}\right)\right\}\right]}\,. \tag{8}$$

RESULTS AND DISCUSSION

We have carried out calculations for the array of alternated as well as array of single type nanospheres, of radius $R = 25\mathrm{nm}$, materials like Cu, Au and Ag, separated by distance $d = 75\mathrm{nm}$. Used effective mass of electron in Cu, Au and Ag are $m_1^* = 1.49m$, $m_2^* = 0.99m$ and $m_3^* = 0.96m$ respectively (Johnson and Cristy, 1972), where $m = 9.1 \times 10^{-31}\mathrm{Kg}$ is rest mass of electron. On using bulk electron densities for Cu, Au and Ag as $8.45 \times 10^{28}\mathrm{m}^{-3}$, $5.90 \times 10^{28}\mathrm{m}^{-3}$ and $5.85 \times 10^{28}\mathrm{m}^{-3}$ respectively (Kittle, 2004), we got their

respective coupling frequencies, $\omega_{1,1} = 1.49 \times 10^{15}\text{rad/s}$, $\omega_{1,2} = 1.53 \times 10^{15}\text{rad/s}$ and $\omega_{1,3} = 1.54 \times 10^{15}\text{rad/s}$, and their individual nanosphere oscillation frequencies, $\omega_{0,1} = 4.75 \times 10^{15}\text{rad/s}$ (Chen *et al.*, 2011), $\omega_{0,2} = 4.87 \times 10^{15}\text{rad/s}$ and $\omega_{0,3} = 4.92 \times 10^{15}\text{rad/s}$. Here we see coupling frequencies and resonance oscillation frequencies of individual dipole for our considered systems are of same order and hence there are possibilities of strong coupling interactions. Fermi velocities of electron on Cu, Au and Ag bulk materials, $V_{F,1} = 1.57 \times 10^6 m/m$, $V_{F,2} = 1.39 \times 10^6$ m/s and $V_{F,3} = 1.38 \times 10^6$ m/s (*Kittle*, 2004) together with their respective bulk mean free paths, $\lambda_{B,1} = 39\text{nm}$ (Sattler *et al.*, 2016), $\lambda_{B,2} = 41\text{nm}$ (Fulay, 2010, and Waser, 2012) and $\lambda_{B,3} = 57\text{nm}$ (Brongersma *et al.*, 2000) respectively. This results, their correspondence relaxation frequencies, $\Gamma_{l,1} = 10.30 \times 10^{13}\ rad/s$, $\Gamma_{l,2} = 8.95 \times 10^{13}\text{rad/s}$ and $\Gamma_{l,3} = 7.94 \times 10^{13}\text{rad/s}$ respectively. Time period of oscillation τ_j for Cu, Au and Ag, $4.20 \times 10^{-24}\text{s}$, $6.33 \times 10^{-24}\text{s}$ and $6.52 \times 10^{-24}\text{s}$ respectively, give their respective relaxation time frequencies due to radiation loss, $\Gamma_{R,1} = 2.53 \times 10^8\text{rad/s}$, $\Gamma_{R,2} = 4.00 \times 10^8\text{rad/s}$ and $\Gamma_{R,3} = 4.22 \times 10^8\text{rad/s}$ respectively. From here we get $\Gamma_{R,j} \ll \Gamma_{l,j}$, and can conclude that effect on damping of nanospheres due to radiation loss is negligible than that of non-radiative loss.

(i) Dispersion Curve:

On the basis of equation 6, dispersion equation for single type of nanospheres array of Cu, Au and Ag is illustrated in figure 2. Here we see that, frequency of signal, propagating through the array, oscillates about certain central value. Allowed frequency region for Cu nanospheres array is slightly lower than that of Au, and Ag has upper frequency region. Band width for the array of Cu, array of Au and array of Ag nanosperes shows almost same magnitudes. Thus array of individual Cu, Au and Ag nanosperes can carry nearly same volume of data although their efficiencies may be different. Dispersion curves for T-mode, denoted by dotted lines, has almost half band width of corresponding L-mode with same period of variation with wave vector $\boldsymbol{K}$. This signifies, T-mode excitation of LSPP on array of nanospheres cannot propagate large amount of data as much as that can be done by corresponding L-mode. This phenomenon also appears on the array of alternated Cu and Au nanospheres and array of alternated Au and Ag nanospheres as shown in figure 3.

