LETTERS

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Demonstration of a 10 kW average power 94 GHz gyroklystron amplifier

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The experimental demonstration of a high average power *W*-band (75–110 GHz) gyroklystron amplifier is reported. The gyroklystron has produced 118 AW peak output power and 29.5% electronic efficiency in the TE_{011} mode using a 66.7 kV, 6 A electron beam at 0.2% rf duty factor. At this operating point, the instantaneous full width at half-maximum (FWHM) bandwidth is 600 MHz. At 11% rf duty factor, the gyroklystron has produced up to 10.1 kW average power at 33% electronic efficiency with a 66 kV, 4.15 A electron beam. This represents world record performance for an amplifier at this frequency. At the 10.1 kW average power operating point, the FWHM bandwidth is 420 MHz. At higher magnetic fields and lower beam voltages, larger bandwidths can be achieved at the expense of peak and average output power. © *1999 American Institute of Physics.* [S1070-664X(99)00712-0]

The continuing need for high power sources of microwave and millimeter wave radiation for such varied applications as high resolution radars,[1] linear accelerators,[2] and magnetic resonance imaging[3] has led to extensive research on gyroklystron amplifiers.[4–17] The gyrotron amplifier has a considerable advantage over conventional millimeter wave sources, such as klystrons or traveling-wave-tube (TWT) amplifiers, in its increased power handing capability. The gyrotron interaction is based on the cyclotron maser instability, in which a cyclotron beam mode imparts energy to an electromagnetic mode with a phase velocity faster than the speed of light. In these devices, the beam can interact with higher order electromagnetic modes. As a result, the transverse circuit dimensions of a gyrotron amplifier are typically comparable to or larger than a free-space wavelength. The gyroklystron is a special case of gyrotron amplifiers in which the beam interacts with standing wave cavity modes. This is contrasted with slow-wave devices, where the phase velocity of the wave is less than the speed of light and transverse circuit dimensions are typically 10% of a free-space wavelength. Because of this small circuit size, thermal loading due to both beam interception and rf heating severely limits the peak and average power that can be achieved at millimeter wave frequencies. For example, the *W*-band coupled-cavity traveling wave tube amplifier, the slow-wave device with the highest average power capability at millimeter wave frequencies, is limited to approximately 5 kW peak and 500 W average output power. Without the heating and breakdown problems associated with small interaction circuits, gyrotron amplifiers are capable of producing significantly higher peak and average powers than their slow-wave counterparts.

Since gyrotron amplifiers can achieve higher output powers than conventional slow-wave devices at high frequencies, they are now being considered for a wide variety of existing and future millimeter wave radar systems where increased power results in increased radar performance.[1] For example, the use of gyrotron amplifiers for cloud physics radars would result in the ability to study clouds at greater ranges than is possible with the extended interaction

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TABLE I. Design and measured values of cavity parameters for the four-cavity gyroklystron amplifier circuit.

	Design			Cold test	
	L (cm)	f_0 (GHz)	Q_L	$f_{0\mathrm{vac}}$ (GHz)	Q_L
Cavity 1	0.36	93.41	126	93.67	130
Cavity 2	0.48	94.21	175	94.24	175
Cavity 3	0.48	93.28	175	92.82	175
Cavity 4	0.87	93.89	162	93.67	160

klystrons currently used. Also, gyrotron amplifiers are of considerable interest for ground-based space debris detection and asteroid tracking. Other radar applications that could benefit from the increased power of the gyrotron amplifier include space object identification and planetary mapping studies by means of inverse synthetic aperture radar.

