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High-Power Ka-Band Amplifier

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Development of a high-power tube suitable to power a Ka-band (34.5-GHz) antenna transmitter located at the Goldstone, California, tracking station is continuing. The University of Maryland Laboratory for Plasma Research and JPL are conducting a joint effort to test the feasibility of phase locking a second-harmonic gyrotron both by direct injection at the output cavity and by using a priming cavity to bunch the electrons in the beam. This article describes several design options and the results of computer simulation testing.

I. Introduction

For the past 7 years, there has been continuing effort in the design and development of a high-power tube to generate 200 to 400 kW of continuous wave (CW) power at 34.5 GHz (Ka-band) for a high-power antenna transmitter to be located at Goldstone, California. Varian Associates completed the design of a 400-kW gyroklystron in 1986 [1]. Subsequently, several studies were made of the feasibility of phase locking a gyrotron oscillator [2,3]. Two methods of phase locking are possible: adding a priming cavity to bunch the beam or direct injection at the output. A recently developed harmonic gyrotron is a promising new device for this transmitter.

The original plan was to generate detailed electrical, mechanical, and thermal designs that would form the basis for the construction and testing of a prototype gyroklystron. Due to lack of funding, construction of the prototype never occurred [1]. Nonetheless, the findings from

the design of the gyroklystron are applicable to the design of a gyrotron with a priming cavity; both devices are similar in performance and in construction.

II. Gyroklystron Amplifier

Table 1 is a list of important design specifications, and Fig. 1 is a schematic diagram of the proposed gyroklystron. The assembly consists of a magnetron injection gun (MIG), two buncher cavities, an output cavity, a collector and RF windows, and a mode converter. Not shown is the superconducting magnet assembly. The total assembly length, including cathode oil tank and mode converter at the output, is 400 cm. The design incorporates the following important technical and conceptual advances:

- (1) Space-charge effects cause increased beam velocity spread in the drift space that connects the gun to the circuit. Nevertheless, beam quality can be main-

tained by compensating for this effect and by minimizing the distance from the gun to the circuit.

- (2) Sufficient loading can be provided by buncher cavities made of graphite, replacing external cavity loads. This requires a circuit design that allows no more than 5 kW of heat dissipation in each buncher cavity.
- (3) Drift sections that are weakly cut off affect buncher cavity designs, appreciably altering beam loading and cavity resonant frequency. Linear stability requires unconventional buncher cavity geometries.
- (4) The amplifier can operate as a mode-locked oscillator, with output phase and frequency controlled at saturation even if the output cavity is unstable in the linear mode. Stability constraints can be relaxed while still allowing the device to perform as required.
- (5) The magnetic field profile in the taper section connecting the output cavity to the collector affects linear gain and nonlinear behavior (hysteresis effects of the amplifier).

A maximum design voltage gradient well below 100 kV/cm was chosen for reliable and long-life CW operation. After considerable effort had been expended to reduce the gradient on the high-voltage seal using previously designed guns, it was concluded that a major redesign was necessary. As a result, a new gun was designed with a larger outer diameter and new internal dimensions; this design resulted in reduction of the surface gradient at the gun anode tip to levels below 75 kV/cm.

Velocity spread, a most important parameter, affects the efficiency of gyrotrons. A MIG cathode usually operates in the temperature-limited mode, and the perpendicular velocity spread of electrons is assumed to be independent of the current as the beam drifts from the gun acceleration region to the first cavity. This assumption of laminar flow required a higher cathode angle, resulting in a cathode loading in excess of 10 A/cm². Because of high loading, this approach was abandoned.

Space-charge effects cause increasing perpendicular velocity spread in the gun drift space. This was a previously unexplored phenomenon in gun design. Electrons emitted from the upper part of the cathode continuously accelerate while those emitted from the lower part decelerate. For electrons with intercepting paths, the result is nonuniform acceleration. Many techniques can be used to reduce the effects of increased velocity spread. Reducing gun drift space length, for example, significantly reduces

the velocity spread; this reduction occurs because velocity spread enhancement is a cumulative effect. The maximum current loading tolerated in the magnet dictates the minimum length between gun and circuit. The addition of a bucking coil reduced velocity spread by 50 percent by modifying the field profile in the gun acceleration region.

The interactive circuit consists of two buncher cavities and an output cavity. Buncher cavities use the dominant TE_{11} mode while the output cavity uses the overmode TE_{12} . Between cavities, drift sections prevent internal feedback. A third buncher cavity to fully bunch the beam before entering the output cavity required large power dissipation, estimated at between 10 and 20 kW for a fundamental mode TE_{11} cavity, and consequently was not included. Final bunching of the electrons occurs in the output cavity to develop the required gain. An overmoded output cavity keeps ohmic wall dissipation to the reasonable levels of less than 1 kW/cm² and provides sufficient stored energy compatible with 400-kW output.

