High-Gain Wide-Band Gyrotron Traveling Wave Amplifier with a Helically Corrugated Waveguide

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First bandwidth measurements of a novel gyrotron amplifier are presented. The coupling between the second harmonic cyclotron mode of a gyrating electron beam and the radiation field occurred in the region of near infinite phase velocity over a broad bandwidth by using a cylindrical waveguide with a helical corrugation on its internal surface. With a beam energy of 185 keV, the amplifier achieved a maximum output power of 1.1 MW, saturated gain of 37 dB, linear gain of 47 dB, saturated bandwidth of 8.4 to 10.4 GHz (21% relative bandwidth), and an efficiency of 29%, in good agreement with theory.

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The cyclotron resonance maser (CRM) instability between a gyrating electron beam (in a guide magnetic field) and a mode of a cylindrical waveguide has been investigated due to its potential for efficient, broadband amplification of radiation [1,2]. The relative dispersion relations of the beam and the radiation have conspired to seriously limit this potential. In the regime of low axial wave numbers, the bandwidth is limited by the curvature of the hyperbolic wave dispersion (as compared to the linear beam dispersion), and the fact that in this regime the wave group velocity is close to zero means that the interaction is prone to undesirable oscillations. On the other hand, if one operates with high axial wave numbers, where the group velocity becomes close to c, then Doppler broadening of the resonance spoils the efficiency of the interaction and limits the bandwidth [3]. Nonetheless, broadband amplifiers have a rather large range of applications, and the ability to increase the radiation power capability above that possible in conventional slow-wave amplifiers is desirable. Gyroklystrons have thus far been developed to offer the high power and frequency capabilities of the CRM instability to amplifier applications, but these experiments use resonant cavities as their interaction spaces, inherently limiting the relative bandwidth $\sim 1\%$ [4].

A number of variations to increase the bandwidth of gyrotron amplifiers have been investigated [5,6]. For example, a series of gyroamplifiers have obtained 16% efficiency at a frequency of 5 GHz with a uniform magnetic field, increasing to 26% efficiency with 7% bandwidth using a tapered field [7]. Theoretical investigation of a gyrotron traveling wave amplifier (gyro-TWT) interaction in a rectangular waveguide having a variable cross section in the form of a two stage tapered device having an intermediate server has predicted an efficiency of 37%, with bandwidth of 1.8% for an axial velocity spread of 10% [8]. In a similar two stage configuration [9], 20% bandwidth over 32–39 GHz with 16% efficiency was experimentally obtained, using bidirectional tapering of both the microwave circuit and magnetic field. Recently, impressive experimental results on a gyro-TWT were achieved by Chu *et al.*, who studied the amplifier at the fundamental cyclotron harmonic. By stabilizing oscillations with the use of an interaction structure with distributed wall losses, this 35 GHz *Ka*-band amplifier produced 93 kW of power at 26.5% efficiency and 70 dB gain with a 3-dB bandwidth of 8.6% [10]. Second and higher harmonic interactions have attracted attention because they reduce the magnetic field required for any frequency of operation in addition to the potential for frequency multiplication (the beam may be perturbed in a low harmonic input interaction and the energy extracted in a higher frequency, higher harmonic output stage) [11–14]. The experimental results presented in this paper also used a second harmonic interaction, halving the required magnetic field, but primarily to enable coupling between a special waveguide eigenmode having a strong quadrupole component and an axis encircling electron beam. All the gyrotron traveling wave amplifier experiments referenced above identified spurious oscillations and insufficient electron-beam quality as major limitations.

A new idea has recently been reported [15,16] which has reopened the potential for a broadband gyrotron traveling wave amplifier where a helical corrugation on the wall of the interaction waveguide couples together a near to cutoff mode and a far from cutoff mode to produce a wave dispersion with a finite and nearly constant group velocity in the region of near infinite phase velocity. This dispersion may be readily matched to an electron beam's linear dispersion characteristic over rather a broad bandwidth. Because the group velocity is large over the resonance, the problem of oscillations is considerably reduced while the small axial wave numbers limit the impact of electron velocity spread. An experiment based on this approach has recently been reported [17] at two rather close frequencies, but the potential of the system for high gain and efficiency

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with good stability to oscillations was demonstrated. This paper presents the first measurements of the bandwidth capabilities of such a gyrotron amplifier experiment.

