

# EXPERIMENTAL INVESTIGATION OF A W-BAND GYROKLYSTRON AMPLIFIER

M. Blank, B.G. Danly, B. Levush, Naval Research Laboratory, Washington, D.C. 20375 and P.E. Latham, Omega P, Inc., New Haven, CT 06520

*Abstract*

A four cavity W-band gyrokylystron amplifier experiment is currently underway at the Naval Research Laboratory. The gyrokylystron has produced 67 kW peak output power and 28% efficiency in the TE<sub>011</sub> mode with a 55 kV, 4.3 A annular electron beam. The full width half maximum (FWHM) bandwidth is greater than 460 MHz. Small signal and saturated gains of 36 dB and 29 dB, respectively, have been observed. The amplifier is zero drive stable and the limiting oscillation is the TE<sub>011</sub> operating mode in the output cavity. Experimental results are in good agreement with theoretical predictions.

## 1 INTRODUCTION

The continuing need for high power sources of millimeter wave radiation for such varied applications as high resolution radars, linear accelerators, and communications, has led to extensive research on gyrokylystron amplifiers. Much like a conventional klystron, the gyrokylystron consists of several resonant cavities separated by drift sections cut-off to the operating mode. As evidenced in numerous experiments, the interaction of the beam with the trapped mode in the cavity, based on the electron cyclotron maser instability, can reliably and efficiently generate high power, moderate bandwidth electromagnetic radiation at microwave and millimeter wave frequencies. For example, a three cavity C-band gyrokylystron amplifier produced 54 kW peak output power and 30% efficiency in the TE<sub>011</sub> at 4.5 GHz [1]. The saturated gain was 30 dB and the FWHM bandwidth was 0.4%. A three cavity X-band gyrokylystron achieved 16 kW peak output power 45% efficiency with a 1% bandwidth [2]. Fundamental and second harmonic two cavity gyrokylystron amplifiers at 9.87 GHz and 19.7 GHz, designed as drivers for linear colliders, achieved peak output powers of 20 MW and 30 MW, respectively, with efficiencies near 30% [3,4]. A two cavity Ka-band gyrokylystron, developed for radar applications, produced 750 kW at 35 GHz in the TE<sub>021</sub> mode at 24 % efficiency [5]. In W-band, a pulsed four cavity gyrokylystron amplifier achieved 65 kW peak output power at 26% efficiency with 300 MHz bandwidth [6]. A continuous wave version of the device demonstrated 2.5 kW average output power. The goal of the present work is to enhance the bandwidth of the W-band gyrokylystron amplifier while maintaining high efficiency, peak output power, and gain.

## 2 THEORY AND DESIGN

This paper presents an experimental study of a four cavity W-band gyrokylystron amplifier operating in the TE<sub>011</sub> mode near the fundamental cyclotron frequency. The circuit consists of a drive cavity, two idler cavities, and an output cavity. The circuit was designed with a time-dependent version of the non-linear code MAGYKL [7]. The wave equation solved in MAGYKL is given by

$$\frac{da}{dt} + \left( \frac{1}{2} + i\Delta_{\omega} \right) a = -\frac{QI_b}{2\omega W_{EM}} \int d\xi \frac{c}{\omega} \left\langle \frac{v_{perp} \cdot \mathbf{E}_c e^{-i\omega t}}{v_z} \right\rangle$$

where  $a$  is the complex amplitude of the fields,  $\Delta_{\omega} = Q\{\text{Re}\{\omega_c\} - \omega\}/\omega$  is the normalized frequency shift,  $Q$  is the quality factor of the cavity,  $\omega$  is the drive frequency,  $\omega_c$  is the cold resonant frequency,  $I_b$  is the beam current,  $W_{EM}$  is the stored energy,  $c$  is the speed of light,  $v_{perp}$  and  $v_z$  are the perpendicular and axial electron velocities,  $\mathbf{E}_c$  is its cold cavity electric field, and  $t$  is the normalized time  $\omega/Q$ .

