A Precision T/R Module for X-Band SAR Applications with a Transmit Chain in HBT-Technology

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***Abstract* — T/R modules suitable for spaceborne SAR instruments have to fulfil very strong requirements given by the challenging environmental and electrical conditions in space. This paper shows that the HBT (Heterojunction-Bipolar-Transistor) technology is able to meet these requirements for future SAR systems.**

For this application a separate breadboard Tx-chain as well as a T/R module have been realised which operate in X-Band and use the HBT technology for the high power chain.

For the breadboard Tx-chain with driver and HPA in balanced configuration an output power of 39.5 dBm with an efficiency of 32.5% at 10% duty cycle was achieved. For the medium power T/R module with HBT driver and HPA in single ended configuration the output power is stabilised by a power control loop to 35 dBm with an overall module efficiency of better than 11.5% at 10% duty cycle.

Full amplitude and phase stability of the T/R module is realised by a phase stable variable gain amplifier (VGA) and a 7-bit phase shifter. An accuracy of ± 0.5 dB in Rx gain and ± 6° in Rx/Tx phase under all operating conditions has been achieved by a novel and highly flexible calibration method.

The paper will discuss the T/R module architecure with emphasis on the Tx-chain with HBT-amplifiers (fabricated at UMS) and the realised concept for the power control loop. Furthermore the T/R module performance will be presented with respect to SAR system requirements.

I. INTRODUCTION

Spaceborne SAR instruments operating in X-Band with active phased array antenna will become reality in the very near future. One key element in this kind of antenna is the T/R module. The antenna consists of thousands of such T/R modules which are connected to discrete radiators or system dependent to a group of radiators each half a wavelength apart from another.

Because every module provides individual phase and during receive mode also amplitude control, a maximum possible flexibility in beamforming is given leading to new SAR modes.

One very important constraint on a spaceborne platform is the limited prime power for running the system. Hence, high power handling capability, high breakdown voltages and high power added efficiency are required for the power amplifiers. The HBT technology has demonstrated its potential to fulfil these demands in the X-band frequency range.

Furthermore, the T/R modules have to operate directly in the space temperature environment. This is critical to the electrical performance of the module, especially if high precision in amplitude and phase control is required.

In summary, the most important requirements, which have to be met by the modules for this applications are:

- full polarimetry: HH, VV, HV, VH
- high efficiency
- temperature stability
- high precision
- low mass
- high reliability
- low cost

In the following the concept, design and realisation of the T/R module with HBT amplifiers in the transmit path are described and measurement results are presented in this paper.

II. T/R MODULE CONCEPT AND REALIZATION

The **architecture** of the presented T/R module shown in Fig. 1 is the optimum architecture for SAR requirements with demand on polarimetric operation (H/V agility). The main characteristics of this architecture are high power switching and a common-path RF control structure.

The polarisation switch enables the double use of the whole RF circuitry and therefore the mass and the size of the module can be reduced significantly. Additionally the minimised number of semiconductor devices increases the reliability and reduces the cost of the modules remarkably.

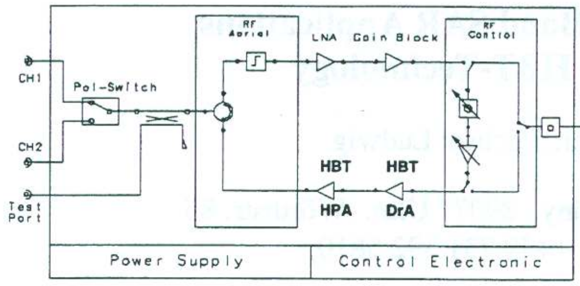

Fig. 1: Block diagram of the T/R module with HBT amplifiers in the transmit chain

By using the common-path structure the complete RF control path (phase shifter and variable gain amplifier) is available in both operation modes (Rx and Tx).

Key components for the T/R module are the Microwave Monolithic Integrated Circuits (MMICs). They have to combine ruggedness, reliability and low power consumption. The high power MMICs (driver DrA, High Power Amplifier HPA) in HBT technology, the RF control devices (SPDT switch, VGA, phase shifter) in MESFET technology and the Low Noise Amplifier (LNA) in PMHEMT technology were all designed at DaimlerChrysler Aerospace (Dasa) / Ulm and processed at United Monolithic Semiconductors UMS / Ulm-Orsay.

