HIGH POWER 35GHz GYROKLYSTRON AMPLIFIERS

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Abstract

High power coherent radiation sources at 35GHz are attractive for high gradient, compact particle accelerators and next generation high resolution millimeter wave radar/communications. A multi-cavity gyroklystron amplifier is considered a promising candidate for high power millimeter wave generation. Experiments on two-cavity and three-cavity gyroklystron amplifiers are underway to demonstrate 140kW, 35GHz coherent radiation amplification. Initial experiments show an efficiency of 32%, a bandwidth of 0.4%, and a saturated gain of 22dB which corresponds to peak power of 130kW. Experimental results are moderately in agreement with large signal simulations. Calculations also show that a stagger tuned three cavity circuit increases the bandwidth to more than 0.7%.

1. TWO-CAVITY GYROKLYSTRON AMPLIFIER

1.1 Design and Experimental Arrangement

35GHz gyroklystron amplifier experiments are currently underway to demonstrate peak radiation power of 140kW and bandwidth > 0.5%. An experimental layout is depicted in Figure 1. A high power electron beam is produced from magnetron-injection-gun (CPI) which is optimally designed for TE_{01} cylindrical cavity mode coupling at fundamental beam cyclotron mode. The gyrating electron beam is adiabatically compressed through a high magnetic field of 13.2kG which is powered by a 14 coil superconducting magnet. An electron trajectory code, EGUN predicts an axial velocity spread of 10% at 60kV, 6.72A, and α=1.5. A capacitive probe is placed directly before the input cavity to measure the beam velocity ratio.

The two-cavity gyroklystron amplifier is designed using large signal non-linear time-dependent gyroklystron codes [1] Cavity dimensions of input and output cavities and drift tube length are optimized for maximum efficiency at a beam axial velocity spread of 15%. For the two-cavity circuit, the resonant frequency of the input cavity is same as that of the output cavity. An operating cavity mode (TE_{011}) is chosen which has low ohmic power dissipation at high average power operation. All the tube components are relevant to 10% duty operation.

An input drive signal for beam modulation is injected through a coaxial coupler [2]. The TE01 mode purity is more than 99% in the central cavity. The coaxial input coupler is also attractive because of a single port excitation through a rectangular TE_{10} mode. By the use of a 3-D finite element code, HFSS [3], the coaxial input coupler is designed and fabricated. Cold-test shows Q of 188 and resonant frequency of 34.89GHz.

The output cavity, as shown in Figure 1, has a small radial step to control cavity external Q and is followed by a non-linear uptaper section which guides the amplified TE_{01} mode to 1.5" diameter circular waveguide with minimum mode conversion. The output cavity length (2.75λ) is optimized for maximum efficiency and gain while ensuring that the cavity is not self-oscillating. The non-linear uptaper has a Dolph-Chevychev profile [4] which has a minimum mode conversion to other TE_{0n} modes. Calculation predicts less than -30dB mode conversion into a TE_{02} mode.

A TE_{01} output vacuum window is designed using HFSS. An 1.5" diameter, half-wavelength thick BeO window which is brazed directly into the conflat flange shows a good rf match better than -25dB over 3.7% bandwidth (34.3-35.6GHz). The measured data is in good agreement with the HFSS prediction. The input waveguide vacuum window is a pillbox window which is that used in CPI coupled cavity tubes.

Lossy ceramic rings (80% BeO, 20% SiC) with different radii are inserted in the drift tube between the input cavity and the output cavity in order to avoid oscillations. CASCADE code [1] predicts high attenuation (<-20dB) of TE_{11} mode in the drift tube filled with the lossy ceramic rings. In addition, a beam tunnel between the input cavity and electron gun is filled with lossy ceramics. Ceramic thickness varies along the beam tunnel so that all the TE modes crossing a beam cyclotron line have a maximum attenuation. The clearance between the gyrating beam and the drift tube is designed at 30mils, which permits high average power operation of the amplifier. A water-cooled beam collector (1.5" diameter and 15" long) is made of copper for good heat conduction. With a careful magnetic field tapering, an average power density of the electron beam dissipated on the collector is estimated less than 0.5kW/cm^2 at 10% duty operation.

A high average power calorimeter is designed and fabricated to measure the gyroklystron output power. In order to have a good rf match, teflon with a 20 degree cone angle is chosen. Cold-test shows rf match better than -20dB over the entire operating frequency range. Two different power calibrations are performed; DC heater power and RF power driven by a conventional TWT and a high power EIO. The power calculations obtained from

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the temperature difference between inlet and outlet thermistors submerged in octanol agree within ± 5% for both calibration methods.

