

HIGHLY INTEGRATED APPLICATION SPECIFIC MMICS FOR ACTIVE PHASED ARRAY RADAR APPLICATIONS

F.L.M. VAN DEN BOGAART
TNO Physics and Electronics laboratory
P.O. Box 96864
2509 JG The Hague
The Netherlands
E-mail: vandenBogaart@fel.tno.nl

Application specific MMIC solutions for active array radar, developed at TNO-FEL, are presented. The use and application of these MMICs in their respective radar systems will be shown. These MMICs address the needs for current and future phased-array topologies as for example the concept of "smart skins". The MMICs functions to be presented are: highly integrated RF-control circuits, wide-band, high gain, high-efficiency solid state power amplifiers, and finally integrated tuneable microwave filters for radar receiver front-ends.

Various MMIC solutions for amplitude and phase control are shown. The design, manufacturing, performance and application of linear vector modulators, variable gain amplifiers, phase shifters and fully integrated multi-functions chips are presented. Prototypes manufactured in state-of-the-art GaAs MMIC process are presented.

High-power amplifiers are described that comply with future active phased-array operations. As typical examples the development of MESFET and HEMT power amplifier at X-band are described with more than 10 Watt output power. These amplifiers are intended as alternatives to replace the cascade chain of the traditional driver and high-power amplifier in TR-modules.

Tuneable band stop filters and band pass filters are described which focus at a reduction of EMI effects in wide band transmit-receive modules. A significant improvement in out-of-band power compression in wide-band front-ends can be achieved by implementing a tuneable narrow-band filter. However, these filters may not degrade the radar performance and hence a filter is required with a low noise figure, low cost, small size, good power-pushing behaviour and which is easy controllable. MMIC tuneable filters at X-band which comply with these requirements and manufactured in MESFET and in HEMT processes are presented.

1 Introduction

Advanced future radars will be based on active array antennas. A typical near future TR module configuration is shown in Figure 1. The MMIC part count will be minimised; the RF functions will be as much as possible integrated. The phase control

function (or true-time delay control function) the amplitude control function and the necessary routing switches will be integrated into one multifunction RF-control MMIC. One solid state power amplifier MMIC will be used to replace the current cascade of driver amplifier (DrA) and high-power amplifier (HPA).

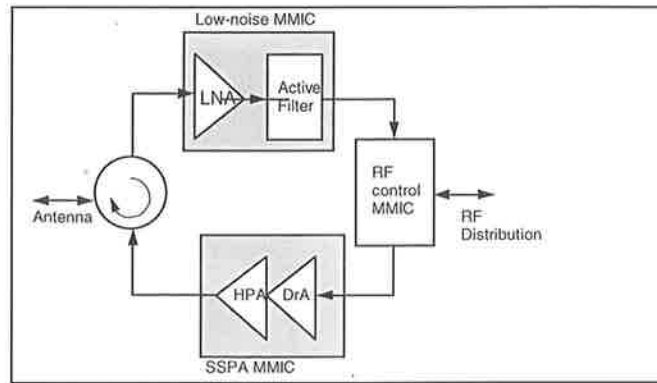


Figure 1: Typical basic architecture of future TR modules.

A large number of future phased-array applications will require a broadband behaviour, up to 30% bandwidth. TR modules operating in a CW as well as in pulsed mode will be used. Such modules require wideband high-power high-efficiency amplifiers, highly integrated RF control MMICs and low-noise front-end MMICs with integrated tuneable band pass filters to maintain dynamic range under severe EMI conditions. Examples of these types of MMICs developed at TNO-FEL are provided in the following sections.

2 Multifunction RF Control MMICs

3 Different typical examples of multifunction RF control GaAs MMICs are shown.

A first example is shown in Figure 2. This is a vector modulator that is developed for the transmit/receive modules of a full polarimetric C-band air-borne phased-array synthetic aperture radar (SAR) called PHARUS [1]. The PHARUS design (acronym for

PHased ARray Universal Sar) uses a dual polarised microstrip antenna with low cross-polarisation and has the possibility for accurate internal calibration.

