Generation of an intense, directed, ultrashort electromagnetic pulse

Yu. N. Lazarev and P. V. Petrov
All-Russian Institute of Engineering Physics, 454070 Chelyabinsk-70, Russia

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A superluminal electron-current pulse might be used to generate a high-power, ultrashort pulse of electromagnetic radiation with a small diffraction divergence. The power would be $W \gtrsim 10^9$ W, the pulse length $T_0 \lesssim 10^{-12}$ s, and the diffraction divergence $\psi_d < 10^{-4}$. The current pulse would arise when the plane front of pump light capable of causing electron emission is incident obliquely on a plane metal surface.

1. Several technological advances—the development of a new generation of radar, rf navigation, and rf meteorological apparatus; the development of long-range radio communications with a high throughput; and the development of compact charged-particle accelerators—all depend directly on the development of microwave devices capable of generating a directed, ultrashort electromagnetic pulse of high power. The pulse length would be $T_0 < 10^{-12}$ s, and the power $W > 10^9$ W. One of the primary obstacles to raising the power of generated radiation in various fields of conventional pulse technology is the small pulse length T_0 itself,[1] which limits the size of the energy-storage region to $\sim cT_0$, where c is the velocity of light. Understandably, achieving a significant increase in the power and total energy of the electromagnetic pulses generated will require developing electronic devices of a completely new type, capable of overcoming this obstacle.

In this letter we propose utilizing the generation of an electromagnetic pulse in the course of superluminal motion of charges in order to produce a directed, ultrashort, high-power electromagnetic pulse.[2] In particular, this effect occurs when a plane front of ionizing radiation is incident obliquely. This ionizing radiation might be laser light, UV light, or x radiation capable of causing emission of charged particles at the surface of a metal (or insulator).[3] The propagation of a current of emitted particles along the bombarded surface at a superluminal velocity results in coherence of the emission of the individual particles, and the radiated power is independent of the length of the electromagnetic pulse which is generated. A characteristic property of a superluminal source is that the electromagnetic pulse is emitted from the surface at the specular angle with respect to the angle at which the ionizing radiation is incident. This circumstance, combined with the short length of the pulse, would make it possible to use a generator of this sort (which is purely theoretical at this point) to generate low-divergence fluxes of electromagnetic energy which have not only a high power, but also a high intensity.

2. Let us evaluate the possible characteristics of an electromagnetic pulse generated by a superluminal current pulse which arises under the influence of ionizing radiation.

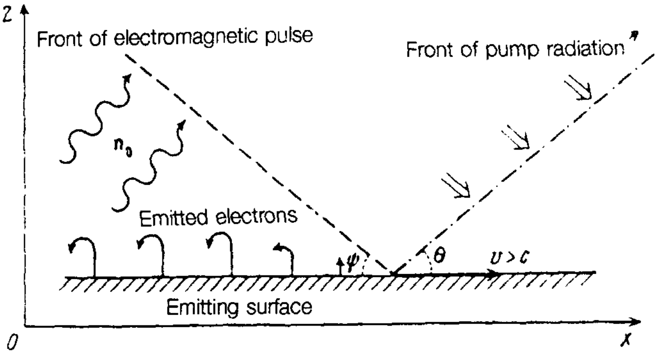

FIG. 1. Schematic diagram of the generation of an electromagnetic pulse by a superluminal electron-current pulse.

When a plane flux of pump radiation, which causes electron emission, is incident on an infinite, plane, ideally conducting surface ($y=0$) at an angle θ, a current pulse of density $j_z=j_z(\tau)$, where $\tau=t-x/v$, forms there. This pulse propagates at a velocity $v=c/\sin\theta>c$ along the X axis (Fig. 1). The motion of the electrons occurs in the electric fields of the plane, the space charge, and the electromagnetic wave that is formed. This motion should be examined on the basis of a joint solution of Maxwell's and Vlasov's equations. However, if we assume that the current distribution along the surface is given, and if we also assume that the components of the electromagnetic field depend on the variables x and t in the same combination as for the exciting current, then it is a fairly simple matter to derive an analytic solution of Maxwell's equations for the nonvanishing field components, namely E_x, E_z, and H_y:

