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MMIC Power Amplifiers as Local Oscillator Drivers for FIRST

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ABSTRACT

The Heterodyne Instrument (HIFI) for the Far-Infrared and Sub-millimeter Telescope (FIRST) requires local oscillators well into the terahertz frequency range. The mechanism to realize the local oscillators will involve synthesizers, active multiplier chains (AMC's) with output frequencies from 71-112.5 GHz, power amplifiers to amplify the AMC signals, and chains of Schottky diode multipliers to achieve terahertz frequencies. We will present the latest state-of-the-art results on 70-115 GHz Monolithic Millimeter-wave Integrated Circuit (MMIC) power amplifier technology.

Keywords: Power amplifiers, MMIC, local oscillators, terahertz, FIRST, HIFI, millimeter-wave, 100 GHz, PHEMT

1. INTRODUCTION

The Far InfraRed and Sub-millimeter Telescope (FIRST) is a European mission with an American contribution whose objective is to study the formation and evolution of galaxies in the early universe as well as stellar formation and the physics of the interstellar medium [1]. Such observations are severely limited by the atmosphere and can only be done in airborne or space-borne platforms. FIRST will be launched in 2007 and will be positioned in the L2 orbit. A recent overview of the mission is presented in [2].

The Heterodyne Instrument for FIRST (HIFI) is a seven-channel heterodyne receiver, which makes use of the low noise detection offered by Superconductor-Insulator-Superconductor (SIS) and Hot Electron Bolometer (HEB) mixers. The required local oscillator sources to pump these mixers are critical to the successful implementation of the mission. Based on the science requirements, the goal of the LO development effort is to provide continuous frequency coverage from 480 to 1250 GHz, plus two bands at 1410-1910 and 2400-2700 GHz, as described in [3]. The baseline approach is to use GaAs power amplifiers from 71 to 115 GHz followed by a series of planar Schottky-diode varactor-multiplier stages to generate the required LO signal. The motivation for the work is to describe the results of the power amplifier development for FIRST.

The power requirements for the amplifiers are aggressive in terms of gain, output power and bandwidth. Table 1 lists the frequency bands of the 5 power amplifier chains. At least 200-400 mW (23-26 dBm) of output power is required for the bandwidths listed in Table 1 to drive the multiplier chains, assuming an input power of 2 mW (3 dBm). Therefore, each amplifier chain will require at least 20-25 dB of gain. We have chosen to use TRW's 0.1-μm AlGaAs/InGaAs/GaAs pseudomorphic High Electron Mobility Transistor (PHEMT) MMIC technology for this effort. The TRW GaAs PHEMT process, using a 2-mil GaAs substrate, has the proven power performance and process maturity required for HIFI's needs. W-band (75-110 GHz) amplifiers have previously been demonstrated with this technology [4].

Table 1. Frequencies of Power Amplifier Bands

Power Amplifier Bands	71-79.5 GHz	80-92 GHz	88-99.5 GHz	92-106 GHz	106-112.5 GHz

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Because of the high gain required, we pursued an approach where several lower-gain driver-amplifier and power-amplifier chip designs were created, with the intent to cascade the chips in order of increasing output-power capability to achieve the goals of HIFI. A combination of 8 different MMIC driver-amplifier and power-amplifier chips were designed at the Jet Propulsion Laboratory, TRW, and the University of Massachusetts, and were fabricated by TRW. We will now outline our results-to-date of the power-amplifier development effort for FIRST.

2. POWER AMPLIFIER CIRCUITS AND MEASUREMENTS

The 0.1-μm power PHEMT device development at TRW has been reported in [5]. The PHEMT structure is grown using molecular beam epitaxy (MBE) on three-inch substrates and uses a pseudomorphic $In_{0.22}Ga_{0.78}As$ channel. The PHEMT device structure is based on a double heterostructure design to achieve a high aspect ratio for 0.1-μm gate lengths. We used an 8-finger 160 μm gate periphery PHEMT as the baseline device, and combined the PHEMTs in parallel as needed to achieve high output power. The devices typically exhibit a gate-to-drain breakdown voltage of 6 V measured at a gate current of 0.1 mA/mm, a peak dc transconductance of 600 mS/mm, a maximum current of 600 mA/mm, a unit current gain frequency f_T of 130 GHz, and a maximum oscillation frequency f_{max} of greater than 200 GHz.

