D1.2

E-/W-band multifunctional sub-system specifications

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Abstract:	This report outlines the specifications of two high-performance W-band systems: a wireless point-to-point system and a short-range radar system. A first order breakdown of the system specifications to front-end sub-system requirements are made. It is found that the front-end sub-system share similar requirements between these two use cases. These requirements will be used for further work on the W-band multifunctional GaN-on-Si MMICS in WP4.
Keywords:	Specification, front-end, system, point-to-point, radar, W-band

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Executive Summary

This report outlines realistic sub-system requirements for the multifunctional W-band GaN-on-Si MMIC that is developed in WP4. The requirements are derived from real world assumptions on W-band point-to-point communication links as well as short-range radars. It is found that the specifications for the two use cases leads to similar requirements on the front-end electronics. This is especially true for wireless communication links operated in time division duplex mode (TDD).

The targeted radar architecture is relative high-power CW radar (e.g. frequency modulated continues wave) for collision avoidance. In this architecture the high-power density of GaN-on-Si increases the range (compared to solutions using GaAs, SiGe or CMOS). The target system output power is in the range of 1-2 W with a minimum operating bandwidth of 92 GHz to 95 GHz (stretch target up to 100 GHz).

The communication system targets a similar output power (at least 0.5W of saturated output power) with an objective of increasing the link margin (compared to a GaAs or SiGe front-end). The increased link marging will be used to accommodate either smaller antennas or longer hop distance. The frequency bands of interest, in the W-band range, is 92 GHz to 100 GHz and 104 GHz to 114 GHz. These bands have very recently been designated as primary candidates for operation in pair wise Frequency Division Duplex (FDD) mode. For the SERENA project we will focus on TDD operation in the lower half (92 GHz to 100 GHz) of this spectrum.

Taking both the radar and the communication system requirements into consideration a front-end subsystem for dual use can be specified. For a front-end having separate receive- and transmit-ports, should have a saturated output power of about 2 W and a noise figure better than 3.5 dB. If the system has a common receive- and transmit-port this numbers would degrade with up to 2 dB to accommodate the insertion loss of a transmit receive switch (or circulator).

To reduce the size and cost of the front-end a multifunctional MMIC will be developed. The main objective of the integration is to reduce the number of mm-wave interconnects. Together with using GaN-on-Si technology the long term vision is to provide a path to affordable high-performance mm-wave front-end systems.

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Chapter 1 Introduction

The objective of this document is to report on plausible system specifications for two high-performance W-band systems. The first is a wireless point-to-point communication system for backhaul applications and the other is short range radar for e.g. collision avoidance. By high-performance it is understood that the system should provide high output power while having small size, low weight and being energy efficient. Key to achieving these attributes is the use of mm-wave GaN-on-Si technology.

This report gives target specifications for the two applications (point-to-point link and short-range radar) and makes a first assessment of the requirements for a multifunctional GaN-on-Si MMIC that can be used as a common building block for the two systems. The design and detailed specifications of that MMIC will be carried out in WP4. This report serves as first order input to WP4.

Chapter Chapter 2 gives a quick introduction to short-range radars and point-to-point communication in the W-band and the target specifications. Chapter 3 makes a first order assessment of the requirements on a front-end (e.g. the multifunctional MMIC) and module (e.g. integration and antenna) level. Chapter Chapter 4 provides a summary and conclusion of the findings.

Chapter 2 Sub-system requirements

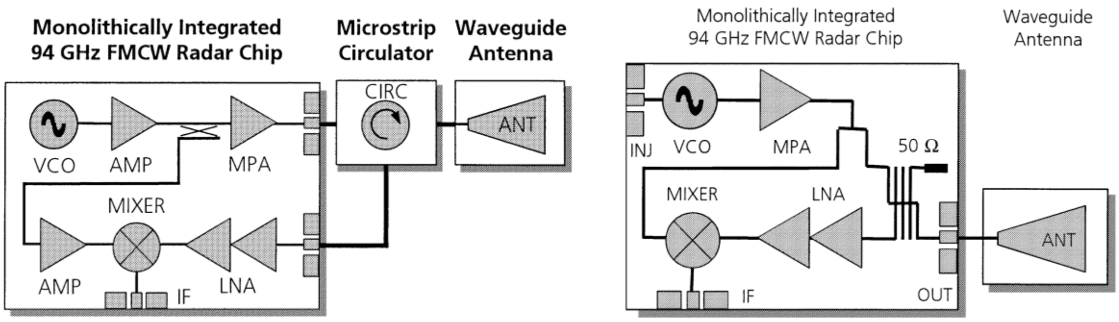
This chapter gives a brief overview of short-range radar and wireless communication in the W-band. It is assumed that the reader are familiar with contemporary microwave and mm-wave electronics and its use in radar and wireless systems. Each of the overviews ends with plausible specifications for a high-performance system.

