Gigatron, a new technology for microwave power devices

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ABSTRACT

AC02-85ER40236

The gigatron is a new design concept for microwave power devices. A gated field-emitter array is employed to produce microwave-modulated electron beam directly from the cathode. A ribbon beam configuration is used to mitigate space-charge effects and provide efficient output coupling. A traveling wave output coupler is used to obtain optimum coupling to a wide beam. RF conversion efficiency is estimated at 75%. Gigatron-family devices have been designed for applications from 3 GHz to 60 GHz frequency, from 30 W microtubes for phased-array antenna drivers to 500 MW drivers for linac colliders.

1. INTRODUCTION

The Accelerator Research Laboratory at Texas A&M University is developing a new technology, called gigatron, which appears to offer great promise for compact microwave power sources. In the gigatron, a fully modulated electron beam is produced from a gated field-emitter array (FEA) cathode. The bunched beam is then accelerated through a high-voltage diode structure into a resonant output coupler. Several significant innovations have been introduced to achieve high-efficiency, high frequency, and high power in a compact device.

Two configurations of the gigatron are envisioned, for medium and high power applications. For medium power applications, a round electron beam is employed. The output coupler consists of a cylindrical cavity operating in the TM_{010} mode. For high power applications, a ribbon beam is employed. The output coupler consists of a section of slotted rectangular waveguide, configured to permit the passage of the ribbon beam parallel to the electric field of a TE_{10} traveling wave. By a suitable matching condition, each component of the ribbon beam encounters the same rf phase: the beam "surfs" on the traveling wave.

The choice of round beam or ribbon beam is governed by the output power required for a given application. One example of a round-beam application is the design shown in Figure 1 and summarized in Table I. It is a tiny 60 GHz gigatron, rated for 1 kW pulse, 30 W average power. It is small enough (1 cm³ tube size) to be integrated directly onto each patch element of a phased-array antenna. Phase control is achieved via a

1a. Microgigatron amplifier configured as a phased-array element driver.

1b. FEA cathode and resonant coupler for coax mount.

control grid. The entire phase controlled power driver can be configured within a 72 cm thick layer directly behind each antenna element. This round-beam design is described in detail in the following section. It can be optimized for a wide variety of parameter choices in frequency, bandwidth, and power.

One example of a ribbon beam application is shown in Figure 2 and summarized in Table II. It is a 1 m long ribbon gigatron, designed to produce 70 MW peak power at 18 GHz. Eight such gigatrons can be configured in a compact (0.5 m³) cylindrical array as shown in Figure 2, to produce 500 MW pulse power with high efficiency. Because the device has extremely large collector surface area, it can support a much larger average power than any known alternative.

2. THE GIGATRON DESIGN CONCEPT

Current technology for millimeter-wave sources is severely limited in power and efficiency for frequencies beyond 10 GHz. Almost all current devices (TWT, klystron, FEL, gyroklystron) employ the same basic e-beam strategy:

- o a dc electron beam is accelerated through a high-voltage diode;
- o the beam is modulated (in energy or direction) by an input cavity;
- o the beam transverses a drift region in which the above modulation produces a phase modulation of the beam current;
- o the rf current passes through an output cavity where the beam is decelerated and the rf power is coupled to an output waveguide.

The main limitations to high-frequency performance arise in the bunching process. The electric potential within an electron beam is depressed by the space charge of the beam itself. The difference in potential of an electron on the edge of the beam and one in the beam center is proportional to the instantaneous beam current. When voltage modulation is applied to the beam in the input buncher, the resulting energy modulation is smeared by the spread in space charge potential. As the beam begins to bunch, the peak current increases, and with it the magnitude of the space charge depression, until the energy spread equals the applied modulation: this defines the space charge limit to the bunching process.

A proper phase-space description of the bunching process is quite complicated, but reproduces the above behavior. As the rf frequency is increased, the dynamics of bunch formation becomes increasingly sensitive to the energy spread in the beam, since the resulting transit-time spread produces a larger phase spread. The buncher also produces transverse as well as longitudinal fields, and thereby perturbs the transverse motion of the beam. Beam stability in the drift region places additional limits on tube performance, and generally requires focussing magnetic fields to confine transverse beam motion. Growth in transverse beam size results in a further phase dispersion in the rf field seen by the beam as it traverses the output coupler.

