Design of a High-Power, High-Gain, Frequency-Doubling Four-Cavity Gyroklystron

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***Abstract*— In this paper we consider the design of a four-cavity microwave circuit for a high-gain K-band gyroklystron. The goal is to use this device to test a high gradient linear accelerator structure. The frequency doubling circular gyroklystron uses a beam voltage of 500 kV, beam current of 200 A in the circular TE_{011} mode and provides an output in the TE_{021} mode. We study the behavior of the four-cavity circuit for different values of perpendicular to parallel velocity ratio ($\alpha = V_\perp / V_z$). These tubes are required to produce 20 MW of power in 1μs pulses at a rate greater than 120 Hz and at a frequency of 22.848 GHz. Maximum efficiency of 38% and large signal gain of 60 dB were achieved for a velocity ratio equal to 1.4.**

Index Terms— **Gyroklystrons, high-power amplifier, microwaves.**

I. Introduction

Future electron-positron supercolliders will require efficient RF amplifiers in the 10-30 GHz range with peak powers well above the ones used in current systems. Much of the research which has focused on enhancing the performance of conventional klystrons has met with some success [3], but results are adversely affected because of the limitations on electric field in the electron gun, cavities and output sections. Other long pulse approaches include the Magnicon [4], CARM [5] and gyroklystrons [6]. High energy short-pulse candidates include relativistic klystrons [7], intense beam traveling tubes [8] and free electron lasers [9].

At the University of Maryland, we have been exploring the suitability of gyroklystrons as drivers for high gradient linear accelerator structures. The selection of the tube and operation modes used depends on a number of application requirements like peak and average power, gain, bandwidth and output field configuration. Significant milestones achieved at the University of Maryland in this direction include a 3-cavity first harmonic coaxial system, which produced over 75 MW of peak power at 8.57 GHz and a three-cavity frequency-doubling system that produced 27 MW at 17.14 GHz [1, 2]. The current focus of our four-cavity (input, buncher, penultimate and output) frequency doubling system is to act as a driver for an accelerator structure.

Section II introduces the concepts involved in the theoretical design of the microwave system. Section III discusses the design methodology and criterions for stable operation of the cavities. Section IV demonstrates the large signal behavior and the optimal configuration for our design. In section V we summarize our observations and results.

II. Theoretical Design

The active region of a gyroklystron is the region located in between the input and output cavities. This region is called the tube or the microwave circuit and is the site for interaction between particles and electromagnetic waves. The active region is split into cavities. Cavities are resonant structures, where the beam actively interacts with electromagnetic waves. The beam is exposed to an external drive signal in the input cavity and an amplified version of the input signal is generated in the output cavity. The cavities added in between help to further bunch the beam, increasing the overall gain and efficiency of the system. Drift regions are introduced in order to reduce any kind of direct electromagnetic interaction between adjacent cavities. They are designed to be regions of cut-off to the operating electromagnetic modes excited in the cavities.

For the design of this microwave tube, we took a previous 20 GHz two-cavity design and scaled it for 11.424 GHz. Then we added two buncher cavities to increase the gain.

The design of the microwave circuit was performed using the COAX code [10]. We start with a geometric description of

Manuscript received October 9, 2001. (Write the date on which you submitted your paper for review.) This work was supported in part by the U.S. Department of Commerce under Grant BS123456 (sponsor and financial support acknowledgment goes here).

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a iven cavity along with the adjacent drift areas. The code then considers each constant cavity section of the input geometry as a separate region. The code returns the resonant frequency and corresponding quality factor of the cavity.

