ELECTROMAGNETIC WAVE SCATTERING IN A SEMI-BOUNDED PLASMA-MOLECULAR MEDIUM

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The phenomenon of noncoherent wave reflection associated with scattering by electromagnetic fluctuations in a semibounded plasma–molecular medium is studied. The differential reflection coefficients are computed for scattering by collective bulk and surface fluctuations.

The purpose of this paper is to investigate noncoherent electromagnetic wave reflection processes from the interfacial boundary of a partially ionized plasma due to scattering by fields in spontaneous fluctuations penetrating the plasma.

Scattered Radiation Sources. We consider a semibounded ($Z > 0$) partially ionized plasma containing charged and neutral particles. According to [1] we will describe the molecular subsystem as an ensemble of pairs of classical electrons and ions connected by the oscillator potential $V(r) = m_e\omega_r^2 r^2/2$ (m_e is the mass of the electron and ω is the transition frequency).

Let a high-frequency electromagnetic wave

$$E^{inc}(R,\ t) = E^{inc}\cos(\tilde{\kappa}_0 R - \omega_0 t),$$
$$\tilde{\kappa}_0 = \left(\omega_0\sqrt{\tilde{\varepsilon}(\omega_0)}\,\sin\vartheta_0/c,\ 0,\ \omega_0\sqrt{\tilde{\varepsilon}(\omega_0)}\cos\vartheta_0/c\right),$$

with ϑ_0 the angle of incidence fall from the external medium ($Z < 0$) with dielectric permittivity $\tilde{\varepsilon}(\omega)$ on the system mentioned.

As a result of the interaction between this wave and the fluctuations a nonlinear current occurs in the medium which plays the part of a scattered radiation source [2]. For the high-frequency external fields in the case under consideration, the scattering current can be written in the form

$$I^{sc}(R,\ t) = \sum_{\sigma=e,m}\delta\rho_\sigma(R,\ t)\,V_{0\sigma}(R,\ t) + e\delta n_m(R,\ t)\,V_{0m}(R,\ t), \tag{1}$$

where

$$\begin{gathered}
V_{0e}(R,\ t) = i\,(eE_0/2m_e\omega_0)\exp[i(\kappa_0 R - \omega_0 t)] + \text{c.c.},\\
V_{0m}(R,\ t) = i\,[e\omega_0 E_0/2m_e(\omega_0^2 - \omega_r^2)]\exp[i(\kappa_0 R - \omega_0 t)] + \text{c.c.},\\
E_{0i} = \lambda_{ij}^{(0)}E_j^{inc};\\
\lambda_{xx}^{(0)} = 2\tilde{\varepsilon}(\omega_0)\,\kappa_{z_0}/[\tilde{\varepsilon}(\omega_0)\,\kappa_{z_0} + \varepsilon(\omega_0)\,\tilde{\kappa}_{z_0}];\ \lambda_{ij}^{(0)} = 0\,(i \neq j),\\
\lambda_{yy}^{(0)} = 2\tilde{\kappa}_{z_0}/(\kappa_{z_0} + \tilde{\kappa}_{z_0});\ \lambda_{zz}^{(0)} = 2\tilde{\varepsilon}(\omega_0)\,\tilde{\kappa}_{z_0}/[\tilde{\varepsilon}(\omega_0)\,\kappa_{z_0} + \varepsilon(\omega_0)\,\tilde{\kappa}_{z_0}];\\
\kappa_{z_0} = [\omega_0^2\varepsilon(\omega_0)/c^2 - \kappa_{\perp 0}^2]^{1/2};\ \kappa_{\perp 0} = \tilde{\kappa}_{\perp 0},
\end{gathered} \tag{2}$$