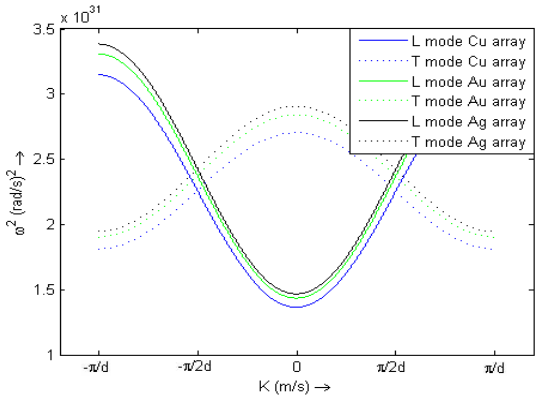

Fig. 2. Dispersion curve for array of nanospheres of (a) Cu, denoted by blue lines (b) Au, denoted by green lines and (c) Ag, denoted by black lines. Dotted lines are drawn for their respective T-modes and solid lines for L-modes.

This phenomenon together with equation 7 of velocity shows that signal can propagate in L-mode almost two times faster than that of corresponding T-mode. Dispersion equation for array of alternated nanosperes made by Cu and Au, and that for array of alternated nanospheres made by Au and Ag is shown in figure 3.

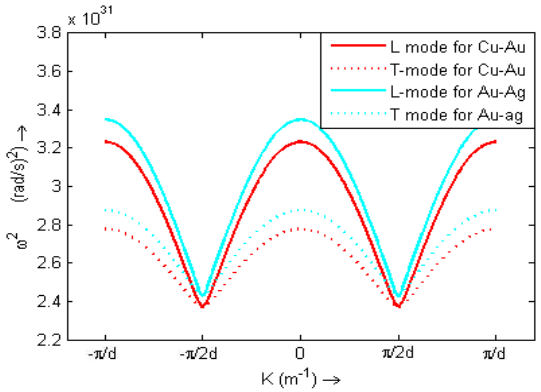

Fig. 3. Dispersion curve for alternated nanospheres of (a) Cu and Au nanospheres, denoted by red color and (b) Au and Ag nanospheres, denoted by cyan colored lines. Here, dotted lines are representing their corresponding T-modes and solid lines are representing corresponding L-modes.

In figure (3), mean value of ω^2 about which its value oscillates with variation of wave vector $\boldsymbol{K}$ is larger for array of alternated Au and Ag nanospheres than that of alternated Cu and Au

nanospheres array. Thus array of alternated of Au and Ag nanospheres array can carry signal of slightly upper energy range than that can be carried by alternated Cu and Au nanospheres array. Dislike of array of nanospheres of only one type of metallic nanospheres, in alternated array of nanospheres of different material, there is variation of ω^2 at T-mode and L-mode in same direction with the change in wave vector $\boldsymbol{K}$. It helps us to generalize that, group velocity variation at T-mode and L-mode occurs along the same direction with the change in signal frequency ω.

(ii) Group Velocity:

We have presented group velocity at L-mode only as there is T-mode group velocity is half of the L-mode.