A large signal analysis was performed using the computer code MAGYKL [11], yielding a predicted output power of 38 MW for an input drive power of 0.04 kW with a velocity ratio of 1.4. This analysis involves solving fairly complex equations that describe the interaction of electromagnetic fields with the electrons that make up the beam. MAGYKL uses the complex amplitude and phase of cold cavity fields as an input, and calculates the normalized current and frequency shift for a beam with specific parameters. Eventually the gain and efficiency of the circuit can be calculated. Another important property that needs to be taken care of in the design of a microwave amplifier is zero-drive stability. This property guarantees that in the absence of any drive power the output power is also zero, so there are no oscillations taking place inside the tube. Self-oscillations affect mode and phase purity of the output signal and reduce the gain and efficiency of the amplifier. We use the code QPB [11] to check for potential self-oscillations in each of our cavities. This code calculates the product of the quality factor Q for a given cavity and the beam power. Based on this product we can calculate the threshold of the onset of self-oscillations. Above this threshold the cavity will be unstable for a constant magnetic field. Start of oscillation Q is given by:

$$Q_{so} = (QP_b)_{so} / V_b I_b$$

We run the code MAGYKL using the output files from COAX for all cavities in the circuit. MAGYKL computes the overall efficiency of the gyroklystron based on the characteristics of the cavities, parameters of the electron beam and the external magnetic field profile applied to the circuit. In order to maximize the efficiency, one can vary several quantities, including the input power, drive frequency, applied magnetic field profile, drift lengths between the cavities, Q and cold cavity frequency of the cavities and the beam parameters.

III. Design Methodology and Cavity Stability

The design discussed in this paper is a four cavity design, the first cavity being a TE_{011} input cavity (first harmonic cavity) which is operated near cyclotron frequency. The second cavity is the first harmonic buncher cavity. The other two cavities are second harmonic cavities operating in TE_{021} mode, at approximately twice the input frequency. The individual dimensions of the cavities have been summarized in Table I. We use a quality factor of 200 for the input cavity and 270 for the output cavity. The magnetic field is constrained by the coil and power supply configuration. The magnet power comes from four power supplies that supply eight coils and limit the flexibility of the profile of the axial magnetic field. The nominal "flat field" length of nearly 35 cm is shown in Fig. 1. The black squares represent the axial location of the four cavity centers.

TABLE I
CIRCUIT PARAMETERS FOR THE FOUR CAVITY 1122 GYROKLYSTRONS

Cavity	Length(cm)	Radius(cm)	Freq(GHz)/Q	Q
Input/1st harmonic	1.495	2.428	11.424	200
Penultimate	2.075	1.521	22.806	200
Output	0.500	1.510	22.848	270
Drift tubes 1-2	3.000	1.296	-	-
Drift tube 2-3	6.500	1.296	-	-
Drift tube 3-4	9.320	1.296	-	-

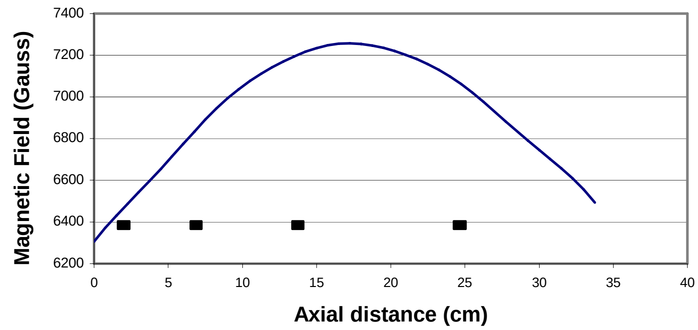


Fig. 1. Optimal magnetic field profile

Figure 2. shows the layout of the four cavity frequency doubling gyroklystron circuit. The outer conductor is represented by the solid lines and the dotted lines represent the magnetic field profile. The evolution of the velocity ratio with the optimal magnetic field profile has also been demonstrated. When we say the velocity ratio is 1.0, we mean that at the entrance of the tube. In the absence of electromagnetic waves, the velocity ratio in the tube varies adiabatically with the changes in axial magnetic field. Thus, this beam with velocity ratio equal to 1.0 has an average velocity ratio of about 1.12 in the center of the tube. The optimized magnetic field profile has an average value of 7.25 kG.