In the **transmit mode** the RF signal enters the T/R module via a coaxial SMA connector. The following 7-bit phase shifter provides the phase information with a very high accuracy and the VGA is used for coarse temperature compensation in transmit mode. Via transmit/receive (T/R) switches the signal reaches the activated transmit path. The Tx-chain of the module consists of a HBT-driver and HBT-HPA in single ended configuration ("medium power module"). After passing the driver and power amplifier (with typical PAE of 40% for the single chips), the circulator and the integrated microstrip coupler (necessary for calibration and test purposes) the signal is routed through the low loss polarisation switch and leaves the module via an attached SMA connector.

At the antenna ports a power level of 35 dBm for the T/R module is available. The output power of the HBT power amplifiers is stabilised by a power control loop, which also allows the power modulation. This leads to an overall efficiency of more than 11.5% for the module at this power level (3.2 W).

In the **receive mode** the RF signal passes the polarisation switch via the SMA connectors at the antenna ports in reverse direction, travels through coupler and circulator and reaches the activated receive path. The non-reflective limiter protects the sensitive LNA against too high RF power levels, which may occur by non sufficient

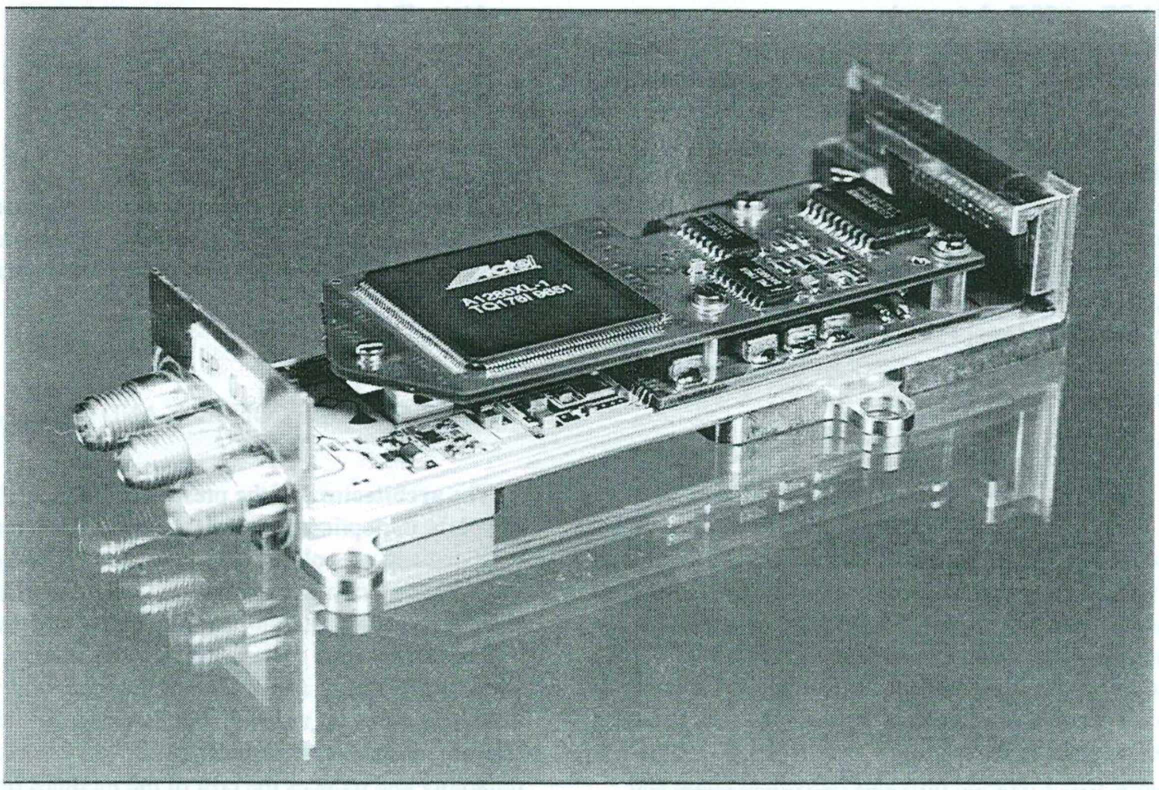

Fig. 2: High precision T/R module in test housing

isolation from the power amplifier or from reflected power due to match variations at the antenna ports during beam steering. The 7-bit phase shifter and the following VGA provide a phase setting range of 360° with a step size of 5.625° and an amplitude setting range from 30 dB to 15 dB with a step size of 0.5 dB. The amplified signal leaves the module via T/R switch and the attached SMA connector. The overall noise figure of the presented module is less than 3.2 dB over 6% bandwidth.

