DESIGN AND OPERATION OF AN OROTRON-A TUNABLE SOURCE OF COHERENT MILLIMETER WAVE RADIATION

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ABSTRACT

Results are given that describe our experimental observations of orotron oscillation and the physical principles which govern the design of this device, a Smith-Purcell free-electron laser for the millimeter and submillimeter wavelength regions.

Introduction

Millimeter wave radiation has been generated by a device which we call an orotron[1] after Rusin and Bogomolov;[2] similar devices are called ledatrons[3] and diffraction radiation generators.[4] The theory has also been developed[1,5] which led to our construction of this device.

In the orotron, shown schematically in Fig. 1, a sheet electron beam passes over and interacts with a metallic reflecting diffraction grating imbedded in a cylindrical mirror which, with a spherical mirror above it, forms an open resonator (or spherocylindrical cavity). This resonator reflects the radiation emitted by the beam back onto the beam and causes the beam to bunch. When the proper conditions of synchronism are met between the electron velocity and the phase velocity of a slow wave propagating along the grating surface, the orotron will radiate coherently at a frequency near one of the resonant frequencies of the open resonator, determined by the Smith-Purcell condition $f = v_0/\ell$, where v_0 is the electron velocity and ℓ is the period (or pitch) of the grating.

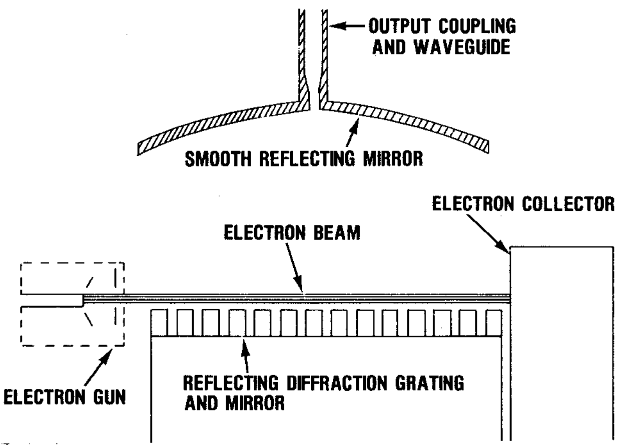

FIGURE 1: SCHEMATIC DESIGN OF OROTRON

Description of Experiment

A block diagram of the experimental equipment is shown in Fig. 2. The orotron, enclosed in a vacuum chamber at a pressure of about 10^{-7} torr, is situated between the pole pieces of a 22-in. Varian magnet. The magnetic field, which serves only to guide the 0.3 mm x 10.0 mm sheet electron beam, can be varied up to 12 kG and has a uniformity of at least 1 G in 2500 G over the region of the beam. This field was usually set near 4 kG, but continuous oscillation of any mode could be achieved at fields between 2 kG and 12 kG. A 4-in. sapphire window on the front of the chamber allows viewing of critical components during operation of the device and is essential for beam alignment since the positions of the beam striking the collector, apertures, or grating could be seen.