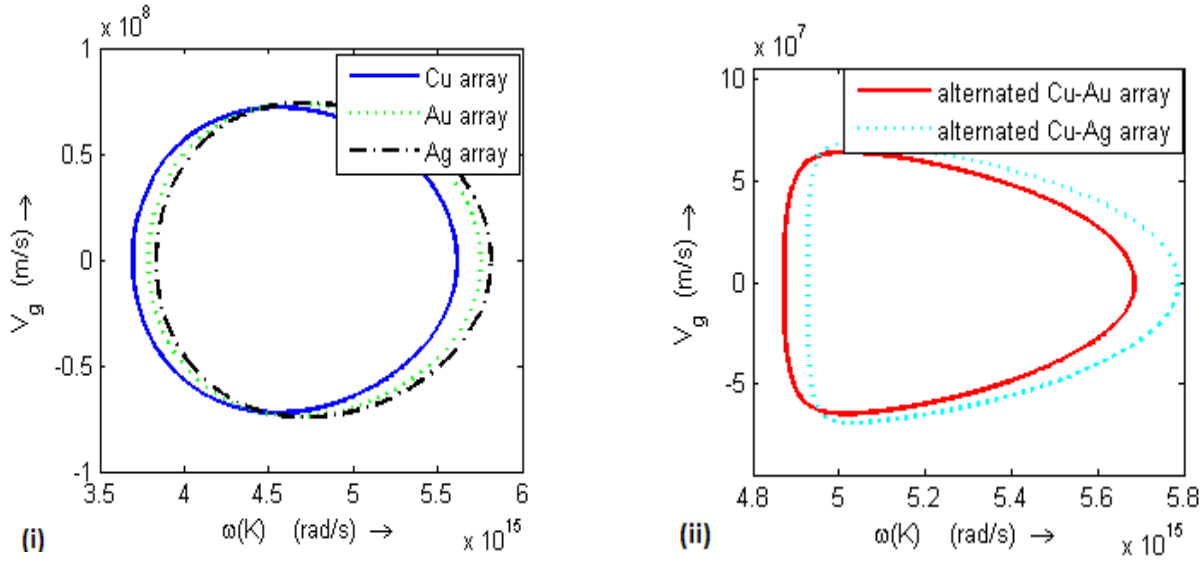

Fig. 4. Group velocity through the array of (i) (a) Cu, denoted by solid line, (b) Au, denoted by dotted line, (c) Ag, denoted by half dotted line and (ii) (a) alternated Cu and Au, denoted by solid line and (b) alternated Au and Ag, denoted by dotted line, nanospheres.

Figure 4 shows that there is gradual increase in group velocity and reaches to peak value, corresponds to the central value of ω, resonance oscillation frequency in case of single material nanospheres chain, about which there is variation in value of ω in dispersion curve, and then again reaches to minimum zero value. There is negative group velocity exist notifies signal propagation and phase velocities are exiting in opposite direction. Velocity grows from negative to positive value as there is change in ω from minimum to mean value of it (resonance oscillation frequency in array of same types of nanospheres). This plot also shows that they have nearly same velocity of signal propagation through array of Cu, array of Au and array of Ag nanopsheres as their respective group velocities are $7.18 \times 10^7 \mathrm{m/s}$, $7.36 \times 10^7 \mathrm{m/s}$ and $7.45 \times 10^7 \mathrm{m/s}$ respectively in L-mode polarization. We also got their respective values in T-mode; $3.53 \times 10^7 \mathrm{m/s}$, $3.62 \times 10^7 \mathrm{m/s}$ and $3.66 \times 10^7 \mathrm{m/s}$ respectively in close agreement with previous carried out work (Brongersma *et al.*, 2000). Furthermore, figure (4) shows that there is decrease in group velocity on using alternated nanospheres array of two different material as V_g at L-modes in array of Cu-Au is $6.40 \times 10^7 \mathrm{m/s}$ and in array of Au-Ag is $6.85 \times 10^7 \mathrm{m/s}$. Frequency within which signal can propagate through the array of alternated nanospheres of Cu and Au starts earlier than that of alternated array of Au and Ag nanosphers. Using the array of alternated nanospheres of Au and Ag, it is possible to transmit slightly larger volume of data as its frequency range, in which signal can propagate, is slightly larger than array of alternated Cu and Au nanospheres.

(iii) Attenuation Coefficient:

Using the equation (8), we can obtain attenuation coefficient for array of single types of nanospshere material as well as two types of nanospheres material.

