Generation of millimeter-wave radiation by means of a Smith-Purcell free-electron laser

Donald E. Wortman, Richard P. Leavitt, Herbert Dropkin, and Clyde A. Morrison
U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, Maryland 20783
(Received 23 February 1981)

Millimeter-wave radiation in the band from 53 to 73 GHz has been generated by means of a Smith-Purcell free-electron laser. Power levels of approximately 100 mW were observed with beam currents of 90 to 100 mA; the threshold currents ranged from 35 to 82 mA. The electronic tuning transconductance and the linewidth were also measured, yielding $df/dV = 0.25$ MHz/V and $\Delta f \leq 0.4$ MHz, respectively. The measured results agree well with predictions based on a linear theory.

There has been a great deal of interest in recent years in the generation of coherent electromagnetic radiation by free-electron lasers.[1-3] One of the more interesting such concepts is based on the Smith-Purcell effect[4] and is known as the orotron,[5] ledatron,[6] or diffraction-radiation generator.[7] In this device, illustrated in Fig. 1, a sheet electron beam passes over the surface of a metallic diffraction grating and radiates into a mode of an open resonator formed by two metallic mirrors (the grating partially covers the lower mirror). The radiation is fed back onto the beam and bunches the electrons. If the proper conditions of synchronism between the electron beam velocity and the phase velocity of an evanescent wave traveling along the grating are met, coherent radiation results.

The Smith-Purcell free-electron laser is simpler in many respects than other free-electron lasers, both from a theoretical[8,9] and an experimental point of view. It can be described by considering a plane wave incident on an infinite grating of period l. The coordinate system is chosen so that the y direction is along the direction of electron motion and the z direction is normal to the grating surface. The x direction points out of the paper in Fig. 1, and we may choose the polarization of the incident wave so that the magnetic field lies in this direction and is given by the Bloch form

$$H_x = H_0 e^{i\gamma y}\psi(y,z) \ , \tag{1}$$

where ψ is a periodic function in y

$$\psi(y,z) = \sum_{n=-\infty}^{\infty} (a_n e^{-\Gamma_n z} + b_n e^{\Gamma_n z}) e^{i2\pi n y/l} \ , \tag{2}$$

as required by the grating periodicity and the wave equation, where

$$\Gamma_n = \begin{cases} \left[\left(\gamma + \frac{2\pi n}{l}\right)^2 - \left(\frac{\omega}{c}\right)^2\right]^{1/2}, & \left|\gamma + \frac{2\pi n}{l}\right| > \frac{\omega}{c} \\ -i\left[\left(\frac{\omega}{c}\right)^2 - \left(\gamma + \frac{2\pi n}{l}\right)^2\right]^{1/2}, & \left|\gamma + \frac{2\pi n}{l}\right| < \frac{\omega}{c} \ , \end{cases} \tag{3}$$

where ω is the angular frequency of the radiation and c is the speed of light.

If the wave is incident at an angle θ relative to the y axis, we choose $b_0 = 1$ and $b_n = 0$ for $n \neq 0$; γ is determined by

$$\gamma = \frac{\omega}{c}\cos\theta \ . \tag{4}$$

We desire a synchronous interaction between an electron beam and the field represented by Eq. (1); thus, the phase velocity of one of the harmonics of Eq. (2) must equal the beam velocity; this condition yields

$$n\lambda = l\left(\frac{c}{v} - \cos\theta\right) \ , \tag{5}$$

where $\lambda = 2\pi c/\omega$ is the radiation wavelength and v is the electron-beam velocity. This is the Smith-Purcell condition.[4] The electron beam *cannot* interact synchronously with the incident wave, since then $n = 0$ and Eq. (5) cannot be satisfied with $v < c$.

