PFC/JA-84-34

High Power Second Harmonic Emission and Frequency Locking in a 28 GHz Gyrotron

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This work was supported by the U.S. Department of Energy Contract No. DE-AC02-78ET51013.

Abstract

Two important new results are presented from a study of second harmonic ($2\omega_c$) emission from a pulsed gyrotron designed for fundamental (ω_c) emission of 200 kW at 28 GHz in the TE_{021} mode. Mode locking between two modes of a gyrotron has been observed for the first time; one mode oscillates at $\omega \approx \omega_c$ and the other at exactly twice that frequency. Strong, single mode $2\omega_c$ emission (80 kW at 50 GHz) is also observed, and such emission is shown to be characteristic of gyrotrons designed for high power emission at the fundamental.

High power, high frequency gyrotrons[1-4] are of great importance to controlled fusion research; their applications include both electron cyclotron resonance heating (ECRH)[5-8] and plasma diagnostics.[9-11] With the growing demand for gyrotrons suitable for these applications, increasing the gyrotron operating frequency becomes of primary importance. Operation at the second ($\omega \approx 2\omega_c$) or higher harmonics ($n\omega_c$, $n > 2$) of the cyclotron frequency, ω_c, would utilize a magnetic field smaller by n than that required for operation at the fundamental.[12-14] Here, ω_c equals $eB_o/\gamma m_e c$, where B_o is the magnetic field, m_e and e the electron mass and charge, c the speed of light, and $\gamma = (1 + U/m_e c^2)$ where U is the electron energy.

We report here the results of a study of second harmonic emission from a gyrotron oscillator designed for high power operation at the fundamental. This study was performed on a Varian 28 GHz gyrotron, which was designed to produce 200kW in the TE_{021} mode in long pulse operation. Although many parameters were varied in this study, such as current and voltage, the data obtained were primarily dependent on the magnetic field at the cavity. Gyrotrons operate in circular TE modes near cutoff, that is $\omega/c = k = (k_\perp^2 + k_\parallel^2)^{1/2}$ with $k_\perp >> k_\parallel$, where $k_\perp$ and $k_\parallel$ are the transverse and axial wavenumbers of the waveguide modes. In this case, we may take $\omega/c = k \approx k_\perp = \nu_{mp}/R$ for TE modes, where R is the cavity radius and ν_{mp} is the p^{th} zero of $J_m'(x)$. The combination of this condition and the condition $\omega \approx n\omega_c$ determine the oscillation mode of a gyrotron oscillator as the magnetic field is varied. We have observed a high power second harmonic cavity mode: 80 kW at 50.38 GHz in the TE_{431} mode with 21% efficiency. This mode was not observed in previous studies of this gyrotron. The magnetic fields corresponding to this mode and the two high power fundamental modes in which this gyrotron also operates are shown in Table 1.

As a second result of this study, we have also observed harmonic emission at exactly twice the frequency of the emission at the fundamental. Because the frequency of the second harmonic emission we have observed is exactly twice the fundamental frequency, it is likely to result from a frequency locking or parametric effect rather than from ordinary cavity emission. Hence, we refer to it as parametric emission. The existence of this parametric emission is interesting both from a scientific point of view and because it could have deleterious effects in gyrotrons designed for plasma diagnostics or communications where spectral purity is of great importance. To our knowledge, such parametric emission has not been previously observed in a gyrotron.

A diagram of the gyrotron and experimental apparatus is shown in Fig. 1. Although capable of long pulse operation (up to 100ms), the gyrotron pulse length was limited to < 300μs for this study; the pulse repetition rate was 1.4 Hz. There is a short length of output waveguide with a side hole coupled to Ka-band (26.5 - 40 GHz) waveguide on the output side of the gyrotron window, followed by an asymmetric mode filter and the main output waveguide (inside diameter = 6.35 cm). The radiation is emitted from the open end of the output waveguide. At the side port, a Ka-band 3 dB directional coupler splits the signal into two Ka-band waveguides. One waveguide is connected to a Ka-band wavemeter, attenuator, and diode. The other waveguide was connected through a transition to V-band (50 - 75 GHz) waveguide. The V-band cutoff occurs at 39.9 GHz. A V-band wavemeter, attenuator, and diode were connected to the V-band waveguide. With this apparatus both the ω_c and $2\omega_c$ signals can be detected, and only gyrotron emission at the second harmonic is detected with the V-band diode.

