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Generation of High-Frequency Radiation by Quasi-Optical Gyrotron at Harmonics of the Cyclotron Frequency

BARUCH LEVUSH AND WALLACE M. MANHEIMER

Abstract—**A quasi-optical gyrotron can operate, in principle, at high harmonics of the electron-cyclotron frequency, as well as at the fundamental. Lower harmonics are suppressed by exploiting their larger diffraction losses. The radiation-field amplitude is kept below the breakdown value by taking advantage of the focusing properties of the quasi-optical resonator. Cavity design parameters and starting currents are presented which characterize the operation of the quasi-optical gyrotron at the eighth harmonic of gyrofrequency.**

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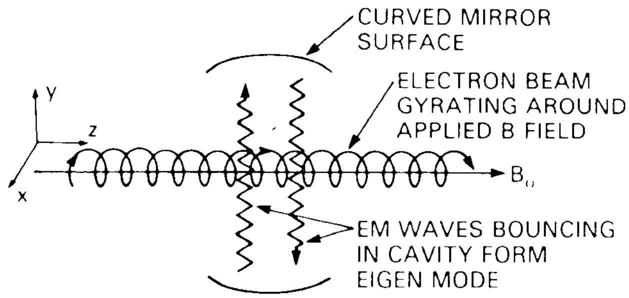

Fig. 1. A quasi-optical gyrotron configuration with the magnetic field in the z direction and the radiation bouncing back and forth in the y direction with its electric-field polarization in the x direction.

I. Introduction

Presently, one of the main efforts in gyrotron research is concerned with further shortening the wavelength of the radiation. To this end, there has been interest in extrapolating gyrotron operation to higher frequencies by utilizing a confocal quasi-optical cavity [1]–[9]. Here, an electron beam travels along a magnetic field perpendicular to the axis of an optical cavity as shown in Fig. 1. In order to operate at higher frequencies, one could envision working at a higher magnetic field or operating at harmonics of the cyclotron frequency. The latter method has been analyzed in a quasi-optical cavity in both a time-independent [1]–[9] and a multimode time-dependent [5]–[8] regime. It has been shown [5]–[7] that, with suitable contouring of the dc magnetic field, a stable single-mode operation of the device at fundamental [5]–[7] and second harmonic of gyrofrequency [8] is possible.

This paper shows that very high cyclotron-frequency harmonics operation is possible in a quasi-optical gyrotron. Although we only consider single-cavity gyrotron configurations with uniform magnetic fields here, it is reasonably clear from earlier work that the efficiency and coherence of the devices could be improved by contouring the guide field and/or by utilizing a double-cavity klystron configuration. Using this scheme, coherent radiation can be produced with power levels of several kilowatts (with efficiency of several percent) at wavelengths ranging from 3 mm, using a permanent magnet, down to 130 μm, using a Nb_3Sn superconducting magnet. The beam energy is typically 260 kV and current $I \simeq 1$ A. This voltage is larger than typical gyrotron voltages, but is still small enough to be available commercially [10].

This investigation is an extension of our earlier work [9] which showed how to select cavity parameters for second- and third-harmonic operation. Here, we show that the same considerations can be applied to much higher harmonic operation. In a quasi-optical configuration, all harmonics are eigenfunctions of the cavity; therefore, the problem is to select cavity and beam parameters so as to achieve reasonable efficiency and coherent oscillation (i.e., suppression of lower harmonics) at the desired frequency. In Section II, we review linear efficiency and suppression of lower harmonics in the optical resonator. In Section III, we calculate specific beam and cavity parameters for gyrotron operation at the eighth harmonic of gyrofrequency.

