Ten years of research and innovation in microwave engineering between Chalmers and industry
It takes a long time to bring fundamental research findings from the university lab to a full-fledged product ready for the global market. This report of GHz Centre 2007–2016 will tell you some of the ingredients how to make this happen, all carried forward by microwaves, be it for wireless communication or in sensor systems.

During one decade, Chalmers has in GHz Centre collaborated with seventeen companies vastly differing in size, business and location. Using our partnership in GHz Centre, we have learned how to combine academic curiosity with the entrepreneurial mind-set in industry. As a result, we advance education, new knowledge and innovation in microwave technology for both university and multiple industries ranging from spin-off companies to large system houses.

GHz Centre has now been launched for another five-year term 2017–2021. By launching a joint consortium with the antenna system centre ChaseOn at Chalmers, we form the largest microwave-antenna effort between a single university and industry so far. We anticipate large progress in research and innovation during these five years.

We are grateful to Sweden’s innovation agency VINNOVA to have given us the opportunity to participate in and contribute to the Swedish Competence Centre programme during all these years.

Jan Grahn
Director of GigaHertz Centre
Omnisys Instruments, Low Noise Factory and Wasa Millimeter Wave are three Chalmers’ spin-off companies active in the terahertz (THz) and low noise amplifier business which all have grown during their collaboration in the GHz Centre. Omnisys are making highly specialised THz electronics for advanced instrumentation used for applications on earth and in space.

Low Noise Factory uses Chalmers’ nanofabrication laboratory for its semiconductor production of world-lowest noise amplifiers on the market.

Chalmers and RISE have helped the industry in GHz Centre to advance measurements for frequencies up to and beyond 1 THz.

Transmitters for telecom. A 3.5 GHz Doherty power amplifier for transmitters marks a world record in the GHz Centre. The Chalmers researchers, in collaboration with Ericsson and others, have also got further than anyone else in the world with load-modulated power amplifiers. Massive MIMO is a future growth area where work in the GHz Centre has had an impact on standardisation work in 3GPP.

Microwave radio oscillators. Another successful area in the GHz Centre is phase noise in oscillators, where Ericsson is one of the partner companies. The research has resulted in a world record in low phase noise at 10 GHz. By switching semiconductor technology from InP HBT to GaN HEMT, the research findings could be transferred to an industrially feasible solution which is suitable for microwave radio communication with high bandwidth and complex modulation at higher frequency bands.

Gallium nitride technology for radar sensors. It is rare for a new semiconductor material to go into commercial use in full systems so rapidly. In 2014, Saab showcased a radar system based on gallium nitride (GaN) HEMT circuits, astonishing the entire world of a new generation of active electronically scanned array.

THz electronics. Omnisys Instruments, Low Noise Factory and Wasa Millimeter Wave are three Chalmers’ spin-off companies active in the terahertz (THz) and low noise amplifier business which all have grown during their collaboration in the GHz Centre.
Foreign semiconductor suppliers such as NXP, Infineon Technologies, Mitsubishi Electric and UMS have assisted in the development of the necessary semiconductor components by picking up on early system requirements from companies in telecommunication, space and defence.

"Everyone involved brings different competence to the mix," Andersson says.

Grahn summarises:

"All the partners in the GHz Centre together make up a dream team in RF/microwave, from component to system level, in a variety of industries that are all important to Sweden's competitive edge. It's been a joy to see the high degree of involvement our centre has generated in many companies."

The project has also given doctoral students access to networks in industry; the research projects have produced publishable results in high-quality scientific journals and the companies have pointed out relevant research fields.

The long-term goals are to create products and systems that generate jobs through growth in fields such as 5G mobile telephony, radio links, satellite equipment, radar sensors and advanced high-frequency instrumentation.

The results are disseminated to all parties.

"The GHz Centre serves as a joint venture where everyone provides their expertise and resources and then benefits from everyone's results. Participants in a competence centre define relevant fields, but they have to be prepared to be involved on long term. Industry provides guidance, but does not dictate what the academia should do.

"Involvement in the centre also involves a certain amount of risk: participating companies don't know if their efforts will lead to commercial gains, even in the long run. Some projects eventually hit a dead end – but even this can be viewed as important: the companies will know not to invest in something that has no or limited potential for success."

---

**Bringing results from academy to industry**

Centre Director Jan Grahn, Professor in Microwave Devices, and Centre Coordinator Cristina Andersson, Industrial Relations Officer at the Department of Microtechnology and Nanoscience, Chalmers.

---

**The GHz Centre from the Director’s perspective:**

On transferring research results faster to industry

The long-term goal of the GigaHertz Centre (GHz Centre) has been to develop knowledge and technology that will result in new wireless products and systems that generate jobs and attract students. At the same time, the centre needs to meet the university's requirements for publication and education.

"At the end of the day, it's about transferring research results in microwave technology to industry faster," says the GHz Centre’s Director and head of its operations at Chalmers University of Technology, Professor Jan Grahn.

In this interview, he and the centre’s Coordinator Dr Cristina Andersson summarise an array of successful transfers from research to industry.