In the formulation, the cavities are modeled by a series of straight uniform sections with abrupt discontinuities at the boundaries. The fields in each section, expanded as a radial series of TE, TM, and TEM modes, are determined through a scattering matrix solution [8]. Theoretical studies have shown that it is necessary to include many modes in the field description to correctly predict the resonant frequency of the cavity. In order to accurately predict the bandwidth of the amplifier, the formulation detailed in reference [7] was modified to include a frequency dependent drive power, as dictated by the resonant frequency and  $Q$  of in input cavity. The theoretical model was used to design the interaction circuit and determine the parameters of each cavity, which are summarized in Table 1.

	Design			Cold Test	
	L (cm)	f <sub>0</sub> (GHz)	Q	f <sub>0</sub> (GHz)	Q
cavity 1	0.43	93.00	125	-	-
cavity 2	0.50	93.52	175	93.56	130
cavity 3	0.50	92.89	175	93.02	128
cavity 4	0.80	93.18	300	93.21	299

Table 1 Summary of cavity parameters.

The drive power is coupled into the circuit through a coaxial cavity [9]. A single cylindrical waveguide excites the  $TE_{411}$  mode of the outer 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 coaxial cavity was analyzed with the High Frequency Structure Simulator (HFSS) and found to have a resonant frequency of 93.0 GHz and a diffractive Q of 150. HFSS simulations also show that 75% of the energy is stored in the  $TE_{411}$  mode and 25% is stored in the  $TE_{011}$  inner cavity mode. Thus, 6 dB of drive power arriving at the input cavity is stored in the outer cavity and is not available for interaction.

Because the second and third cavities are terminated by drift sections that are cut-off for the  $TE_{011}$  mode at 93 GHz, the diffractive Q's are quite large. The design Q's of 175 are achieved through dielectric loading of the cavities. The output cavity consists of a 0.8 cm straight section, followed by an iris which is cutoff to the  $TE_{011}$  mode at 93 GHz, and a 5 degree linear uptaper to the collector radius. The wave is coupled out diffractively and there is no ceramic loading the output cavity. The first and second cut-off drift lengths are loaded only by the dielectrics on the upstream walls of the idler cavities, and the drift length separating the penultimate cavity and output cavity is unloaded.

### 3 EXPERIMENTAL RESULTS

The circuit was built and cold tested on a vector network analyzer. The cavities were excited and sampled through two 0.075 cm diameter holes positioned 180 degrees apart in the side wall. The transmission spectra for the idler and output cavities are shown in Fig. 1 and the measured resonant frequencies and Q's are summarized in Table 1.

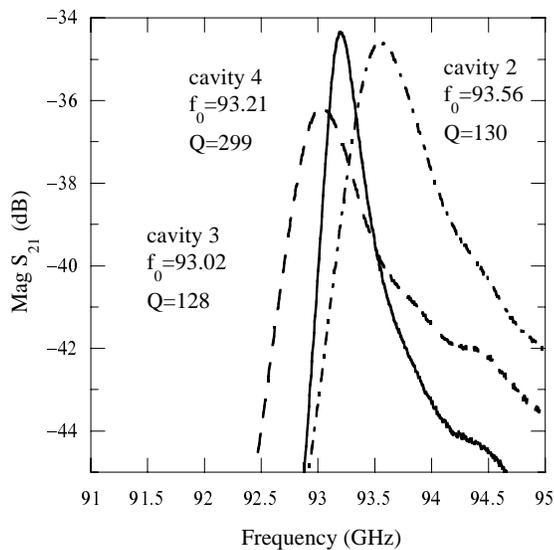


Figure 1 Cold test transmission spectra for cavity 2

(dashed-dot line), cavity 3 (dashed line) and cavity 4 (solid line).