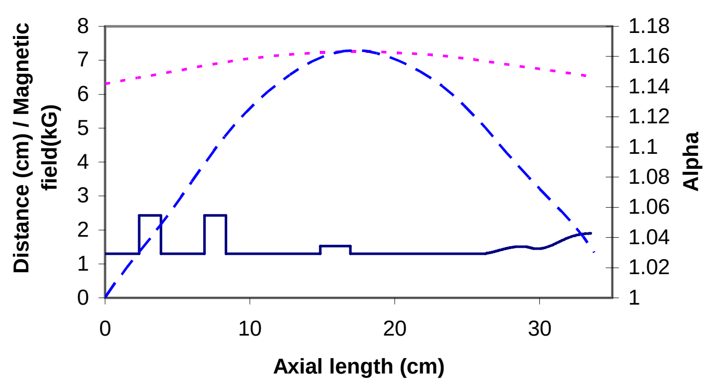
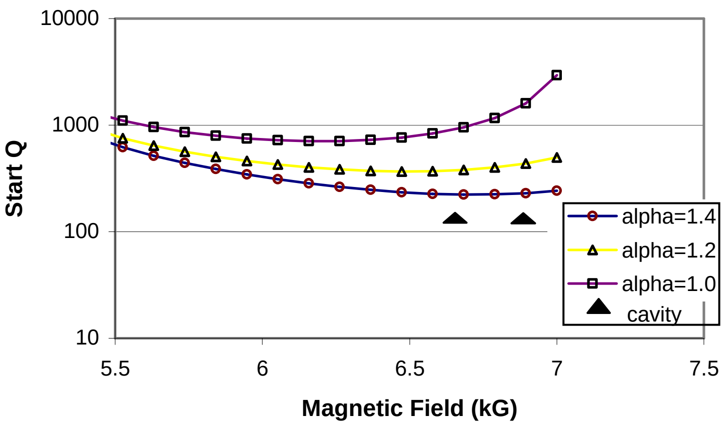
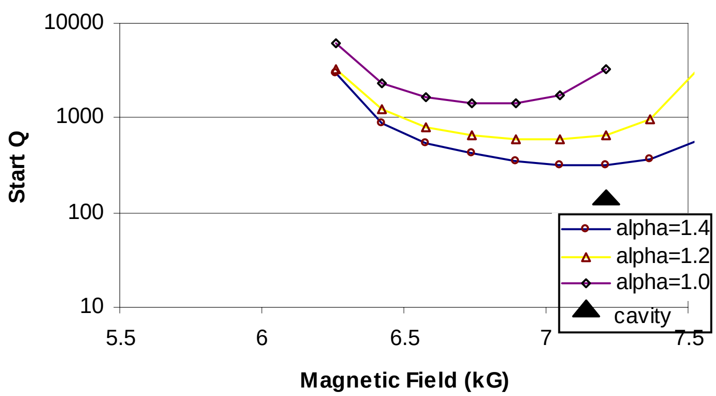


Fig. 2. Layout of a four-cavity frequency-doubling gyroklystron circuit. Dotted lines represent the optimal magnetic field profile and the dashed lines represent the evolution of the average velocity ratio.

A summary of the results obtained for the theoretical stability of these cavities with variable values of velocity ratio and magnetic field can be seen in Fig. 3. Also seen in these figures are the design cavity quality factors (represented by black triangles) for the magnetic field values at the center of the cavities. The value of minimum Q decreases with the increase in the value of velocity ratio. From Fig. 3(a) we observe that first harmonic cavities are stable at any magnetic field for any value of velocity ratio up to 1.4.The corresponding start-oscillation curves for the penultimate and output cavities can be seen in Fig. 3(b) and Fig 3(c) respectively. The buncher cavity is stable up to a velocity ratio of 1.4 but the output cavity is stable at all magnetic fields up to a velocity ratio of 1.15. The system achieves an efficiency of 23.94% at that value of axial velocity ratio. We also checked the stability of other existing modes in the frequency range of 10-12 GHz and 21-25 GHz. All the modes in the output cavity were found to be stable for velocity ratios from 1.0 to 1.2.