A dream team in RF/microwave

Having a university lead and shoulder the responsibility for a competence centre is a strength. The GHz Centre is proof of this. Compared with earlier programmes in the 1990s, when large companies like Ericsson and Saab dominated the participation, the GHz Centre now also included many smaller, highly specialised spin-off companies like Omnisys Instruments, Low Noise Factory, Wasa Millimeter Wave, Gotmic, Swegan and Comheat Microwave. RISE (previously SP Technical Research Institute of Sweden) and National Instruments have contributed to several projects with valuable measurement technology and techniques.

Foreign semiconductor suppliers such as NXP, Infineon Technologies, Mitsubishi Electric and UMS have assisted in the development of the necessary semiconductor components by picking up on early system requirements from companies in telecommunication, space and defence.

"Everyone involved brings different competence to the mix," Andersson says.

Grahn summarises:

"All the partners in the GHz Centre together make up a dream team in RF/microwave, from component to system level, in a variety of industries that are all important to Sweden's competitive edge. It's been a joy to see the high degree of involvement our centre has generated in many companies."

The project has also given doctoral students access to networks in industry; the research projects have produced publishable results in high-quality scientific journals and the companies have pointed out relevant research fields.

The long-term goals are to create products and systems that generate jobs through growth in fields such as 5G mobile telephony, radio links, satellite equipment, radar sensors and advanced high-frequency instrumentation.

The results are disseminated to all parties.

"The GHz Centre serves as a joint venture where everyone provides their expertise and resources and then benefits from everyone's results. Participants in a competence centre define relevant fields, but they have to be prepared to be involved on long term. Industry provides guidance, but does not dictate what the academia should do.

"Involvement in the centre also involves a certain amount of risk: participating companies don't know if their efforts will lead to commercial gains, even in the long run. Some projects eventually hit a dead end – but even this can be viewed as important: the companies will know not to invest in something that has no or limited potential for success."
Cristina Andersson and Jan Grahn emphasise the importance of cultivating a research culture of collaboration and trust between academia and the business community in a changing wireless world. With this form of collaboration, participating industries can learn of research results long before they are published. Yet the involvement of many participants in a competence centre and sharing the results does not prevent companies from protecting parts of their results with patents.

The next five years
The challenges of the next five years at the GHz Centre include integrating CMOS into 5G transmitters which can handle signal processing with respect to antenna functions in millimetre-wave antenna arrays. There are also thermal issues for gallium nitride transistor circuit technology to resolve, as well as its integration challenge for the millimetre-wave spectrum. The trend towards ever-higher frequencies creates a need to develop cryogenic amplifiers for the 100–200 GHz range. One spectacular application for cryogenic amplifiers in the microwave field is direct reading of qubits from a quantum computer.

“In this multi-faceted environment for wireless hardware, I look forward to incredible opportunities for synergy effects in the coming five years,” Grahn summarises.

Yet the involvement of many participants in a competence centre and sharing the results does not prevent companies from protecting parts of their results with patents.

The first-generation competence centre in microwave technology, the Chalmers Centre for High-Speed Technology (CHACH), wound down its activities in 2005. This was a few years after Professor Jan Grahn came in and whipped the organisation into shape.

“It wasn’t until 2007 that Vinnova granted new funding to the competence centre,” Olanders says. “We decided to continue operations for a transition period without government funding, and we had four or five companies with us. It worked pretty well.

“Jan Grahn initiated discussions in 2005 to create a centre for microwave, millimetre-wave and terahertz technology. This led to the start of the GHz Centre in 2007 with four main projects: broadband transceivers, switched RF power amplifiers, frequency generation and terahertz components.”

Peter Olanders, Chair of the board at the GHz Centre, describes the outstanding advantages of working together in a precompetitive environment. And how participation in the GHz Centre gives the companies and Chalmers a competitive advantage.

After ten years as one of Vinnova’s competence centres in information and communication technology, the GHz Centre was approved for another five years.

“We see this as a confirmation from Vinnova that this was a successful initiative,” says Dr Peter Olanders, Chair of the board at the GHz Centre in 2007–2016. He is also research leader at Ericsson. In this interview, he gives his view of the GHz Centre’s secrets to success and argues why it is important for industry, especially Ericsson, to participate in the collaboration.

The Chair’s perspective: Researchers and leading-edge companies in an unbeatable team

“The great advantage of the GHz Centre is the ability to work together and achieve great results in such a fantastic culture. Everyone gets something out of this.”

Peter Olanders
Chair of the board at the GHz Centre
Knowledge transfer
Our researchers are also teaching at Chalmers, which means that students get an updated view of the industrial views and needs in wireless. Here, Sebastian Gustafsson (centre of picture) supervises Master’s students in a multi-antenna measurement lab.

In addition to technological results, the GHz Centre has also generated a number of significant skilled researchers.

“Ericsson and other companies have been able to recruit many people from the GHz Centre and boost their staff’s skills, e.g. with industrial doctoral students and adjunct Professors. Industry has also provided project managers in GHz Centre.