2.1 Short range radar

Radar stands for RAdio Detection And Ranging and it has been used since the second world war with the aim to detect, track and identify various unknown objects (e.g. for air surveillance). Radar technology advances have since then enabled higher frequencies (higher resolution and smaller size) and better performances e.g. in terms of longer detection ranges and improved sensitivities. However, radar systems working in the higher microwave frequency bands and especially at millimetre-waves (i.e. above 30 GHz or so) have until quite recently been associated with relatively bulky and costly system implementations (e.g. for defence and scientific applications). The on-going development of more highly integrated (silicon based) mm-wave front-end technologies is largely driven by wireless communication (5G) and automotive radar sensors but there are other mm-wave sensing applications that also may benefit from technology advances in terms of reduced cost and higher power efficiency.

Active mm-wave antennas (arrays) are also of interest in short-range (collision-avoidance) radar sensors in autonomous and airborne vehicles (e.g. cars, drones and helicopters) for enhanced safety in harsh and non-visible weather conditions (e.g. during take-off, landing and for detecting and locating hazards with small cross-sections such as overhead power lines) [1-2]. Compared with some previously developed W-band radar sensors which use mechanically scanned antennas for beam-steering, an electronically steerable antenna can result in a less bulky radar sensor solution and also higher reliability if the cost and performance targets can be met. A GaN HPA was proposed by the US company MMICMAN to enable a more compact and power efficient solution if used in W-band phased arrays for brown-out radar applications, for example (rotary aircrafts can experience a condition called brown-out or white-out when landing in environments with sand, dust and snow which can cause severe equipment damage and personal injury unless properly addressed) [3]. Estimates made by the US government show that $100M per year in damage are caused by these conditions and many service members have lost their lives due to reduced visibility conditions when landing in such harsh environments [3]. Compared with current COTS solutions (GaAs, InP and silicon), a GaN based high power MMIC will enable an improved radar detection range which can reduce the number of radar sensor units required to cover the surrounding space of the vehicle (or alternatively, the increased effective radiated power means that smaller antennas may be used to achieve the same detection range).

Doppler cloud radars can be used to characterise cloud, fog and precipitation properties in space-borne missions performing environmental monitoring and scientific studies of the Earth. Commercially available cloud radars (35 and 95 GHz) are still very expensive (i.e. over 500 kEuros) which hampers their widespread deployment [4]. Most of the cost comes from the transmitter itself as W-band pulsed radars typically transmit 1-2 kW to achieve the sensitivity required for such studies. To drastically reduce the cost, an alternative radar architecture may be used which instead of transmitting a large amount of energy for a very short time period (as a pulse) transmit much less energy continuously. Frequency Modulated Continuous Wave (FMCW) radar systems are often deployed in various short-range applications and some of the main advantages over pulsed radars are relaxed output power requirements (which more easily can be realised using solid-state electronics) and a simple architecture [4]. Two single-chip FMCW radar front-end architectures are depicted in Figure 1 a and b, respectively (an off-chip circulator or an on-chip hybrid coupler may be used to obtain a high isolation between the transmitter and receiver paths when a common antenna is used) [5].



a) b)

Figure 1: Two single-chip FMCW radar transceiver architectures using a common antenna for TX/RX: a) with an off-chip circulator and b) with an on-chip hybrid coupler, respectively [5].