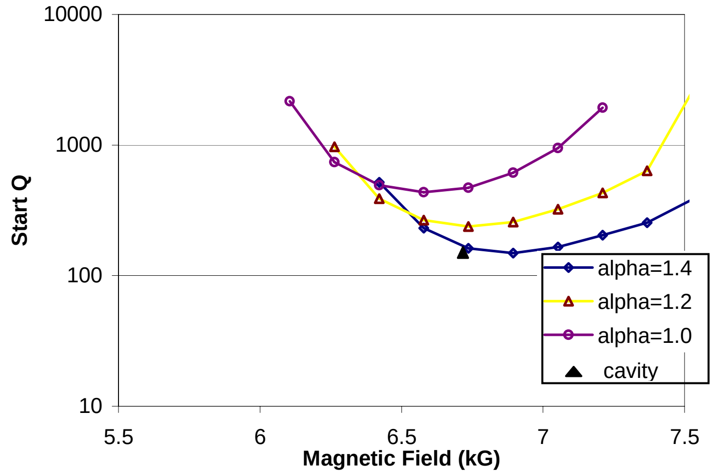


Fig. 3. Start oscillation curves as a function of average velocity ratio for the operating modes of (a) first harmonic cavities, (b) second harmonic buncher cavity, and (c) second harmonic output cavity. Curves plotted represent the threshold quality factors for a 100 MW beam as a function of axial magnetic field. Cavities which have quality factors that lie above this curve at a given magnetic field will be unstable to the operating mode.

IV. Large Signal Behavior and the Optimal Configuration

The design parameters used for investigating the large signal behavior of the circuit are given in Table II.

TABLE II
DESIGN PARAMETERS

Parameter	Value
Beam Voltage (kV)	500
Beam Current (A)	200
Drive frequency (GHz)	11.424
Maximum magnet power (kW)	95
Maximum axial magnetic field (kG)	7.26
Nominal magnetic “flat field” length (cm)	23
Desired output power (MW)	>20
Average velocity ratio	1.0
Axial velocity Spread (%)	3
Maximum drive power (kW)	1.6

As mentioned earlier, a number of parameters need to be varied before arriving at the optimal tube efficiency. For our design we varied drive power, magnetic field profile, number and types of cavities, cold resonant cavity frequencies, cavity spacing and tube length. The drive power was limited to no more than 1 kW and the drive frequency was set to 11.424 GHz.

In Fig. 4, we plot tube efficiency with different values of velocity ratio limiting the velocity spread to 3%. It can be seen from the figure that the efficiency increases with increasing values of the velocity ratio. For each value of velocity ratio, the input drive power is optimized to achieve maximum efficiency. For velocity ratio, alpha=1.0 we obtained a maximum efficiency of 20.02% at a drive power little above 1 kW. Maximum efficiency of 38% and output power of 38 MW was achieved for velocity ratio of 1.4 at an input drive power of 42W.

