Intensification of light by an electron beam near an absorbing surface

A. N. Oraevskiĭ and I. V. Smetanin
P. N. Lebedev Physics Institute, Russian Academy of Sciences, 117924 Moscow, Russia

(Submitted 14 June 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **62**, No. 3, 242–245 (10 August 1995)

A fundamentally new scheme is proposed for generating coherent optical radiation. The scheme is based on the amplification of light by a high-current, low-voltage (<1–3 MeV) electron beam near the surface of a resonantly absorbing material. © *1995 American Institute of Physics.*

Generators of electromagnetic radiation which employ high-current relativistic electron beams are very attractive because of their high conversion efficiency and high output power (up to gigawatt level). The wavelengths of the generated radiation, however, are determined mainly by the geometry of the retarding and waveguide structures and range from several centimeters up to submillimeters. The possibility of extending generation into the optical range is usually tied to free-electron lasers; this nonetheless requires relatively high electron energies (tens of MeV) and high beam quality, which generally requires a low beam current and, correspondingly, low gain and low output power.[1,2]

In the present paper we propose a fundamentally new scheme for an optical-radiation generator. The scheme is based on the amplification of an electromagnetic wave by a magnetized electron beam near an absorbing surface. Physically, the amplification mechanism in the situation under consideration is due to the development of a dissipative beam instability. The resonance character of the absorption of most media at optical frequencies gives rise to a narrow (of the order of the linewidth) gain spectrum. The proposed scheme is promising for sources of powerful, coherent, infrared radiation.

For clarity, we shall analyze the simplest case — planar geometry, which is standard in the theory of microwave generators. A uniform monoenergetic electron beam propagates with the velocity $v=\beta c$ along the z axis in the half-space $x>0$ above the flat surface of an absorbing medium which occupies the region $x<0$ and which is characterized by the complex permittivity $\varepsilon=\varepsilon_1+i\varepsilon_2$, $\varepsilon_2>0$. A strong "guiding" magnetic field is applied along the z axis, so that the beam can be regarded as completely magnetized. We shall show that in such a system an electromagnetic wave propagating along the interface together with the beam can be amplified. We assume that the amplified signal is monochromatic (with frequency ω) and that it has a TM-type structure. In the present report we restrict the analysis to the linear approximation (weak signal). A quasistationary gain regime is considered, so that the z and t dependence of the quantities on the coordinates z and t are described by the factor $\exp\{i(hz-\omega t)\}$, where h is the wave number along the z axis.

It is physically obvious that for the case at hand the solutions representing surface waves concentrated near the boundary $x=0$ are of greatest interest. In the approximations indicated it is easy to solve simultaneously Maxwell's equations and the equations of motion. For the z component of the electric field of the wave we have

$$E_z=Ae^{-\kappa x},\quad x>0,\quad E_z=Ae^{-i\mu x},\quad x<0. \tag{1}$$

Here $\kappa^2=(h^2-\omega^2/c^2)(1-\Omega^2/(hv-\omega)^2)$ and $\mu^2=\varepsilon\omega^2/c^2-h^2$ are parameters which determine the characteristic transverse extent of the field in the beam and in the medium, respectively; $\Omega^2=4\pi n_0 e^2/m\gamma^3$ is the Langmuir frequency of the beam with density n_0, and, $\gamma=(1-\beta^2)^{-1/2}$. Having in mind amplification at optical frequencies, we shall focus our attention mainly on the high-frequency limit $\Omega^2/\omega^2\ll 1$. Choosing solutions that vanish in the limit $x\rightarrow\pm\infty$, we require that

$$\mathrm{Re}\,\kappa>0,\quad \mathrm{Im}\,\mu>0. \tag{2}$$

Finally, using the boundary conditions at $x=0$, we obtain the dispersion relation

$$\frac{\varepsilon}{\mu}=i\,\frac{\kappa}{h^2-\omega^2/c^2}\,. \tag{3}$$

The dispersion relation (3) contains two pairs of solutions. The first pair lies near the points $h^2=\varepsilon\omega^2/(\varepsilon+1)c^2$, which correspond to the characteristic waves of a system with no electron beam and rapidly decaying waves. The coupling of these waves with the beam is very weak. We are interested in the second pair of solutions of Eq. (3), which lie near the Čerenkov resonance $h\sim\omega/v$. These are fast and slow waves (with respect to the beam); the closeness of the phase velocities of these waves to v ensures efficient exchange of energy with the electrons in the beam. As a result, the fast waves are attenuated and the slow waves are amplified at the rates $(\delta h=h-\omega/v)$:

$$\mathrm{Im}(\delta h)\sim\pm\frac{\Omega/\sqrt{2}}{|\varepsilon-1||1+\varepsilon/\gamma^2|}\,(\sqrt{A^2+B^2}-A)^{1/2},$$

$$\mathrm{Re}(\delta h)\sim\mp\frac{\Omega/\sqrt{2}}{|\varepsilon-1||1+\varepsilon/\gamma^2|}\,(\sqrt{A^2+B^2}+A)^{1/2}, \tag{4}$$

where $A=1+|\varepsilon|^2/\gamma^2+(1+\varepsilon_1/\gamma^2)(\beta^2|\varepsilon|^2-2\varepsilon_1)$ and $B=-\varepsilon_2\gamma^{-2}(\beta^2|\varepsilon|^2-2\varepsilon_1)$.

