TNO'S MESSAGE

In both the military arena and in other domains, the TNO radar group is renowned and in a number of radar areas, international experts even consider TNO to be the world's leading radar group. We are pleased to receive such compliments just as we are proud of our radar experts.

MMIC technology has become an essential part of modern radar systems, one that has been researched and developed for more than 25 years by TNO at its location in The Hague. With unique models and design tools, an excellent MMIC test facility and bold initiatives in developing prototypes, we have been able to make giant leaps in MMIC technology. In cooperation with major industrial partners, this technology has been further developed and incorporated in a formidable electronically-scanned radar. The impressive performance of the Dutch air defence and command frigates and new Holland-class patrol vessels is, to a considerable extent, based on the MMICs that have been developed and tested by TNO.

These activities have not gone unnoticed as other markets, like space, have also taken advantage of our modern radar technology and our MMICs in their applications. Such diversity in MMIC applications is another reason to be proud of what has been achieved.

This publication looks back on the past few decades as well as recent challenges and disappointments. It also looks ahead to future developments. Diverse threats, different management concepts, new tasks and the changing circumstances in which military equipment has to operate require innovative radars with MMICs that are not only smaller but also more powerful, smarter and more energy-efficient. In the industry of the future (smart industry), with the Internet-of-Things as an important enabler, remote sensing and, therefore, MMICs will play a key role.

TNO has not gained its international reputation in MMICs without broad support and commitment. TNO researchers have benefited from the support of many colleagues in the Netherlands and beyond. In this respect, the Dutch government, and in particular the Ministry of Defence, the universities of technology and the defence industry, with Thales Netherlands B.V. as a key player, deserve our gratitude. The excellent technology position of TNO in MMICs would not have been possible without good cooperation with all these partners. Together we will continue, intensifying our cooperation with respect for each other's culture and rules, and we are ready to welcome new partners in an environment of open innovation.

I wish our current researchers as much success as their predecessors: your work matters. Be inspired!

Wim Nagtegaal,
Vice-Admiral retd.
Chairman Defence Research Council.
Member TNO Board

25 YEARS OF MMICs FOR PHASED ARRAYS AT TNO

Frank van Vliet, Frank van den Bogaart

This book is meant to celebrate. It celebrates that 25 years ago the MMIC activities really have started at TNO (after a preparation of two years), and that these activities have sustained over such a long period in time. It celebrates all the achievements but also all the hard work that was needed to come this far.

But this book is more. It tries to give something back. It gives back an overview of the results obtained, a culmination of lessons-learned, including some of the reasoning behind these lessons. It is our gift back to our partners that have so responsibly supported us over this long period, highlighting the most important system drivers and technology trends.

And even then, this book is more. It is an invitation. An invitation to all readers to shape the future of MMICs for phased-arrays together with us, to create breakthroughs that will once more deeply improve phased-array sensor systems. It challenges the reader to come up with further innovative ideas. It is an invitation to pose questions, to set specifications and requirements that are (too) challenging, and then to work with us to solve and answer them.

We look forward to shaping this future together with you, colleagues, users, the industrial and scientific community. Shaping this future in order to have something to celebrate in 5, 10 or 25 years from now as well!

I INTRODUCTION

In 1988, one single TNO MMIC was taped out to one mask set. It was TNO's first MMIC, realised in a 0.7 µm GaAs MESFET technology from Philips in Limeil-Brévannes in France, with a transistor count of less than 10 on a single die and implemented as a building block for a vector modulator. In 2014, 25 years later, TNO produced roughly 30 original MMIC designs on 10 different mask sets in III-V and IV-IV semiconductor technologies. Not a single of these technologies even existed in 1988. If we include the commercial mask sets, the volume is too large and diverse to count reliably. Implemented circuits encompass complete multi-band receivers, high power amplifiers and T/R core chips, and technologies include GaAs, GaN and SiGe; MEMS and ferrite integration are pursued in parallel.

In 1988, one single TNO employee was on a secondment to the 'Laboratoires d'Electronique et de Physique Appliquées' from Philips in greater Paris (LEP, later known as PML, Philips Microwave Limeil, and even later known as OMMIC). In 2014, 25 years later, TNO houses a group of approximately 15 people, loosely denoted the MMIC group, with well over 250 man-years of experience in MMIC design for phased-arrays. Six of these have worked on the subject at TNO for over 20 years each.

In these 25 years, TNO published more than 100 scientific papers on MMICs. The EuMIC conference, and its predecessor the GAAS Symposium (GaAs and Associated Compound Semiconductor Symposium), has had a TNO booth every year since their conception in the

Figure 1 Microwave prizes, won at GAAS 2001 and at EuMIC 2006

European Microwave Week. The Symposium has been chaired since 2004 by TNO whenever it was organized in The Netherlands: Giuliano Gatti from ESTEC chaired GAAS1998, Frank van den Bogaart chaired GAAS2004, Frank van Vliet co-chaired EuMIC2008 and chaired EuMIC2012.

In these 25 years, material systems have evolved from exclusively GaAs now including GaAs, GaN and SiGe, working on the side also on ferrites, packaging and other related technologies. Even on GaAs, which has been the workhorse for microwave components over this entire 25 year period, we are still reporting major innovations year after year. And our license income has reached a record level in 2014.

In these 25 years, the problems to be solved have changed their nature. We now no longer solve electrical problems: we solve electrical, electromagnetic, thermal and mechanical problems in as much a multiphysics approach as we can manage.

In these 25 years, TNO has set many trends and records. The current results on integrated limiters (with a limiting power up to one kiloWatt!) are a recent example here-of, but the many-thousand transistor 8-channel consumer phased-array MMIC with integrated control is another nice example.

In these 25 years, many topics have been subject of phased-array MMIC research. Work on beamsteering, work on digital control, conformal arrays, smart skins, single-chip radars, digital radar, too much to cover even in a book like this. And then there is also the work in related fields, such as wireline and wireless communications, advancements in technology and opto-electronic integration. Looking from a distance, we can however define three main themes:

- Research on individual microwave functions that enabled active phased-arrays in the first place, this theme is described in Section II-A;
- Research on highly integrated core chips, in combination with high-power high-efficiency power amplifiers that in the first place simplified T/R module design dramatically and in the second place enabled more than 10W at X-band for a single transmit-receive module, this theme is described in Section II-B;
- Research on integrated receivers for digital beamforming systems, and the corresponding technology re-partitioning, this theme is described in Section II-C.

To enable these main themes, real breakthroughs were needed to model accurately passive and active components, to efficiently design complex linear and non-linear circuits at microwave frequencies, to characterize non-linear components under high-power conditions, to simulate non-linear and harmonic behaviour and to test efficiently large numbers of circuits.

These themes and breakthroughs will be covered in some detail in the following section.

II MMICs FOR PHASED ARRAYS

II-A The introduction of active phased arrays. The late eighties and early nineties were the true pioneering years for active phased-arrays and forced the development of affordable solid-state transmit-receive modules and the associated GaAs monolithic microwave integrated circuits (MMICs).

The landscape of radar systems with planar array antennas at the end of the eighties was dominated by passive phased-arrays (such as Lockheed Martin's SPY-1, a passive S-Band phased-array (using a corporate feed network and ferrite phase-shifters) that entered active service in 1983 on the USS Ticonderoga; Raytheon's Patriot, a passive C-band phased-array (using a monopulse space feed and fully filled with ferrite phase-shifters) that gained fame in the first Gulf war). These systems were challenging the rotating radars with parabolic dishes that had been around since roughly World War II.

