Final Centre Report of Stage 3

GigaHertz Centre

Stage 1 (2007-2008)
Stage 2 (2009-2011)
Stage 3 (2012-2014)

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Cristina Andersson, Chalmers University of Technology

Steering Board Chairperson Peter Olanders, Ericsson AB

Management team:

Jan Grahn, Herbert Zirath, Christian Fager, Thomas Eriksson, Mattias Thorsell, Hans Hjelmgren, Dan Kuylenstierna, Peter Sobis, Per-Åke Nilsson

Chalmers and industry partners

Gothenburg
21 April 2015

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0. Summary

The VINN Excellence Centre GigaHertz Centre (GHz Centre) carries out leading microwave research by collaboration between Chalmers University of Technology (Chalmers) and industry. The overall mission of the GHz Centre is to bring scientific results from Chalmers to commercial exploitation primarily through its company partners.

Since its start year 2007, GHz Centre has doubled in turnover and number of partners. Chalmers participates through two departments and three laboratories. In Stage 3 (2012-2014) one research institute and twelve companies are GHz Centre partners. The industrial partners are found in six different countries among three continents. Industry is strongly supporting the GHz Centre by financing more than half of the centre (52%) including a large portion cash (35%). GHz Centre company partners are found in the whole supply value chain from global system houses, semiconductor manufacturing, sub-system industry, design tools, to Chalmers' own spin-offs. The end users businesses target mainly three different markets: telecom, defence and security, and space, all essential for Swedish growth. In the long run, GHz Centre results will give us more energy-efficient communication, a safer world and better survey of climate changes.

Ghz Centre has contributed with state of the art results in several RF/microwave research areas: Energy-efficient microwave power digital transmitters, measurement and modelling of gallium nitride (GaN) HEMT microwave transistors, low-phase noise oscillators and, ultra low-noise amplifiers and THz Schottky diode receivers. The academic output from 2007-2014 is 58 journal publications, 98 peer-reviewed conference publications and 45 conference presentations (19 invited). So far, 13 PhDs have been examined from GHz Centre research.

After almost 8 years of joint research between Chalmers and industry, large impact from GHz Centre is now recognised by the industry:

- High mobility in people between industry and university including hiring of 10 PhDs from Chalmers to relevant industry
- Exceptional high ratio of scientific co-publishing between Chalmers and industry now reaching 50%. GHz Centre results have influenced 8 companies to update their technical roadmaps
- 2 patents, 12 licenses and 197 cases of early disclosing of scientific results and inventions from Chalmers to partners
- 8 companies manufacturing new or improved products using results from GHz Centre
- 10 companies utilizing results in the industrial development for products
- 2 small- or medium sized companies growing
- 9 concrete cases of impact where research is absorbed by industry exemplified in so-called GHz Centre success stories

Two of the most remarkable concrete GHz Centre success stories are the acceleration of GaN HEMT technology from the lab into advanced radar systems at Saab, and the rise of a low-noise amplifier spin off company from Chalmers. Other examples of GHz Centre impact are novel power amplifier topologies for radio base stations, awarded space contracts for an SME, and GaN transistor models now becoming industrial standard.

1. Long-term Vision, Mission and Strategy

The mission of the GHz Centre is to bring scientific advances aimed for future wireless communication and sensor technologies faster to industrial prototyping and exploitation.

This mission is carried by a shared vision between Chalmers and industry dedicated to the novel high-frequency technologies shaping tomorrow's wireless world. The strategy, described in detail in the Research Programme Stage 3, pinpoints the scientific and educational targets together with utilisation of their output, i.e. know-how and people from Chalmers to industry.

The GHz Centre has become one of the most attractive collaboration for companies in the RF/microwave field. Since our start 2007, the number of companies have almost doubled and GHz Centre is now attracting leading industry from all over the world. Moreover, the GHz Centre has gained investments far beyond what is found at other similar centre environments. Our international advisory board formulated in their last report:

"The high number of publications, patents, effective collaboration between academy and industry, and successful results leading to highly innovative new demonstrations and products proves that the GHz Centre has already paved the way for a long-term collaborative centre with international visibility."

2. Research Area, Competence Profile and Critical Size

GHz Centre has involved world-class scientists and engineers at Chalmers *and* leading companies in RF/microwave technology.

Our competence lies in crucial parts of the supply value chain from the electronics to the system aimed for telecommunication, defence, security or space. The components studied in GHz Centre all carry a potential to build the infrastructure for wireless communication and sensing. Some examples are access networks in mobile communication systems, phased-array radar for airborne systems, frequency converters for satellite communication and THz spectrometers for atmospheric science. Such applications are of profound importance for the modern sustainable society and its challenges in transport, climate and security.

Chalmers core competence originates in high-frequency electronic devices for wireless and sensing in the range 1-1000 GHz. The vast majority of the needs in industry is below 100 GHz and therefore, the bulk of the research in GHz Centre is directed towards this frequency range. Traditionally, microwave research at the university is divided into separated sub-disciplines. However, in GHz Centre, we meet the multidisciplinary needs from wireless industry by involving four different laboratories at Chalmers and SP Technical Research Institute of Sweden (SP). In this way, projects can tackle all the way from the device to the circuit, to the module and even to the system, involving digital signal processing and the antenna. As a result, shared PhD students, adjunct professorships and joint know-how has been created between Chalmers and industry. Such collaboration was not systematically carried out prior to Centre start. GHz Centre has therefore contributed to unify and revitalise research faculties scattered between departments at Chalmers in new powerful constellations for industrial collaboration.

GHz Centre gathers a critical size of around 90 people where almost one third is at Chalmers and SP Technical Research Institute of Sweden (SP), the rest at the companies. In total, around 1/3 has a PhD degree, the rest is on MSc level. The companies in GHz Centre contribute with the industrial engineering expertise on manufacturing, integration and implementation. GHz Centre engages three global leading system industries (telecom, defence, and satellites), four semiconductor fabs, one leading design tool manufacturer, two Swedish SMEs and two Chalmers spin off companies.

The GHz centre is by far the largest single programme at the RF/microwave/antenna research in Sweden. Compared to other relevant centres in the world, e.g. Berkeley Wireless Research Centre or UCSD Center for Wireless Communications, we are comparable in number of company partners albeit smaller in budget. GHz Centre is unique to combine system houses, semiconductors (fabs and in-house circuit processes) and academic competence from 1 to 100 GHz and beyond. Thus we are not aware of any other equivalent research centre *involving industry* in the world.

Chalmers has excellent experimental environments to support GHz Centre. A most advanced microwave/mm-wave characterization laboratory is to the disposal for the projects. For example, the laboratory has been vital for the modelling in the GaN HEMT technology. Even special measurement techniques have been developed in the centre. During Spring 2014, 4.4 M€ was donated (in competition) to Chalmers from Knut and Alice Wallenberg Foundation to create a national laboratory for (sub)mm-wave characterization, again a compelling proof of the strong position of measurement science in GHz Centre and Chalmers.

The cleanroom at MC2 is among the most modern for a university worldwide enabling the processing of full monolithic microwave integrated circuits (MMICs). We are running on 100 mm wafers both state of the art GaN and InP HEMT circuits as well as a THz monolithic integrated circuits (TMICs) using membrane high-frequency GaAs Schottky diodes. Moreover, Chalmers also provides the models and development of design kits necessary for the MMIC design. At partner companies, packaging and test benches are to the disposal for demonstration experiments.

GHz Centre is embedded in a large research environment based upon a number of faculty grants from Swedish, European Commission (FP7, H2020 and ERC) and European Space Agency (ESA) financing bodies. The total body of microwaves and antennas at Chalmers constitute one of Europe's largest research environments in the field, involving around 100 people at three departments. This research forms an important asset in future GHz Centre project definitions where new competences and ideas can be searched for. The total funding at Chalmers is around 15 M€ per year in materials, components, antennas and systems for wireless communication and sensors. Research activities considered fundamental science today (such as graphene electronics) may well become the needed-driven research tomorrow carried out with industry in GHz Centre.

Through the European Radio and Microwave Interest Group (EuRaMIG) initiative from GHz Centre, an industrial-driven network was created by GHz Centre in Europe for microwave stakeholders, now lead by European Microwave Association (EuMA). The GHz Centre board members have been active in leading a core group involving people from the most prominent microwave companies, institutes and universities in Europe. A vision paper has been produced highlighting the opportunities and challenges for European microwave actors. Meetings with the important European public authorities European Commission (EC) European Space Agency (ESA) and European Defence Agency (EDA) have been conducted. As a result, we are now invited by the EC to Horizon 2020 stakeholder meetings in Brussels.

After eight years of operation, GHz Centre stands for a most unifying and systemised approach to have academy and industry working together. Compared to the traditional research excellence milieus, GHz Centre has added crucial values:

- Much more multi-disciplinary research covering essential parts of the supply value chain from devices to systems of importance for academic *and* industrial competitiveness.

- Much more focused research involving several companies hence fostering leadership at university and networking of competent people and between various industries

- Much more compelling evidence of the centre impact from research to innovation to uptake in industry (described in section 5)

- Much more global: The first research centre at Chalmers to become internationally attractive in industrial multi-lateral collaboration involving company partners from six countries at three continents

3. Research Program and Results

The research and innovation in GHz Centre is in the field of RF/microwave technologies. In particular, GHz Centre addresses RF power components, microwave monolithic integrated circuits (MMICs) and their integration in modules, sub-systems and systems. The research is therefore multidisciplinary involving semiconductor processing, device physics, characterisation and modelling, circuit design, packaging, antenna integration, digital signal processing and system level analysis. This richness in technically advanced yet scientifically challenging subjects lend themselves excellent to long-term collaborations academy-industry in multi-lateral programs aimed for different markets. Our research spans from 1 to 1000 GHz.

More specifically, our core research lies within:

- Digital microwave transmitters for mobile communication networks
- Robust and high-power microwave components using the new gallium nitride transistor (GaN HEMT) technology
- Low phase noise oscillators for microwave backhaul
- Front-end modules for very low-noise receivers in space systems and physics

The topics above were concretized in four projects during Stage 1. During Stage 2 and Stage 3, we have largely developed these projects with more partners, researchers and ideas. However, the basic application targets for system industry has remained the same. This reflects that the industrial partnership in GHz Centre with telecommunication (Ericsson), defence (Saab) and space (Ruag, Omnisys) stays on solid ground all throughout the centre lifetime. We have added necessary and complementary partnerships with other companies from components to systems. Some changes in project plans have been necessary when technologies have matured (e.g. InGaP HBTs to GaN HEMTs for oscillators) alternatively needs in industry have shifted (e.g 4G to 5G in telecom). However, no dramatic changes in the research program has been necessary during the years.

The research productivity January 2007 - Dec 2014 is summarised below.

Research parameter	**Stage 1**	**Stage2**	**Stage 3**	**Sum**	**Goal 2016**
Peer-reviewed journal and conference publications	13	65	78	**156**	**180**
Conference / WS presentations	4	15	26	**45**	*
Invited talks	1	7	11	**19**	*
PhD examinations	0	5	8	**13**	**10**
Success stories+patents	0	1	9	**11**	**15**

*No goal defined

We are well in line with the ten-year goals. Two of the key performance indicators, the number of conference contributions and invited talks, have steadily increased. As seen from Section 10, the scientific publication rate per person and year is higher than the average VINN Excellence Centre in Sweden. Following the recommendation after the international evaluation Stage 2, the number of examined PhDs has been enhanced beyond its original goal. Success stories, showing the utilisation of research into industry, are now clearly paying off, see Section 5.

Very short descriptions are given below on the current research in GHz Centre. Details are given in the referred publications listed in appendix g as well as instructions how to download these.

Energy Efficient MIMO Transmitters

Research partners: Chalmers, Ericsson, Infineon Technologies, National Instruments, NXP Semiconductors, SAAB

Project leader: Assoc. Prof. Christian Fager, Chalmers
Deputy project leader: Prof. Thomas Eriksson, Chalmers

Motivation

Multi-antenna (MIMO) techniques and expanded frequency bands are essential to meet the demand for increased capacity in mobile networks. Multi-antenna solutions are widely adopted in advanced radars, but these face challenges in terms of increased functionality and bandwidth. Energy efficiency is in both cases crucial to minimize cost, weight, and environmental impact. A transmitter design methodology that integrates efficient PAs, antennas, array configurations, and signal processing is needed.

Oobjectives

The overall goal was to demonstrate energy efficient linearized transmitter modules for wideband MIMO applications. The first objective was to investigate PA architectures with improved bandwidth and efficiency. The second objective was to develop modelling and characterization methods to emulate operation of these PAs in a multi-antenna transmitter context. The third objective was to investigate advanced signal processing techniques to mitigate PA and MIMO transmitter impairments.

