RECENT ADVANCES IN GYROTRONS

by

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SUMMARY

The gyrotron is a new type of microwave tube capable of producing high-power output at millimeter wavelengths. Oscillator results have been described in recent Soviet publications. This paper describes work in progress to develop oscillators of the gyrotron type to deliver 200 kW CW at 28 and 60 GHz. Although considerable progress had been made with gyroklystron amplifier stability to the point that amplifier gains of over 40 dB had been measured in a pulsed experimental gyroklystron amplifier, efficiency problems, potential dilution of effort and reconsideration of requirements resulted in dropping gyroklystron amplifier effort in favor of the gyrotron oscillator. Pulsed oscillators have been delivered which produced 246 kw peak power at 28 GHz with 38% efficiency. A CW oscillator has been tested to 212 kW with 40% efficiency and 119 kW with 46% efficiency also at 28 GHz. Other areas of R and D are discussed, including gyro-TWT amplifiers with increased instantaneous bandwidth (5 - 10%).

INTRODUCTION

The gyrotron is a microwave vacuum tube based on the interaction between an electron beam and microwave fields where coupling is achieved by the cyclotron resonance condition. This type of coupling allows the beam and microwave circuit dimensions to be large compared to a wavelength. Thus the power density problems encountered in conventional microwave tubes are avoided in the gyrotron. Rather complete histories and descriptions of the gyrotron have been published in the literature.[1,2] The gyrotron and the cyclotron resonance maser are based on the same interaction. Previously published results in terms of high average power at millimeter wavelengths with good device efficiency include 12 kW CW at 2.78 mm wavelength with 31% efficiency, 22 kW CW at 2.0 mm wavelength with 22% efficiency and 1.5 kW CW at 0.92 mm wavelength with 6.2% efficiency.[3,4] These results have so far been limited to oscillator devices, although possible amplifier configurations have been discussed.

The purpose of this paper is to outline the basic characteristics of the gyrotron type devices and to describe work going on at Varian using this interaction. The goal of recent activity at Varian was the production of 200 kW CW at 28 GHz for electron cyclotron heating in the Elmo Bumpy Torus experiment at Oak Ridge National Laboratory. The current Varian activity is directed toward the production of 200 kW CW at 60 GHz, and the refinement of the 28 GHz designs.

Basic Characteristics

An important characteristic of the gyrotron is that it requires the application of a dc magnetic field which is specifically related to the operating frequency by the cyclotron resonance condition. This relationship is given by the equation:

$$\omega = \omega_c + \frac{\pi \upsilon_{\parallel}}{L} \qquad (1)$$

where ω is the operating frequency, ω_c is the cyclotron frequency or angular velocity of the electron given by

$$\omega_c = \frac{eB}{\gamma m_o} \qquad (2)$$

$\upsilon_{\parallel}$ is the axial electron velocity and L is the cavity length. B is the magnetic field, e is the electron charge, m_o is the rest mass and γ is the relativistic mass factor. The term $\frac{\pi \upsilon_{\parallel}}{L}$ is typically very small compared to ω_c.

A frequency of 28 GHz requires a magnetic field of 11.3 kG for L = 5λ. For 60 GHz a magnetic field of 24.2 GHz will be required. For higher frequencies higher fields are needed. This leads to the use of superconducting solenoid magnets.

In the gyrotron, bunching of the electron beam occurs as a result of a relativistic effect. This can be seen from Equation 2 where a change in electron kinetic energy changes γ which in turn changes electron angular velocity. Microwave electric fields in the early part of the cavity apply an angular velocity modulation to the electrons. As the electrons drift further through the cavity, angular bunching takes place as a result of the angular velocity modulation. Toward the end of the cavity the phase between the electron bunches and the microwave electric fields is adjusted so that the electrons give up kinetic energy. When the energy given up by the electrons exceeds the cavity losses, an oscillation results and output power is available.

Although a relativistic effect is involved in the interaction, efficient gyrotrons have been built using beam voltage as low as 18 kV. An optimum voltage range is probably 50 to 100 kV.

The frequency of the single-cavity gyrotron oscillator is influenced by both the cavity resonance and the value of the dc magnetic field. In general, the output frequency is almost linearly related to the dc magnetic field over the half-power bandwidth of the cavity. Practical cavity Q's are in the range of 500 to 5000. Higher frequency stability requires tighter control on magnetic field.

In a gyroklystron, an input cavity is used to modulate the beam and subsequent cavities are used for further amplification or energy removal. In the gyroklystron, instantaneous bandwidths of 1% are practical.

Another variation which has larger bandwidth is the gyro-TWT. In this case a propagating waveguide is used for continuous interaction with the beam. Instantaneous bandwidths of up to 10% should be obtainable and magnetic tuning should double the available bandwidth. Only moderate gain and efficiency have yet been achieved, but efficiency as high as 50% is predicted by the gyro-TWT theory.[5]

All of the gyrotron devices require an unusual type of electron beam where most of the electron energy is transverse to the axis of the tube. This has required the development of new, special electron gun configurations.