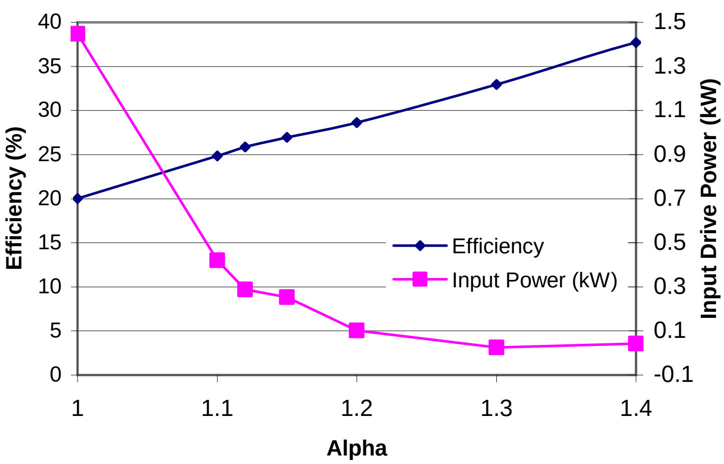


Fig. 4. Dependence of efficiency on velocity ratio

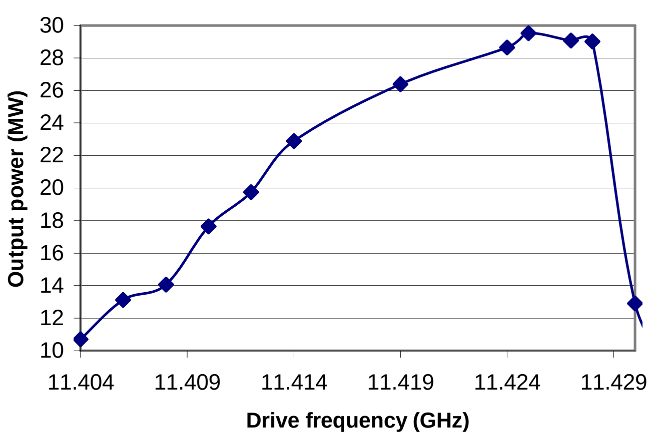


Fig. 5. Bandwidth curve for the 1-1-2-2 design (alpha=1.2)

In Fig. 5. we explore the bandwidth capabilities for the 1-1-2-2 microwave system design. We plot the output power against drive frequency for a fixed input drive power. The bandwidth is most strongly affected by the output cavity Q. Maximum output power for alpha=1.2 is obtained for a drive frequency of 11.425 GHz. For the drive frequency, we found the system to have a bandwidth of 21 MHz which is almost half of the theoretical expected bandwidth of 57.12 MHz. We doubled the bandwidth observed for the drive frequency and obtained the bandwidth for the second harmonic cavities. The bandwidth for the second harmonic cavities was found to be 22 MHz which was also half of the theoretical bandwidth of 84.6 MHz.

In Fig. 6, we plot the dependence of efficiency on axial velocity spread for the 1-1-2-2 gyroklystron design when the velocity ratio (alpha) is fixed at 1.0. We allow the input drive power to vary for maximizing the efficiency. The fall in efficiency with increasing velocity spread is demonstrated. The maximum efficiency of 22.99% is obtained for a velocity spread of 0% and an input drive power of 1.725 kW. It is observed that beyond a velocity spread of 5% , efficiency continues to fall even with an increase in input drive power.

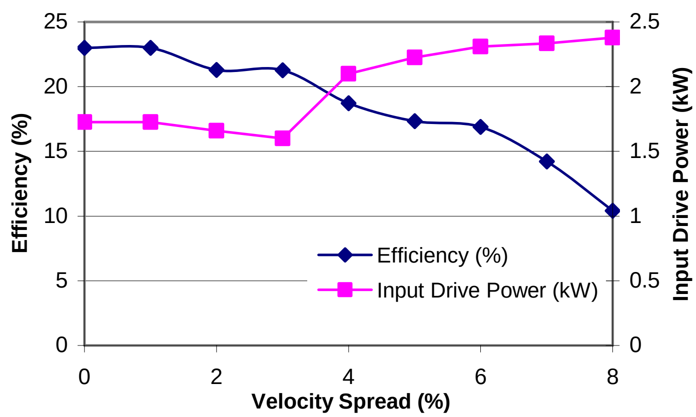


Fig. 6. Dependence of efficiency on axial velocity spread for alpha=1.0

Fig. 7. demonstrates the change in efficiency with applied magnetic field. The change in efficiency is represented by the solid black line and the dotted line represents the change in input drive power required to obtain maximum efficiency. Here we consider the flat field instead of the magnetic field generated using the current sources. That explains why the maximum efficiency achieved is only around 29% for an input power of 0.174 kW at 6.856 kG. The velocity spread is fixed at 3% and the velocity ratio at 1.4. The average value of input drive power is around 0.22 kW for the entire range of magnetic field values considered.

