The Gyrotron: A High-Frequency Microwave Amplifier

A. Kupiszewski
Radio Frequency and Microwave Subsystems Section

The purpose of this article is to introduce a proposed microwave amplifier mechanism for future generations of millimeter high-power uplinks to spacecraft and planetary radar transmitters. Basic electron-electromagnetic field interaction theory for RF power gain is explained, and the starting point for general analytical methods leading to detailed design results is presented.

I. Introduction

The next generation of spacecraft uplinks and planetary radar transmitters will probably operate at higher frequencies in the 20- to 35-GHz range. Present crowding at S- and X-bands as well as increased resolution and ranging available at higher frequencies make such a shift desirable. However, a cursory examination of readily available microwave amplifiers shows that there are no conventional high-power ($>$ 10 kW) tubes useful for such purposes. Recently, much effort has been directed towards development of these higher frequency amplifiers. One such device of high potential is the gyrotron, a cyclotron resonance maser utilizing magnetic coupling between cavity or waveguide fields close to cutoff and relativistic electrons gyrating in large dc magnetic fields. Its basic advantage over klystrons and TWTs is that the electronic interaction volume does not scale down with wave length, hence high power can be obtained without the conventional heat transfer problems inherent in small interactive volumes.

The history of the gyrotron is in itself quite interesting. Theory for the device was developed as far back as 1958–59 by R. Q. Twiss and J. Schneider (Ref. 1), but power output levels were then measured in milliwatts. Interest in the U.S. lagged, and funding was shifted elsewhere. In the U.S.S.R., however, research continued unabated, and some impressive results were achieved, for example 22 kW CW at 2 mm (Ref. 2). Due to such success, attention in the U.S. has again focused on this class of amplifier with contemplated applications including plasma heating and mm-wave radar.

II. Description

Gyrotrons may be operated over a wide range of frequencies from 2 to 235 GHz, depending only on selection of cavity and magnetic field strength. Figure 1 shows a typical arrangement for a gyrotron. Electrons from an annular cathode biased at several thousand volts form a hollow beam. (Hollow, circular beams are used in the interest of efficiency, since there is no RF component on the axis of symmetry. Breakup is inhibited by the short drift space and relatively high voltages involved, Ref. 3). The beam is then compressed by an axisymmetric magnetic field according to the adiabatic invariant $v_{\perp}^2/B$ = constant, where $v_{\perp}$ is the Larmor orbit velocity and B is the magnetic field strength. This is a magnetic mirror effect similar to that used to confine plasmas, where perpendicular, azimuthal electron energy is increased at the expense of logitudinal drift energy. In the interaction space, which has a gently varying cross section to maximize efficiency, the electrons are guided by highly uniform fields. Magnetic coupling to the RF cavity fields is responsible for the microwave amplification, and, after completing interaction, the electrons settle on an extended collector surface in a region of weaker magnetic field.

In these respects, the gyrotron is just like klystrons and TWTs. An electron beam provides energy for microwave amplification. Spent electrons impact on an extended, water-cooled collector surface, which is the bulkiest, heaviest part of the tube. There the similarity ends. Instead of longitudinal bunching for microwave amplification, the gyrotron uses cyclotron resonance and azimuthal bunching.

One of the most important characteristics of gyrotrons is the high efficiencies theoretically obtainable. With proper gun design and good electron optics, the axial symmetry favors circumstances where all electrons interact with the RF fields under identical conditions. High efficiencies are contingent upon such relative uniformity. Losses in the magnetic mirrors and the interaction space are minimized due to solenoid design, which ideally reduces magnetic field variations to within a few tenths of one percent of maximum field strength. An example of a high-efficiency tube design with all of the aforementioned characteristics is the gyrotron TWT designed by Chu, Drobot, Granatstein, and Seftor (Ref. 4). The important parameters given are an output power of 342.5 kW CW with 51.0 percent calculated efficiency for a beam voltage and current of 70.82 kV and 9.48 A, respectively, and a magnetic field strength of 17.87 kG. The output frequency is 35 GHz with a maximum gain of 20 dB and a -3 dB bandwidth of 910 MHz.