$\varepsilon(\omega)$ is the high-frequency dielectric permittivity of the plasma–molecular medium

$$\begin{gathered}
\varepsilon(\omega) = 1 + \sum_{\sigma=e,m}\chi_\sigma(\omega);\\
\chi_e(\omega) = -\omega_{pe}^2/\omega(\omega + i\nu_e);\ \chi_m(\omega) = -\omega_{pm}^2/[\omega^2 - \omega_r^2 + i\nu_m\omega];\\
\omega_{pe}^2 = 4\pi e^2 n_e/m_e;\ \omega_{pm}^2 = 4\pi e^2 n_m/m_e,
\end{gathered}$$

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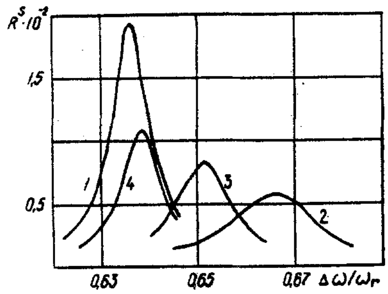

Fig. 1

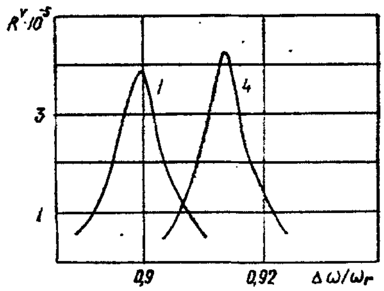

Fig. 2

e, n_e, and ν_e are the charge, mean density and effective collision frequency for electrons; n_m is the mean molecule density; ν_m is the dissipation constant of molecular polarization; $\delta\rho_\sigma(\boldsymbol{R}, t)$ are electrical charge fluctuations in subsystems of free ($\sigma = e$) and bound ($\sigma = m$) electrons and $\delta n_m(\boldsymbol{R}, t)$ are molecule density fluctuations.

Noncoherent Reflection Coefficient. Using the known solution of the problem of excitation a semibounded plasma by given sources [3], it is easy to compute the noncoherent reflection coefficient by defining it by means of the relationship

$$< P_z^{sc} > = \int\limits_0^\infty d\omega \int\limits_{(\vartheta \leqslant \pi)} d\Omega \, \frac{d^2R}{d\omega d\Omega} \, | \boldsymbol{P}^{inc} |, \tag{3}$$

where $\langle \boldsymbol{P}^{sc} \rangle$ and $\boldsymbol{P}^{inc}$ are the scattered and incident radiation Poynting vectors. We consequently obtain

$$d^2R/d\omega d\Omega = \Psi(\boldsymbol{\kappa}_{\perp 0}, \, \omega_0, \, \boldsymbol{\kappa}_\perp, \, \omega) \, F(\Delta\boldsymbol{\kappa}, \, \Delta\omega). \tag{4}$$

Here

$$\Psi(\boldsymbol{\kappa}_{\perp 0}, \, \omega_0, \, \boldsymbol{\kappa}_\perp, \, \omega) = \frac{\omega^2}{2\pi\omega_0^2} \left(\frac{\tilde{\varepsilon}(\omega)}{\tilde{\varepsilon}(\omega_0)} \right)^{1/2} \frac{\tilde{\kappa}_z^2}{|\kappa_z|^2} \, G_{ij}(\boldsymbol{\kappa}_\perp, \, \omega) \, \lambda_{i\kappa}^{(0)} \lambda_{jl}^{(0)} e_\kappa e_l;$$

$$G_{ij}(\boldsymbol{\kappa}_\perp, \, \omega) = (\delta_{ij}^{\perp} - \kappa_{\perp i} \kappa_{\perp j} / \kappa_\perp^2) |\lambda_{yy}|^2 + \frac{\varkappa_i \varkappa_j^*}{{\kappa_\perp}^2} \left| \frac{\varepsilon(\omega)}{\tilde{\varepsilon}(\omega)} \right|^2 \frac{|\lambda_{zz}|^2 \tilde{\kappa}^2}{\tilde{\kappa}_z^2}; \tag{5}$$

$$\boldsymbol{\varkappa} = (\kappa_x \kappa_z^2/\kappa^2, \; \kappa_y \kappa_z^2/\kappa^2, \; -\kappa_z \kappa_\perp^2/\kappa^2);$$

