DIFFUSIVE RADIATION IN INFRARED REGION*

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Abstract

We consider generation of diffusive radiation by a charged particle passing through a random stack of plates in the infrared region. Diffusive radiation originates due to multiple scattering of pseudophotons on the plates. To enhance the radiation intensity one needs to make the scattering more effective. For this goal we suggest to use materials with negative dielectric constant.

INTRODUCTION

There is substantial interest in the development of infrared sources for applications to biophysics, nanostructures, material science and etc. Three category of sources: gas lasers, solid state devices and electron beam driven devices are available now. Gas lasers can produce different lines but are inherently not tunable. Solid state devices are continuously tunable however operate at low temperatures [1, 2]. The lack of electron beam driven devices is that usually they require large facilities [3, 4], see however [5]. A charged particle passing through a stack of plates placed in a homogeneous medium is known to be radiating electromagnetic waves. Radiation originates because of the scattering of electromagnetic field on the plates. Considering this problem theoretically it was shown [6, 7] that the spectral angular radiation intensity can be represented as a sum of two contributions

$$I = I_0 + I_D \tag{1}$$

where

$$I_0(\theta,\omega) = \frac{e^2}{2c}\frac{B(|k_0 - kcos\theta|)\sin^2\theta}{[\gamma^{-2}+\sin^2\theta k^2/k_0^2]^2}\frac{\omega^2}{k_0^4c^2} \tag{2}$$

and diffusive contribution is determined as

$$I_D(\theta,\omega) = \frac{5e^2\gamma^2}{2\varepsilon c}\frac{l_{in}^2(\omega)}{l^2(\omega)}\sin^2\theta\exp\left[-\left(\frac{l}{l_{in}}\right)^{1/2}\frac{1}{|\cos\theta|}\right] \tag{3}$$

Here θ is the observation angle, $k_0 = \omega/v$, v is the particle velocity, $k = \omega\sqrt{\varepsilon}/c$, B is the correlation function of random dielectric constant field created by randomly displaced plates. On assumption that parallel plates with equal probability can be at any point of z axis correlation function determined as follows

$$B(q_z) = \frac{4(b-\varepsilon)^2)n\sin^2 q_z a/2}{q_z^2}\frac{\omega^4}{c^4}. \tag{4}$$

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where $n = N/L_z$ is concentration of plates in the system, a is their thickness, b is their dielectric constant and ε is the average dielectric constant of the system. In Eq.(3), l and l_{in} are average elastic and inelastic mean free paths of photon in the medium. Inelastic mean free path is mainly associated with the absorption of electromagnetic field in the medium. Elastic mean free path is associated with photon refraction on plates. It depends on the falling angle on plates. In the case when photon falls normally elastic mean free path is determined as follows

$$l = \frac{4k^2}{B(0)+B(2k)} \tag{5}$$

Note that just this quantity enters into spectral angular intensity Eq.(3). Eqs.(3,5) are correct in the weak scattering limit $\lambda/l \ll 1$ and for observation angles $\theta = \pi/2-\delta, \delta \gg (1/kl)^{1/3}$. Last restriction over angles appears because when $\theta = \pi/2$ pseudophotons are moving parallel to plates and no any refraction happens and the condition of weak scattering is failed. When the conditions of multiple scattering of electromagnetic field are fulfilled the diffusive contribution to the radiation intensity Eq.(3) is the main one because $I_D/I_0 \sim l_{in}/l$. As it is seen from Eq.(3) the radiation intensity is determined by elastic and inelastic mean free paths of photon in the medium. In the next section we will investigate mean paths in the infrared region in detail. It follows from Eq.(4) that when $ka \gg 1$, $B(2k)/B(0) \sim 1/(ka)^2 \ll 1$. Therefore in both cases $ka \gg 1$ and $ka \ll 1$ the photon mean free path has the form

$$l \sim \frac{k^2}{B(0)} \tag{6}$$

where $B(0) = k^4(b-\varepsilon)^2na^2/\varepsilon^2$. Substituting this expression into Eq.(6) and taking into account that $k = \omega\sqrt{\varepsilon}/c$, we have

$$l \sim \frac{\varepsilon}{\frac{\omega^2}{c^2}(b-\varepsilon)^2na^2} \tag{7}$$

Substituting Eq.(7) into Eq.(3) one can be confirmed that $I_D \sim \varepsilon^{-3}(\omega)$. Therefore the radiation intensity enhances in the wavelength region where $\varepsilon(\omega) \ll 1$. Remind that ε is the average dielectric constant of the system which for a layered stack has the form:

$$\varepsilon(\omega) = nab(\omega) + (1-na)\varepsilon_0(\omega)avcon) \tag{8}$$