This air-borne SAR will be used to image the earth's surface. Each of the 48 transmit/receive modules of the SAR is using two vector modulators. The vector modulators control the beam-forming of the radar, one for each polarisation. The band-width of the SAR is 40 MHz which is fully covered by the vector modulator. The SAR-system is upgradable to a bandwidth of 100 MHz.

The vector modulator is designed as a Monolithic Microwave Integrated Circuit on GaAs. The circuit includes an active quadrature power splitter that consists of a 2-stage amplifier with flat gain and relative low-noise figure, a quadrature phase relation that is obtained by lumped element high-pass and low-pass filters, and a biphase amplifiers consisting of differential amplifier and a push-pull amplifier.

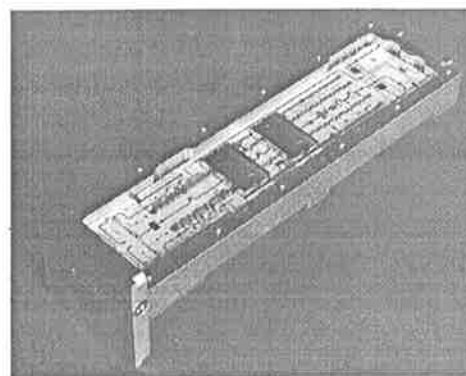
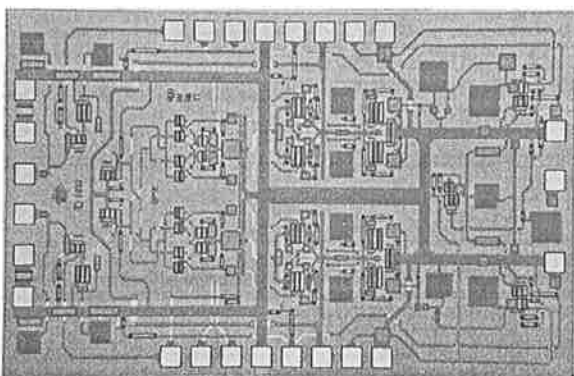


Figure 2: Chip photograph of PHARUS vector modulator (left) and TR module (right)



Figure 3: Radar image from Amsterdam (left), Pharus mounted under a Cessna (right)

PHARUS (PHased ARray Universal Sar) is a full polarimetric C-band aircraft SAR (Synthetic Aperture Radar), that can be used to image the earth's surface. It is designed and built by the TNO Physics and Electronics Laboratory (TNO-FEL) in The Hague, the National Aerospace Laboratory (NLR) in Amsterdam and the Delft University of Technology (TU Delft) in Delft, under program management of the Netherlands Agency for Aerospace Programs (NIVR) in Delft. Figure 3 shows PHARUS mounted under an aeroplane and a typical radar image of the city of Amsterdam obtained with this radar.

Figure 4 shows a 2nd example of RF control MMIC. It is low power GaAs multi-function X-band MMIC for space-based synthetic aperture radar (SAR) application. It exhibits 7 bit phase and amplitude control. This is an alternative approach to the vector modulator principle. The multi-function chip (MFC) consists of switches (SW) for selection of the transmit or receive mode, a 7-bit phase shifter (PS), a 7-bit attenuator (Att) a low-noise amplifier (LNA) and 2 medium-power amplifiers (MPA). The MFC frequency range is 9 to 11 GHz for both transmit and receive. The phase setting of the MFC is from 0° to 360° with an accuracy better than $\pm 3^\circ$. The gain setting range is more than 20dB with an accuracy smaller than ± 0.21 dB. The input and output return losses are better than 14 dB for all ports. The gain for transmit and receive is 3 dB. The noise figure for the receive chain is better than 4.5 dB with a third order intercept point of 13.5 dBm. The P-1dB compression point of the transmit chain is better than 14 dBm. The bias supply voltages are +5 and -5 Volts. The total power consumption of the chip is about 0.3 Watt regardless of the transmit or receive mode. The size of the MFC is 4.2 x 4.2 mm².