Major research results

We have reported several innovative PA architectures with state-of-the art performance. A new technique for design of Doherty PA combining networks has been presented, also being patented by Ericsson [C83, P2]. This allows the ultimate efficiency and output power potential of the transistors to be exploited, as demonstrated in a record efficient 3.5 GHz prototype. The same technique was recently explored, with our generalized theory for class E PAs [J28], to realize a wideband and highly efficient 700-1050 MHz class E outphasing transmitter [PhD11]. To further stretch the bandwidth limits, we presented a PA where a continuum between outphasing and Doherty modes was utilized to demonstrate state-of-the-art average efficiency of >45% across 1-3 GHz (100%) bandwidth [J41]. The excellent performance of these PA designs is only unleashed with co-designed input signals. An optimized dual-input digital pre-distortion linearization technique was presented and used to maximize the efficiency and linearity under the PA hardware constraints [C81, J23]. With these types of transmitters being intended for use in highly integrated large antenna array systems, it essential to predict their interactions with the antenna and the resulting radiated field properties. We therefore proposed a new approach to analyse nonlinear effects in MIMO transmitter systems with wideband signals [C85]. The method uses a new type of PA behavioural models and has enabled a new understanding of nonlinear effects due to mismatch and antenna mutual coupling. The results will help to speed up the development and prototyping of future wireless communication and radar systems.

Gallium Nitride Oscillators

Research partners: Chalmers, Ericsson, Ruag Space, Sivers IMA[1]

Project leader: Assistant Prof. Dan Kuylenstierna, Chalmers

Motivation

High-purity signal generation is a key issue in wireless communication systems and radar systems. The voltage controlled oscillator (VCO) is one of the bottle necks in modern communication systems using advanced modulation formats like higher order QAM or OFDM. Currently state-of-the art low-phase noise VCOs are designed in InGaP HBT technology, with key properties for low phase noise such as low flicker noise and relatively high breakdown voltage. A technology with significantly higher breakdown voltage is GaN HEMT. Thus, a voltage-controlled oscillator based on a GaN HEMT can potentially reach very low phase noise.

Objectives

The main objective of the project has been to advance state-of-the-art for oscillators and VCOs in terms of phase noise and tuning range. The objectives were: i) Low frequency noise measurements of GaN HEMTs under high current/high voltage operation, ii) Design of GaN HEMT MMIC oscillators, iii) Design of hybrid VCO based on SiC varactors with high breakdown voltage, iv) Design of low-phase noise oscillator based on high-Q external resonator.

Major research results

During this project we have taken major steps towards the understanding about how to design low-phase noise oscillators and VCOs in GaN HEMT technology. The relation to state-of the art is described in publications [J29], [J44], [J47], [C87], [C88]. We have developed a method for minimization of phase noise in integrated balanced oscillators. The method was first developed for oscillators in InGaP HBT technology [J44] studied in GHz Centre Stages 1 and 2. The method was later generalized to cover also GaN HEMT technology [J47]. Some of the fundamental differences in GaN HEMT technology compared to InGaP HBT are the lower gm and higher flicker noise. The lower gm has the implication that the start-up condition may be more crucial to fulfil leading to a need for larger devices. The other major difference between InGaP HBT and GaN HEMT technology is the relatively high flicker noise in the latter. High flicker noise makes it difficult both to reach good phase noise and to predict what level of phase noise that can be reached. In [J44] we report on a method to accurately predict phase noise in the -30dB/decade region where the oscillator is affected by flicker noise. In [J47] it is described how to design an oscillator to reach good near carrier phase noise and figure of merit despite the relatively high flicker noise. The key is to design the oscillator with waveforms resembling those of a switched-mode power amplifier. Under this operation, the transistor exhibits less flicker noise and operates with high efficiency which favours phase noise as reported in [C88]. In [C87] we presented a comparison between low frequency noise of different transistor technologies. It is demonstrated that GaN HEMT has excellent potential for far-carrier phase noise properties. To reach better near-carrier phase noise, a high-Q metal cavity based oscillator with excellent performance was demonstrated [C88]. This GaN HEMT oscillator presented a phase noise of -135dBc/Hz

[1] GHz Centre Stage 3 partner 2012-2013.

@100kHz from a 12.26 GHz carrier, which is by far the best reached for a GaN HEMT based oscillator, and comparable to state-of the art also for other technologies.

Advanced Characterization and Modeling for Technology Optimisation of Multifunctional Circuits

Research partners:
Chalmers, SP, ComHeat Microwave, Ericsson, Infineon Technologies, Mitsubishi Electric Corporation, NXP Semiconductors, Saab, United Monolithic Semiconductors

Project leader: Assistant Prof. Mattias Thorsell, Chalmers
Deputy project leader: Associate Prof. Hans Hjelmgren, Chalmers

Motivation
Gallium Nitride (GaN) semiconductor devices have matured from the research labs into products. However, the operation is affected by memory effects related to self-heating and electron traps. Characterization of long term memory effects requires new characterization methods and setups, as well as new or extended models to take these effects into account.

Objectives
- Increased understanding of dispersive effects, such as trapping and self-heating
- Develop new measurement setups to investigate long term memory effects and characterization of transistors for multi-standard and multi-band transmitters
- Model development for accurate circuit design and evaluation of system performance

Major research results
The characterization of dispersive effects have resulted in two journal publications that will be published in the beginning of stage 4, and hence not reported here. However, the impact of a varying load impedance on the memory effects of GaN HEMTs was investigated in [C77]. Several new measurement setups have been investigated and developed in the project. One of them makes use of oscilloscopes for nonlinear characterization. The input circuitry needs to be compensated for, and a new correction method that does not depend on the vertical scale setting has been developed in [J56]. A new nonlinear measurement system capable of concurrent measurements at RF and baseband has been developed to improve the characterization of dispersive effects [C62]. Multi-band radios is needed as we get more and more frequency bands allocated at different frequencies for mobile communication. A new setup to characterize transistors and amplifiers for this purpose was presented in [C76].
The model development in the project has addressed numerous topics such as switches, electron mobility, and Schottky currents. Microwave switches are key components in many communication systems, and they operate at both negative and positive drain voltage. A new symmetrical large-signal FET model for microwave switches was developed in [J48]. Accurate numerical simulations of GaN HEMTs rely heavily on the electron mobility model. In [J34] we present a method to extract a temperature and field dependent model from DC and microwave large-signal measurements. Reduced gate leakage current is important to avoid electric breakdown and thermal run-away. A theoretical model for one-dimensional current transport through a reverse biased Schottky contact on GaN HEMTs has been developed. [J33] and later extended to large reverse voltages in [J45]. The system performance aspect was addressed in the development of a new theory for design and analysis of DLM amplifiers in class-J operation, which was presented in [J32].

THz Space Components

Research partners:
Chalmers, SP, Omnisys Instruments, Low Noise Factory, Wasa Millimeter Wave

Project leader: Dr. Peter Sobis, Omnisys Instruments
Deputy project leader: Dr. Per-Åke Nilsson, Chalmers University

Motivation
Advanced high-frequency instrumentation in space and science requires high-performance components not available on the open market. This is in particular true for high-frequency measurements requiring extremely low-noise level or output power beyond 100 GHz. Since the markets are small, companies and university have large incentive to develop such device technologies together.

Objectives
This project aims at developing cutting edge receiver technology for the next generation of scientific instruments for space born and terrestrial applications in radio astronomy and earth science. The main research objective was to develop state-of-the-art cryogenic InP HEMT low-noise amplifiers operating in the microwave region and room temperature Schottky diode receivers operating in the higher submillimeter wave range. An important objective was to develop state of the art device technology in Chalmers cleanroom facility.

Major research results
We have demonstrated a transistor technology optimized for ultra low-noise amplification at cryogenic temperatures 5-15 K. The technology was 130 nm gate length InP HEMT. This has involved research from the very basic material growth and understanding of the transport mechanisms in devices to the qualification of complete MMIC processes. One of the key results was a new state of the art noise temperature of 1.2 K for a cryogenic InP HEMT three-stage hybrid 4-8 GHz LNA K [J31] thus surpassing an almost ten year old record. The breakthrough was made possible by a combination of material and process optimization, device modelling, Monte Carlo simulation, pulsed measurement study as well as a reduction of extrinsic parasitic contributions in the InP HEMT [J36, J38, J52]. An InP HEMT MMIC process was developed on 4 in. wafers.A 24-40 GHz LNA with an average noise temperature of 13.2 K and a gain of 28 dB was demonstrated. A 0.5 GHz- 13 GHz LNA had a noise temperature below 7 K in the entire frequency band [J37]. These designs are being transferred to www.lownoisefactory.com. Finally, in a Nature Materials paper published between Chalmers and Caltech, it was shown how the low noise in a cryogenic InP HEMT LNA was limited by phonon black-body radiation [J53].
We have demonstrated a THz monolithically integrated circuit (TMIC) process for GaAs membrane Schottky diodes on 1 in. wafers [J39, C55, C73]. The process currently holds a record low receiver noise at 557 GHz of 1300 K DSB measured at room temperature. Several novel Schottky based circuit demonstrators operating in the 300-1200 GHz frequency range have been developed [J30, J50, C71], including a 440 GHz X4 integrated Schottky TMIC multiplier LO module with over 5% efficiency and 5 mW of output power developed for the ISMAR instrument [J94]. Thereto we have demonstrated a broadband 530-625 GHz GaAs Schottky TMIC mixer with a module integrated cryogenic InP HEMT IF LNA circuit, measuring a receiver noise of 1300 K DSB, when cooled to 140 K [J94]. The receiver is

developed for the SWI instrument, which is part of the scientific payload of the ESA JUICE mission to Jupiter. Also an improved method for the S-parameter characterization of membrane waveguide integrated circuits and devices at THz frequencies has been demonstrated [J40, J51].

4. Centre Partners

GHz Centre Partner	No of employees	Location(s) (in corporation with GHz)	Main product	No of years in GHz	Interest in GHz Centre	Interaction since GHz start yr 2007
Chalmers University of Technology	2,800	Gothenburg, Sweden	University	8	Education (PhD in particular), research, and its utilisation in industry and society	Leadership Participation in 12 projects
SP Technical Research Institute of Sweden	1,200	Borås, Sweden	Governmental Research Institute	6	Measurements and modelling on RF power components	Participation in 4 projects
Comheat Microwave AB	2	Uppsala, Sweden	Power amplifier solutions	8	RF power modeling and measurements	Participation in 3 projects
Ericsson AB	110,000	Kista	Telecommunication	8	Power amplifiers, signal processing, GaN HEMT, oscillators	Chairpersonship Participation in 9 projects
Infineon Technologies AG,	27,000	Villach, Austria	Semiconductors	8	GaN HEMTs for PAs	Participation in 5 projects
Low Noise Factory AB	4	Mölndal, Sweden	Low-noise amplifiers	3	Cleanroom process InP HEMT MMICs, optimization of InP HEMT	Participation in 1 project
Mitsubishi Electric Corporation,	120,000	Kamakura, Kanagawa, Japan	Semiconductors	6	Large-signal modelling TCAD	Participation in 2 projects
National Instruments, US	6,800	Austin, USA	Test equipment, virtual instrumentation software	1	RF measurements and design of digital transmitters	Participation in 1 project
NXP Semiconductors BV	24,000	Nijmegen, The Netherlands	Semiconductors	8	GaN HEMTs for digital transmitters	Participation in 5 projects
Omnisys Instruments AB	30	Gothenburg, Sweden	(Sub)mm-wave subsystems	8	Schottky diode mixers, MMICs	Participation in 3 projects
Ruag Space AB	350	Gothenburg, Sweden	Reliable on-board satellite equipment	5	Emerging robust microwave devices such as GaN-based oscillators	Participation in 1 project
Saab Aktiebolag	14,000	Gothenburg, Sweden	Products, services and solutions for defense and civil security	7	GaN HEMT circuits replacing traditional solutions in present systems.	Participation in 5 projects
Sivers IMA AB	25	Kista, Sweden	Microwave oscillator products	5	New oscillator designs	Participation in 3 projects

United Monolithic Semiconductors (UMS)	250	Ulm, Germany	Semiconductors	3	GaN HEMTs, GaN MMICs	Participation in 1 project
Wasa Millimeter Wave AB	2	Gothenburg, Sweden	Compact mm- and sub-mm wave sources, mixers and amplifiers	6	Schottky diodes	Participation in 2 projects

Overall strategy

GHz Centre follows a strategic plan. See GHz Centre Research Programme Stage 3 This plan leads to a number of specific measureable goals describing educational, research and impact.

The fundament of GHz Centre is intense interaction and communication between the partners. GHz Centre is a common undertaking between the partners in the form of a joint venture where all parties invest money, resources and in particular, competences. This means that the research programme is agreed in consensus. Academy (Chalmers) brings up ideas from own or other breakthroughs in science. Industry guides academy in the choices of research subjects for potential future long-term commercialisation.

The research programme in Stage 3 ended up in four research projects. Each project had an assigned project leader, deputy project leader and a detailed project plan where the person-hours from both Chalmers and participating companies are monitored. A philosophy of GHz Centre is to strive for relatively large projects with several company partners around a common research ideas beyond the short-term needs in industry. This creates long-term objectives in the projects where strong links between different companies in the supply value chain can be created. An excellent example is taking new semiconductor innovations such as GaN HEMT from the lab to the systems in defence, telecom and space.

Several companies are partners in more than one project. Several PhD students and researchers are involved in several projects. Projects share the same laboratory infrastructure, models and MMIC tape outs. The research in GHz Centre is therefore transparent and “project silos” efficiently suppressed.

The mechanism for innovation and translation of technology is made through different means. One essential strategy is to have company partners describe exploitation routes and plans already in the planning of the project. In this way, it becomes clear how different markets address different needs from the same technology platform built up. Potential IP is transferred at an early stage through disclosure procedures described in the communication plan of the GHz Centre.

