Cryogenic W Band Power-Combined Amplifier Designs for Applications in the Range of 71 to 106 GHz

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Abstract
This paper summarizes the development of W Band amplifiers for the Local Oscillator (LO) chains for the Herschel HIFI (Heterodyne Instrument for Far Infrared) Instrument. Key amplifier development issues and their solutions are presented, which have been applied on the way to realizing stable, wide-band amplifiers capable of producing 240 mW or greater RF power output across the 71 to 106 GHz frequency range. Development challenges addressed include: MMIC(Monolithic Microwave Integrated Circuit) chips, amplifier topology, signal splitter and combiner development and matching across the band, power output control and leveling. The chosen design solutions are presented, including device, component and material selection for amplifier operation at cryogenic temperatures. Room temperature and cryogenic (120 Kelvin) data is shown for the amplifier.

Keywords: GaAs, MMIC, mm-wave, W Band Amplifier, Amplifier Development, Local Oscillator, Heterodyne Receiver, Herschel Space Observatory

1. INTRODUCTION AND HIFI INSTRUMENT OVERVIEW

This paper summarizes the development and manufacturing approach for W Band amplifiers for the Local Oscillator (LO) chains for the Herschel HIFI (Heterodyne Instrument for Far Infrared) Instrument. The HIFI receivers cover the frequency range of 480 GHz to 1900 GHz in six bands, using low noise superheterodyne receivers having superconducting HEB (Hot Electron Bolometers) or SIS (Semiconductor-Insulator-Semiconductor) mixers operating at about 2 Kelvin. These receivers, comprising the HIFI Instrument, will be the principal instrument of the Herschel Space Observatory. This European Space Agency observatory spacecraft is to be launched in 2007 to the L-2 Libration Point, where it will perform a 5 year mission to conduct a variety of astrophysics observations of star forming regions in the Milky Way Galaxy, as well as others.

NASA/JPL, with Northrop Grumman Space Technology(NGST, formerly TRW) as the principal contractor partner, is developing the amplifiers for the local oscillator chains, multipliers for the Local Oscillator, and mixers for the receivers. JPL is also assembling the LO chains for two of the receiver "Bands".The local oscillator (LO) chains consist of a frequency synthesizer having a K Band output from 23.6 to 37.6 GHz. This source frequency is tripled to produce the "W" band input for the power amplifiers. The amplifiers, cooled to an operating temperature of approximately 130K, amplify this 0 to +3dBm "W" Band signal up to + 23.6 dBm, or ~230 mW. The amplifier output is then coupled into a multiplier chain to produce the final LO injection signal in the range of 480 GHz to 1900 GHz. This LO injection signal is optically coupled into the receiver mixers, which operate at ~2 K.

Key amplifier design issues include design to fit available space, improvement of MMIC chip designs, signal splitter and combiner development and matching across the band, matching of chip characteristics for those chips installed in the parallel power combined arms of the amplifier, power output leveling across the band and moding problem solutions for the microstrip line sections installed between MMICS. Operation over such a wide temperature range also introduces design challenges that will be discussed.

The HIFI Power Amplifier design uses 0.1um GaAs(Gallium Arsenide) HEMT(High Electron Mobility Transistors) MMIC(Monolithic Microwave Integrated Circuit) amplifier chips. The amplifier designs each use six MMICs to achieve the gain and output power level delivered by these amplifiers.

2. W BAND MMIC CHIP DEVELOPMENT

In Figure 1 we show a two-stage, 71-84 GHz MMIC power amplifier, of similar type as those in Ref. [1], fabricated by TRW using a 2 mil thick, 0.1 □m GaAs PHEMT process. The design topology makes use of 4-way and 8-way microstrip power combiners to combine the FETs. The photograph indicates the two stages and the 8-parallel FETs combined in Stage 2. The combiner utilizes odd-mode suppression resistors placed between the FETs. This type of cell is common for combining devices in parallel to achieve more power.