Although the diodes at the side port output coupler were useful for locating the regions of oscillation at the second harmonic, the ω_c and $2\omega_c$ signals were also monitored in the far field of the output waveguide (Fig. 1). For direct measurement of the far-field pattern of the radiation emitted from the gyrotron, a large box, lined with microwave absorbing foam, was constructed. The Ka- and V-band diodes were placed on movable arms in this box for far-field measurements.

The frequency of the observed emission was measured by two independent methods. The first method was the use of wavemeters in Ka- and V-band waveguide. This method has reasonable accuracy and has the advantage of only being sensitive to the radiation in the designated band. The second method was a harmonic mixing technique with an accuracy of ± 5 MHz for a single pulse. A diagram of the harmonic mixing apparatus is shown in Fig. 2 and described in detail elsewhere.[4] For the strong ω_c and $2\omega_c$ modes, power measurement was obtained by calorimetry with a modified Varian model VLA-8050C water calorimeter. Estimates for the power of the weaker $2\omega_c$ modes were obtained from a calibration of the diode responsivity and an integration over the far field pattern.

The theoretical efficiency of a gyrotron at the n^{th} harmonic can be obtained by a numerical integration of the equation of motion for an electron moving in combined axial magnetic and rf electric fields. Numerical results have been presented by Nusinovich and Erm[15] for n=1 and n=2 in the form of a contour plot of efficiency as a function of two parameters, the normalized beam current,

$$I_0 \equiv (0.24 \times 10^{-3})\, I\, Q_T \left(\pi \frac{\beta_\perp}{\beta_\parallel}\right)^{2(3-n)} \left(\frac{L}{\lambda}\right)^{5-2n} \left(\frac{n^n}{2^n n!}\right)^2 \frac{J^2_{m\pm n}(k_\perp R_e)}{[\nu^2_{mp}-m^2]J^2_m(\nu_{mp})}$$

and the normalized cavity length, $\mu \equiv \beta_\perp^2 L/\beta_\parallel \lambda$. In these equations, I, Q_T, L, R_e, $\beta_\perp$, $\beta_\parallel$, and λ are the current, total cavity Q, effective cavity length, electron beam radius, transverse and axial electron velocity divided by c, and the wavelength ($2\pi c/\omega$), respectively. The efficiency of operation at $2\omega_c$ in a gyrotron designed for operation at ω_c can be obtained from a scaling of I_o and μ.[14] The values of I_o and μ for the fundamental correspond to gyrotron operation in the high efficiency zone ($0.4 \leq \eta_\perp \leq 0.7$, $\eta_\perp$= transverse efficiency). At nearby values of the magnetic field, there exist cavity modes resonant at $\omega \approx 2\omega_c$. We have found that the values of I_o and μ for these second harmonic modes often fall in a high efficiency zone ($0.2 < \eta_\perp < 0.4$) [see Ref. 14 for a detailed analysis]. This implies that gyrotron oscillators designed for high efficiency operation at the fundamental will in general have efficient $2\omega_c$ modes nearby. It is the observation of a correlation of high efficiency between ω_c and $2\omega_c$ modes that is demonstrated by the present results.

Experimental evidence of strong second harmonic emission in a gyrotron designed for operation at the fundamental is provided by the observation of the TE_{431} cavity mode at 50.38 GHz. The mode was identified by an accurate measurement of the frequency and confirmed by a measurement of the far-field radiation pattern which is in reasonable agreement with theory. The voltage and current for which this mode was excited are 77.5 kV and ~ 5A. An output power of 80kW was observed with a water calorimeter; this corresponds to a total efficiency of 21%. The theoretical total efficiency was calculated from a nonlinear theory and is approximately 40%.[15] A scan of calorimeter power versus magnetic field shows that the TE_{431} $2\omega_c$ mode is well separated from the TE_{221} fundamental mode, which occurs at a slightly higher magnetic field.

In addition to the observation of high power, $2\omega_c$ cavity emission in the TE_{431} mode, frequency-locked, parametric emission was also observed. Under certain operating conditions, and present simultaneously with fundamental emission in either the TE_{021} or TE_{221} modes, harmonic emission at exactly twice the frequency of the fundamental mode was observed. We have observed this parametric emission during operation in both the TE_{021} and TE_{221} modes; however, the parametric emission associated with the TE_{221} mode is much stronger than that associated with the TE_{021} mode.