Gyroklystron Amplifier Development Program

Analytic models were developed to predict cavity coupling factors and small signal gain. These have been described previously.[6] A particle tracing computer code was used to predict output power and efficiency. A TE_{011} cavity of length 1.5λ was chosen for the input cavity, and a TE_{021} cavity 2λ long was selected for the output. The TE_{021} cavity was to allow reduced power density for later scaling to higher frequency. The results for an experimental amplifier are shown in Table I.

Table I
Gyroklystron Performance

Peak Output Power	76.3 kw
Beam Voltage	78.4 kV
Beam Current	11.2 A
Efficiency	8.69%
Gain	41.1 dB

The low efficiency is attributed to too long a drift space between the input and output cavity.

Gyrotron Oscillator Development

As a backup to the amplifier development a single cavity oscillator design was initiated. Power output calculations were performed for the oscillator using a beam voltage of 80 kV, a beam current of 8 amperes and a ratio of transverse velocity to axial velocity of two. A TE_{021} cavity of length 5λ was chosen. The calculation predicted a maximum output of 260 kW. In order to make the calculation self-consistent the power given up by the beam must equal the power delivered to the load plus the power lost in the cavity walls. This condition can be satisfied by properly adjusting the total loaded Q of the cavity.

The minimum Q that can be achieved by opening one end of a constant diameter cavity can be shown, by energy storage and group velocity considerations to be $4\pi\ (L/\lambda)^2$. To achieve a lower Q, more sophisticated techniques are required. Based on these considerations a loaded Q of 400 was selected as a design goal.

A digital computer code was used to determine appropriate electrode shapes in the gun to generate the beam. The simulation predicted a spread in transverse velocity of 3% and a corresponding axial velocity spread of 11%. The velocity spread must be minimized to obtain high efficiency. The cathode is operated temperature limited to control beam current.

Measured performance of the pulsed oscillator is shown in Table II.

Table II
Pulsed Oscillator Results

Peak Output Power	246 kw
Frequency	28 GHz
Beam Voltage	80 kV
Beam Current	8 A
Efficiency	38 %

Realization of a CW gyrotron requires a larger collector to handle the higher average power. Two approaches have been investigated.

The first approach attempts to separate the rf from the electron beam prior to the collector by use of a triple miter bend. Because of the overmoded structure, competition from non-circular electric modes prevented reaching the goal of 200 kW even in a pulsed mode. However, the tube did attain 105 kW CW. A tube similar to this has delivered 50 kW CW into the Elmo Bumpy Torus at Oak Ridge National Laboratory.

The second approach is to bring the rf out through the collector. Additional coils are used in the collector region to distribute the beam over the enlarged portion of the collector. The performance of this tube is shown in Table III.

Table III
CW Gyrotron Performance

Power Output	212 kW
Frequency	28 GHz
Beam Voltage	80.0 kV
Beam Current	6.7 A
Efficiency	39.5 %

Development effort is now being directed toward 60 GHz. The design goals are outlined in Table IV.

Table IV
60 GHz CW Gyrotron Design Goals

Power Output	200 kW
Beam Voltage	80 kV
Beam Current	8 A
Efficiency	31.3 %

Both the 28 and 60 GHz gyrotron work is being conducted under subcontract to Oak Ridge National Laboratory, operated by Union Carbide Corporation for the Department of Energy.

Gyro-TWT Development

Three experimental gyro-traveling wave tubes have been built and tested. All tubes used a fundamental cyclotron resonance interaction with the circularly polarized TE^0_{11} dominant waveguide mode. The tubes differed in the length of the single circuit section and in the amount of distributed loss used. The experiments were conducted at 5 GHz, with the object of producing a design that could be scaled to 94 GHz.

Results on the third experiment include measurements of stable gain as high as 24 dB small signal and 18 dB saturated. A saturated power output of 50 kilowatts at a total beam efficiency of 16.6% was measured with a 3 dB saturated power output bandwidth of 6%.

The gyro-TWT development was funded by the Rome Air Development Center, Griffiss Air Force Base, N.Y.

Conclusions

The gyrotron interaction makes it possible to achieve orders of magnitude higher power levels at millimeter wavelengths than was possible with conventional klystrons and TWTs.

At the higher frequencies superconducting magnets are needed.

The result reported here in, i.e., the oscillator output of 212 kW CW at 28 GHz with 40% efficiency, is competitive on a scaled basis with previously published results and represents record average power output for any frequency above 8 GHz.

Considerable work is still needed on gyroklystrons and gyro-TWT amplifiers. The feasibility of high gain in a gyroklystron has been demonstrated by the results presented here. Good progress has been made on amplifier stability, but additional work is needed on efficiency. This may require some basic investigations into beam quality, velocity spread and space charge effects. With proper development the gyrotron interaction can supply a family of devices for use in systems which require high power at millimeter wavelengths.

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