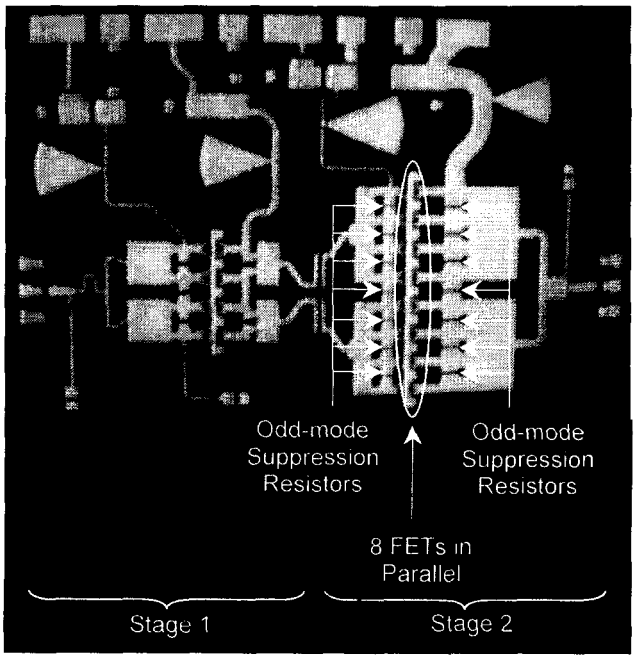

Fig. 1 Two Stage MMIC Power Amplifier Chip

Early versions of this chip and similar chips for the HIFI Program produced oscillations in Ka-Band, which could not be corrected with off-chip bypass capacitors or other stabilization networks. The oscillations occurred between 30-50 GHz upon turn-on of the drain voltage, typically between Vd=0.8 V to Vd=2.4V. The strongest oscillation observed was at 33 GHz. Since the oscillations occurred near the operating voltage of 2.5-3V and were expected to be more pronounced when cooled to the 120K operating temperature, we did simulations of the amplifier chips in order to understand and eliminate the oscillations. Details of the analyses of the nature of the oscillations and the methods we have used to eliminate them are presented in Ref [2]. These methods can be applied to all types of high frequency MMIC amplifiers to determine stability in a MMIC design.

3. HIFI AMPLIFIER DEVELOPMENT

3.1 Amplifier materials and component choices

Operation at cryogenic temperatures presents unique challenges for the Herschel HIFI application. Size, weight and power consumption also had to be addressed. An aluminum amplifier housing is attractive because of low mass and high thermal conductivity. Yet, owing to its high coefficient of thermal expansion, aluminum becomes a difficult choice for this application where a 200 degree change in temperature will be experienced. Iron based alloys could have been employed to achieve a low coefficient of thermal expansion, but at the expense of mass and thermal conductivity. For this application, A-40 Al-Si alloy was chosen as a compromise to achieve a moderate and acceptable coefficient of thermal expansion, good thermal conductivity, and low mass.

3.2 Amplifier configuration

The five Herschel HIFI LO bands that must be covered span the frequency range of 71 to 113.5 GHz. The most obvious waveguide choice for this frequency range is WR-10, which has a range from below 75 to above 110 GHz. Although 71 and 113.5 GHz are outside of the traditional WR-10 waveguide band, 71 GHz is still well above the WR-10 waveguide cutoff frequency (59 GHz), while 113.5 Ghz is below the next higher order propagating mode in WR-10 waveguide (118 GHz). Since WR-10 waveguide was chosen as the waveguide medium for the amplifier input and output ports, a common amplifier chassis design is used for all Herschel HIFI LO bands.

Figure 2 shows a photograph of the Herschel HIFI W Band power amplifier. The WR 10 waveguide input port is visible on the chassis. The output port is on the opposite chassis end. The DC input and sense lines enter the chassis through a 21 pin micro-D connector.

