Design of a 70-GHz Second-Harmonic Gyroklystron Experiment for Radar Applications

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***Abstract*—A second-harmonic gyroklystron circuit has been designed to produce 140 kW of peak power near 70 GHz. A 70-kV 8-A beam with an average velocity ratio of 1.35 and an axial velocity spread of 8% rms interacts with four cavities operating in circular electric modes. The input cavity operates in the TE_{011} mode and has been utilized previously in a number of successful first-harmonic gyroklystrons. The remaining cavities operate in the TE_{021} mode and have been designed to be compatible with the existing first-harmonic test bed. The simulated gain is about 33.4 dB, and the expected instantaneous bandwidth is nearly 0.091%.**

***Index Terms*—Amplifiers, gyrotrons, microwave sources, millimeter waves.**

I. Introduction

RECENTLY, gyrotrons [1] have been studied at many institutions as potential sources for a number of applications requiring medium-to-high peak and average power RF. Gyrotron oscillators have achieved unprecedented powers near 100 GHz with highly overmoded cavities. In applications where narrow-to-moderate band amplifiers are required, such as drivers for linear colliders and some radar systems, gyroklystrons appear to be a viable candidate from X-band to W-band [2]–[4]. For these applications, only moderately overmoded cavities can be used due to restrictions on the dimensions of the beam tunnels.

Researchers at the Naval Research Laboratory are spearheading an effort in the United States to develop gyroamplifiers for radar applications at 35 and 94 GHz [4], [5]. All of their designs have featured moderate energy beams (i.e., voltages below 80 kV) interacting with cavities that operate in the TE_{011} mode. A recent collaboration with industry and academia resulted in a 94-GHz four-cavity tube with an average and peak power capability of 10.1 and 92 kW, respectively, a bandwidth of 420 MHz, and an efficiency of 33% [4].

Furthermore, with a three-cavity first-harmonic tube, a bandwidth of 0.82% has been achieved at 34.9 GHz with a gain and efficiency of 30 dB and 32%, respectively [17].

At the University of Maryland, we are designing a 70-GHz second-harmonic gyroklystron tube which can be hot tested on the NRL 35-GHz experimental test facility. A simplified schematic of the second-harmonic tube is shown in Fig. 1. The parameters for the tube are given in Table I. The basic design philosophy for our tube was to utilize the NRL test bed and

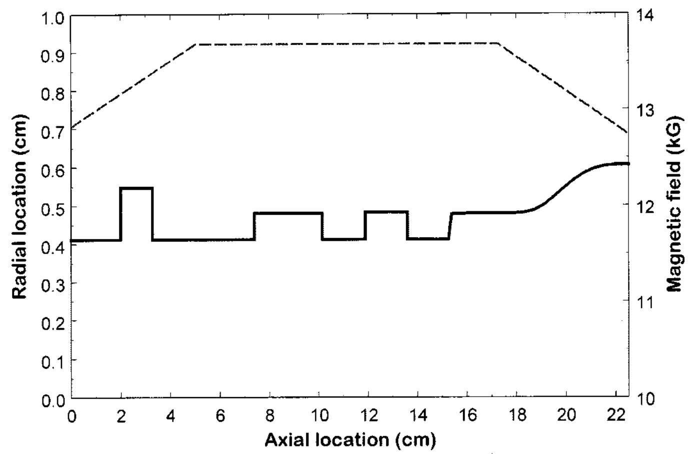

Fig. 1. Microwave circuit (solid line) and the applied magnetic field (dashed line).

the section of the microwave tube from the beam compression tunnel up to and including the input cavity.

The drift tube radii are the same as for the 35-GHz design and are sufficiently small so that the TE_{01} mode is cutoff at 35 GHz and the TE_{02} mode is cutoff at 70 GHz. The lengths are selected to optimize system performance. The lossy dielectrics that will be used to stabilize the tube are not accounted for in the simulations, but it is assumed that the 35-GHz tube configuration will be used in the 70-GHz tube. The center frequencies are stagger-tuned by ±50 MHz in an attempt to increase the bandwidth of the tube.