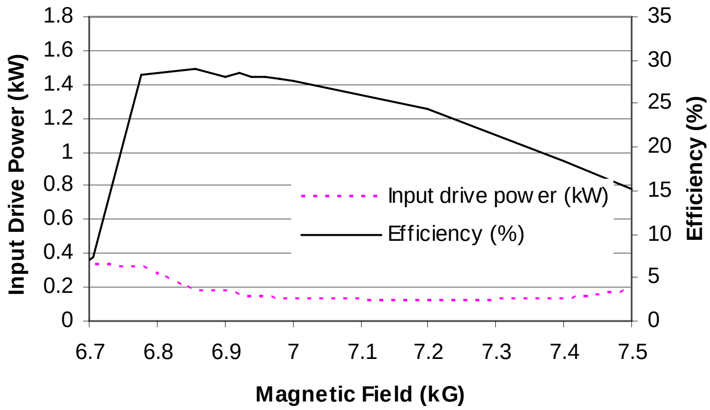


Fig. 7. Change in efficiency with change in magnetic field

In Fig. 8. we plot the drive curve between input drive power and the output power. The maximum output power of 20 MW and a large signal gain of 41 dB are obtained at an input drive power of 1.5 kW for a velocity ratio of 1.0 and velocity spread of 3 %.

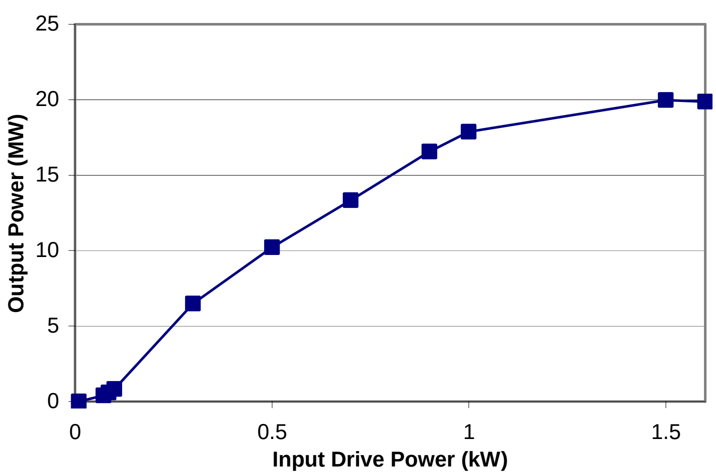


Fig. 8. Output power vs. the input drive power (alpha=1.0)

V. SUMMARY

In this paper, we have investigated the design of a high gain, frequency doubling four-cavity gyroklystron that has an average velocity ratio near 1.0. We also studied the stability of the four cavities and found that except for the output cavity all other cavities can operate stably up to a velocity ratio of 1.4. The operation of the output cavity is stable up to a velocity ratio of 1.15. The effect of a number of factors like axial velocity spread, velocity ratio and magnetic field on the efficiency of the system was studied. After varying all the factors, a maximum efficiency of 38 % and a maximum large signal gain of 60 dB are obtained. This output was attained at a frequency of 22.848 GHz for an input drive power of 42 W with a velocity spread of 3 % and axial velocity ratio of 1.4. This 1-1-2-2 microwave system was found to be zero drive stable for the values of velocity ratio from 1.0 to 1.15. For an axial velocity ratio of 1.15, the maximum efficiency is around 27% and the large signal gain is 50 dB for a velocity spread of 3%.

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