The surface of the helically grooved waveguide of the gyro-TWT can be represented in cylindrical coordinates r, φ, and z as follows:

$$r(\varphi, z) = r_0 + l\cos(\overline{m}\varphi + \overline{h}z), \qquad (1)$$

where r_0 is the waveguide mean radius, l, $\overline{m}$, and $\overline{h} = 2\pi/d$ are the amplitude, azimuthal, and axial numbers of the corrugation, respectively, and d is the corrugation period. The desired change of the dispersion will be achieved if the corrugation couples two partial rotating waves of a waveguide with a radius of r_0; one partial wave is near cutoff, mode (A), and has a small axial wave number, $h_A \ll k$, where $k = \omega/c$, while the other partial wave, a traveling wave (B), has a large axial wave number, $h_B \sim k$. For such conditions to be realized, the axial wave numbers and azimuthal indices of the waves and the corrugation should satisfy the Bragg conditions:

$$h_B \approx \overline{h}, \qquad m_A + m_B = \overline{m}. \qquad (2)$$

The resonant coupling of the waves corresponds to the intersection of their dispersion curves or, more exactly, the intersection occurs between mode A and the first spatial harmonic of wave B with cutoff frequencies ω_0 and ω_{0B}, respectively (Fig. 1).

If the corrugation amplitude l is small compared with the wavelength, the field structure and dispersion characteristics of the helically corrugated waveguide can be calculated by means of the method of perturbation [18]. The eigenwaves $W_\pm$ and W_1 (Fig. 1), which arise as a result of coupling the partial waves A and B, can then be found. When parameters of the corrugation are properly chosen, the wave W_1 has the desirable dispersion. The relative frequency gap between W_1 and "spurious" waves $W_\pm$ at "zero" axial wave number is of the order of the coupling coefficient of the waves σ, which is proportional to the relative amplitude of the corrugation l/r_0 and depends also on the azimuthal and radial indices of the partial waves. For a relatively small corrugation depth, when $\sigma \leq 0.1$, the method of perturbation provides good agreement with "cold" experiments [15]. It is clear from the dispersion curves of the helically corrugated waveguide (Fig. 1) that mode $W_\pm$, having a region with a small group velocity, can be easily excited similar to an operating mode of a conventional gyrotron oscillator. But, for attractive amplification regimes, when the corrugation is sufficiently deep, a large separation of curves W_1 and $W_\pm$ occurs. The mode $W_\pm$ can still be excited but at magnetic fields significantly higher than the operating values.

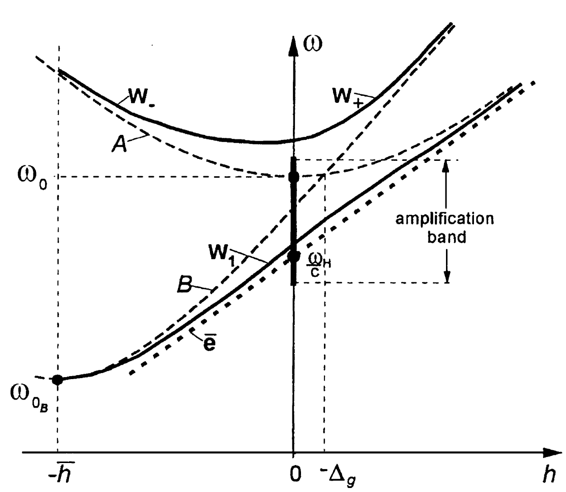

FIG. 1. Dispersion diagram for a helically corrugated waveguide; A, B: the partial near-cutoff and traveling waves of a smooth waveguide, respectively, which are coupled due to the helical corrugation of the inner surface; W_1 and $W_\pm$: the operating and spurious eigenwaves of the corrugated waveguide gyro-TWT; $\overline{e}$: unperturbed electron cyclotron wave.

In the new experiment, an improved version of the University of Strathclyde direct action accelerator was used. A 120 ns accelerating voltage pulse of amplitude 185 kV was applied across a Pierce-like diode [19] drawing a rectilinear electron beam with a current of 20 A and a diameter of 8 mm from the velvet emitting surface (Fig. 2). The electron beam passed a microwave coupler where the input radiation was introduced through the side of the cylindrical drift region from a rectangular WG16 waveguide (8.2–12.5 GHz). After the input coupler, the input radiation is passed through a "quarter wave plate" consisting of an elliptically deformed waveguide region converting it to circular polarization. Transverse velocity was imparted to the electron beam in a "kicker" consisting of four pairs of small (short) rectangular multiturn coils arranged in a Helmholtz-like configuration. The arrangement of these coils was such that the electron beam perceives a single full turn rotating transverse magnetic field component as it drifts through the kicker. In the present experiment, with an axial guide magnetic field (provided by a water cooled dc solenoid) of 0.21 T, a pulsed current of 112 A applied to the kicker produced a beam with a pitch factor of 1.2 and a transverse velocity spread $\Delta v_\perp / v_\perp$ of $<15\%$. The resulting electron beam described a helical, axis encircling trajectory, with the electron gyroradius being greater than the transverse diameter of the electron beam itself. The CRM instability can provide effective coupling only between the radiation and an axis encircling electron beam in the case where the interaction harmonic number is equal to the azimuthal mode index of the radiation.