$$E_x(\tau,z)=\frac{2\pi}{vb}\left[\int_0^z dz' j_z\left(\tau-\frac{z-z'}{c}\sqrt{1-\frac{c^2}{v^2}},z'\right)\right.$$
$$+\int_0^\infty dz' j_z\left(\tau-\frac{z+z'}{c}\sqrt{1-\frac{c^2}{v^2}},z'\right)$$
$$\left.-\int_z^\infty dz' j_z\left(\tau-\frac{z-z'}{c}\sqrt{1-\frac{c^2}{v^2}},z'\right)\right]. \qquad (1)$$

We assume that the conditions for the applicability of the dipole approximation are satisfied. These are the conditions that the emitted electrons are nonrelativistic ($\bar{v}_e\ll c$, where $\bar{v}_e$ is the average electron velocity) and that the emission current is localized near the emitting surface, in a region of size

$$\Delta z\sim\bar{v}_eT_p<T_p\frac{cv}{\sqrt{v^2-c^2}},$$

where $T_p\simeq T_0$ is a time scale of the variation in the current (this condition holds in the case of a space-charge-limited current). Under these conditions, at $z\gg\Delta z$, we have

$$E_x(\tau,z)\simeq \frac{4\pi}{v}\dot{P}\left(\tau-\frac{z}{c}\sqrt{1-\frac{c^2}{v^2}}\right),\quad H_y(\tau,z)\simeq \frac{4\pi}{\sqrt{v^2-c^2}}\dot{P}\left(\tau-\frac{z}{c}\sqrt{1-\frac{c^2}{v^2}}\right). \qquad (2)$$

Here P is the surface density of the dipole moment, and

$$\dot{P}\equiv \frac{dP}{dt}=\int_0^\infty dz' j_z(t,z).$$

It can be seen from these expressions that the electromagnetic wave which is radiated propagates along the direction $\mathbf{n}_0=(\cos\theta,0,\sin\theta)$, which makes an angle $\psi=\pi-\theta$ with the X axis. We also see that the amplitude of this wave is proportional to the rate of change of the dipole moment, which is created by the emitting particles.

In the case of a surface with finite dimensions $\sim L$ along the X and Y axes, expressions (1) and (3) are valid only within the Fresnel zone. In the wave zone, the expressions for the components of the electromagnetic field can be calculated in terms of retarded potentials. If the observation point, at a distance R from the generator, lies in the $y=0$ plane, we find the following results for directions $\mathbf{n}$ which are close to the wave emission direction $\mathbf{n}_0$, working in the dipole approximation:

$$H_y\approx \frac{2\sin\theta}{c^2R}\int_s dx'dy'\ddot{P}\left(t-\frac{R}{c}+\frac{x'\cos\theta}{c}\vartheta\right),\quad \cos\vartheta=\mathbf{n}\cdot\mathbf{n}_0\simeq 1. \qquad (3)$$

It follows that the diffraction angle and the boundary of the Fresnel zone are determined by

$$\psi_d=\frac{2cT_p}{L\cos\theta},\quad R_f\sim \frac{L^2\cos\theta}{8cT_p}. \qquad (4)$$

Correspondingly, under the condition $\vartheta\ll\psi_d$, we have

$$H_y\approx 2\frac{L^2\cos\theta\,\ddot{P}(t-R/c)}{c^2R}. \qquad (5)$$

The expressions derived for the amplitude of the electromagnetic wave in the wave zone, (3) and (5), show that the radiation intensity is $I\approx \frac{c}{4\pi}H_y^2$ and that, correspondingly, the power of the microwave source associated with it is determined by the dimensions of the irradiated surface and by the rate of change of the dipole moment: $\dot{P}\sim P/T_p$, $\ddot{P}\sim P/T_p^2$. The size of the generation region, $S_\perp\sim L^2\cos\theta$, does not depend on the duration of the emitted signal.

3. Some key parameters determining the characteristics of the generators are the surface dipole-moment density P and the time scale of the variations in the current, T_p. Let us estimate them.