$$\kappa_z = [\omega^2 \varepsilon(\omega)/c^2 - \kappa_\perp^2]^{1/2}; \; \tilde{\kappa}_z = [\omega^2 \tilde{\varepsilon}(\omega)/c^2 - \kappa_\perp^2]^{1/2} = \frac{\omega}{c} \sqrt{\tilde{\varepsilon}(\omega)} \cos\vartheta;$$

$$\boldsymbol{\kappa}_\perp = \left(\omega \sqrt{\tilde{\varepsilon}(\omega)} \, \sin\vartheta \cos\varphi / c, \; \omega \sqrt{\tilde{\varepsilon}(\omega)} \, \sin\vartheta \sin\varphi / c \right); \tag{5}$$

$$\lambda_{ij} = \lambda_{ij}^{(0)} (\omega_0 \to \omega, \; \boldsymbol{\kappa}_{\perp 0} \to \boldsymbol{\kappa}_\perp);$$

ϑ and φ are angles governing the radiation direction and $\boldsymbol{e}$ is the incident wave polarization vector.

In the Born approximation when the incident and scattered waves do not experience the influence of the boundary [i.e., $\varepsilon(\omega) = \tilde{\varepsilon}(\omega)$], $\lambda_{ij} = \delta_{ij}$ and $G_{ij}(\boldsymbol{\kappa}_\perp, \omega) = 4^{-1}(\delta_{ij} - \overset{+}{\kappa}_i \overset{+}{\kappa}_j/\kappa^2)$, where $\overset{+}{\boldsymbol{\kappa}} = (\boldsymbol{\kappa}_\perp, -\kappa_z(\omega))$; $F(\Delta\boldsymbol{\kappa}, \Delta\omega)$ is a quantity determined by the fluctuation spectra as

$$F(\Delta\boldsymbol{\kappa}, \, \Delta\omega) = F^v(\Delta\boldsymbol{\kappa}, \, \Delta\omega) + F^{vs}(\Delta\boldsymbol{\kappa}, \, \Delta\omega) + F^s(\Delta\boldsymbol{\kappa}, \, \Delta\omega) =$$
$$= \left(\frac{e}{m_e c^2} \right)^2 \sum_{\sigma,\sigma'} \alpha_{e\sigma} \alpha_{e\sigma'}^* \{ [\delta_{\sigma m} \delta_{\sigma' m} e^2 < \delta n_m^2 >_{\Delta\boldsymbol{\kappa},\Delta\omega} + \delta\rho^\sigma \delta\rho^{*\sigma'} >_{\Delta\boldsymbol{\kappa},\Delta\omega}^v] \cdot L +$$
$$+ < \delta\rho_{\Delta\kappa_z}^\sigma \delta\rho_{\Delta\kappa_z}^{*\sigma'} >_{\Delta\boldsymbol{\kappa}_\perp,\Delta\omega}^{vs} + < \delta\rho_{\Delta\kappa_z}^\sigma \delta\rho_{\Delta\kappa_z}^{*\sigma'} >_{\Delta\boldsymbol{\kappa}_\perp,\Delta\omega}^s \}. \tag{6}$$

Here

$$L = \frac{1}{2} \operatorname{Im}(\kappa_z + \tilde{\kappa}_z); \; \Delta\boldsymbol{\kappa} = (\Delta\boldsymbol{\kappa}_\perp, \, \Delta\kappa_z);$$

$$\Delta\kappa_\perp = \kappa_\perp - \kappa_{\perp_0};\ \Delta\kappa_z = \kappa_z + \kappa_{z_0};\ \Delta\omega = \omega - \omega_0; \tag{7}$$

$$a_{\sigma\sigma'} = \chi_\sigma(\omega)\, n'_\sigma/\chi'_\sigma(\omega)\, n_\sigma,$$

$\langle\delta\rho^\sigma\delta\rho^{*\kappa'}\rangle_{\Delta\kappa,\Delta\omega}{}^v$ and $\langle\delta\rho_{\Delta\kappa_z}{}^\sigma\delta\rho_{\delta\kappa_z}{}^{*\sigma'}\rangle_{\Delta\kappa_\perp,\Delta\omega}{}^{s,vs}$ are the bulk, surface, and cross components of the correlation function of the electrical charge density in the system under consideration [4-6] and $\langle\delta n_m{}^2\rangle_{\Delta\kappa,\Delta\omega}$ is the spectral density of the correlation function of the molecule density fluctuations.