At the lower microwave frequencies, where the inter-element spacing of an array left plenty room for electronics, phased-arrays were developed without the need for MMICs. At intermediate frequencies (such as S- and C-Band), experiments were carried out with GaAs-based front-ends that would later lead to rotating active phased-arrays, e.g. the UK's Multi-function Electronically Scanned Adaptive Radar (MESAR) programme (1982-1995) that would later result in BAE Systems' SAMPSON radar.

At X-Band, the Dutch EXperimental Phased-Array Radar (EXPAR) program was fairly unique. Volume constraints and electronic requirements were very tough and on the active phased-array architecture many pioneering efforts were needed. The only other large European X-Band initiative was the Airborne Multirole Solid State Active Array Radar (AMSAR), a programme launched in the early nineties to replace the CAPTOR.

Major design choices were the area of heavy debate, regarding for example the use of downconverters per antenna element (still present in the EXPAR demonstrator study), the use of phase shifting versus time-delays, the use of vector modulators versus separate phase-shifters and amplitude control, the analogue versus digital control of all the settings, the use of balanced hybrid high-power amplifiers (HPA) versus single chip HPAs, the use of active filters and many more.

CAD software to design integrated microwave circuits underwent major changes. TNO acted as an industry leader in accommodating these: from home-written linear S-parameter based microwave simulators, via Philips' internal spice-like simulator PHILPAC, via the legendary Touchstone (netlist-based manipulation of S-parameters with graphical layout) via EEsof's Libra introducing schematic editors and harmonic balance simulations to provide harmonic simulations), evolving into EEsof's Series IV which included methods to simulate non-linear behaviour in time- and frequency domain of transistors at microwave frequencies. These simulators would later merge with Hewlett Packard's Microwave Design System into ADS, and were complemented with electromagnetic solvers in the nineties (Sonnet, Momentum, HFSS and later many other packages). The availability of these contributed largely to the maturing of MMIC design.

Measurement systems were also not available. The chuck of the first probe-station was moved manually, unimaginable from the current automated-probing-of-full-wafers perspective. It is instructive to recall that the first load-pull measurement setup at TNO, which has run for many years, employed not only in-house software, but also a vector modulator built around an MMIC that was developed in-house. So you needed to manufacture an MMIC to advance the MMIC design state-of-art. This in-house developed load-pull system allowed impedances up to the outer border of the Smith Chart, thus enabling the design of truly high-power and high-efficient power amplifiers.

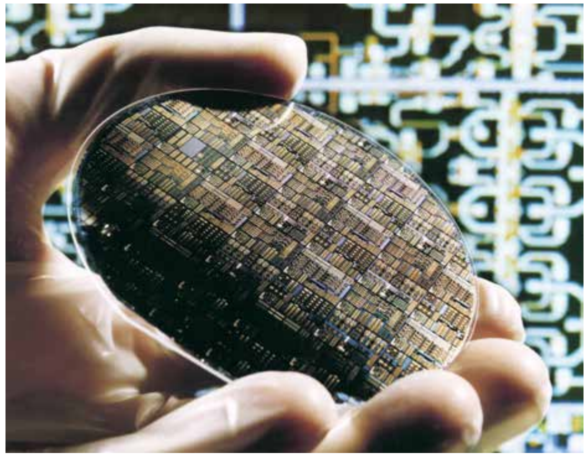


Figure 2 Early GaAs wafer

Figure 3 Manual wafer prober close-up

Figure 4 HP8510B measurement setup>

A passive phased-array antenna is, loosely defined, an array antenna which has no active components at element level and has to rely on a powerful central microwave source (such as a traveling wave tube or a Klystron). Usually, the signal of this central transmitter is passively divided over the array elements, for example through a corporate feed network or through free-space. The beam is pointed with the help of passive phase shifters like ferrite phase shifters in the early days and diode phase shifters later on, which obviously must be present at element level.

The start of active phased-array systems was through Transmit-/Receive-modules that implemented beamforming at microwave frequencies. Developments in solid-state electronics enabled small-size and modules that could be produced in large quantities for an affordable prize. In order for this to work, a number of functionalities were needed in these modules: low-noise amplifiers to secure the system noise figure, variable gain amplifiers to set receive and transmit gain levels, phase shifters to point the antenna beam, switches to choose between transmit and receive, circulators to duplex the receive and transmit signals, isolators to protect the amplifiers and power amplifiers to provide sufficient power at element level. Except for the circulators and isolators, none of these components were available for the radar bands given the tight volume constraints, but MMIC technology was emerging that was deemed to serve all these functions.

At this time, around 1987, GaAs MESFET technology was rapidly emerging, preceding GaAs pHEMT by some years. In direct competition were bipolar devices on GaAs (HBTs) as well as different III-V semiconductor material systems such as InP and InSb. GaAs technology enabled to greatly reduce the cross section of transmit/receive elements, down to dimensions that matched the phased array grid. This grid is typically a half times a half wavelength or a quarter times one wavelength.

GaAs gate lengths were rapidly diminishing. In 1989, a 0.7 µm MESFET was an outstanding technology, in 1992 a 0.5 µm MESFET was ruling, and in 1996, a 0.25 µm pHEMT device was offering lower noise and higher power densities. This has remained relatively unchanged. Many process details have improved over the years (breakdown voltage, reliability, noise figure, etc.) but for the applications at hand the III-V technology has remained relatively stable. For higher frequencies (30 GHz and above) though, a myriad of technologies with very short gatelenghts emerged. The technology was developing rapidly, but did not yet have large-volume customers. The mobile market, emerging around the late 90's, in fact triggered large-volume manufacturing of GaAs devices.

From 1987 onward, one by one, the necessary components were implemented in GaAs as single-component functions. For each of these components, the problems were different:

LNAs. The trade-off between noise figure, gain, bandwidth and linearity was, and continues to be, a slowly-progressing struggle. As the required receiver array size can directly be related to the element noise figure (an increase in noise figure can at system level only be solved by a larger array), this aspect receives ample attention from the system engineers.

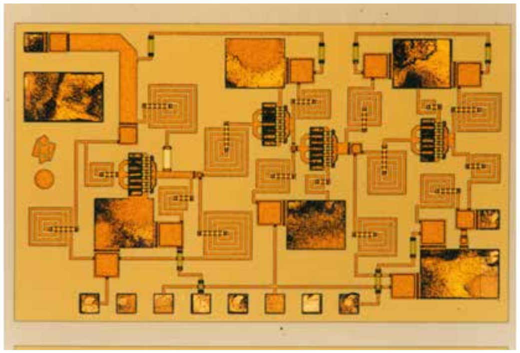


Figure 5: EXPAR LNA

Phase control. The accuracy of the phase control (over frequency, temperature, production etc.) is of direct consequence to the array's side-lobe level. When implemented with phase shifters, the input and output return loss must be good to avoid ripple over frequency. Insertion loss must be low, in order to avoid additional amplifiers, and variation over frequency and states must be low as well to avoid the control to become too complex. Cross-errors from phase control to amplitude variation and from amplitude control to phase variation had to be avoided for the same reasons. Binary and non-binary phase shifters as well as analogue vector modulators were investigated for their potential to solve this.