A special design feature consists of manufacturing the TE_{112} mode buncher cavities out of graphite in place of external loads. A cold test of the closed graphite cavity gave an ohmic Q of about 150. The drift sections shift resonance down by about 2 GHz and modify the mode profile. The external Q also approximately doubled with the addition of drift sections. The solution to the problem presented by weakly cutoff drift sections was to operate the buncher cavities in the TE_{112} mode. This solution provided stable operation and no mode competition with TE_{111} . Axial beam velocity spread did affect gain and output power. A 23-percent reduction in saturated output power occurred for a 15-percent axial velocity spread. Limiting axial velocity spread to less than 10 percent is necessary to maintain acceptable gain and output power.

A normalized magnetic field of 0.937 provides optimum performance, which is also close to the stability boundary. At low drive power levels, computer simulations predict a constant linear gain, up to between 3.5 and 4 watts of drive, where a large nonlinear increase in power occurs. The jump in power was 3 dB and the phase decreased by 60 deg. At this higher output power level, the phase again became constant, indicating amplifier operation. When reducing drive, the output did not follow the same path as when drive was increasing—the sudden jump in output power occurred at a lower drive power level. One conclusion drawn was that when operating under CW-saturated conditions, a well-defined line dividing stable and unstable operation does not exist. When the magnetic field was increased past the stability boundary, sufficient drive power locked the output, causing output phase and frequency

to follow input drive within a narrow bandwidth. For all practical purposes, the device performed as a phase-locked saturated amplifier.

If beam wave interaction occurs in the up-taper region of the output cavity (as it surely must unless the magnetic field suddenly decreases right outside the output cavity), the sudden rise in gain and the hysteresis effects of output power with drive power previously seen in a computer simulation disappear. Allowing interaction in the up-taper did not change saturated output power.

Table 2 summarizes sensitivities to key operating parameters. Computer simulations provided the values. Two parameters that are difficult to predict due to incomplete theory are harmonic emissions and the noise figure. Based on results of measurements made on other gyrotrons, second harmonic emission should be less than -20 dBc. As for the noise figure, an estimate of 83 dB due to shot noise in a temperature-limited beam is calculated. The noise contribution of electrostatic modes was not calculated.

III. Two-Cavity Phase-Locked Gyrotron

If operating at one power level is acceptable, then an oscillator could be phase locked to provide communication and radar signals. Victor Granatstein, Peter Latham, and Yuval Carmel made two feasibility studies of gyrotrons with two cavities, one developing a new gyrotron and the other modifying the Varian VGA-8003 by adding a priming cavity [2,3]. Use of a priming cavity allows bunching of the electrons in the beam. With the beam bunched, frequency and phase of the output can be controlled. Except for a decrease in output power from 400 kW to 200 kW and linear amplifier operation, the requirements remained practically unchanged from those previously used for the gyrokystron design. Both designs meet minimum requirements for this transmitter. The modified VGA-8003 meets the minimum requirement of 25 dB for carrier suppression but not the goal of 60 dB. Table 3 gives a comparison of results of these two feasibility studies. Table 4 summarizes the sensitivity to variations in operating parameters.

In the first feasibility study, the output cavity operates in the circularly polarized TE_{11} mode. With an operating output power capability of 330 kW, the calculated peak cavity surface dissipation was 2.5 kW/cm^2 , which is excessive. By limiting the output power to 260 kW, the peak wall loss equals 2 kW/cm^2 and average losses equal 1.2 kW/cm^2 . These preliminary values are quite high but actual values will probably be somewhat lower in the final design. Other major requirements are an efficiency of at least 30 percent with a bandwidth of better than

30 MHz. To operate from commercially available generators requires 35 dB of gain. Calculations show a buncher cavity with a Q of 22, a drift length of 8 cm, and an output cavity with a minimum diffractive Q of 44—all values that are easily achievable in a practical device. This design meets the major requirements.

The addition of a priming cavity and drift space to the Varian VGA-8003 free-running gyrotron oscillator is an alternative to the previous two-cavity phase-locked gyrotron. The VGA-8003 operates in the TE_{01} mode, which has much lower cavity wall losses. For the VGA-8003, an efficiency of 37 percent compared favorably to 26 percent estimated for the previous design. The VGA-8003 requires two mode converters, one to convert TE_{01} to TE_{11} and another to convert linear to right-hand polarization. The addition of a priming cavity and drift section lengthens the VGA-8003, which affects magnet design and efficiency as a result of increased velocity spread. TE_{01} mode cavities are overmoded and allow mode competition. Whatever the approach, a full design remains to be made. The conclusion reached is that use of a priming cavity is a possible means of phase locking a gyrotron to meet the requirements for a DSN Ka-band transmitter.

