Design and Technology of T/R Modules for Phased Array Radar Applications

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Abstract:

Due to the given requirements and the large number of elements, Transmit / Receive (T/R) Modules form the key elements of modern active phased array antennas. General requirements for airborne and space-borne applications are low mass and high efficiency of the modules. Systems with synthetic aperture radar (SAR) need dual polarisation capability to increase the SAR system performance, additionally. The actual design of a T/R Module demonstrator for a future military earth observation satellite with a synthetic aperture radar will be presented.

To meet the requirements for miniaturisation highly integrated components have to be used. The RF performance will be met by monolithic microwave integrated circuits (MMICs) in Gallium Arsenide (GaAs) technology. Different devices in various technologies will be presented, as well as their performance parameters. Besides the RF components, the digital control electronics have to be miniaturised as well. These circuits are realised in MCM-D technology, i.e. multi chip modules, using bare chips, on Al_2O_3 substrate in thinfilm technology. Modern assembly technologies like Flip Chip mounting will be applied.

Two different T/R Module technology demonstrators, designed and developed by Daimler-Benz Aerospace, SI Sicherungstechnik will be presented.

1 General Requirements

The performance of modern radar systems with active phased array antennas is mainly driven by the performance of the T/R Modules. The large number of individual T/R Modules ensures a great degree of redundancy in case of failure of elements (graceful degradation). Due to the close connection of the T/R Modules to the radiating elements, the losses in both cases, transmit and receive, are low, compared to passive systems, leading to a low receive noise figure and high transmit efficiency.

The major functions of a T/R Module are the generation of the transmit power, the low noise amplification of the receive signals, the phase shift in the transmit and receive mode for beam steering, and the variable gain setting for aperture weighting during reception.

T/R Modules in active antennas for space-borne synthetic aperture radars require low mass and low power consuming components (high efficiency). An additional requirement for SAR applications for earth observation is the polarisation agility. Each T/R Module has to feed a horizontally and a vertically polarised antenna, alternatively.

Opposite to the civil applications, military applications for earth observations ask for a simultaneous reception of both polarisations. Two independent receive paths have to be provided in the T/R Modules.

The signal bandwidth in civil applications (X-SAR, XABB, DESA), is approx. 150 MHz. The higher resolution in military applications is achieved with wider bandwidths.

2 Concept of a T/R Module for High Resolution SAR

The requirements for T/R Modules for military earth observation SAR applications can be met using various architectures. The polarisation agility can be achieved with a polarisation switch behind the circulator. The major disadvantage is the insertion loss of the switch, leading to a lower efficiency and a higher receive noise figure. In addition two simultaneous receive channels are needed to meet the full polarimetric requirement.

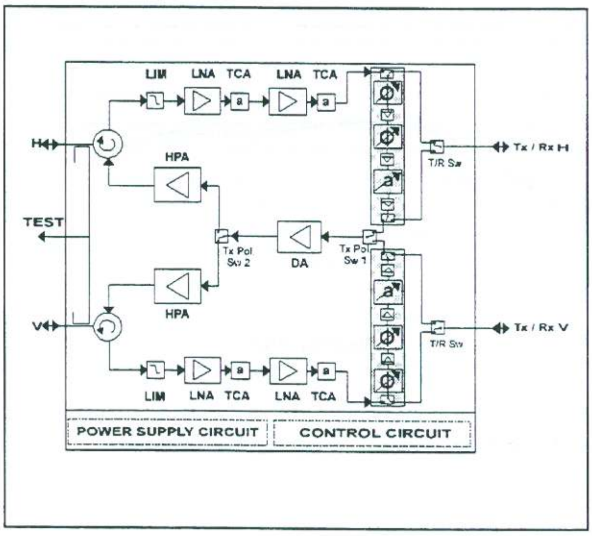

Fig. 1: Optimised Dual Channel T/R Module

The most promising architecture, therefore, is the optimised dual channel configuration, with two independent receive channels and two high power amplifiers (HPAs). The polarisation switch is located in front of the HPAs, where the insertion loss is of minor importance. A schematic diagram of this architecture is shown in **Figure 1**. The phase and amplitude setting for both polarisations is established by two independent Multifunction MMICs (Core Chips).