In the NASA sponsored “Three Band Cloud and Precipitation Radar Project” JPL is developing a W-band 1D linear phased array using GaN-on-SiC MMICs (PA and LNA) for space-borne missions performing environmental monitoring and scientific studies of the Earth [6]. Such W-band GaN amplifiers can enable more compact electronically steerable transceiver arrays for cloud Doppler radars that will dramatically increase new science data retrieval rates. The SERENA E-/W-band subsystem is a significant advancement beyond the current state-of-the-art in terms of GaN integration as we are targeting an E-/W-band GaN-on-Si based single-chip transceiver front-end MMIC (incl. HPA, LNA, mixer and possibly a T/R-switch). Such a GaN-on-Si single-chip transceiver front-end will enable a much higher level of integration (and thus smaller size and lower cost) while on the same time being able to achieve an output power level (1-2 W) and noise figure (3 dB) which are similar or better than that of corresponding single-function GaN-on-SiC and GaAs MMIC solutions within this frequency range.

Exemplary performance characteristics of some previously reported W-band radar sensors (or sub-systems) are listed in Table 1. The angular and range resolutions will improve as the wavelength is reduced (i.e. moving up in frequency) for a given aperture size and by choosing a wider bandwidth. Radars used for aircraft landing-aid/anti-collision, environmental monitoring of the earth and bird detection at airports typically require an output power level of approximately 1 Watt to obtain a detection range in the order of one or several kms [4, 6-10]. For a given target scenario, the detection range can be increased by improving the output power and receiver noise figure (or alternatively, smaller antennas may be used in order to achieve same detection range). Compared with the use of non-planar antennas such as horns, lenses and reflectors planar antenna arrays could enable a more compact, flexible and reliable sensor system solution if the performance and cost targets can be met. A main challenge is to demonstrate compact, light-weight and affordable mm-wave radar sensors for airborne platforms such as fixed wing airplanes and rotorcrafts (incl. drones) which impose stringent requirements in terms size, weight, power and cost [7]. Compared with some previously developed 94 GHz radar sensors that carried a price tag of about $500K (and thus were only suitable for larger aircrafts at very small quantity production) the cost will have to be reduced at least by an order of magnitude to enable a more widespread deployment of such mm-wave radar systems for improved situational awareness (e.g. imaging radars for landing-aid, cable warning and sense-and-avoid) [7]. The radar system provider Honeywell (US) has performed field tests with a 20 lbs mechanically scanned 94 GHz imaging radar unit using an external 2W solid-state power amplifier [7]. Such Enhanced Flight Vision Systems (EFVS) are presently being targeted by industrial and academic collaborations at the European level (e.g. within the EC funded Clean Sky2 program) [8]. Research topics are aiming at significantly improving critical mm-wave building blocks to enable small-size and affordable 94 GHz radars with multi-km range coverage (incl. ITAR-free ≥1 W power amplifier and signal source MMICs as well as surface mount packaging technologies) [8].

Table 1: Exemplary performance characteristics of some previously reported W-band radar sensors.

Parameter	Values	Applications (examples)
Frequency range	92-95 GHz (92-100 GHz)	• Landing-aid/anti-collision Radar [7-9] • Climate monitoring/Doppler Radar [4, 6] • Radars for bird detection at airports and airfields [10]
Output power	0.5-1 W (2 W)	
Detection range	1-5 km	
Range resolution	2-5 cm	
Angular resolution	0.5-2° (1-3 mrad)	
Noise Figure	5-8 dB	

2.2 Point to point wireless communications

The main challenge for point to point wireless communications at mm-wave frequencies is to provide enough system gain at a reasonable cost. The system gain (in logarithmic scale) is defined as the transmitted power plus the antenna gains minus the required received signal power. High system gain is the key to establishing high availability point-to-point communications over distance. Typically the targeted yearly availability is in the range of 99.99% to 99.999%. The main external factor affecting the availability is the amount of precipitation at the location of the communication link.

Figure 2 shows the path loss versus frequency with rain intensity as a parameter. For frequencies above E-band the rain attenuation is fairly flat and predictions at E-band can mostly be re-used also for the higher frequency bands. The inset of the figure shows the number of 250 MHz channels that can be allocated in the frequency bands that is reversed for fixed wireless use.