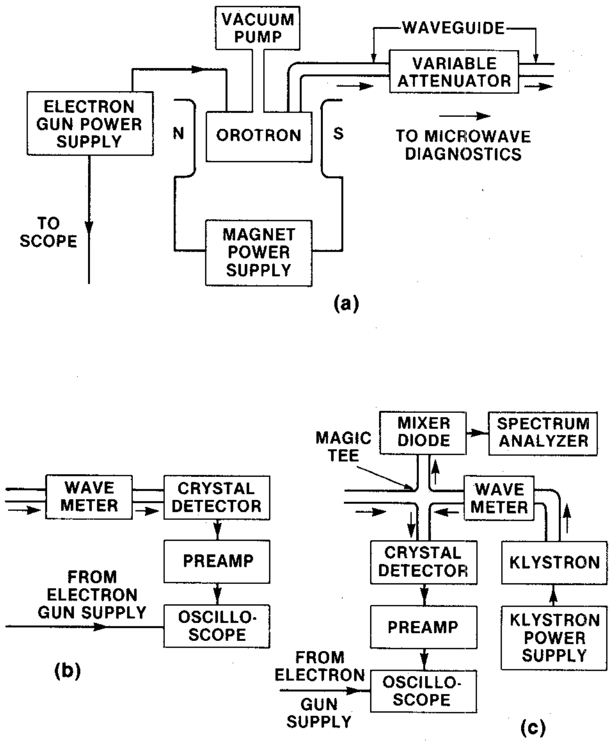

FIGURE 2: BLOCK DIAGRAM OF THE EXPERIMENT. (a) THE OROTRON, POWER SUPPLIES AND MAGNET, AND THE WAVEGUIDE WITH VARIABLE ATTENUATOR. (b) MICROWAVE DIAGNOSTICS FOR BASIC POWER AND FREQUENCY MEASUREMENTS. (c) MICROWAVE DIAGNOSTICS FOR SPECTRAL MEASUREMENTS.

Output radiation from the device was fed into the microwave diagnostic equipment (b or c of Fig. 2). In the power and frequency measurements, the signal was detected by a high sensitivity Shottky diode after passing through the E-band attenuator and frequency meter. For spectral and linewidth measurements, the orotron output radiation was directed onto a mixer diode along with approximately 70 GHz radiation from a klystron. The difference frequency was then fed into a Hewlett-Packard spectrum analyzer.

The electron gun and associated electronic components that power the device are shown schematically in Fig. 3. During space-charge limited operation, the electron speed at the grating is determined by the potential difference between the cathode and the grating, and the electron current is determined by the potential

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difference between the cathode and the anode. The focus electrode potential is usually near that of the cathode and is used primarily to minimize the scalloping (or rippling) of the electron beam; it was used sometimes to control beam current. Apertures are also mounted on either end of the grating to aid in beam alignment and to electrically isolate the grating from the gun optics.

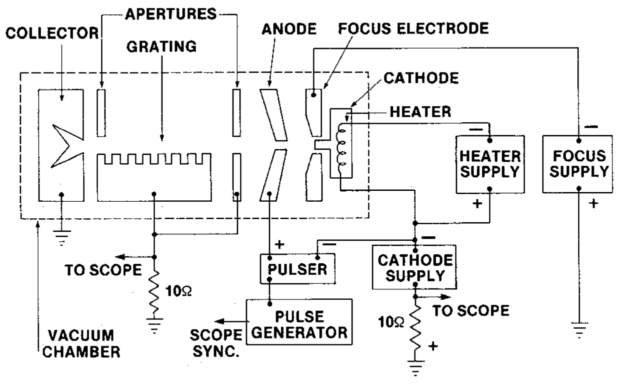

FIGURE 3: WIRING DIAGRAM FOR THE OROTRON.

The diffraction grating, made of copper alloy C147, is 40 mm long, 10 mm wide, and 5 mm thick. The rectangular grooves of the grating are 0.15 mm wide and 0.88 mm deep; the pitch or period of the grating is 0.4 mm. These grating parameters were determined by optimizing the first term in the expansion of the electromagnetic field above the grating.

The cathodes were machined from 5 mm x 10 mm barium-impregnated dispenser cathodes, obtained from Spectromat, to the final size of 0.3 mm x 10 mm. The gun was constructed and tested by Northrop Corp. and originally met the specifications of delivering 150 mA at an anode-cathode potential difference of 2500 V. Some deterioration of the cathode's performance was noted after its installation in the orotron.

Results and Discussion

The millimeter wave radiation generated by the Harry Diamond Laboratories orotron has been tuned in frequency on a single mode from 53 to 73 GHz as shown in Fig. 4. Oscillation has been observed for several modes of the open resonator of the device, with starting currents ranging from 35 mA to 82 mA at beam voltages between 1600 and 3000 V. The electronic tuning transconductance within a single mode was found to be df/dV - 0.25 MHz/V as determined by mixing the orotron signal with a signal from a klystron. The spectrum of the orotron output signal, also measured by this method, yielded a linewidth less than 0.4 MHz. Output power in a quasi-CW mode was limited to about 10 mW by a 100 mA maximum beam current from the electron gun and by the coupling aperture of the upper mirror. A typical power vs. current curve is shown in Fig. 5. Pulse widths were varied between 2 and 200 μs with no noticeable differences in the behavior of the device. Oscillation ceased when the electron beam was raised to more than about 0.1 mm above the grating and again fell when too much of the beam intercepted the grating as shown in Fig. 6. The predominant mode of oscillation was identified as TEM_{207} as determined by scaling results of other measurements made at about 15 GHz with an automatic, computer-controlled network analyzer and a model whose dimensions were scaled up by a factor of five.