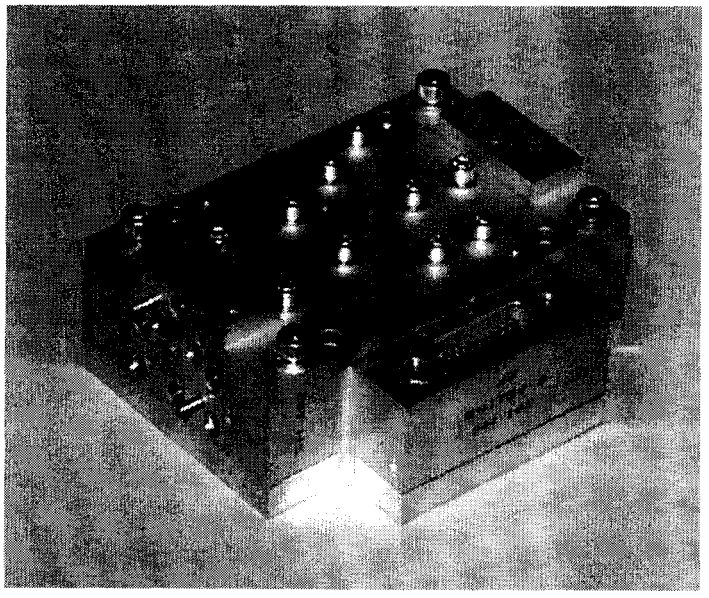

Fig. 2 Herschel HIFI W Band Power Amplifier

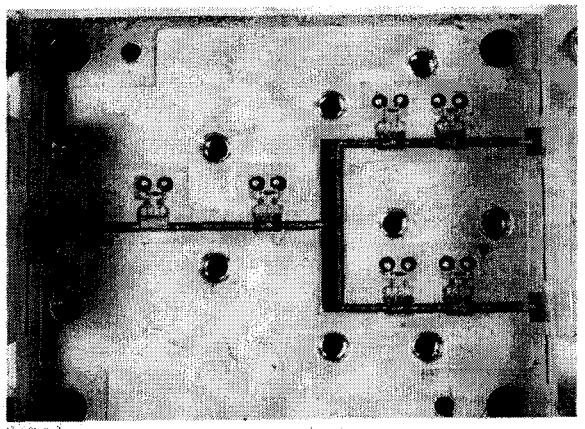

Fig. 3 Amplifier RF Cavity

Figure 3 shows the RF circuitry channelized inside the amplifier housing. Waveguide to microstrip transition is accomplished on the input port and on the output ports prior to power combining in the waveguide Magic "T" hybrid. The dc bias circuitry resides below the RF cavity and is brought up to the amplifier devices with glass bead feedthroughs, as can be seen in Figure 3. The six amplifier MMIC chips are clearly visible, along with the Wilkinson power splitter. The substrate material used for the microstrip elements is 125 micron quartz.

The TRW 0.1 micron GaAs process was chosen to achieve the required MMIC amplifier performance to well in excess of 100 GHz. The average Gm(transconductance) for the process is typically 695 mS/mm with Ft and Fmax greater than 120 GHz and 200 GHz, respectively, Ref. [3]. The Herschel HIFI LO bandwidth specification imposed a limit on the device size that could be employed to achieve power at such frequencies. A single power MMIC might have been able to achieve close to the required 230 milliwatts from the amplifier, but this would have required that the amplifier be operated at drain voltages that might compromise long term reliability. For this reason, two power devices are operated in parallel, at reduced drain voltages to achieve the necessary 240 milliwatts output to drive the L.O. multiplier chains. The block diagram of the amplifier is shown in Figure 4.

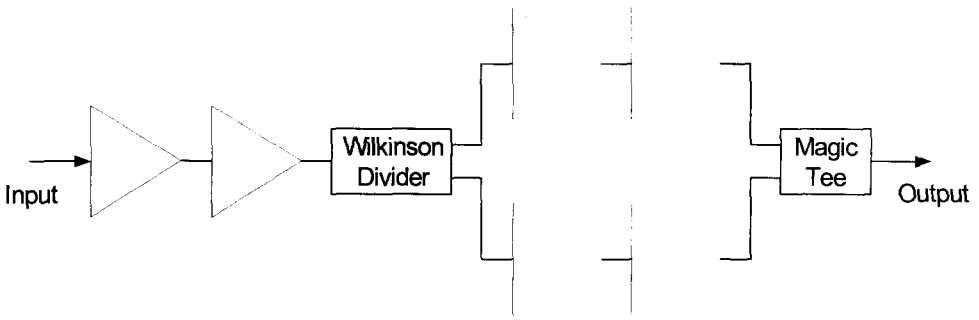

Fig. 4 Block Diagram of the Herschel HIFI Power Amplifier

A Wilkinson style power splitter was chosen because it is best suited for a low loss implementation in microstrip that is compatible with interconnecting substrates within the amplifier chassis. The five Herschel LO bands were covered using three Wilkinson splitter designs.