The design of a T/R Module for a future space-borne earth observation satellite is in progress in the program EUCLID CEPA 9 RTP 9.3. The module design is based on the architecture shown in **Figure 1**.

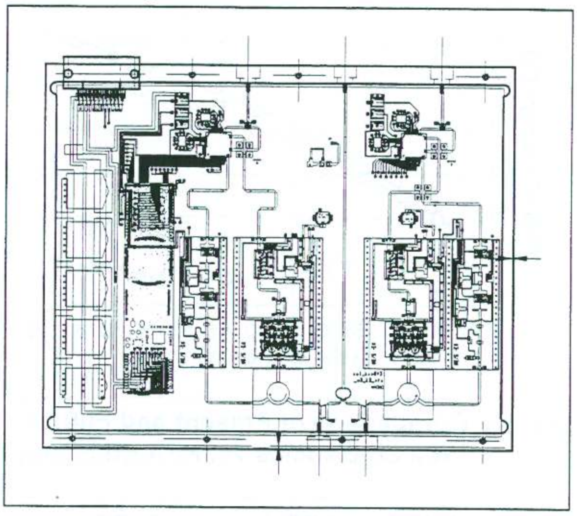

Fig. 2: Preliminary Layout of an SAR T/R Module

Figure 2 depicts the layout of the X-band T/R Module (TRM) for this program. In this application the common-leg structure has been applied. Each common path consist of one GaAs Multifunction MMIC only, on which two T/R switches, interstage amplifiers, a phase shifter (PHS), and a variable gain amplifier (VGA) have been integrated. These Core Chips, developed by TNO Physics and Electronic Laboratory (FEL-TNO), will be used for setting Tx and Rx phase, and Rx gain, respectively.

For high resolution SAR applications supreme requirements have to be met by the T/R Modules. Especially, in terms of phase and amplitude stability versus temperature the requirements can only be met by using a temperature compensating algorithm.

A detailed description of the set-up and principle of the digital control electronic (DCE), with implemented look-up table for a multi dimensional compensating algorithm consisting of 4 Mbit storage capacity, is described in Section 3.3.

The internal set-up of the TRM consists of a 15 mil multilayer thickfilm alumina (Al_2O_3) substrate at the control area, for inter-connecting DCE and core chips, and an additional 15 mil thinfilm alumina substrate at the HPA - circulator region, because an extremely small line width for the directional couplers interdigital capacitors are implemented to meet the requirements for the test and calibration path. The complete electronic circuitry (digital, power and RF) is mounted on a single aluminium silicon carbide carrier (AlSiC) with two cut-outs for the circulators.

To meet the mechanical requirements of the housing small diameter SMP connectors are applied. Thus, a total thickness of the T/R Module of 10 mm can be achieved.

Table 1 gives a list of the T/R Module requirements for a high resolution SAR system. Simulation results show that the specifications can be met, except the PAE requirement. Further effort is necessary to reach the 22 % threshold.

Parameter	Requirement
Output Power Level	+39 dBm (7.9 W)
PAE	> 22 % (25 % goal)
Noise Figure	< 2.5 dB
Rx Gain	30 dB
Phase Setting Range	0° - 360°
Phase Stability vs. Frequency and Temp.	± 6°
Rx Gain Setting Range	0 to -15 dB
Rx Gain Stability vs. Frequency and Temp.	± 0.25 dB
Size (L x W x H)	65 x 80 x 10 mm^3
Weight	< 70 g

Table 1: TRM Requirements for a High Resolution SAR Application

3 T/R Module Technology

To meet the general requirements for miniaturisation, low weight and low prime power consumption highly sophisticated components in modern technologies have to be used.