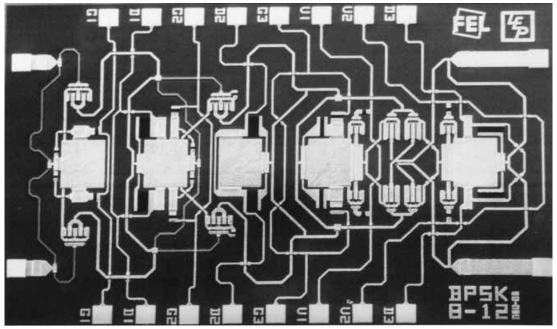


Figure 6 First BPSK phase shifter, the basis for the first vector modulator

Amplitude control. Amplitude control is needed to apply an amplitude taper to the array aperture and to correct for gain differences between Transmit-/Receive channels. One of the main problems is to maintain a high linearity also in the low-gain states. Similar problems arise as for phase control, including the accuracy that needs to be maintained over the full control range and the difficulty in avoiding phase-changes when changing the amplitude. Furthermore the required amplitude control range can be over 30 dB, maintaining the noise figure and phase invariance. In direct relation to the array performance, the control should be on a logarithmic or on a linear scale. A particularly intriguing implementation has been a variable gain amplifier, where the gain was realised through dual-gate FETs. The dual-gate FET was then implemented in a segmented way (with smaller and larger FETs being controlled individually), so that the transistors in the same amplifier stage could independently turned on or off.

The topology of phase and amplitude control MMICs has been the topic of much research. They have been implemented as vector modulators (which was actually the first MMIC developed at TNO) with analogue control, as separate phase shifters and variable gain amplifiers with analogue control. Later, when core chips became feasible, a solution with digitally controlled bits of phase shifters and attenuators and integrated LVCMOS control was favoured in terms of dissipation and microwave performance.

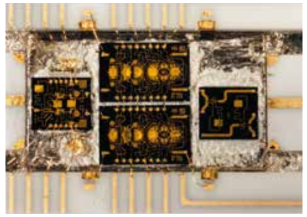


Figure 7 Hybrid vector modulator employing two BPSK phase shifters, an active 90 degrees splitter and a passive combiner

Power amplification. In contrast to passive phased arrays, the radiated microwave power is not generated through a central source like vacuum tubes, but each TR module generates its own RF power and hence needed a solid-state approach. In a sense, the MMIC high-power amplifier (HPA) was the most fundamental hurdle to overcome. Similar to the considerations for receiver noise figure, the power available per antenna element is a determining factor for the power aperture which the phased-array can produce. Initially, power levels of 2 Watt per HPA were pursued, values that today correspond to drive powers. The demonstration of 5 Watt on a single die, illustrated in a ceramic package on the photo below, revolutionary changed the necessary aperture. At a first look, the package seems large, but what we see is the enormous progress in the state-of-art, as TNO's 5 Watt HPA was much smaller than the previously envisaged parallel combination of two 2 Watt power amplifiers, and was a pivotal result in

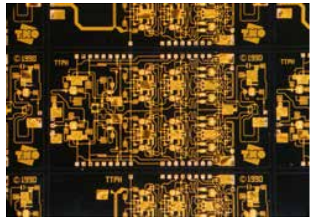


Figure 8 First MMIC vector modulator, based on the BPSK modulators

the development of the 10 Watt parts that would much later become the industry standard.

Isolation and protection. Around the core MMIC functions mentioned above, several other functions need to be properly addressed, including the duplexing of the transmit and receive function in case of co-located transmit- and receive-antennas (often implemented with circulators), the protection of the HPA (often implemented with a ferrite isolator), the routing of the transmit and receive path in case of the re-use of phase and amplitude control for transmit and receive (often implemented with PIN or similar diodes). Many efforts have been spent on protection of the sensitive front-end electronics. This can be addressed in the antenna elements themselves or at the input of the receiver, with dedicated, hybrid diode-based limiting structures. A solution that allows for integration and is less well-known is to integrate the limiter on GaAs with e.g. the LNA; an example is shown below.

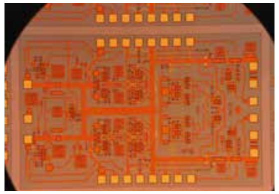


Figure 9 Differential Vector Modulatort

The importance of frequency selectivity becomes more-and-more a key requirement in modern active phased arrays, but appropriate solutions still do not exist and are already a hurdle for many years for designers of active phased arrays all over the world. Finally, and to conclude the components investigated for the built-up of Transmit-/Receive channels, integrated filters have been thoroughly investigated as our solution to implement frequency selectivity, including passive and active, distributed and concentrated, tuneable and fixed-frequency filters. The filter depicted below is an X-Band tuneable high-Q filter; for these types of filters the main concern was and is the attainable dynamic range.

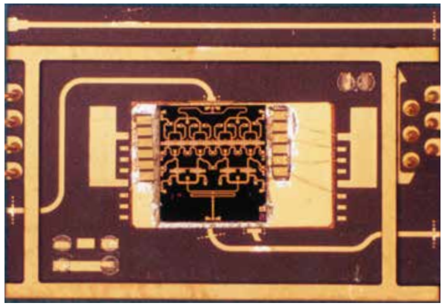


Figure 10 5 Watt GaAs HPA in ceramic package

Around the year 2000, high-speed optical systems started to become an alternative for the traditional wired RF cables. It became clear in an early stage that knowledge of the design of integrated microwave systems was needed and necessary to solve timing and EM problems in multiplexer and demultiplexer circuits for high speed systems. The knowledge gained in the high-frequency IC domain enabled TNO to position itself also in the area of high speed multiplexers, demultiplexers and trans-impedance amplifiers.

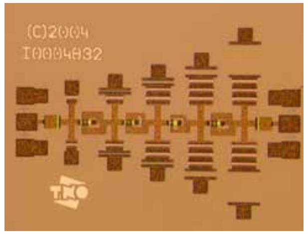


Figure 11 Limiter in PPH25X

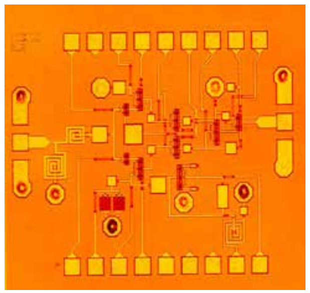


Figure 12 X-Band active tuneable filter

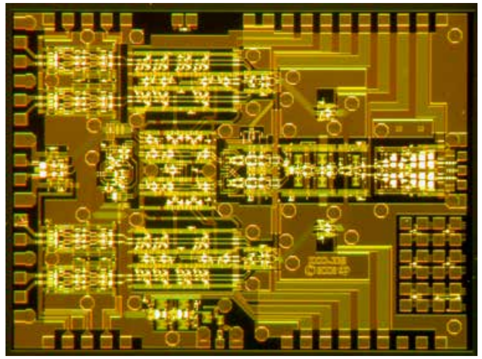


Figure 13 43 Gbps 41 MUX

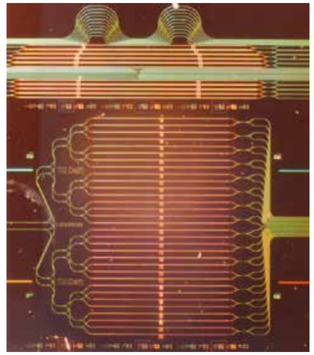


Figure 14 InP beamformer OEIC

In summary, the introduction of military active phased-arrays was characterised by strong technology demands that necessarily pushed the state-of-art. The main driver was to enable functionalities that could in no other way be achieved. It was the state-of-technology that allowed the system progress at just this point in time. The microwave components necessary were typically implemented dedicated to specific military programmes, as a result the realised systems were quite expensive.