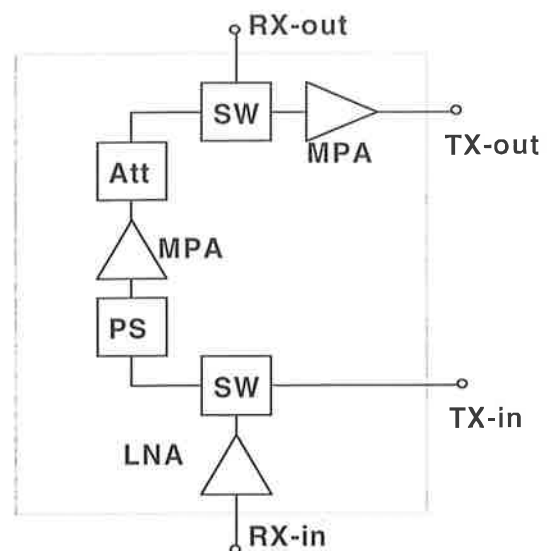
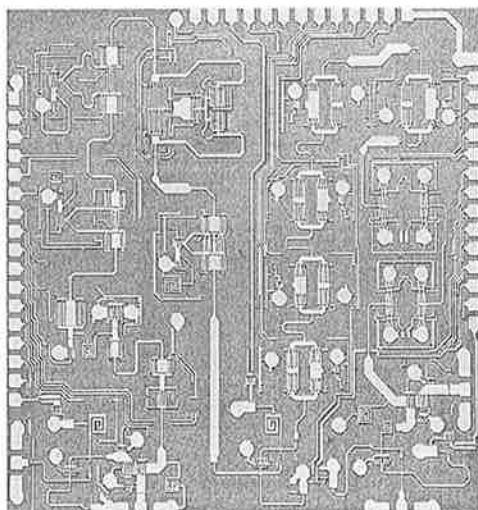
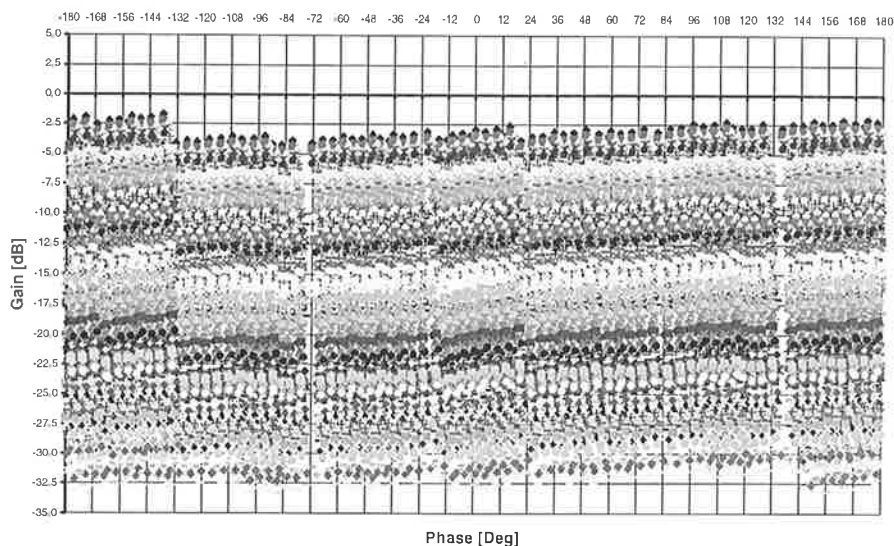


Figure 4: Chip photograph of a X-band multi-function MMIC with 7 bit phase and 7 bit amplitude control



(left) and circuit topology (right).

Figure 5: Typical example of a gain-phase map of the multi-function MMIC at a fixed frequency .

The integration of functions combined with the low power consumption and the excellent specifications, are making this multi-function chip extremely suitable for future high performance space-based synthetic aperture and phased-array radars [2]. A typical performance chart is given in Figure 5. This figure shows all gain-phase states at a fixed frequency. Thus showing the large control range of this circuit.

The 3rd example of RF control circuits is shown in Figure 6. This is a gain control device with 8-bit digitally controlled variable gain amplifier (VGA) including low-noise amplifying stages and medium-power amplifying stages. The circuit is for use in a

multi-function naval phased array radar system, [3].