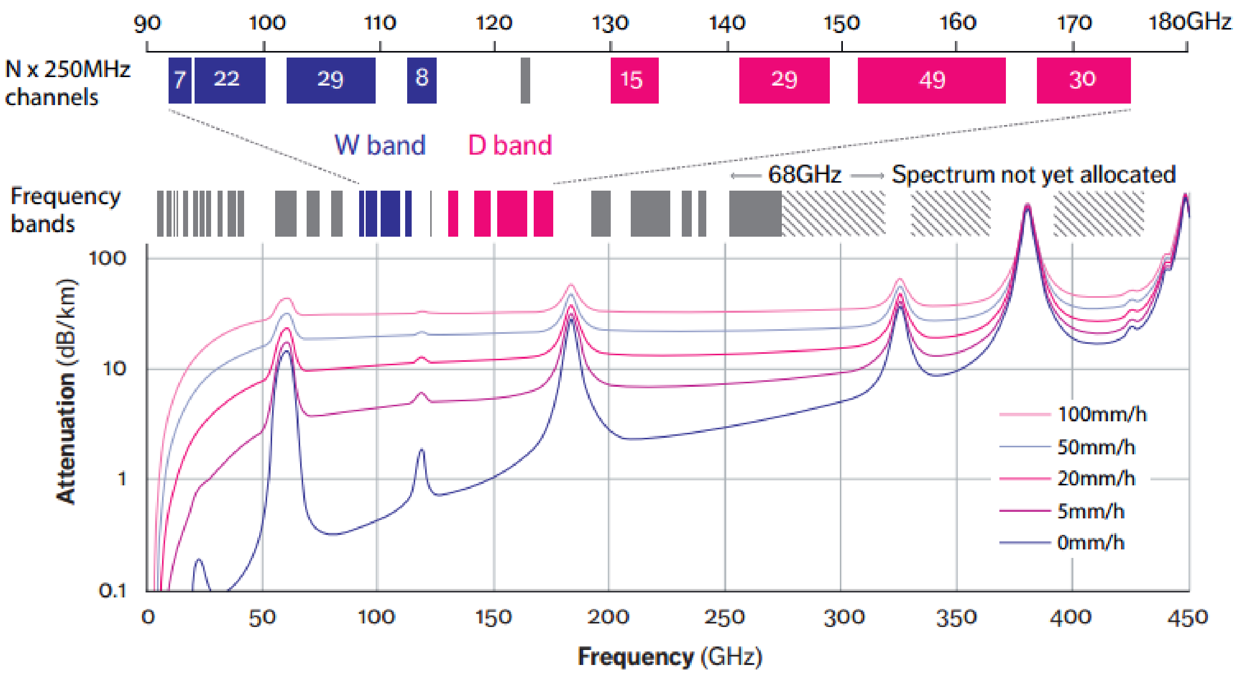


Figure 2: Atmospheric attenuation beyond 100 GHz

In the M3TERA project (Horizon 2020 project 644039), a D-band point-to-point communication system is studied. Specifically the D1.1 report outlines target sub-system specifications for a radio system operating in the 141 GHz to 148.5 GHz frequency band. In the context of M3TERA the specifications were derived with the intention to use SiGe technology to manufacture the front-end RFICs. The front-end specifications for the SERENA E-/W-band sub-system demonstrator will be based upon the work in M3TERA with changes made were appropriate due to changing system requirements, technology capability and changes in spectrum regulation.

Table 2: E-/W-band target system specifications

Parameter	SERENA	M3TERA “wish-list”	M3TERA SiGe	Remark
Frequency (GHz)	92 – 100, 104-114	141 - 148.5	141 – 148.5	SERENA will focus on TDD in the lower band 92 – 100 GHz
Link distance (km)	0.5 – 5 km	0.5 – 5 km	0.5 – 1 km	
Data rate	2 Gbps	2 Gbps	2 Gbps	Demand in 2020 for last mile backhaul. Expected to increase up to 10 Gbps in 2025.
Bit error rate (BER)	< 1e-12	< 1e-12	< 1e-12	

Parameter	SERENA	M3TERA "wish-list"	M3TERA SiGe	Remark
Minimum modulation for a 500 MHz carrier	16 QAM	16 QAM	16 QAM	Lower order supported for upholding link availability with reduced capacity
Saturated transmitter output power, OPSat (dBm)	27 dBm	20 dBm	10 dBm	
Receiver Noise Figure (dB)	< 7 dB	< 7 dB	< 10 dB	
Min. antenna gain for 15 dB link margin	35 dBi	40 dBi	45 dBi	See antenna discussion below
Duplex mode	FDD/TDD	FDD/TDD	FDD/TDD	SERENA will focus on TDD

