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Research Article

# Reflectivity and Transmissivity of Radiofrequency Photons from One-Dimensional Plasma

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***Abstract***— The transmissivity and reflectivity of photons incident with low energies in the radiofrequency region and interacting with a one-dimensional, two-component hot plasma have been calculated across a broad range of temperatures, specifically from T=100K to 1200K. The system under consideration is modeled as weakly coupled quantum plasma in one dimension. The theoretical analysis reveals a clear dependence of the transmissivity and reflectivity percentage on temperature when photons reflect off and transmit the surface of the plasma. In addition, the results obtained by varying the number densities and also mass of the mobile component carrying positive charge have also been reported and have shown significant influence on the observed variations. A comparison of the corresponding findings across different temperatures for a one-component, one-dimensional plasma has also been made.

***Keywords*** — One-Dimensional Plasma; Reflectivity; Transmission; Nano-structures; Radio Waves; Radiofrequency Photons; Complex Refractive Index

## 1. Introduction

Due to the development of sophisticated fabrication techniques [1–5] one-dimensional (1D) plasma systems are recognized with growing importance in the fields of material science and plasma technology. Recent advances in fabrication techniques, such as nanofabrication and micro-manufacturing, have made it possible to create and manipulate these systems with unprecedented precision. These quasi-uni-dimensional systems [6–8] exhibit unique physical characteristics [9–11], which render them highly significant for practical applications. The characteristics of such degenerate systems have been the subject of numerous theoretical investigations [12–18]. This communication presents a theoretical analysis aimed at examining at two-component one-dimensional quantum plasma across a finite temperature range. The degree of coupling in this plasma, characterized by its single-dimensionality and the movement of both charged components, is quantified using the coupling $\Gamma(=ne^2/k_BT)$ which in this study remains $\Gamma \leq 1$, indicating that the system is weakly coupled. Moreover, the system is essentially a slightly to moderately quantum system for the whole temperature range of $100k \leq T \leq 1200$ K as $2r_s < \lambda_{th}$, when, $\lambda_{th}$ is the de-Broglie wavelength and $2r_s$ is the inter-particle separation. Photon reflectivity and transmittance from such weakly linked hot plasma have been calculated in the current study.

This Paper is organized in five sections. Section one lays an introduction to the research work of current study and section 2 describes the previous work carried related to one dimensional plasma. In section 3, theoretical layout and mathematical formalism is described. Section 4 contains results and figures for the performed computations along with related discussions. Section 5 narrates drawn conclusions and future scope of the work.

## 2. Related Work

A plasma is defined as an assembly of charged particles in proportion to remain electrically neutral and is categorized as the fourth state of matter along with other states viz. solid, liquid and gases. These systems can be realized in nature in intergalactic space, in stars or in intra-cluster mediums. These can be generated in laboratories via various methods including heating [19] of any neutral gas or by applying electromagnetic field on charged particles or by fabrication of semiconductors. A plasma can be realized with different dimensionalities viz. three dimensional (3D) or two dimensional (2D) or they can be a one dimensional (1D) plasma systems, depending upon the degrees of freedom, that the components of the system have. One –dimensional plasma systems are physically unrealizable and such a system can be present in inter-galactic space. Quantum wires obtained on fabrication of semiconductor-metaloxide-semiconductor on silicon surfaces can yield such uni-dimensional nanostructures [6-11]. Theoretical investigation of three dimensional [20-22] and two dimensional plasmas [23-24] with one and two mobile components. In recent studies, theoretical investigation of one dimensional plasma for quantization of its equilibrium dynamics and pair correlation functions [25-27] is performed. In present study, optical properties, reflectivity and transmissivity of one dimensional two component plasma is reported.

## 3. Theory/Mathematical Formalism

Radio waves comprising low energy photons (E-$10^8$ eV) when incident normally upon any material surface encounter a complex refractive index which can be expressed as

$$\eta_{\pm}(\kappa,\omega) = \eta_{1\pm}(\kappa,\omega) + \iota\,\eta_{2\pm}(\kappa,\omega) \tag{1}$$

Where, $\eta_1$ is the real part of the total refractive index & $\eta_2$ is the corresponding imaginary part of the refractive index.