II. Beam and Cavity Parameters for High-Harmonic Quasi-Optical Gyrotron Operation

We now utilize the technique developed in [9] to describe the interaction of a beam with the wave field in the quasi-optical

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gyrotron at high harmonics. As was shown in [9], the cavity is characterized by the half length of the cavity L_y, the mirror radial of curvature R_M, the radiation wavelength λ, and the mirror radial size ρ (assuming a circular-shaped mirror). In terms of these parameters, the spot size of the radiation at the center of the cavity is given by

$$r_0 = \left[\frac{\lambda L_y}{\pi}\left(\frac{R_M}{L_y} - 1\right)^{1/2}\right]^{1/2} \tag{1}$$

and the spot size at the mirror can be calculated to be

$$r_{0M} = \left[\frac{\lambda R_M}{\pi} \frac{1}{\left(\frac{R_M}{L_y} - 1\right)^{1/2}}\right]^{1/2}. \tag{2}$$

Consideration of the spot size at the mirror is important for two reasons; first of all, r_{0M}/ρ governs the diffraction losses at the mirror, and second, the field at the mirror must be below some breakdown limit, $E_{\max}$. However, the quasi-optical gyrotron generally works best at high field E_0 at the spot. If E_0 is larger than $E_{\max}$, one could also exploit the focusing properties of the quasi-optical cavity to reduce the field at the mirror.

The field at the mirror in terms of the field at the spot is given by

$$E_M r_{0M} = E_0 r_0 \tag{3}$$

so

$$E_M = E_0\left[1 - \frac{L_y}{R_M}\right]^{1/2}. \tag{4}$$

Then, as shown in [9], the fractional loss due to diffraction Υ is

$$\Upsilon = \exp - \left[\frac{\rho}{r_{0M}}\right]^2. \tag{5}$$

The relation between diffraction losses at the different harmonics n and m are related by

$$\Upsilon_n = (\Upsilon_m)^{n/m}. \tag{6}$$

The electric and magnetic fields in the resonator are approximated by

$$\begin{aligned} E_x &= E(z)\sin ky \cos \omega t \\ B_z &= E(z)\cos ky \sin \omega t \end{aligned} \tag{7}$$

where $k = \omega/c$ and

$$E(z) = E_0 \exp - (z^2/r_0).$$

Then, [9, eq. (12)] shows that the linearized small-signal efficiency for an electron beam uniform in y is given by

$$\eta_n = \frac{\pi}{4}\frac{1}{(\gamma_0 - 1)\gamma_0}\left(\frac{E_0}{B_0}\right)^2 \xi_0^2 \left(\frac{\Omega_0}{\omega}\right)^2 J_n'(\xi_0)\exp\left[-\left(\xi_0\frac{\Delta\omega}{\omega}\right)^2\Big/2\right] \cdot \left[\frac{\beta_{\perp 0}^2 \Delta\omega}{2\omega}\xi_0^2 J_n'(\xi_0) + \xi_0 J_n(\xi)\left(1 - \frac{n^2}{\xi_0^2}\right)\right] \tag{8}$$

where $\gamma_0 = [1 + (P_{z0}^2 + P_{\perp 0}^2)/m^2c^2]^{1/2}$, $\xi_0 = kP_{\perp 0}/m\Omega_0$, $\Omega_0 = eB_0/mc$, $\xi_0 = (r_0\omega/c)/\beta_{z0}$, $\beta_{z0} = P_{z0}/m\gamma_0 c$, $\beta_{\perp 0} = P_{\perp 0}/m\gamma_0 c$, $\Delta\omega = \omega - n\Omega_0/\gamma_0$, J_n, and J_n' are a Bessel function and derivative of a Bessel function of order n, respectively. The nonlinear efficiency is found by integrating particle orbits, [9, eqs. (9)–(11)], through the cavity fields.

The threshold condition for starting the excitation in the resonator is

$$\eta P_{b,\text{in}} \geqslant \omega \epsilon_{\text{stored}}/Q \tag{9}$$

where $P_{b,\text{in}} = IV$ is the total electron beam power flowing into the interaction cavity (I is the current and V is the voltage), ϵ_{stored} is the stored field energy where

$$\epsilon_{\text{stored}} = \left(E_0^2/16\pi\right)\pi r_0^2 L_y \tag{10}$$

and the losses in the cavity are characterized by the Q factor. To calculate Q, we assume power reflection coefficient $1 - \Upsilon$, so that a fraction Υ is transmitted through or diffracted around the mirror as output radiation. Neglecting the dissipation in the mirrors, we get for