Eight different amplifier designs were fabricated to achieve the power, gain, and bandwidth requirements for HIFI. Wide band medium power (~20-50 mW) driver amplifiers were designed as the first driver-stage, narrower-band higher-power (~100 mW) driver amplifiers were used as the second-stage, and high power amplifiers (~200 mW) completed the chain.

The MMIC power amplifiers were designed using either microstrip-line or coplanar waveguide(CPW) matching networks. CPW has the advantage of ease of a shunt element, that is, a single HEMT with common source configuration can be easily implemented in the layout design. However, for large device periphery (high output power) designs, since a number of PHEMT devices need to be combined in parallel, it becomes difficult to arrange the layout because the source ground cannot be easily realized, especially in millimeter-wave frequency range. The microstrip-line environment is preferred to stack common source transistors in parallel with a via-hole source-ground between the PHEMT devices. Therefore, we used a microstrip-line environment to design the high output power amplifiers and driver chips while we chose a CPW environment to design the medium-power driver amplifiers.

2.1 Wide-Band Coplanar Waveguide Driver Amplifiers

The photographs of the two CPW medium power driver amplifiers are shown in Fig. 1. The top photo is a 3-stage design, intended to cover the frequency range of 65-100 GHz, while the lower photo shows a 4-stage design covering 75-110 GHz. Both chips are 1.2 mm x 2.3 mm in size. The matching networks are implemented with high and low impedance transmission lines, and lumped element capacitors are used in the interstage and bias networks. The device peripheries are 160-160-160 μm, and 160-160-160-320 μm respectively. Since the 8-finger, 160-μm PHEMT device is used for a unit device cell, the output stage of the 4-stage CPW amplifier (320-μm total gate width) is composed of two separate unit PHEMT devices and combined with a CPW Y-junction. If more devices were to be combined in parallel using CPW, higher *N*-way combiners with low loss must be carefully designed.

Both CPW amplifiers were mounted in a WR10 waveguide housing (described in Sec. 3) and tested for small-signal gain. Figure 2 shows the 3-stage and 4-stage amplifier small-signal gain as a function of frequency, measured with vector network analyzer frequency-extenders to cover W-band. Both designs perform well over 20-30 GHz of bandwidth. The operating conditions for the 3-stage design were drain voltage, V_d = 2.5 V, gate voltage V_g = 0.1V, drain current I_d = 150 mA, and for the 4-stage design, . V_d = 3 V, V_g = 0 V, and I_d = 210 mA.

2.2 Microstrip Driver Amplifiers

Figure 3a shows a typical microstrip driver amp chip. Three design variations were fabricated, to cover 70-81, 89-105, and 100-113 GHz (the power amp bands associated with Band 6b, Bands 5,6a and 7a, and Band 7b of HIFI, respectively). All three driver amps follow a common circuit architecture, which is a single-ended two-stage design. The first stage employs two cells of 8-finger, 160-μm PHEMT devices and second stage has twice the device periphery with four PHEMT devices in parallel, for a total output periphery of 640 μm. Reactive matching elements were optimized for increased bandwidth. Electromagnetic simulations were performed for all the passive structures using Sonnet [6]. The microstrip driver amplifiers were tested for gain using on-wafer small signal measurements, using the method of Ref [7]. The three microstrip driver amplifiers depict high gain performance of 12, 7, and 7 dB as shown in Fig. 3b, for V_d=1.5V, V_g=0V, I_d=.25A.

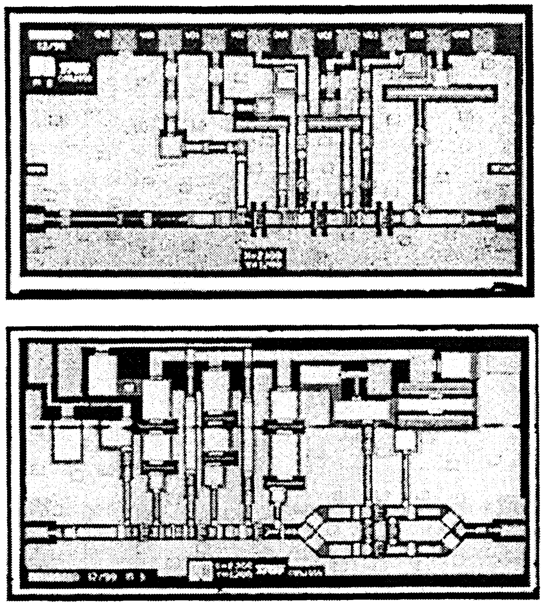


Figure 1. Top: 3-stage CPW amplifier; Bottom: 4-stage CPW amplifier, showing CPW Y-junction for power-combining.