A simple thin circular hole on the waveguide is used to sample rf signal for frequency measurement and monitoring rf pulse shapes.

1.2 Experiment Results

Typical experimental beam parameters are V=60kV, I=6.72A, α=1.5, and B=13.2kG. Maximum power is obtained with -0.7% downtaper of the magnetic field in the output cavity region. Figure 2 shows a drive curve, efficiency as a function of input drive power at 34.942GHz. This result is compared with non-linear code simulations for various beam axial velocities. The maximum efficiency is measured at 32±2%, corresponding to amplified radiation power of 130kW. This is the highest power at 35GHz ever reported in US power tube amplifiers.

Instantaneous bandwidth is measured and compared with theory as shown in Figure 3. Although the peak efficiency is lower than the predicted value, the measured bandwidth of 0.4% agrees very well with simulations. The discrepancy between the experiments and theory is maybe due to the lack of self-consistent calculation of output cavity field when beam is present and improper modeling of a beam velocity distribution function. The present code assumes a flat-top velocity distribution. The beam loaded frequency upshift is also observed as shown in Figure 3. There is a 70MHz upshift (0.2%) with respect to the cold resonance frequency, which is in good agreement with code prediction.

Rf oscillations in the output cavity are observed when beam current exceeds a threshold current. Figure 4 shows start oscillation current as a function of magnetic field. Measured oscillation frequency is near 34.93GHz which indicates that the oscillation originates from a TE_{011} cavity mode. Maximum efficiency is achieved just below the starting oscillation point which is in the region of negative beam loading in the cavity. It is also plotted with calculated starting oscillation curves for various beam α and spreads. From this comparison, beam α is estimated to be 1.5, which is consistent with the value obtained from EGUN code simulation.

MAGIC [5] is used to examine transient behavior of the two-cavity gyroklystron. As shown in Figure 5, when the phase of input drive frequency instantaneously changes by π, a 13nsec delay is observed in the output cavity. Further investigation will be performed with experiments.

2. THREE-CAVITY GYROKLYSTRON AMPLIFIER

In order to enhance gain and bandwidth, a stagger tuned three-cavity gyroklystron is designed using the non-linear codes and the stability code. The best design parameters are 30% efficiency, 35dB saturated gain and 0.7% bandwidth at $\Delta v_Z/v_Z$=15%, Q(1)=130, Q(2)=150, and Q(3)=175. The bandwidth increases nearly by a factor of 2 compared with that of the two-cavity gyroklystron. Further increase of gain and bandwidth is possible by adding more buncher cavities at the expense of lower efficiency.

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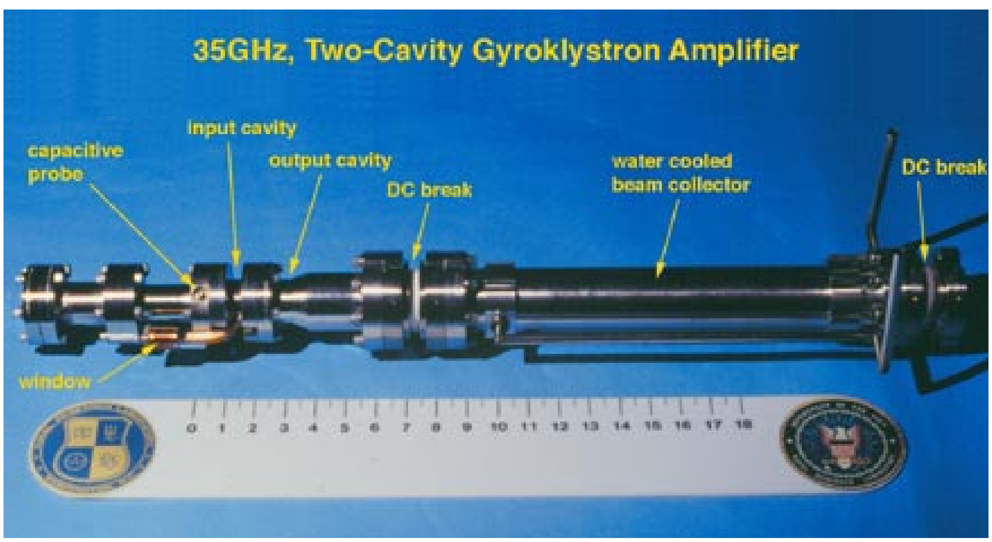

