# Noninertial radiation from metals in interaction with ultrashort pulses of coherent infrared radiation

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It has been shown for the first time theoretically and experimentally that under certain conditions radiation originating at the surface of a metal subjected to ultrashort infrared laser pulses is related to the heating of the electron gas, and noninertially follows the shape.

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It has been shown[1] that in the interaction of ultrashort laser pulses with metals, under certain conditions the temperature of the electron subsystem is "detached" from that of the ion subsystem and noninertially follows the shape of the laser pulse. For a laser pulse of sufficiently high intensity the electron temperature $T_e$ is from one to several thousands degrees. Here, therefore, along with the phenomena of thermo- and photoemission of electrons discussed in Ref. 1, temperature luminescence of the electron gas in the metal should also take place. Thus, a significant portion of the radiation will be in the visible region of the spectrum. It is clear that the luminescence will noninertially follow the shape of the laser pulse, if $T_e$ is noninertial.

We shall determine a region of the parameter for which the electron temperature $T_e$ is noninertial, and we shall evaluate its extent. Thus, we shall refine the result given in Ref. 1 by calculating the electron thermal conducting $\chi = \chi_0 (T_e/T_i)$ as a function of $T_e$, which was assumed to be constant in Ref. 1. The quantity $\chi_0$ is the thermal conductivity of the metal at $T_e = T_i$. In this case by satisfying the noninertial conditions which were formulated in Ref. 1 from the equations for the temperatures $T_e$ and $T_i$, and taking into account the function $\chi = \chi(T_e)$ and assuming $T_e \gg T_i$, we obtain the following results.

In the case of a large sample for which

$$d >> \left(10^7 \frac{\chi_0 q}{T_0 a^2}\right)^{1/3} >> \kappa^{-1},$$

where $d$ is the thickness of the sample; $q(t)$ is the beam power density at time $t$ in W/cm$^2$ containing the factor $(1 - R)$, where $R$ is the reflection coefficient; $T_0$ is the initial temperature of the sample; $\alpha \sim 10^{17} - 10^{18}$ erg/sec deg cm$^3$ is the coefficient for the thermal exchange of electrons with the lattice[2,3]; and $k$ is the linear light absorption coefficient at the surface of the metal:

$$T_e(t) = \left(\frac{3 T_0}{2 a \chi_0}\right)^{1/3} [10^7 q(t)]^{2/3}. \quad (1)$$

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For the case of a sufficiently thin sample

$$d << \left(10^7 \frac{\chi_0 q(t)}{T_0 a^2}\right)^{1/3}$$

$T_e$ is equal to

$$T_e = \frac{10^7}{a d} q(t). \tag{2}$$

Here $q(t)$ contains the factor $(1-R-T)$, where $T$ is the light transmission coefficient.

Equations (1) and (2) corresponding to a noninertial response are valid for the condition:

$$\gamma T_e / a \lesssim \tau \lesssim C_i / a. \tag{3}$$

Here $\gamma$ is the linear coefficient for the electron heat capacity, and $\tau$ is the laser pulse width.

Assuming $T_0 = 300$ K, $\chi_0 = 3\times 10^7$ erg/sec deg cm, $C_i = 4\times 10^7$ erg/deg cm$^3$, and $\gamma = 0.7\times 10^3$ erg/deg$^2$ cm$^3$ for the massive sample, it follows from Eq. (1) that $T_e \approx (2-4)\times 10^3$ deg and the inertia-free condition [Eq. (3)] becomes $10^{-12}$ sec $\lesssim \tau \lesssim 10^{-10}$ sec. In the case of a plate of thickness $d \approx 2\times 10^{-6}$ cm where $q = 3\times 10^8$ W/cm$^2$, from Eq. (2) we get $T_e \approx (2-10)\times 10^3$ deg. Thus, Eq. (3) becomes $10^{-11}$ sec $\lesssim \tau \lesssim 10^{-10}$ sec.