IV. Single-Cavity Phase-Locked Gyrotron

Use of a developed gyrotron without any modifications is particularly attractive because it minimizes tube development cost and risk. The only available gyrotron, the VGA-8003 manufactured for Lawrence Livermore by Varian Associates, requires a small shift in frequency from 35 to 34.5 GHz. The present tube is not tunable and the output frequency may be anywhere in a 100-MHz bandwidth for optimum performance. For DSN application it would be necessary to optimize performance close to 34.5 GHz.

Phase control in a single cavity gyrotron can be achieved by feeding a signal from a microwave reference source back into the gyrotron's output cavity. The relationship between phase-locking bandwidth and gain, which is exact for a single cavity, is

$$\frac{\delta\omega}{\omega_0} = \frac{1}{Q} \sqrt{\frac{1}{1+G}}$$

where ω_0 and Q are the cavity resonant frequency and quality factor, respectively. Here $\delta\omega$ is the locking bandwidth, which is 1/2 the total bandwidth, and G is the gain. When $G \gg 1$, the expression reduces to Adler's relation [4]

$$\frac{\delta\omega}{\omega_0} = \frac{1}{Q} \sqrt{\frac{P_i}{P_o}}$$

Typical values for Q and output power P_o from Table 5 require 3.3 kW of drive power P_i into the output cavity of the gyrotron for a locking bandwidth of 15 MHz. Allowing for transmission losses, the driver requires an output of 5 kW, but no tubes are available for this power level. Available drivers are 100 W for a travelling wave tube and 1 kW for a klystron. This reduces locking bandwidth to about ± 7 MHz for a 1-kW driver and ± 2.3 MHz for the 100-W driver. To obtain additional bandwidth the center frequency of oscillation may be shifted by varying the beam voltage.

The dependence of resonant frequency on beam voltage was derived by Victor Granatstein, Peter Latham, and Yuval Carmel in a report prepared for JPL [5]. The equation relating pitch angle to beam voltage is

$$\frac{V_b}{\alpha} \frac{d\alpha}{dV_b} = \frac{1 + \alpha^2}{2}$$

Using typical values for the VGA-8003 from Table 5,

$$\frac{d\omega}{\omega} = 0.026 \frac{dV_b}{V_b}$$

a change of 2.8 kV corresponds to a frequency change of 30 MHz. The stability limit of the DSN beam supply is 0.01 percent, which maintains resonant frequency to ± 100 kHz. The addition of a phase detector that compares the gyrotron's output with a reference signal could be used to generate an error signal to control the beam supply with a high-power pass tube. For example, frequency hopping of 8 MHz in less than 10 μ sec and frequency ramping of 78.4×10^6 MHz/sec requires the beam voltage to shift the resonant frequency for the injected signal to reacquire locking. Although this appears feasible, detailed design analysis needs to be completed. The frequency response of the closed-loop phase detector and modulator is a major limitation to controlling beam voltage.

The cathode voltage is the only practical parameter that can be used to shift the gyrotron frequency. The magnetic field controls gyrotron output frequency, but a fundamental problem exists in modulating this parameter. Magnetic field changes take too much time to diffuse through the conductive copper walls of the microwave cavity. A changing magnetic field induces eddy currents in the walls, and the flux inside the cavity is not fully changed

until the eddy currents have decayed. The time for the eddy currents to decay is roughly 10 msec.

The use of a developed gyrotron shifts the costs and risks to the development of a high-power circulator and a high-voltage pass-tube modulator. The circulator isolates the locking signal from the high-power signal out of the gyrotron. Preliminary calculations suggest that such a circulator is realizable in a beam waveguide transmission line [7]. A quasi-optical circulator placed in the beam waveguide directs the gyrotron signal to the antenna while directing the driver locking signal back to the output cavity of the gyrotron. Design of this component is critical to carrying out this phase-locking approach.

