

Smart Antenna Skins, including Conformal Array, MMICs and Applications

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ABSTRACT

Low-cost technologies are presented for future space-borne and airborne SAR systems. These technologies include state-of-the-art highly integrated circuits to miniaturise front-end, solutions to lower-cost interconnection technologies, new beamforming aspects and new architectures.

The 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 and wide-band, high gain, high-efficiency solid state power amplifiers.

Various MMIC solutions at X-band and at Ka-band for amplitude and phase control are shown. The design, manufacturing, performance and application of fully integrated multi-functions mixed-signal chips 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. The impact of new substrate materials like GaN will be shown.

The preferred architectures, advantages and realised for optical beamforming techniques are shown.

INTRODUCTION

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 1: *Pharus mounted under a Cessna airplane.*

Figure 1 shows PHARUS mounted under an airplane. Pharus is an active phased-array radar and consists of 48 TR modules, operates at 5.3 GHz, is dual polarised, has 20W output power per module, 40 MHz bandwidth, has 3.75 m range resolution and up to 1 m. azimuth resolution. Figure 2 shows a typical radar image taken by Pharus.



Figure 2: *Picture of TNO-FEL taken by Pharus*

Each of the 48-transmit/receive modules, figure 3, of the SAR is using two vector modulators. The vector modulators control the beamforming of the radar, one for each polarisation. The bandwidth of the SAR is 40 MHz, which is fully covered by the vector modulator. The vector modulator is designed as a Monolithic Microwave Integrated Circuit on GaAs. The circuits 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 bi-phase amplifiers consisting of differential amplifier and a push-

pull amplifier. And is a first version of a multi-function MMIC circuit.

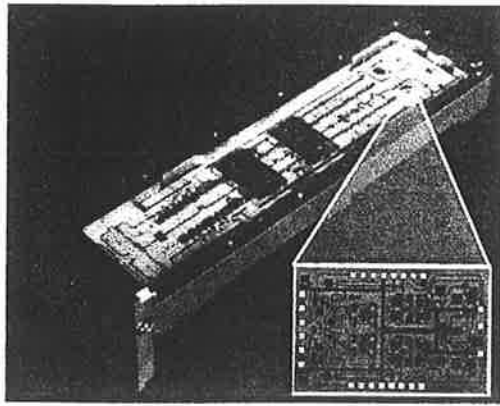


Figure 3: Pharos TR module.

Typical for the generation of these modules is the large number of components and a complicated assembly technology. Production is based on the manufacturing of single modules.

A typical near future TR module configuration is shown in Figure 4. The MMIC part count will be minimised; the RF functions will be as much as possible integrated into one MMIC. The phase control function (or true-time delay control function) and the amplitude control function will be integrated into one multifunction RF-control MMIC. A solid state power amplifier MMIC will be used to replace the current cascade of driver amplifier and HPA.

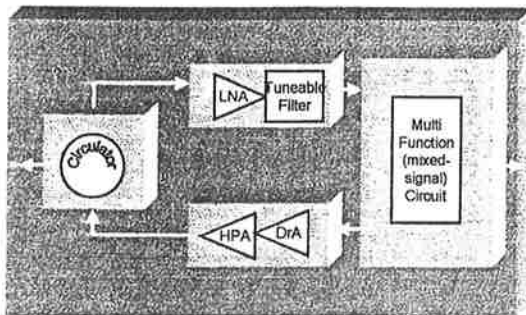


Figure 4: Typical basic architecture of future TR modules.

HIGHLY INTEGRATED MMICs

Figure 4 shows a low power GaAs multi-function X-band MMIC for space-based synthetic aperture radar (SAR) application with 7-bit phase and amplitude control. This is an alternative approach to the vector modulator principle. The multi-function chip (MFC) consists of switches for selection of the transmit or receive mode, a 7-bit phase shifter,

a 7-bit attenuator and several amplifiers. 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 accuracy better than $\pm 3^\circ$. The gain setting range is more than 20dB with 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.

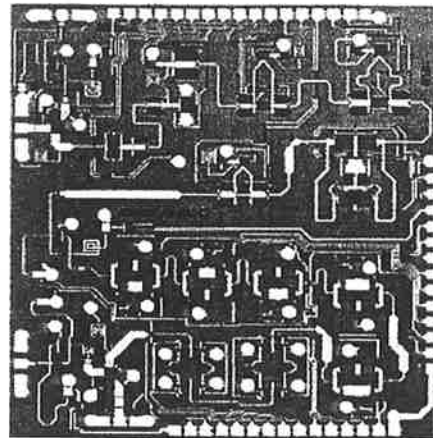


Figure 5: A 7-bit phase and amplitude control MMIC

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 4.2×4.2 mm². 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 (ref 2).