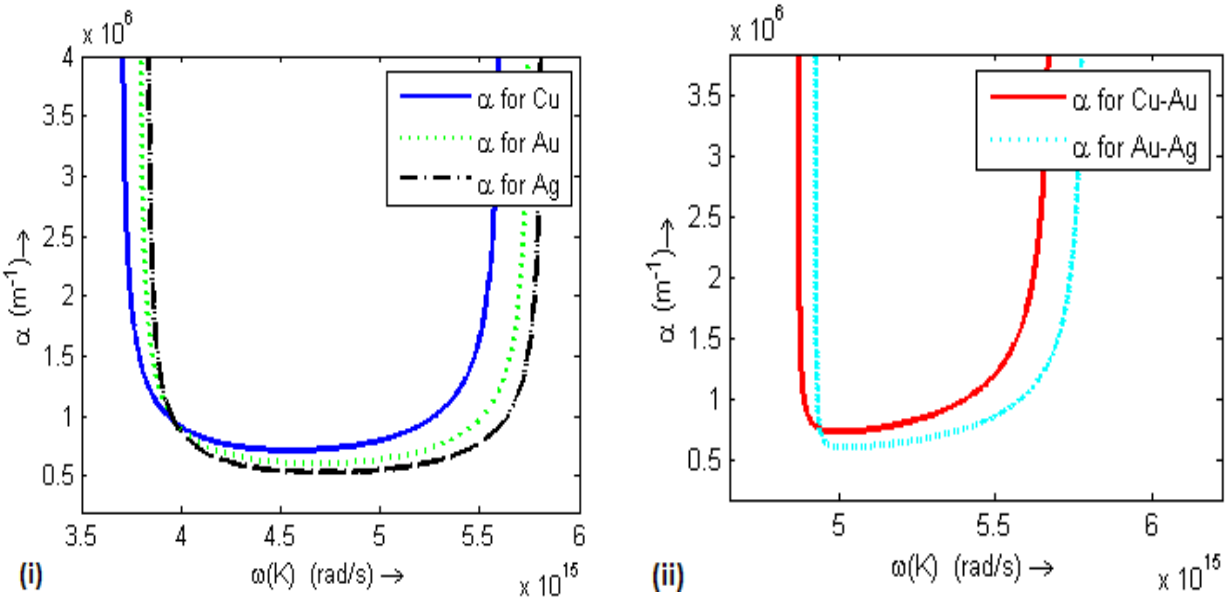

Fig. 5. Attenuation coefficient for the nanospheres array of (i) (a) Cu, denoted by solid line, (b) Au, denoted by dotted line , (c) Ag, denoted by half dotted line and (ii) (a) alternated Cu and Au, denoted by solid line, (b) alternated Au and Ag, denoted by dotted line.

Attenuations are large at the extreme value of the frequencies and almost constant within these values. This phenomenon also appears in the case of alternated nanospheres array as given in figure 5. There is minimum attenuation at the resonance oscillation frequency of individual nanospheres at which there exists maximum group velocity in each chain. Minimum attenuation coefficient for array of nanospheres of Cu is largest, $0.71 \times 10^6 \mathrm{m}^{-1}$, and of Ag is smallest, $0.53 \times 10^6 \mathrm{m}^{-1}$, among arrays of Cu, array of Au and array of Ag nanospheres. For the array of Au nanospheres, it is $0.60 \times 10^6 \mathrm{m}^{-1}$ at L-mode of polarization. These values, attenuation coefficients, get doubled in T-mode.

Minimum attenuation coefficient for array of alternated Cu and Au nanoapheres is $0.73 \times 10^6 \mathrm{m}^{-1}$ and that of alternated nanospheres of Au and Ag is $0.60 \times 10^6 \mathrm{m}^{-1}$. These values corresponds to attenuation 2α, $3.17 \mathrm{dB}/500 \mathrm{nm}$ and $2.60 \mathrm{dB}/500 \mathrm{nm}$. From equation 8, it is clearly seen that for small group velocity, there is very large attenuation. On the other hand we have discussed that at L-mode, signal can pass almost two times faster than at T-mode and hence give rise attenuation nearly twice of corresponding L-mode. So it may not be desirable to discuss T-mode than L-mode.