As evidenced by numerous experiments, gyroklystron amplifiers can reliably and efficiently generate high peak power and moderate bandwidth electromagnetic radiation at millimeter wave frequencies. For example, a two-cavity *Ka*-band (26–40 GHz) gyroklystron, developed for radar applications, produced 750 kW at 35 GHz in the TE_{021} mode at 24% efficiency and 0.1% bandwidth.[12] Two- and three-cavity *Ka*-band gyroklystrons operating in the TE_{011} modes produced 210 kW at 0.36% bandwidth[13] and 225 kW at 0.82% bandwidth,[14] respectively. In *W*-band, a pulsed four-cavity gyroklystron amplifier achieved 65 kW peak output power at 26% efficiency with 300 MHz bandwidth.[10] A continuous wave version of the device demonstrated 2.5 kW average output power, a result that represented the highest average power from an amplifier in this band prior to the work described below. Another *W*-band gyroklystron amplifier produced peak output powers up to 80 kW and bandwidths up to 640 MHz.[15–17] In this paper, the generation of very high average power from this type of amplifier is reported.

Below, the design and experimental demonstration of a *W*-band gyroklystron amplifier is described. The circuit consists of a drive cavity, two idler cavities, and an output cavity. The circuit was designed using a time-dependent version of a nonlinear code.[18] In this formalism, the cold cavity electric fields are determined by a scattering matrix method.[19] A linear theory analysis[20] was used to determine the stability of each cavity and drift section for the nominal operating parameters. A more detailed description of the theoretical tools and design methodology can be found in Ref. 21.

To determine the optimal circuit parameters, an extensive study was made of the tradeoffs in gain, power, and bandwidth that come through varying cavity and beam parameters. A complete description of this design study can be found in Ref. 22. For the optimized circuit parameters detailed in Table I, the predicted efficiency and peak output power versus frequency for a 65 kV, 6 A electron beam is shown in Fig. 1. As shown in Fig. 1, efficiencies up to 25% and bandwidths greater than 700 MHz are expected for beam velocity ratios, $\alpha = v_\perp / v_z$, between 1.5 and 1.7 and a rms perpendicular velocity spread of 2.2%. The output power and efficiency are sensitive to relatively small changes in the beam velocity ratio.

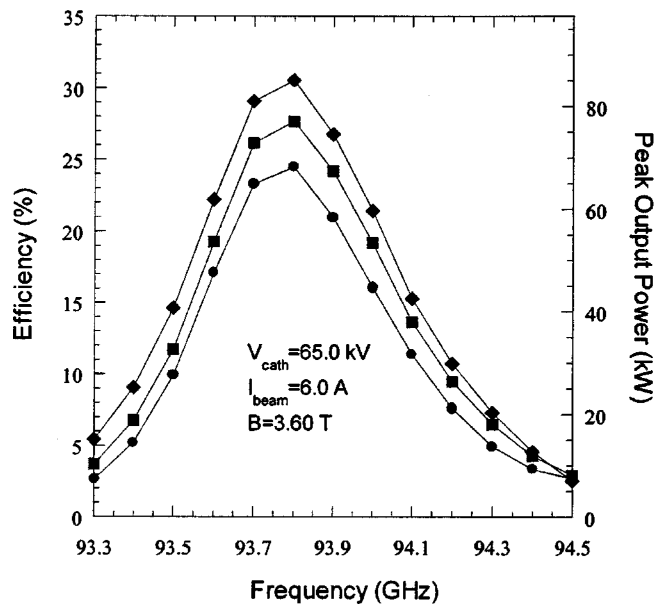

FIG. 1. Theoretical prediction for peak output power and efficiency vs drive frequency for the four-cavity gyroklystron amplifier detailed in Table I for beam velocity ratios $\alpha = 1.5$ (closed circles), $\alpha = 1.6$ (closed squares), and $\alpha = 1.7$ (closed diamonds).

In the experiment, the beam is formed by a 65 kV, 6 A magnetron injection gun which was designed to have very good beam quality, with perpendicular rms velocity spreads near 2%.[23] The beam α is controlled by the voltage on the modulating anode, which is nominally 17 kV above cathode potential, and by the superconducting coil that controls the magnetic field over the cathode. The interaction circuit is positioned in the flat field region of the 4T superconducting magnet. The power generated in the idler cavities, which is approximately 400 W average at the nominal operating point, is diffractively coupled out of the cavities and dissipated in external loads. Following the output cavity is a nonlinear up taper to the collector, which also serves as the output waveguide. The shape of the taper was specially designed to minimize mode conversion while tapering up to a large radius in a short length. The power is coupled out of the device through a CVD (chemical vapor deposition) diamond window. Cold tests showed that for frequencies in the range of 93–95 GHz, between 0.25% and 1% of the power incident on the window is reflected. A water load is positioned on the atmospheric side of the vacuum window, and the temperature rise of the water for a given volumetric flow rate is used to measure the average rf power.