All of the new cavities are designed to operate in the TE_{021} mode and to resonantly interact near the second harmonic of the gyrofrequency. The output cavity was designed to maximize the interaction efficiency while maintaining a relatively low Q for bandwidth considerations. The flat section in this output cavity is quite long at approximately six freespace wavelengths. The design Q of 506 is a significant fraction of the minimum Q for the cavity. Thus, the nonlinear uptaper at the end of the flat section provides the necessary reflection and no coupling aperture is required for the design. Because of the minimum Q limit, significantly lower Q's cannot be achieved without a substantial loss in efficiency. The output cavity is designed to have a mode purity at the end of the taper of 99.86% in the TE_{02} mode.

The buncher and penultimate cavity designs pose several challenges. The operating mode for these cavities is the TE_{021} mode. Because the TE_{01} mode is not cutoff in the drift region at 70 GHz, any mode conversion that might occur at the cavity end walls could result in cross talk between cavities. The normal way to minimize mode conversion in circular cavities is to use adiabatic wall transitions. However, because the drift tube

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TABLE I
THE 70-GHz SECOND-HARMONIC GYROKLYSTRON MICROWAVE CIRCUIT PARAMETERS

Cavity	Radius (mm)	Length (mm)	Q factor	Frequency (GHz)	Mode
Input	5.478	12.85	188	34.887	TE_{011}
Buncher	4.805	27.50	450	69.852	TE_{021}
Penultimate	4.832	17.15	450	69.752	TE_{021}
Output	4.806	26.00	506	69.803	TE_{021}
Drift tube	Radius (mm)	Length (mm)			
Input - Bunch	4.115	41.15			
Bunch - Penult	4.115	17.42			
Penult - Output	4.115	19.27			
Uptaper	6.054	40.00			

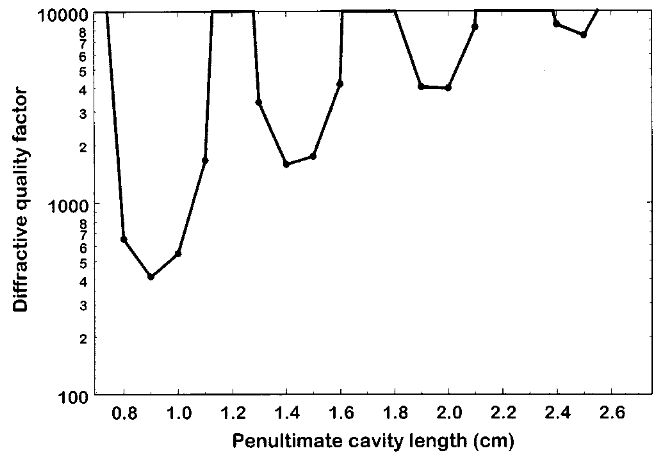

Fig. 2. Diffractive quality factor of the buncher configuration as a function of cavity length.

lengths are relatively small in this tube, those transitions would produce unacceptably low intercavity isolation values. Instead, we utilize a resonant effect to minimize mode conversion. In Fig. 2, we plot the diffractive quality factor of the buncher cavity as a function of cavity length. The cavity wall radius is adjusted to maintain a resonant frequency of 69.852 GHz in the TE_{021} mode. The diffractive Q is a measure of the amount of mode conversion from the TE_{02} to the TE_{01} mode and the lower the Q, the greater the mode conversion. The resonance effect is clear from the picture: Q maxima occur approximately every 5.2 mm. At these lengths, the TE_{02}-to-TE_{01} mode conversion at each waveguide transition destructively interferes with the other transition. The other trend seen in the figure is that the worst case Q gets larger as the cavity length increases.