“What we appreciate in particular is that Chalmers also demands strong involvement from the company partners. Chalmers’ environment is scientifically, technologically and collaboratively superior. Earning your PhD at the GHz Centre is unique as regards actions, quality, mind-set and way of working.”

HENRIK SANDSJÖ

The next five years
“In 2015–2016, the GHz Centre had a joint project with the Chase antenna system centre at Chalmers to jointly build up a very interesting testbed for massive multiple input and multiple output (MIMO). We have all realised that it will require tight collaboration to integrate RF circuits and antennas. Therefore, the parties in the GHz Centre and ChaseOn at Chalmers decided to implement a common consortium and board for the years 2017–2021. GHz Centre and ChaseOn still remain as two separate competence centres, but under a joint consortium contract.

“The objectives of these centres differed during the application phase, in part because they belong to different disciplines in the wireless field, but also because they represent two different academic cultures. Thus, it is very encouraging that these centres have been able to collaborate so well together.”

Shared environment pays off
“The great advantage of the GHz Centre is the ability to work together and achieve great results in such a fantastic culture. Everyone gets something out of this. Naturally, sharing results can also lead to risks, especially for smaller companies, but the benefits outweigh this disadvantage.”

All participants work in a precompetitive environment. How open can they be, considering competition aspects?

“Relatively open. But soft knowledge is valuable and can only be developed by working together. Universities are meant to be open. In the long term, this is the only way universities can survive. Researchers must be allowed to think outside the box and to create new solutions we haven’t thought of before. And if we as participants are the first to market an idea, this can lead to a competitive edge.”

In addition to technological results, the GHz Centre has also generated a number of significant skilled researchers.

“Ericsson and other companies have been able to recruit many people from the GHz Centre and boost their staff’s skills, e.g. with industrial doctoral students and adjunct Professors. Industry has also provided project managers in GHz Centre.

“What we appreciate in particular is that Chalmers also demands strong involvement from the company partners. Chalmers’ environment is scientifically, technologically and collaboratively superior. Earning your PhD at the GHz Centre is unique as regards actions, quality, mind-set and way of working.”
The overall mission of the GHz Centre is to bring scientific results in microwave engineering faster from Chalmers to commercial exploitation primarily through its company partners. These are found in businesses such as telecom, defence and space, all decisive for Swedish competitiveness.

Key results
2007–2016

The Nanofabrication Laboratory
Part of the research in GHz Centre is carried out in the Nanofabrication Laboratory at Chalmers where compound semiconductor processing is developed for THz Schottky diodes in GaAs, ultra-low noise InP HEMT circuits and wide bandgap transistor technology in SiC and GaN. This cleanroom facility is part of the Swedish research infrastructure for micro- and nanofabrication, Myfab (www.myfab.se).

Key figures and results during ten years

235 early results disclosed from Chalmers to industry

15 PhDs out of which more than 10 are in industry positions

We have helped GaN HEMT technology from the university lab to the system level, accelerating the paradigm shift of new compact power modules for AESA radar

200 scientific reports with almost 50% academic-industrial co-authorship, proving the intellectual calibre of our collaboration

3 small microwave companies growing, hiring around 30 more people in Gothenburg, many of them PhDs from GHz Centre

We have helped telecom industry to advance standardization in beamforming for 5G

396 we have helped to IP, methods and improved device models being adopted by company partners for design of microwave circuits

200 scientific reports with almost 50% academic-industrial co-authorship, proving the intellectual calibre of our collaboration
Base station power amplifier efficiency increased from 10% to 50%

Chalmers’ successful research into power amplifiers has been of great benefit to its partner companies in the GHz Centre, and not only in telecom. Good insights at Chalmers into the needs from industry have resulted in world-leading research findings.

The changes in mobile telephone generations have radically altered requirements for transmitting amplifiers, with constantly increasing demands in linearity. The transition from phase-shift keying (PSK, and its variant minimum-shift keying, MSK, in GSM), to quadrature amplitude modulation (QAM), considerably tightened these requirements. The transition to orthogonal frequency-division multiplexing (OFDM) in 4G was an even more radical step.

Around year 2000, the efficiency of base station power amplifiers was only around 10%. There was an obvious need to find completely new solutions. Chalmers carried out research into different types of power amplifiers early on, including a range of different switched power amplifiers (in classes D, E, F and J), load-modulated power amplifiers, outphasing (Chireix/LINC), carrier bursting and envelope elimination and restoration (EER)/supply modulation.

Being able to examine the findings of the Chalmers researchers and contribute a requirement profile for real applications was one of the reasons for Ericsson joining the GHz Centre along with a number of other partner companies.

The studies started with E and F class switched power amplifiers. The goal was to attain a high efficiency, but there were problems in modulating the amplifiers using wideband signals.

“In future it may be necessary to revisit the switched technologies, for power amplifiers (PA) with lower outputs using CMOS technology. We still have class E as an option,” says Bo Berglund, Senior Expert RF Technology at Ericsson AB and Adjunct Professor at Chalmers.

The research breakthrough lies in a new generalised way of synthesising the combining network on the Doherty amplifier output. This has applications in symmetrical Doherty and also in outphasing architectures.