This circuit uses a large number of bonding pads. Hence, the assembly is rather complicated. But a more important possible drawback for low-cost applications is that it requires also a complicated control distribution network. The new generation GaAs processes, that also enable a large yield for digital circuits, could provide a solution. Mixed digital and analogue circuits are feasible in these processes. An example is shown in figure 6. This figure shows the same circuit as is shown in figure 5, however, a serial parallel digital converter is included in the circuit. Thus the number of bonding pads is drastically reduced.

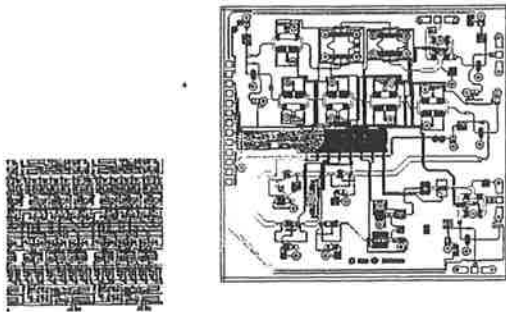


Figure 6: X-band Mixed-Signal Core Chip for SAR-applications

HIGH POWER AMPLIFIERS

Figure 7 shows the increase of output power levels of X-band HPAs in the last years. It clearly shows the trend towards higher output levels. However, based on radar simulations, output levels of the order of magnitude of 10-15 Watt seems to be sufficient for most X-band active array applications.

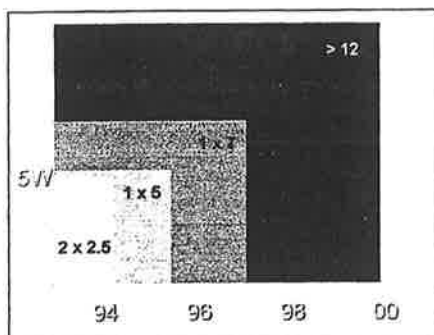


Figure 7: Output power levels in X-band TR modules

Figure 8 shows a 12-Watt high power amplifier (HPA) manufactured in a MESFET process.

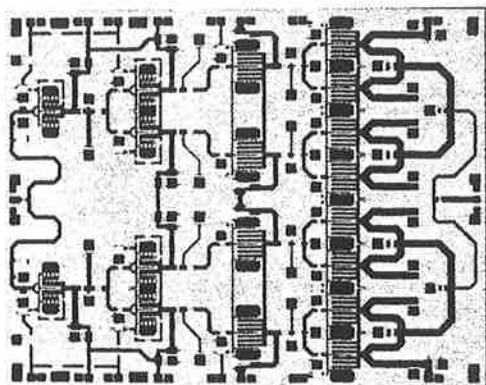


Figure 8: 12 W MESFET HPA

The goal this amplifier was to demonstrate: the feasibility of wideband (>30% bandwidth) high-power amplifiers at X-band, the best obtainable power added-efficiency (PAE), and manufactured in a reliable, cost-effective and mature technology.

The 12 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 HPA goals are 12-14 Watt output power, more then 18 dB LS-gain, more then 25% PAE and more then 30% bandwidth.

The size equals 6.7 x 5 mm².

These values show that the large-signal gain, i.e. the gain when the amplifier is in compression, is not sufficient for a dual chip TR module. The size is already too large.

Figure 9 shows a high-power amplifier is PHEMT technology. This technology enables amplifiers with a very large signal gain, 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 manufactured at Fraunhofer IAF.

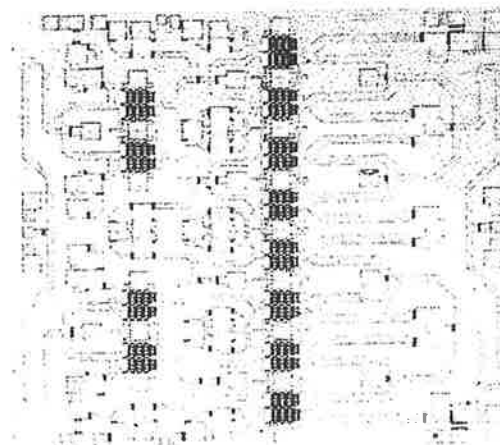


Figure 9: 2-stage MODFET 9-Watt HPA

It can be concluded that with the current available GaAs process high-power amplifiers are feasible with output powers up to 10 Watt, and that require input levels about 12 dBm.