The input drive power is coupled into the interaction circuit through a coaxial input coupler described in Ref. 21. A single rectangular waveguide excites the TE_{411} mode of the outer coaxial cavity. Power is then coupled from the TE_{411} mode in the outer cavity to the TE_{011} mode in the inner cavity through four slots positioned symmetrically around the azimuth of the cavity. The input coupler was designed using HFSS, a finite-element electromagnetics code. Two different drivers were used in the experimental demonstration. For low-duty testing (<0.2% rf duty factor) the drive power was supplied by an extended interaction oscillator (EIO), which is mechanically tunable from approximately 92.5 to

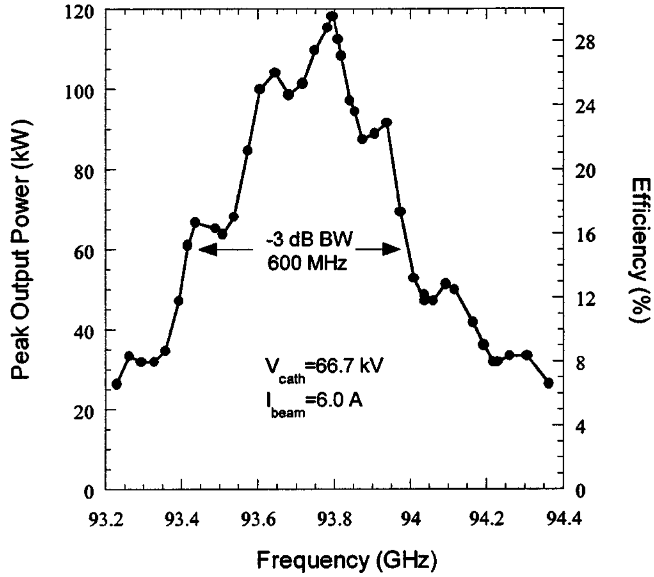

FIG. 2. Measured peak output power and efficiency vs frequency for a 66.7 kV, 6 A electron beam.

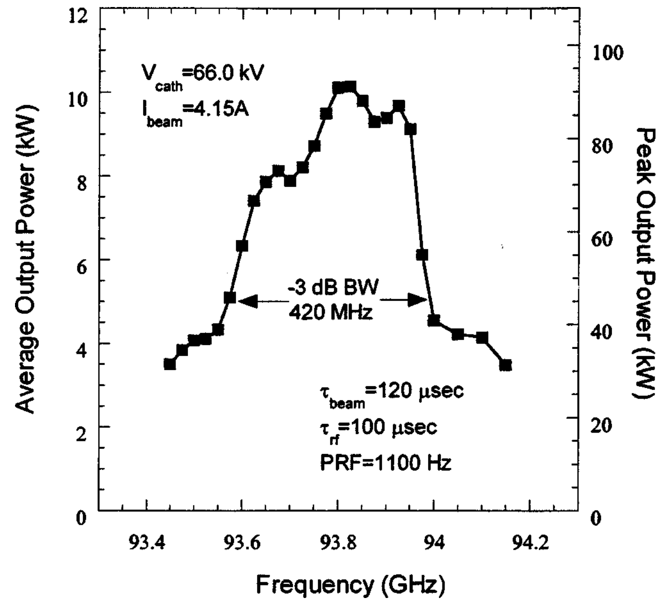

FIG. 3. Measured average and peak output power for a 66 kV, 4.15 A electron beam and 11% duty factor.