For low loss power combining at the output of the amplifier, a waveguide magic tee hybrid was chosen. The magic tee hybrid provides close to full band performance. For this application, two tee-buttons were designed such that all five Herschel LO bands were addressed by use of only two magic tee designs.

4. AMPLIFIER PERFORMANCE

4.1 Room temperature performance example

The Development Model(DM) amplifiers were assemblies of five MMIC amplifier chips assembled at JPL, using individual mounting blocks. These amplifiers consist of a preamp MMIC, a driver stage, a magic "T" splitter followed by parallel driver and power amplifier chips. The two power amplifier MMICs are then paralleled through a second magic"T" hybrid. These DM amplifiers have routinely produced outputs of +25dBm or greater, as seen in Fig. 5, and even greater output, when cooled.

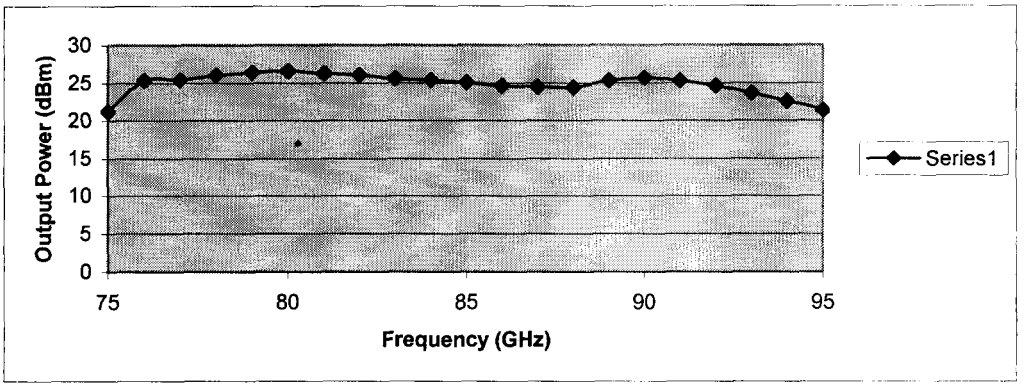

Fig. 5 DM(Development Model) Chain # 13 Room Temperature S 21, 0dBm input level

4.2 Cryogenic performance examples

Figure 6 shows the 120K power vs output drain bias from less than 1V to more than 2.5V for amplifier 102.