The measures for creating strong links and integration are manifold but obviously, the Centre has to create a number of meeting places. Apart from dedicated office places for industry at MC2, Chalmers, we regularly meet at our workshops, centre days, seminars, project reporting, board meetings, and conferences. All this has worked well as exemplified by the high attendance of industry at our workshops, typically around 50% or the large number of adjunct Professors and industrial PhD students at Chalmers. At GHz Centre home page, larger events are listed where microwave industry and Chalmers interact. GHz Centre is thus a centre with a rich number of activities connecting people across all levels in the organization in our joint effort.

5. Impact on partners (and the rest of the society)

Overview of results absorbed and utilised by industry (and society) to establish new products

After 8 years of operation, GHz Centre can demonstrate ample evidence on how research is transferred from academy to industry. GHz Centre has systematically mapped the effect from research in impact parameters which can be seen as key performance indicators how know-how becomes products, and how people move between organisations (mobility).

Beyond job creations and growth, the impact from results is important for the society to tackle the grand challenges. More efficient power amplifiers in radio base stations from Ericsson will help to communicate faster at lower energy cost. The satellite radiometers by Omnisys Instruments will help to survey climate changes occurring from CO_2 emissions. The progress in GaN HEMTs is used by Saab in radar ssytems to increase our security. The advanced low-noise technologies from Low Noise Factory will be used to probe variations in cosmic microwave background, *i.e.* to answer fundamental questions on the origin of the universe. Such examples of progress is made possible by the vision and mission of GHz Centre, also beyond the ten-year perspective of a VINN Excellence Centre.

The road from research to innovation to full-blown commercialisation is normally non-linear and occurs stepwise. The results from GHz Centre may constitute a major or minor (still essential) part of a product. GHz Centre results may be hardware, models, algorithms, methods, techniques or designs. In addition, people and the developed know-how are part of the impact, often the most valuable ones in technology transfer.

The final products among GHz Centre companies vary from semiconductors to complete systems. A trademark in the set up of GHz Centre is the presence of *different actors in the supply value chain* from research to customer: Spin-offs, chip industry, component manufacturing, design tools, sub-systems and system houses. Most importantly, the latter addresses *three different markets*: Telecom, defence & security and space, all essential areas of strength for Sweden which support and create tens-of-thousands of jobs for the export industry.

This section is divided in three sections which reflect various stages of commercialisation by partners (and the society).

1. Manufacturing and selling of new or improved products

Scientific results from GHz Centre	**Industries exploiting the result**	**Products**	**Comment**
GaN HEMT models and device parameters and extraction techniques	Mitsubishi, Infineon, NXP, UMS	Semiconductor circuits in new GaN HEMT foundry processes. Doherty- and switched-mode power amplifier designs	Other companies outside GHz Centre have also been active in developing the GaN HEMT models
Design and processing of GaN HEMT circuits	Saab, NXP	Wide-band circuits Radar systems Electronic warfare systems	
Cryo-optimized InP HEMT discrete transistors and circuits	Low Noise Factory	Amplifier modules for cryogenic low-noise amplifiers up to 100 GHz	
Algorithms for linearization	NXP, Infineon	Power amplifiers Pre-distortion amplifiers	Long-term memory effects in GaN devices
Chip designs	Sivers IMA	Mm-wave products	
THz components. Diodes and MMICs	Omnisys Instruments	Satellite-based radiometers	

2. Demonstrators, test beds, prototypes and methods, to be used in future products

The results here are utilised in the industrial development of products anticipated for market introduction. The time scale for this may differ; Details are normally not disclosed by the companies.

Scientific results from GHz Centre	**Industries exploiting the result**	**Products**	**Comment**
Power amplifier topologies	Ericsson, NXP, Infineon	Transmitters for radio base stations in 4G mobile communication	
Schottky diode multipliers	Wasa Millimeter Wave	Power sources 70-280 GHz for signal generation and radar	
Pulse width modulation techniques	NXP, Infineon	Switched-mode power amplifier (SMPA) designs Hardware demonstrators for RF-PWM and baseband-PWM transmitters	
Doherty power amplifiers	NXP, Ericsson	Components	Partly developed in Chalmers research projects outside the GHz centre projects
GaN-based low noise amplifiers	Ericsson	Radio base stations	
GaN HEMT process technology	UMS, Infineon, NXP	GaN foundry process	Partly developed in Chalmers research projects outside the GHz centre projects
THz mixer modules	Omnisys Instruments	Subsystems for space instrumentation: STEAMR, GeoStationary	

		Atomspheric Sounder, JUICE	
RF measurement methods	NXP	Power amplifier drivers	
Design of GaN MMIC circuits	Ericsson, Sivers IMA, Infineon, Saab	Oscillator components Microwave backhaul systems Electronic warfare circuits Integrated multilevel SMPA for direct-filter-connect	Partly developed in Chalmers projects outside the GHz centre projects
Large-signal measurements and modelling	Comheat Microwave	LF Power components: LDMOS transistors on high resistivity substrate Latchfree LIGBT devices	Partly developed outside the Centre
Testing of GaN HEMT circuits for space	Ruag Space	Units, e.g. frequency converters, for satellite communication	

3. Industry growth or new companies

The growth of established GHz Centre companies with a size of hundreds to 100,000 employees are of course impossible to trace back to results emanating from the GHz Centre. The hiring of people from Chalmers to GHz Centre industries is described below.

Three spin off companies from the microwave research environment at Chalmers were formed just prior to the GHz Centre start (partly enabled by the predecessor of GHz Centre, VINNOVA Competence Centre CHACH 1995-2006): Gotmic AB, Wasa Millimeter Wave and Low Noise Factory. Two of these have become partners in GHz Centre: Wasa Millimeter Wave in Stage 2 and 3, Low Noise Factory in Stage 3.

Two of the SMEs showing large growth the last 5 years which at least partly can be traced to GHz Centre results are Low Nose Factory (from one to four employees) and Omnisys Instruments (from 14 to 31 employees). Part of this growth is directly due to hiring of PhDs from Chalmers from GHz Centre, see section 8 below.

Competence enhancement for Sweden (and society)

Enhanced competence for Sweden from GHz Centre can estimated by the number of publications, PhDs, workshops, project meetings and centre days. The best way is to measure this through true mobility of people between academy and industry, and the resulting know-how produced and implemented together. Furthermore, GHz Centre is an international centre where industrial competences not found in Sweden (semiconductor manufacturing, devices and design tools) complement the Swedish strengths (subsystems and systems in telecom, defence and space).

Competence enhancement through people's mobility in GHz Centre is detailed in Section 8. Four other parameters for competence enhancement is shown below:

1. Co-published scientific papers Chalmers- industry

GHz Centre Stage	**1**	**2**	**3**	**4**	**Total**
Co-authored Chalmers-industry	23%	43%	50%	-	**45%**

According to bibliometric studies on university – industry scientific co-publishing (CWTS Centre for Science and Technology Studies, University of Leiden), the numbers of GHz Centre are exceptionally high: Chalmers total average is 14% which itself is a high number for a university (Chalmers was last year in this category ranked 3rd among all universities in the world in the Leiden CWTS list.)

Updated roadmaps of new RF/MW technologies for industrial exploitation
Roadmaps for the introduction of new RF/microwave technologies depend critically on new technical know-how. Such roadmaps may ultimately determine whether a company will test or introduce a new technology or not. The following GHz Centre partners have reported updated roadmaps from results in the GHz Centre:

1. Ericsson: GaN HEMTs, PA development
2. Infineon: GaN HEMT, PA architectures, PA linearization concepts, Switched-mode PA and transmitter, RF-power devices for MIMO transmitters
3. Low Noise Factory: InP HEMT, in particular for cryo applications
4. NXP Semiconductors: GaN HEMT
5. Omnisys Instruments: (Sub)mm wave components
6. Saab: GaN HEMT
7. Wasa Millimeter Wave: mm-wave modules based on Schottky diodes
8. Sivers IMA: GaN HEMT, hybrid vs integrated oscillators

2. Manuscripts and inventions disclosed at an early stage from Chalmers to all industrial partners in GHz Centre

Chalmers discloses scientific manuscripts, theses and inventions *before* submission to all GHz Centre partners as agreed upon in the communication plan for the GHz Centre. Such information can be valuable for partners. Industry has a right to postpone publication during three months if content is considered patentable or reveals company secrets.

Stage	**No of industry partners receiving disclosures from Chalmers**	**No of disclosures: Scientific manuscripts, inventions, theses**
1	7	30
2	10	91
3	13	76

3. Patents and licensing

Two patents have been made through GHz Centre:

- "A High Efficiency Wideband Dynamic Load Modulation PA Architecture" by C. Andersson, D. Gustafsson (2011). Application N PCT/EP2012/059354.

Owner: Ericsson
Free license: Comheat Microwave, Infineon, Mitsubishi, NXP, UMS, Saab, SP, Chalmers

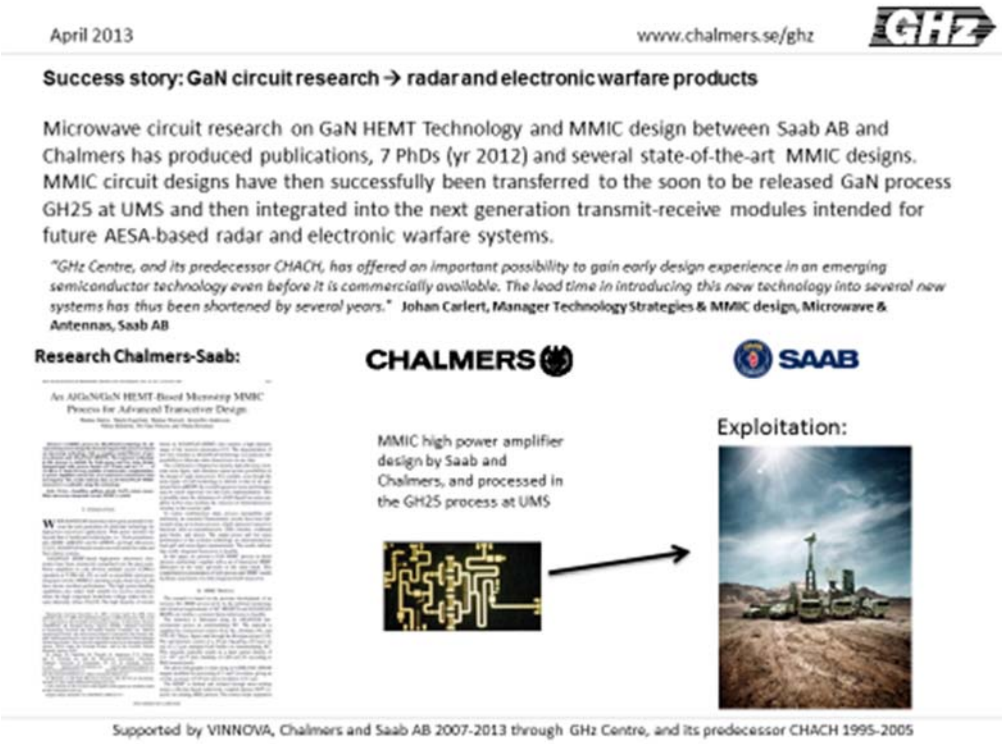
- “Amplifier Apparatus and Method” by M. Özen and C. Fager, 2013. Patent Pending.

Owner: Ericsson
Free license: Saab, NXP, Infineon, National Instruments, Chalmers

<u>Concrete example of research and innovation to the market</u>

The slides shown below are possibile to download at
www.chalmers.se/en/centres/ghz/success-stories

1. <u>From a new semiconductor to system products</u>



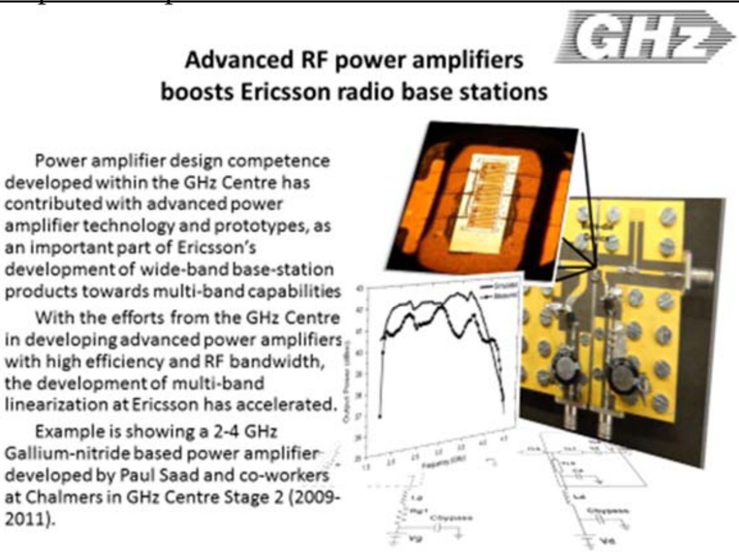
Gallium nitride (GaN) appeared in academic research as a viable transistor (so-called HEMT) solution for microwave generation around 20 years ago. Chalmers started research with some minor efforts in industry with another wide bandgap material silicon carbide. In 2001, the first GaN HEMT was demonstrated at Chalmers. Since then, the research and testing of GaN HEMTs has been rapidly expanding. GHz Centre has been instrumental in this.