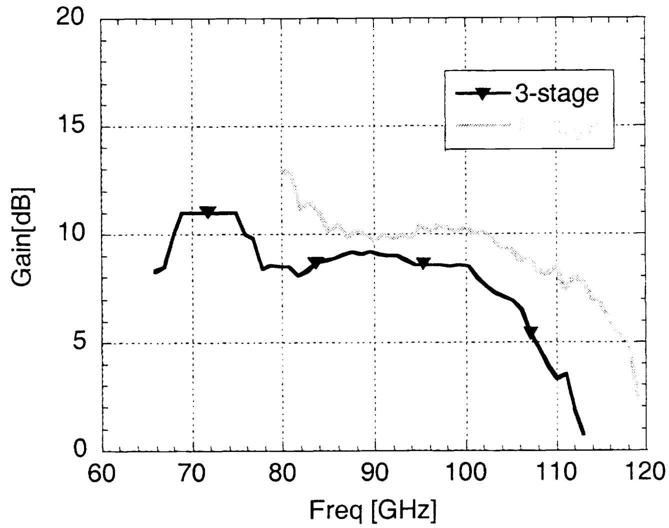


Figure 2. Small signal gain as a function of frequency for the 3-stage and 4-stage CPW designs of Figure 1.

2.3 Microstrip Power Amplifiers

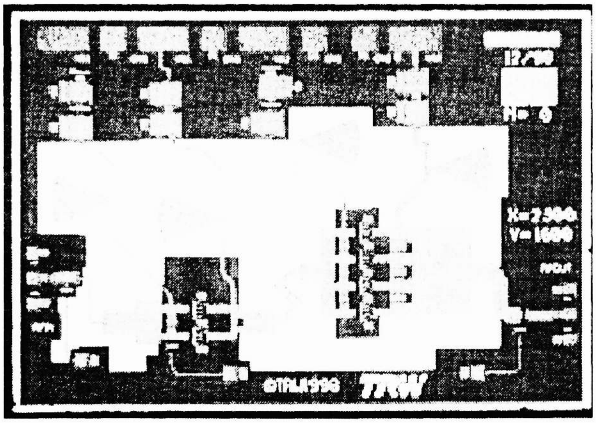
Three microstrip power amplifier designs were also fabricated. The topology used for the microstrip power amplifier designs has been reported in [4]. The power amplifiers also follow a common circuit architecture, which is similar to that of the microstrip driver amplifiers with twice the gate peripheries for both the first and second stages (4 PHEMTS in parallel for the first stage, 8 PHEMTS in parallel for the output stage, for an output periphery of 1.28 mm.) Figure 4a shows a photograph of the 89-105 GHz chip. The 70-81 and 100-113 GHz chips have a similar topology. The chip sizes for all of the microstrip amplifiers are 2.3 x 1.6mm^2. A measured typical small-signal gain of at least 8, 7 and 4 dB is achieved at 72-81, 90-101, and 100-113 GHz, respectively at V_d =1.5 V with V_g = 0 V, I_d=.5A and is shown in Fig. 4b. The details of the microstrip driver and power amplifiers appear in [8] and [9].

3. POWER MEASUREMENTS

All of the MMIC chips were diced and tested in a WR-10 waveguide module (with a pair of microstrip-line to waveguide transitions [10]) for small signal response and output power. A closeup photograph of the 4-stage CPW driver amplifier mounted in the waveguide package is shown in Figure 5. The upper-left photo in Figure 5 shows a larger view of the waveguide mount, while the lower photo depicts the whole amplifier module. Below we present output power measurements of the amplifiers. All of the results are for continuous wave (cw) operation.

3.1 Wide-band CPW Amplifier Measurements

Figure 6 shows the output power data as a function of frequency for the two wide-band CPW amplifiers of Sec.2, packaged in the WR10 waveguide module. The input power for the 3-stage design was 10 mW (10 dBm), and the input power for the 4-stage design was 8 mW (9 dBm). The 3-stage design exhibits 20-38 mW of output power over 75-100 GHz, while the 4-stage design shows between 25-44 mW of output power, due to the increased output stage device periphery. Both amplifiers show several dB of gain compression over the small signal gain curves of Figure 2. The 3-stage design dissipates .15A(I_d) x 2.5V(V_d) = 375 mW of DC power, for a power-added efficiency of between 2.5% and 7.5 % between 75 and 100 GHz. The 4-stage design uses .25 A x 3 V = 750 mW of DC power, for a power-added efficiency of around 2-4.5%. Each of these amplifiers are ideally suited as driver amplifiers for the second-stage microstrip designs to follow.