95.5 GHz. The EIO produces up to 2 kW peak output power at pulse lengths up to 2 μs. For high-duty testing, a coupled-cavity TWT amplifier was used. This amplifier produces up to 100 W peak output power over the 93 to 95 GHz frequency range at duty factors up to 100% (cw). The drive power is measured with a calibrated directional coupler at the gyroklystron input flange and the frequency of the input and output rf signals are measured with a spectrum analyzer. Losses in the drive line between the source and gyrotron input flange were found to be approximately 3 dB.

Parametric studies of circuit operation with beam current and magnetic field variations were made at low rf and beam duty to determine the best operating point for subsequent high duty operation. As shown in Fig. 2, the gyroklystron produced up to 118 kW peak output power and 29.5% electronic efficiency in the TE_{011} mode using a 66.7 kV, 6 A electron beam at 0.2% rf duty factor. At this operating point, the instantaneous full width at half-maximum (FWHM) bandwidth was 600 MHz and the gain was 24.7 dB. At higher magnetic fields the bandwidth increases and the peak output power and gain decrease. This trend is predicted by the theoretical model, which shows that at lower fields, the input cavity operates in the negative beam loading regime, which increases the Q of this cavity and leads to lower bandwidth and higher gain and output power. As the magnetic field is increased, the cavity moves into the positive beam loading regime, where the negative beam Q decreases the overall Q of the cavity, resulting in wider bandwidth and lower gain and output power.

Also evident in Fig. 2 is the ripple in the peak output power across the frequency band. This effect is due to reflections from the CVD diamond window, which create standing waves between the window and output cavity and modulate the output power of the device. This effect was modeled with the MAGY code, a fully self-consistent nonlinear formalism.[24] The code showed that the spacing and amplitude of the output power across the band is consistent with reflections from the output window. The code also showed that the amplitude of the ripple is reduced at higher magnetic fields, as was observed experimentally. More detailed theoretical analyses of the measured data will be presented in forthcoming papers.

Upon completion of the low duty demonstrations, the EIO was replaced with the 100 W coupled-cavity TWT driver amplifier for high duty tests. Because of input power limitations, a high-gain operating point was chosen for the high duty tests. Figure 3 shows the measured peak and average output power versus drive frequency for a 66 kV, 4.15 A electron beam. The rf pulse width was 100 μs and the pulse repetition frequency was 1.1 kHz, corresponding to 11% rf duty factor. The gyroklystron produced 10.1 kW average output power, corresponding to 90 kW peak output power

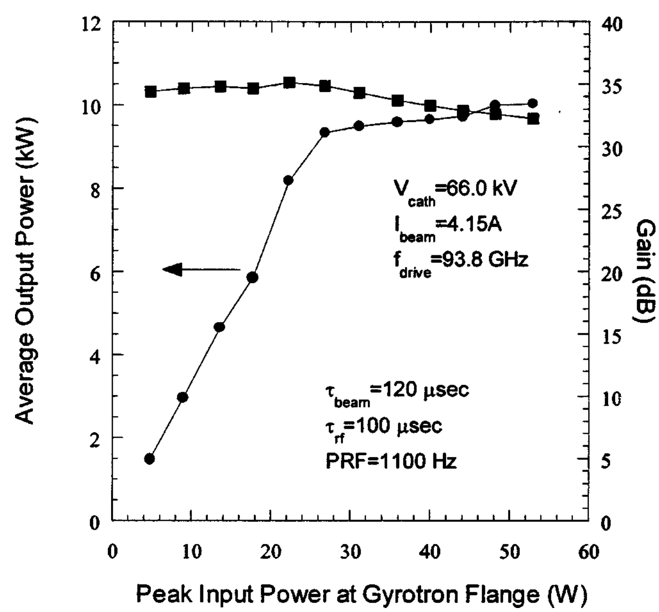

FIG. 4. Measured average output power and gain for a 66 kV, 4.15 A electron beam and 11% rf duty factor. The drive frequency was held fixed at 93.8 GHz.