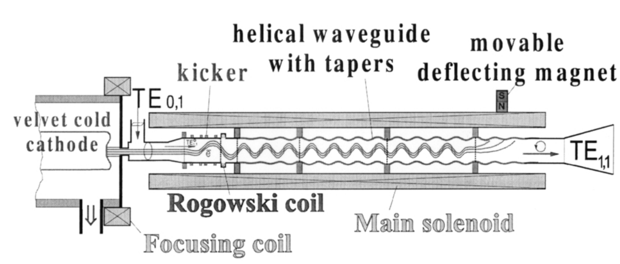

FIG. 2. Schematic diagram of the gyro-TWT with a helically corrugated waveguide.

In the present experiment, the operating mode was synthesized by coupling the $TE_{2,1}$ mode (azimuthal index, $m_A = 2$) and the counter-rotating $TE_{1,1}$ mode ($m_B = 1$) as the near and far from cutoff modes, respectively, on a threefold helical corrugation in the wall of a cylindrical copper waveguide having a mean diameter of 28.2 mm. The corrugated waveguide was 60 cm in length and the corrugation was 2.2 mm in amplitude with a period of 37.5 mm plus entrance tapers of 12 cm length at each end, where the amplitude of the corrugation was tapered linearly to meet the smooth 28.2 mm bore of the input and output waveguides. The operating band was below the cutoff frequency of the $TE_{2,1}$ mode of the smooth input/output waveguides. Therefore, at the input of the corrugated waveguide, radiation in the $TE_{1,1}$ mode, counter-rotating with respect to the helix, converts totally to the operating mode of the amplifier. The output radiation at the other end undergoes the opposite transition so that the output radiation from the amplifier is in the fundamental mode of the cylindrical waveguide, counter-rotating with respect to the electron beam. The theoretically predicted dispersion plot for this waveguide is illustrated in Fig. 3.

Distributed losses were introduced over a 5 cm length in the center of the interaction waveguide to counter the possibility of oscillations. Cold test experiments measured 6 dB losses between 8 and 10.5 GHz. A permanent magnet could be used to vary the length of the interaction space by deflecting the electron beam to impact on the waveguide wall; this facilitated study of the gain process as a function of interaction length.

The input signal for the experiment was provided by a conventional broadband helix TWT with a peak output power of 400 W driven by a solid state oscillator producing up to 20 mW. A calibrated variable attenuator was used to control the input power. The radiation power launched into the operating wave was calibrated as a function of frequency.

The input power provided to the amplifier was sufficient to saturate the CRM interaction as illustrated in Fig. 4(a) where the output power is plotted against the input power at a frequency of 9.2 GHz (using the calibrated attenuator in the input waveguide to control the launched radiation power). Using an input power of 200 W, Fig. 4(b) illustrates the effect of changing the interaction length on the gain, clearly showing saturation in the region close to the end of the helical waveguide. In this plot, the length origin is taken to be the start of the input taper to the helix, and the location of the microwave absorbing section was 42 cm.

A bandpass filter was used to verify that the amplified output radiation followed the input frequency. The experiment proved to be zero drive stable. By combining a carefully calibrated attenuator and rectifying detector, the gain of the amplifier was measured as a function of the input frequency, both in the saturated and linear regimes. The results of these measurements are presented in Fig. 5. A saturated gain of 37 dB was obtained with a relative bandwidth (3 dB points) of 21% centered on 9.4 GHz. A linear gain of up to 47 dB was measured. Taking the saturated gain plot and comparing that to the calibrated input signal in the operating mode, the efficiency was calculated as a function of frequency and is illustrated in Fig. 6. The microwave output signal had a peak of 1.1 MW at a frequency of 9.4 GHz corresponding to an efficiency of 29%. This performance compares well with the predictions of nonlinear theory, Fig. 6. The simulations were performed for the experimental parameters taking a mean electron pitch factor of 1.2 and a distribution for the transverse velocity spread approximating a Gaussian with a 10% standard deviation.

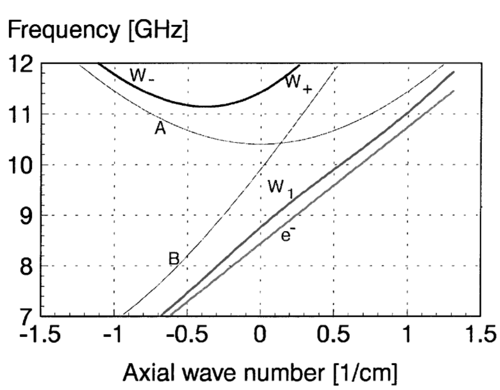

FIG. 3. Dispersion diagram for the operating helically corrugated waveguide: dotted and solid lines correspond to partial and eigenmodes, respectively.