3.1 GaAs MMIC

The active components of the T/R Modules are realised as highly integrated microwave circuits (MMIC) in Galium Arsenide (GaAs) technology. Bare chips are used in the higher frequency ranges (C- / X-band). In L- and S-band the chips are integrated in appropriate housings.

The major MMIC components of the T/R Modules are digitally controlled 6-bit phase shifter (PHS) and 6-bit variable gain amplifier (VGA), low noise amplifier (LNA), driver amplifier (DA), and high power amplifier (HPA). The phase shifter elements are realised as switched filter structures or switched lines. The VGAs are built up as segmented dual gate

FETs, switched attenuators, or as vector modulators. The advantage of the segmented dual gate FET solution is the small GaAs size. Advantage of the switched attenuators is the higher third order intercept point, leading to a higher dynamic range (linearity) of the receive path.

The LNAs are 2- or 3-stage amplifiers in HEMT technology with typical noise figure of 1 dB in X-band. A major step to higher integration levels is achieved with the Multifunction MMIC (Core Chip), where phase shifter, variable gain amplifier, buffer amplifiers and T/R switches are integrated on one single MMIC. The Core Chips are realised either in HEMT or MESFET technology. Improved electrical performance (lower loss, higher isolation) is achieved in HEMT technology at slightly higher cost. **Figure 3** shows the chip photograph of a Multifunction MMIC, developed by SI Sicherungstechnik GmbH & Co. KG, the former Siemens Defence Electronics Group. The size can be given by 3.1 mm x 3.3 mm.

In terms of efficiency the driver amplifier and the high power amplifier are the dominating components. The HPAs, with the corresponding driver amplifiers, are available up to 8 W output power level with efficiencies of approx. 40 % in MESFET technology. Engineering samples of 10 W to 12 W amplifiers exist.

With their high reliability (MTBF) the MESFET technology is leading in power amplifier production. Alternative technologies like HBT or power HEMT provide good results in output power and efficiency, but with significantly lower reliability.

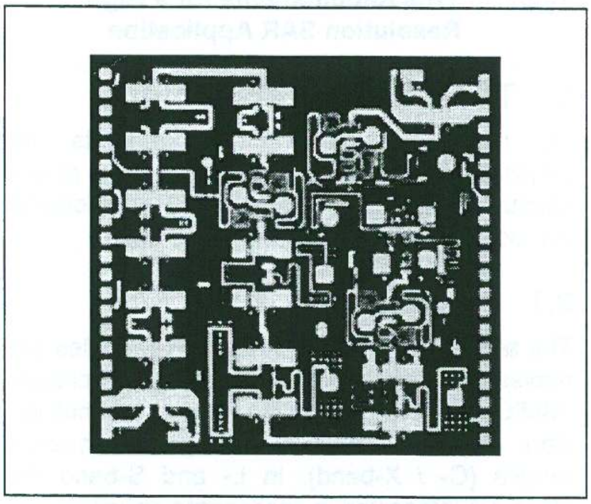

Fig. 3: Photograph of Multifunction MMIC

3.2 T/R Module Efficiency (PAE)

As already described above, the increase of T/R Module power-added efficiency (PAE) is one of the key issues for space-borne applications. In this context it is often heard that the major impact can be achieved by enhancing the PAE of the high power amplifier. It cannot be denied that the HPA has a great influence of the TRM efficiency. But nevertheless, the higher the PAE of the HPA the more important becomes every power consuming component inside the TRM. To illustrate this effect **Figure 4** presents a comparison of present and future TRM efficiencies versus the efficiency of the applied HPA. In both cases a duty cycle of 10% and one Rx channel switched on during the receive period is assumed. The diagram in **Figure 4** is independent of the HPA technology, thus, it is valid for HPAs realised in HBT, MESFET or PHEMT technology etc.