Table 1. Parameters of Microgigatron

$\omega/2\pi$	rf frequency	60 GHz
P	rf peak power	1.6 kW
P _o	maximum average power	30 W
G _{av}	power gain	20 dB
η	rf efficiency	74%
V	beam voltage	50 kV
I _b	peak beam current	0.2 A
$\Delta\phi$	beam phase width	60°
dφ/dV	grid phase modulation	0.65°/V

Table 2. Parameters of Example Gigatron

$\omega/2\pi$	rf frequency	18 GHz
P	rf peak power	70 kW
G _o	power gain	27 dB
	rf efficiency	74%
V	beam voltage	200 kVDC
	peak beam current	390 A
ϕ	rf phase	230°
$\Delta\phi$	beam phase width	60°
$l \cdot w$	cathode size	100 x .1 cm ²
$a \cdot b$	waveguide coupler (WR42)	1.1 x .4 cm ²
g, h	slot width, height	.2 cm, .3 cm
β	electron velocity/c	.70
β^E	phase velocity/c	1.37
θ^P	ribbon tilt angle	27°
ψ	magnetic bend angle	22°
E _o	peak rf field	125 MV/m

2. Gigawatt Ribbon Gigatron

The above effects limit the efficiency of conventional rf tubes to ~2-20% for frequencies above 10 GHz. The maximum output power is shown in Figure 3 as a function of frequency for various tube designs. The structures of high power tubes are in general quite complicated, and require magnetic guide fields and multiple output cavities.

The proposed source removes the requirements of buncher and drift region, thereby cutting the Gordian knot of tube design. The beam is produced from a gated field-emitter cathode; the beam is fully modulated from birth. It is accelerated across a high-voltage diode and then enters an output coupler where the beam is decelerated against the coupler field to drive output power. The residual beam is collected in a conventional collector cup. There is no bunching cavity and no significant drift region. The tube design approaches an impulse approximation, in which the beam has minimum time to respond to perturbing forces. As shown below, the result is high efficiency of rf conversion, high power capability, compact structure, no requirement of magnetic guide fields, and suppression of parasitic modes. These advantages should translate into improved performance and reduced cost for both medium and high power applications.

The principle of gigatron operation is illustrated in Figure 4. A fully modulated ribbon electron beam is produced from a strip cathode of gated field-emitter array (FEA). The ribbon beam is accelerated through a high-voltage diode structure, and enters a drift slot leading to the output coupler. The output coupler consists of a slotted waveguide connected to form a resonant loop. The waveguide slot is configured to permit passage of the ribbon beam through the waveguide, parallel to the electric field of a traveling wave. The electron beam is decelerated by the wave, and thereby drives the wave amplitude. Optimum phase match to the electron beam is maintained over an arbitrary beam width by phasing the electron beam emission from the cathode to tilt the ribbons with respect to the direction of acceleration. By a suitable matching condition, the transverse position of the electron packet traversing the coupler slot can be made to move sideways at the same rate as the phase velocity of the traveling wave. The beam "surfs" with the wave, and optimum coupling can be preserved over an arbitrary beam width.

The advantages of the gigatron include a) low-loss coupling of input power to the FEA structure; b) e-beam fully modulated before acceleration; c) elimination of space-charge limits to high power/high frequency by using ribbon beam geometry; d) close coupling to the ribbon beam in the output coupler reduces phase dispersion at high frequency; e) provision of optimum output coupling over a wide beam front, using the traveling wave coupler; e) elimination of the requirement for static guide fields that characterize nearly all high frequency power tubes; f) simple, compact structure. Table II summarizes the important parameters of a particular design which has been evaluated recently. The following text describes each aspect of the gigatron design. Numerical calculations are specific to the parameters of Table II.

3. Rf power vs frequency for conventional devices.
(from ref. 8)

4. Ribbon beam geometry and traveling wave coupler.

5. Gated field-emitter array cathode.

2.1. Gated field-emitter cathode

The gated field-emitter (FEA) cathode appears to offer an attractive new technology for achieving a high current, fully modulated electron beam directly from a cathode structure. C.S. Spindt et al.³ and H. Gray et al.⁴ have developed microfabrication techniques by which they can prepare planar arrays of field-emitting points. Gray uses directional etching techniques to produce atomically sharp needle and knife-edge arrays directly on silicon. A silicon-insulator-metal gate structure is then deposited on the cathode substrate, and plasma-etched to form a planar array of micro triodes. Application of a modest (25 V rms) gate-cathode voltage results in full modulation of emission current. Currents of $>100 \text{ A/cm}^2$ (up to 1000 A/cm^2) have been routinely achieved. There is no evidence of in-service deterioration during extended life tests.