The GHz Centre has set a world record with a 56% efficiency GaN-based Doherty power amplifier for 3.5 GHz.

“It’s fantastic to go from an efficiency of around 10% to 50–60%, something we didn’t think was possible before,” Berglund says. “We are grateful for having benefited from the expertise at Chalmers, and also for the research which didn’t lead anywhere: otherwise there would have been a risk that we’d have tried to develop something with no potential.”

Load-modulated power amplifiers

In the evaluations of the different power amplifier topologies, Christian Fager is extremely proud of the success they have had with load-modulated power amplifiers. He is a Professor at Chalmers and a project leader in the GHz Centre.

“We undertook a thorough review of the design. It’s based on varactor diodes which are produced in Chalmers’ nanofabrication laboratory. Chalmers has reached further than anyone else in the world in the field of multi-band load-modulated power amplifiers.

“The efficiency increases by close on 30 percentage points when we activate load modulation during back-off. We’ve also used digital linearisation techniques here to meet the spectral requirements.”
“In parallel with the research into load-modulation circuits, we designed special algorithms to drive the hardware as energy-efficiently as possible. This development started with the load-modulation work, and continued with the development of algorithms for other concepts such as Doherty amplifiers, out-phasing, carrier bursting, etc.,” says Professor Thomas Eriksson at Chalmers, deputy leader of the project.

Higher bandwidth and output
“Initially we focused on increasing the efficiency of the power amplifiers. Now the goal is to increase the modulation bandwidth as well,” Berglund says.

In 2006, Ericsson started to produce multi-standard systems for 2G, 3G and 4G. The bandwidths increased from 20 to 60 and then to 100 MHz. This took place at the same time as the need for a high modulation bandwidth as well,” Berglund says.

The problem of designing power amplifiers with good linearity while also having high efficiency and wide bandwidth, has been an engineering challenge.

GaN for higher frequencies
“We are still using (silicon) LDMOS transistors up to around 2 GHz, but for 2.5 to 5 GHz gallium nitride (GaN) HEMT is the best option from an efficiency perspective,” Berglund says. “GaN transistors withstand higher temperatures and can have higher cut-off frequencies than silicon transistors.”

The Chalmers research includes characterisation, modelling and optimisation of its own production processes. Fager clarifies:

“Much of the current research in the GHz Centre involves the circuit architecture and digital signal processing to improve the signal performance. Earlier research focused mainly on increasing the efficiency of the power amplifiers. In the future we see significant benefits in system-based energy efficiency,” Fager says. “This will include temporarily switching off parts that are not in use. We will be able to build transmitters with combined digital and analogue elements, which take this into account.”

5G requires innovation
5G involves a paradigm shift. All the hardware and signal processing needs to be developed from scratch and new frequency bands operating at millimetre wavelengths will be added. In addition, 5G also requires a high modulation bandwidth. Chalmers has extensive experience of research into millimetre-wave technology and has carried out early trials using multi-antenna systems.

Massive multiple input and multiple output (MIMO) was proposed back in 2006, but then primarily as a theoretical concept. At the time there was scepticism about the concept in Ericsson's product development unit. But around 2011 it started to become clear that it might be a realistic alternative.

“At the GHz Centre we are part of a research environment that is constantly evolving and adapting to the problems that arise. We won't get stuck! And we don't yet know what the research on massive MIMOs will lead to,” Berglund comments.

5G has created new challenges. To tackle them it's not enough simply to develop hardware. A combination of hardware and software is necessary to achieve the required system performance.

“It's more and more important to linearise everything. We're now talking about signal design, which is particularly relevant to MIMO,” Eriksson says. “This is where we can make use of the algorithms we had previously developed for load modulation and Doherty, and use that knowledge to linearise an entire antenna array.”

New problems to solve
With massive MIMO in the future 5G there are new problems to solve such as the fact that closely packed transmitter modules with their associated antennas create interference.

In the GHz Centre, researchers have carried out dynamic simulations of a wide range of PA modules and analysed the results. This has resulted in a method for predicting the output signals from each antenna in an antenna array of an arbitrary format as well as the total far field pattern that the transmitters produce with each conceivable signal. These results can then be used to study the effects of the antenna design and the spacing of its elements.

Active participants
Berglund summarises their involvement in the GHz Centre:

“A major advantage is that it is an established framework. Unlike bilateral programmes, in the GHz Centre we've been able to involve our own staff and have been expected to contribute to research which is aimed at reaching the ultimate limit of technology development. Being so far ahead of the field has, for example, given us advantages in the standardisation work we are involved in. The 3rd Generation Partnership Project (3GPP) still has no industrial standard for massive MIMO. We are at a crucial phase where the hardware plays a major role.”

“The research into transmitting amplifiers for telecoms has also brought many synergies with other applications such as medical imaging systems or radar for self-driving cars. These are some of the areas in which we are carrying out further research in the GHz Centre and in the antenna systems centre ChaseOn at Chalmers,” Fager says.
Saab was the first global defence company to showcase delivery-ready gallium nitride-based radar sensors. Collaboration in the GHz Centre allowed Saab to speed up its development work to achieve this goal.

