Coherent radio waves from emissions produced by action of short laser pulses on a metal surface

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We consider the radio waves produced by production or disappearance of laser-emission electrons. We demonstrate the feasibility of obtaining trains of short radio waves by spatial modulation of the emission. Expressions are obtained for the spatial distribution of the radiation and the intensity is estimated. It is noted that the spectrum of these radio waves can be used to estimate the shape of a bunch of electrons produced by a picosecond light pulse, and the waveform of the light pulse itself.

The achievement of short and ultrashort laser pulses of duration $\tau \sim 10^{-12}-10^{-11}$ sec, and the possibility of further contraction or truncation of the fronts to $\tau \sim 10^{-13}$ sec, permits one to anticipate radiofrequency radiation of fairly short wavelength $\lambda \sim c\tau$ (0.3–3 mm at $\tau \sim (1-10) \times 10^{-12}$ sec) from electron emission generated by the action of laser pulses on a metal surface. The emission can be induced by the photoelectric effect or by localized heating, and can be enhanced by a strong drawing electric field. This field can accelerate the electrons and increase their radiation efficiency, since the radiation intensity depends strongly on the kinetic energy of the electrons, and after the accelerated emission electrons strike the surface there is radiated an electromagnetic pulse which is more intense than when these electrons were produced.

We will examine the transition[1] radio-frequency radiation occurring when electron bunches land on or take off a surface. We assume that the electrons are emitted (or incident) instantaneously with a running density $N_1(z)$. Then the Fourier component of the radiation field at a distance R_0 will be

$$\mathbf{E}_\omega = \pm \frac{qe^{ikR_0}}{2\pi c^2 R_0}[\mathbf{n}\times[\mathbf{n}\times(\mathbf{v}-\mathbf{v}')]] \int_{-L}^{L} e^{-ikz\cos\theta} N_1(z)\,dz,$$

where q is the charge, $\mathbf{v}$ and $\mathbf{v}'$ are the electron velocity and the projection of the velocity on the surface of the metal, and $\langle \mathbf{v} - \mathbf{v}' \rangle = 2\langle v_n \rangle \mathbf{n}$, where $\mathbf{n}$ is the normal to the surface.

We consider an interference factor of the form

$$\Phi = \int_{-L}^{L} e^{-ikz\cos\theta} N_1(z)\,dz.$$

For a uniform distribution $N_1(z) \approx N_{10} = \text{const}$, we get

$$\Phi = 2N_{10}L\frac{\sin(kL\cos\theta)}{kL\cos\theta},$$

where $2N_{10}L = N^*$ is the total number of electrons in a bunch of length L.

For a periodically modulated injection (for example when the light or the electron bunch is chopped up by a raster) we will examine the simplest case, $N_1 = \tilde{N}_{10}(1 + \cos\varkappa z)$, where $\tilde{N}_{10}$ is the average running number of electrons, $\varkappa = 2\pi/d$ is the modulation constant, and d is the spatial period of the chopping. In this case,

$$\Phi = 2\tilde{N}_{10}L\left\{\frac{\sin(kL\cos\theta)}{kL\cos\theta} + \frac{\sin(k\cos\theta+\varkappa)L}{(k\cos\theta+\varkappa)L} + \frac{\sin(k\cos\theta-\varkappa)L}{(k\cos\theta-\varkappa)L}\right\}.$$

For example, if $kL\cos\theta \gg 1$ and $k\cos\theta = \varkappa$, then

$$\Phi \approx 2\tilde{N}_{10}L\frac{\sin(k\cos\theta-\varkappa)L}{(k\cos\theta-\varkappa)L} \approx 2N_0L\frac{\sin x}{x}.$$

The width of the spectrum is determined from the condition $x \sim \pm\pi$; since at the maximum we have $k_m\cos\theta = \varkappa$ ($\lambda_m/d = \cos\theta$), the width is $\Delta k = \pi/L\sin\theta$, or $\Delta k/k_m \approx \pi/\varkappa L \approx d/L$. Thus, at $d/L \sim 10^{-3}-10^{-2}$ it is possible to have radiation with a degree of monochromaticity of $\Delta\omega/\omega \sim 10^{-3}-10^{-2}$.

The electron-emission delay time in the case of the photoelectric effect is usually small compared with the oscillation period in the frequency band of interest to us. In the case of thermionic emission, the time of emission is comparable to the cooling time of the burn spot: $t = \delta^2/D_T$, where δ is the thickness of the absorption layer (usually $\delta \sim 10^{-6}-10^{-5}$ cm) and D_T is the coefficient of temperature conductivity ($D_T \sim 0.1-0.3$ cm^2/second), i.e., $t \sim 10^{-19}-10^{-11}$ second, and in some cases the thermionic emission cannot be regarded as instantaneous.

The effective electron emission velocity is determined either by the initial velocity (the electron energy is $\mathscr{E}_0 = 1-10$ eV for photoelectrons or thermoelectrons), or by the work of the external field over a time interval of the order of the period of the received wave ($v_\lambda \approx eE/m\omega$, $\mathscr{E}_0 \sim 10^2-10^3$ ev). The effective velocity of the electrons striking the surface of the electrode is $v \approx \sqrt{eU/m}$, where U is the electrode potential difference. The time duration of the incidence is $\Delta t \sim t\Delta v/v$, where $t \approx 2l/v$ is the time of flight across an interelectrode gap of length l, and Δv is the spread of the normal velocity component. For example, for $U \sim 100$ keV, the electron velocity is $v = 1.5 \times 10^{10}$ cm/sec, and for $l = 3$ cm and $\Delta v \approx 10^8$ cm/sec ($\Delta\mathscr{E}_0 = 3$ eV), we get $\Delta t \sim 3 \times 10^{-12}$ sec, i.e., $\lambda_{coh} \sim c\Delta t \sim 1$ mm. At the same time, the spread of modulation upon cutoff by a screen in the case of emission $\Delta d = \Delta vt \approx 3 \times 10^{-2}$ cm, which is fairly small.

We estimate the energy density and the power of the radiation:

$$\frac{d\mathscr{E}}{d\Omega} = \int \frac{c}{4\pi}|\mathbf{E}_\omega|^2\,d\omega, \quad P = \frac{1}{\tau}\frac{d\mathscr{E}}{d\Omega}$$

(τ is the radiation pulse duration). Substituting the expression for $|\mathbf{E}_\omega|$ in the form

$$|\mathbf{E}_\omega| \sim \frac{qN_1L}{\pi c^2 R_0}v_n \sim \frac{jS\tau_{em}}{\pi c^2 R_0}v_n$$

and assuming $\tau_{em} \sim \tau \sim 1/\omega_{max}$, we obtain at a current density $j \approx 10^4$ A/cm^2 and a spot area $S = 30 \times 10^{-2}$ cm^2 the value $P \sim 10^4$ watts.

Given the spatial density distribution of the electron bunch produced by the light, then, at small transverse dimensions of the bunch, the radio emission spectrum will depend only on the number of electrons, $\dot{N}(t)$, impinging on the surface in a unit of time. In this case, we get

$$\mathbf{E}_\omega = \sum_i \mathbf{E}_{\omega 0} e^{i\omega\tau_i} \to \mathbf{E}_{\omega 0} \int e^{i\omega\tau} \dot{N}(\tau)\, d\tau \approx E_{\omega 0} \dot{N}_\omega,$$

which enables us to find the correspondence between E_ω and $\dot{N}_\omega$.

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[1] V. L. Ginsburg and I. M. Frank, Zh. Eksp. Teor. Fiz. **16**, 25 (1946).

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