The VGA design is built around a 6-bit segmented dual-gate FET. The dimensions of the dual-gate FETs in the segmented structure are optimised for a gain behaviour that is linear in magnitude with the bit-state. On-chip level shifters are used in order to reduce external control logic. The gates of all the RF-amplifying FETs are biased by an on-chip active circuits in order to decrease the temperature and process parameter sensitivity and to circumvent the use of external circuitry. Noise figure reduction of the chip is achieved by placing a two-stage low-noise amplifier in front of the 6-bit segmented dual-gate. The FET in the second stage is a 2-bit "coarse tune" structure that provides 4dB gain range for calibration and tracking of the T/R modules.

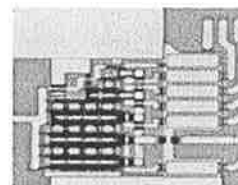
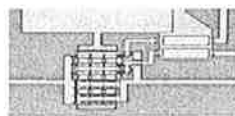
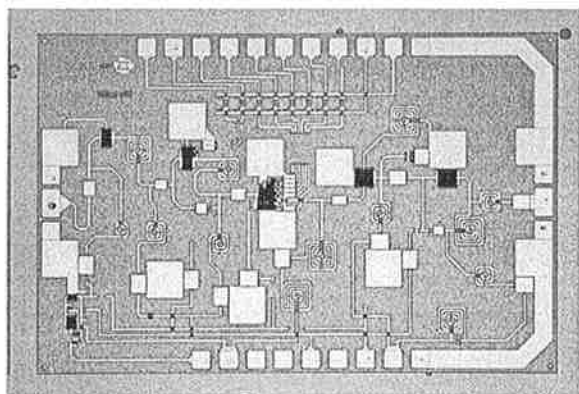


Figure 6: Chip photograph of 2 + 6 bit variable gain amplifier (VGA) with segmented dual-gate FETs as digital-controllable gain device (left), and the magnified segmented dual-gate FETs (middle and right).

Varying output return losses due to state switching are isolated by a common-gate FET amplifier that is connected to the 6-bit dual-gate FET structure. An output amplifier increases the gain and output power of the total design.

Measured results show a gain range of more than 25 dB with an additional 20% coarse tuning range, a nominal gain higher than 20 dB, low input and output return losses, a noise figure better than 4 dB and a moderate output power compression point over a 30% bandwidth. The phase variation over the entire gain range is small.

3 High power amplifiers

The near-future targets for high-power amplifiers for application in wideband X-band TR modules are: more than 30% bandwidth at X-band, more than 10 Watt pulsed and CW output power, more than 30 dB large signal gain, best obtainable power added efficiency (PAE > 30%), manufacturing in a reliable, mature and cost-effective technology.

Figure 7 shows a 10 Watt high-power amplifier (HPA) manufactured in a MESFET process. The

HPA described in this paper is developed within the scope of the WEAG/TA1/CTP8.1 programme. This programme was carried out by a consortium consisting of Siemens HL (now Infineon), Dassault Electronique (now Thomson-Detexis), Fraunhofer-IAF and TNO-FEL. The goal of the 10 Watt amplifier described below was to demonstrate the feasibility of wideband (>30% bandwidth) high-power amplifiers at X-band with the best obtainable power added-efficiency (PAE) in a pulsed mode of operation and in a CW mode of operation and manufactured in a reliable, cost-effective and mature technology.

The 10 Watt HPA is manufactured in the Siemens DIOM20HP process. This process consists of 0.5 μm MESFETs, a self-aligned gate technology, localised ion implantation, MIM capacitors, via holes and air bridges. This technology assures a very good reproducibility, high reliability and low manufacturing costs.

The 10 W MESFET HPA goals are more than 40 dBm output power, more than 15 dB gain in compression, more than 25% PAE and more than 30% bandwidth.

The size equals 26 mm².