$$Q = \frac{4L_y\omega}{\Upsilon c}. \tag{11}$$

Hence, using (13) and (14), the power output is

$$P = \eta IV = \frac{\Upsilon c}{64}E_0^2 r_0^2. \tag{12}$$

Since ϵ and Q are both proportional to L_y, the power output is independent of L_y. If this were the only consideration, L_y would not enter as a design parameter since the particle equations in the linear and nonlinear regime do not depend on L_y either. However, another important consideration is whether the radiation generated is single moded or multiple moded. Since the mode spacing is $\Delta\omega/\omega = 1/4\ \lambda/L_y$, at the very small wavelengths we consider here, large L_y's mean very closely spaced modes and a greater likelihood of multimode operation with the associated reduction in efficiency.

To calculate whether the output radiation is single moded or multimoded would require a time-dependent calculation of the type done in [5]–[8]. However, the numerical scheme utilized there is so inefficient at the high harmonics we consider that its use is precluded. We will draw conclusions then based on the results in [5]–[8] for time-dependent calculations at the fundamental and second harmonic.

In [5]–[8], there were two ranges of λ/L_y studied. First, if $L_y/\lambda \leq 50$, the results were nearly always single moded. As L_y/λ is increased to 2.5×10^3, the results became more likely to be multimoded. However, even if the output radiation were multimode, there were always precise phase relations between the modes and the spectrum that would depend in some way on mode spacing. Thus, while multimode, the radiation was coherent and not turbulent and the efficiency decrease was not large. For $L_y/\lambda > 2.5\times10^3$, a radiation spectrum is produced in which the spectral shape becomes independent of mode spacing. In all cases, the radiation was more likely to be single moded in a quasi-optical klystron configuration, if the prebunching frequency and phase was properly selected.

Therefore, we recognize three possible ranges for L_y/λ. First, if $L_y/\lambda < 50$, the radiation will, in all likelihood, be single moded in either a single- or double-cavity configuration. Second, if $50 < L_y/\lambda < 2500$, a coherent spectrum of modes will be excited. Here, a two-cavity klystron configuration could help to eliminate unwanted sidebands. Third, if $L_y/\lambda > 2500$, a radiation spectrum independent of mode spacing is generated. The cavity designs we give here will be in either the first or second range of L_y/λ.

We now exploit the fact that, as the wave frequency (i.e., harmonic number) increases, the spot size decreases so that diffraction losses also decrease.

In order to operate a quasi-optical gyrotron at a harmonic n, the linearized power into the cavity at that harmonic $\eta_n IV$ must exceed the power loss $\omega/Q_n \epsilon_{\text{stored}}$. However, at all lower harmonics, the opposite must be true. Relating Q_m to Q_n by (6), (11), and (12), one easily calculates that the ratio of starting current at the nth harmonic I_n to that at the mth harmonic is

$$\frac{\eta_n I_n}{\eta_m I_m} = \Upsilon_m^{(n/m-1)}. \tag{13}$$

To find a regime where the nth harmonic will oscillate but lower harmonics will not, we use (13) to pick a cavity so that I_n is less than all I_m for $m < n$. Before doing so, however, note that η_n depends on detuning parameter $\Delta\omega/\omega$. To determine the minimum starting current at each harmonic, we must maximize η_n and η_m over detuning parameter. Then, the quasi-optical oscillator can operate at harmonic n for currents between the starting current I_n and the starting current of a lower harmonic, I_{n-1}.

III. Specific Design Parameters for $n = 8$

To operate at high harmonics, we find that both larger beam energy and pitch angle are required than for operation at the fundamental or low harmonics. Accordingly, we consider $\gamma_0 = 1.51$ (260 kV beam) and pitch angle $\alpha = 1.25$ rad, so that $p_{\perp 0}/p_{\parallel 0} = 3$. Then, the eighth harmonic corresponds to 5.3 times the nonrelativistic cyclotron frequency.