The digital **control electronic** of the module has the task to provide the RF components with power and to control the components during transmit and receive mode. Main component here is a highly integrated silicon FPGA (Field Programmable Gate Array). For the control electronic a design with a "3-dimensional" PCB was chosen.

A novel and highly flexible calibration and temperature compensation technique has been developed which allows stable operation in a wide temperature range [1]. It is based on look up tables, which contain only the individual errors of the control elements, and a complex digital logic, which calculates the sum of individual errors for a required gain phase combination.

In the **module** the complete RF electronic, which consists of several alumina substrates (Al_2O_3), the highly integrated GaAs MMICs and the digital control electronic are assembled on a special subcarrier. In this way best thermal match with Al_2O_3 substrates, titanium housing and GaAs, as well as good thermal conductivity and a very low weight is given. In order to fulfil the requirements for space applications the titanium housing can be hermetically sealed.

The compact module design with dimensions of 116.6 x 21 x 49.5 mm³ enables a low mass of only 98 g. A photo of the T/R module is shown in Fig. 2.

III. TX CHAIN IN HBT-TECHNOLOGY AND POWER CONTROL LOOP

GaAs HBTs have demonstrated substantial improvements in the power amplifier performance for microwave applications in terms of output power, power added efficiency and frequency range. The low output conductance of HBTs associated with the high transconductance, high breakdown voltage and low variation of current gain with collector current density will be used to achieve high power amplification with high output power handling and power added efficiency.

The HBT process at United Monolithic Semiconductors UMS uses a standard AlGaAs/GaAs multi-mesa process. The HBT technology incorporates stepper lithography for high fabrication throughput, ledge passivation for high reliability and thermal management by top heat sink. Recent investigations have shown an extrapolated lifetime for the HBTs of 10^7 h (at 10 % duty cycle). The active emitter area of each finger is 2 x 30 µm². The monolithic power amplifier for the HPA with an efficiency PAE above 40% consists of 8 unit cells with 12 fingers each. Passive components and via holes are compatible with the standard GaAs foundry.

For the realisation of the T/R module with a Tx chain in HBT technology an existing X-band SAR module at Dasa was used as basis. In this module the integrated Tx chain was replaced by the HBT amplifiers with a driver and high power amplifier in single ended configuration. In this way the HBT MMICs can be tested in an representative electrical and thermal environment and prove the fully functionality of this module.

For stabilising the module output power in transmit mode a power control loop (PCL) was designed and realised. By the PCL process tolerances of the HBT semiconductors and temperature variations of the module are compensated without manual tuning. Furthermore it guarantees the long term stability of the module.

The two possibilities for controlling the output power of a HBT amplifier are:

- regulating the collector voltage or
- regulating the base current.

The two control mechanisms were investigated on a separately built breadboard Tx chain, which consists of a driver and high power amplifier in balanced configuration, Wilkinson power dividers, pre-amplifier and control electronic. A layout of the breadboard Tx-chain is depicted in Fig. 3. A maximum output power of 39.5 dBm (8.9 W) at a power added efficiency of 32.5% was reached.

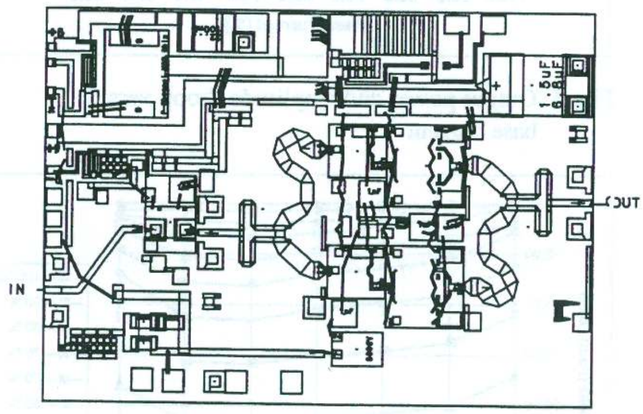

Fig. 3: Layout of the breadboard Tx-chain

The variation of the output power and amplitude droop was measured by changing the collector voltage and the base current at driver and high power stage simultaneously. In Fig. 4 the collector voltage was varied from 8 V to 2.5 V and in Fig. 5 the base current was varied from 100% (referenced to the nominal base current) to 20%, respectively. The frequency dependence of the output power by regulating the base current is shown in Fig. 6.