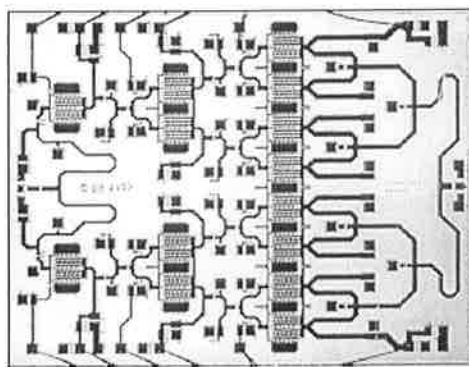


Figure 7: 10 W MESFET HPA

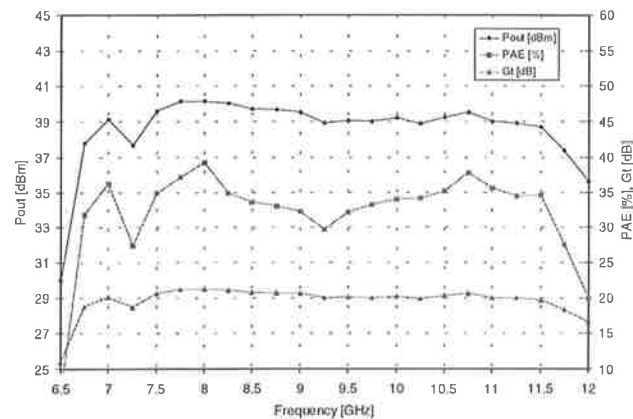
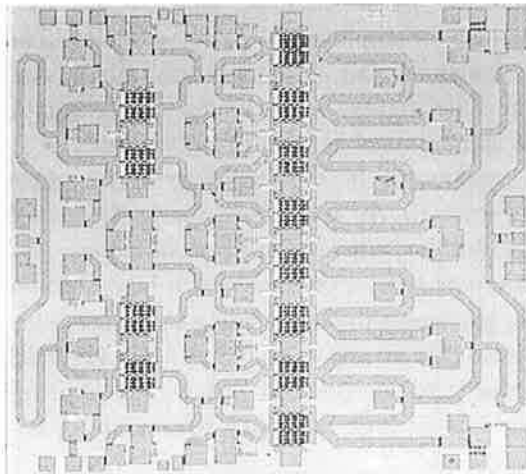


Figure 8: Chip photograph of a Power HEMT SSPA (left), and typical performance (right)

Such amplifiers manufactured in a MESFET exhibit typically a relative low gain. As a result, the MESFET technology is less suitable for high-gain power amplifiers at a small chip surface.

Figure 8 shows a high-power amplifier is PHEMT technology. This technology enables amplifiers with a very large gain in compression, typical more than 30 dB. Hence, 3-stage amplifiers manufactured in such processes enable the replacement of the current cascade of a driver amplifier and a MESFET amplifier. The amplifier shown in this figure is a 2-stage amplifier with more 20 dB large-signal gain. The large-signal gain improvement compared to the above 3-stage MESFET amplifier is significant.

While the chip area is much smaller: 26 mm² versus 16 mm². This amplifier is manufactured at Fraunhofer IAF, Freiburg, Germany. It exhibits more than 39 dBm output power in a very large frequency band with more than 30% PAE.

4 Integrated Tuneable filters

Wideband receive modules are very sensitive to electro-magnetic interference. Large out-of-band signals which can be man-made jammers or interference of other radar and communication equipment can saturate the receiver and hence cause a significant reduction in the dynamic range of the TR modules.

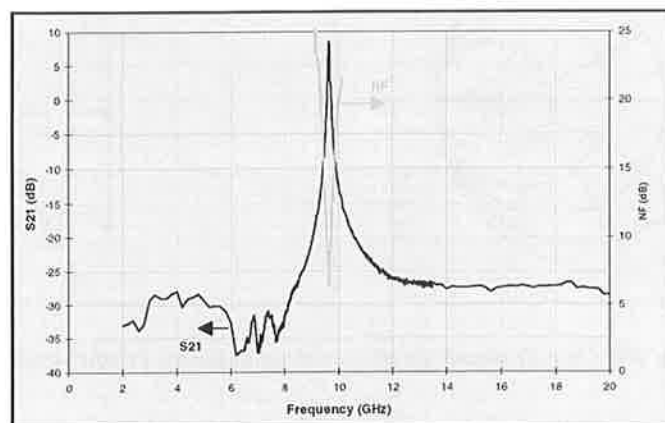
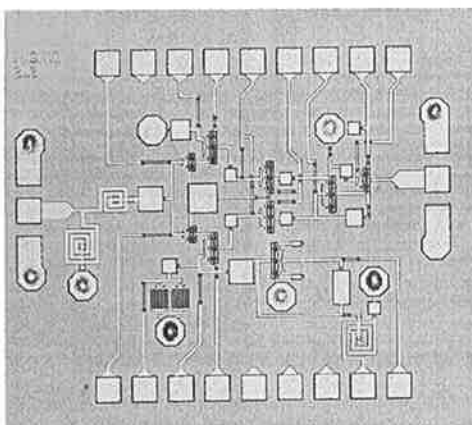