Upon completion of the cold test, the circuit was installed in the test stand. Figure 2 shows a schematic of the gyrokystron amplifier experiment. A 4 A, 55 kV annular electron beam is produced by a double anode magnetron injection gun. The magnetic field at the cathode, which is nominally 1.5 kG, can be varied to control the beam velocity ratio,  $\alpha$ . The beam is adiabatically compressed as it enters the region of high magnetic field generated by the 4 T superconducting magnet. The four cavities of the gyrokystron circuit are positioned in a region of constant magnetic field. The output cavity tapers up to the collector, which is followed by a quartz vacuum window. A conically shaped, water backed teflon load is positioned on the atmosphere side of the vacuum window. The temperature rise of the water is used to measure the average rf power. The frequency of the input and output rf signals are measured with a spectrum analyzer. The drive power is supplied by a 1 kW peak power EIO, which is mechanically tunable from approximately 92.5 GHz to 95.5 GHz. The EIO provides pulses up to 2 microseconds in duration with a duty cycle up to 1%. The beam and EIO are typically pulsed at 250 Hz for an rf duty cycle of 0.05%.

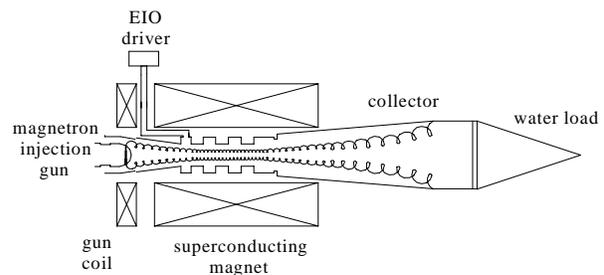


Figure 2 Schematic of the experimental test stand.

Figure 3 shows the measured and predicted output power and efficiency as a function of frequency for the amplified  $TE_{011}$  mode. A peak saturated output power of 67 kW, corresponding to 28% efficiency, was achieved with a 55 kV, 4.3 A electron beam. The FWHM bandwidth is greater than 460 MHz. The input power, measured at the output of the EIO, was 87 W, which gives 29 dB saturated gain. For the theory curve in Fig. 3, the experimentally determined values of cold resonant frequencies and Q's for the idler and output cavities were used. The HFSS predictions of the drive cavity resonant frequency and Q were assumed. The experimental values of beam voltage, beam current, and magnetic field in the

interaction circuit were used. The beam  $\alpha$  was taken to be 1.5, and the perpendicular velocity spread was assumed to be 9%, values that were obtained through a combination of modeling and empirical determination. As shown in Fig. 3, the theoretical predictions are in good agreement with experimental data.

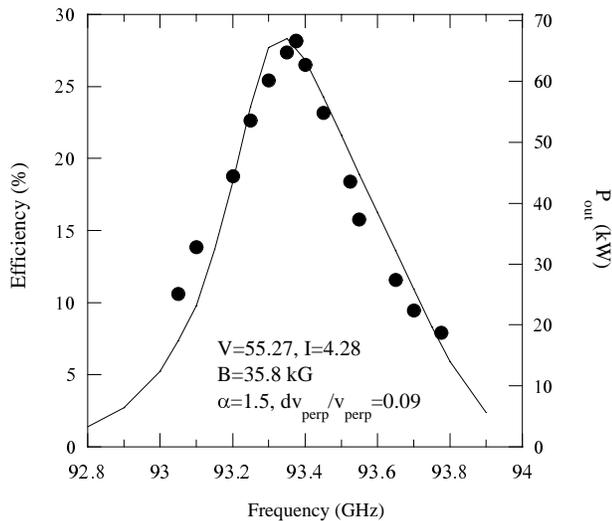


Figure 3 Measured values (filled circles) and theoretical predictions (solid curve) of peak output power and efficiency.

The limiting oscillation in the circuit was found to be the  $TE_{011}$  operating mode in the output cavity. The start oscillation current was measured and the results are shown in Fig. 4.