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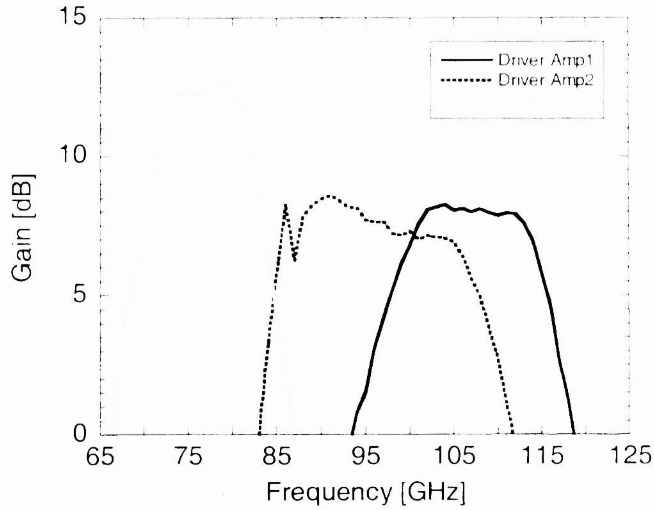
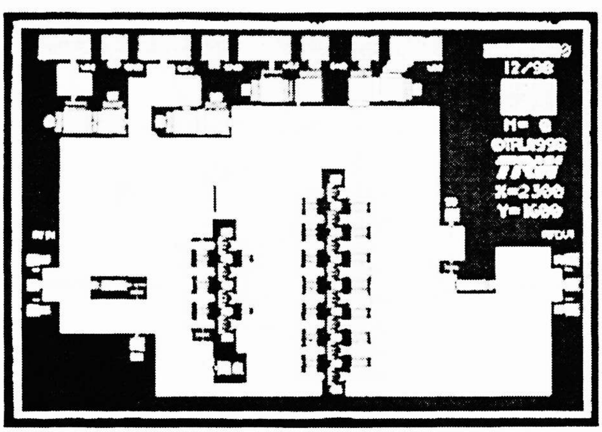
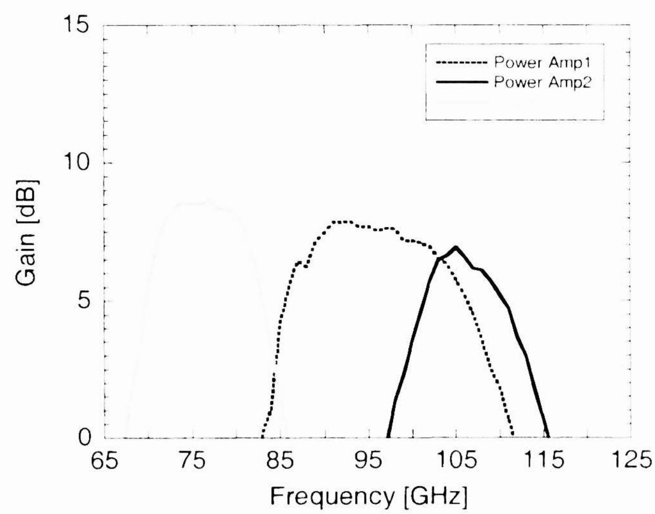


b)

Figure 3a. Chip photograph of microstrip driver amplifier covering 71-82 GHz. 3b. Small signal gain of the three microstrip driver amplifiers. Driver Amp3 is the result of the chip in the photograph in 3a.



a)



b)

Figure 4a. Chip photograph of microstrip power amplifier covering 89-105 GHz. 4b. Small signal gain of the three microstrip power amplifiers. The Power Amp 2 curve is the result of the chip in the photograph of 4a.