The nominal beam parameters and the simulated results at the peak power point are given in Table II. The magnetic field profile that was used to achieve these results is indicated by the dashed line in Fig. 1. A piecewise linear field is used for simplicity. The magnet system in the NRL test bed features about a dozen independently controlled coils, so it is assumed that a good approximation to the theoretical field profile can be found. We assume that the beam parameters are valid for the starting magnetic field of 12.82 kG. The field is increased slowly to the optimal value of 13.685 kG. The field is decreased in the output cavity to optimize efficiency at a rate of about 180 Gauss per centimeter. For an adiabatic transition, the average velocity ratio (α) and the axial velocity spread (Δv_z) in the peak field region should be about $\alpha = 1.49$ and $\Delta v_z = 9.74\%$, respectively.

The start oscillation curves for each of the cavities are shown in Fig. 3. The curves are calculated using QPB, which assumes flat magnetic fields in each cavity [6]. Instability is indicated by any Q that exceeds the curve for the corresponding mode at any magnetic field. In each figure, the curve for the operating mode and the curves for any other modes with relatively low start Q's are given. The operating Q's in all cavities are known and given in Table I: the input Q is determined experimentally, the output Q is diffractive, and dielectric material will be inserted into the intermediate cavities until the required Q's are achieved. The actual Q's of the spurious modes are only known for the output cavity since those Q's are predominantly diffractive. The operating point in each cavity is indicated by the intersection of the horizontal and vertical lines. The average magnetic field in

TABLE II
SYSTEM PARAMETERS AND SIMULATED RESULTS

System parameters	
Beam voltage (kV)	70
Beam current (A)	8
Average velocity ratio	1.35
Axial velocity spread (%)	8.0
Average beam radius (mm)	2.55
Axial magnetic field (kG)	13.685
Drive frequency (GHz)	34.9154
Drive Power (W)	64
Simulated amplifier performance	
Power (kW)	140
Efficiency (%)	25.12
Gain (dB)	33.4
Bandwidth (%)	0.091

the input cavity is indicated in Fig. 3(a). The operating point is chosen to be stable to all modes and operation around that magnetic field has been achieved previously [5]. The principle troublesome spurious mode is the TE_{212}, which is potentially unstable in all but the output cavity.

The buncher cavity length was chosen to be 2.75 cm for two reasons. As can be seen in Fig. 3(b), the start Q is within a factor of two of the operating Q, which should help with gain. Also, the instability region for the TE_{212} mode is confined to significantly lower magnetic fields. The penultimate cavity length was chosen to be 1.715 cm because the best efficiency points were found there. The operating Q is about 25% of the start Q. The region of instability for the TE_{212} mode starts at about 13.55 kG and may be a problem. If cold testing reveals a start Q for the TE_{212} mode which is above the threshold, either a 2.75-cm cavity can be used (which would reduce the efficiency by a few percent), or the magnetic field can be locally decreased in the vicinity of the cavity.

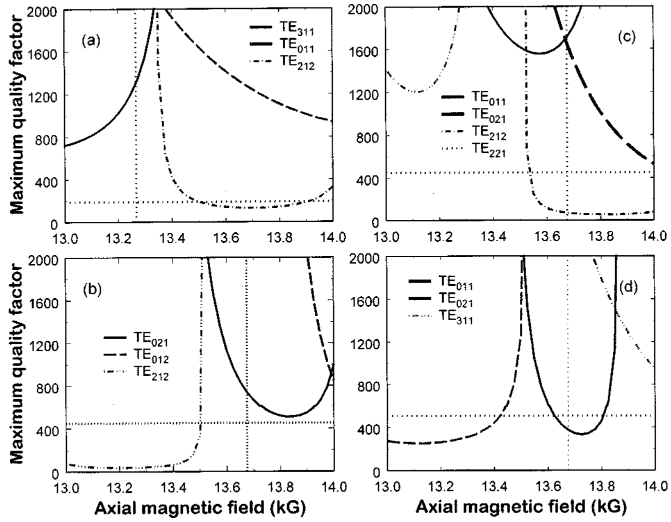

Fig. 3. The start oscillation curves for the: (a) input cavity, (b) buncher cavity, (c) penultimate cavity, and (d) output cavity.