The reflectivity of incident photons is connected to this wave-vector, $\kappa$, and frequency, $\omega$, dependent refractive index and is given through Fresnel's [19, 20] expression as follows:

$$R = \frac{(\eta_1 - 1)^2 + {\eta_2}^2}{(\eta_1 + 1)^2 + {\eta_2}^2} \tag{2}$$

The Transmissivity of photons, in the absence of absorption attenuation, can be given as follows:

$$T = 1 - \frac{(\eta_1 - 1)^2 + {\eta_2}^2}{(\eta_1 + 1)^2 + {\eta_2}^2} \tag{3}$$

The refractive index is connected to the dielectric function The dielectric function is a complex function comprising real and imaginary parts which can be individually related to the real and imaginary parts of refractive index as follows:

$$\eta_{1\pm}(\kappa,\omega) = \left[\frac{\left[\varepsilon_{1\pm}^2(\kappa,\omega) + \varepsilon_{2\pm}^2(\kappa,\omega)\right]^{1/2} + \varepsilon_{1\pm}(\kappa,\omega)}{2}\right]^{1/2}$$

$$\eta_{2\pm}(\kappa,\omega) = \left[\frac{\left[\varepsilon_{1\pm}^2(\kappa,\omega) + \varepsilon_{2\pm}^2(\kappa,\omega)\right]^{1/2} - \varepsilon_{1\pm}(\kappa,\omega)}{2}\right]^{1/2} \tag{4}$$

Here, $\varepsilon_{1\pm}(\kappa,\omega)$ is the real part of the complex dielectric function and $\varepsilon_{2\pm}(\kappa,\omega)$ is the imaginary part of the total dielectric function.

The expressions for $\varepsilon_{1\pm}(\kappa,\omega)$ & $\varepsilon_{2\pm}(\kappa,\omega)$ for one dimensional & two component plasma are given as follows [27-29]:

$$\varepsilon_{\pm}(\kappa,\omega) = \varepsilon_{1\pm}(\kappa,\omega) + i\varepsilon_{2\pm}(\kappa,\omega)$$

$$\varepsilon_{1\pm}(\kappa,\omega) = 1 + \sqrt{2}\,\frac{{\omega_{p_\pm}}^2}{\kappa^2 {v_{th\pm}}^2}\,\frac{m_\pm v_{th\pm}}{h\kappa}\left[\begin{aligned}&\exp\left[-\left(\frac{\omega}{\sqrt{2}\,\kappa v_{th\pm}} + \frac{h\kappa}{2\sqrt{2}\,m_\pm v_{th\pm}}\right)^2\right]\left(\frac{\omega}{\sqrt{2}\,\kappa v_{th\pm}} + \frac{h\kappa}{2\sqrt{2}\,m_\pm v_{th\pm}}\right)\\ &\times\left\{1 + \frac{1}{3}\left(\frac{\omega}{\sqrt{2}\,\kappa v_{th\pm}} + \frac{h\kappa}{2\sqrt{2}\,m_\pm v_{th\pm}}\right)^2 + \ldots\ldots\right\} - \exp\left[-\left(\frac{\omega}{\sqrt{2}\,\kappa v_{th\pm}} - \frac{h\kappa}{2\sqrt{2}\,m_\pm v_{th\pm}}\right)^2\right]\\ &\left(\frac{\omega}{\sqrt{2}\,\kappa v_{th\pm}} - \frac{h\kappa}{2\sqrt{2}\,m_\pm v_{th\pm}}\right)\times\left\{1 + \frac{1}{3}\left(\frac{\omega}{\sqrt{2}\,\kappa v_{th\pm}} - \frac{h\kappa}{2\sqrt{2}\,m_\pm v_{th\pm}}\right)^2 + \ldots\ldots\right\}\end{aligned}\right] \tag{5}$$

$$\varepsilon_{2\pm}(\kappa,\omega) = \sqrt{\frac{\pi}{2}}\,\frac{{\omega_{p\pm}}^2}{\kappa^2 {v_{th\pm}}^2}\,\frac{m_\pm v_{th\pm}}{h\kappa}\left[e^{-\left(\frac{\omega}{\sqrt{2}\,\kappa v_{th\pm}} - \frac{h\kappa}{2\sqrt{2}\,m_\pm v_{th\pm}}\right)^2} - e^{-\left(\frac{\omega}{\sqrt{2}\,\kappa v_{th\pm}} + \frac{h\kappa}{2\sqrt{2}\,m_\pm v_{th\pm}}\right)^2}\right] \tag{6}$$