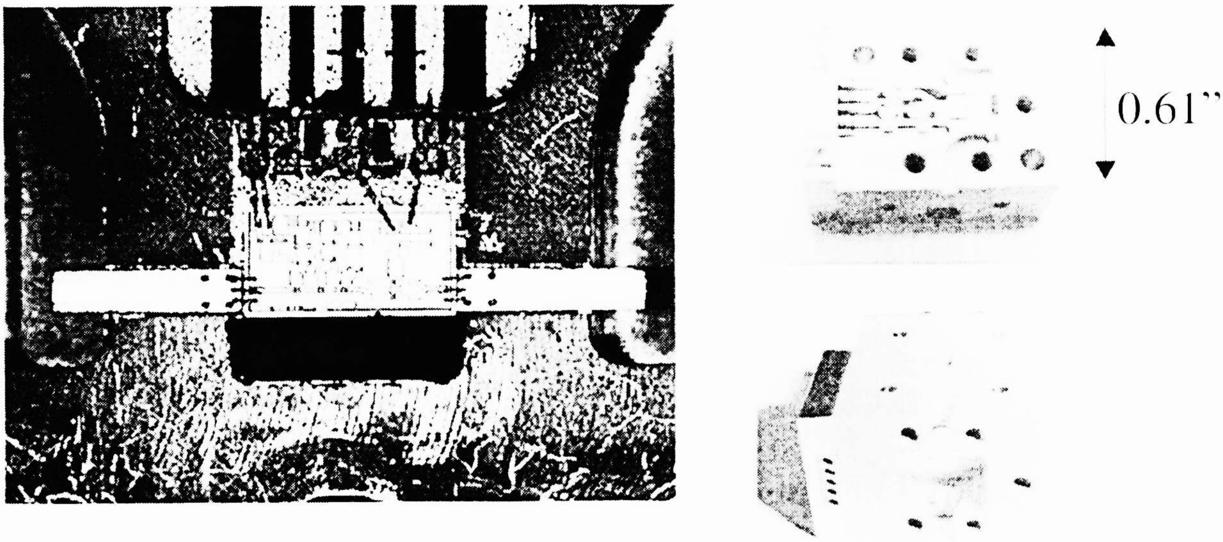


Figure 5. Left-hand photograph shows CPW driver chip with waveguide-to-microstrip probe transitions in a waveguide mount. Upper right photo shows the overview of the waveguide mount without its cover. Lower right photo shows the waveguide module with cover intact.

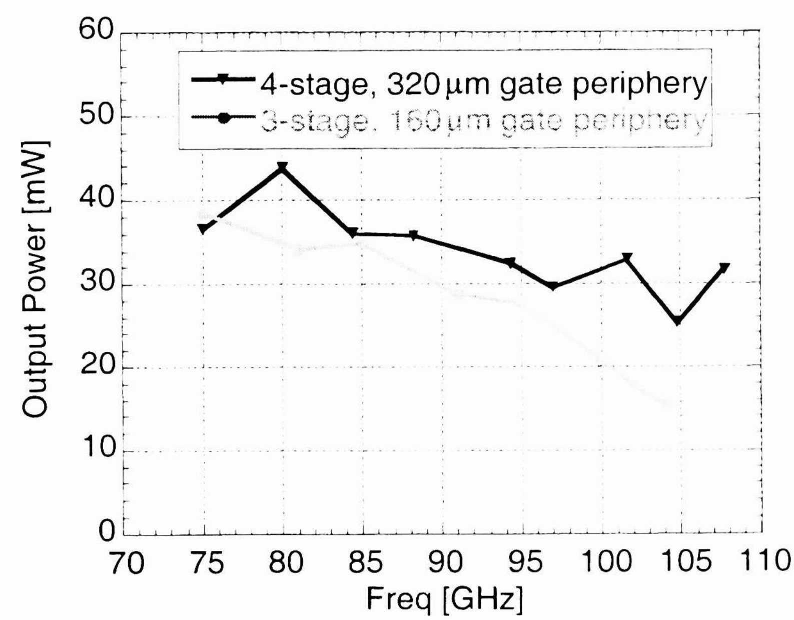


Figure 6. Output power vs. frequency for the wide-band cpw designs of Figure 1. The input power for the 4-stage design was 8 mW; the input power for the 3-stage design was 10 mW.