V. Second Harmonic Gyrotron

The University of Maryland Laboratory of Plasma Research recently acquired a second harmonic free-running gyrotron oscillator from the People's Republic of China. That gyrotron has produced over 200-kW of output power at 35 GHz with an efficiency of 35 percent. Its success is largely due to the use of a special complex cavity [6]. Dr. H. Z. Guo, who invented this cavity, is now working at the University of Maryland. Phase-locking of this gyrotron is feasible using the same techniques previously discussed in this article for the VGA-8003. Some advantages of this device are especially attractive. Use of the second harmonic reduces the cyclotron frequency by a factor of two; consequently, the magnetic field strength is also reduced by two. The magnetic field for a 35-GHz gyrotron requires nominally 13,000 gauss, which can be generated only with a superconducting magnet. For a second harmonic gyrotron, a magnetic field of 6500 gauss is easily achieved with room temperature solenoid magnets or even permanent magnets.

When phase locking a second-harmonic gyrotron by means of a priming cavity, the locking signal frequency is 17.5 GHz. Drivers at this lower frequency are available with higher output power. Phase locking directly into the output cavity requires a signal at the fundamental cyclotron frequency of 35 GHz. Still, the advantage of a lower magnetic field is preserved. Figure 2 is a schematic of the proposed second harmonic gyrotron with a priming cavity. The output propagates in the TE_{03} mode, and conversion to TE_{11} can be done efficiently.

VI. Future Work

The feasibility tests of a phase-locked second-harmonic gyrotron are continuing under a joint effort by the University of Maryland Laboratory for Plasma Research and

JPL. Two methods are still being considered: direct injection at the output cavity and bunching the electrons in the beam. JPL has responsibility for developing a quasi-optical circulator. The University of Maryland has

a second-harmonic gyrotron from China and is developing a modulator to pulse this tube. The goal is to show the capability of phase locking a gyrotron and to generate specifications for a Ka-band transmitter.

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Table 1. Design specifications.

Parameter	Requirement
Center frequency, GHz	34.5
Instantaneous bandwidth, MHz	34 (30 for gyrotron)
Saturated gain, dB	50 (minimum 35)
RF saturated output power, kW	400 CW (minimum 200)
Harmonic power	TBD
Phase switching, 180 deg, nsec	400
Out of band power, percent	<1 at 0.1 Hz from carrier
Amplitude modulation, dBc	-40 (1 Hz to 1000 Hz)
Group delay dispersion, psec	1.2 (± 6 MHz)
Frequency hopping, MHz	8 in 10 μ sec
Frequency ramping, Hz/nsec	0.04
Carrier suppression, dB	25 with 60 goal
RF output mode	TE_{11} circular polarized
Extraneous modes, dB	-15
Ellipticity, dB	<1
Stability, output power, dB	0.1
DC beam power supply, MW	1.1 maximum
DC beam voltage, kV	100 maximum
Efficiency, percent	40 (minimum 30)
Duty	CW (up to 4-hr pulse)

Table 2. Gyrokystron pushing factors.

Parameter	Phase	Power
Cathode voltage	0.01 deg/volt	0.0013 dB/volt
Filament voltage	90 deg/volt	1.45 dB/volt
Linear drive power	8 deg/dB	0.98 dB/dB
Saturated drive power	5 deg/dB	0.029 dB/dB
Circuit field	0.98 deg/gauss	0.00615 dB/gauss
Gun field	26 deg/gauss	0.74 dB/gauss
Body coolant temperature	0.7 deg/deg C	0.003 dB/deg C
Collector coolant temperature	1 deg/deg C	~ 0

Table 3. Two-cavity gyrotron expected transmitter performance.

Parameter	New design	Modified VGA-8003
Center frequency, GHz	34.5	35
Instantaneous bandwidth, MHz	200	50
Duty	Continuous	Continuous
Output power, kW	260	230
RF output mode	TE_{11}	TE_{01}
Harmonics, dB	< -20	< -20 dB
Drive power, W	~100	~100
Efficiency, percent	>26	~37

Table 4. Two-cavity gyrotron pushing factors.

Parameter	New design	Modified VGA-8003
Change in output power, percent	0.5	0.4
Change in beam current, percent		
Change in output power, percent	0.8	1.0
Change in beam voltage, percent		
Change in phase, deg	3.3	1.8
Change in beam current, percent		
Change in phase, deg	20	41
Change in beam voltage, percent		
Change in output power, dB	0.2	0.3
Change in injector power, dB		
Change in output phase, deg	—	1.0
Change in input power, dB		
Change in beam current, percent	0.083 ^a	0.083 ^a
Change in filament voltage, percent		
Change in output power, percent	0.013	0.02
Change in cavity temperature, deg C		
Change in output power, percent	~0	~0
Change in collector temperature, deg C		
Change in phase, percent	0.08	0.03
Change in cavity temperature, deg C		
Change in phase, percent	1.5	1.5
Change in collector temperature, deg C		
Change in phase, percent	1.8	1.8
Change in waveguide temperature, deg C		
Change in output power, percent	~0	~0
Change in waveguide temperature, deg C		

^a Based on Varian Associates, Inc., estimates for VGT-8195 TWT Gun.