Also in that period, roughly between 1997 and 2003, optical techniques for phased-array application have been thoroughly investigated. The research questions included the possibility for antenna remoting (over coherent or non-coherent links, an important problem that was solved was the near-carrier phase-noise issue), the possibility of optical true-time delay beamforming that had the promise of extremely wideband performance (resulting in silicon wafer-level integrated waveguiding structures of several meters) and opto-electronic RF generation, with the demonstration of an optical PLL as the research vehicle. Many intriguing concepts and technology demonstrators have been achieved, the 16-channel coherent optical, beamforming signal distribution OEIC realised at the TU Delft is a unique example.

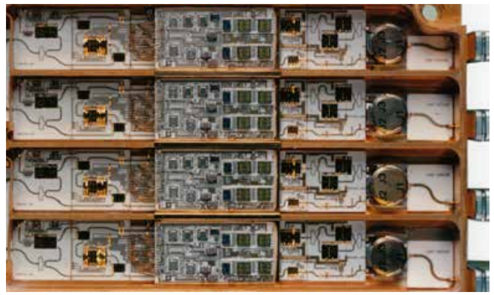


Figure 15 EXPAR quadpack

In summary, the introduction of military active phased-arrays was characterised by strong technology demands that necessarily pushed the state-of-art. The main driver was to enable functionalities that could in no other way be achieved. It was the state-of-technology that allowed the system progress at just this point in time. The microwave components necessary were typically implemented dedicated to specific military programmes, as a result the realised systems were quite expensive.

Typical systems that were based on these developments and TNO contributed to included PHARUS (PHased ARray Universal SAR, a dual-polarised C-Band synthetic aperture radar, a development of TNO, TU Delft and NLR) and APAR (Active Phased-Array Radar, a naval X-Band multi-function radar) by Thales Netherlands.

II-B: Optimizing microwave technologies. Around the year 2000, the feasibility of active electronically-scanned arrays was well established. Resulting from the NATO Anti-Air Warfare Study (NAAWS), which itself was based on a renewed threat identification by Project Group 33: anti-ship cruise missiles, the first anti-air warfare (AAW) suite based on a combined L- and X-Band sensor suite had become available to Germany and The Netherlands and relied on active phased array for the X-band sensor.

The technology baseline for the transmit-receive modules were GaAs integrated circuits that were either hermetically packaged, or mounted on ceramic substrates and then hermetically sealed on module level. GaAs pHEMT processes (0.7-0.15 µm) were the most popular processes for the MMICs. The complexity of the MMICs was still low, they were generally developed as a single-function-per-chip.

The cost level of these front-end solutions was a significant portion of these sensor systems, as there were many ICs per transmit-receive channel, and up to tens of thousands of channels per system, which was a strong incentive for cost-saving. This could be achieved by using mature microwave technologies that integrated as much functions as possible. The beamforming paradigm, (microwave beamforming) was not yet challenged.

As opposed to the individual MMIC functions that enabled the first active phased-array systems, more complex integrated microwave functions were now pursued, referred to in different communities as supercomponents or multifunction components. This integration encompassed phase-shifters and time-delays, amplitude control, digital control, power generation, low-noise amplification, switching and duplexing.

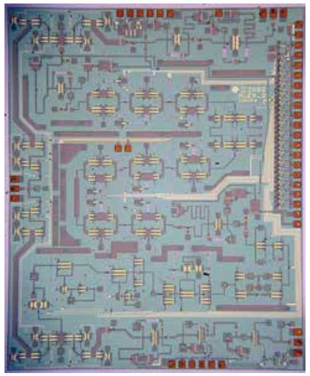


Figure 16 core chip

T/R modules: . The different characteristics for power technologies versus small-signal technologies (in terms of gain, power density, linearity, noise figure) effectively eliminated the possibility of a single-chip T/R module: A technology optimised for small-signal performance would not deliver sufficient power at a satisfactory efficiency. Furthermore, the physical size of both a multifunction component as well as a power amplifier became increasingly large. As a result, a two-chip solution is the lowest chip-count that you will find in practice.

When increasing the area of an MMIC, the yield slowly decreases. A lot can be said about the mechanisms behind this (defect densities, maximum gatewidth per MMIC, optical inspection and much more), but in the end a maximum chip area of 20-25 mm2 is often targeted for this reason. This puts additional pressure on integrating sufficient power as well as sufficient functions on a single die.

To cut a long story short: integrated power amplifiers and core chips form the heart of advanced AESAs, sometimes complemented with separate limiters and LNAs.

Core chips
Several different architectures for these multi-function components have been investigated over the years, strongly interacting with the front-end arrangement. For arrays with separate transmit and receive antenna's, an MMIC lign-up with a dedicated receive and a separate transmit small-signal MMIC, complemented with a power amplifier would make sense. For arrays with a single transmit and receive antenna, it would make sense to integrate the two small-signal MMICs, in order to reduce chip-count. This MMIC is called a core chip, as it forms the core of the transmit-receive function. If the phase and amplitude control is now shared between transmit and receive, this is referred to as a common-leg core chip: the phase- and amplitude-control are in a branch of the circuit common to the transmit and the receive path. This latter arrangement is economical in chip area, and lowers the calibration load for the array system.

Core chips: feasibility for radar. The possible importance of core chips was realised in the mid-nineties, and led to several military R&D programs to demonstrate its feasibility. They are known under cryptic programme names such as RTP 9.7 (with the first technology demonstration of a core chip), RTP 9.17 (demonstrating the possibility to coat these core chips with BCB) and Mimosa (under the WEAG Common European Priority Area Microelectronics (CEPA-2).

Based on several preceding efforts that demonstrated the feasibility, the first X-Band core chip with radar-grade specifications was presented in 2004 at the IEEE International Microwave Symposium in Fort Worth, TX. A room capable of holding several hundred people was fully filled, with people standing at the walls and the back of the room. These phased-array sessions were typically described as a sea full of sharks where lame results don't survive. Although many improvements have been made later, all the essential ingredients were already present: 6-bit digital amplitude and phase control, common-leg topology, integrated low-noise and driver amplifiers and large switch isolation.

Core chips: optimisation for manufacturability. Many complementary developments have taken place on core chips since their introduction. Level shifters were integrated to facilitate the control of all amplitude, phase and switch control bits. Pad positioning was optimised to facilitate packaging and minimize the problems arising from coupling outside the MMIC/package. Experiments were carried out with integrated serial-to-parallel converters in order to reduce the amount of I/O pins. At the time these converters were realised, they could not be made with sufficient yield yet, but ten years later the exact same design has found its way into a multitude of core chips.

A wideband approach was investigated to try to find a solution that fitted both wideband as well as multiple narrow-band systems. For the wideband requirements this worked out well, but the compromises, for example in the loss of the time-delay elements (which is significantly higher and more frequency-dependent than the loss of a phase shifter), made it less suitable for narrow-band systems. As a result, a family of core chips, covering L- to Ku-Band applications has arisen over the years.

In a further effort to reduce costs, integration of core-chips for multiple channels on a single die were investigated. In the early days of MMIC design, the integration of dual-channel receivers for precision-ESM (electronic support measures) was already demonstrated. On the basis of this, 4-, 8- and 16- element core chips were investigated, but turned out to be not feasible due to the I/O requirements and the required area. What did turn out to be feasible was the integration of multiple receive beamforming MMICs. This has resulted in two entirely different 8-channel Ku-Band receive MMICs.