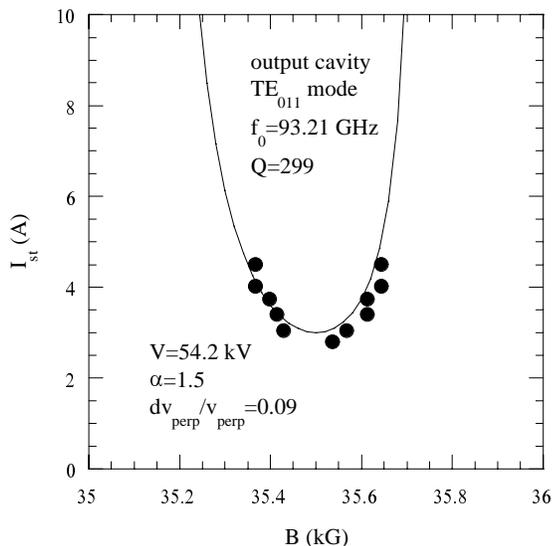


Figure 4 Measured values (filled circles) and theoretical prediction (solid curve) for start oscillation current of the  $TE_{011}$  mode in the output cavity.

The measured data points, indicated by the filled circles, are compared with the theoretical start current, shown with the solid line. In the theory, the measured values of beam current, cold resonant frequency, and cold cavity  $Q$  were used. The beam  $\alpha$  was taken to be 1.5, and the perpendicular velocity spread was assumed to be 9%. As shown in Fig. 4, the experimental data and theoretical predictions are in good agreement.

#### 4 SUMMARY

In summary, a four cavity W-band gyrokystron amplifier circuit was designed, built, and tested. Peak output powers of 67 kW, corresponding to 28% efficiency, were achieved in the  $TE_{011}$  mode with a 55 kV, 4.3 A electron beam. The FWHM bandwidth is greater than 460 MHz. The small signal and saturated gains are 36 dB and 29 dB, respectively. The circuit is zero drive stable and the limiting oscillation is the  $TE_{011}$  operating mode in the output cavity. The experimental data is in good agreement with predictions of theory using calculated values of beam velocity ratio and velocity spread. Future experiments will focus on increasing bandwidth through more aggressive stagger tuning and reduced output cavity  $Q$ .

#### 5 ACKNOWLEDGEMENTS

The authors would like to thank M. Barsanti, F. Robertson, B. Sobocinski, and M. Ngo for their technical assistance. This work was supported by the Office of Naval Research. The computational work was supported in part by a grant of HPC time from the DoD HPC Center NAVO.

#### REFERENCES

- [1] W.M Bollen, A.H. McCurdy, B. Arfin, R.K. Parker, A.K. Ganguly, IEEE Trans. Plasma Sci. **13**, 417 (1985).
- [2] E.V. Zasyrkin, M.A. Moiseev, E.V. Sokolov, V.K. Yulpatov, Int. J. Electron. **78**, 423 (1995).
- [3] W.G. Lawson et al., Phys. Rev. Lett. **67**, 520 (1991).
- [4] H.W. Matthews et al., IEEE Trans. Plasma Sci. **22**, 825 (1994).
- [5] E.V. Zasyrkin, M.A. Moiseev, I.G. Gachev, I. I. Antakov, IEEE Trans. Plasma Sci. **24**, 666 (1995).
- [6] I.I. Antakov, E.V. Zasyrkin, E.V. Sokolov, Conf. Digest of the Eighteenth Intl. Conf. On Infrared and Millimeter Waves, Proc. SPIE **2104**, 166 (1993).
- [7] P.E. Latham, W. Lawson, V. Irwin, IEEE Trans. Plasma Sci **22**, 804 (1994).
- [8] J.M. Neilson, P.E. Latham, M. Caplan, W. Lawson, IEEE Trans. Microwave Theory Tech. **37**, 1165 (1989).
- [9] G.S. Park, C.M. Armstrong, R.H. Kyser, J.L. Hirshfield, R.K. Parker, Int. J. Electronics **78**, 983 (1995).