We have improved upon the fabrication procedure of Gray in two respects that are critical to achieve high-frequency modulation. First, the silicon surface is metalized after formation of the field-emitting tips, as shown in Fig. 5. This provides a metal base surface for low-impedance charging of the FEA tips. In the devices fabricated by Gray and Spindt³, charging current must flow through the bulk of the silicon substrate. Even with heavy doping, the silicon substrate presents an unacceptable charging resistance ($\rho > .01 \Omega \text{ cm}$) at high frequency.

Second, a fabrication process has been devised whereby an optimum field geometry can be produced for quiescent electron optics. The optics of the electron beam emission from the FEA cathode determines the initial emittance of the beam in the gigatron. We have calculated the beam dynamics during field emission using the computer code MASK⁵. Beam is assumed to be emitted from the tip into a cone of half-angle $\pi/4$. Figure 6 shows the transport at several time intervals after emission from a two gate FEA structure. The tip/gate geometry of the cathode forms an approximate point-to-parallel optical lens. As a result the emitted beam will have a much smaller emittance than the previous estimates based simply on assuming a transverse temperature $T_{\perp} \sim \text{eV}$. The beam divergence produces negligible transverse growth at the anode aperture, and hence does not pose a limitation to gigatron performance. If in fact the effective emittance is very small, the improved FEA cathode may be an excellent candidate for electron sources for linacs, FEL's etc.

2.2. Resonant input coupler

The field-emitter array presents a highly reactive load to a modulation driver. Matching can be optimized by configuring the cathode within a sequence of coupled lumped-constant resonant circuits, as shown in Figure 7. The gate/base junction of the FEA constitutes a capacitance C_1 . A metalized quartz fiber is mounted adjacent to the FEA, and the metal-insulator-metal layers (without tips) are continued laterally to form a tuning capacitance C_2 . The gate layer metalization and quartz fiber metalization are interrupted along the region where the fiber contacts the insulating layer, so that rf currents to/from the gate layer must flow around the fiber - it is an inductor L . The system $C_1 - L - C_2$ then forms a resonant circuit whose frequency can be controlled by choice of the radius r of the inductive fiber:

$$L = \mu_0 \pi r^2 / x \quad (1)$$

The cathode and resonant coupler are divided lengthwise into segments of equal length $x = 5 \text{ mm}$. The metalized inductor is fabricated separately and bonded to the gate layers of C_1 and C_2 by conventional ultrasonic bonding.

6. Acceleration of an electron bunch from an FEA cathode.

7. FEA cathode and resonant coupler.

8. Equivalent circuit of FEA cathode and resonant coupler.

Figure 8 shows an equivalent circuit of the cathode system, including dc bias network, resonant network, and impedance matching network. Each resonant circuit is capacitively coupled (C_c) to an impedance matching network which matches rf power from a waveguide into the sequence of input couplers. Resonance occurs at an angular frequency

$$\omega = \frac{1}{\sqrt{LC_0}} \quad (2)$$

where C_0 is the equivalent capacitance of C_1 , C_2 , C_c . The resistance R in the equivalent circuit is the effective series resistance to current flow in the resonant circuit:

$$R = (\frac{1}{4} w + 2\pi r) R_s / x \quad (3)$$

where $R_s = .04 \Omega$ is the surface resistance of the metalizations. The Q of the resonant circuit is

$$Q = \frac{1}{\omega C_0 R} = \frac{2}{\omega C_1 R} \quad (4)$$

The resulting load impedance Z_L for critical coupling is

$$Z_L = (\frac{1}{1+1}) Q^2 R / 4 \quad (5)$$

Using parameters of Table I, each resonant network has

$$\begin{aligned} C_1 &= C_2 = 72 \text{ pF} \\ C_c &= 5 \text{ pF} \\ L_c &= 2.2 \text{ pH} \\ r &= 50 \text{ } \mu\text{m} \\ R &= 9 \times 10^{-3} \Omega \\ Q &= 28 \\ Z_L &= 2 \Omega \end{aligned} \quad (6)$$