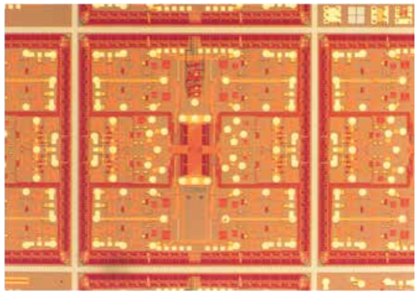


Figure 17 8-Channel Phase Control Device

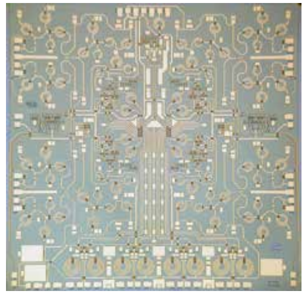
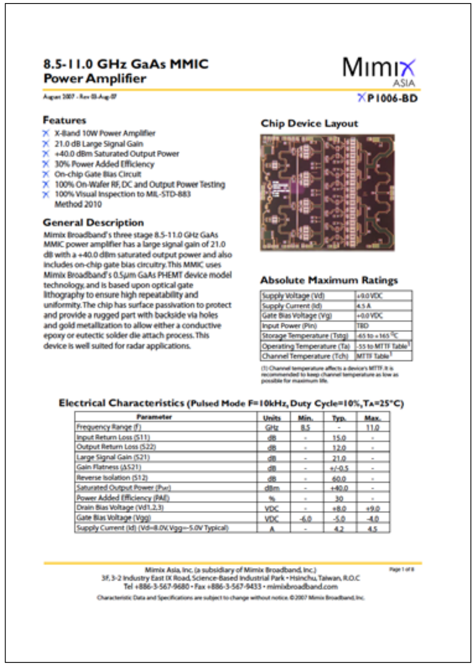


Figure 18 Ku-Band 8-channel downconverter

The first effort fully concentrated on the digital control integrated in excess of 2500 transistors on a single die. In microwave GaAs' terms, this was unprecedented. The request for such complex MMICs came initially from companies which were looking for other (high-volume) applications of phased-array antennas, for example to integrate a phased-array antenna in the roof of a car to enable satcom; military and space requirements came later. The required functionalities did not match with available MMICs and required new, different solutions. TNO contributed also to such systems through MMICs with unconventional functions and a very high level of different functions integrated on a single die. In the example in the figure, the digital circuitry is routed around the edge and facilitates a daisy-chain system configuration. Many chips could be connected in this daisy-chain digital architecture allowing for a control of all



8.5-11.0 GHz GaAs MMIC Power Amplifier

Mimix ASIA

August 2007 - Rev 08-Aug-07

XP1006-BD

Features

- X-Band 10W Power Amplifier
- 21.0 dB Large Signal Gain
- +40.0 dBm Saturated Output Power
- 30% Power Added Efficiency
- On-chip Gate Bias Circuit
- 100% On-Wafer RF, DC and Output Power Testing
- 100% Visual Inspection to MIL-STD-883 Method 2010

Chip Device Layout

General Description

Mimix Broadband's three stage 8.5-11.0 GHz GaAs MMIC power amplifier has a large signal gain of 21.0 dB with a +40.0 dBm saturated output power and also includes on-chip gate bias circuitry. This MMIC uses Mimix Broadband's 0.5μm GaAs PHEMT device model technology, and is based upon optical gate lithography to ensure high repeatability and uniformity. The chip has surface passivation to protect and provide a rugged part with backside via holes and gold metallization to allow either a conductive epoxy or eutectic solder die attach process. This device is well suited for radar applications.

Absolute Maximum Ratings

Supply Voltage (Vd)	+9.0 VDC
Supply Current (Id)	4.5 A
Gate Bias Voltage (Vg)	+0.0 VDC
Input Power (Pin)	TBD
Storage Temperature (Tstg)	-65 to +165 °C
Operating Temperature (Ta)	-55 to MTTF Table[1]
Channel Temperature (Tch)	MTTF Table[1]

(1) Channel temperature affects a device's MTTF. It is recommended to keep channel temperature as low as possible for maximum life.

Electrical Characteristics (Pulsed Mode F=10kHz, Duty Cycle=10%, T_A=25°C)

Parameter	Units	Min.	Typ.	Max.
Frequency Range (f)	GHz	8.5	-	11.0
Input Return Loss (S11)	dB	-	15.0	-
Output Return Loss (S22)	dB	-	12.0	-
Large Signal Gain (S21)	dB	-	21.0	-
Gain Flatness (ΔS21)	dB	-	+/-0.5	-
Reverse Isolation (S12)	dB	-	60.0	-
Saturated Output Power (Psat)	dBm	-	+40.0	-
Power Added Efficiency (PAE)	%	-	30	-
Drain Bias Voltage (Vd1,2,3)	VDC	-	+8.0	+9.0
Gate Bias Voltage (Vgg)	VDC	-6.0	-5.0	-4.0
Supply Current (Id) (Vd=8.0V, Vgg=-5.0V Typical)	A	-	4.2	4.5

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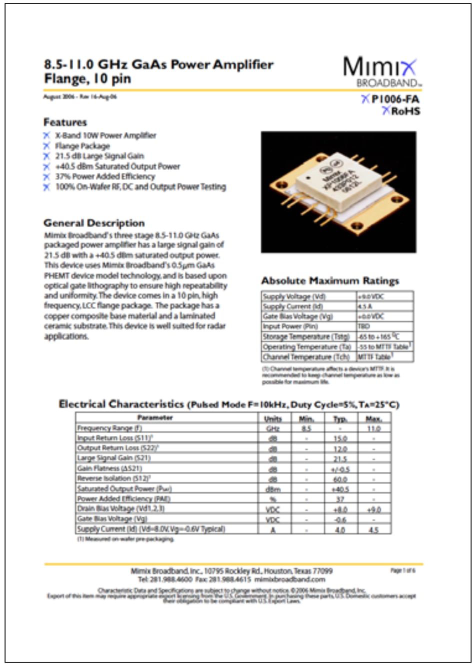

8.5-11.0 GHz GaAs Power Amplifier Flange, 10 pin

Mimix BROADBAND

August 2006 - Rev 16-Aug-06

XP1006-FA
RoHS

Features

- X-Band 10W Power Amplifier
- Flange Package
- 21.5 dB Large Signal Gain
- +40.5 dBm Saturated Output Power
- 37% Power Added Efficiency
- 100% On-Wafer RF, DC and Output Power Testing

General Description

Mimix Broadband's three stage 8.5-11.0 GHz GaAs packaged power amplifier has a large signal gain of 21.5 dB with a +40.5 dBm saturated output power. This device uses Mimix Broadband's 0.5μm GaAs PHEMT device model technology, and is based upon optical gate lithography to ensure high repeatability and uniformity. The device comes in a 10 pin, high frequency, LCC flange package. The package has a copper composite base material and a laminated ceramic substrate. This device is well suited for radar applications.

Absolute Maximum Ratings

Supply Voltage (Vd)	+9.0 VDC
Supply Current (Id)	4.5 A
Gate Bias Voltage (Vg)	+0.0 VDC
Input Power (Pin)	TBD
Storage Temperature (Tstg)	-65 to +165 °C
Operating Temperature (Ta)	-55 to MTTF Table[1]
Channel Temperature (Tch)	MTTF Table[1]

(1) Channel temperature affects a device's MTTF. It is recommended to keep channel temperature as low as possible for maximum life.