A press preview in May 2014 Saab succeeded in surprising journalists from leading military-focused global journals. They knew in advance that a new radar system would be presented, but not that this system, the Giraffe 4A, would be based on high electron mobility transistors (HEMT) using gallium nitride (GaN) technology. The well respected journal Aviation Week reported that Saab had supplied GaN HEMT-based radar systems to customers before any other manufacturer.

Research conducted by Professor Herbert Zirath and Research Professor Niklas Rorsman resulted in Chalmers’ first GaN HEMT in 2001. This took place in the framework of the Chalmers Centre for High-Speed Technology (CHACH), a Vinnova programme that preceded the GHz Centre. Johan Carlert at Saab, one of the companies involved in CHACH, explains how he and Zirath had already spent a couple of years speculating on how components with a wide bandgap could be used in radar systems of the future. At the time the focus was on wide bandgap components based on silicon carbide (SiC).

Around 2005 Chalmers had developed a monolithic microwave integrated circuit (MMIC) process using silicon carbide to create high power transistors for power amplifiers. The process was transferred to GaN on an SiC substrate in 2006. Everything moved swiftly after that! The fact that Saab could run a live demo for customers in 2014 with a complete radar system based around GaN transistors has to be regarded as exceptionally fast.

“It wouldn’t have been possible without the kind of collaboration we had in the GHz Centre.” Carlert says. “The GHz Centre allowed us to speed up our development.”

Promising future
GaN allows not only a higher efficiency in power amplifiers for microwave applications, but also greater thermal conduction in the SiC substrate and to the fact that GaN allows you to run at a higher channel temperature than gallium arsenide (GaAs) transistors do.

What is unusual about a consortium such as the GHz Centre is the fact that it includes not only the academic and system house sectors but also foreign semiconductor suppliers such as Infineon and UMS.

“It’s a unique form of cooperation which brings together the entire supplier chain. Saab in its capacity as a system house contributed its requirements profile, Chalmers provided the processes and UMS the industrial semiconductor production. Each antenna grid contains a thousand or more antennas with the associated power amplifiers with GaN HEMT.”

Giraffe 4A is not the only radar system based on GaN components, but three other new models in the Giraffe range are also using this technology. GaN components will now also be used in the naval version Sea Giraffe 4A and in the airborne radar system GlobalEye, as well as in electronic countermeasures.

The advantages of GaN are a higher output and the option to create efficiency-enhanced power amplifiers. This in turn results in lighter system components, which is particularly important for airborne equipment.

“Take our radar system GlobalEye for example: thanks to GaN we have managed to extend its range without increasing the weight of the equipment. Nor does it consume more electricity, which can be translated into an unchanged aviation fuel consumption despite the higher output power from the radar sensor. We’ve gained all this without jeopardising its service life or having to make other compromises. GaN has given us all the best characteristics without us needing to sacrifice anything.”
Experience in the GHz Centre in recent years has shown that it is possible to achieve much more with GaN technology in the future.

“In the GHz Centre we’re now working on improving the linearity,” explains Dr Mattias Thorsell, Assistant Professor at Chalmers. “There is a particular interest in high linearity in the small specialist companies and in the telecom sector. What surrounds the GaN layer is complex. There are major challenges in developing and reconfiguring semiconductor processes for new materials.”

Apart from his position at Chalmers, Thorsell is also employed part time at Saab, which contributes to a rapid exchange of expertise.

He also talks about further development with the aim of managing a larger heat dissipation, which might be achieved by replacing the SiC substrate with a diamond substrate. Other challenges are lattice defects, memory effects and linearity.

“In my work I seek to acquire knowledge of what changed materials will lead to,” Thorsell says.

Carlert says that power amplifiers for the S and X bands and for wide-band electronic countermeasures are the primary applications for GaN HEMT for power amplifiers, but that it would also be interesting to build receiver inputs in GaN for these bands.

“Experience in the GHz Centre in recent years has shown that it is possible to achieve much more with GaN technology in the future. We have learnt to build new components so that we can produce new systems in the long term.”

New applications
The current GaN semiconductor process is optimised to produce a high output power at a high frequency. A low-noise optimised GaN process would allow us to produce a low noise amplifier (LNA) which withstands a high input power. We would no longer need to have a circulator, but could make do with an antenna switch to switch between the transmitter and receiver.

The circulator is a bulky component. If it could be eliminated, it would be possible to combine the transmitting amplifier and LNA to produce a much more compact structure than today.

“Eliminating the circulator also allows us to increase the bandwidth considerably, something which advanced multifunctional radar sensors for unmanned aerial vehicles (UAVs) can make use of.”

Long-term funding
Carlert stresses that one of the most important features of the GHz Centre is its long-term perspective.

“Development normally takes time and it’s only in the last two years that we’ve managed to produce concrete results from ten years’ work in the GHz Centre. Saab has also been able to recruit well-trained staff, ranging from doctoral students to fully fledged project managers. With a completely new generation of scientists and engineers and research findings, we’ve succeeded in building new prototypes in a difficult and important development.”

