High-Power 140-GHz Quasioptical Gyrotron Traveling-Wave Amplifier

J. R. Sirigiri, M. A. Shapiro, and R. J. Temkin

Plasma Science and Fusion Center, Massachusetts Institute of Technology, 167 Albany Street, Cambridge, Massachusetts 02139, USA

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We present the design and experimental results of a novel quasioptical gyrotron traveling-wave tube (gyro-TWT) amplifier at 140 GHz. The gyro-TWT produced up to 30 kW of peak power in 2 μs pulsed operation at 6 Hz achieving a peak gain of 29 dB, a peak efficiency of 12%, and a bandwidth of 2.3 GHz. The device was operated in a very higher-order mode of an open quasioptical interaction structure, namely, a confocal waveguide. The diffraction loss from the open sidewalls of the confocal waveguide was used to suppress mode competition in this highly overmoded circuit resulting in a stable single-mode operation. The experiment achieved record high power levels at 140 GHz for a gyro-TWT. These experiments demonstrate the effectiveness of using overmoded quasioptical waveguide interaction structures for generating high power in the millimeter and submillimeter wave bands with a gyro-TWT.

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High average-power gyrotron traveling-wave tube (gyro-TWT) amplifiers can extend modern communication and radar systems into the W band (94 GHz) and beyond. Conventional slow-wave TWTs are not a viable option above the Ka band (26.5–40 GHz). Fast-wave gyrotron amplifiers can operate at very high power in the millimeter wave regime of the spectrum due to the inherent advantage of a simple smooth walled interaction structure which can be operated in a mildly higher-order mode. The recent demonstration of 90 kW of peak power and 10.1 kW of average power at 94 GHz [1] by a gyroklystron operating in the TE_{01} mode have enabled the first operation of a high power W-band radar [2]. The gyroklystron is analogous to a conventional klystron and uses a series of resonant cavities for amplification, which ultimately limits its bandwidth. Clustered cavities have been proposed for increasing the bandwidth but have not yet been demonstrated [3]. The gyro-TWT on the other hand employs a nonresonant traveling-wave circuit which endows it with a much wider bandwidth. However, the gyro-TWT is very susceptible to spurious oscillations including the backward wave oscillation (BWO) which is not present in a gyroklystron. Recently, major success has been achieved in gyro-TWT experiments at 35 GHz using the fundamental TE_{11} mode in a heavily loaded circuit with distributed loss; 93 kW at 70 dB gain was obtained in one experiment [4] and 137 kW at 47 dB gain and 17% efficiency in a second experiment [5]. Power levels of up to 180 kW, 30 dB gain and 10% bandwidth were achieved in a 35 GHz gyro-TWT using a helically corrugated cylindrical interaction structure [6]. Although these are very impressive advances, they face significant obstacles in extension to operation at higher frequency, such as 95 GHz at high average power. The reason is that these devices employ fundamental or lower-order modes of the interaction structure in order to reduce or avoid mode competition. The difficulty in transporting a high power electron beam through such small structures and the excessive Ohmic loading on the walls are expected to limit the average power that can be generated at high frequency.

In this Letter, we report the theory and experimental demonstration of a gyro-TWT which contains two important innovations: first, a quasioptical, mode-selective interaction structure that greatly reduces the mode density and thus mode competition and, second, a break (sever) in the structure which eliminates competing backward wave modes through pure diffractive loss without any nearby material absorbers. Together, these two innovations allow stable operation of the overmoded interaction structure at high frequency and high power, with a clear potential for high average-power operation. We utilize a quasioptical open waveguide, namely, a confocal waveguide which consists of two copper mirrors of finite aperture separated by a distance equal to the radii of curvature of the mirrors as the interaction structure for the gyro-TWT. Gyrotrons with slotted resonators have previously been investigated [7] to suppress some competing modes which are present in cylindrical resonators. This technique is effective for lower-order modes. Quasioptical gyrotrons were also investigated [8] demonstrating good mode control in a higher-order mode oscillator.

A transverse cross section of the confocal waveguide with the operating HE_{06} eigenmode is shown in Fig. 1. This structure has advantages over conventional structures derived from a cylindrical waveguide. First, in a confocal waveguide, which is more like a planar (one transverse dimension) structure the density of modes with a high diffractive Q (lower diffraction losses) increases linearly with the mirror separation. On the other hand, in a cylindrical waveguide, which is routinely used in gyro-TWTs, the density of high-Q modes increases quadratically with the diameter of the waveguide.