As is shown in (12), the current for start oscillation at the eighth harmonic is given by

$$I_8 = 4.34 \times 10^7 \frac{\gamma_8 \hat{E}_0^2}{\eta V} \tag{14}$$

where we have introduced the dimensionless electric field

$$\hat{E}_0 = \frac{\sqrt{\pi}\, e E_0 r_0}{mc^2}. \tag{15}$$

Also, I is in amperes and V is in volts, but CGS units are used elsewhere. Since η is the linearized efficiency and proportional to E_0^2, I_8 is, of course, independent of E_0. In Table I are given start oscillation currents for the eighth harmonic at various values of $\omega r_0/c$. Performing the optimization of η_8 on variation of $\Delta\omega/\omega$, we used (8) and assumed that $T_8 = 10^{-3}$.

In Table II, we calculate the ratio of starting currents between the seventh and eighth harmonic as a function of Υ_8. It turns out that I_7/I_8 is independent of the $\omega r_0/c$ value. For Υ_8 as small as 10^{-3}, it is clear that there is an appreciable range of currents for which the eighth harmonic will oscillate but the seventh will not.

We now give results of calculations of nonlinear efficiency. The calculations assume a cavity with radiation at the eighth cyclotron harmonic with fixed amplitude $\hat{E}_0$ and phase. The nonlinear efficiency is calculated by integrating the orbits of an ensemble of particles through the cavity as described in [9]. In the orbit integrations, the fast ($\sim 1/\omega$) time scale is averaged out so that the integration time step size can be much larger than Ω_c^{-1}. In all nonlinear orbit calculations, we have assumed that the electron beam is localized at field maxima. This gives roughly twice the efficiency one would calculate for the technologically simpler case of a uniform in y electron beam. The nonlinear efficiency, assuming $\omega r_0/c = 45$, is calculated as a function of $\hat{E}_0$ for three different frequency shifts, $\Delta\omega/\omega = 1$, 1.3, and 1.6 percents. The results are shown in Fig. 2. The result is characteristic [8] for gyrotrons operating in a quasi-optical cavity, namely, larger frequency shifts give larger efficiencies, but at larger electric fields.

TABLE I
Starting Currents at the Eighth Cyclotron Harmonic as a Function of $\omega r_0/c$, with $\Upsilon_8 = 0.1$ Percent and $\gamma_0 = 1.51$

$\omega r_0/c$	20	45	90
I_8(Amp)	1.33	0.54	0.27

TABLE II
Ratios of Starting Currents at Seven Harmonic to Starting Current at Eight Harmonic as a Function of Υ_8

Υ_8(percent)	1	0.5	0.1
I_7/I_8	1.1	1.2	1.5

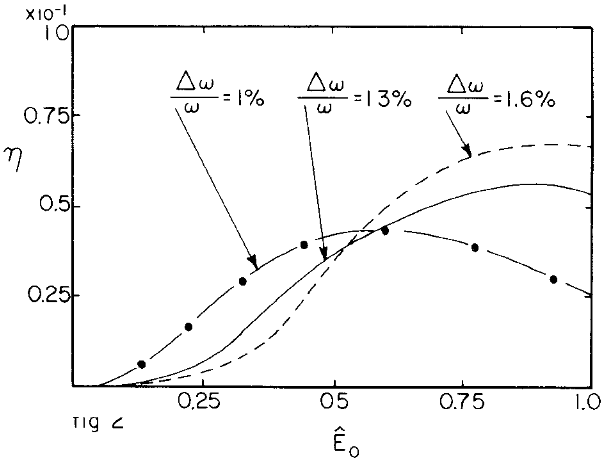

Fig. 2. Nonlinear efficiency as a function of $\hat{E}_0$ at $n = 8$ for a beam with $\alpha = 1.25$ radian, $\gamma_0 = 1.51$, and $\omega r_0/c = 45$. Solid, dashed, and dashed-dot lines represent $\Delta\omega/\omega = 1$, 1.3, and 1.6 percents, respectively.