CONCLUSION

Among the arrays of nanospheres of Cu, Au and Ag, we got that group velocities is highest in the array of Ag nanospheres, $V_{g,3} = 7.45 \times 10^7 \mathrm{m/s}$, and lowest in the array of nanospheres of Cu, $V_{g,1} = 7.18 \times 10^7 \mathrm{m/s}$. Their corresponding attenuation coefficients are smallest, $\alpha_{L,1} = 0.53 \times 10^6 \mathrm{m}^{-1}$ and largest $\alpha_{L,1} = 0.71s \times 10^6 \mathrm{m}^{-1}$ among them. Their band width of array of Ag nanospheres is larger, although by very small value, and hence it is better among these arrays of nanospheres. Among the array of alternated nanaopshers of Cu and Au, and alternated nanosphers array of Au and Ag, large bandwidth, small attenuation, and higher group velocity exist for array of alternated nanospheres of Au and Ag but not on other. Thus among these two alternated nanospheres array, Au and Ag combination is best. In comparison of alternated and non-alternated nanosphers array, array of Ag nanospheres array is best. Coupling between two different metallic nanospheres is found to be weaker than that exist between same types of metallic nansopheres. Further study can be carried out in the system of alternated nanosphers hosted in some other metallic substrate can help to increase coupling phenomena (Chen *et al.,* 2011*)*. To obtain relatively higher

speed of signal propagation and lower attenuation further research can be carried out by changing the shape of nanostructures used in constructing array (Maier *et al.*, 2002*)* and host material.

REFERENCE

Atwater, H. A. (2007). The promise of plasmonics. *Scientific America*, **296:** 56.

Barnes, W. L., Dereux, A., and Ebbesen, T. W. (2003). Surface plasmon subwavelength optics. *Nature*, **424**: 824.

Brongersma, M. L.; Hartman, J. W., and Atwater, H. A. (2000). Electromagnetic energy transfer and switching in nanoparticle chain arrays below the diffraction limit. *Phys. Rev. B.*, **62**: R16356.

Brongersma, M. L.; Zia, R., and Schuller, J. A. (2007). Plasmonics–the missing link between nanoelectronics and microphotonics. *Appl. Phys. A.,* **89**: 221.

Chen, K. N.; Liu, H.; Wang, S. M.; Zheng, Y. J.; Zhu, C.; Wang, Y., and Zhu, S. N. (2011). Coherent magnetic plasmon modes in a contacting gold nano-sphere chain on a gold Slab. *Opt. Exp.*, **19**: 23782.

Jackson, J. D. (2013). Classical Electrodynamics, 3rd edition, Wiley, Delhi.

Johnson, P. B., and Christy, R. W. (1972). Optical constants of the noble metals. *Phys. Rrev. B.*, **6**: 4370.

Kittle, C. (2004). Introduction to Solid State Physics, 7th edition, Wiley, Delhi.

Kreibig, U., and Zacharias, P. (1970). Surface plasma resonances in small spherical silver and gold particles. *Zeitschrift für Physik*, **231**: 128.

Maier, S. A.; Kik, P. G.; Atwater, H. A.; Meltzer, S.; Requicha, A. A.; and Koel, B. E. (2002). Observation of coupled plasmon-polariton modes of Plasmon waveguides for electromagnetic energy transport below the diffraction limit. *International Symposium on Optical Science and Technology*, pp. 71-81. International Society for Optics and Photonics.

Ozbay, E. (2006). Plasmonics: merging photonics and electronics at nanoscale dimensions. *Science*, **311**: 189.

Quinten, M.; Leitner. A.; Krenn, J. R., and Aussenegg, F. R. (1998). Electromagnetic energy transport via linear chains of silver nanoparticles. *Opt. Lett.*, **23**: 1331.

Ritchie, R. H. (1957). Plasma losses by fast electrons in thin films. *Phys. Rev.*, **106**: 874.