Electrical Characteristics (Pulsed Mode F=10kHz, Duty Cycle=5%, T_A=25°C)

Parameter	Units	Min.	Typ.	Max.
Frequency Range (f)	GHz	8.5	-	11.0
Input Return Loss (S11)[1]	dB	-	15.0	-
Output Return Loss (S22)[1]	dB	-	12.0	-
Large Signal Gain (S21)	dB	-	21.5	-
Gain Flatness (ΔS21)	dB	-	+/-0.5	-
Reverse Isolation (S12)[1]	dB	-	60.0	-
Saturated Output Power (Psat)	dBm	-	+40.5	-
Power Added Efficiency (PAE)	%	-	37	-
Drain Bias Voltage (Vd1,2,3)	VDC	-	+8.0	+9.0
Gate Bias Voltage (Vg)	VDC	-	-0.6	-
Supply Current (Id) (Vd=8.0V, Vg=-0.6V Typical)	A	-	4.0	4.5

(1) Measured on-wafer pre-packaging.

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Figure 19 Mimix datasheets of the (packaged) XP1006

receiver MMICs over a single digital interface. The amount of transistors integrated is believed to be a record at that moment, and may still be. An 8 times 4 combination manifold, seen in the centre of the MMIC, is also a unique structure that stretched the electromagnetic simulators to the edge. The digital circuits were characterised by transistors with very small gatewidth dimensions (typically an order of magnitude smaller than the smallest transistor in a microwave circuit), which forced another design and modelling approach.

The second effort is a more conventional 8-channel receive-only MMIC with amplitude and phase control and downconversion.

Power amplifiers

The other crucial component in T/R modules that remained was the power amplifier. Together with the core-chip of choice, this power amplifier needed to form a matched chip-set, which could preferably be obtained from two independent sources. European GaAs technologies reached a mature level and were particularly fine in terms of efficiency and robustness to compression.

Increase in efficiency has been a leitmotiv in this era. Newer technologies offering higher gains per stage and higher Mean-Time-To-Failure (MTTF) became available. Combined with a maturing design philosophy and the introduction of more advanced amplifier classes (class E, class F, class inverse-F), this has resulted in a class of amplifiers with power added efficiencies in the 30-50% range. They were realised almost exclusively in pHEMT technologies, with 0.5 or 0.25 μm gatelength, depending on the frequency of operation.

A particular problem that came back several times was the gain of the amplifier. When the output power increased, something it contin-

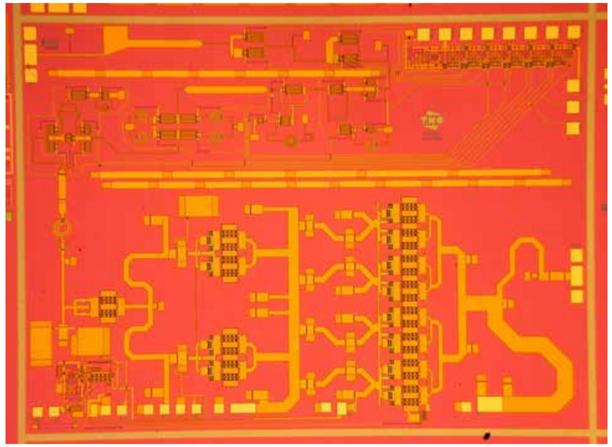

Figure 20 X-Band 5 Watt phase-shifting power amplifier

ued to do over time to support system needs, the gain would normally slightly decrease or remain constant at best. Hence, the newly required input power would increase with the same amount, and an update on the core chip output power would be required. The same would even more be true when two parallel HPAs were employed.

Supporting global customers with a sales channel, with support engineers, with a helpdesk and a sales office is not something that is natural to an R&D organisation like TNO. The availability of these components for the development and manufacture of end products became however more and more important. The access of system houses to our MMICs has been tackled through licensing the designs to commercial parties that sell and service the designs. An impressive portfolio has been developed over the years that supports our customer base in their supply management. Part of these designs are in the open domain, available to anyone who comes along; many other designs have been licensed for specific customers only.

Conclusion

Microwave technologies were optimised for manufacturing, more than for feasibility demonstration. Cost of manufacturing was a major driving factor ('the three most important drivers: cost, cost and cost', quote from the TNO strategy in 2004). Integration and packaging played an increasing role, reducing the complexity and cost of the modules as a

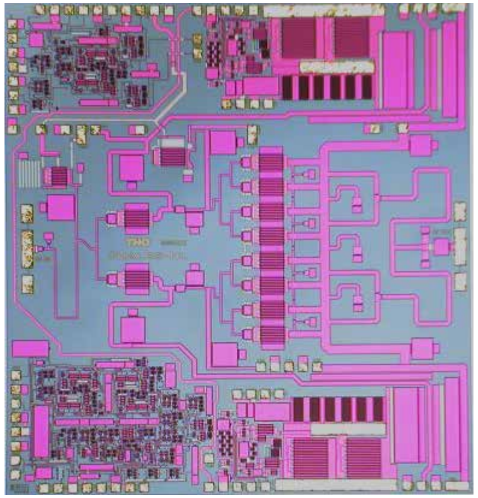

Figure 21 integrated power amplifier and power supply

whole. Many of the described developments have led to industry standard components, some of which are commercially available up to today.

In summary, integrated power amplifiers and core chips form the heart of advanced AESAs, sometimes complemented with separate limiters and LNAs. The efforts at TNO have led to technology that today forms the basis for a multitude of phased-array systems.

II-C: Enabling multi-beam systems
In parallel to the core chip developments in GaAs described in the previous section, the importance of silicon for applications in the microwave domain became evident in the early 2000's.

As silicon implementations had the promise of offering cheap solutions, efforts have started, initially particularly for the Dutch MoD, to investigate feasibility. With first vector modulators resulting from a programme called STAR at S- and C-Band, it turned out that it would be tough to beat GaAs in terms of price, but that it did offer a unique advantage in terms of integration level. In other words, if you try to replace GaAs with Silicon, you will miss the real advantage of offering higher integration levels and integrating different kinds of functionality.

In terms of dynamic range, Silicon Germanium (SiGe) is preferred over Silicon CMOS. For the same fT, CMOS needs a smaller feature size than SiGe, leading in general to lower supply voltages and higher noise levels. Dynamic range is of ultimate importance for phased-array radar resulting in a natural preference for SiGe over CMOS.

From this moment on, the Silicon efforts have focussed on SiGe implementations, trying to exploit the advantages in integration level. On the system side, increased flexibility was one of the major drivers. If a phased-array with microwave beamforming needed an additional antenna beam, the whole active antenna array would need a re-design. The promise of hybrid beamforming (digital beamforming on receive, analogue beamforming on transmit) was that only the processing hard- and software would need to be updated.

As a consequence, the front-end technology needed a major re-partitioning. For the transmit chain, GaN was emerging rapidly, offering the perspective of higher power levels and power density levels. The common-leg architecture, that had been so successful in a generation of systems, was however no longer an obvious choice, as the receive chain did not need the III-V analogue beamforming functionality in case of digital beamforming on receive. As hybrid beamforming was introduced, also the technology basis would become a hybrid mix of III/V (GaAs or GaN) and IV/IV (SiGe) technologies.

GaAs transmit chains
Never throw away your old shoes before you have new ones. Based on the GaAs power amplifiers that complemented core chips as discussed in the previous section, the transmit path of phased-array systems with hybrid beamforming could be realised in GaAs as well. The necessity for and specifications of the amplitude control in the transmit path are however much less stringent than in the receive path. As a consequence, the beamforming functions in the transmit path can be integrated in the driver or power amplifier, leading to integrated phase--shifting power amplifiers.