Here, $v_{th+} = \sqrt{k_B T / m}$ is the thermal velocity of the positive component and $v_{th-} = \sqrt{k_B T / m_-}$ is the thermal velocity of the negatively charged mobile component of the plasma and plasma and $\omega_{p\pm} = \sqrt{\pi n_\pm e^2 \kappa^2 (\ln \kappa) / m_\pm}$ , $\omega_{p\pm}$ [30] are the 1D plasma frequencies for positive and negative components.

 

## 4. Results and Discussion

The complex dielectric function of the plasma under discussion has been calculated using expressions (5) and (6). This function is then utilized in expressions (1) and (4) to assess the refractive index and, consequently, the reflectivity from expression (2) and the transmissivity from expression (3), of low energy photons ($E \approx 10^{-8}$ eV). In Figure 1, the computed results for reflectivity have been plotted for a wide range of temperatures, as the variation of R% with the incident photon energy: T=100K with (— — —), T=200K with (— ·· —), T=500K with (− · − · −), T=1000K with (…….), and T=1200K with (———) curves. Assuming that

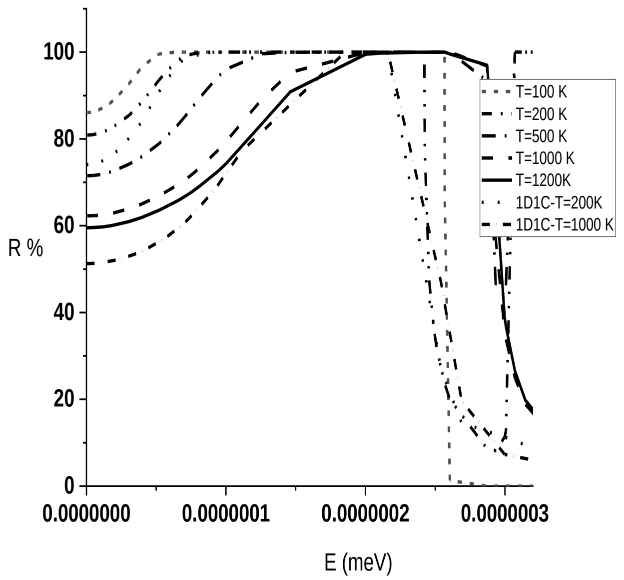


**FIGURE 1**. REFLECTIVITY $R$ %, versus photon energy, E, for T= 100K with (— — —), T=200 k (— ·· —), T=500 K (− · − · −), T=1000 K (…….) and T=1200 K (———) for $\kappa$ = 5.0 cm$^{-1}$, $n_{\pm}$ = 4.2x10$^{6}$ cm$^{-1}$ and $m_+=2.5*m_e$. One component plasma for T=200 K (− − −) and T=1000K (— · —).

the mass of the positive component is $m_+=2.5*m_e$ (i.e. two and half times the mass of the negatively charged mobile component), the calculations have been done for $\kappa$ =5.0 cm$^{-1}$ and number density $n_{\pm}$ = 4.2x10$^{6}$ cm$^{-1}$. The value of the is taken to be 0.02 [31]. As shown in Fig.1, as the temperature rises from T=100 K to T=1200 K, the value of R% at $E \approx 0$ declines from R%=85 at T=100K to R%=60 at T=1200K. At T=100 K, R% experiences a slight increase with the rise in energy, reaching, $E \approx 5x10^{-8}$ eV, at which point it achieves a reflectivity value of 100%. This high reflectivity persists for energy levels from $E \approx 5x10^{-8}$ eV to 2.3x10$^{-7}$ eV before plummeting to almost zero. This behaviour contrasts with the patterns observed at T=1000K and T=1200K, where R% gradually rises up to $E \approx 2.25x10^{-7}$ eV, reaches 100% reflectivity, and then begins to decline rapidly.