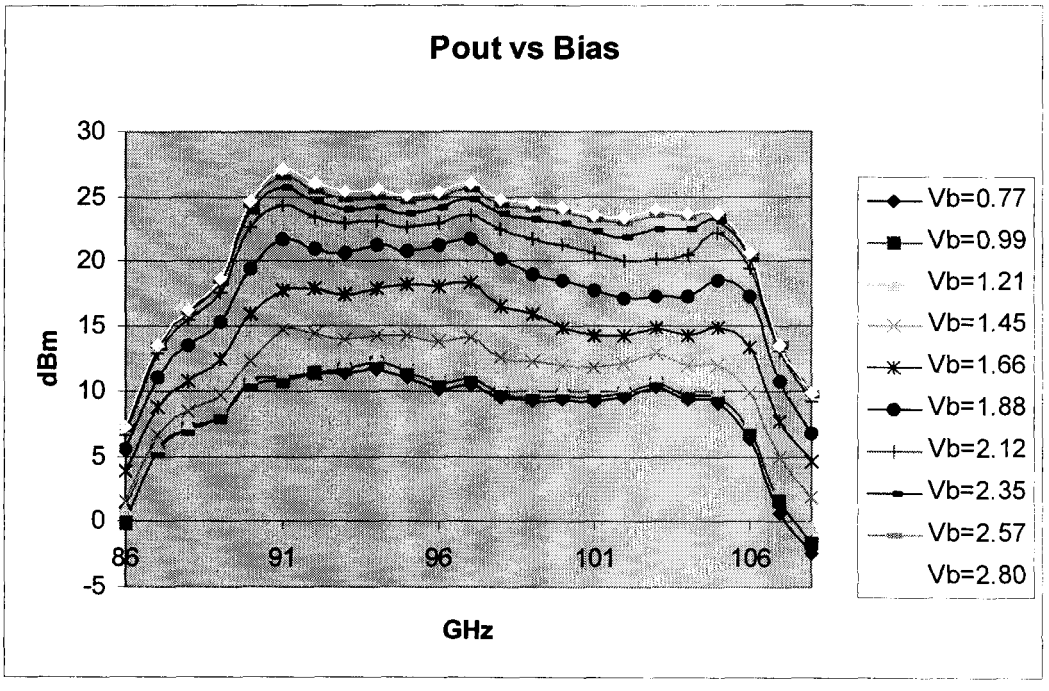

Fig. 6 S/N 102 power vs output drain voltage, 120K, 0dBm input

All the other parameters (gates, input drains, RF level) were kept constant. From Figure 6, it can be shown that the output power increases slowly with turn on, then rapidly between 1.3 and 2.3V, and then saturates between 2.3 and 2.95V. We have found that the best power output, when at 120K, occurs at 3.1 (+/-0.1) V, however, long term operation at this high drain voltage may create a reliability liability, especially at high levels of RF input power.

The data shows that the power amplifiers can be used to adjust the RF power output by more than 13dB by controlling one bias line(drain 2). The local oscillator control unit is currently designed with sufficient resolution to step the output power in steps of 0.08dB or less per step. The variability of the power amplifier dissipation (assuming we need 1V to 3V to adjust the power) would be on the order of 2 Watts.

6. SUMMARY AND CONCLUSIONS

The NASA/JPL Herschel HIFI Project, in partnership with NGST, has developed GaAs "W" Band power amplifier MMICs, which are stable at all frequencies(no in-band or out-of-band oscillations. These MMIC chip designs have been developed in three design types or categories for use in the power amplifiers developed for the Herschel HIFI instrument receiver L.O. chains.

Using these MMIC devices, multi-chip amplifiers have been developed for the HIFI Instrument L.O. chains. The power amplifiers utilize six MMICs to produce up to 240 mW(or more when operating at cryogenic temperatures) "W" Band RF output to drive the LO multiplier chains. The Herschel HIFI amplifiers include single MMIC amplifiers, 5 chip DM amplifiers, and the 6 chip Engineering Model amplifiers described in this paper. The 25 flight and flight spare amplifier deliveries are expected to be made to SRON(Space Research Organization, Netherlands) and ESA(European Space Agency) during 2003.

7.ACKNOWLEDGEMENT

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8. REFERENCES

[1] HWang, L. Samoska, T. Gaier, A. Peralta, H.H. Liao, Y. C. Leong, S.Weinreb,Y.CChen,M.Nishimoto, R. Lai, "Monolithic power amplifiers covering 70-113 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-49, pp 9-16, Jan. 2001.

[2] L. Samoska, Kun-You Lin, Huei Wang, Yun-Ho Chung, Michael Aust, Sander Weinreb, and Douglas Dawson, "On the Stability of Millimeter-Wave Power Amplifiers," *IEEE International Microwave Symposium Digest 2002*, Vol. 1, pp.429-432.

[3]Y.C.Chou, D.Leung, R. Lai, R. Grundbacher, D. Eng, J. Scarpulla, M. Barsky, P.H. Liu, M. Biedenbender, A. Oki, and D Streit, "Evolution of DC and RF Degradation Induced by High Temperature Accelerated Lifetest of Pseudomorphic GaAs and InGaAs/InAlAs/InP HEMT MMICs," *40th Annual International Reliability Physics Symposium, Dallas, Texas, 2002* pp. 241-247