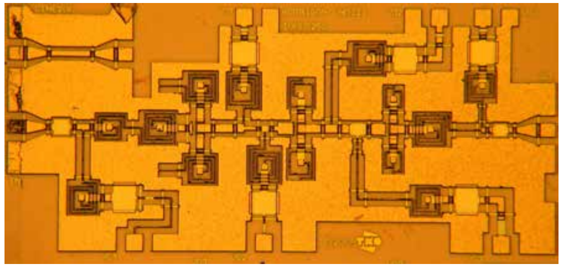

Figure 22 Robust LNA MMIC from the KorriGaN programme

Promising is further the integration of the power supply with the power amplifier. With proper dimensioning, the resulting PA can be used to modulate the pulse. In a program named SWAP, TNO and Thales Nederland together developed an X-Band integrated power supply and amplifier under an contract of the European Defence Agency (EDA). To date, this effort is the state-of-art, and offers a unique advantage of pulse control. The MMIC has not found its way into products yet.

GaN: robust receivers and power amplifiers
As early as 1998, a large Dutch-Swedish MoD programme started to work on GaN and SiC. Originally, the SiC work was located in Sweden, with the GaN work being located in The Netherlands, but gradually the GaN work became the most important topic for both countries. The initial work contained a lot of material research, but already produced GaN power amplifiers. It was on a landmark workshop prepared at Charles de Gaulle airport in Paris and held in Gothenburg, Sweden, in 2002 that the European GaN scene really took shape. There, the basis was laid for the KorriGaN programme, a 40 MEuro programme incorporating all the major phased-array (technology) players of Europe. The programme successfully aimed at installing a European GaN supply chain. It started in December 2004 and ended in 2009,

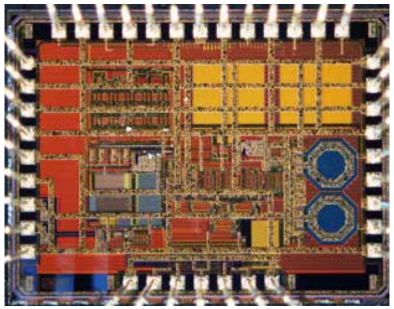

Figure 23 SiGe type-III PLL for integrated radar chirp generation

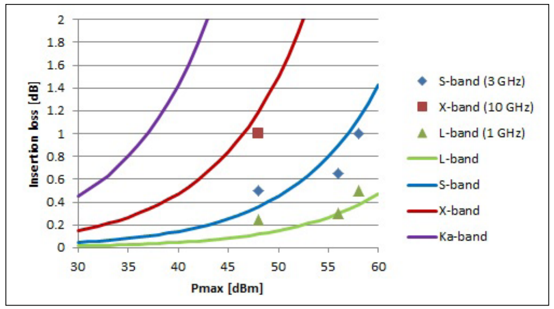

Figure 24 Design chart for the trade-off between limiter frequency, power and insertion loss

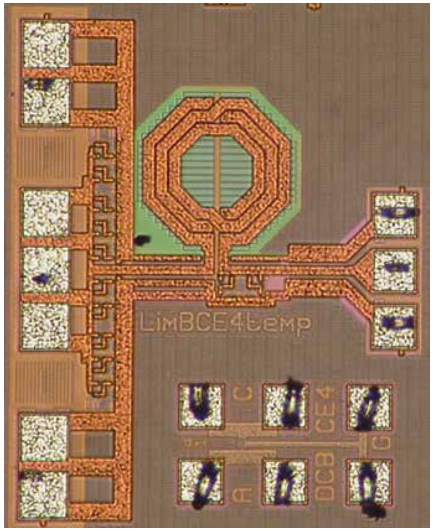

Figure 25 First integrated SiGe limiter in 0.25 μm BiCMOS

and was the biggest programme the European Defence Agency had contracted, counting in total 27 partners. Successors to KorriGaN (Manga and Magnus) are still ongoing. TNO activities incorporated the work on robust low-noise amplifiers (with TNO being responsible for all the robust LNA work in KorriGaN and in a large ESA-funded programme), switches (to allow future circulator-free transmitters) and high-efficiency high power amplifiers.

SiGe Integrated receivers
SiGe can play a big part in the receive path. If a full receiver (including filtering, downconversion and analogue-to-digital conversion can be integrated in a T/R module, the remaining part of the digital beamforming can be addressed in a central computing unit. After the first silicon vector modulator efforts, this integrated receiver was targeted by TNO in the Dutch MoD programme MISTRAL, a contract that was performed together with Thales Nederland. Originally, this programme was envisioned under an EDA contract, but the other country could not get funded in time.

The largest challenges in the receiver are the dynamic range and selectivity requirements. Contrary to many commercial integrated receivers, the MISTRAL efforts focussed on a super-heterodyne architecture. With pride, we report that this receiver is probably the first that meets real phased-array specifications. Also issues such as spurious local-oscillator radiation are properly addressed.

More recently a Type-III phase-locked loop was developed with the University of Twente, targeting low-noise chirp generation at microwave frequencies. The type-III character ensures that a zero static-error may be achieved for a linear chirp signal, as opposed to a conventional, type-II, PLL which can ensure a zero static-error for a constant-frequency signal. This component can be of crucial importance when, in future times, also the signal generation would no longer be realised centrally.

SiGe Protection
In terms of protection against hostile electromagnetic signals, such as jammers and other transmitters, phased-arrays require a very different strategy than rotating systems. In case of rotating systems, only one or a few receivers need to be protected against enormous power levels (as the signal combination has already taken place in free space). This can typically be addressed by bulky high-power limiters realised in e.g. waveguide technologies. For a phased-array, there are many elements that need to be protected against power levels that are challenging, but generally lower than for conventional rotators, as the protection takes place before the signal combination.

One approach is to integrate LNAs in GaN, as this material is inherently capable of handling higher power levels due to its wide bandgap. A disadvantage, however, is that the DC power requirements of these LNAs is significant and that the problem may remain for the stages after the GaN front-end. If this LNA is for example followed by a SiGe down-converter, the risk exists that the GaN LNA survives an incident pulse, but the downconverter does not.

A recent breakthrough is the integration of really high-power limiters in SiGe. Initial efforts around 2008 suggested that the technology parameter that matters is I2max/Cin. Upon analysing this parameter over different technologies, it turned out that small-signal SiGe is the best material of choice. Furthermore, this material is suitable for integration with the remainder of the receive chain!

After many experiments, optimising the physical diode structure and its layout, and taking proper care of input dimensioning, we have proven that limiters up to the kilo-Watt level can be realised, in any standard SiGe process in a trade-off with frequency of operation and insertion loss, see the graph below. The measurement set-up to test these diodes required excessive input power, searching for the right sources was part of the challenge.

Conclusion
In summary, changing demands from the now mainstream phased-array systems were matched in time with technology developments in GaAs, GaN and SiGe. As a result, more flexible multi-beam systems could be realized that could not exist without these front-end developments. The level of integration was continuously increasing and a technology repartitioning was inevitable. The technology forms the basis for a suite of systems based on hybrid beamforming.

III ABOUT THIS BOOK

About part one. In the first part of this book, the national perspective of the MMIC work described before is sketched. This perspective is a perspective of the military demand for more versatile sensors, and is meant to provide the context for the second part of the book, in which the impact of MMIC technology as such is described.

The national context and national driving factors are described by two key players. The first contribution is by the Royal Netherlands Navy, a navy proud of its long tradition. A navy which has demonstrated time and time again to be able to cope with change in the military domain in a visionary way. The second contribution is by the Dutch radar industry, reporting over a period in which its name has changed from Hollandse Signaalapparaten via Thomson into Thales Nederland. The main highlight which will be addressed by these contributions is the APAR system, currently installed on the Dutch Air Defence and Command Frigate, and in use by a number of NATO countries. The foundations for the technology needed, its conception and development as well as its employment can be found here.