At $E \approx$ 2.6-2.7 x10$^{-8}$ eV, R% remains 15-20% and almost saturates thereafter. On the intermediate temperatures, i.e. at T= 200K & 500K. The trend of variation is different as compared to lower and also higher temperatures. For T=200K& 500K, the R% increases and acquires 100% value for $E \approx 7.0x10^{-8}$ eV, & 12.0x10$^{-8}$ eV respectively and stays constant to 100% value up to energy $E \approx 2.6x10^{-7}$ eV & 2.9x10$^{-7}$ eV respectively. Thereafter, the R% decreases to a minimum, i.e. 7% and 40% for T= 200K & 500K respectively, takes a turn and increases thereafter. For the entire temperature range R%, acquires a constant value for E>3.0x10$^{-7}$ eV. For comparison sake, corresponding results for one component plasma at T=200K & 1000K have also been plotted with **(− − −)** & **(— · —)** curves respectively. This is evident from the figure that trend of variation in one component plasma is minutely different as compared to two-component plasma except at $E \approx 0$ where R% for one component plasma is markedly lower as compared to the two-component plasma, which reflects the role of mobility of the second component on the reflectivity of photons.

In Figure 2, the transmissivity $T$ computed from expression (3) has been shown as the variation of *T*% with the incident photon energy for a wide range of temperatures: T=100K with (— —), T=200K with (— ·· —), T=500K with (− · − · −), T=1000K with (…….), and T=1200K with (———) curves, corresponding to similar mass of the positive component, wave vector and number density considerations of figure1. In contrast to reflectivity, the transmissivity at $E \approx 0$ is higher for

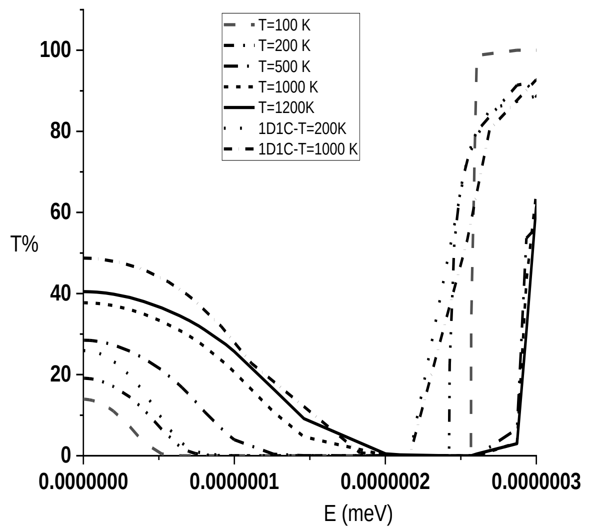


**FIGURE 2.** Variation of transmissivity, $T$ %, with photon energy, E, for T= 100K with (— — —), T=200 k (— ·· —), T=500 K (− · − · −), T=1000 K (…….) and T=1200 K (———) for $\kappa$ = 5.0 cm$^{-1}$, $n_{\pm}$ = 4.2x10$^{6}$ cm$^{-1}$ and $m_+=2.5*m_e$. One component plasma for T=200 K (− − −) and T=1000K (— · —).

higher temperatures, is nearly 40% at T=1200K and ~ 15% at T=100K. At all temperatures from T=100 K to T=1200 K, the percentage of transmission decreases with an increase in