3.2 Microstrip Amplifier Measurements

For the high power measurements, the microstrip driver amplifiers and power amplifiers were also packaged separately in the WR10 waveguide mount. For the 71-82 GHz band, the amplifier modules were cascaded in order of increasing output stage gate periphery: the microstrip driver (640 μm) was followed by the microstrip power amplifier (1.28 mm). For the two higher frequency bands (89-105 and 100-113 GHz), a cpw driver amplifier was inserted at the beginning of the cascaded chain as a gain block, followed by the corresponding microstrip driver amp and microstrip power amp. Power measurements were performed at V_d = 2.5 V for all the amplifiers to maximize output power and bandwidth of the chips. Output power was measured at the output of the waveguide package. A backward-wave oscillator (BWO) was used as the W-band source. Three frequency bands are covered in three separate chains of modules. Fig. 7 shows the maximum output power vs. frequency at the output of the cascaded modules. Each amplifier chain demonstrated at least 20 dBm (100 mW) output power in its frequency range. The 100-113 GHz power amplifier has a peak power of greater than 250 mW (25 dBm) at 105 GHz, which is the best output power performance for a monolithic amplifier above 100 GHz to date. It is also noted that the waveguide transition in the package has an insertion loss of ~0.35 dB up to 107 GHz, and ~0.5 dB from 107-115 GHz [10]. For the output power results at the MMIC chip end, the numbers mentioned above need to be corrected by this loss factor.

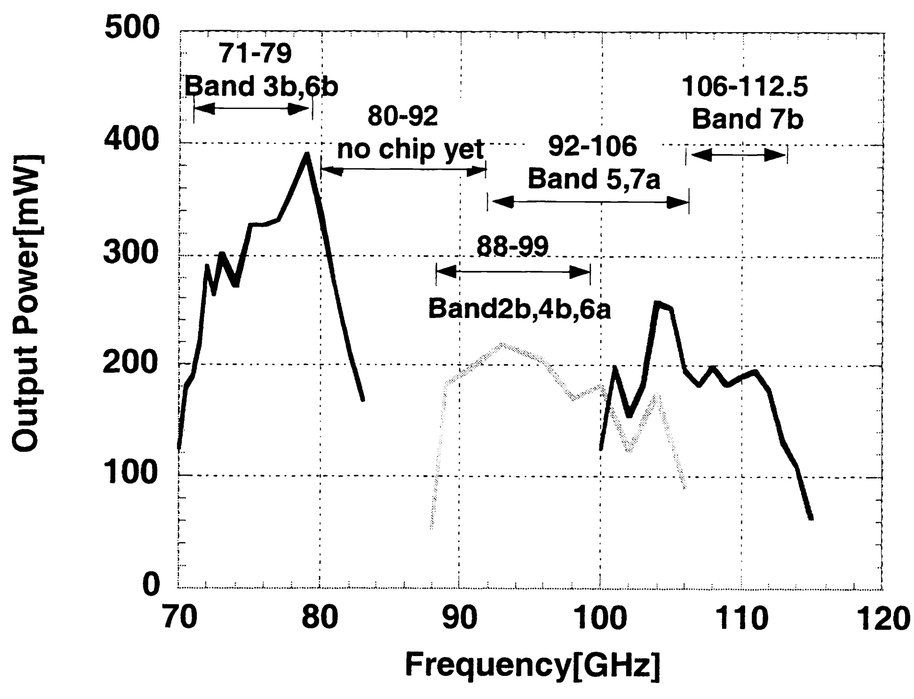


Figure 7. Output power as a function of frequency for the three chains of amplifiers. The single amplifier modules of Figure 5 were cascaded in groups of 2 or 3 to obtain the data. In the plot, the bands of FIRST/HIFI which will make use of these amplifiers are identified.

4. CRYOGENIC MEASUREMENTS

In the HIFI instrument, the power amplifiers will be cooled to 100K along with the multiplier chains. To test the functionality of the amplifier modules, the 89-105 GHz amplifier chain was cooled to 100 K using a cryogenic refrigerator. The chain consisted of one microstrip driver amplifier followed by a microstrip power amplifier. A BWO supplied the input RF power. A marked increase in the observed output power was observed upon cooling the amplifier modules. Figure 8 shows the comparison between the room temperature output power measurement and the 100K measurement. A slightly higher drain voltage was used for the measurement at 100K, to maximize the peak output power. A peak power of 350 mW is observed at 93-94 GHz for the 100K measurement, an increase of over 100 mW. A 1-2 dB increase was observed across the band.

We performed an additional experiment where we increased the drain voltage to 5 V while the amplifier was cooled to 100K. We observed that the output power increased to 0.5 W at 94 GHz. This result is in contrast with the room temperature data, where increases in drain voltage did not result in increases in output power beyond V_d = 2.5-3 V. When cooled, the power amplifiers can be operated at a higher drain voltage and drain current, and this results in approximately a factor of 2 increase in output power over the room temperature data. We did observe that when a large RF signal was applied to the power amplifiers at V_d = 5V, the amplifier failed due to excessive gate leakage current. Fortunately, we can run the amplifiers well below the breakdown condition and still meet the output power requirements of HIFI.