Figure 9: Chip photograph of a tuneable band pass filter and its gain and noise performance (right)

A drastic improvement in the dynamic range by implementing a narrow-band tuneable band pass filter in the receive front end is anticipated. The bandwidth of such a filter should be in the order of magnitude of the instantaneous bandwidth of the radar signal and the tune range should cover the operating frequency bandwidth.

It is required that such filters must be implemented as close as possible to the antenna elements to obtain the best possible improvement in dynamic range. Thus the filter should be low cost and miniaturised, this implies a monolithic integration. In addition, the electrical performance of the TR module on receive may not be affected by this filter, in particular the system noise figure and the large-signal behaviour. A typical example is shown in figure 9. It is observed from this figure that a Q-factor of about 100 is feasible with an associated noise figure of 7 dB and a gain of 8 dB.

Monolithic integration of high-selective tuneable filters at X-band has not been addressed until now but is gaining more and more attention from system designers due to the fact that phased arrays are more and more wideband. Various options exist for tuneable-filter topologies that allow monolithic integration on GaAs. A trade-off study [4] indicated that a filter consisting of a varactor diode and an

active inductor as a resonant tank is the most promising one for application in TR modules. This topology combines all requirements: small size, acceptable noise figure, large tuning range, narrow pass band and a limited number of control lines.

The key component in this topology is an active inductor, Figure 10. An active inductor can be used to compensate for the losses in the resonant circuit. As a result a resonant tank is created with a high Q-factor and which gives also the opportunity to design filters with insertion gain as shown above. A novel approach of the active inductor principle allows a significant improvement of the high frequency behaviour.

Earlier reported examples of broad band active inductors cover a wide range of inductance values (0.5 - 50 nH) with Q-factors ranging from poor to outstanding (5-200). These active inductors perform up to roughly 30% of the transition frequency of the employed device (0.3 f_t). Increasing the high-frequency properties of active inductors requires a different approach. Instead of realising a broadband active inductor, we have focused on narrow band active inductors.

Finally, figure 11 shows a filter integrated with a low-noise amplifier to reduce the noise figure to the required value.

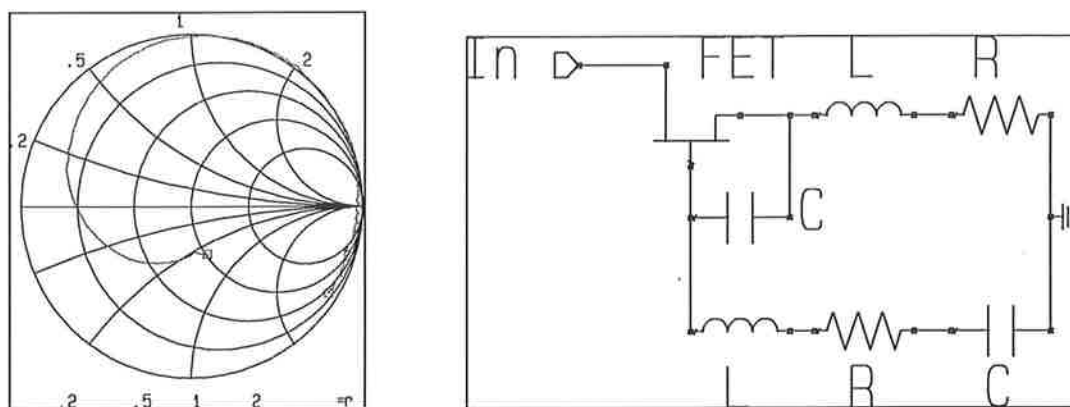


Figure 10: Circuit topology of an active inductor (right) and its performance given in a Smith Chart