The APAR system is a landmark in radar development, and would be impossible without MMIC technology. It took an extraordinary effort leading to unprecedented results. Many factors have contributed, such as the state-of-technology, the state-of-affairs, national conditions and an attitude to make the impossible possible. The research on and development of MMICs plays a pivotal role in this.

About part two. In the second part of this book, the current impact of MMIC activities is illustrated by seven well-chosen topics. Per topic, a note on the early history is combined with the impact as perceived by our partners and complemented by one or more short TNO examples. Together, this gives a flavour to the importance and impact of MMICs.
The topics are chosen either on a technology level, or on the application that they influence. Technology-wise, small-signal MMICs (such as LNAs, phase shifters and core chips), GaAs high-power amplifiers, GaN high-power amplifiers and SiGe receivers are subsequently addressed. Application-wise, military systems, space-born systems and commercial manufacturing are addressed. All of these topics have an introduction, a main story-line and some examples that come directly out of the TNO kitchen.

The contributions start with an overview from one of the largest military industries in the world, Airbus Defence and Space. Do not forget to check on the impact which the integration of separate functions in a single core-chip has had on module yield as described by Sanmina Corporation, this is one of the key factors in active array acceptance. Check out the contributions on power amplifiers, which address the early days of GaAs, but also the advent of GaN and some state-of-art HPAs that have influenced virtually all existing non-US active arrays. Virtually all core-chips and a large share of the MMIC HPAs that are around can be traced back to TNO research activities.

Read about the Dutch pride in SiGe technology. Started as an activity of Royal Philips, the company now known as NXP Semiconductors has grown into a truly global player. Have a look on the history of MMICs for spaceborne systems. The European Space Agency has been very early in starting the MMIC research, but the adoption in sensor arrays takes a long time. And check out the commercialization aspects, which have contributed largely to the impact of the designs on actual systems. Part two ends, how else, with market perspective, telling the story of getting out of the research phase into volume production.

All in all, MMICs have a system footprint that largely exceeds their tiny size!

About part three. In the third part of this book, we have asked leading experts from around the globe to share their insight in the trends for MMICs. Every contribution illuminates a different aspect of MMICs, and the total is believed to bring a unique outlook to where the field is going.

The topics covered in part three range broadly: from III-V semiconductor material technology, via the possibilities and limitations of digital design to bio-inspired processing.

In the III-V domain, please read on the limitations to DARPA's heterogeneous integration approach in the story from Marc Rocchi. Learn from Mark Rodwell on the strategy for coping with excessive current densities through the use of refractory metals for (sub-)mm-wave power amplifiers. Extrapolate the current design techniques into the high mm-wave bands together with Herbert Zirath and value the GaN strengths together with Rik Jos.

In the IV-IV domain, Domine Leenaerts and Peter Magnée indicate the future of Si BiCMOS, extrapolating past trends in an intelligent future outlook. The famed mixed-signal design techniques are explained, with a keen eye on its limitations by Ed van Tuijl, who has been around from the moment that they emerged. Bogdan Staszewski opens a window on digital-RF, a whole new way of integrating RF subsystems that might affect every RF system. The final contribution in these silicon contributions is from Peter Baltus c.s. on wireless power and information transfer. They present a view on the low-cost and zero-power approach needed for the Internet of Things.

The really far-out view is put forward by Alain Cappy, sketching a picture of all the branches of science that we need to overcome the limitations of current information processing systems.

About part four. "The farther backward you can look, the farther forward you are likely to see", according to Sir Winston Churchill. With this in mind, we are fortunate to end the book with a contribution by the Museum Waalsdorp, located at the same facilities where also the MMIC group has worked over these 25 years. It is a privilege to have this museum so close-by.

Publications form only the top-of-the-iceberg in the knowledge gained. We tried hard, however, to provide an extensive list of publications covering 1989-2014. They indicate what we have contributed to the scientific community, how we share the built-up in knowledge, but also how this knowledge is used. Remark the large number of partners as (co-)authors.

We hope you will enjoy the enormous amount of examples, applications and background information, and much more!

ABOUT THE AUTHOR

Frank van Vliet was born in Dubbeldam, The Netherlands, in 1969. He received the M.Sc. degree, with honours, in Electrical Engineering in 1992 from Delft University of Technology, The Netherlands. Subsequently, he received his Ph.D. from the same university on MMIC filters; during this time he was affiliated to the MMIC design group at TNO. He has continued to work there ever since and was seconded to LEP (Paris, France) and FhG-IAF (Freiburg, Germany), both twice. He has fulfilled many roles, always in connection to MMIC design and characterisation, and is currently principal scientist. In 2007, he was additionally appointed full professor in Microwave Integration (part-time) in the Integrated Circuit Design (ICD) group of the University of Twente, where he founded the Centre for Array Technology (CAT). He has participated in thirty Ph.D. evaluation committees, and currently supervises eight Ph.D. students. He takes pride in bringing microwave research from its earliest stages all the way up to the level where it impacts manufactured state-of-the-art systems.

His research interests include MMICs in all their aspects, advanced measurement techniques and phased-array technology. He (co-)authored approximately 150 peer-reviewed publications. He is a member of the European Space Agencies (ESA) Component Technology Board (CTB) for microwave components, a member of the European Defence Agencies (EDA) CapTech IAP-01, chair of the 2012 European Microwave Integrated Circuit conference (EuMIC 2012), founded the Doctoral School of Microwaves, and serves on the TPC of EuMIC, the IEEE International Symposium on Phased Array Systems and Technology, the IEEE Compound Semiconductor IC Symposium (IEEE CSICS) and the IEEE Conference on Microwaves, Communications, Antennas and Electronic Systems (IEEE COMCAS). He was guest editor of the IEEE Microwave Theory and Techniques (MTT) 2013 Special issue on Phased-Array Technology.

ABOUT THE AUTHOR

Frank van den Bogaart was born in Helmond, The Netherlands, in 1956. He received his M.Sc. degree in Electrical Engineering from Eindhoven University of Technology, The Netherlands. He started his career in 1982 at the Physics Labortaory of TNO in The Hague in the field of passive and active phased-array antennas. From 1987 to 1989 he was with the PHILIPS research labs Laboratoires d'Électronique et de Physique appliquées in Limeil Brévannes near Paris in France were he started to develop and design MMICs for X-band phased-array radars. On his return to The Netherlands he created the fabless MMIC Design Centre at TNO which focussed on microwave and millimetre-wave MMICs for military, space and communication applications. He co-initiated WEAG TA1 on high-power high-efficiency MMIC amplifiers that founded the basis that still sets the deign trends for such pHEMT HPA's. From 1997 to 2005 he was the department head at TNO of a group fully dedicated to MMIC design. Since then he had several managerial functions within TNO, but MMICs and phased arrays always continued to be in the core of his activities.

He serves on the TPC of the EuMIC, the EuMC, IEEE COMCAS and on the 2014 IEEE Radar Conference. He chaired the Gallium Arsenide and other Compound Semiconductors Symposium (GAAS) in 2004 in Amsterdam, The Netherlands. He was the general chair of the European Microwave Week (EuMW) in 2008 in Amsterdam. He founded in 2010 the annual Defence and Security Forum within the EuMW. He is the member of the board of the European Microwave Association and serves in many other advisory boards. In 2011 he co-founded D-RACE, the Dutch Radar Centre of Expertise which is a strategic alliance between Thales Netherlands and TNO. He was knighted in the Order of Oranje-Nassau by his Majesty King Willem-Alexander on 25 September 2014. He received this royal honour for his work on radar technology, within and outside TNO, and for his services to the Ministry of Defence.