Table 5. Specifications for Varian gyrotron oscillator VGA-8003.

Parameter	Minimum	Maximum	Typical
Output cavity mode	—	—	TE_{01}
Frequency, GHz	34.5	35.5	35.0
Q	250	300	275
Beam voltage, kV	70	90	85
Beam current, A	4	10	7
$\alpha = v_{lo}/v_{zo}$	1.5	2.0	1.75
Magnetic field, kG	—	—	13.6
Beam radius, cm	—	—	0.254

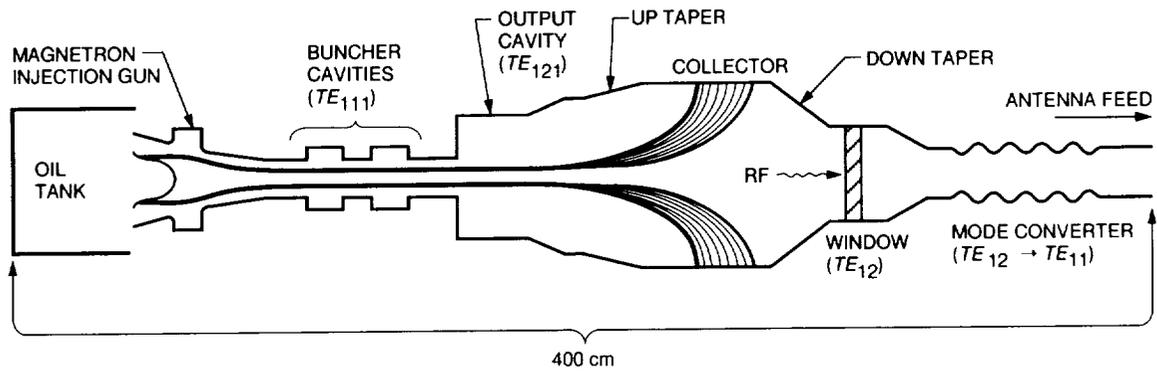


Fig. 1. Schematic of proposed gyrokystron amplifier.

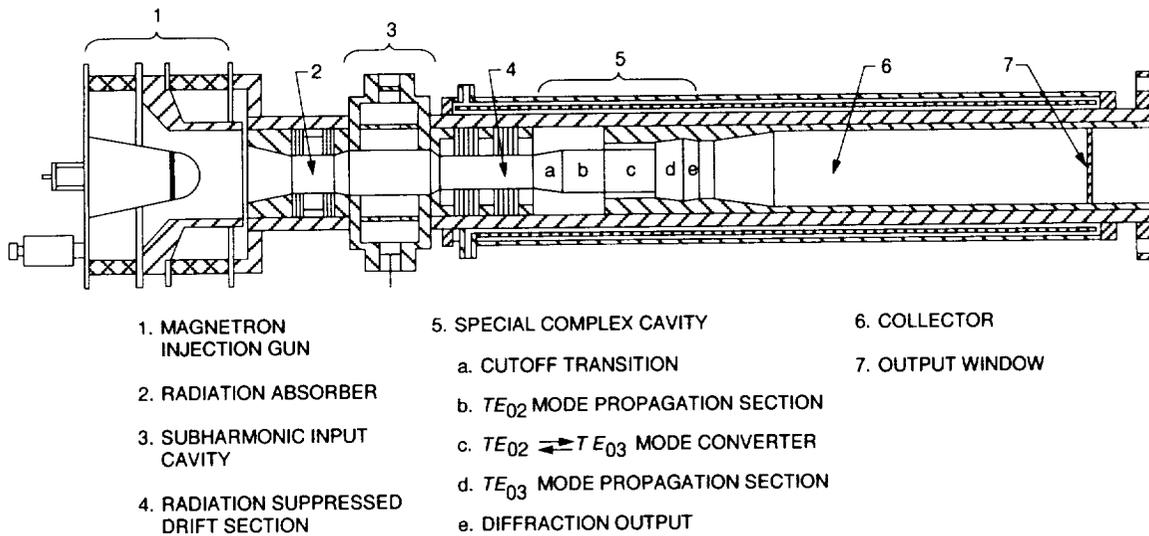


Fig. 2. Schematic design of a Ka-band, compact, phased-locked gyrotron with subharmonic injection.