Amplification is achieved in a gyro-TWT by a convective instability supported by a mildly relativistic annular gyrating electron beam and a transverse electric

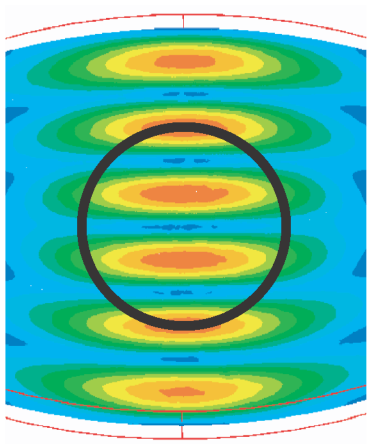

FIG. 1 (color online). The HE_{06} eigenmode of the confocal waveguide. The 3.6 mm diameter electron is the beam shown as a dark ring.

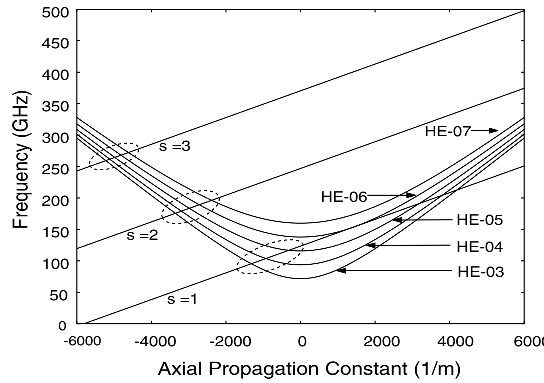

FIG. 2. Mode spectrum of the confocal gyro-TWT interaction structure. The potential BWO excitation points are located inside the dotted ellipses.

mode in a waveguide immersed in a strong static axial magnetic field (B_0). The grazing intersection between the dispersion of the cyclotron mode on the electron beam and a transverse electric waveguide mode near the waveguide cutoff results in a high gain and moderate bandwidth. The beam mode dispersion relation is given by

$$\omega - s\Omega/\gamma - k_z v_z \gtrsim 0, \quad (1)$$

and the waveguide mode dispersion relation can be expressed as

$$\omega^2 - k_z^2 c^2 - k_\perp^2 c^2 = 0, \quad (2)$$

where ω is the frequency of the wave, $\Omega(= eB_0/m_e)$ is the nonrelativistic cyclotron frequency of the gyrating electrons, e and m_e are, respectively, the charge and the rest mass of the electron, γ is the relativistic mass factor, s ($= 1$ in the current experiment) is the cyclotron harmonic number, k_z and $k_\perp$ are the longitudinal and transverse propagation constants, respectively, of the waveguide mode, v_z is the axial velocity of the electrons, and c is the velocity of light. We have modeled the interaction by kinetic theory [9] and by the self-consistent single particle theory [10] to evaluate the linear and nonlinear growth rates. The effect of the azimuthal asymmetry of the interaction structure on the beam-wave interaction has been taken into account by a method as outlined in [10]. A detailed discussion of the theoretical results is presented in [11].

The mode spectrum of the confocal waveguide is shown in Fig. 2. The HE_{0n} nomenclature of the modes represents n nodes of the mode in the direction perpendicular to the mirrors and 0 nodes along the mirrors. In Fig. 1 a hollow electron beam of diameter 3.6 mm is also shown intersecting the second maximum of the HE_{06} operating mode. The HE_{06} operating mode is like the TE_{03} mode of a cylindrical waveguide, but it is azimuthally asymmetric with a transverse field profile which is different than a cylindrical waveguide mode and hence we have chosen to use the HE_{06} nomenclature [12]. The annular electron beam is produced by a magnetron injection gun (MIG). Within the beam, electrons have a gyroradius of $\gamma v_\perp/\Omega$, or about 0.43 mm. The individual gyro-orbits of the electrons cannot be seen in Fig. 1, but taken together they form the annular ring shown in Fig. 1. The mirror aperture is 5.7 mm and the separation of the mirrors which is also equal to the radius of the curvature of each mirror is 6.79 mm. The experiment used an available triode MIG previously described in a gyrotron oscillator research experiment in [8]; a 139–142 GHz extended interaction klystron driver capable of producing 200 W peak power in 2 μs pulses and a superconducting magnet. The operating mode was determined by two main considerations, namely, the existing electron beam of diameter 3.6 mm had to lie on a maximum of the electric field of the operating mode and the mode had to be of a sufficiently higher order to limit the Ohmic heat loading on the walls to be about 1 kW/cm^2 for 100 kW cw power flowing through the circuit. This latter requirement implies that an industrial version of this amplifier could in theory operate continuously (cw) at the full 100 kW power level.