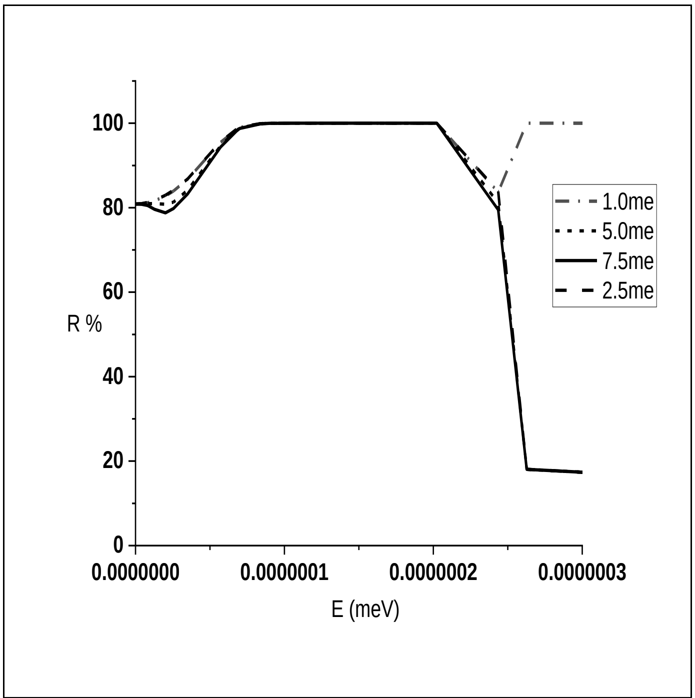


**FIGURE 3.** Reflectivity $R$ %, versus photon energy, E, for T=200 K for two component plasma for $\kappa$ = 5.0 cm$^{-1}$, $n_{\pm}$ = 4.2x10$^{6}$ cm$^{-1}$ with different masses of the positive component, $m_{+}$ :(— · —)$1m_e$ ; (— — —)*2.5*m$_e$*; (………)*5.0*m$_e$*; (————)*7.5*m$_e$.*

photon energy, attains zero value and increases with a further increase in the energy of photons to attain a maximum value. However, the zero transmittance zone is longer for the lowest considered temperature of T=100 K where *T*% remains zero for energy levels ranging from E$\approx$5x10$^{-8}$ eV to 2.3x10$^{-7}$ eV whereas for higher temperatures of T=1000K and T=1200K, T% gradually decreases to 0% at E$\approx$2.25x10$^{-7}$ eV and then rises rapidly.

In Figure 3, variations of reflectivity of photons, R% with energy E (eV) have been plotted when mass of positive component is varied, for $m_+$=1.0*m$_e$ with **(— · —)**, $m_+$=2.5*m$_e$ with **(— — —),** $m_+$=5.0*m$_e$ with **(…….)** and $m_+$=7.5*m$_e$ with (————) curves. Temperature and number density are considered to be 200K and 4.2x10$^{6}$ cm$^{-1}$ respectively whereas, wave-vector is taken to be $\kappa$=5.0 cm$^{-1}$. Fig.3 clearly indicates that the patterns of the variation in percentage reflectivity with energy of photons, is similar for different masses of the positive component except at $m_+$=1.0*m$_e$ where R% remains (=100%) constant up to E $\approx$ 2.25x10$^{-7}$ eV, decreases slightly up to 80% and turns100% again & thereafter remains constant. For all other cases for different masses, the trend of variation is almost the same, R% increases gradually up to R%=100 for E$\approx$5.0x10$^{-8}$ eV, remains constant at 100% for an energy range E>5.0x10$^{-8}$ eV to E$\approx$2.25x10$^{-7}$ eV, then decreases to 18%, increases slightly(=20%) and remains constant then. This can be observed from the variation that increase in the mass of the positive component has resulted in the decrease in the reflectance of photons.

Variation of R% with energy E for different number densities have been plotted in Figure 4. Temperature and wave-vector are taken to be 200K and $\kappa$=5.0 cm$^{-1}$ respectively. The mass of the positive ion is taken to be $m_+$=2.5*m$_e$. Variations of R% versus E have been plotted for number densities, $n_{\pm}$ = 4.2x10$^{6}$ cm$^{-1}$ with **(— · —)** curve, $n_{\pm}$ = 5.6x10$^{6}$ cm$^{-1}$ with **(— — —)** curve and $n_{\pm}$ = 0.56x10$^{6}$ cm$^{-1}$ with (————) curve, hence density dependence for an order has been investigated.

It can be observed from the figure that with an increase in number density reflectivity R% remains 100 for a longer energy range, at $n_{\pm}$ = 0.56x10$^{6}$ cm$^{-1}$ , is for E$\approx$6.25-8.0x10$^{-8}$ eV, at $n_{\pm}$ = 4.2x10$^{6}$ cm$^{-1}$ , is for E$\approx$5.0x10$^{-8}$ to 2.1x10$^{-7}$ eV and at $n_{\pm}$ = 5.6x10$^{6}$ cm$^{-1}$ , R=100% for E $\approx$ 5.0x10$^{-8}$ to 2.8x10$^{-7}$ eV. This may indicate that an increase in the number density results in more photons being reflected from the one dimensional plasma. The trend for variation for all densities, however, remains the same.