Everyone involved in semiconductors is aware of the enormous challenge in convincing an industry in changing from an established chip solution to a new technology. One of the major obstacles is that the full value chain from material, process, design, models, testing, packaging and full system integration must be solved. This is a global undertaking going from basic research to system verification. GHz Centre is one of the few places where such competences can meet and help research coming faster out in products and growth.

The GaN technology itself is complex and much details in the device and characterisation allow research in the GHz Centre. For Ericsson and Infineon the characterization of long-term memory effects has given important insight into critical device physics, which is very valuable knowledge for GaN based PA design and the adaption of linearization algorithms. For Ericsson this knowledge is also very useful in discussions with GaN device suppliers.

Saab has designed GaN front-end MMICs within GHz Centre. These circuits originates from the Chalmers microstrip GaN MMIC process where prototypes were manufactured and then characterized and evaluated by Chalmers and Saab. For large scale production these circuits have now been transferred to industrialized GaN processes among other GHz Centre partners, like UMS GH25. On 12 May 2014, Saab officially announced that five new active electronically scanned array (AESA) radars were launched in their products catalogue. The GaN HEMT technology was a key issue in this, see e.g. http://aviationweek.com/blog/thats-what-i-call-confidence. *"I'm proud to present this important milestone in our surface radar development,"* says Micael Johansson, head of Saab's business area Electronic Defence Systems. Saab also recently announced in Swedish press that *"much of the basic research with GaN has been conducted with Chalmers*".[2] Saab believes that their participation in the project has reduced the time to market by roughly 2-5 years, and the company is now among the first to offer AESA-based systems with GaN inside.

2. Advanced RF power amplifiers for radio base stations in communication

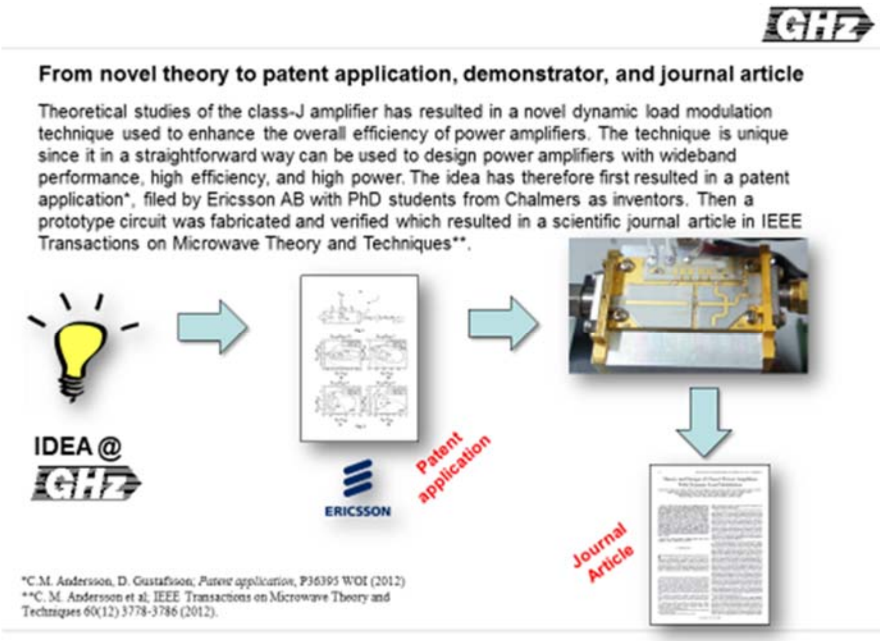


An essential ingredient in the GHz Centre has been new topologies in RF power amplifiers for more efficient and linear transmitters in telecommunication. The GHz centre research has helped Ericsson to accelerate their development in this field.

This research has attracted not only system industry (Ericsson) but also semiconductor businesses (NXP, Infineon, Mitsubishi etc) manufacturing the components highlighting the complementarity and international approach in GHz Centre.

One example of patenting is shown below where Ericsson registered the IP and Mitsubishi co-authored the publication with Chalmers.

[2] http://www.svd.se/naringsliv/branscher/industri-och-fordon/miljardforskning-bakom-saabs-nya-radarsystem_3605952.svd?utm_source=sharing&utm_medium=clipboard&utm_campaign=20140531



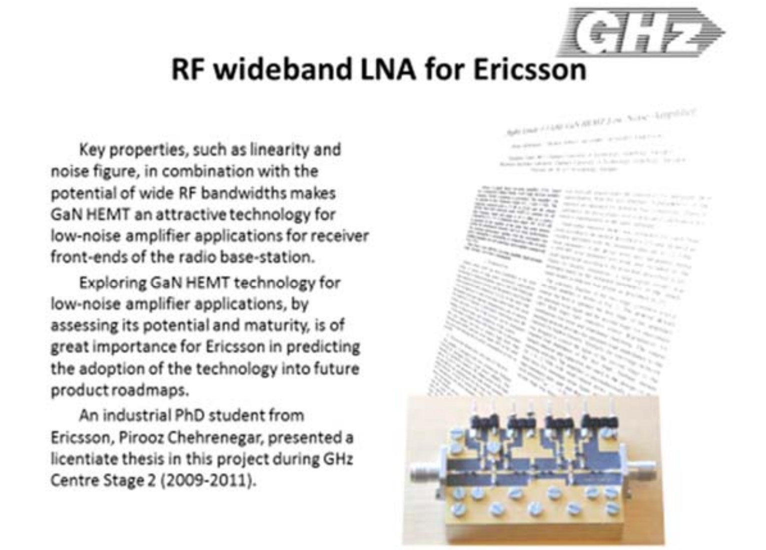
3. <u>Setting an industrial GaN HEMT standard: The Chalmers-Angelov model</u>

The GaN HEMT large-signal model developed by Dr. Angelov in GHz Centre is introduced in the IC CAP design software thus becoming an industrial standard. This model has become the choice for the semiconductor and design houses in GHz Centre:

http://www.eetimes.com/document.asp?doc_id=1280294

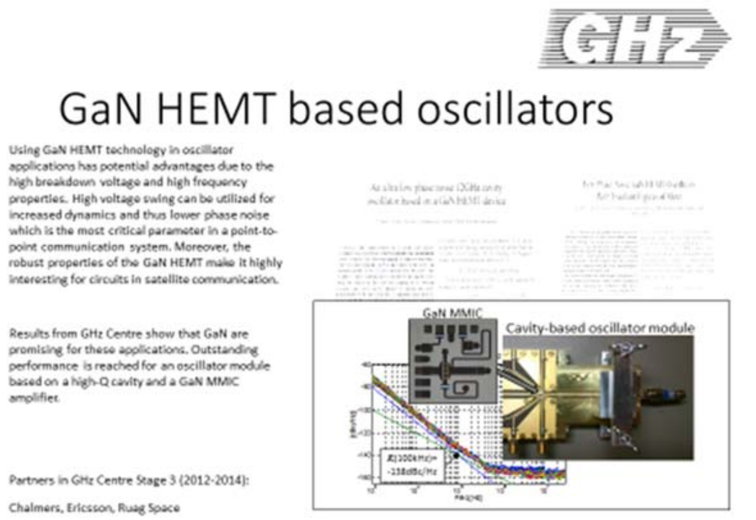
E.g. Mitsubishi is using the large-signal model to optimize the circuit design for specific applications and Infineon will use it in their design nkit as well.

4. <u>RF GaN LNAs for radio base stations</u>



GaN-based HEMT low-noise amplifiers has been tested in GHz Centre for radio base stations reeivers. In this work, an industrial PhD student was involved.

5. <u>Low-phase noise oscillators for microwave radio and space</u>

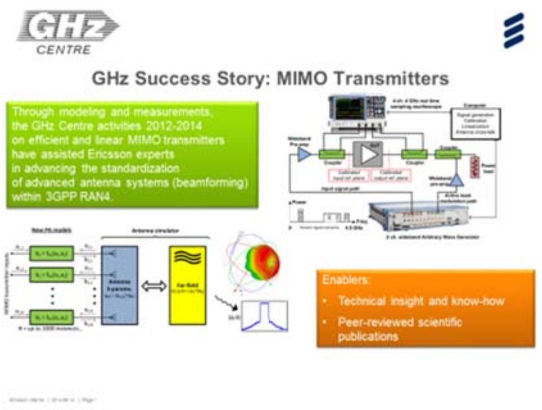


In GaN HEMT oscillators, the industry has stated their needs and the exploitation:

-Ericsson AB: With the ever increasing requirements on traffic capacity in wireless networks for backhaul applications, the need for higher data through put per Hz bandwidth forces more sophisticated modulation schemes to be used. The phase noise performance of the cavity-based oscillator would enable even more complex modulation formats and increased data rate in future generations of microwave link products.

-Ruag Space AB: As bandwidth and frequency of operation is increasing, phase noise requirements for satellite based telecommunication systems have become more stringent. The excellent results have allowed RUAG to start the development of a state-of-the-art oscillator for space applications in collaboration with the research expertise at Chalmers. 7

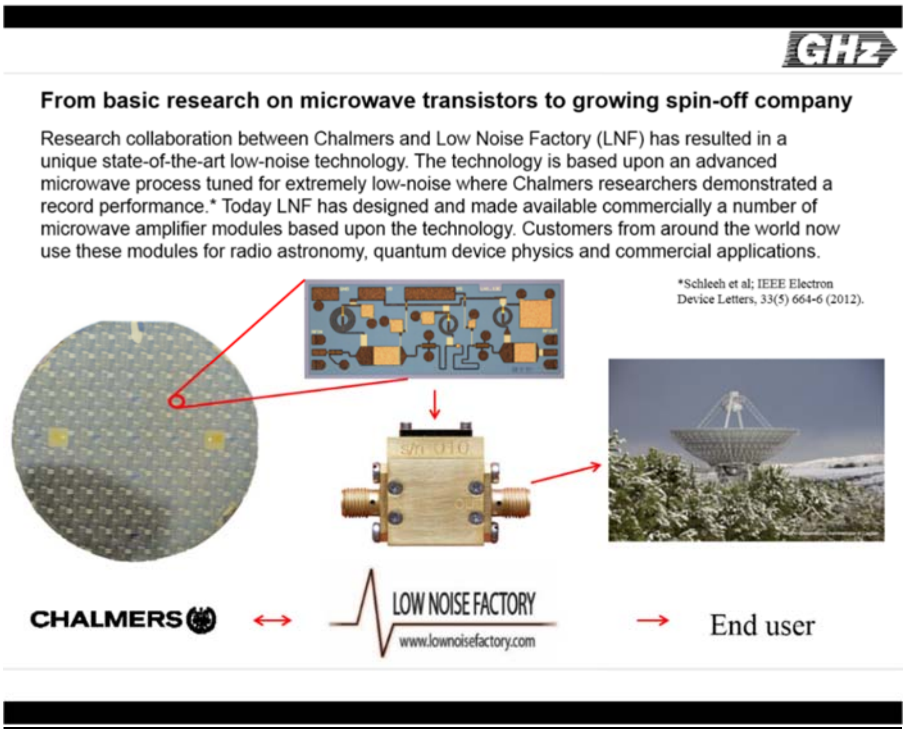
6. Standardization of beamforming antenna systems: MIMO transmitters



7. Helping SME to reach new markets: SiversIMA enters into mm-wave business

Swedish article describing how Sivers IMA is helped by GHz Centre to enter new markets: http://etn.se/index.php?view=article&catid=62%3Areportage&id=55868%3ASivers+.

8. Low-noise amplifier technology boost SME



The research at Chalmers in GHz Centre is based upon understanding device physics and materials for low-noise amplification. The company Low-Noise Factory (LNF) was a spin-out from Chalmers around ten years ago. While the researchers at Chalmers focused on the scientific aspects of InP HEMTs and established a unique low-noise MMIC process (not available in industry) in the Chalmers' cleanroom, the company solved the engineering challenges associated with design and packing including verification of module performance in ultra low-noise amplifiers.

LNF has so far shipped around 1000 microwave amplifiers. Amplifers are sold to radio astronomy facilities (e.g. Allen Telescope Array) as well as to low-temperature physics laboraotries and even to the D-Wave quantum computers.[3] The company is now also targeting large array radio astronomy markets such as ALMA and square kilometre array (SKA) where 100-10,000 low-noise units are needed.

One of the most essential achievements (also together with Chalmers) is low-noise amplifiers for deep space stations at European Space Agency (ESA), European Space Operations Centre (ESOC), Darmstadt, Germany:

"Upgrading the stations means an increase in the return of science data from space missions by 20%," says project manager Stéphane Halté at ESOC. The upgrade enables ESA's 35 m-diameter antennas to perform like 40 m-class dishes, and much less power will be needed aboard the spacecraft. *"This performance boost is a significant benefit for our deep space satellites, now exploring Mars and Venus and soon to go to Mercury, the Lagrange points and Jupiter,"* says Andrea Accomazzo, responsible for interplanetary mission operations at ESOC.

[3] http://www.nature.com/news/google-and-nasa-snap-up-quantum-computer-1.12999

9. <u>THz device research enabling national and international contracts for SMEs</u>

Based on results from GHz Centre, Omnisys Instruments has been awarded with the contract for development of the STEAMR instrument a limb sounding radiometer at 340 GHz with an array receiver of 8 beams. STEAMR is optimized for upper troposphere, i.e. observations down to 6 km altitude. The research profile is towards global climate change and more precisely on stratospheric/troposoheric exchange, ozone changes and water vapour. Key component in STEAMR is a Schottky mixer with integrated LNA that shows world class Trec performance. The STEAMR contract is part of a bi-lateral mission between Sweden and Canada called ALiSS, (Atmospheric Limb Sounding Satellite).