The nominal operating voltage (V_0) is 65 kV with a beam current (I_0) of 7 A and a velocity pitch factor, $\alpha(= v_\perp/v_z)$, equal to 1.2, where $v_\perp$ and v_z are the transverse and longitudinal velocities, respectively, of the electrons. The operating magnetic field is 5.3 T. The pitch factor could be varied in the experiment by changing either the modulating anode voltage of the electron gun or the magnetic field at the cathode. A schematic (not to scale) of the experimental setup is shown in Fig. 3 where a detailed view of the confocal interaction structure is also shown.

The crossing intersection between the beam cyclotron modes, defined by Eq. (1), and any waveguide modes, defined by Eq. (2) for negative values of k_z, shown in Fig. 2

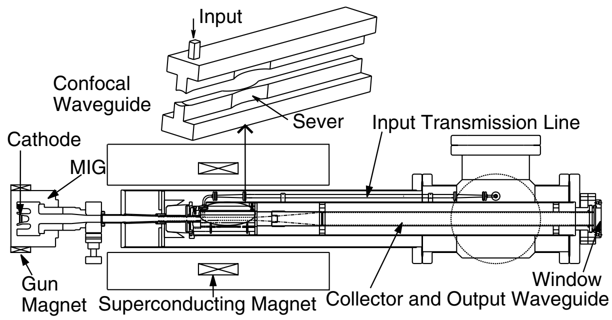

FIG. 3. Schematic of the confocal gyro-TWT experiment. The confocal waveguide structure is shown in an expanded view.

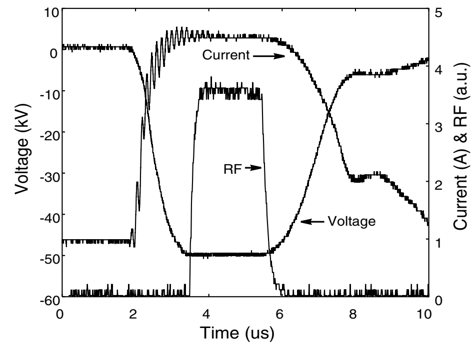

FIG. 4. Beam voltage, current, and output rf traces during a typical shot in the gyro-TWT operation.

can cause the excitation of BWO modes above a threshold value of the beam current for a particular interaction length. The threshold length for the excitation of the strongest BWO mode due to the interaction of the HE_{05} mode and the $s = 1$ beam mode for the chosen nominal operating beam current and velocity pitch factor was calculated using the theory described in [10] and found to be 6 cm. This prevents us from obtaining the design gain of 38 dB in a single gain section which would have to be about 9 cm in length according to theory. Hence, two gain sections separated by a heavily lossy sever section were used in the gyro-TWT as is commonly practiced in high gain conventional traveling-wave tubes [13]. 3D electromagnetic analysis on Ansoft High Frequency Structure Simulator indicates a cold circuit loss of about 44 dB for the HE_{05} mode in the sever. The loss for the design mode, HE_{06}, is also greater than 40 dB. However, the bunched electron beam quickly reestablishes the field in the second gain section and the effective loss due to the sever is only 3.5 dB for the forward growing HE_{06} wave. Contemporary severs usually implemented by a heavily lossy dielectric loading of the interaction structure in the sever region cannot be used in a high average-power device. Hence, we implemented a novel quasioptical sever which is formed by gradually reducing the aperture of the mirrors (Fig. 3) in the desired location of the sever to provide attenuation due to diffraction losses. Such a scheme while providing the necessary attenuation allows the distribution of the radiated power over a wide area amenable to absorption by a large lossy-dielectric shell which can be easily cooled.

In these initial experiments the output power from the confocal waveguide was directly coupled into a 28.4 mm diameter cylindrical pipe through two adiabatic cylindrical uptapers. The output waveguide in our experiment also served as a collector for the spent electron beam. The drive signal was fed to the amplifier through a 3 m long overmoded transmission line which included a window and a miter bend in the TE_{11} mode. Cold tests indicated a 3.6 ± 0.5 dB loss for the whole line. For a homogeneous magnetic field over the entire 12 cm length of the interaction structure, nonlinear self-consistent simulations indicated that a peak output power of 100 kW can be generated at 140 GHz with 38 dB saturated gain and 28% efficiency. The theoretically predicted constant drive saturated bandwidth is 4 GHz.