For operation in the TE_{221} mode, the measured frequency of the fundamental emission was 26.78 GHz; the frequency of the $2\omega_c$ emission associated with the TE_{221} mode is 53.56 GHz, which is exactly twice the fundamental frequency. At a slightly higher value of the magnetic field, the fundamental emission frequency is pulled by dispersion to a value of 26.81 GHz and the $2\omega_c$ emission is found at 53.62 GHz. The harmonic frequency is thus observed to track the ω_c frequency as the magnetic field is varied, further evidence of a frequency locking phenomenon. Observation of the relative powers indicates that the fundamental and second harmonic powers also show a positive correlation. In addition, this parametric emission is only observed when strong fundamental emission is also occuring. This contrasts with the previously described cavity $2\omega_c$ emission which is suppressed by emission at the fundamental and thus has a negative power correlation with the fundamental.

An estimate of the power at the harmonic was made with a calibrated diode and an integration over the far field pattern. For an output power of ~ 150 kW in the TE_{221} mode, the harmonic power level was ~ 100 W. While harmonic content of this magnitude is negligible for gyrotron applications such as plasma heating, it is potentially detrimental for applications such as communications and plasma diagnostics.

For operation in the fundamental TE_{021} mode at a frequency of 28.04 GHz, very weak emission at 56.07 GHz was also detected. Varying the magnetic field changes the frequency at the fundamental (by up to 1%) due to dispersion in the cavity resonance. Emission at the second harmonic was observed to remain locked at exactly twice the fundamental frequency. We estimate that the power of this harmonic emission is about 1 W.

The origin of this parametric harmonic emission associated with the TE_{221} and TE_{021} modes is not known. Because the eigenmodes of a right circular cylinder do not form an equidistant spectrum, there are in general no cavity eigenmodes at exactly twice the value of k for the fundamental. Consequently, the generation of radiation at harmonics of the cyclotron frequency does not occur at an exact multiple of the fundamental frequency. The parametric emission data has been analysed using the waveguide and cyclotron resonance conditions, but we are unable to identify with certainty any likely cavity modes responsible for the $2\omega_c$ emission associated with either the TE_{221} or TE_{021} fundamental modes. To our knowledge, this is the first experimental evidence of the locking of two modes in a gyrotron. Although a theory of mode locking and parasitic mode excitation has been developed by Nusinovich, that theory is not directly applicable to the locking of two modes at different harmonics observed here.[16] It is possible that the parametric harmonic emission observed here results from emission at the second harmonic component of the beam which is modulated by the strong field at the fundamental. A similar phenomenon is observed in klystrons. The emission could occur in the cavity or uptaper/collector region of the gyrotron; strong frequency pulling and a low Q could account for the difficulty of identifying the emission as a particular cavity mode. Ergakov and Moiseev[17] have described a theory of harmonic emission from a premodulated beam in a gyroklystron, a phenomenon similar to the present result.

In summary, two important results concerning harmonic emission in gyrotrons have been described. One result, observation of parametric second harmonic generation, is of scientific interest and has important implications for gyrotrons designed for plasma diagnostics and communications. The exploitation of mode locking in gyroklystrons may also prove useful. The second result, the generation of high power, high efficiency second harmonic cavity emission, supports the theoretical argument that in gyrotrons designed for low Q operation at the fundamental, emission at the second harmonic will be strong and efficient. This is a potential problem for high power gyrotrons, but it is also a potential technological benefit, allowing the study of ECRH in plasmas at higher frequencies than are available from a fundamental gyrotron.

We are grateful to M. Mauel and M. Dunham for allowing us the opportunity to perform the above experiments with their gyrotron. We thank R. Shefer for loan of the Ka-band microwave equipment, K. Kreischer for many helpful discussions, and J. Byerly for assistance with the experiment. The Plasma Fusion Center research was conducted under U.S.D.O.E. Contract DE-AC02-78ET51013; the Lincoln Laboratory portion of this work was sponsored by the Department of the Air Force.