Moreover, in 2013, Omnisys was also selected by ESA as supplier to provide two 557 GHz mixers with embedded LNA for SWI, the Submm-Wave instrument on Jupiter Icy Moon Explorer, JUICE. Juice is the next large mission in ESAs science program directed on chemistry, meteorology and structure of Jupiter’s middle atmosphere. JUICE will investigate and characterize the atmospheres of Ganymede, Europa and Callisto and focus on exploration of their habitable zones. The 557 GHz mixer is developed within GHz Centre and also within the FP7 project Teracomp. JUICE is planned to be launched in 2022 and planned to reach Jupiter in 2030.

Omnisys was also awarded by ESA with the contract for an 875 GHz receiver front-end for an Airborne Icecloud Imager Demonstrator It will act as an airborne pre-cursorfor a possible future ESA satellite instrument which will monitor ice clouds. Omnisys Instruments will develop and deliver two receiver chains based on Schottky development within GHz Centre.

For Wasa Millimeter Wave, the possibility to custom design Schottky diode membrane circuits has made it possible to participate as main supplier and developer of sub-millimeter wave radar front-ends in an international project within the EU FP-7 program. Wasa is also launching a new product series of full-band signal sources up to 280 GHz based on the technology developed in GHz Centre.

6. Financial Report for Stage 3

The Stage 3 economy is described in detail in the financial reports Chapter 11i. Also details for the budget are given in the Research Programme Stage 3. The total economy of GHz Centre is summarised in this table:

GHz Centre Stage 3		Industry	Institutes	Chalmers	Vinnova	SUM	Proportion of total
In kind work	29.2 MSEK	87%	1%	12%	0%	100%	32%
In kind material	17.5 MSEK	39%	1%	60%	0%	100%	19%
Cash	45.4 MSEK	35%	1%	18%	46%	100%	49%
TOTAL	**92.1 MSEK**	**52%**	**1%**	**25%**	**23%**	**100%**	**100%**

The industrial contribution to GHz Centre has steadily increased since the start and is now more than 50% of the total contribution (35% cash).

GHz Centre is indirectly supported by a strong research environment at the two departments. The total research funding is around 70 MSEK per year at the involved laboratories at Chalmers. GHz Centre is the largest single project with more than 20% of the total funding. Some research projects (but far from all) at the departments are highly relevant for the activities and reported in Table 12 “Related Research grants”. Such results are not reported in this document because of other contracts and IPR agreements. The most related research grants to GHz Centre are on GaN HEMT technology development (national and EDA), THz modules (EU), low-noise amplifiers (ESA) and bi-lateral industrial projects on communication (VINNOVA).

In kind contributions

Inkind contributions in GHz Centre are always separated in people (hours) and material (resources like labs, test benches, rooms, hardware etc). The nature of in kind contributions are specified in the GHz Centre Research Programme and even more detailed in the project plans with names on individuals from the partner organisations and the in kind material put to the disposal of GHz Centre and its projects.

As specified in the GHz Centre Research Programme, Chalmers has a relatively large in kind contribution from the measurement and cleanroom laboratories used by the partners in GHz Centre. Two VR (Swedish Research Council) contracts are also used for inkind contributions by Chalmers.

Industry provides in kind to GHz centre mainly with their competence in the form of engineers and researchers taking active part in the projects. Also some material is provided in kind e.g. subsidised GaN MMIC runs, components and instruments.

7. Organisation and Management of the Centre

If not stipulated in the consortium agreement Stage 3, the organisation and the role, relationships and activities of the various groups (including names on individuals) are described in detail in the GHz Centre Research Programme Stage 3.

GHz Centre constitutes one single centre and not individual projects. Strong synergetic effects in the centre come from:

- A very active Steering Board which compromises almost all partners guaranteeing industrial leadership
- Shared positions between the projects for Chalmers involved people, also for PhD students
- One scientific responsible, the Director, also acting Full Professor at Chalmers, well-positioned in the faculty and Chalmers organisation
- Projects with critical mass which gather several companies, many of them members in more than one project
- Transparency between the projects through regular joint meetings in the management group as well as with the Steering Board
- World-leading advisors in our International Advisory Board (IAB)
- Common activities such as centre days, workshops, seminars, meetings, and lobbying

Status and role of the Centre

GHz Centre is hosted by the Department of Microtechnology and Nanoscience (MC2) at Chalmers. The Professors in the GHz Centre are active in the executive functions (Heads, deans etc) at the two involved departments MC2 and Signals and Systems (S2). All the senior researchers in GHz Centre are members of the faculty. Open meetings with the faculty are held regularly to discuss future directions of GHz Centre when forming a new Stage with industry. At the Chalmers central administration, GHz Centre is assigned the status as a formal centre listing of Excellence Centres in Information and Communication Technology. Among all these centres, GHz Centre is the one with largest industrial involvement and highest degree of globalisation.

Process for research, innovation, communication and equality

The challenge for any VINN Excellence Centre is to attract leading companies to become involved in relatively long-term multi-lateral collaboration using their best competence (people) and their own money, not to mention their cash contributions. Therefore, projects must be carefully selected and aligned to gather significant interest *both* in industry *and* academy. GHz Centre does this through constant updating of our positions in intense collaborative undertaking by daily communication in projects, boards and groups. Hence a mutual trust between partners has been developed during many years of collaboration. We see that the VINN Excellence model works using our strategy: Results which originate from research and innovation will migrate from academy to industry and vice versa.
The philosophy have been to strive for maximum openness and as such, the Centre is well integrated in the academic environment of the involved two Departments. Routines are now well-established for project planning, research programs and disclosing early results to all partners, all carried out with a minimum of administrative overhead. Efficient communication is guaranteed through our communication plan described in the research programme Stage 3. The plan for equality, described in the same document, shows that we have reached our goal of 10 females during the Stage 3 which is 5 times more than when we started in Stage 1. All positions at Chalmers for GHz Centre are announced openly so that we are able to recruit people from all over the world.

8. Personnel of High Competence

As witnessed by the attractiveness for companies all over the world to join GHz Centre, we are gathering a high level of competence to the centre. The quest is rather how to use this competence or more precisely, how to "mobilise" the competence.

GHz Centre has taken several measures to stimulate mutual mobility among the partners: (1) three office spaces at MC2 are at the disposal for industry people in GHz centre visiting Chalmers (2) mobility is regularly reported in the projects, e.g. manifested through co-authorship between Chalmers and the industrial partners in the publications (for figures, see Section 5 on impact) (3) unique measurement and cleanroom labs are at hand at Chalmers which attract industrial partners, and (4) industry is financing three of their own employees as so-called industrial PhD students in currently three of the four GHz Centre projects. These industrial employees spend around 80% of their time at Chalmers and become a fully integrated part of the GHz Centre research teams (5) Finally, four of the industrial partners have or are being applied for adjunct Professor positions at Chalmers, meaning that companies let their best experts physically spend around 20% of the time in the GHz academic milieu supervising and teaching PhD students.

In the framework of the projects, Chalmers researchers are visiting the companies for meetings and giving lectures, also to the foreign partners NXP, Infineon and Mitsubishi.

The concrete cases of mobility (more than three weeks of exchange) between Chalmers and partners is listed below:

Industry people spending > 3 full-time weeks at Chalmers

1.	Rik Jos, NXP Semiconductors	Adjunct Prof. Chalmers
2.	Mingquan Bao, Ericsson	
3.	Pirooz Chehrenegar, Ericsson	Former ind. PhD student
4.	Mikael Hörberg, Ericsson	Industry. PhD student
5.	Peter Sobis, Omnisys Instruments	Former industry PhD student
6.	Hans-Olof Vickes, Saab	Adjunct Prof. Chalmers
7.	Ulf Gustavsson, Ericsson	Former industry PhD student
8.	Arne Öistein Olsen, Wasa Millimeter wave	
9.	Niklas Wadefalk, Low Noise Factory (co-employed)	
10.	Sten Gunnarsson, Sivers IMA	
11.	Thomas Emanuelsson, Ericsson	Adjunct Prof.ship, Chalmers Jan 2015
12.	Jörgen Stenarson, SP	
13.	Klas Yhland, SP	Adjunct Prof., Chalmers
14.	Bo Berglund, Ericsson	Adjunct Prof.ship, Chalmers Jan 2015

Chalmers people spending > 3 full-time weeks at industry

1. Kristoffer Andersson at Ericsson
2. Anna Malmros at Infineon[4]
3. Herbert Zirath at Ericsson (co-employed)
4. Joel Schleeh at Low Noise Factory (co-employed)
5. Jan Stake at Wasa Millimeter Wave (founder)
6. Tomas Bryllert at Wasa Millimeter Wave (founder)
7. Niklas Wadefalk at Low Noise Factory (founder)
8. Mustafa Özen, NXP
9. Christer Andersson, Mitsubishi

Chalmers former PhD students and researchers in GHz Centre hired by relevant industry the last three years:

1. Aik Yean Tang to Omnisys

[4] Related research grant to GHz Centre

2. Haying Cao to Ericsson
3. Hossein Nemati to Ericsson
4. Paul Saad to FBH-Berlin, later Ericsson
5. Christer Andersson to Mitsubishi (the first European employee at the *Electro-Optics & Microwave Electronics Technology Department*)
6. Ali Soltani Tehrani to Qamcom AB
7. Sepideh Afsadoost to Ericsson
8. Kristoffer Andersson to Ericsson
9. Joel Schleeh to Low Noise Factory
10. Per Landin to Ericsson (TBC)

International recruitments to GHz Centre at Chalmers at PhD level and above:

1. Post doc Judith Spiegel, Université Catholique de Louvain, Louvain, Belgium (2010-2012)
2. Post doc Helena Rodilla, University of Salamanca, Salamanca, Spain (2011-present)
3. Assistant Professor Koen Buismann, TU Delft, The Netherlands (October 2014-)

The Chalmers senior researchers active in GHz Centre are active in the undergraduate and graduate education at Chalmers. This is very efficient in transferring the industrial mindset learned through GHz Centre to the students. A number of Master and BSc projects have been run in GHz Centre thus meaning that students directly interfere with the industrial collaboration in GHz Centre. Moreover, GHz Centre project leaders arranged a DPD student competition at IMS 2014.

One GHz Centre deputy project leader has the role as Programme Coordinator at Chalmers for the Master Programme in *Microwave, Photonics and Space Engineering*. Project leaders and Professors have been given regular courses in *Wireless and Photonics System Engineering*, *Active Microwave Circuits*, *Microwave Student Projects* and *Analogue Construction*. Thomas Eriksson and Kristoffer Andersson developed a new course directly from the GHz centre model of joining microwave design and communication systems research: The course *Wireless Link* is now given at three Masters programs at Chalmers. Professors Herbert Zirath and Jan Stake were also strongly involved in the undergraduate teaching in courses in *MMIC Design* and *Microwave Engineering*. Several seniors in GHz Centre including the Director have been teaching graduate courses in advanced microwave subjects, e.g. *Modelling of Microwave Devices*, and *Advanced High-Speed Devices*. Guest lectures from industry have been initiated for students in the introductory Master Courses *Wireless Communication* and *Wireless and Photonics System Engineering*. Every year, we also arrange *Wireless Evenings* to gather undergraduate students and selected industries to attract young people to choose the course curriculum in microwave engineering for a future academic or industrial career.

Since the start of GHz centre, the number of PhD students has more than doubled. Of the 14 PhD students in present GHz Centre, 60% had their BSc degree at another university and 50% outside Sweden. Several students were recruited to GHz Centre through the international Master programmes given by MC2 and S2 at Chalmers.We are already at the recruitment interviews asking students if they are prepared to work abroad. The list of international activity in Chapter 11h clearly shows that GHz Centre students have ample opportunity to study abroad and several have done so as part of their PhD studies.

We are constantly taking actions to improve equal opportunities and gender balance through the recruitment processes. The conclusions from the gender project carried out during Stage 2 gave us a strategy to recruit more females to GHz Centre. As a result, we have increased the number of females from 2 (Stage 1) to 10 (soon 11) (Stage 3).

9. Plans for Development

Stage 4 (2015-2016)

For GHz Centre Stage 4, the main objectives of GHz Centre is kept. During 2013 and 2014, several meetings between Chalmers faculties and the companies has been held to formulate Stage 4. The conclusions were:

- Almost all present Stage 3 companies declares that they intend to continue their partnership with GHz Centre in Stage 4.
- Two new companies addressed interest to join and finally became new partners.
- The decision to implement changes when going from Stage 2 to Stage 3 in the oscillator project (replacing InGaP with GaN) and THz project (adding low-noise HEMTs) was correct. As a result, we will continue during Stage 4 with testing and implementations of results at companies.
- The two other projects on digital transmitters and GaN modeling are subject to some change when going from Stage 3 to Stage 4: This reflects the on-going change in industry, e.g. the transition to 5G in telecom industry and the constant evolution of semiconductor technologies to higher frequencies and lower cost (e.g. SiGe BiCMOS). Also GaN HEMT technology is developed in new areas towards new applications. A most valuable new company partner for 5G development is a design tool house, National Instruments.
- The format of GHz Centre Stage 4 is virtually the same as Stage 3: Consortium agreement, research organization and project set up etc. The IAB has already agreed on serving for Stage 4 and will be used as a most important feedback in the discussions of the future.
- The most important action during Stage 4 will be to prepare for beyond 2016, see below. A strategic task force between Steering Boards in GHz Centre and the CHASE Antenna Systems Centre hosted by Chalmers will be assigned for Stage 4 to carry out the preparation for 2017 and beyond. As part of this joint work, a new common project between GHz and CHASE was decided to run during Stage 4.