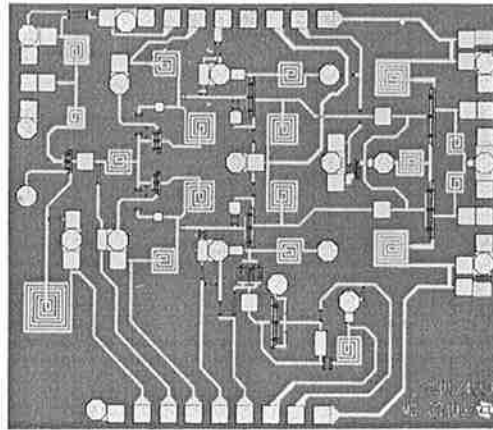


Figure 11: Tuneable filter with integrated low-noise front-end

5 Conclusions and Observations

From the examples shown above it is clear that a dual-chip microwave TR-modules is a viable option in the very near future.

High-power amplifiers with an output power in the range 10-15 Watt with 30-50% PAE and more than 30 dB gain in compression are reality. These amplifiers are manufactured in a GaAs MESFET or PHEMT technology.

Microwave high-power amplifiers manufactured in a GaAs HBT technology are not presented in this paper. They are certainly feasible up to 10 Watt output powers at 10 GHz, but only in dedicated applications.

Promising semi-conductor materials for extreme high-power amplifiers are Gallium-Nitride (GaN) and Silicon-Carbide (SiC). X-band power amplifiers up to 50 Watt seem to be possible with these technologies in the coming 5 years.

Multi-function MMICs with very high integration levels are feasible. These circuits will enable "RF-systems on-chip". The preferred technology at this moment is GaAs. However. In certain applications with less demanding noise, linearity and power requirements, Silicon (CMOS, bipolar) will be a major competitor for GaAs. Also at X-band frequencies.

GaAs still seems to be the most likely candidate to obtain low noise figures at microwave frequencies.

Low-noise amplifiers in Indium-Phosphide (InP) technologies have shown a significant better noise figure. However, InP has a number of disadvantages over GaAs (cost, maturity of technology, quality of material, no immediate volume application). As a result market introduction is delayed. The availability in the near future of InP grown on GaAs may become an alternative: it will combine both the advantages of GaAs and InP.

It should be noted that packaging, assembly and mounting aspects are not discussed in this paper. However, these aspects will be of major importance since the price of the MMICs drops to the level of the packaging costs.

Also micro-machining and microwave MEMS are not discussed in this paper. These technologies will contribute in the next 10 years to a significant price and size reduction of TR-modules.

References

- [1] T.C.B. Tieman, F.L.M. van den Bogaart, P.J. Koomen, "Single chip C-band linear MMIC vector modulator on GaAs developed for an airborne active phased-array synthetic aperture radar", GAAS94 Symposium Proceedings, April 28-30, 1994 pp237-239.
- [2] A. de Boer, M.W. van der Graaf, A.P. de Hek, T.C.B. Tieman, "A GaAs Multi-function X-Band MMIC for space-based SAR application with 7 bit phase and amplitude control".
- [3] J. Bennett, K. Lewinski, P. Shearing, B. Velsher,

J. van Houten, A. Tiesinga, "Quadpack X-Band T/R Module for Active Phased Array Radar", GAAS98, October 1998.

- [4] F.E. van Vliet, F.L.M. van den Bogaart, T.C.B. Tieman, "Miniature Microwave Filters: Overview

and Progress", 1995 Digest of Nomadic Microwave Technologies and Techniques for Mobile Communications and Detection, 16 November 1995.



Frank L.M. van den Bogaart graduated in electronic engineering from the technical University of Eindhoven, where he received the M.Sc. degree in 1980.

In 1982 he joined the TNO Physics and Electronics Laboratory (TNO-FEL) where his main activities focused on the development of microwave electronics for phased array radars. In particular the design and development of Monolithic Microwave Integrated Circuits (MMICs). During 1988 he was a visiting scientist at the Philips Research Laboratories (LEP) in Limeil-Brévannes, France. He published and presented more than 20 papers and holds a patent on integrated active isolators. His current interests include front-end technology (opto-electronic integrated circuits, MMIC's and antennas) and radar signatures.