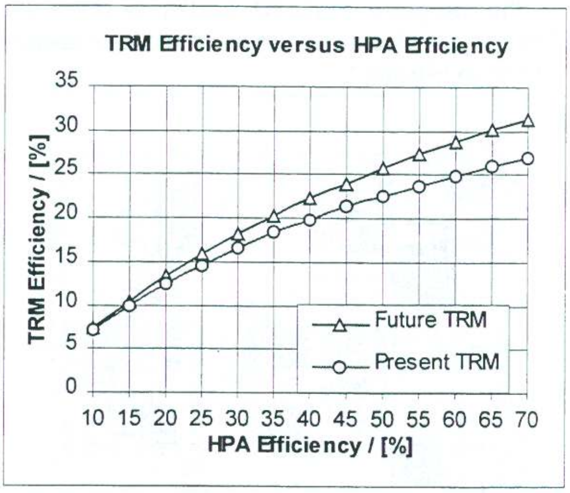

Fig. 4: Comparison of Present and Future TRM Efficiencies vs. HPA Efficiency

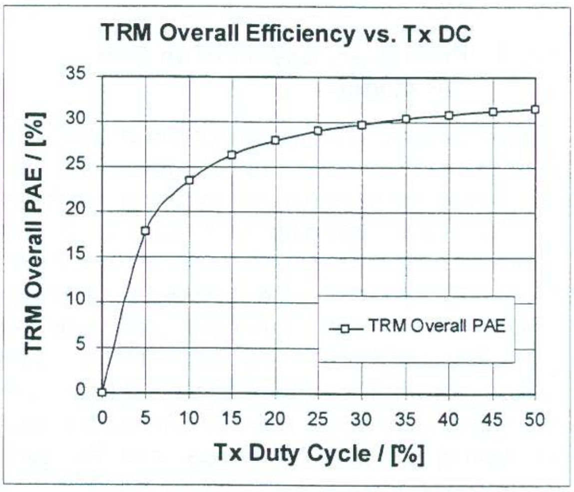

Fig. 5: TRM Efficiencies vs. Tx Duty Cycle

A further important parameter for calculating the TRM overall power-added efficiency is the value of the Tx duty cycle. This parameter defines the ratio between the Tx pulse width and the pulse repetition interval (PRI). Due to the fact that the impact of the HPA and its PAE is reduced by decreasing the Tx duty cycle the influence of all power consuming components within the T/R Module, which are switched on permanently or during Rx only, increases rapidly. Thus, a great effort has to be done to reduce the power consumption of every active device within the TRM to achieve highest TRM overall power-added efficiency.

Figure 5 shows the TRM overall power-added efficiency versus Tx duty cycle. This diagram clearly depicts the high impact of the Tx duty cycle on the TRM overall PAE. Especially within the range of 0% to 15%, which is common applied for space-borne applications, the influence of the power consumption of the digital control electronic, LNAs, Core Chips (VGA & PHS) etc. cannot be neglected.

3.3 Digital Control Electronics

The digital control electronics (DCE) must be able to control all relevant processes inside the T/R Module. Due to the need of high precision T/R Modules in a high resolution SAR system, the modules must be able to compensate manufacturing tolerances of GaAs MMICs, as well as any kind of temperature dependent behaviour of all active and passive components within the RF paths. Furthermore, the need of a higher level of miniaturisation, and a reduced power consumption becomes more and more important for the DCE, as well.