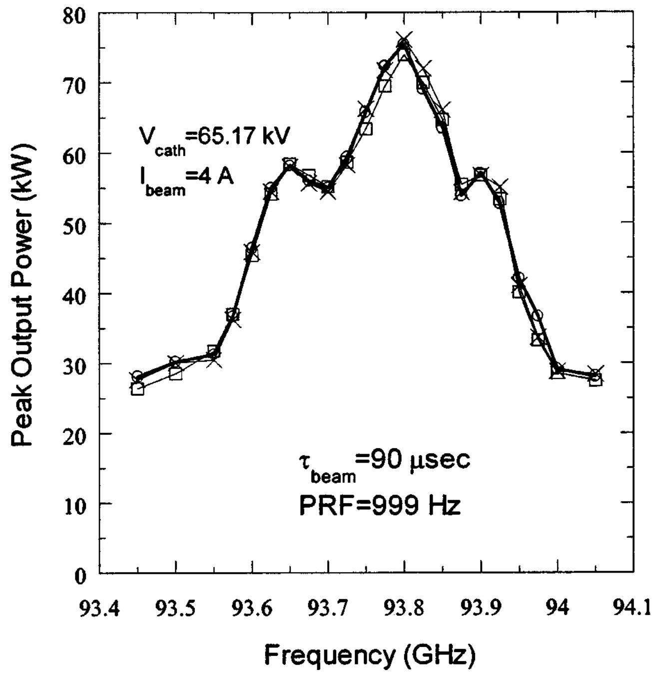

FIG. 5. Peak output power for rf beam pulse widths of 10 μs (open circle), 40 μs (open square), and 70 μs (cross). For each curve, the beam pulse width, pulse repetition frequency, beam current, beam voltage, and all other parameters were held fixed.

and 32.9% efficiency. The measured FWHM bandwidth was 420 MHz. Figure 4 shows the average output power and gain versus drive power. As shown in Fig. 4, the maximum output power of 10.1 kW average and 92 kW peak is achieved for 53 W peak driver power, corresponding to 32 dB gain.

Figure 5 shows the peak output power versus drive frequency for rf pulse widths of 10, 40, and 70 μs. For each curve, the beam current and beam voltage pulse widths were held fixed at 90 μs and the pulse repetition frequency was 1 kHz. As seen in Fig. 5, for rf duty factors ranging from 1% (10 μs pulse width) to 7% (70 μs pulse width), the differences in peak output power over the operating bandwidth were negligible. The measured results show that for duty factors in this range (1%–7%), there were no significant changes in the circuit or circuit performance resulting from thermal effects.

Parametric studies were also performed at high duty. By increasing the magnetic field, bandwidths up to 600 MHz could be obtained with reduced peak and average output powers, typically near 50 and 5 kW, respectively. The theoretically predicted trend of reduction in the amplitude of the bandwidth ripple at higher magnetic fields was also observed at high duty. In addition, calorimetric measurements were made for the window, the interaction circuit, and other cooled components of the device and were found to be close to the theoretically predicted values of losses.

In summary, a four-cavity TE_{011} mode high average power gyroklystron amplifier was designed, built, and successfully tested. At low duty, the amplifier produced up to 118 kW peak output power at 600 MHz bandwidth. At high duty, 10.1 kW average output power and 420 MHz bandwidth were achieved at 11% rf duty. These results represent world record setting performance for an amplifier at this frequency.

Future work will be centered on improving certain aspects of the device performance. Because of the limited availability and relatively high cost of high-power, high-duty drivers at millimeter wave frequencies, improving the gain of the device is desirable. A subsequent amplifier currently in construction will be comprised of five cavities to improve the gain by more than 10 dB. Future work will also consider bandwidth improvement by replacing the output cavity with a traveling wave output section, a configuration commonly referred to as a gyrotwystron amplifier. A low-duty prototype of a *W*-band gyrotwystron has demonstrated 50 kW peak output power and 900 MHz FWHM bandwidth.[25] For bandwidths greater than 2 GHz, gyro-traveling-wave tube amplifiers are under investigation.

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