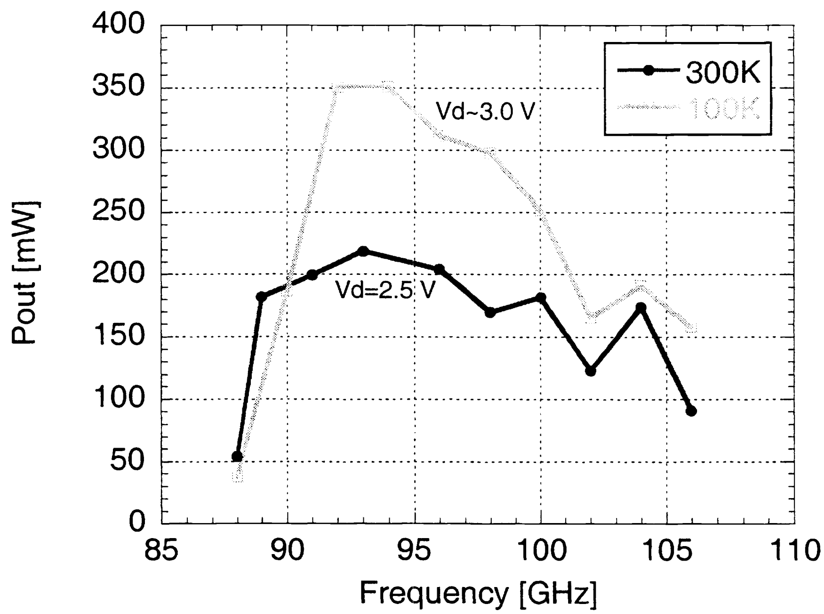


Figure 8. Output power of a chain of two amplifiers as a function of frequency, measured at 100K and 300K.

5. POWER-COMBINING

While the MMIC power amplifiers combine 4 (.640 mm device periphery) to 8 (1.28 mm device periphery) PHEMTs in parallel on-chip using a microstrip power combiner, in general microstrip power combining has the disadvantage of being fairly lossy. To achieve higher power than what is currently possible from a PHEMT amplifier with 1.28 mm of device periphery, we have chosen to power-combine amplifiers using magic tees built in WR10 waveguide. Figure 9 identifies the 4-ports of the magic tee: the E-arm, the H-arm, and the two co-linear arms. Two magic tees were built in-house and connected with WR10 waveguide bends as shown in Figure 10. In the figure, DA= driver amp and PA = power amp. The BWO was used as the RF source, and the input signal (approximately 50 mW) was sent into the E-arm of the magic tee. The power was divided equally between the co-linear arms of the tee, and coupled into two amplifier chains which were reasonably well

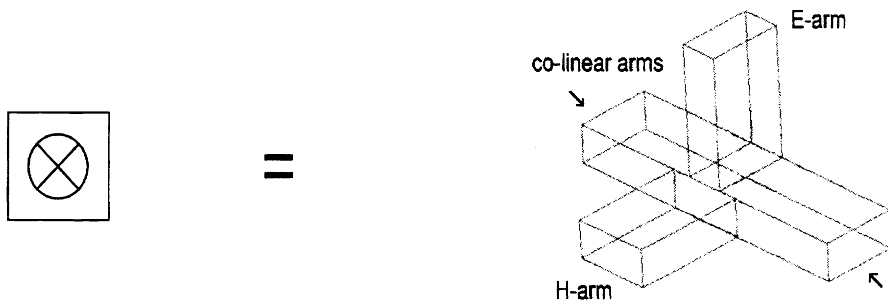


Figure 9. At left is the symbol used for the magic tee. At right, the configuration of the E-arm, H-arm, and co-linear arms are shown in more detail.