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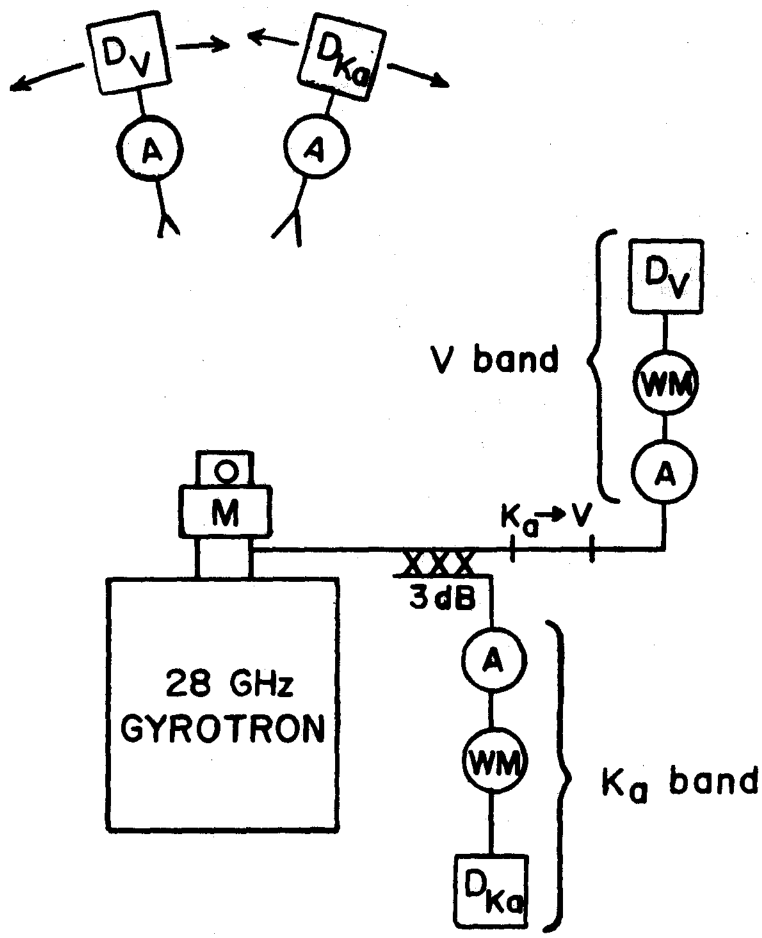
Figure Captions

Fig. 1 Diagram of Experiment. M: Mode filter, O: Output Waveguide, A: Attentuator, WM: Wavemeter. D_{ka} and D_V are detectors for the Ka- and V-bands.

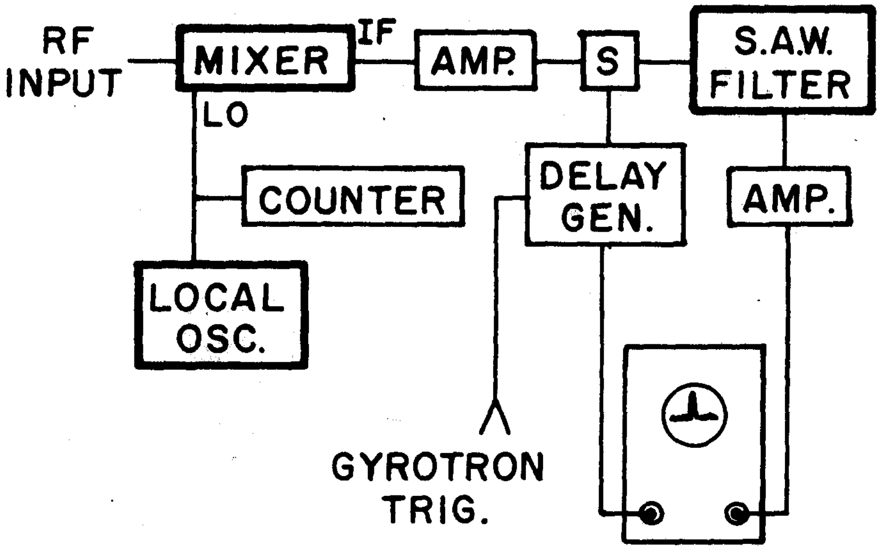
Fig. 2 Diagram of Harmonic Mixing System. AMP: Amplifier, S: Switch, IF: intermediate frequency, S.A.W. filter: Surface acoustic wave filter.

Table 1. High Power Oscillation Modes

Mode	Harmonic	Freq.[GHz]	Magnetic Field [T]
TE_{431}	$2\omega_c$	50.38	1.00
TE_{221}	ω_c	26.78	1.06
TE_{021}	ω_c	28.04	1.10



D_V
D_{Ka}
A
A
D_V
V band
WM
A
O
M
$K_a \rightarrow V$
XXX
3 dB
A
28 GHz
GYROTRON
WM
K_a band
D_{Ka}


RF INPUT
MIXER
IF
LO
AMP.
S
S.A.W. FILTER
COUNTER
DELAY GEN.
AMP.
LOCAL OSC.
GYROTRON TRIG.