Thorsell gives his view of cooperation in the GHz Centre in his capacity as a researcher at Chalmers:

“It’s important for Chalmers to build up expertise in the right areas. From an academic perspective we’ve gained insights into what research we should launch. Numerous meetings have resulted in better mutual understanding.”
Research into oscillators has been a key area for the GHz Centre since its start ten years ago. After five years the focus changed from oscillators built with InGaP heterojunction bipolar transistors (HBT) to GaN high electron mobility transistors (HEMT). As a result, new and original oscillator designs for wireless communication have been demonstrated between Chalmers and industry.

The move towards greater bandwidth and higher-order modulation formats in modern mobile communication systems put higher demands on the oscillator noise performance than before. GaN HEMT for the oscillator design may be less commercially mature than InGaP HBT, but it is expected to have a large potential to meet the needs of the next generation of mobile systems, radio links and radar sensors.

Many universities have published articles about low phase noise in oscillators. “Very few have achieved such good results as the research undertaken in the GHz Centre. We have reported on integrated oscillators with a phase noise of -120 dBc/Hz at 100 kHz offset from a 10 GHz carrier signal and oscillators with an external cavity that achieve a phase noise of -145 dBc/Hz at the same frequency and offset,” says Dan Kuylenstierna, Associate Professor at Chalmers and project leader in the GHz Centre.

It was a challenge in the GHz Centre to come up with a solution that would be suitable for future commercial applications. “After five years’ research into oscillators with InGaP HBT we decided to investigate the potential of using GaN HEMTs instead. SiGe HBTs can certainly provide even lower phase noise, but with a limited cut-off frequency.”

One weakness of GaN HEMTs is their higher flicker noise (1/f noise). On the other hand a GaN HEMT can produce a higher output power compared with an InGaP HBT. This can result in a higher signal to noise ratio at a greater frequency distance from the carrier signal, something of benefit for future broadband communication networks. This applies both to the new 5G frequency band and to radio links on the E band as well as new forms of communication on millimetre-wave bands.

“When you go up in frequency the phase noise becomes a killer since it increases as the frequency rises. In the framework of the GHz Centre we have studied tailor-made GaN HEMT, designed in Chalmers own process and in commercial technologies such as those from UMS and Qorvo.”

From MMIC to separate high-Q resonator

Mikael Hörberg has had a split role as a developer at Ericsson and as an industrial doctoral student in the GHz Centre. He has now defended his thesis on “Low phase noise GaN HEMT oscillator design based on high-Q resonators.”

To achieve low phase noise, Hörberg separated reflection amplifiers (which contain GaN HEMTs) from the resonator. This was made up of an aluminium cavity. Although the surfaces are not silver-plated the resonator has a Q-value of 4,000, compared with around 40 in a GaN HEMT microwave monolithic integrated circuit (MMIC). The phase noise is extremely low: “The fact that we reached -145 dBc/Hz at 110 kHz offset on 10 GHz with a fixed frequency oscillator was a milestone to start out from,” Hörberg says.

The next stage was to make the oscillator tunable without excessively loading the Q-factor in the resonance circuit. Rough tuning is achieved via MEMS switches on a quartz substrate in the bottom of the cavity.
cavity. The switches make contact with the bottom of the cavity, located around 2.5 mm below the MEMS switches. 5% tunability around 10 GHz can be attained with three MEMS switches. Depending on the switch configuration, the phase noise is as low as -140 dBc/Hz to -129 dBc/Hz 100 kHz from a 10 GHz carrier signal.

"Few people have achieved better performance,” Kuylenstierna comments. A weakness in many current systems is that voltage-controlled oscillators produce too much phase noise to meet higher-order modulation such as QAM or OFDM. In the oscillator with MEMS tuning there are also plans to add a varactor for fine tuning in order to control the oscillator in a phase-locked loop (PLL).

Hörberg has now returned to his position at Ericsson. “I am grateful for my experiences as an industrial doctoral student in the GHz Centre. It has given me knowledge that I can now transfer to industrial applications.”

Knowledge and understanding
Kuylenstierna describes the ongoing work. “We’ve not only achieved good results but have also worked on tracking and understanding phase noise. We analyse each contribution to it. We’re now working on a trade-off between the output power and phase noise. We’ve come much closer to the theoretical limit for a fixed frequency oscillator. “By using the Keysight ADS software, it’s possible to simulate the wave form and predict the phase noise. But the noise modulation is non-linear. Since ADS is a linear small-signal simulator, you can analytically calculate the phase noise from these results. “We can measure the phase noise at component level. A major problem in manufacturing is that there aren’t any component manufacturers that have a good model for flicker noise.”

In the past Chalmers measured flicker noise with equipment developed in-house. A newly purchased PXI instrument from Keysight provides the same results but is much easier to use and has a higher capacity.

Looking ahead
The aim of oscillator research in the GHz Centre is to transfer the research findings into a technology with the potential for commercialisation through the centre’s partners. “We conducted research at component level in the past. Now we are focusing on systems to a greater extent. Industry has helped us to understand how to use oscillators and what is needed. The GHz Centre has proved to be a good forum for collaboration. It allows academic research and industrial research to be combined in a unique way.”