2.3 Unique capabilities offered by mm-wave GaN-on-Si technology

At mm-wave frequencies a high gain antenna is physically small compared to a at lower frequencies. Hence it is technically possible to build systems with very high gain antennas. However, as the antenna gain increases the width of the beam decreases making it very difficult to align (and maintain alignment) of the link. Hence, the maximum antenna gain is in practice limited to maximum 50 dBi. For backhaul applications in urban environments (e.g. small-cells) the link lengths will be relatively short and the links will be mounted to less rigid platforms (e.g. lamp posts etc.). For such deployments the link will be susceptible to mast sway and it is thus desirable to increase the beam width and mitigate sway effects. For antenna gains in the range of 35 dBi the effects of mast sway is negligible, and would therefore be a good choice for a W-band system.

Without a substantial increase in transmitter output power the lower gain antennas would severely lower the overall system gain and hence limit the maximum hop distance. Introducing power amplifiers made using mm-wave GaN technology can increase the transmit output power by a factor of up to ten times. The system specified in Table 2 takes a conservative approach and assumes that the saturated output power can be reduced by a factor of five. This will allow the use of smaller and less directive antennas which are easier to align and less susceptible to mast sway.

2.4 Spectrum regulation

At the time of the SERENA proposal there were no tangible efforts to standardize the spectrum above E-band. Recently, both American (FCC) and European spectrum regulators are actively seeking to finalize spectrum regulations on W-band and above 100 GHz spectrum. A consequence of these regulations will be the formation of paired spectrum that can be used for frequency division duplex (FDD). This approach follows a similar pattern as that seen for the lower frequency bands (E-band and below) with a dedicated frequency pair for up- and down-link.

In the W-band it is proposed to form a lower and upper band at 92 GHz – 100 GHz and 104 GHz – 114 GHz, respectively. In the SERENA proposal we set forth to develop a dual use front-end in the 92 GHz to 95 GHz frequency band. That front-end could be used both for time division duplex (TDD) radio communication as well as short range radar. The recent movements in spectrum regulations makes it more interesting (for a wireless backhaul perspective) to also study front-ends in the 92 GHz to 100 GHz and 104 GHz to 114 GHz frequency bands.

SERENA will keep the main focus on 92 GHz to 95 GHz but will investigate: 1) the feasibility of extending the front-end range to 92 GHz to 100 GHz and 2) investigate power amplifiers in the 104 GHz to 114 GHz frequency band.

Chapter 3 Sub-system specifications

The objective of this chapter is to provide target specifications for a W-band front-end sub-system that can either be used for short-range radar or point-to-point communication. These specifications will serve as input to WP4 where the detailed design of the multifunctional MMIC will be carried out.

3.1 E/W-band GaN-on-Si multifunctional single-chip front-end

This section covers the electrical and mechanical specifications of the GaN-on-Si multifunctional single-chip front-end. The E-/W-band single-chip transceiver front-end (GaN-on-Si MMIC) will consist of an up/down conversion mixer, PA, LNA and optionally a transmit/receive (T/R) switch. By including the up/down conversion in the MMIC, the system integration will be simplified (since the interface will now be on an IF interface). Two alternative configurations are considered to provide isolation between transmit and receive modes. The first configuration will use the typical T/R switch and the other will use the isolation between two separate antenna apertures (see Figure 3).