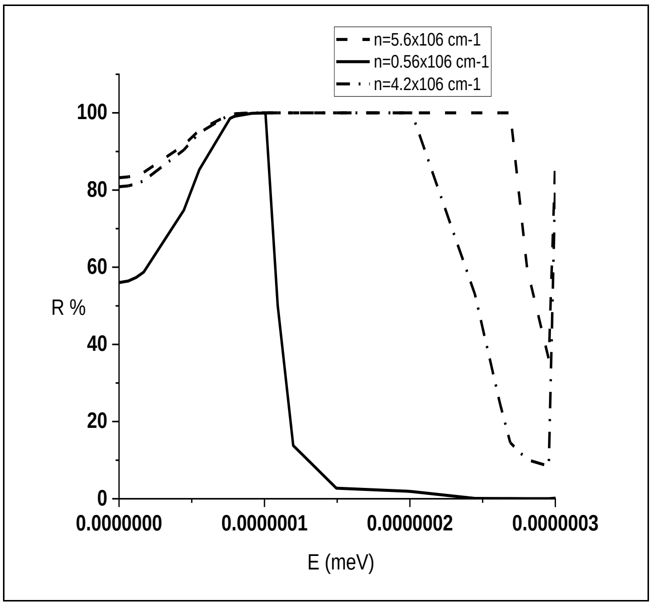


**Figure 4. R**eflectivity, $R$ %, versus photon energy, E, for T=200 K for plasma with two mobile components plasma for $\kappa$ = 5.0 cm$^{-1}$ and *$m_+$=2.5*m$_e$* when number densities, are varied $n_{\pm}$ = 4.2x10$^{6}$ cm$^{-1}$ (— · —); $n_{\pm}$ = 5.6x10$^{6}$ cm$^{-1}$(— — —)**;** $n_{\pm}$ = 0.56x10$^{6}$ cm$^{-1}$ **(————).**

In Figure 5, results for the transmissivity as computed from the expression (3) and those correspond to considerations of Figures 3 have been shown in Figure 5(a) and those to Figure 4 have been shown in Figure 5(b), to visualize the mass and density dependence of the transmission percentage of the incident photons.

 

In both cases illustrated through Fig 5(a) and Fig 5(b), the patterns of variations have been observed in contrast to those of reflectivity percentages for all mass and density variations. While reflectivity percentage with different masses of positive component increases with increase in the photon energy, the transmissivity of 1D plasma decreases with E, and attains a zero transmission zone in the energy range of 5.0-22.50x10$^{-8}$ eV. However, the null transmittance is increased with the increase in the mass of the positive component and is the largest, though minutely, when $m_+$=7.5*$m_e$. The comparisons of transmittance and reflectance percentages, as observed in figures 3 and Figure 5(a) respectively, have indicated that the heavier positive components of one dimensional plasma, when they are mobile, tend to transmit from the plasma surface while the lighter mobile positive component are having tendency to reflect from the plasma surface.

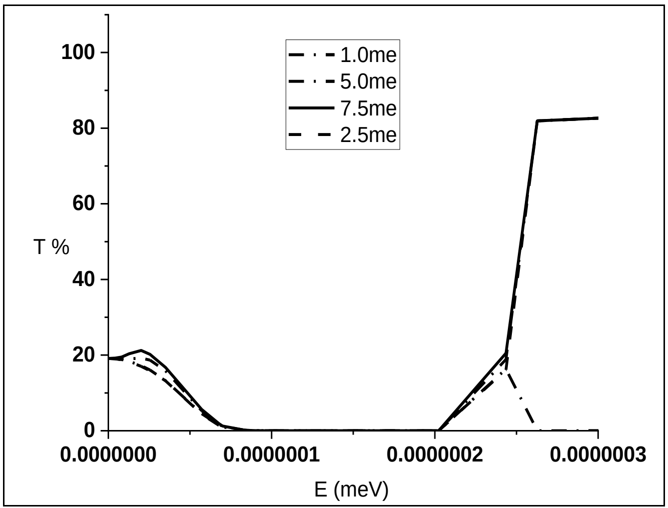


**FIGURE 5(a)**: Transmissivity, T %, versus photon energy, E, for T=200 K for two component plasma for $\kappa$ = 5.0 cm$^{-1}$, $n_\pm$ = 4.2x10$^6$ cm$^{-1}$ when mass of the positive component is varied, $m_+$ :(— · —)$1m_e$ ; (— — —)*2.5*$m_e$*; (………)*5.0*$m_e$*; (————)*7.5*$m_e$.*