Therefore, on the one hand, for actual values of the parameters a noninertial value for $T_e$ is possible and, on the other hand, $T_e$ should be large enough so that the electron gas in the metal, as will be seen from the following calculation, would radiate enough to record a number of photons. We emphasize that the noninertial condition satisfies the inequality $T_i \ll T_e$ and, consequently, in this way the photon emission is completely determined by the temperature $T_e$ as long as the number varies exponentially with $T_e$.

Under the assumption concerning the equilibrium nature of the electron emission within the metal, the number of photons emitted from the surface of the metal of area $S$ and frequencies $\omega \geqslant \omega_0$ is equal to

$$N_{\text{ph}} \sim (1-R) s\tau k T_e / \hbar 4\pi^3 \left(\frac{\omega_0}{c}\right)^2 e^{-\frac{\hbar\omega_0}{kT_e}},$$

where $c$ is the speed of light. Assuming $\hbar\omega_0 = 1.5$ eV, $T_e = (3-5)\times 10^3$ deg, $S = 10^{-2}$ cm$^2$, $\tau = 10^{-11}$ sec, and $R = 0.9$, we obtain $N_{\text{ph}} \sim 10^7$ photons, or the emitted power corresponds to $\sim$ W/cm$^2$.

In this work experiments were carried out to study the light from the surfaces of different metals under the effect of ultrashort laser pulses. The measurements were made using a neodymium laser ($\lambda = 1.06\,\mu$) which generated a train of 15–20 pulses with an average pulse width for each of $10^{-11}$ sec, an overall pulse width of 150–200 nsec, and an average pulse energy of $\sim 10^{-3}$ joules.

The time-dependent characteristics of the light were studied using an ELU-FT

photomultiplier and an S1-11 oscillograph with a time resolution of $5\times10^{-9}$ sec. The measurements were made in a broad spectral band excluding the band with $\lambda_1 = 1.06\ \mu$ and $\lambda_2 = 0.53\,\mu$. The metals used were tungsten, copper, silver, and gold. The experiments showed that for all the materials listed above the pulse width for emission is smaller than the time resolution provided by the measurement technique. The time-dependent characteristics of the light were not measured for the irradiation of large samples ($d \ll k^{-1}$) sputtered on glass, and for the irradiation of a metallic film at the air-film and film-glass interfaces. In all the experiments the power density of the laser pulse was such that there was no visible damage to the metal.

Since the relaxation time of the lattice temperature, even for thin films on a glass substrate (with a low temperature conductivity), may be less than the resolution time for the measuring technique, the experiments, which were carried out do not give complete information concerning the relation between luminescence and the temperature of the electron or ion subsystems. In this connection a study was made of the luminescence spectrum. The spectrum was measured using a photoelectronic technique described in Ref. 4 for thin films of copper and silver (with a thickness of $10^{-6} - 10^{-4}$ cm). According to the measurements the luminescence spectrum was continuous corresponding to Planck's radiation with a color temperature of 3600 K for copper and 3500 K for silver (10% error). The temperature was determined at a subthreshold laser pulse power density, where the threshold was taken to be the power density at which at the focal point on a thin film visible damage was observed in a microscope (the boiling temperatures of copper and silver are, respectively, 2660 and 2490 K).

Thus, it follows from the experimental results that for subthreshold laser pulse power densities there is a separation between the electron and ion temperatures. The electron temperature is at least one and a half to two times higher than the temperature of the ion subsystem. From what has been said it follows that at these conditions the electron temperature $T_e$ and consequently the luminescence should noninertially follow the shape of the laser pulse.

Experiments have shown the necessity and possibility of using modern photochronographs for studying the temporal characteristics of the luminescence. Use of the "Agat" photochronograph at the present time has yielded results which confirm the data given above. A detailed description of these results will be published in a separate work.

This phenomenon may find application in the noninertial conversion of ultrashort laser pulses with pulsewidths of $10^{-10}$ to $10^{-12}$ sec in the infrared region to visible radiation with power densities greater than $10^8$ W/cm$^2$. Such conversion may open up the prospect of broadening the spectral range of modern photoelectronic detectors.

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