The following research activities were decided for Stage 4, see Research programme and Budget Stage 4.

- Silicon-based Transmitters for Millimeter-wave Antenna Arrays
- Towards a dispersion free GaN HEMT
- Gallium Nitride Oscillators
- Integrated THz Electronics
- Massive MIMO Testbed (jointly with CHASE). This project will not be carried out with VINNOVA funding.

The General Assembly for Stage 4 where the Board election takes place was held in January 2015.

After VINN Excellence (2017 and beyond)
GHz Centre has since late 2012 discussed on the future after the VINN Excellence period. During 2013 and 2014, these discussions among faculty and with industry intensified and important consensus on the way forward has been reached. In total, 18 meetings in a strategy group have been held including one 24 hour workshop outside Gothenburg in March 2013.

1. <u>Background analysis of the development in technology and applications</u>
When GHz Centre was formulated year 2005-2006, the driving forces were efficient power amplifiers, robust wideband circuits, mm-wave/THz circuits and microwave photonic integration (the latter subject eventually deselected in the research programme). Today, many of these challenges have been overcome and solved although market introduction may still be awaiting, in particular for the higher frequencies. However, the driving forces from the system applications in telecommunication, defence and space still remain the same as they did ten years ago. This is a natural reflection of the strength and stability among Swedish industry actors with needs in RF/microwave for their products. In fact, the development and re-structuring of wireless industry in (west) Sweden the last ten years has been most favourable for GHz Centre with more collaboration and hiring opportunities for the community.

Today we see a development towards higher bandwidths, frequencies, integration and lower cost for most RF/microwave-based applications. Any revolution in our field such as massive deployment of graphene or other post CMOS technologies is not foreseen at the moment. This may change with time and as a result, we will always have an awareness of breakthroughs in science for wireless. For the next years, however, such ground-breaking research will be covered by traditional research funding and this is to some extent already done, e.g. through graphene flagship in H2020. Again, the embedding of an industry-sponsored centre in a strong research milieu such as Chalmers is vital.

In telecommunication, data rates will go to several Gb/s while maintain low(er) cost and high(er) energy efficiency. Integration, adaptivity and intelligence are key words. Other trends are large number of antennas per unit (massive MIMO), smaller cells and higher frequency (mm-wave). All this with be driven by the launch of a new 5G standard for the 2020’s. EU projects such as METIS are already paving the way in this direction and Chalmers and Ericsson are part of this.

In defence and security business, the trend is towards autonomous platforms such as UAVs. Bandwidths will be (much) larger and frequencies go up well into the mm-wave range. Radar sensors in general must be more compact, intelligent and energy efficient, still being robust. Fully digitalised T/R solutions are foreseen. Also in space business, the trend is towards higher integration and lower cost by new packaging, antennas and semiconductor technologies. In space industry, the need for extreme robustness and associated space qualification are added to the list of challenges for future RF/microwave.

2. <u>Situation at Chalmers: GHz Centre and CHASE</u>
Today, the situation for wireless research at Chalmers involving industrial involvement is almost fully focused at MC2 and S2, the former on electronics hardware, the latter on systems and antennas. GHz Centre has been extremely successful in bringing MC2 and S2 departments together by marrying RF design with signal processing meeting the industrial needs for more power-efficient transmission. CHASE is also member of the VINN

Excellence Centre family focusing on antenna systems, all carried out within S2 and a number of company partners.

GHz Centre and CHASE have been benchmarked against each other with respect to research programs and basic set up.[5] While there are large similarities in basic agreement and organisation, there also exists large differences with respect to companies, application targets, and funding. Compared to GHz Centre, CHASE is a much broader centre with more application targets but also more diluted with respect to funding and project sizes. Nonetheless, the benchmarking revealed that there is a large potential to combine the strengths of the two VINN Excellence centres.

3. <u>A new centre collaboration in microwave and antennas 2017-2026</u>

The strategic group from GHz Centre arrived at a conclusion that the technical development outlined above necessitates that the next generation of centre between Chalmers and industry should broaden the scope to include both electronics hardware and antennas. In autumn 2013, we therefore decided to invite CHASE for a new task force formation. The current task force consists of the Directors, the Chairmen, two faculty professors and two other companies from both Steering Boards. Thus all significant industry and academia is represented.

The goal of the task force is to formulate a common centre platform between Chalmers and industry in microwave/antennas starting 2017. The task force is expected to deliver a first report to the Boards autumn 2014. So far we have agreed on the following setup of the proposed centre:

Objectives

- Strengthen the competitiveness of Chalmers and industry
- Support and strengthen new businesses such as spin outs
- Contribute to the Grand Challenges outlined in H2020

Goals

- In the field of microwaves and antennas, among the top three leading centres in the world
- 30-50 company partners
- Turnover 50 MSEK/yr, on the long run 100 MSEK/yr with at least 1/3 from industry and 50% from external funding (in competition)
- Measure impact from the centre among partners: Research papers, PhDs, transfer of results to industry

Strategy

- Critical mass of actors with a long-term vision (10 years)
- A global centre based upon multi-lateral collaboration involving the most competent actors in the field
- Ideas from academy, guiding by industry and vice versa
- Profiling and focus
- Foster a new generation of researchers for the 2020's
- Support from several funding bodies including EU
- Outreach of our results

[5] J. Grahn and S. Sjödin, Task force GHz-CHASE February 2014.

10. Further information

VINNOVA has officially published[6] average outcome of eighteen VINN Excellence Centres (2012) hence allowing a comparison with GHz Centre.

Parameter	GHz Centre (June 2014)	Average VINN Excellence Centre (2012)	Comment
No of persons engaged in the Centre at university	26	38.2	32% less academic people in GHz Centre
Scientific publications/yr	21.7	24.8	12% lower publication rate in GHz
Examined PhDs /yr	1.67	2.89	42% lower PhD dissertations in GHz
Joint publications university-industry/yr (%)	45%	14%[7] (Chalmers average)	221% higher in GHz
People hired in industry/yr	3.3	1.94	70% larger company hiring rate in GHz
Cash industry contribution MSEK / yr	5.28	1.77	198% larger in GHz
In kind industry contribution MSEK / yr	10.4	4.4	136% higher in GHz
Manufacturing and selling of new or improved products	5 partners	2.3 partners	117% higher in GHz
Demonstrators, test beds, prototypes and methods, to be used in future products	9 partners	6.5 partners	38% higher in GHz
Patens / licenses	2 / 12	4.2 / 0.2	Fewer patents but much more licensing in GHz

From the table above and other data in this report, we make the following observations of GHz Centre in relation to an average VINN Excellence centre:

- Embraces a significantly smaller academic environment of the total research milieu meaning lower total scientific production/yr. However, per person the scientific production is larger.
- Involves higher portion of senior researchers than graduate students at the university meaning less number of PhDs/year
- Produces much larger scientific co-authorship between academy and industry
- Generates much larger industrial contributions in cash and inkind
- Creates much larger industrial impact among centre partners

[6] http://www.vinnova.se/en/Publications-and-events/Publications/Products/Results-from-18-VINN-Excellence-Centres-reported-in-2012/

[7] VINNOVAs report does not analyse the number of joint publications between industry and university. For comparison, we have used numbers from the acknowledged Leiden CWTS data base based on bibliometric data in university-industry publishing patterns: www.socialsciences.leiden.edu/cwts/

11. Facts about the Centre

See following Appendices a-j.

a. *CV* in summary of the Centre Director

Curriculum Vitae Jan Grahn, male, born 1962.02.14
Affiliation: Chalmers University of Technology, Department of Microtechnology and Nanoscience (MC2), Microwave Electronics Laboratory

Education and degrees

1999	Docent (Associate Professor Degree), Royal Institute of Technology (KTH),
1993	PhD, Electrical Engineering, KTH
1986	MSc, Engineering Physics, Uppsala University

Current and previous academic positions

2014-	Full Professor, Chalmers
2008-2014	Professor, Chalmers
2001-2008	Associate Professor, Chalmers
2000-2001	Associate Professor, KTH
1996-2000	Research associate, KTH
1993-1996	Assistant Professor, KTH
1991-1992	Visiting scientist, INPG, CEA-LETI, Grenoble

Academic and teaching merits

- Current research: Components for ultra-low noise & power microwave/mm-wave circuits
- 190 publications in peer-reviewed journals and conferences
- 14 invited talks
- 8 PhD students (5 as main supervisor), 2 postdocs
- 11 MSc students
- 8 undergraduate & graduate courses
- Acting international evaluator for scientific journals, research proposals and appointments

Current leadership positions

- Centre Director, GigaHertz Centre
- Member of Executive Group, Department of Microtechnology and Nanoscience (MC2)
- Deputy Head, Microwave Electronics Laboratory, MC2

- Principal grant holder of 201 MSEK (cumulative)
- Large network in microwave academia & industry (~1000 people)
- Senior Member IEEE (MTT, EDS) and European Microwave Association

Former leadership achievements

2009-2012	Director, Area of Advance Information and Communication Technology, Chalmers
2011, 2015	Chairperson NT-L, NT-13 panel, Swedish Research Council (VR)
2008-2010	Leadership training, VINNOVA
2005-2010	Board member Microwave Road (www.microwaveroad.se)

2003-2014	Led nine successful negotiations between Chalmers and industrial consortia resulting in 50 MSEK cash to long-term research & innovation funding from industry
2008	General Chairperson for the largest Swedish microwave conference (300 delegates)
2008-2010	Vice Head, Industrial Relations, MC2
2007	Initiated together with industry European Radio Microwave Interest Group (EuRaMIG), a network for microwave technology stakeholders in Europe (www.euramig.org)
2006	Initiated and formed GigaHertz Centre between Chalmers and industry (www.chalmers.se/ghz)
2003-2007	Board Member SSF Strategic Research Centre STRINGENT, Linköping University
2002-2006	Deputy Director SSF Strategic Research Centre High-Speed Electronics and Photonics
2001-2006	Centre Director, Chalmers Centre of High-Speed Technology (CHACH)

b. Centre Partners Stage 3 (2012-2014)

TABLE 1

If more than one business unit of the company is involved in GHz Centre, relevant sub-units are listed below the organization name.

1. Chalmers University of Technology
   Department of Microtechnology and Nanoscience – MC2
   Department of Signals and Systems – S2
   Key contact: Jan Grahn, Professor and Centre Director, Göteborg, Sweden

2. SP Technical Research Institute of Sweden
   Key contact: Contact person: Håkan Nilsson, Manager, Borås, Sweden

3. Comheat Microwave AB (SME)
   Key contact: Klas-Håkan Eklund, CEO, Uppsala, Sweden

4. Ericsson AB
   Ericsson AB, Kista, Sweden (radio base station unit)
   Ericsson AB, Göteborg, Sweden (radio base station unit)
   Ericsson Research (Microwave and High Speed Research Centre)
   Key contact: Peter Olanders, Research manager, Kista, Sweden

5. Infineon Technologies AG
   Key contact: Franz Dielacher, R&D manager, Villach, Austria

6. Low Noise Factory AB
   Key contact: Niklas Wadefalk, CTO, Mölndal, Sweden

7. Mitsubishi Electric Corporation
   Key contact: Masatoshi Nakayama, Manager RF amplifier team, Kamakura, Kanagawa, Japan

8. National Instruments, US
   Key contact: Takao Inoue, Ph.D. Sr. RF Platform Engineer, Austin, TX, USA

9. NXP Semiconductors
   Key contact: Rik Jos, RF expert and Adjunct Professor, Chalmers, Nijmegen, The Netherlands

10. Omnisys Instruments AB (SME)
    Key contact: Martin Kores, CEO, Göteborg, Sweden

11. Ruag Space AB
    Key contact: Paul Häyhänen, Vice President, Microwave Products Unit, Göteborg, Sweden

12. Saab AB
    Saab Electronic Defence Systems, Göteborg
    Key contact: Johan Carlert, Manager, Göteborg, Sweden

13. Sivers IMA AB (SME) (2012-2013)
    Key contact: CEO Olle Westblom, Kista, Sweden

14. United Monolithic Semiconductors (UMS)
    Key contact: Hervé Blanck, Manager Technology Development, Ulm, Germany

15. Wasa Millimeter Wave AB (SME)
    Key contact: Arne Øistein Olsen, CTO, Göteborg, Sweden

c. Board of Directors

TABLE 2

The Board of Directors in GHz Centre Stage 3:

- *Chairperson:* Peter Olanders, Manager, Ericsson AB, Kista, Sweden
- Herbert Zirath, Professor High-Speed Electronics, Chalmers, Göteborg, Sweden
- Arne Svensson, Professor, Chalmers, Göteborg), Sweden (appointed by President of Chalmers)
- Klas-Håkan Eklund, CEO, Comheat Microwave AB, Sollentuna, Sweden
- Franz Dielacher, R&D manager, Infineon AG, Villach, Austria
- Rik Jos, RF expert, NXP Semiconductors, Nijmegen, The Netherlands
- Martin Kores, CEO, Omnisys Instruments AB, Göteborg, Sweden
- Paul Häyhänen, Ruag Space, Göteborg, Sweden
- Johan Carlert,, Manager, Saab AB, Göteborg, Sweden
- Olle Westblom, CEO, Sivers IMA AB, Kista (2012-2013)
- Håkan Nilsson, Manager, SP Technical Research Institute of Sweden, Borås, Sweden
- Hervé Blanck United Monolithic Semiconductors, Ulm, Germany
- Arne Øistein Olsen, CTO, Wasa Millimeter Wave, Göteborg, Sweden

Invited public authority representative at the Board meetings:

- Bengt Nilsson (2012-2013), Tommy Schönberg (2014), VINNOVA, Stockholm, Sweden

d. Management Team Stage 3

TABLE 3

- Jan Grahn, Professor, Chalmers
  Centre Director
- Cristina Andersson, Chalmers
  Centre Coordinator
- Herbert Zirath, Professor, Chalmers
  Member of Steering Board
- Christian Fager, Associate Professor, Chalmers
  Project leader EMIT
- Thomas Eriksson, Professor, Chalmers
  Deputy Project leader EMIT
- Mattias Thorsell, Assistant Professor, Chalmers
  Project leader ACC
- Hans Hjelmgren, Associate Professor, Chalmers
  Deputy Project leader ACC
- Dan Kuylenstierna, Assistant Professor, Chalmers
  Project leader GANOSC
- Peter Sobis, PhD, Omnisys Instruments
  Project leader SPACETHZ
- Per-Åke Nilsson, PhD, Chalmers
  Deputy project leader SPACETHZ

e. International Scientific Advisory Board (IAB) GHz Centre

TABLE 4

- Professor Fadhel Ghannouchi, iCORE/CRC Chair, Director iRadio Laboratory, The University of Calgary, Canada, IAB member Stage 1,2,3,4

- Professor Arttu Luukanen, Director MilliLab, VTT, Helsinki, Finland, IAB member Stage 3,4

- Professor Dr.-Ing. Ilona Rolfes, Institute of Microwave Systems, Ruhr University Bochum, Germany, IAB member Stage 3, 4

IAB Alumni:

- Dr. Ing.Marianne Germain, Co-Founder & CEO, EpiGaN, Leuven, Belgium
  IAB member Stage 2

- Professor Larry Larson, Director Center for Wireless Communications, University of California at San Diego, San Diego, USA (present: Brown University),
  IAB member Stage 1, 2

- Professor Joy Laskar, Director Georgia Electronic Design Center, Georgia Tech Atlanta, USA, (present: Anayas360). IAB member Stage 1,2

- Professor Masaaki Kuzuhara, Department of Electrical and Electronics Engineering University of Fukui, Fukui, Japan
  IAB member Stage 1

Research Program

TABLE 5

Staff allocation is listed below of the GHz Centre research projects and management for the full Stage 3 (2012-2014).

The total number of hours are given (cash + in kind).

A person-year corresponds to 1680 hours per year.
The FTE (full-time equivalent) is person-year in %.

Note that in the financial report in Chapter 11i, only people working > 5 % are listed.

EMIT	Name	Gender	Position	Hours	FTE [%]
Chalmers, MC2	Christian Fager	M	Associate Professor	3024	60
	Paul Saad	M	PhD student	1360	27
	Mustafa Özen	M	PhD student	3780	75
	Ankur Prasad	M	PhD student	637	13
	Christer Andersson	M	PhD student	277	6
Chalmers, S2	Thomas Eriksson	M	Professor	1764	35
	Ali Soltani Tehrani	M	PhD student	1008	20
	Jessica Chani	F	PhD student	4032	80
	Per Landin	M	Post-doc	2520	50
	Katharina Hausmair	F	PhD student (VR project)	2688	53
Ericsson	Ulf Gustavsson	M		2520	50
	Lars Ridell-Virtanen	M		250	5
	Johan Thorebäck	M		250	5
	Peter Wright	M		250	5
	Daniel Åkesson	M		250	5
	Thomas Emanuelsson	M		150	3
	Tobias Svensson	M		225	4
	Björn Gävert	M		225	4
SAAB	Hannes Illipe	M	Senior Design Engineer	750	15
	Bengt Svensson	M	Senior Design Engineer	200	4
Infineon	Peter Singerl	M		300	6
	Christian Schuberth	M		300	6
NXP Semiconductors	Rik Jos	M	Fellow RF Technology / Adj. Professor	540	11
	Fred v Rijs	M	Senior Principal Engineer	160	3
	Mark vd Heijden	M	Principal Engineer	160	3
National Instruments	Takao Inoue	M	Senior RF Platform Engineer	250	5
	Payman Tehrani	M		50	1
			Sum cash hrs	**15882**	**11.0**
			Sum inkind hrs	**25400**	**5.5**
			Sum total hrs	**41282**	**16.4**

ACC	Name	Gender	Position	Hours	FTE [%]
Chalmers	Mattias Thorsell	M	Project leader	4200	83
	Kristoffer Andersson	M	Deputy project leader	2688	53
	Iltcho Angelov	M	Researcher	258	5
	Hans Hjelmgren	M	Researcher	504	10
	Christer Andersson	M	PhD Student	2268	45
	Ankur Prasad	M	PhD Student	1701	34
	Sebastian Gustafsson	M	PhD Student	2688	53
	Olle Axelsson	M	PhD Student	1680	33
SP	Jörgen Stenarsson	M		504	10
	Klas Yhland	M		504	10
Comheat Microwave	Klas-Håkan Eklund	M		2520	50
	Lars Vestling	M		1260	25
Ericsson	Lars Ridell-Virtanen	M		252	5
	Johan Thorebäck	M		252	5
	Peter Wright	M		252	5
	Daniel Åkesson	M		252	5
	Tobias Svensson	M		225	4
	Björn Gävert	M		225	4
	Thomas	M		150	3
	Emanuelsson	M			
Infineon	Helmut Brech	M		150	3
	Peter Singerl	M		150	3
Mitsubishi Electric	Masatoshi Nakayama	M	RF manager	270	5
	Koji Yamanaka	M	Engineer	420	8
	Toshiyuki Oishi	M	Engineer	270	5
	Hiroshi Ohtsuka	M	Engineer	270	5
	Yutaro Yamaguchi	M	Engineer	270	5
NXP Semiconductors	Rik Jos	M	Fellow RF Technology / Adj. Professor	540	10
	Fred van Rijs	M	Senior Principal Engineer	160	3
	Vittorio Cuoco	M	Principal Engineer	160	3
Saab	Niklas Billström	M		750	15
	Joakim Nilsson	M		750	15
	Hans-Olof Vickes	M		750	15
United Monolithic Semiconductors	Hervé Blanck	M		200	
	NN2				
			Sum cash hrs	**16995**	**337**
			Sum inkind hrs	**10298**	**205**
			Sum total hrs	**27293**	**542**

GANOSC	Name	Gender	Position	Hours	FTE [%]
Chalmers MEL	Szhau Lai	M	Ph. D. Student	3360	67
	Dan Kuylenstierna	M	Ph. D., Proj leader	3024	60
	NN	M	Ph. D student	3360	67
	Bertil Hansson	M	Ph. D., Researcher	100	2
	Herbert Zirath	M	Professor	100	2
	Iltcho Angelov	M	Ass. Professor	100	2
EAB Mölndal	Minquan Bao	M	Ph.D., Engineer	1500	30
	Thomas Emanuelsson	M	Senior specialist	100	2
	Joakim Een	M	M. Sc.	100	2
	Biddut Banik	M	Ph. D.	100	2
Sivers IMA	Christer Stoij	M	M.Sc.	500	10
	Anette Brandt	F	M. Sc	500	10
	Sten Gunnarsson	M	Ph. D.	200	4
Ruag AB	Jörgen Nilsson	M		300	6
	Robert Petersson	M		200	4
	Fredrik Uddgren	M		300	6
	Paul Häyhänen	M		100	2
			Sum cash hrs	**9744**	**193**
			Sum inkind hrs	**4200**	**83**
			Sum tot	**13944**	**277**

SPACETHZ	Name	Gender	Position	Hours	FTE
Chalmers	Per-Åke Nilsson	M	Scientist	2016	40
	Joel Schleeh	M	Ph.D	1638	32.5
	Klas Eriksson	M	Ph.D	504	10
	Bertil Hansson	M	Scientist	504	10
	Vladimir Drakinskiy	M	Scientist	1512	30
	Huan Zhao	F	Scientist	1512	30
	Johann Hanning	F	Ph.D	1512	30
	Aik-Yean Tang	F	Ph.D	882	17.5
SP	Klas Yhland	M	Scientist	453.6	9
	Jörgen Stenarsson	M	Scientist	453.6	9
SP	Klas Yhland	M	Scientist	126	2.5
	Jörgen Stenarsson	M	Scientist	126	2.5
LNF	Niklas Wadefalk	M	RF Designer	1512	30
	Ann	F	Technician	756	15
Omnisys	Peter Sobis	M	RF Designer	2268	45
	Tony Pellikka	M	RF Designer	504	10
	Ulrika Krus	F	Microwave Engineer	252	5
	Christina Tegnander	F	Mechanical Engineer	252	5
	Jan Jönsson	M	Mechanical Engineer	252	5
	David Runesson	M	DC/Power Designer	252	5
	Slavko Dejanovic	M	RF Designer	252	5
Wasa	Oistein Olsen	M	RF Designer	352.8	7
	Tomas Bryllert	M	RF Designer	151.2	3
			Sum cash hrs	4267.2	218
			Sum inkind hrs	2570.4	140
			Sum total hrs	**6837.6**	**358**

f. **Publication and Presentation Activity**

TABLE 6

The results have been produced 2007.01.01-2014.12.31 and are given in cumulative order in the following structure (some publications are reported 2015):

- Journal Publications
- Conference Proceedings (refereed)
- Conference or workshop presentations
- Invention disclosures
- Patents
- PhD theses
- Licentiate theses (corresponds to a half PhD thesis)
- MSc theses
- BSc theses
- Other (General GHz Centre presentations and reports)

Only work funded by GHz Centre partners, *i.e.* VINNOVA, industry and Chalmers, is included here. Related work is not presented here since these do not obey under the GHz Centre IPR rules.

Citations are given for journal articles. Citations source: Web of Science Core Collection.
* means a co-published article between Chalmers and a (commercial) company partner in GHz Centre.

The project name (acronym) where the result has been produced is given in parentheses after each post:

GHz Centre Stage 1 (2007-2008):

- SMPA: Switched-Mode Power Amplifiers
- WIDEBAND: Wideband WBG transceivers
- FREQ: Frequency Generation
- THZ: Terahertz Sensors

GHz Centre Stage 2 (2009-2011):

- DIGIPA: Digitally Enhanced Power Amplifiers
- EXPO: Exploring the potential of future GaN and LDMOS technologies
- INTOSC: Integrated Oscillators
- THZ+: THz Radiometers

GHz Centre Stage 3 (2012-2014):

- EMIT: Energy Efficient MIMO Transmitters
- ACC: Advanced Characterization and Modeling for Technology Optimization of Multifunctional Circuits
- GANOSC: GaN Oscillators
- SPACETHZ: THz Space Components

Impact factors for journals:

Journal	Impact factor	Source
IEICE T. on Electronics	0,4	Cite factor
IET Microwaves, Antennas & Propagation	0,681	Cite factor
IEEE T. on Circuits and Systems I - Express Briefs	1,327	IEEE Xplorer
Solid-State Electronics	1,397	Cite factor
IEEE Microwave Magazine	1,495	IEEE Xplorer
IEEE Microwave and Wireless Components Letters	1,784	IEEE Xplorer
IEEE T. on Electron Devices	2,062	IEEE Xplorer
IEEE T. on Terahertz Science and Technology	2,111	Cite factor
IEEE T. on Microwave Theory and Techniques	2,229	IEEE Xplorer
IEEE T. on Circuits and systems I: regular papers	2,24	IEEE Xplorer
Journal of Applied Physics	2,789	IEEE Xplorer
IEEE Electron Device Letters	2,849	IEEE Xplorer

Downloadable content:

The journal publications, PhD and licentiate theses and "Other" may be downloaded at GHz Centre webpage http://www.chalmers.se/ghz/EN/publications

The presentations at internal activities such as GHz Centre Day, workshops or project meetings are not shown in these Tables. These can be found at the http://www.chalmers.se/ghz/EN/events

For password protected content at the www.chalmers.se/ghz, see instructions in Chapter 11j.