III. Interaction Mechanism

To gain an understanding of the interaction mechanism, including theoretical results for bandwidth and efficiency, it is necessary to employ classical calculations based on Vlasov theory. The scope of such an endeavor, however, exceeds the aims of this introductory report, so only an overview of the process for arriving at a condition for amplification in a cylindrical cavity gyrotron will be given. More details will be addressed in future articles.

Starting with the Vlasov Equation (a continuity equation relating spacial changes in the electron distribution function to variations in time), one has the following:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + \frac{q}{m} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_v f = 0 \qquad (1)$$

where

f is the electron distribution function

$\mathbf{v}$ is the velocity vector

q is the charge on the electron

$\mathbf{E}$ is the electric field

$\mathbf{B}$ is the magnetic field

m is the electron mass

The distribution function and the cavity field can be split into

$$f = f_0 (\mathbf{x}, \mathbf{v}) + f_1 (\mathbf{x}, \mathbf{v}, t) \qquad (2)$$

$\mathbf{E} = \mathbf{E}_1$ (the electrons have already been accelerated before entering the cavity)

$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1$ ($\mathbf{B}_0$ is the dc magnetic field)

(3)

Using perturbation theory and linearizing to first order, the expression for the perturbed distribution is obtained.

$$f_1 (\mathbf{x}, \mathbf{v}, t) = - \int_{-\infty}^{t} \frac{q}{m} (\mathbf{E}_1 + \mathbf{v} \times \mathbf{B}_1) \cdot \nabla_v f_0 \, dt' \qquad (4)$$

And, for the TE_{011} mode in cylindrical geometry,

$$\mathbf{B}_1 = \hat{\mathbf{r}} E_0 \frac{k_\parallel}{\omega} J_1 (k_\perp r) \cos k_\parallel z \sin \omega t - \hat{z} E_0 \frac{k_\perp}{\omega} J_0 (k_\perp r) \sin k_\parallel z \sin \omega t \qquad (5)$$

$$\mathbf{E}_1 = \hat{\theta} E_0 J_1 (k_\perp r) \sin k_\parallel z \cos \omega t \qquad (6)$$

The time averaged power absorbed by the electrons is given by

$$\langle P_{abs} \rangle_{time} = \langle Nq \int d\bar{v}\, \mathbf{v} f_1 \cdot \mathbf{E}_1 \rangle_{time} \qquad (7)$$

Further integration yields the following:

$$\langle P_{abs} \rangle_{time} = \frac{q^2 E_0^2 \pi \rho\,(k_\perp a)\, v_\perp^3}{2mk_\parallel^2\, v_\parallel^3} \cdot \frac{2k_\parallel\, v_\parallel}{\omega}\, G_\omega\,(v_\parallel, v_\perp) \cdot [\beta + Q_\omega\,(X)] \tag{8}$$

where E_0 is the RF field amplitude

- Ω is the cyclotron frequency in the rest frame
- ω is the frequency in radians of the cavity field
- $N(r, \theta)$ is the electron density
- c is the speed of light in vacuum
- $v_\parallel$ is the drift velocity, $k_\parallel$ is the parallel wave number
- $v_\perp$ is the Larmor orbit velocity, $k_\perp$ is the perpendicular wave number
- a is the cavity radius

$$\rho(k_\perp a) \equiv \int_0^{2\pi} d\,\theta \int_0^{a} r\,drN\,(r,\theta)\,J_1^2\,(k_\perp r) \tag{9}$$

$$Q_\omega(X) = X - \frac{1}{2G}\frac{\partial G}{\partial X}\left[\frac{\Omega^2}{k_\parallel^2 c^2} - X^2\right] \tag{10}$$

$$G_\omega(X) = \text{lineshape function} = \frac{\cos^2 \frac{\pi X}{2}}{(1 - X^2)^2} \tag{11}$$

$$X = \frac{\omega - \Omega}{k_\parallel v_\parallel} \tag{12}$$

$$\beta = \frac{\Omega\, v_\parallel c}{k_\parallel c v_\perp^2} \tag{13}$$

By inspection, it can be seen that the condition for amplification is

$$-\beta > Q_\omega(X) \tag{14}$$

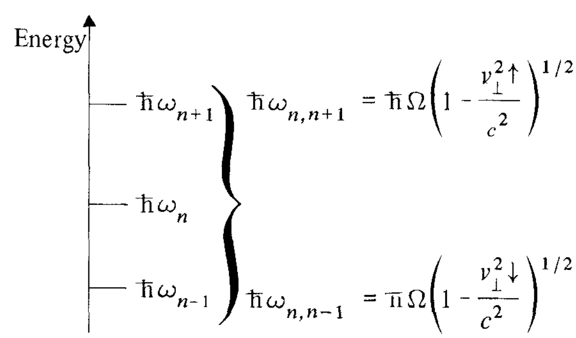
Although the process outlined above gives detailed, correct results for the lineshape function, it is easier to understand the amplification mechanism if it is viewed quantum mechanically. Power absorbed by the electrons traversing the cavity can be expressed (Refs. 5 and 6) as