The emission current corresponding to the above modulation characteristic is $I_m = 2700 \text{ A peak}$, $I_0 = 55 \text{ A}$ off-phase from a $(1 \text{ mm} \times 1 \text{ mm})$ cathode. The power supplied from the input modulator that is required to supply this emission is

$$P_e = I_m V_m \frac{\sin(\Delta\phi/2)}{\pi} = 15 \text{ kW} \quad (7)$$

The input power P_m required to drive each resonant network is

$$P_m = R(\omega C_1 V_m)^2 / 2 = 2.5 \text{ kW} \quad (8)$$

In the overall cathode there are $N = 2l/x = 400$ networks. The total input rf power requirement is

$$P_{in} = P_e + NP_m = 150 \text{ kW} \quad (9)$$

The rf gain of gigatron is therefore

$$G = \log(P_{out}/P_{in}) = 27 \text{ dB.} \quad (10)$$

2.3. Traveling Wave Coupler

The ribbon-beam geometry makes it possible to couple strongly to a high-current beam even at high frequency. There is, however, a problem in matching the phase of the RF field stored in the coupler with that of each beam bunch as it passes through the coupler slot. A coupler extracts energy from an electron by decelerating it across a gap g (see Fig. 2). The coupler must store energy to produce a decelerating field E sufficient to extract a significant fraction of the electron energy:

$$Eg \sim V \quad (11)$$

The decelerating field is oscillating at the desired frequency, $E = E_0 \cos(\omega t + \phi)$. Coupler structures are normally designed as standing-wave resonators. In the gigatron, however, the beam is wide ($l \gg \lambda$). The phase ϕ in a standing-wave structure would thus vary through several full cycles across the width of the beam. Some elements of the beam would be accelerated while others would be decelerated, so that no net energy transfer would result.

The traveling-wave coupler of Fig. 4 removes this difficulty. The coupler is a segment of waveguide which is slot coupled to the beam. The ribbon beam is modulated such that the incident beam front makes an angle θ with respect to the beam direction. A simple model requiring uniform acceleration across the beam yields a relation between the beam angle θ , electron velocity β_e , and the waveguide phase velocity β_p :

$$\beta_e = \beta_p \tan \theta \quad (12)$$

The beam will then drive this traveling wave at a constant phase across the entire beam width. The beam "surfs" with the traveling wave.

Radiation into the diode region is strongly attenuated and would not disrupt the ribbon bunch structure. Waveguide magnetic fields require further refinements to this simple model. Each beam component is bent sideways by an angle ψ due to the in-phase magnetic field ($B = E/\beta_p c$) of the traveling wave:

$$\psi = \int \frac{eB \, dl}{\sqrt{2meV}} = \frac{eE_0 \cos \phi}{b_p c \sqrt{meV}} = 22^\circ \quad (13)$$

The coupler must return sufficient beam energy to its input to generate the required decelerating field. This can be accomplished either by linking two traveling-wave couplers end to end in a resonant loop or by configuring the waveguide in a circular ring driven by a helical beam. The required Q is

$$Q = \omega \frac{[\text{stored energy}]}{[\text{output power}]} = \omega \frac{[\epsilon_0 E_0^2 g^2 al / 2b]}{P_0} = 1250 \quad (14)$$

The unloaded Q for the TE_{10} mode is

$$Q = \frac{b}{\delta_c} \left[1 + \frac{b}{a} \left(\frac{\omega_0}{\omega} \right)^2 \right]^{-1} = 3000 \quad (15)$$

where $\delta_c = 0.53 \, \mu\text{m}$ is the skin depth of copper at 18 GHz.

3. DEVICE PERFORMANCE

We have calculated beam transport through the gigatron. Calculations were performed using the MASK⁵ computer code. Fig. 9 shows the trajectories of successive bunches through the diode region. Fig. 10 shows

9. Calculated ribbon beam trajectories through diode region.

the trajectories of two successive ribbons through the coupler structure. Trajectories are shown on five points across each ribbon. Both transverse position and energy are shown for each trajectory. Slot width and height, coupler peak field, RF phase, and beam phase width were varied to optimize RF efficiency while transporting residual beam to the collector. For the optimized parameters, RF conversion efficiency of 74 % is obtained. No beam is intercepted before entering the collector structure.

We now have operational FEA cathodes at Texas A&M. The IV curves of these cathodes are presented in Figure 11. The cathodes were made for us by C.S. Spindt, and employ this traditional fabrication approach. We have built a vacuum assembly for testing the IV characteristics of cathodes in pulse mode, including provision for rf modulation. We have also built the complete vacuum structure for a round-beam gigatron prototype, with design parameters 12 GHz, 40 kW. During the coming year we plan to develop a FEA cathode embodying the above improvements.

10. Electron energy and bunch motion through the traveling wave coupler.

11. Experimental I/V response of FEA arrays.

4. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge stimulating discussions with W.B. Herrmannsfeldt, K.R. Eppley, R. Miller, R. Taylor, J. Welch of SLAC, C.A. Spindt of SRI, K. Chang, K.L. Parker and R. Rogers of Texas A&M. This work is supported by U.S. Department of Energy contract No. DE-AC02-85ER40236.

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