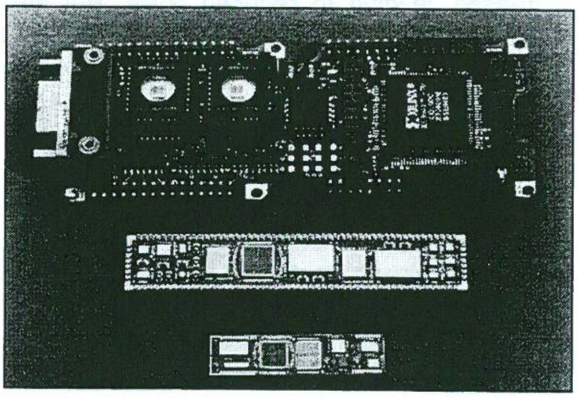

Fig. 6: Comparison of three T/R Module Digital Control Electronics

Three generations of DCEs, which have been developed by SI Sicherungstechnik during the last 5 years, are shown in **Figure 6**. The first design was used in the XABB T/R Module (1993), the second one for controlling the SI T/R Module Demonstrator (1996), **Figure 7,** and the third unit will be applied within the EUCLID CEPA 9 RTP 9.3 T/R Modules (1998).

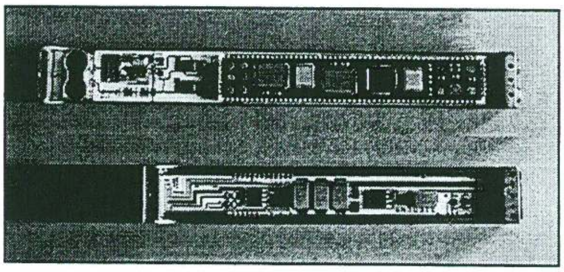

Fig. 7: Modern T/R Module Demonstrator

This DCE consists of a thinfilm multilayer alumina substrate (15 mil, MCM-D technology), using bare chips, mounted in Flip Chip and conventional bonding technology, and has been manufactured, already. This device is able to control two Core Chips individually, and applies a three dimensional compensating algorithm using a storage capacity of 4 Mbytes. Further functions are:

- Reception of serial control data
- Decoding of T/R Module address
- Decoding of control signals and strobes
- Transfer of monitor data (bidirect. PCM bus)
- Internal timing control
- Monitoring of RF circuit temperature and Tx output power level
- Conversion of logic levels from +5V/0V to -5V/0V
- Data correction of two 7-bit VGA and two 7-bit PHS data for setting two Multifunction MMICs individually
- JTAG loading of firmware
- Small size of 8.5 x 35 mm^2.

3.4 T/R Module Demonstrator

Recently, an X-band T/R Module demonstrator has been built up by SI to demonstrate the ability of manufacturing a small sized T/R Module applying a multi dimensional compensating algorithm for controlling two individual Rx channels combined with an SAR required performance. This module applies two 2-stage low noise amplifiers in series, having a noise figure of less than 1.3 dB, and a gain of 35 dB. The Tx path consists of a single 8 W GaAs MMIC HPA and a pre-connected 1 W GaAs MMIC driver amplifier, both realised in MESFET technology. The Tx insertion gain is approx. 29 dB depending on the RF input signal level. Two Core Chips containing a 7-bit PHS and 7-bit VGA have been applied to control Tx and Rx phase, and Rx amplitude.

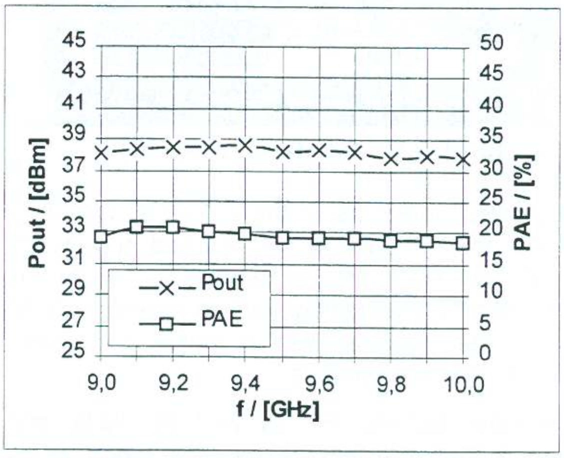

Fig. 8: Output Power and TRM Overall Efficiency versus Frequency

The Tx output power level is higher than 38 dBm over the investigated frequency range. The power-added efficiency has been determined up to 21 %, **Figure 8**. In the receive mode the demonstrator module has a maximum insertion gain of 32 dB, which can be adjusted within a range of 0 dB to -18 dB, and a noise figure (NF) of less than 2.5 dB, **Figure 9**.