$$P = N\hbar(\omega_{n,n+1}\, \rho_{n,n+1} - \omega_{n,n-1}\rho_{n,n-1}) \tag{15}$$

where N is the number of electrons

- $\hbar$ is Plank's constant divided by 2π
- $\omega_{n,n+1}$ is the frequency in radians of an upward transition from level n to n + 1
- $\omega_{n,n-1}$ is the frequency in radians of a downward transition from level n to n − 1
- $\rho_{n,n+1}$ and $\rho_{n,n-1}$ are the respective transition probabilities

For free-free, higher-order transitions (i.e., n very large), it follows that $\rho_{n,n+1} \approx \rho_{n,n-1}$. Amplification, i.e., $P < 0$, occurs only if $\omega_{n,n-1} > \omega_{n,n+1}$. With even a mildly relativistic electron beam (~10 kV), such a condition can be easily achieved due to Lorentz corrections to the cyclotron frequency. Looking at the energy levels, one finds that differences can be expressed as Lorentz corrected percentages of the cyclotron frequency.



The lower energy levels have a smaller $v_\parallel$ than the higher levels, which produce an unequal energy spacing between levels. This unequal spacing accounts for the emission exceeding absorption. It should be noted, however, that pursuit of this line of reasoning leads to Lorentzian lineshapes and not $G_\omega(X)$, which is confirmed by experiments (Ref. 7). Hence, present work in this field is based almost exclusively on classical calculations utilizing relativistic corrections.

IV. Summary

Gyrotrons are cyclotron resonance masers that show great promise in becoming the next generation of deep space transmitters due to high efficiencies at K-band frequencies with high-power outputs. Similarities to klystrons enhance the basic appeal of gyrotrons. Handling and maintenance technologies should not differ much except in the area concerning cyrogenically-cooled superconducting magnets. Further research continues to produce impressive results with respect to power and efficiency at ever higher frequencies. Future reports on this subject will address new advances, efficiency calculations, and potential integration problems with existing systems.

References

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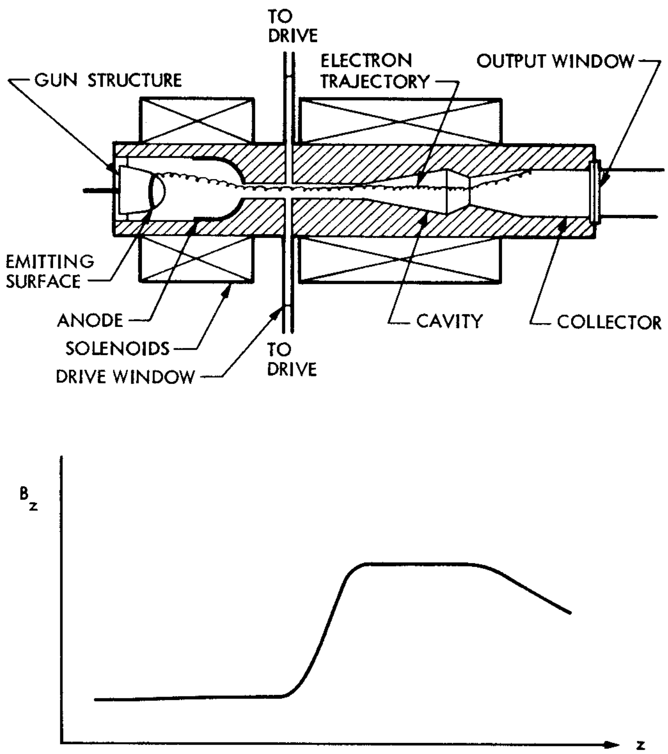

Fig. 1. Gyrotron amplifier