We next consider the dependence of efficiency on pitch angle for the case of $\Delta\omega/\omega = 1.3$ percent and $\omega r_0/c = 45$. The results are shown in Fig. 3. Our typical value, $\alpha = 1.2$–1.3 ($p_{\perp 0}/p_{\parallel 0} = 2.5$–$3.6$), gives both reasonable efficiency and is practically achievable [11]. In Fig. 3 are shown calculated efficiencies as a function of $\hat{E}_0$ at different values of $\omega r_0/c$. The value generally selected, $\omega r_0/c = 45$, appears to be optimal, although $\omega r_0/c = 90$ is also feasible, especially when working at higher electric fields.

Since we are considering operation at a very high harmonic ($n = 8$), a natural question is how sensitive the results are to thermal spread. Since the resonance condition $\omega = n\Omega/\gamma$ does not depend on pitch angle α, the results are very insensitive to spread in α (emittance) [8]. A more serious concern is the dependence on energy spread. Fig. 4 gives η as a function of $\hat{E}_0$ for a beam with $\Delta\omega/\omega = 1.2$ percent, $\omega r_0 = 45$, and $\alpha = 1.25$ with a Gaussian spread in γ_0, $f(\gamma_0) = 1/(\sqrt{\pi}\,\delta\gamma)\exp - [(\gamma_0 - \Delta\gamma)/\Delta\gamma]^2$ at three different energy spreads, $\Delta\gamma/\gamma_0 = 0$, 1 percent, and 2.5 percent. An energy spread of 1 percent is tolerable, but an energy spread of 2.5 percent seriously degrades the efficiency of the resonator.

Assuming that the energy spread comes principally from the induced electrostatic potential across the beam, we find $\Delta\gamma/\gamma = \pi n e^2 r_b^2/\gamma mc^2 = 2 \times 10^6\, I(\text{amps})/\gamma V_z(\text{cm/sec})$. For the beams we consider, $I \sim 1$, $V_z \sim 3 \times 10^9$, the fractional energy spread will be very small, well under 1 percent.

To summarize, efficiencies in excess of 5 percent are theoretically achievable at the eighth cyclotron harmonic for a quasi-optical gyrotron resonator for a pencil beam, centered at field max-

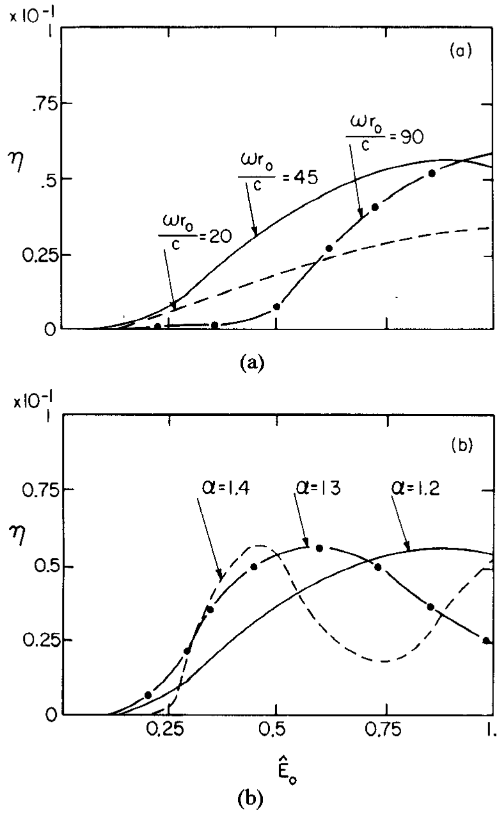

Fig. 3. Nonlinear efficiency as a function of $\hat{E}_0$ at $n = 8$ for a beam with $\gamma_0 = 1.51$, $\Delta\omega/\omega = 1.3$ percent, and (a) $\omega r_0/c = 45$, where solid, dash-dot, and dashed lines represent $\alpha = 1.2$, 1.3, and 1.4, respectively; (b) $\alpha = 1.25$, where dashed, solid, and dash-dot lines represent $\omega r_0/c = 20$, 45, and 90, respectively.