Future systems will use a greater bandwidth. “It’s perhaps not quite so important to have low phase noise close to the centre frequency. At greater distances white noise is more of an issue. We’ve investigated where the boundaries lie. In a valuable internal collaboration, the department of Electrical Engineering at Chalmers received raw data from us, thus enabling them to carry out calculations.”

In massive MIMO a large number of oscillators have to be synchronised. This is a complex problem and Kuylenstierna sees a need for interdisciplinary research here between the industrial and academic sectors.

The next stage of the research at the GHz Centre is to optimise oscillators for millimetre-wave communication and MIMO systems.
THz electronics is based on very specialised devices in compound semiconductors for highest speed and lowest noise figure. Such technology is not commercially available and must be fabricated in nanofabrication facilities such as the cleanroom laboratory at Chalmers.

In GHz Centre, GaAs Schottky diodes for THz mixers as well as InP HEMTs for ultra-low noise amplifiers are developed between Chalmers and spin-off companies.

When Sweden’s future industry comes up in discussion, many immediately think of big markets and volumes. Two successful examples of the opposite are Omnisys and Low Noise Factory, which both work in narrow niches focused primarily on technical needs in science such as physics and astronomy. Both are spin-offs from Chalmers that have grown and become profitable. Via the GHz Centre, they work intensively with Chalmers researchers as well as each other.
Omnisys found profitable business in the space industry

Omnisys products are largely developed based on results from Chalmers’ microwave and millimetre-wave research, but with a clear system focus. Today they deliver, among others, to the European Space Agency.

Omnisys was founded in 1994 by Dr Anders Emrich and Stefan Andersson. They were both working at the Onsala Space Observatory when they got the idea to start a business making highly specialised space electronics. Today the company boasts sales of 50 MSEK, has been profitable for many years and employs 32 people.

They began their collaboration in application-oriented electronics way back in 1995, when the competence centre Chalmers Centre for High-Speed Technology (CHACH) was born. This was the predecessor of the GHz Centre.

Anders Emrich, who was one of CHACH’s founders, says, “Back then there were no shared expectations between authorities, academia and industry. Companies thought they would get everything free, and the researchers demanded academic freedom and Vinnova (then Nutek) invested 6 MSEK per year but expected results that would have required a billion SEK budget.”

The situation improved over time, and the experiences from CHACH played a key role when the GHz Centre was founded in 2007. The conditions at that point were completely different.

“The large companies were a lot more knowledgeable and the researchers were more open. We as a small company have been able to contribute with our flexibility and breadth.”

To a large degree, Omnisys has chosen to work with its own industrial doctoral students to develop exciting new technology in several fields, from digital technology with the company’s own ASIC design, to designing and manufacturing high-frequency receivers and quasi-optical systems.

These projects allowed for the development of cutting-edge technology for specific uses. Perhaps even more importantly, the company has established a critical skill base and new collaborations, which has resulted in whole new opportunities for future growth. One example is Dr Peter Sobis, a former industrial doctoral student who is now on staff at Omnisys, while still active at Chalmers with research and development in THz electronics.

“He spends most of his time at the GHz Centre. It’s worked very well, but the work in a competence centre also requires great dedication from the in-going parties. All participants in the GHz Centre put in thousands of hours of their own time, which creates knowledge that can be transferred to industry.”

World record, from 300 GHz to 1.2 THz
Omnisys has set a world record in receiver sensitivity on the majority of receiver bands in the 300 GHz to 1.2 THz frequency range. There are still no low-noise amplifiers (LNAs) for these frequencies yet. Rather, the antenna signal goes directly into a special mixer, which is a direct result of Chalmers’ research. The mixer was developed by a team at Chalmers and Omnisys on the initiative of Anders Emrich. Professor Jan Ståke headed the Chalmers part of the team.

The core of the mixer is two Schottky diodes made of gallium arsenide (GaAs). The diodes are connected in anti-parallel and integrated on an extremely thin GaAs substrate, about 3 µm thick. Ten years ago, only a handful of labs in the US were able to manufacture diodes that were fast enough.

“But we wanted a European manufacturer to ensure we wouldn’t suffer from any export restrictions from the US. Thanks to the GHz Centre, we developed Schottky diodes with the desired properties."
The amplifiers referred to in the title are highly specialised, ultra-low-noise amplifiers for frequencies between 0.3 and 115 GHz. Low Noise Factory holds a unique position in the world markets of radio astronomy and quantum computing.

After having developed cooled low-noise amplifiers (LNAs) at Caltech in Pasadena in California, Niklas Wadefalk moved back home to Gothenburg. He had previously worked in the same field at Chalmers, for the Odin satellite, the Herschel Space Observatory and other projects.

As a research engineer at Caltech, he designed and built several cryogenically cooled LNAs for the Allen telescope array for the non-profit corporation SETI, which searches for life in the universe. When the project was finished, one of the key people at SETI, Jill Tarter, asked Wadefalk if he’d be interested in starting a company to produce more cooled LNAs. Because in fact there was no other company in the world that could deliver what SETI wanted.