The gyro-TWT was tested over a wide range of operating parameters during the course of this work. Stable single-mode operation was observed at 50 kV, 3.9 A for alpha values up to 0.9. Typical voltage, current, and amplified rf signal traces are shown in Fig. 4. A plot of the experimentally measured bandwidth compared to the theoretical prediction is shown in Fig. 5. In the set of runs, a peak power of 27 kW was measured at a gain of 29 dB corresponding to an efficiency of 11.6%. The output power was measured by a Scientech calorimeter, model 36-0401. The surface absorbing layer of the calorimeter is increased to optimize absorption at 140 GHz as described in [14]. The pulse shape of the amplified signal was monitored by a WR-8 video detector to ensure zero-drive stability of the amplifier during operation and also to determine the peak power from the average-power measurements from the calorimeter. In Fig. 6, the experiments show that the output power could not be saturated with increase in the input drive power over 139–142 GHz,

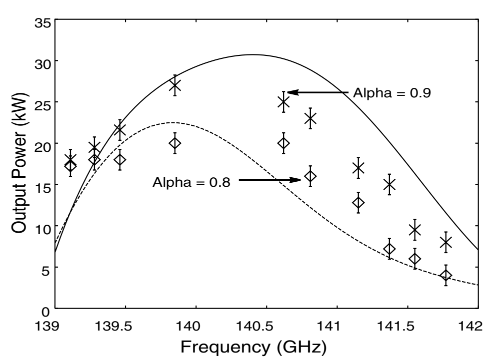

FIG. 5. Comparison of the experimentally measured bandwidth (◇ for $\alpha = 0.8$ and × for $\alpha = 0.9$) with theoretical predictions (dotted line: $\alpha = 0.8$; solid line: $\alpha = 0.9$) for $V_0 = 50$ kV and $I_0 = 3.9$ A.

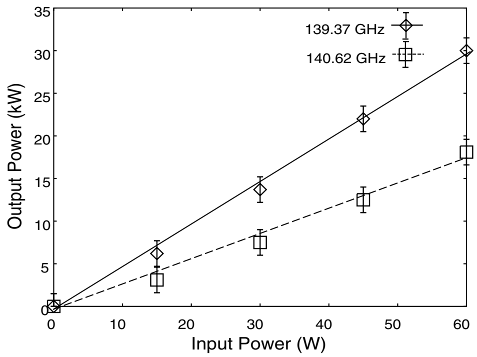

FIG. 6. Gain characteristics of the confocal gyro-TWT. The operating parameters are $V_0 = 70$ kV and $I_0 = 4.0$ A. The gain values are 27 and 25 dB at 139.37 and 140.62 GHz, respectively. The solid and dashed lines are best fit lines to the experimental data.

indicating that the gain was lower than the design value. This also explains the lower efficiency observed in the experiments when compared to the design value. The input power available at the input of the confocal waveguide was limited to 60 W. The reason for the lower output power and gain is that in the experiment the magnetic field has 0.5% homogeneity only over a 5.0 cm length while during the design we assumed a homogeneous magnetic field over the entire 12 cm length of the interaction structure. Also, the longitudinal velocity spread in the electron beam was likely to be higher than the 9% value that was assumed for the design operating beam parameters of 65 kV and 7 A. For the data shown in Fig. 5 velocity spread of 3% and 5% was assumed for alpha values of 0.8 and 0.9, respectively, at an operating voltage of 50 kV and a beam current of 3.9 A. A further increase in the velocity pitch factor to $\alpha = 1.0$ resulted in diminished output power, which suggests an increase in velocity spread of the beam at higher values of pitch factor. Peak power of up to 30 kW was measured over a narrow bandwidth of 0.3 GHz corresponding to a crossing intersection between the beam and the waveguide modes. The largest measured bandwidth was 2.3 GHz at $\alpha = 0.9$. The theoretically predicted and experimentally measured output power agree well for $\alpha = 0.8$ except at 139 GHz. This could be due to a transmission line resonance at 139 GHz which may result in higher input power coupled at that frequency. Operation at higher beam voltage resulted in a lower gain and output power possibly due to a higher velocity spread, besides causing problems with beam tunnel oscillations and reflected electrons. Operation at higher values of beam current resulted in the excitation of the HE_{05} BWO mode at 128.62 GHz and a near cutoff gyrotron oscillation at 137.54 GHz.

In our experiments the choice of an overmoded yet mode-selective circuit qualifies the device for high average-power operation while avoiding the concomitant problem of mode competition. Furthermore, the overmoded circuit has advantages in fabrication and cooling due to its larger transverse circuit dimensions. Also an internal mode converter can be designed using familiar quasioptical techniques for converting the semi-Gaussian operating mode into a free space Gaussian beam for easy coupling into a corrugated waveguide for low loss transmission to an antenna. The first demonstration of zero-drive stable single-mode amplification in this highly overmoded gyro-TWT is a promising development for building high average-power (≥ 100 kW) amplifiers in the W band and beyond. Such devices may be very useful for W-band radar and communication.

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