In the absence of an electron beam, Poynting's

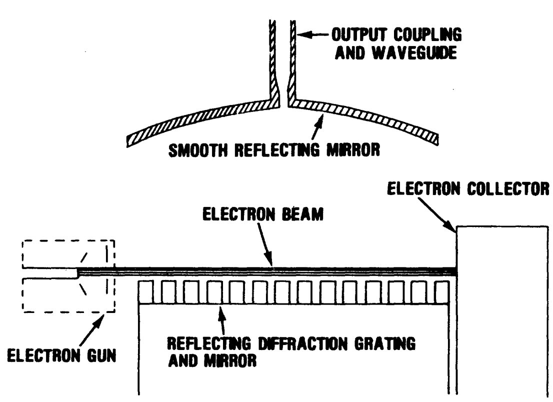

FIG. 1. Schematic diagram of the orotron.

theorem requires that $|a_0| \leq 1$, with the equality holding for a perfectly conducting grating if $l < \lambda/2$ (which is the case here). However, the electron beam behaves as an active medium, and the synchronous interaction between the beam and the grating field produces *stimulated Smith-Purcell radiation,* characterized by $|a_0| > 1$. In the Smith-Purcell free-electron laser considered here (the orotron), the axis of propagation of the open resonator is perpendicular to the direction of electron motion, so that $\cos\theta = 0$ in Eq. (5). We consider radiation on the fundamental, so that $n = 1$ and Eq. (5) becomes, in terms of the frequency $f = \omega/2\pi$,

$$f = v/l \quad . \tag{6}$$

The design of our experiment is based on the linear theory developed by us.[8] The orotron is situated between the pole pieces of a Varian 22-in. magnet that produces a uniform magnetic field of up to 12 kG over a 16.5-cm gap. The purpose of the magnetic field is to guide the electron beam over the grating; the field plays no essential role in the radiation mechanism. The orotron is enclosed in a vacuum chamber that is pumped down to a pressure less than 10^{-7} Torr by a Varian 60-l/s vacion pump. A clear window on the front of the chamber allows viewing of all the essential components during operation and is useful in visual alignment. Output radiation is fed through an *E*-band (60–90 GHz) waveguide, through a variable attenuator, and into one of two microwave diagnostic setups. A high-sensitivity Hughes Schottky-diode detector is used for the power measurements.

A spherocylindrical open resonator was chosen to optimize the coupling between the electron beam and the rf field.[7] The aluminum upper mirror is spherical, with a radius of curvature of 110 mm. The output is coupled through a circular hole of radius 1.5 mm at the center of the upper mirror into an *E*-band waveguide whose long direction is perpendicular to the direction of electron flow. The copper-coated, stainless-steel lower mirror is cylindrical, with a radius of curvature of 110 mm; the cylinder axis is along the direction of electron flow. A copper diffraction grating 40 mm long and 10 mm wide is imbedded along the axis of the lower mirror. The grating period is determined from Eq. (6); we choose $v = 3 \times 10^7$ m/s at $f = 75$ GHz, and therefore $l = 0.4$ mm. The grating has grooves of rectangular cross section whose dimensions are determined by optimizing[8] the coefficient a_1 in Eq. (2); the resultant groove width is 0.15 mm and the depth is 0.88 mm. The mode spectrum of the resonator-grating combination was determined by building a scaled model (×5) and testing it at $f = 15$ GHz with a Hewlett-Packard automatic network analyzer. As expected,[8] the TEM_{20q} modes have the highest quality factors ($Q \sim 5000$ in the actual orotron).

The electron gun is a simple Pierce gun[10] designed to emit a beam 0.3×10 mm^2 in cross section with a current of 150 mA at an accelerating voltage of 2500 V. An extra electrode allows independent control of beam voltage and beam current and permits operating the device in a quasi-cw mode with 20- to 200-μs current pulses. Barium-impregnated tungsten dispenser cathodes obtained from spectramat are used. The cathodes were mounted into the remainder of the electron gun structure and tested by Northrop Corporation.