In the Born approximation the expression for the differential coefficient of reflection related to scattering by bulk fluctuations is simplified to the form

$$d^2R/d\omega d\Omega = \frac{\omega^2}{2\pi\omega_0^2}\left(\frac{\tilde{\varepsilon}(\omega)}{\tilde{\varepsilon}(\omega_0)}\right)^{1/2}(\delta_{ij} - \overset{+}{\kappa}_i\overset{+}{\kappa}_j/\kappa^2)\, e_i e_j F^v(\Delta\kappa,\ \Delta\omega), \tag{8}$$

which agrees for $n_m = 0$ with the well-known result for the differential coefficient scattering in the case of an unbounded plasma [2].

It follows from (6) that the scattered radiation spectrum in the domain of existence of collective excitations in a plasma contains resonances in the neighborhood of the frequencies $\omega = \omega_0 \pm \omega_{\Delta\kappa}$ and $\omega = \omega_0 \pm \omega_{\Delta\kappa_\perp}$, where $\omega_{\Delta\kappa}$ and $\omega_{\Delta\kappa_\perp}$ are the natural bulk and surface wave frequencies in a semibounded plasma-molecular medium [4-6]. The characteristic dependence of the normalized noncoherent reflection coefficients

$$R^{v,s} = (d^2R/d\omega d\Omega)/(e^2T_e/m_e^2c^5)$$

on $\Delta\omega/\omega_r$ in the domain of bulk and surface resonances is represented in Figs. 1 and 2. The curves presented correspond to the following values of the parameters $\omega_{pm}/\omega_r = 5\cdot10^{-4}$, $\nu_m/\omega_r = 10^{-6}$, $\omega_{pe}/\omega_r = 0.9$, $\nu_e/\omega_{pe} = 10^{-2}$, $\omega_0/\omega_r = 5$, $\varepsilon(\omega) = 1$, $\vartheta_0 = 0$, $\vartheta = \pi/3$, $= \pi/3$, 1 – $c/s_e = \infty$, 2 – $c/s_e = 1000$, 3 – $c/s_e = 200$, 4 – $c/s_e = 100$, where $s_e = (T_e/m_e)^{1/2}$, and T_e is the electron temperature.

As regards wave scattering by molecule density fluctuations, then in the case of a rarefied molecular subsystem

$$\langle\delta n_m^2\rangle_{\Delta\kappa,\Delta\omega} = \frac{2n_m}{\Delta\omega}\operatorname{Im}\frac{(\Delta\omega + i\nu)\,W(Z_m)}{\Delta\omega + i\nu W(Z_m)}, \tag{9}$$

where $W(Z)$ is the dispersion plasma function, and $Z_m = (\Delta\omega + i\nu)/\Delta\sigma s_m$ (ν and s_m are the effective collision frequency and the thermal velocity of the molecules). Depending on the relationship between ν and $\Delta\kappa s_m$ the formulas (6) and (9) describe the Doppler-broadened maximum ($\nu \ll \Delta\kappa s_m$) or the homogeneously broadened line ($\nu > \Delta\kappa s_m$) in the scattered radiation spectrum.

In the gas-dynamic limit, the known hydrodynamic fluctuation spectrum should be substituted in (6) [7], which yields a general formula suitable for analyzing scattering in both the case of a small frequency change and in the domain of the Mandel'shtam-Brillouin doublet with reflection and refraction of the incident and scattered fields taken into account.

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