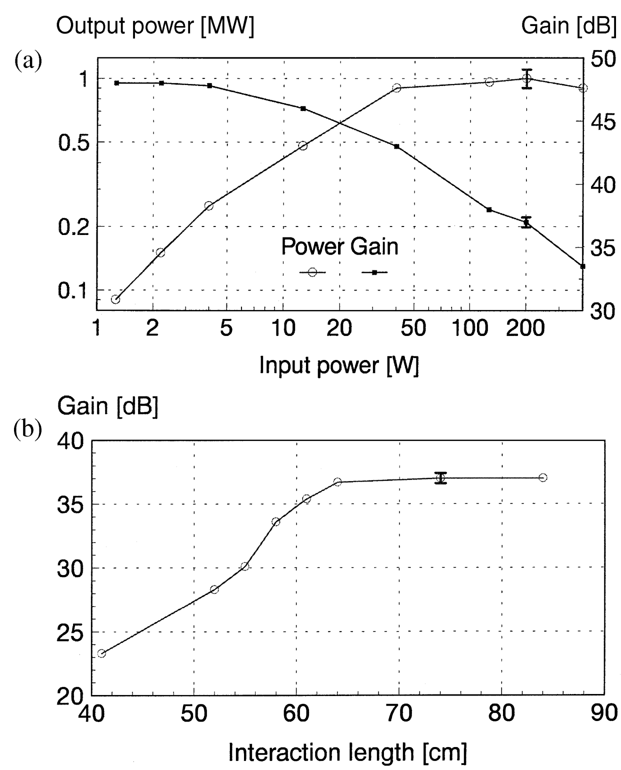

FIG. 4. (a) Measured output power and gain versus input power at a drive frequency of 9.2 GHz. (b) Measured output power as a function of interaction length at 9.2 GHz.

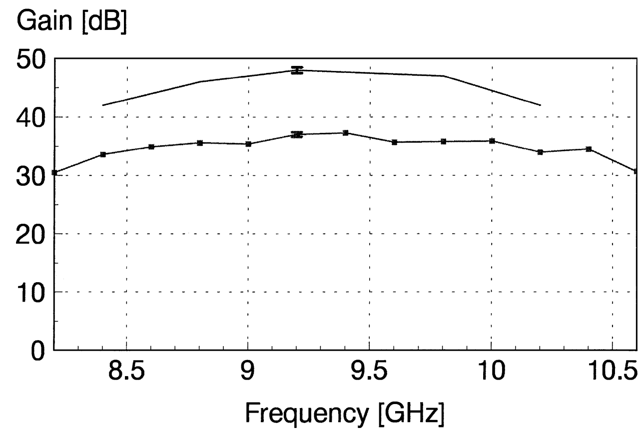

FIG. 5. Measured saturated gain and linear gain (solid line) as a function of frequency.

This experiment confirms that, with the addition of a small amplitude helical corrugation to the wall of a cylindrical waveguide, broadband amplification of guided radiation by the CRM instability can be achieved with high efficiency and good stability against oscillations. The high efficiency of this second harmonic gyroamplifier compares well with the performance of second harmonic gyrotron oscillators.

The realization of a broadband gyroamplifier with efficiency close to that of a comparable gyrotron oscillator has some important implications for a range of potential applications in radar and broadcast telecommunications where requirements exist for broadband amplifiers having a higher power/frequency capability than the current generation based on slow-wave instabilities. If this new approach proves to scale in a manner comparable with early gyrotron oscillators which also used low order resonant modes [20], then the potential for high peak power >100 kW, high frequency >100 GHz broadband amplifiers could create new applications.

Further experiments are planned at both the IAP, Nizhny Novgorod, Russia, and at the University of Strathclyde, Glasgow, Scotland, United Kingdom. These further experiments will explore the potential of this new concept with lower energy <100 keV electron beams and will look at increased beam pulse durations (using a thermionic cathode electron gun) both of which are important for future applications.

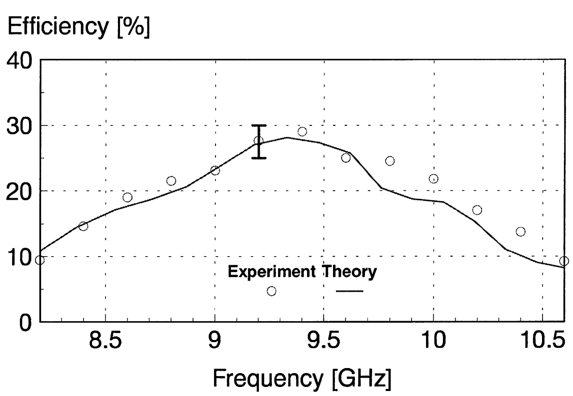

FIG. 6. Measured saturated efficiency as compared to calculated efficiency as a function of frequency.

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