Oscillation was observed on a number of open resonator modes under a variety of conditions. The orotron operated in a quasi-cw mode, as evidenced by the flatness of the output as a function of time. The observed rise time of the output ($\lesssim 1$ μs) is a consequence of the pulse circuitry and is not an inherent characteristic of the device. The radiation shows definite threshold characteristics, as illustrated in Fig. 2. For the TEM_{207} mode, as shown in the figure, the threshold current is 55 mA, in excellent agreement with the value of 56.3 mA calculated using the linear theory developed by us previously,[8] as corrected for effects arising from the finite electron-beam temperature. It is somewhat disappointing that the beam current could not be made larger than about 100 mA because of the limitations of our cathode, since this restriction limits power outputs to about 100 mW. The observed frequency (63 GHz in this case) is in excellent agreement with the frequency given by the theory, Eq. (6). (The grating period is actually 0.43 mm instead of 0.4 mm.)

A series of measurements were made by varying the cathode potential and the mirror spacing simultaneously in such a manner that oscillation on the TEM_{207} mode of the open resonator was maintained

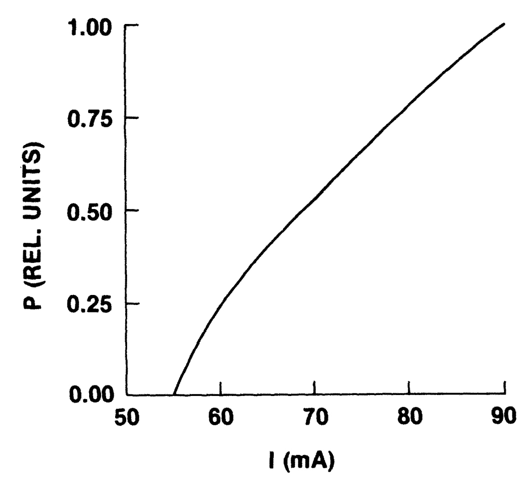

FIG. 2. Output power vs input beam current for the TEM_{207} orotron mode at 63 GHz. The threshold current is 55 mA for this mode.

throughout the tuning range, from 53.6 to 73.2 GHz. Precise frequency measurements were not made below 60 GHz, because of the limitations of the available wave meter; these frequencies were estimated from Eq. (6) with $l = 0.43$ mm. The results of these measurements are shown in Fig. 3. Frequencies calculated by means of Eq. (6) for $f > 60$ GHz match well with the observed results.

The electronic tuning transconductance and the spectral profile of the orotron output were measured by means of a heterodyning circuit. Outputs from an Oki klystron operating at 70.3 GHz and the orotron operating at 70.8 GHz were combined using a Hughes mixer diode. The difference in frequency of orotron outputs corresponding to a change of 10 V in the beam accelerating voltage was measured accurately by this method, and a value of $df/dV = 0.25$ MHz/V was deduced. This value is in excellent agreement with the result of 0.238 MHz/V obtained from the linear theory,[8] as corrected for thermal effects. The full width of the difference spectrum, which includes the spectral width of both the orotron and the klystron, was determined to be 0.4 MHz. This result is consistent with the prediction based on the theoretical value of df/dV and the regulation of the cathode power supply, which give $\Delta f = 0.17$ MHz for the orotron spectrum.

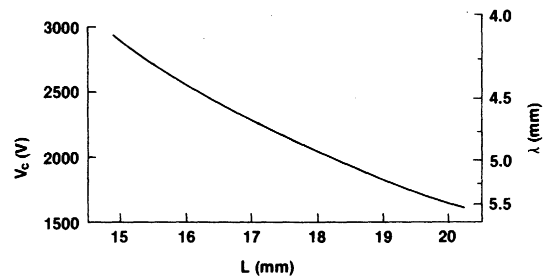

FIG. 3. Tuning range of the orotron. For this figure, the beam accelerating voltage V_c and the mirror separation L were varied simultaneously in such a way that oscillation on the TEM_{207} mode was maintained throughout the tuning range. Oscillation was observed from $\lambda = 4.1$ to 5.6 mm.