Here ε_0 is the dielectric constant of a homogeneous medium into which plates with dielectric constant $b(\omega)$ and thickness a are randomly embedded. If a homogeneous medium is vacuum then $\varepsilon_0 \equiv 1$. Choosing for plates materials with $b(\omega) < 0$ one can make the average dielectric constant of the system quite small $\varepsilon \ll 1$. Correspondingly, the photon elastic mean free path will be small and the radiation intensity will be large in a such system. For dielectric constant of a simple metal one can use plasma formula $b(\omega) = 1 - \omega_p^2/\omega^2$, where ω_p is the plasma frequency . Therefore for frequencies $\omega < \omega_p$ the dielectric constant will be negative. Plasma frequency for simple metals is of order $20 - 100eV$ therefore the region where dielectric constant is negative lies from extreme ultraviolet to far infrared. For realization of diffusive mechanism of radiation absorption should be weak. This means that the plates should be very thin less than the depth of skin layer of metals in order to the photons can penetrate through them. In the optical region the skin layer of metals is of order of several hundred angstroms. Therefore making a stack with such thin plates and vacuum within them will be very difficult. In the other hand such a situation can be realized when a charged particle slides over a rough metallic surface. In this case the randomly located hills and valleys will serve as plates and vacuum spacings between them, respectively. Such an experiment was carried out many years ago[8]. An enhancement of radiation intensity compared to normal falling case was observed. Estimations of hill and valley sizes show that conditions for generation of diffusive radiation exist in the experiment [8].Unpolarized character and frequency dependence of observed radiation are well described by diffusive radiation intensity formulae [6]. Hence we think that in the experiments [8] the diffusive radiation was observed. The energy of charged particle should be enough for penetration of the system with inessential lost of its energy. A few MeV electron energies are enough for penetration mm thickness of material. Let us estimate the number of emitted infrared photons for a stack of 50 plates with average thickness of $20\mu m$ and average distance between plates $200\mu m$.

In alkali halide crystals, in semiconductors like $GaP, InSb$, and etc. the dielectric constant is negative in the region between the frequencies of transversal and longitudinal optical phonons, see [9]. For example, for the compound MgO in the frequency region $550 - 650cm^{-1}$ the real part of dielectric constant take values in the interval $-6, -2$ and the imaginary part in the interval $0.6 - 0.2$. The above mentioned interval lies in the far infrared region. It follows from Eq.(7) that in case $2\pi a \leq \lambda$ the minimum of mean free path and therefore the maximum of radiation intensity is achieved for average plate thickness $a \sim \lambda/2\pi$. For the above mentioned frequencies this is about $20\mu m$. Choosing such values for average thickness of plates one can reach the localization limit $\lambda/2\pi$ [10, 11] for photon mean free path l . Note that the Eq.(3)is correct in the weak scattering diffusive regime $l \gg \lambda/2\pi$. Remind that an electromagnetic wave is localized provided that $l \leq \lambda/2\pi$. The above mentioned value for plate thickness $20\mu m$ is feasible and one can make a stack of such plates. Such a system could serve as s good source for far infrared radiation. One needs l_{in} in order to estimate the number of emitted using Eq.(3). The inelastic mean free path of the photon in a random stack can be estimated as follows:

$$l_{in} \sim \frac{\lambda\sqrt{\varepsilon}}{\pi f Imb(\omega)} \tag{9}$$

where f is the fraction of plates in the system. Taking $f \sim 0.1$, $Imb \sim 0.4$ and $\varepsilon \sim 0.5$, one gets $l_{in} \sim 557\mu m$. Using Eq.(3) one can estimate the integrated over all angles number of emitted photons in the interval $\Delta\omega$ as

$$N_{ph} \sim \frac{20\pi}{3}\alpha \left(\frac{l_{in}}{l}\right)^2 \frac{\Delta\omega}{\omega} \tag{10}$$

where α is the fine structure constant. Because $l \ll l_{in}$ the exponential decaying factor in Eq.(3) plays important role only for very large angles $\theta \approx \pi/2$.Therefore we ignored it when estimating the total number of emitted photons. Substituting $l_{in} \sim 562\mu m, l \sim \lambda/2\pi \sim 17\mu m$ into Eq.(10)and taking $\Delta\omega \sim \omega$ one has approximately $N_{ph} \sim 167$ infrared photons per one electron. This implies that using commercially available $5 - 6MeV$, $1mA$ linear accelerator a total output power of $2.4mW(10^{18}photon/s)$ can be produced.

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