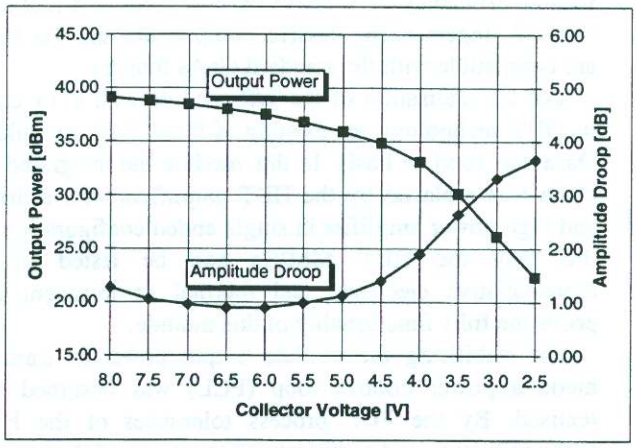

Fig. 4: Output power and amplitude droop versus collector voltage

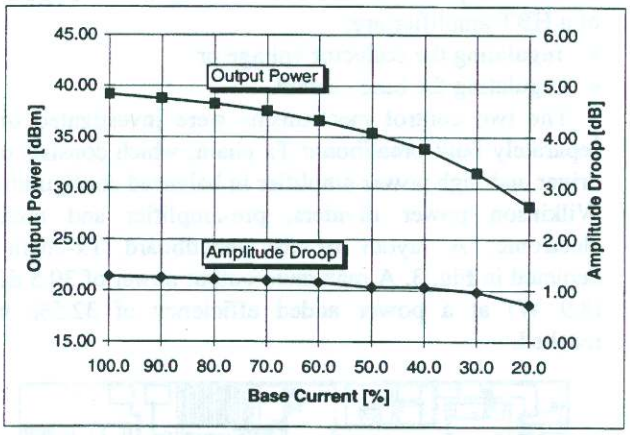

Fig. 5: Output power and amplitude droop versus base current

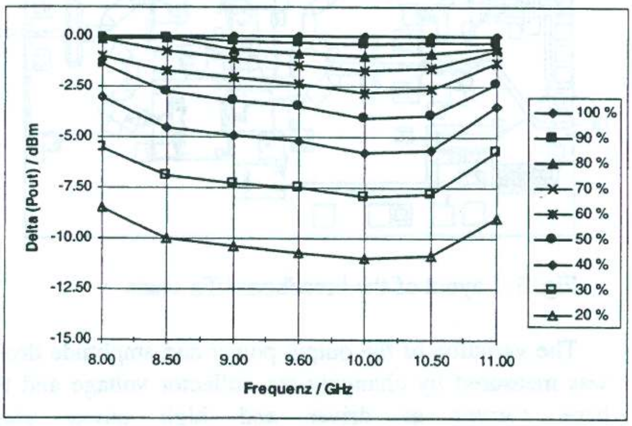

Fig. 6: Output power versus frequency and base current

With both control mechanisms a dynamic range for the output power of more than 10 dB was achieved. The variation of the base current however shows the following advantages:

- nearly constant amplitude droop
- uniform and broadband frequency behaviour
- regulation on the low current base electrode instead of the high current collector electrode.

For these reasons the power control loop of the HBT module was realised by the principle of base current regulation. Additionally the PCL has the task of power modulation of the HBT amplifiers. The concept of the realised PCL is shown in Fig. 7.