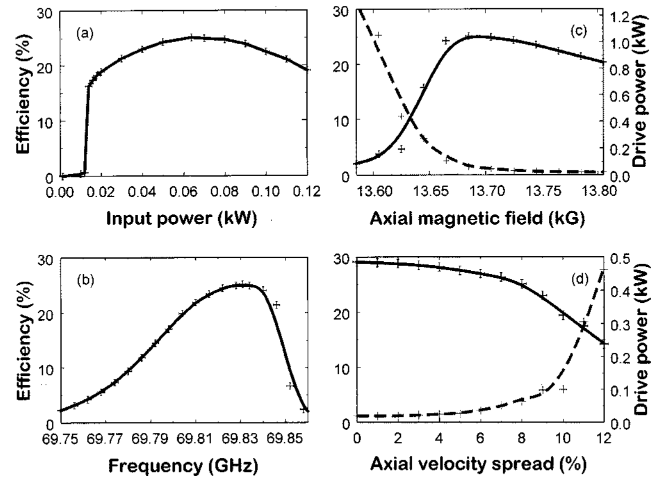

Fig. 4. Simulated performance of the microwave tube: (a) drive curve at the nominal operating parameters, (b) frequency dependence, (c) dependence of efficiency on magnetic field, and (d) dependence of efficiency on beam quality. The input power is adjusted as indicated by the dashed line in (c) and (d) to maximize efficiency.

The start-oscillation curves for the output cavity are given in Fig. 3(d). The vertical line indicates the maximum magnetic field in the cavity; the minimum field in the uptaper is about 12.8 kG. The operating point appears to be unstable. The magnetic field tapering appears to result in an output cavity that is zero-drive stable, as will be seen in the drive curve below. The Q of the TE_{011} mode is about 50, so the output cavity is stable to that mode everywhere.

The large-signal performance is evaluated by the MAGYKL code [7]. The maximum efficiency is 25.12% at an output frequency of 69.831 GHz. The peak power of about 140 kW is achieved with a drive power of 64 W. The simulated tube performance for several parametric variations is given in Fig. 4. In each figure, only one or two parameters are varied and the remaining parameters are held fixed at the optimal values. The drive curve is given in Fig. 4(a). The tube appears to be zero-drive stable, or at least the zero drive efficiency is extremely low. As is typical with harmonic tubes, the small-signal behavior is nonlinear. The efficiency increases rapidly up to 20 W and then gently increases to the maximum value. The dependence of efficiency on output frequency is shown in Fig. 4(b). The 3-dB instantaneous bandwidth is about 0.091%.

The dependence of efficiency on peak magnetic field is indicated in Fig. 3(c). The shape of the magnetic field is preserved as in Fig. 1, i.e., the field profile is raised or lowered uniformly. The drive power is adjusted at each field point in order to maximize efficiency. As expected, the efficiency drops rapidly at fields below 13.66 kG. The magnetic field decreases more gradually on the high field side of the curve. The dependence of the efficiency is shown in Fig. 4(d). Again, the drive power is adjusted to maximize efficiency. The spread indicated is the spread at the beginning of the microwave circuit (i.e., the design value is 8%). If the beam quality is better than expected, efficiencies of about 29% can be realized. On the other hand, the efficiency drops fairly rapidly above the 8% level, as does the gain of the tube.

In this letter, the design of a second-harmonic 70-GHz gyroklystron tube was presented. The simulated results include an efficiency of 25.12%, a gain of 33.4 dB, and a bandwidth of 0.091%. While these results are reasonably good, the efficiency and bandwidth are significantly below those measured in the first-harmonic 35-GHz tube. The difference in efficiencies is no doubt due in part to the fact that second-harmonic systems are more sensitive to velocity spread than are first-harmonic tubes, and the spread in this gun is quite large. The reduction in bandwidth is due in part to the fact that the second-harmonic cavity Q's are about three times higher than their first-harmonic counterparts. To better examine the capabilities of second-harmonic gyroklystrons for radar applications, it would be prudent to design a system from scratch that optimizes the second-harmonic performance.

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