The next step in the miniaturisation of such amplifiers will be the introduction of metamorphic transistors in the coming years. These transistors exhibit a larger gain than the current transistors.

Gallium-Nitride is a promising material for the next generation high-power amplifiers. Compared to GaAs, GaN exhibits a much larger breakdown voltage. As a result single transistors with about 10-Watt output power seem to be feasible. A significant size reduction can be achieved with these amplifiers. But, more important, due to the higher breakdown voltages, also savings regarding complexity and cost of the DC-DC converters become feasible.

MEMS

Micro Electro Mechanical Systems offer significant cost savings in phased-array antennas. Especially applications are foreseen to replace the FET-switches in phase shifters and in TR-switches, but also in tuneable filters, ref 3. The table below shows an indication about the possible cost savings.

Technology	Unit Cost	Power	Loss
MEMS	10\$	10mW	1.5dB
GaAs MMIC	40\$	20mW	6-8dB
Ferrite	100\$	400mW	1.2dB
Diode	20\$	200mW	2dB

ELECTRO OPTICAL BEAMFORMING NETWORKS

The use of photonics for phased-array applications has been discussed for quite some time. Main difficulties up to now have been the component count and cost for relatively complex systems. The advances in photonic integration are very promising to bring down volume and weight of phased-array beamforming networks as compared to their electrical counterparts.

In addition, photonics enables the use of antenna remoting and optical signal processing.

In general two classes of optical beamforming networks can be distinguished: coherent beamforming and incoherent beamforming. Coherent adding of optical signals requires control over the optical phase but has the

advantage of additional circuit gain, which reduces the required dynamic range of the modulators.

Using a coherent detection scheme, phase and amplitude of an optical signal can be directly transferred to a microwave signal. In this way modulation of phase and amplitude of a microwave signal can be performed using optical phase and amplitude modulators. Also, advanced optical materials may be used for this signal processing. A typical architecture of a coherent beamforming network is shown in figure 10, ref. 5,6

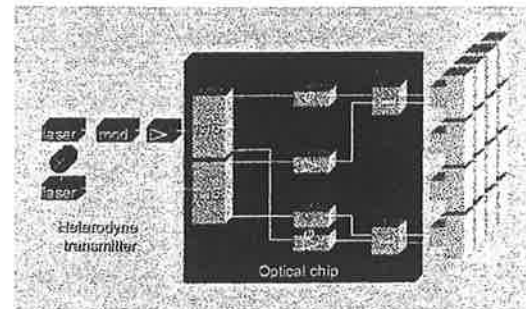


Figure 10: Typical architecture of optical beamforming on transmit.

The optical chip of figure 10 is shown in more detail figure 11. The 32 horizontal structures are the phase and amplitude modulators that use changes of the refractive index and in the absorption due to the electro-optic effect. The doping profile of the chip is chosen in such a way that the waveguide layer gets depleted when a reverse bias is applied to the waveguide. At high voltages, the modulator acts as an electro-absorption modulator, due to the electrical field induced shift of the band edge. A phase shift of 180 degrees can be set with a voltage in the range of 0 to -5 V. An attenuation to 15 dB can be achieved with a voltage swing of -20 V.

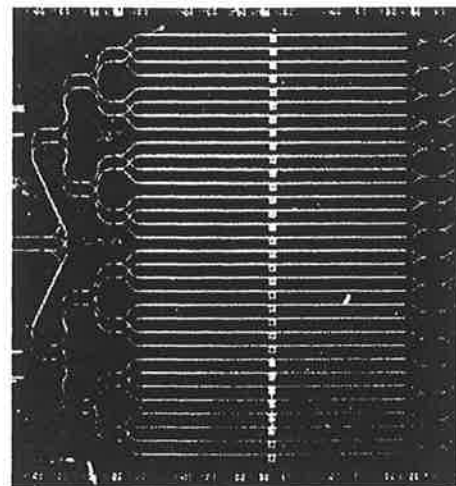


Figure 11: Optical InP phased-array chip

Further, the OEIC shown illustrates the use of splitters and combiners, based on MMI couplers. The OEIC hence can potentially perform the complete beamforming for 16 antenna elements.