Figure 1. Two-cavity gyroklystron amplifier

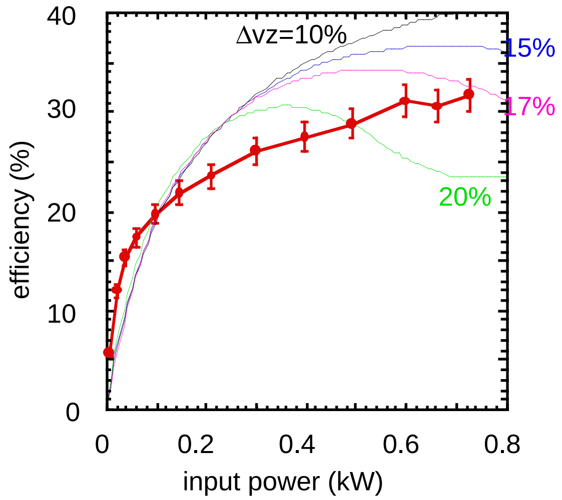

Figure 2. Experimental results on the drive curve. Simulation curves are Δvz=10%, 15%, 17%, and 20%.

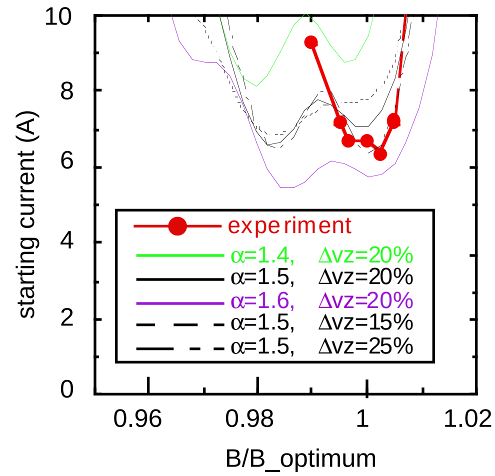

Figure 4. Start oscillation curve as a function of magnetic field detuning.

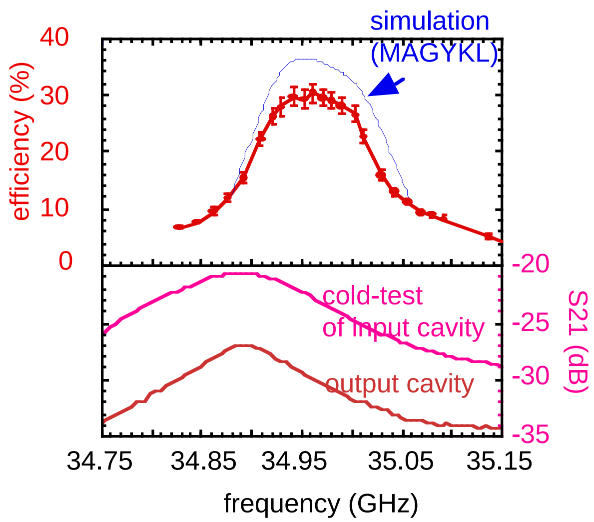

Figure 3. Large signal bandwidth

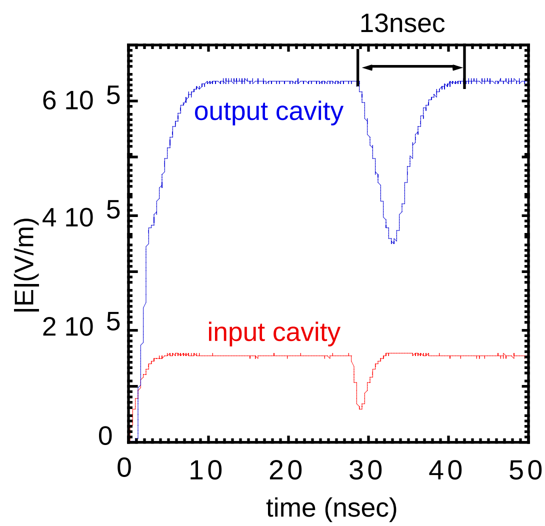

Figure 5. MAGIC simulations on the transient behavior of two-cavity gyroklystron. A phase shift by π in the input drive signal is switched on at 28nsec.