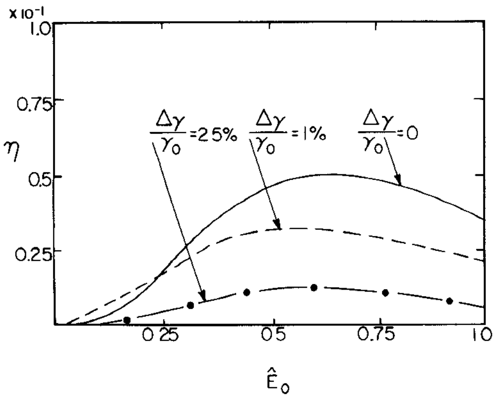

Fig. 4. Nonlinear efficiency as a function of $\hat{E}_0$ at $n = 8$ for a beam with Gaussian spread in γ_0 with $\alpha = 1.51$, $\gamma_0 = 1.51$, $\Delta\omega/\omega = 1/2$ percent, and $\omega r_0/c = 45$. Solid, dashed, and dash-dot lines represent $\Delta\gamma/\gamma_0 = 0$, 0.01, and 0.025, respectively.

ima, having energy of 260 kV, $\alpha \simeq 1.25$, $\Delta\gamma/\gamma_0 < 1$ percent, and $\omega r_0/c = 45$. For the technologically simpler case of a uniform beam, the calculated efficiencies are in excess of 2–3 percent. Also, by properly choosing the mirror size, it is possible to find a range of beam currents where the eighth harmonic is the lowest oscillating frequency. While these figures may be somewhat optimistic because of the idealized nature of the calculation, it is important to note that we did not consider efficiency-enhancement schemes either. Previous experience has shown that either contouring the guide field, and/or using a double-cavity klystron configuration, the efficiency could be significantly enhanced.

TABLE III
CAVITY PARAMETERS FOR QUASI-OPTICAL GYROTRON OPERATING AT EIGHTH HARMONIC OF GYROFREQUENCY WITH $\gamma_0 = 1.51$, $\Upsilon_8 = 0.1$ PERCENT FOR DIFFERENT B_0

B_0 (kG)	$\omega r_0/c$	$\hat{E}_0$	$\hat{E}_{Br}$	R_M/L_y	L_y (cm)	ρ (cm)
7	45	<1	1.28	2	43	7.7
50	45	.4	.18	1.3	12	1.52
150	90	.6	.12	1.042	42	2.63
150	45	.3	.06	1.042	10.6	1.32
150	45	.5	.06	1.015	18	2.2

To conclude, we give specific designs for an eighth harmonic resonator (assuming $\Upsilon_8 = 10^{-3}$) at three magnetic fields. These are a permanent magnet with $B = 7$ kG, $\lambda = 0.29$ cm; a Nb-Ti super-conducting magnet with $B = 50$ kG, $\lambda = 400$ μm; and a high field Nb_3Sn super-conducting magnet with $B = 150$ kG, $\lambda = 134$ μm. The breakdown field is assumed to be 2×10^5 V/cm, so the field at the mirror must be equal to or less than this. In dimensionless units, $\hat{E}_{BR} = 0.2\ (\omega r_0/c)1/B$, where B is kG. To design the cavity, we assume first a confocal cavity with $R_M/L_y = 2$. Generally this is satisfactory for lower frequencies. However, as the frequency increases (at constant $\omega r_0/c$), the field at the mirror begins to increase until, at some frequency, it exceeds the breakdown field. At this point, the mirrors must be moved further back, increasing L_y. In Table III are shown design parameters for quasi-optical cavities at the three selected values of magnetic field. The beam current is in the range shown in Tables I and II. For the 7-kG field, 0.29-cm wavelength case, a shorter cavity (smaller L_y) can be used if desired because the field is so much below the breakdown field, so that $L_y/\lambda < 50$ can be satisfied. For the shorter wavelengths, so that L_y falls in the second range $50 < L_y/\lambda < 2.5 \times 10^3$ so that a coherent multimode state will most likely be generated. It is here that a double-cavity klystron configuration could help by making the output more single moded.

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