In 2005, Wadefalk founded Low Noise Factory (LNF). The search for a suitable environment for the business took him home to Gothenburg and Chalmers, with its Nanofabrication Laboratory and expert researchers.

“As a member of the GHz Centre, we’ve been able to develop our company significantly. In 2012 there were three of us at LNF – now there are nine, including four PhDs trained at Chalmers…”

“Extremely low noise
Each LNA from Low Noise Factory contains an indium phosphide (InP) HEMT-based MMIC. One of the company’s LNAs – the LNC4_8C – is based on discrete InP HEMT transistors. It’s the company’s bestselling model. The amplifier is a hybrid design, built with chip and wire technology.

High electron mobility transistors (HEMT) have a complex structure, and InP HEMT is difficult to process. Researchers at Chalmers have been developing a unique low-noise InP HEMT process for a long time.

A chip for a discrete HEMT measures just 420×430 µm, while an MMIC measures 2.00×0.75 mm. It is soldered in place with indium and bonded with 25 µm gold thread.

The LNF-LNR4_8C model, for 4–8 GHz, has the industry’s lowest noise temperature, 32 K, at room temperature. A cooled LNA for the same frequency range has a noise temperature of 2.3 K! To achieve such a low noise temperature, the amplifier needs to be cooled to 4 K. Using a cooled LNA rather than room temperature allows to reduce the antenna area in a radio telescope to up to one fifth.

Cryo testing
Each LNA produced is tested in its intended environment and delivered with an individual datasheet. It is tested both at room temperature and cooled in a box set up for either coaxial or waveguide LNAs. The cryo cooler can be programmed to cycle the temperature between 300 and 4 K hundreds of times to investigate the amplifiers’ durability. The test instruments operate from 10 MHz to 140 GHz. The noise temperature is measured with the hot-cold method.
Measuring technique for THz demands new thinking

Characterising components for the sub-millimetre wave regime requires extremely accurate measuring procedures. Johanna Hanning from Chalmers came up with an elegant solution.

Doctoral student Johanna Hanning demonstrated a solution for calibrating and using a vector network analyser (VNA) to measure up to 1.5 THz.

“Extraction of S-parameters in order to create models of components for such high frequencies has never been done before,” says Jan Stake, Professor at Chalmers.

“We previously design components in a blind manner. A crucial point in parameter extraction is the calibration of the VNA, where we through GHz Centre collaborate with RISE Research Institutes of Sweden (previously SP).”

Johanna Hanning’s doctoral work started from the need to measure S-parameters and characterise components on a membrane in a stripline structure inside a waveguide. The membrane is just 3 µm thick.

Calibration kit

Traditionally, probes are used to measure on components in the millimetre-wave range. Now there are probes up to 1 THz, but not for measuring on packaged stripline structures in which integrated waveguides are a part of the structure.

“We want to be able to measure diode parasitics in the appropriate environment” Stake says.

Hanning has created a set of calibration and measurement setup that reduces uncertainty associated with tolerance levels of the connections between the waveguides.

Fixed positions

Hanning’s solution to the problem is to use a common flange for both waveguide ports, with a fixed distance between them. The calibration blocks and the block with the device under test are then screwed onto the flange.

“With this mechanical design, we don’t need to move the extenders, which eliminates the risk of phase errors. It also allows shorter connection waveguides, which further reduces the phase error due to manufacturing tolerances.”

Important measuring technology

To transfer research results to industrial applications, it is necessary to be able to measure, characterise and model them.

“We want to be able to achieve models for building THz receivers, which means we need to develop the measuring technology for THz,” Stake says. “That wouldn’t have been possible without the GHz Centre. The connection to RISE and up to 15 companies in the GHz Centre makes an interesting blend.” What is needed is research on THz metrology that can make it possible to manufacture devices with high reproducibility.

Ten years with the GHz Centre

Jan Stake summarises what ten years with the GHz Centre has meant to industrial development:

“Omnisys has built radiometers for the world’s biggest radio telescope, ALMA. They’ve built 600 GHz equipment (and 1200 GHz in the pipeline) for the JUICE space instrument. For the next generation of weather satellites, METOP 2G, Omnisys is building a receiver with Schottky diodes from Chalmers. The receiver is currently being qualified for use in space by Omnisys and ESA.

“With the JUICE project, Chalmers’ Schottky diodes will be sent into space for the first time. “The combination of low-noise amplifiers from Low Noise Factory and receiver mixers from Omnisys with Chalmers’ Schottky diodes is unique. Nothing beats this!”

ISMAR is another space mission equipped with receivers for 874 GHz, in which the company Wasa Millimeter Wave is a supplier. This is yet another company that has spun off from Chalmers and is also a partner of the GHz Centre.
The GigaHertz Centre is a joint research and innovation centre between Chalmers University of Technology and industrial partners. The mission of GHz Centre is to carry out collaborative leading research in selected high-frequency technologies and to bring the results from Chalmers to an industrial exploitation phase primarily through its company partners. GHz Centre has been run since 2007. Between 2017–2021 it is part of the Competence Centre program funded by the Swedish Governmental Agency for Innovation Systems (Vinnova).