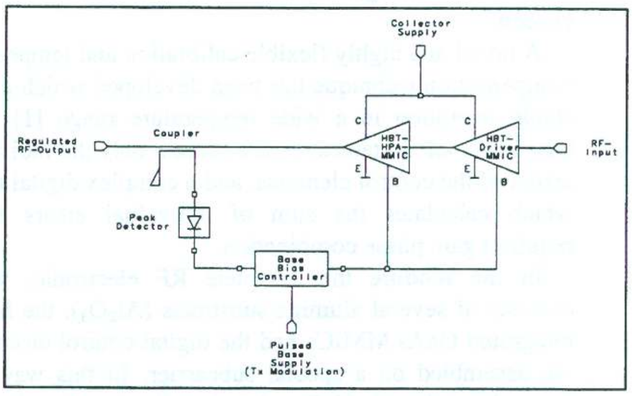

Fig. 7: Concept of the realised power control loop

A part of the Tx output power is coupled out via a microstrip coupler and fed to a diode peak detector. The peak detector generates a DC control voltage proportional to the output power and the following base bias controller regulates the base currents of the HBT driver and high power MMIC in dependence of the DC control voltage. The base bias controller also provides the Tx modulation of the transmit chain by switching off the HBT amplifiers at the base electrode during receive mode.

IV. MEASURED PERFORMANCE

The presented X-band T/R module for SAR applications with the transmit chain in HBT-technology has been successfully tested.

The output power of the T/R module was stabilised to +35 dBm (3.2 W) by the power control loop and an overall module efficiency of more than 11.5% was reached. The efficiency is based on the single ended configuration of the HBT amplifiers and on full radar mode operation, which means that the power consumption of the transmit path, receive path and the entire control electronic was taken into account.

The T/R module was measured over temperature with activated and deactivated power control loop. The module was mounted on a hot chuck and the actual base plate temperature was read out by the internal module temperature sensor. Fig. 8 shows the output power versus the module temperature and proves the powerful effectiveness of the PCL. From 30°C to 65°C the output power with activated PCL is only decreased by 0.25 dB, whereas without PCL the output power varies from +0.8 dB to - 0.2 dB.

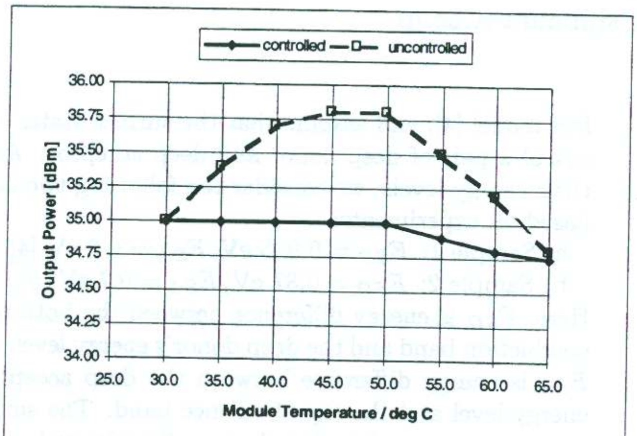

Fig. 8: Output power of the HBT modul with and without power control loop

The accuracy of Rx gain is ± 0.5 dB. The phase accuracy for Rx and Tx setting is in the range of ± 6° over all conditions after calibration. The overall noise figure is less than 3.2 dB in the frequency range from 9.3 GHz to 9.9 GHz. The main performance characteristics of the presented module are summarised in Table 1.

V. CONCLUSION

A high precision T/R Module for spaceborne SAR instruments in X-Band and with a transmit chain in HBT-technology has been presented and the potential of using HBT amplifiers for a SAR T/R module has been demonstrated. Furthermore a power control loop for both Tx output power stabilisation and Tx modulation was developed and its effectiveness was proven by measurements.

The achieved module performance is the basis of today for an advanced X-Band SAR sensor with active antenna, which will become reality tomorrow.

Table 1: Electrical and mechanical characteristics

Frequency Range 9.6 GHz ± 100 MHz	
Rx Gain	30 dB
Tx Output Power	35 dBm or 3.2 Watts
Rx Gain setting range	30 - 15 dB
Rx Gain step size	0.5 dB
Rx Gain accuracy	± 0.5 dB
Overall Noise Figure	< 3.2 dB
Phase Control Range	360°
Phase Quantisation	6 bit or 5.625° step size
Phase setting accuracy	± 6 range
Module envelope size	116.6 x 21 x 49.5 mm^3
Weight	98 grs
Overall module efficiency @ 10% Tx duty cycle*	> 11.5 %

*: calculation with full radar operation

VI. ACKNOWLEDGEMENT

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