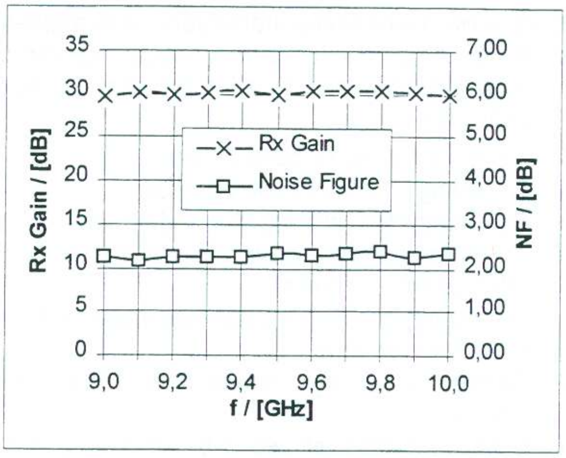

Fig. 9: Rx Gain and NF versus Frequency

3.5 T/R Module Duo Pack

Besides the previously described SI TRM demonstrator a T/R Module duo pack has been built up by SI Sicherungstechnik also to demonstrate the technological status of T/R Module development by SI. **Figure 10** shows a photograph of the TRM duo pack. This high sophisticated T/R Module contains dual TX and Rx channels, which can be controlled individually by one Core Chip each, a three-dimensional temperature compensating algorithm applying 4 Mbit storage capacity, miniaturised non-reflective limiter circuits, and 8 W single chip GaAs MMIC HPAs realised in MESFET technology.

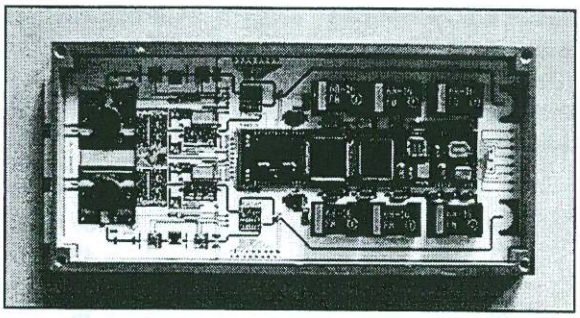

Fig. 10: T/R Module Duo Pack

All interconnections of the individual circuitries within the T/R Module are realised by a hybrid multilayer substrate, a combination of thinfilm and thickfilm technology, which provides all RF structures, as well as all digital and power supply interconnections.

All input signals, RF as well as digital and power lines, are fed via a vertical feed-through which is placed at the bottom side of the multilayer substrate. This kind of connector is able to provide all input interconnections between TRM and feed network within one single integration step.

At the antenna side the RF lines are straight feed through the wall to demonstrate the option of integrating TRM and radiator element in an ease way.

To reduce the weight of the T/R Module duo pack no connectors, as described above, and no carrier plates are applied, thus, the multilayer substrate as well as the high power MMICs are directly mounted onto the groundplate of the housing. This plate is realised of Aluminium Silicon Carbide (AlSiC) to ensure thermal expansion matched by this material.

The total size has been determined as 70 x 33 x 5 mm^3 having a weight of less than 30 g. This module operates at X-band with 25 % bandwidth.

4 Summary

The technical and technological basis for design and development of high performance T/R Modules is given. Further efforts have to be made in cost effective production of large quantities for full scale antenna systems. One major step is the use of commonalties between different programs in module design, as well as in MMIC design. Therefore the quantity is increased, leading to reduced costs. But also the general use of synergy between civil and military applications will drop the T/R Module cost.

5 References

[1] R. Schäffner, G. Eckert:
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