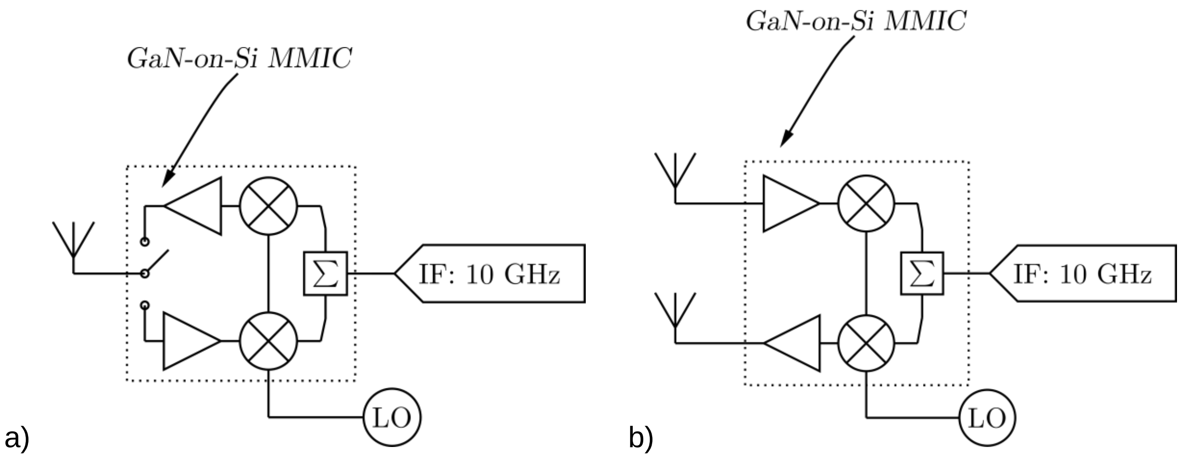


Figure 3: Transceiver architectures of the E-W-band GaN-on-Si multifunctional single-chip front-end (proof-of-concept subsystems): a) with and b) without including an on-chip T/R switch, respectively.

3.1.1 General

The table below gives mechanical and electrical target specifications for the multifunctional MMIC. The current objective is not to optimize the size of the MMIC but rather showing the capabilities of the GaN-on-Si technology. In a potential product the size of the MMIC will be minimized to optimize the cost.

The relative large pads are chosen to be compatible with commercial ribbon-/wire-bond production and the SERENA integration platform (PCB embedding).

Table 3: E/W-band multifunctional single-chip front-end general specifications

Parameter	Target	Unit	Comment
MMIC die size	4 x 4	mm x mm	
MMIC die thickness	100	um	Typical

Parameter	Target	Unit	Comment
Pad-size	100 x 100	um x um	Typical
Switch time (RX to TX)	10	us	Maximum
Switch time (TX to RX)	10	us	Maximum
Switch control voltage (VSW, VSWQ)	-10	V	Minimum

3.1.2 Power amplifier

The power amplifier (PA) is the most critical block to setting the performance of the front-end module. The PA is the most power consuming part of the front-end system and hence the efficiency is of paramount importance. This is especially true for airborne systems where the available power can be very limited. For a communications system the power consumption is important from an environmental perspective. Furthermore, a low power consumption reduces the amount of heat that the mechanics surrounding the front-end system have to disperse to the surroundings.

The table below gives conservative target specifications for the multifunctional MMIC. The targets are based on preliminary simulations using the PDK for OMMICs 60nm GaN-on-Si MMIC technology.

Table 4: E/W-band power amplifier specifications

Parameter	Target	Unit	Comment
Small-signal gain	10-20	dB	Typical
Output power (P4dB)	30	dBm	Minimum
Power consumption	5-10 (PAE=10-20%)	W	@ P4dB
Input return loss	10	dB	Minimum
Output return loss	10	dB	Minimum
Supply voltage (VTD)	10	V	Typical
Gate voltage (VTG)	-1 to 0	V	Typical
RF frequency range	92-95	GHz	92-100 GHz as stretch target

3.1.3 Transmit/Receive switch

Two front-end architectures will be investigated. For the architecture having a single transmit- and receive-port a transmit/receive switch or a circulator is required. To achieve the smallest size and lowest cost a switch solution is often preferred over the more bulky circulator. Furthermore, the circulator based solution can be constructed using a MMIC having separate transmit- and receive-ports.

Table 5: E/W-band TR switch specifications

Parameter	Target	Unit	Comment
Transmission loss	1-2	dB	Typical
Isolation	10-20	dB	Typical
Linearity (P1dB)	36	dBm	Typical
Input return loss	10	dB	Minimum
Output return loss	10	dB	Minimum
Gate voltage ON (Von)	2-3	V	Typical
Gate voltage OFF (Voff)	-10	V	Typical
RF frequency range	92-95	GHz	92-100 GHz as stretch target

3.1.4 Low noise amplifier

The low noise amplifier (LNA) should provide a high gain and low noise figure in order to maintain a high receiver sensitivity. Furthermore, the 60 nm GaN-on-Si technology opens up new possibilities to combine the LNA, PA and up-/down-converter circuit functions in an E/W-band multifunctional single-chip MMIC. A GaN-on-Si based LNA can also have a high linearity (P1dB around 16 dBm) which will result in an enhanced dynamic range of the receiver.

Table 6: E/W-band low noise amplifier specifications.