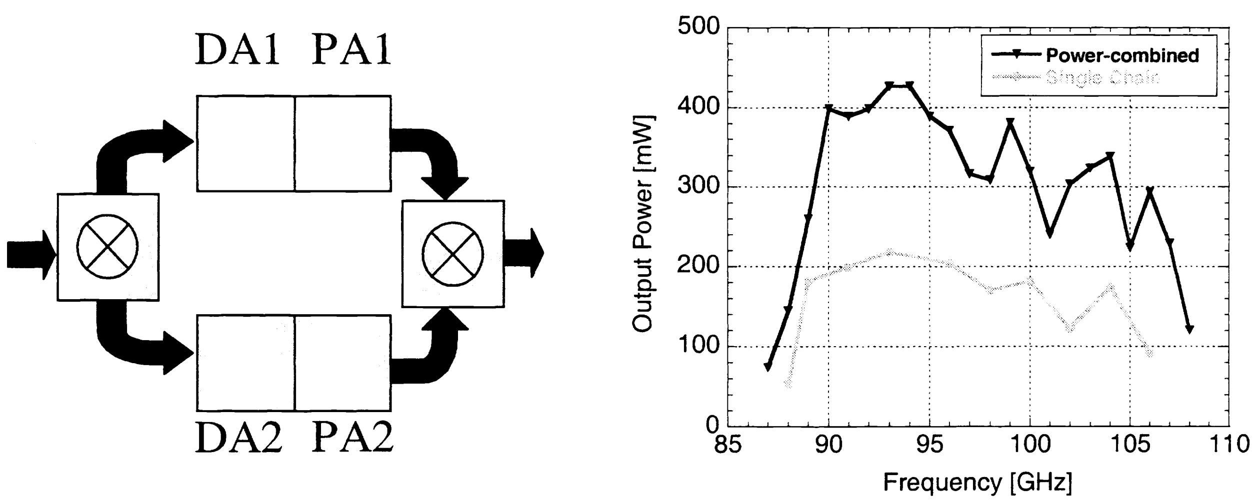


Figure 10. Left, schematic showing configuration of amplifiers and magic tees. DA=microstrip driver amplifier; PA = microstrip power amplifier. At right, output power as a function of frequency is shown for a single amplifier chain and the magic-tee power-combined chain, measured at room temperature.

matched for gain. The H-arm of both magic tees was terminated with a matched load. The amplifiers were recombined into the co-linear arms of the output magic tee, and the resulting power-combined signal was measured at the E-arm of the output magic tee. In order to achieve phase matching between the two amplifier arms, a waveguide shim 16 mils long (corresponding to ~35 degrees at 95 GHz) was inserted before DA2. This resulted in maximum gain (and power) of the power-combined structure across the 88-106 GHz band. The right-side of Figure 10 shows the output power results as a function of frequency for the two chains of power-combined amplifiers. The power-combined result is compared with the result of a single amplifier chain. Both results are obtained for V_d=2.5V; I_d=0.8A for the single chain, while I_d=1.6 A for the power-combined chain. Because the waveguide magic tees are low loss, almost a factor of two increase in output power is observed in the power-combined amplifiers. We have obtained over 200 mW between 89-107 GHz, and over 400 mW between 93 and 94 GHz, at room temperature. We expect further increases in output power upon cooling.

6. APPLICATIONS TO FIRST/HIFI

Our power amplifier results are particularly significant for the needs of FIRST. Foremost, referring to Figure 7, a single chain of a driver amp cascaded with a high power chip produced >100 mW from 70-83 GHz (~17% bandwidth), and over 300 mW between 75-80 GHz. The peak output power for this chain occurred at 79 GHz, with 390 mW of output power. The high power between 79 and 80 GHz is particularly significant for the 1.9 THz (79 GHz x 2 x 2 x 3 x 2) line of CII, to be observed with HIFI. Other significant results include a record power-bandwidth of greater than 100 mW from 89-105 GHz, and better than 100 mW from 100-114 GHz. The power-combined results of the 89-105 GHz amplifier chain meet or exceed the requirements for Band 5 of HIFI: over 200 mW from 92-106 GHz. A few selected spectral lines of interest to FIRST, along with their frequencies, required power amplifier band, and current state-of-the-art power amp results, are shown in Table 2. Typical power-added efficiencies for an amplifier chain are in the range of 4%-9%, with DC input power levels of 2.2 Watts for a single amplifier chain, and 4 Watts for a power-combined chain.

Spectral Line	Frequency [THz]	Power Amp Frequency Required [GHz]	Pout[mW]
NII	1.461	91-92	390-400*
CII	1.900	79-80	340-400
NII	2.459	102-103	280-300*
HD	2.674	111-112	160-190

Table 2. * Power-combined result

7. SUMMARY

We have achieved record bandwidth and output power using GaAs PHEMT MMIC power amplifiers and waveguide power-combining, over most of the WR10 waveguide band. Our results demonstrate the feasibility of high power sources at 100 GHz and higher. The output power achieved will be used to drive chains of Schottky diode multipliers to demonstrate local oscillator sources in excess of 2 THz for the HIFI instrument.

ACKNOWLEDGMENTS

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