Legal contracts, IAB reports and project plans are handed out on request:
mail to ghz@chalmers.se

Journal publications

1. M .Thorsell, K. Andersson, M. Fagerlind, M. Südow, P.-A. Nilsson, N. Rorsman, "Thermal Study of the High-Frequency Noise in GaN HEMTs*," IEEE Transactions on Microwave Theory and Techniques*, vol.57, no.1, pp.19-26, January 2009. (WIDEBAND) times cited: 16
2. H. Cao, A. Soltani Tehrani, C. Fager, T. Eriksson, and H. Zirath, "I/Q Imbalance Compensation Using a Nonlinear Modeling Approach," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, pp. 513-518, 2009. (SMPA)times cited: 30
3. H. M. Nemati, C. Fager, M. Thorsell, and H. Zirath, "High-Efficiency LDMOS Power-Amplifier Design at 1 GHz Using an Optimized Transistor Model," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, pp. 1647 - 1654, 2009. (SMPA) times cited: 19
4. H. M. Nemati, C. Fager, U. Gustavsson, R. Jos, and H. Zirath, "Design of Varactor-Based Tunable Matching Networks for Dynamic Load Modulation of High Power Amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, pp. 1110-1118, 2009. (DIGIPA)* times cited: 44
5. I. Angelov, M. Thorsell, M. Fagerlind, K. Andersson, A. Inoue, K. Yamanaka, and H. Noto, "On the Large Signal Evaluation and Modeling of GaN FET*," IEICE Transactions on Electronics*, vol. E93.C, no. 8, pp. 1225-1233, 2010. (EXPO)* times cited: 0
6. P. Saad, C. Fager, H. Cao, H. Zirath, and K. Andersson, “Design of a Highly Efficient 2–4-GHz Octave Bandwidth GaN-HEMT Power Amplifier,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 7, pp. 1677-1685, July 2010. (EXPO) times cited: 33
7. P. Saad, C. Fager, H. Cao, H. Zirath, and K. Andersson, “A highly efficient 3.5 GHz inverse class-F GaN HEMT power amplifier,” *International Journal of Microwave and Wireless Technologies*, pp. 317-324, 2010. (EXPO) times cited: 5
8. M. Thorsell, M. Fagerlind, K. Andersson, N. Billström, and N. Rorsman, “An X-band AlGaN/GaN MMIC receiver front-end," *IEEE Microwave and Wireless Components Letters*, vol. 20, no. 1, pp. 55-57, January 2010. (EXPO)* times cited: 8
9. U. Gustavsson, T. Eriksson, and C. Fager, "Quantization Noise Minimization in Delta Sigma-modulation based RF Transmitter Architectures," *IEEE Trans. Circ. Syst. I*, vol. 57, pp. 3082-3092, 2010. (DIGIPA)* times cited: 10
10. H. M. Nemati, H. Cao, B. Almgren, T. Eriksson, and C. Fager, "Design of Highly Efficient Load Modulation Transmitter for Wideband Cellular Applications," *IEEE Trans. Microwave Theory Tech.*, vol. 58, pp. 2820-2828, 2010. (DIGIPA)* times cited: 13
11. A. Soltani Tehrani, H. Cao, S. Afsardoost, T. Eriksson, M. Isaksson, and C. Fager, "A Comparative Analysis of the Complexity/Accuracy Tradeoff in Power Amplifier Behavioral Models," *IEEE Trans. Microwave Theory Tech.*, vol. 58, pp. 1510-1520, 2010. (DIGIPA) times cited: 41
12. L. H. Hsu, D. Kuylenstierna, R. Kozhuharov, M. Gavell, C. Kärnfelt, H. Zirath, E. Y. Chang, and W. C. Lim, “Flip-Chip Based Multi-Chip Module for Low Phase-Noise V-Band Frequency Generation,” *IEEE Trans. Microwave Theory Tech.*, v. 58, n. 9, 2408-2418, 2010. (INTOSC) times cited: 0

13. H. Cao, H. M. Nemati, A. Soltani Tehrani, T. Eriksson, J. Grahn, and C. Fager, "Linearization of Efficiency-Optimized Dynamic Load Modulation Transmitter Architectures," *IEEE Trans. Microwave Theory Tech*., pp. 873-881, 2010. (DIGIPA) times cited: 15
14. H. M. Nemati, P. Saad, C. Fager, and K. Andersson, "High-efficiency amplifier," *IEEE Microwave Magazine*, vol. 12, no. 1, pp. 81-84, 2011. (EXPO) times cited: 4
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g. International Activity

TABLE 7

GHz Centre can list international collaborations with 9 universities, 2 governmental labs or institutes, and 6 industries. In total, 13 individuals have been or will be able to temporarily shift research environment by PhD student exchange or post doc contracts in GHz Centre. In addition, we have also an extensive international network through the international advisory board and the EuRaMIG.

- Industrial collaborations:

NXP Semiconductors, Nijmegen, The Netherlands (formal GHz Centre partner)
Contact: Rik Jos, Research Fellow and RF expert, NXP
Rik Jos is also adjunct Professor at Chalmers.
Rik Jos spends 20% of his time at Chalmers in GHz Centre.

Infineon Technologies, Villach, Austria (formal GHz Centre partner)
Contact: Franz Dielacher
Franz Dielacher is very active in the Board and the EuRaMIG project. He also provides contacts with ENIAC.

Mitsubishi Electric Corporation, Kamakura, Kanagawa, Japan (formal GHz Centre partner)
Contact: Koji Yamanaka

IAF Fraunhofer Gesellschaft, Freiburg, Germany
Contact: Michael Schlechtweg
This collaboration took place mainly in Stage 1.
This collaboration takes part through Omnisys Instruments where MMICs were designed and processed in the IAF 100 nm MHEMT process. Several joint papers have been produced.

WIN Semiconductor, Taiwan
Collaboration on MHEMT wafer runs for integrated MMIC oscillator designs

Cree Inc., Rayleigh, North Carolina, US
GaN HEMTs for power amplifiers

Triquint Semiconductor, Hillsboro, Oregon, US
GaN HEMTs for power amplifiers

NMDG, Bornem, Belgium
Collaboration on large-signal network analysis

- Academic exchanges

- Dr. Sergio Pires, Univ. Aveiro to GHz Centre (Prof. José Carlos. Pedro)
- PhD student Rob Smith, Cardiff to GHz centre (Prof. Paul Tasker)
- PhD student Hossein Nemati, GHz Centre to Cardiff University (Prof. Paul Tasker)
- PhD student Ulf Gustavsson, GHz Centre to University of Aveiro, Aveiro, Portugal (Prof. José Carlos. Pedro)
- PhD student Mattias Thorsell, GHz Centre to Vrije University Brussels, Belgium (Prof. Yves Rolains)
- PhD student Paul Saad, GHz Centre to Tor Vergata University, Rome, Italy (Prof. Paolo Colantonio)
- PhD student Mustafa Özen, GHz Centre to NXP Semiconductors, Nijmegen, The Netherlands (Prof. Rik Jos)
- PhD student Haiying Cao, GHz Centre to University of Delft, Delft, The Netherlands (Prof. L. van de Vreede)
- PhD student Alan Clarke, University of Cardiff, Cardiff, UK (Prof, P. Tasker) to GHz Centre
- PhD student Aik Yean Tang, GHz Centre to Jet Propulsion Laboratory, Pasadena, California, USA (Prof. Peter H. Siegel)
- PhD student Christer Andersson, GHz Centre to Mitsubishi Electric, Kanagawa
- PhD student Junghwan Moon, POSTECH, Korea (Prof. Bumman Kim) to GHz Centre
- PhD student Joel Schleeh, GHz Centre to Caltech/JPL, USA (Prof. Sandy Weinreb),
- Associate Professor Christian Fager to UCSD, San Diego (Prof. P. Asbeck)

- International Scientific Advisory Board members

- Arttu Lukkanen, VTT, Finland
- Marianne Germain, EpiGaN, Leuven, Belgium
- Ilona Rolfes, Ruhr Universität Bochum, Germany
- Fadhel Ghannouchi, Univ. Calgary, Canada
- Larry Larson, UCSD, USA
- Joy Laskar, GeorgiaTech, USA
- Masaaki Kuzuhara, University of Fukui, Japan

- EuRaMIG

Through the European Radio and Microwave Interest Group (EuRaMIG) in Europan Microwave Association, we have also established a network with major microwave players in Europe. The most essential non-Swedish members in the EuRaMIG core group are:

- Franz Dielacher, Infineon Technologies, Villach, Austria (Chairperson)
- Marc Rocchi, OMMIC, Paris, France
- Klaus Beilenhoff, UMS, Ulm, Germany
- Rik Jos, NXP Semiconductors, Nijmegen, Holland.
- Wolfgang Heinrich, Ferdinand Braun Institut, Berlin, Germany (also President in European Microwave Association)
- Tom Brazil, UC Dublin, Ireland
- Rüdiger Quay, IAF Fraunhofer, Freiburg, Germany
- Georg Fischer, Nurnberg-Erlangen University
- Jean-Louis Cazaux, Thales Alenia Space
- Wolfgang Bösch, TU Graz
- Roberto Sorrentino, Perugia Univ.

h. Financial Reports

TABLE 8: Overall resources available
TABLE 9: Overall expenditures
TABLE 10: Research personnel
TABLE 11: Project expenditures
TABLE 12: Related research grants

See Appendices at the end of this report

i. Websites

Detailed information of results and activities in GHz Centre are available on the GHz Centre home page. Here links are provided to partners, research, results, publications, events, workshops, presentations, theses and success stories. Many but not all documents are subject to download, in some cases using a password; See below.

Official homepage for GigaHertz Centre:

www.chalmers.se/ghz

- Welcome page with News and official viewgraph presentation and folders
- About
- Research
- Partners
- Events (see password info below)
- International Advisory Board
- Contact
- Publications (see password info below)
- Success stories

Due to copyright reasons, journal publications are only possible to download using a pass word.
This pass word can also be used for downloading internal meeting presentations (e.g. GHz Centre Days) listed under Events.

If you request a listed conference publications or presentation not possible to download, send a mail to ghz@chalmers.se

The GHz Centre legal contracts and project plans are handed out on request.
Send a mail to ghz@chalmers.se

12. Response to the evaluation report before start of stage 3

GHz Centre Stage 2 was subject to an international evaluation 29-30 September 2011. 17 recommendations were given and actions to comply with these were described in the research programme Stage 3.

GHz Centre Baord and Director presented the reports from the two international evaluations for the IAB. In their report from November 2013, IAB states: *"The Centre has carried out two international evaluations and implemented or taken action on, if not all, most of the recommendations."*

Below is the result of the implementations from evaluation report Stage 2.

Recommendation	**Action**
1. That the Board and management develop mechanisms to detect if the Centre is indeed enabling speedier translation of scientific advances to its company partners.	As seen in the Section 5 on Impact, there is now compelling evidence that this mission is valid and carried through.
2. The Centre should carry out a commercial risk analysis before terminating the InGaP HBT-based MMIC theme.	Accomplished by Chalmers and involved companies in the project plan and progress reports of the oscillator project.
3. The Centre should budget for an increased ratio of PhD to senior researchers.	We have increased from 10 to 13 PhDs.
4. That the Centre benchmark its research output at project level against the academic state of the art.	Implemented in project plans and reports.
5. That the Centre increases the total number of patents plus publications per FTE/Yr in Stage 3.	The research productivity has increased, see Section 3. The No of patents have increased.
6. That the Centre urgently establishes consensus on an IPR model and a matching Board structure that removes the apparent tension over intellectual property ownership and management.	Accomplished through the modified consortium agreement Stage 3.
7. That the Centre develop metrics that distinguish between and enable recording of commercialization and research successes.	Accomplished, see section 5 on measuring impact from GHz centre. To be followed up Stage 4.
8. That the Board take responsibility for strategic planning, goal setting, guidance to management, and monitoring of performance ensuring that the added value of having a Centre is maximised	Addressed through the implementation of the GHz Centre Research Programme Stage 3.
9. That the Centre Director, working with the management team, leads, proposes, executes and reports on activities against the Centre's agreed strategic and operational plans.	Addressed through the implementation of the GHz Centre Research Programme Stage 3.

10. That the Board and management improve goal setting (utilising the advice of the IAB) to establish realistic goals for all aspects of Centre operations in Stages 3 and 4.	A new set of goals were formulated for Stage 3, see Research Programme.
11. That the Board and management work together to improve and clarify the current KPI matrix scoreboard to ensure that the chosen key performance indicators truly provide information on progress on the Centre's short and long-term goals and delivery on the Centre Mission.	A new set of indicators showing the way towards the goals were agreed upon in the Board and stated in the GHz Centre Research Programme Stage 3.
12. That improved communication be a major feature of Stage 3 plan and progress on this be monitored closely by the Board.	The communication plan was re-written in the Research Programme. Together with the revised organisation, we have now settled a high degree of transparency between the projects thus avoiding "silos" in the centre.
13. That the Board be more pro-active in ensuring that the finances of the Centre follow the operational plans approved by VINNOVA.	This recommendation was based upon a misunderstanding (typo) of the economy Excel file. We have fully followed the financial plan and it has been approved by the Board and VINNOVA.
14. That the Centre develop and implement individual career training programs for young research scientists.	GHz Centre has fostered a new generation of young scientists as witnessed by promotions and successful careers among young scientists. Developing training programs for young scholars are not within the scope of the centre. GHz Centre actively encourage young scientists to follow career program given by VINNOVA and the responsible body, i.e. Chalmers and its departments.
15. That the Centre should use its strong links to industry as a selling point to attract more undergraduate and PhD students to supply industry and academia with increased numbers of trained specialists.	This is implemented in all undergraduate involvement from GHz Centre described in Section 8.
16. That the Centre increases the proportion of women among undergraduate students, PhD students, postdoctoral fellows, the ISAB, WP coordinators, Management Team, Board, and Centre Partner Key Contacts.	We have increased from 2 (Stage 1) to 7 (Stage 2) to 10 (Stage 3).
17. That the Centre uses gender-neutral language in all its documents and communications.	Done.