Relations (4) show that radiation amplification in this scheme is determined mainly by absorption in the medium at the signal frequency: The instability vanishes completely for a transparent medium $(\varepsilon_2\rightarrow 0)$. Physically, the amplification mechanism being discussed is due to the development of a dissipative beam instability:[3] The indicated solutions correspond to fast and slow space-charge waves; the negative-energy wave is a slow wave which is unstable because of the existence of a dissipation channel in the system (absorbing medium).

The conditions for the existence of the solutions being discussed are determined by the inequalities (2). These requirements are equivalent to a restriction on the velocity of the electrons in the beam

$$\beta^2>\frac{2\varepsilon_1}{|\varepsilon|^2}. \tag{5}$$

Correspondingly, the range of frequencies at which amplification is possible is determined by the expression

$$\frac{2\varepsilon_1}{|\varepsilon|^2} < 1. \tag{6}$$

The proposed scheme is promising in the optical range: As follows from the relations (4)–(6), the optimal conditions for generation arise near resonance absorption lines. The absorption spectra of most materials, however, correspond to optical (from IR to UV) frequencies. It is easy to see that the gain spectrum in this case is very narrow — of the order of the linewidth. This automatically ensures that the generated radiation will have a high degree of coherence.

The main advantage of this scheme is that the generation of optical radiation does not require, as in the case of free-electron lasers and Čerenkov sources, high electron energy and it permits the use of high-current, low-voltage ($\leqslant 1-3$ MeV) accelerators. The signal frequency ω does not appear explicitly in Eq. (4); it appears only because of the resonance character of the frequency dependence $\varepsilon_2(\omega)$. The inequality (5) is the only condition (and it is a very weak one) imposed on the electron energy.

We should point out a very important feature of this scheme. In the conventional generators based on relativistic electron beams, amplification occurs under resonance conditions, where the velocity of the electrons is close to the phase velocity of a characteristic wave of the electrodynamic system. Here, however, as we saw above, in the absence of the beam the characteristic waves decay rapidly and the amplified mode consists of the emitted electromagnetic wave and a longitudinal potential density wave, so that the indicated synchronism holds automatically.

We also note that in the case under discussion, in addition to emission, the beam is modulated at the wavelength of the optical signal. It would be of interest to discuss the possible use of this effect for prebunching of electron beams in free-electron lasers. Analysis of the self-bunching of a beam propagating in a resonantly absorbing gaseous medium[4] shows that this mechanism is promising.

The results presented above were obtained for the case of a monoenergetic beam. Analysis of the kinetic equation shows that the limit on the scatter of the energy spread of the electrons in the beam has the standard form:[5]

$$\frac{\Delta\gamma}{\gamma} < \frac{\mathrm{Im}\,\delta h}{h}. \tag{7}$$

The gain (4) is also structurally similar to the analogous expressions obtained in the theory of Čerenkov microwave generators. In the present scheme one can therefore count on the realization of a substantial gain at optical frequencies and energy parameters close to those characteristic for standard microwave electronics.

In conclusion, we wish to give some estimates. For a weakly relativistic ($\gamma = 1.5$), high-current $n_0 = 10^{12}$ cm^{-3} (≈ 3 kA/cm^2) electron beam and SrF_2 as the absorbing surface [the absorption line center ~ 10 THz and $\varepsilon_{1\,\mathrm{max}} \sim 25$ (Ref. 6)] near the edge of the absorption line ($\varepsilon_1 \sim 0.5$, $\varepsilon_2 \sim 4.5$) we have a gain of ~ 0.5 cm^{-1} for an IR signal

($\lambda \sim 30$-μm) signal. The requirement for beam quality is $\Delta \gamma / \gamma < 10^{-3}$. The linear approximation (the density perturbation is small compared to n_0) remains valid up to amplitudes ~ 1 kV/cm.

Financial support for this work was provided by the Russian Fund for Fundamental Research (projects 93-02-14271 and 94-02-06072) and the International Science Foundation (grant N9T300).

[1]T. C. Marshall, *Free-Electron Lasers*, MacMillan Publishing Co., N. Y., 1985.
[2]C. W. Robertson and P. Sprangle, Phys. Fluids B **1**, 1 (1989).
[3]B. B. Kadomtsev, A. B. Mikhaĭlovskiĭ, and A. V. Timofeev, Zh. Éksp. Teor. Fiz. **47**, 2266 (1964) [Sov. Phys. JETP **20**, 1517 (1965)].
[4]A. N. Oraevskiĭ, Kvant. Élektron. **7**, 495 (1980) [Sov. J. Quantum Electron. **10**, 282 (1980)].
[5]M. V. Kuzelev and A. A. Rukhadze, *Electrodynamics of Dense Electron Beams in Plasma* [in Russian], Nauka, Moscow, 1990.
[6]C. Kittel, *Introduction to Solid-State Physics*, Wiley, N. Y., 1986.

Translated by M. E. Alferieff