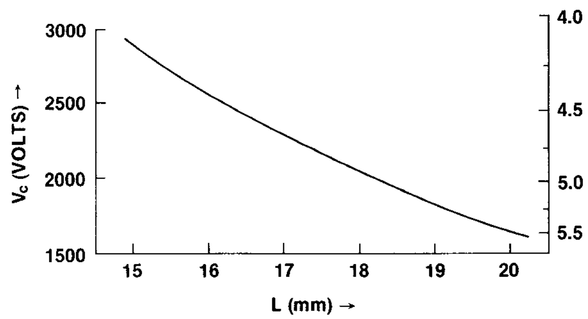

FIGURE 4: TUNING RANGE FOR THE OROTRON. FOR THIS FIGURE, THE VOLTAGE AND MIRROR SEPARATION, L, WERE VARIED SIMULTANEOUSLY IN SUCH A WAY THAT OSCILLATION ON THE TEM_{207} MODE WAS MAINTAINED THROUGHOUT THE RANGE. OSCILLATION WAS OBSERVED FROM f = 53.6 GHz (λ = 5.6 mm) to f = 73.2 GHz (λ = 4.1 mm).

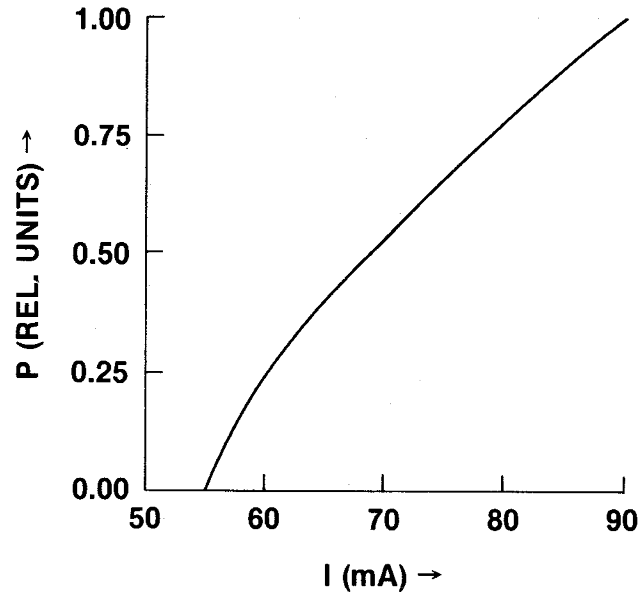

FIGURE 5: OUTPUT POWER VS. INPUT BEAM CURRENT FOR THE TEM_{207} OROTRON MODE AT 63 GHz. THE THRESHOLD CURRENT IS 55 mA FOR THIS MODE.

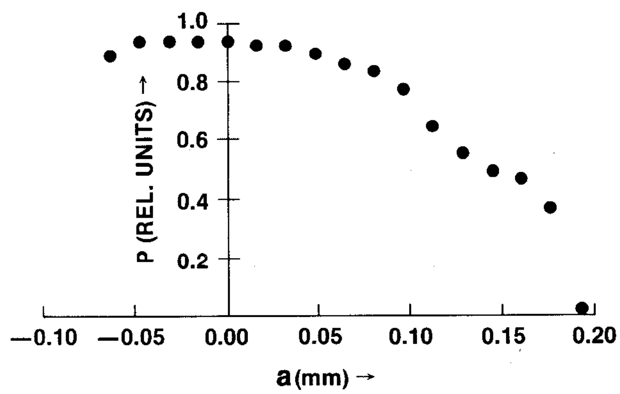

FIGURE 6: OUTPUT POWER VS. DISTANCE OF ELECTRON BEAM ABOVE THE GRATING (TEM_{207} MODE). ZERO DISTANCE IS DEFINED ARBITRARILY AS THE POINT WHERE THE OUTPUT POWER PEAKS.

Additional measurements are contemplated and should be completed soon at wavelengths near 4 mm, with an electron gun currently being tested by Northrop. This gun is expected to deliver more beam current to generate considerably more power, and the output coupling has also been changed. Cold test measurements are being made with a scaled model to determine the effects of various parameters, such as the grating width, in the hope of improving the performance of the present device.

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