The surface dipole-moment density is determined by the kinetic energy of the emission electrons, $E\approx m_e-v_e^2/2\sim\epsilon$, where ϵ is the average photon energy of the ionizing radiation:

$$P=\frac{E}{4\pi e}\sim\frac{\epsilon}{4\pi e}. \qquad (6)$$

In the formation of the current pulse, there are two time scales:[4]

·the time scale of the variation of the intensity of the pump radiation, T;

·the time scale of the variation in the electron current (or of the charge distribution in the cloud of emitted electrons), ω_{Le}^{-1}, where $\omega_{Le}^2=4\pi e^2 n_e/m_e$ is the electron plasma frequency, e and m_e are the charge and mass of an electron, and n_e is a characteristic value of the density of the emitted electrons.

In the case $T\omega_{Le}\gg 1$—a case of interest—the dynamics of the formation of the current pulse is determined exclusively by the electron plasma frequency: $T_p=\omega_{Le}^{-1}$.

For definiteness, we assume that the intensity of the pump radiation varies linearly in time, $q=q_0 t/T$. The flux density of the ejected electrons can then be estimated from $n_e=Yq_0 t/\epsilon v_e T$, where Y is the quantum yield of the emission electrons. Taking the value of the electron density at the time $t=T_p$ as a characteristic value, and noting the relatively weak dependence of T_p on the electron energy, we find the following approximate expression (q_0 is in units of W/cm^2, T in nanoseconds, and ϵ in eV):

$$T_p=T^{1/3}\left(\frac{m_e\epsilon v_e}{4\pi e^2 Y q_0}\right)^{1/3}\approx 1.3\times 10^{-10}\epsilon^{1/2}\left(\frac{Yq_0}{T}\right)^{-1/3}\ (\mathrm{s}). \tag{7}$$

Using expressions (4)–(6) and (8), we can estimate the intensity and power of the microwave radiation in the wave zone:

$$I=\frac{c}{4\pi}H_y^2\sim\frac{1}{\pi c^3}\frac{S_\perp^2}{R^2}\frac{P^2}{T_p^4},\quad W=I\pi\psi_d R^2\sim\frac{4}{c}S_\perp\frac{P^2}{T_p^2}. \tag{8}$$

For an average energy $\epsilon=10$ eV of the pump photons, and for an electron emission intensity $Yq_0/T\sim 10^{12}$, with $S_\perp\sim 10^4$ cm^2, the power of the electromagnetic pulse reaches a value $\sim 10^9$ W at a pulse length $T_0\sim 10^{-14}$ s with a divergence $\psi_d<10^{-4}$.

It thus follows from the expressions derived here that the power and total energy of a microwave source with a superluminal current pulse can be increased by 1) increasing the area of the irradiated surface, 2) raising the energy of the emitted electrons, 3) using materials with a high quantum yield for the bombarded surfaces, and 4) increasing the intensity of the pump radiation.

4. The energy of the electrons which are fed by the superluminal light pulse can be increased by accelerating the electrons in a diode in which the cathode is a photoemitter, and the back side of the anode is the emitting surface. The electron emission from the cathode surface can be initiated by the plane front of long-wave laser light ($\lambda\lesssim 1$ μm). Estimates like those presented above show that at a voltage of about 250 keV between the anode and the cathode, with an area of about 100 cm^2 and a quantum yield $Y\approx 0.5$ electron/photon, in the case in which a laser with a pulse energy ~ 1 mJ, a pulse length $\lesssim 10^{-11}$ s, and a wavelength $\lambda\lesssim 0.5$ μm is used, it would be possible to produce an electromagnetic pulse with a power $\sim 10^{11}$ W at a pulse length ~ 10 ps.

In summary, these estimates permit the conclusion that the development of a microwave source based on a superluminal current pulse would make it possible to overcome the standard obstacle to the power of an ultrashort electromagnetic pulse which results from the dimensions of the energy-storage region. Apparatus which already exists could be used to develop a source of electromagnetic energy with a power on the order of a gigawatt and a pulse length ~10 ps.

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