A number of different modes of the open resonator were excited by varying the mirror separation and keeping the cathode potential fixed so that $f = 63$ GHz. Four distinct transverse modes were excited in this manner, identified as A, B, C, and D in Table I. One of these (B) is TEM_{20q}, but the others are not definitely identified. Longitudinal mode indices are in the range $4 \leq q \leq 9$. The separation between adjacent modes with the same transverse mode indices is approximately $\lambda/2$ as expected. Threshold currents range from 35 to 70 mA. Starting currents at other

TABLE I. Observed modes of orotron oscillation at $f = 63$ GHz.

L (mm)	I_s (mA)	P (rel. units)	Mode[a]	q[b]
10.2	50	0.20	A	
10.3	60	1.00	B	4
10.8	50	0.12	C	
10.9	65	0.40	D	
12.6	42	0.30	A	
12.7	55	0.56	B	5
13.0	55	0.06	C	
13.3	60	0.28	D	
15.0	43	0.20	A	
15.1	48	0.60	B	6
15.5	45	0.07	C	
15.8	60	0.22	D	
17.4	39	0.38	A	
17.5	56	0.68	B	7
18.0	56	0.07	C	
18.3	70	0.48	D	
19.8	35	0.40	A	
19.9	55	0.64	B	8
20.4	60	0.07	C	
22.2	36	0.39	A	
22.3	50	0.58	B	9
23.2	70	0.32	D	

[a]Each letter corresponds to a particular pair of transverse mode indices (nm). [b]Longitudinal mode index.

frequencies are as high as 82 mA.

Measurements of output as a function of the distance of the electron beam from the grating indicate that oscillation disappears at distances greater than about 0.2 mm, consistent with the theoretical predictions.

We thank the following individuals for their contributions to various aspects of the research: Anthony J. Caiazzo, John Cesca, Bill Delancey, and Seth Butler, all of Harry Diamond Laboratories; Gunter Dohler and Rick Scafuri, of Northrop Corporation; and Anaconda Copper Company.

[1]D. A. G. Deacon, L. R. Elias, J. M. J. Madey, G. J. Ramian, H. A. Schwettman, and T. I. Smith, Phys. Rev. Lett. 38, 892 (1977).

[2]A. V. Gaponov, A. L. Gol'denberg, D. P. Grigor'ev, I. M. Orlova, T. B. Pankratova, and M. I. Petelin, JETP Lett. 2, 267 (1965) [Pis'ma Zh. Eksp. Teor. Fiz. 2, 430 (1965)].

[3]J. E. Walsh, T. C. Marshall, and S. P. Schlesinger, Bull. Am. Phys. Soc. 21, 692 (1976).

[4]S. J. Smith and E. M. Purcell, Phys. Rev. 92, 1069 (1953).

[5]F. S. Rusin and G. D. Bogomolov, JETP Lett. 4, 160 (1966) [Pis'ma Zh. Eksp. Teor. Fiz. 4, 236 (1966)].

[6]K. Mizuno, S. Ono, and Y. Shibata, IEEE Trans. Electron Devices 20, 749 (1973).

[7]V. K. Korneenkov, A. A. Petrushin, B. K. Skrynnik, and V. P. Shestopalov, Radiophys. Quantum Electron. 20, 197 (1977) [Izv. Vyssh. Uchebn. Zaved. Radiofiz. 20, 290 (1977)].

[8]R. P. Leavitt, D. E. Wrotman, and C. A. Morrison, Appl. Phys. Lett. 35, 363 (1979); see also A. Gover and A. Yariv, Appl. Phys. 16, 121 (1978).

[9]F. J. Crowne, R. P. Leavitt, and T. L. Worchesky, Phys. Rev. A 24, 1154 (1981) (following paper).

[10]J. R. Pierce, *Theory and Design of Electron Beams* (Van Nostrand, New York, 1954).