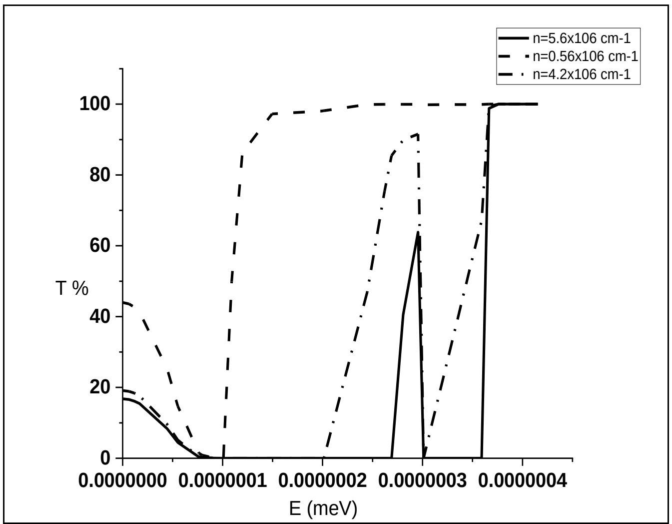


**FIGURE 5(b)**: Transmissivity, T %, versus photon energy, E, for T=200 K for plasma with two mobile components for $\kappa$ = 5.0 cm$^{-1}$ and $m_+$=*2.5*$m_e$* with different number densities, $n_\pm$ = 4.2x10$^6$ cm$^{-1}$ (— · —); $n_\pm$ = 5.6x10$^6$ cm$^{-1}$(— — —); $n_\pm$ = 0.56x10$^6$ cm$^{-1}$ (————).

Figure 5(b), displays the variation of transmissivity percentages of incident photons from the 1D plasma: number densities, $n_\pm$ = 4.2x10$^6$ cm$^{-1}$ with **(— · —)** curve, $n_\pm$ = 5.6x10$^6$ cm$^{-1}$ with **(— — —)** curve and $n_\pm$ = 0.56x10$^6$ cm$^{-1}$ with (————) curve, This can be clearly observed from the figure that the transmittance at E-> zero increases with decrease in the energy, is the least for a plasma with number density $n_\pm$ = 0.56x10$^6$ cm$^{-1}$ and is the greatest when number density of plasma constituents is $n_\pm$ = 5.6x10$^6$ cm$^{-1}$. The trend for variation of transmittance has also been observed to be different for different number densities. Though, T% decreases to zero % for all the three considered densities, for the 1D plasma system rare among the three, the transmittance has gained to 100 % rapidly after that and stays to 100% zone in a huge energy range of 6x10$^8$ eV to nearly 8x10$^8$ eV. On the other hand, the for the other two denser plasma systems, with the photons exhibit zero transmissivity for a longer energy span, nearly 6.0x10$^8$ to 2.0 x10$^7$ eV for and approximately 6.0x10$^8$ to 2.5x10$^7$ eV for. Hence, the zero transmittance range for incident photon energy increases with increase in the number density of plasma systems.

## 5. Conclusion and Future Scope

From the study, one may conclude that reflectance as well as transmittance of photons from a two-component one-dimensional plasma is prominently dependent upon temperature and number densities of electrons and positive ions. Reflectivity and transmissivity percentage are also observed to be dependent upon the masses of the mobile components which are positively charged. As the study is confined to low-energy photons specified in the radiofrequency region, the results obtained may relate to the optimized performance of various astronomical applications including interstellar space and other various applications of radio wave spectroscopy. The involved dependence of the quantum system on its physical environment may further be used in the approximation of distinct properties of various 1-dimensional nanostructures which may lead to their cost-effective fabrication with desirable output characteristics.

**Data Availability**
Data is available on request from the corresponding author.

**Conflict of Interest**
None

**Funding Source**
None

**Authors' Contributions**

1) Grima Dhingra: conceptualization, computations and calculations, Writing and Editing of the manuscript.

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