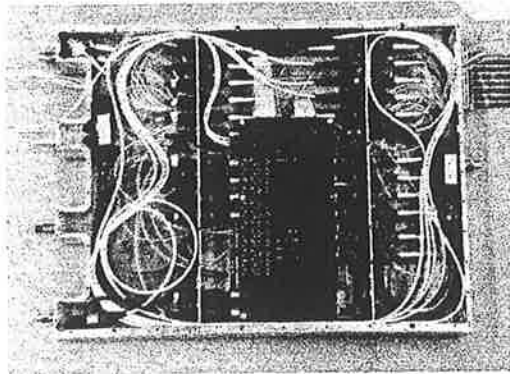


Figure 12: Top view of the photonic demonstrator, it includes 4 RF inputs, 4 2-bit switched delays with 31.25 ps for the smallest bit, 12 SiO₂ switches and an 4:1 optical combiner.

Another advantage of the optical approach is the huge bandwidth that it offers: the response is flat from DC to tens of GHz. It is limited by the bandwidth of the photo detectors that can extend over 100 GHz. Other advantages of using photonics are the frequency independent low loss of optical fibres in comparison with coax cables, the insensitivity to electromagnetic interference (EMI) and the possibility of incorporating long true time delays, enabling large instantaneous bandwidth radar systems as well as very large antennas.

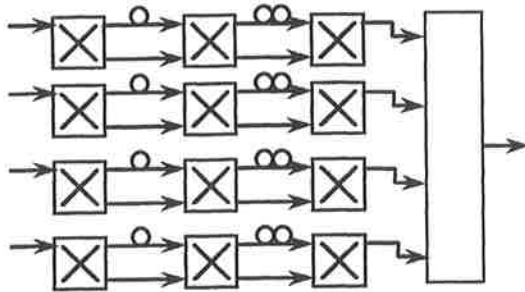


Figure 13: Switched delay line configuration and fibre coupler.

In figure 12 a photonic true-time beamformer with large time delays from potentially low cost components is shown, ref. 6. An uncooled DFB laser, a CATV photodiode and SiO₂ switches have been used. The complete beamforming part is frequency independent. The optical link has a noise figure of 30 dB and an SFDR of 101 dB.Hz^{2/3}. For the delay

lines standard 9/125 um fibre is used which is cut to the desired length with a precision of 1 mm, which corresponds to 5 ps. This is an typical example of a 2 bit optical beamformer for use at sub array level.

The topology of the switch delay line matrix is shown in figure 13.

SMART SKINS/SCALEABLE APERTURE

The techniques shown above make the concept of low-cost sub-assemblies possible.

These sub-assemblies as shown in figure 14, includes multi-layer substrates that carry as well as digital control lines also the RF lines. The second layer from the bottom is the radiator layer, shown in this figure as rectangular waveguides. The top layer has a dual function: looking from the radiator layer to the outside it functions as a spatial selective filter to improve the radiation pattern, looking from the outside to the inside it operates a frequency selective surface.

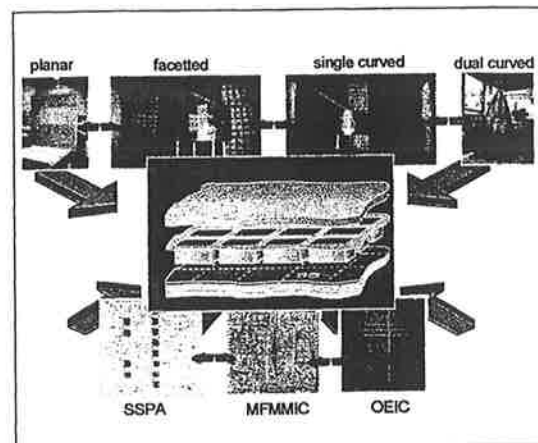


Figure 14: Top view of the photonic demonstrator.

The antennas shown in this picture are dealt with in more detail in the paper of H.J. Visser et.al. that is also presented at this symposium, ref 7. The theory of the array antennas described in depth in ref 8.

Finally figure 15 shows a possible scaleable architecture consisting of the tiles presented above. A part of the RF beamforming is done in the subarrays in a stripline or microstrip technology. The beamforming to the subarrays may be an optical network.

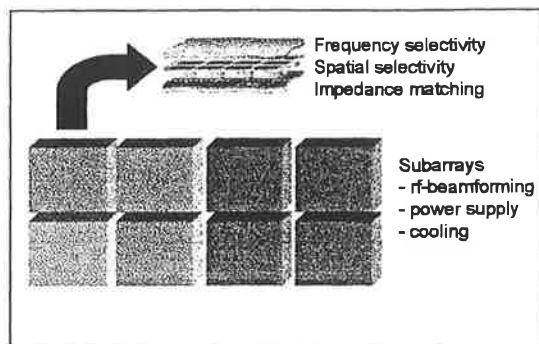


Figure 15: Scaleable active phased-array radar

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