Parameter	Target	Unit	Comment
Small-signal gain	15-25	dB	Typical
Noise figure	2-3	dB	Typical
Linearity (P1dB)	16	dBm	Typical
Power consumption	0.5-0.8	W	Typical
Input return loss	10	dB	Minimum
Output return loss	10	dB	Minimum
Supply voltage (VTD)	6	V	Typical
Gate voltage (VTG)	-1 to 0	V	Typical
RF frequency range	92-95	GHz	92-100 GHz as stretch target

3.1.5 Up- and down-converter

The multifunctional single-chip front-end has a transceiver architecture with an intermediate frequency (IF) and an IQ conversion to a complex baseband. The RF signals are down respectively up converted to the IF using RF mixers. The IF is 5-10 GHz. The IF signals are converted to the complex baseband and vice versa with I/Q modulators and demodulators.

Table 7: E/W-band Up-and down-converter specifications.

Conversion gain	2	dB	Typical
Linearity (IIP3dB)	20	dBm	Typical
Power consumption	0.5-0.8	mW	Maximum
RF frequency range	92-95	GHz	92-100 GHz as stretch target
IF frequency	5-10	GHz	Typical

3.2 E/W-band active antenna module

For evaluation purposes the E-/W-band single chip front-end will be integrated on a test-board that will be coupled to W-band waveguides. This will provide a path to test the front-end system with commercial off the shelf (COTS) antennas.

3.2.1 General

The main objective of the multifunctional W-band MMIC to be developed in WP4 is to demonstrate (and test) the viability of integrating a full front-end in GaN-on-Si technology. Hence, the properties of the final module assembly is less of a concern. During later stages of SERENA the potential of extending the integration platform beyond 39 GHz will be evaluated. The table below lists parameters that is currently out of scope for this report but will be considered in WP4 and WP6.

Table 8: E/W-band active antenna module general specifications

Parameter	Target	Unit	Dependency	Comment
Module size	TBD	cm x cm		Maximum
Module thickness	TBD	cm		Maximum
Power handling (@ input)	TBD	dBm		Maximum
Mean-time-between-failures	TBD	hours		Minimum
Temperature range	0-70	°C		Typical
Humidity range	TBD	V		Typical

3.2.2 Antenna

In Section 2.3 the reduction of antenna size was mentioned as a driving force behind using GaN-on-SI technology in a W-band point-to-point communication system. The table below gives a guiding example of a 35 dBi antenna for point-to-point application. The specifications represents a reduction of about 7 dB in directivity compared to antennas being deployed in commercial E-band radio links. Even though the gain is reduced, the total gain is still too high to be readily implemented as a planar antenna. Hence, we foresee to use a COTS antenna in the form of a reflector or a dielectric lens.

Table 9: E/W-band antenna specifications

Parameter	Target	Unit	Dependency	Comment
Gain	35	dBi		Typical
Beam width	2	degrees		
Return loss	10-20	dB		Minimum
Polarisation	TBD			Typical
RF frequency range	92-95	GHz		92-100 GHz as stretch target

3.3 Integration and economical aspects

One of the concerning problems with mm-wave systems is how to interface the sub-systems. To date the most common way of integrating mm-wave sub-systems (power amplifiers, low noise amplifiers, filters, antennas, etc.) is to use rectangular waveguide technology. Rectangular waveguide is a mature technology, offering very low loss. The main drawbacks are the bulk and cost.

SERENA takes on a two pronged approach to the cost problem. By integrating as much functionality as possible in a single MMIC, the number of mm-wave interconnects are minimized. Which provides substantial reduction in volume and mass compared to a system designed with discrete sub-systems interconnected with waveguides.

The second approach is to use GaN-on-Si instead of GaN-on-SiC. GaN-on-Si technology has the potential to scale the wafer size from 4” to 8” and beyond. With such large diameter wafers the process can move into low cost CMOS fabrication facilities which will bring down the cost per fabricated circuit. In the long run GaN-on-Si has the potential to bring down the cost below that of GaAs and close to that of SiGe (but with higher performance).

A remaining challenge is how to realize the chip to antenna interface. For very high frequency (220 GHz) the chip can include a patch or probe that can radiate directly into a waveguide. For W-band frequencies such an arrangement would be too large to be economically feasible to integrate on chip. The SERENA integration platform could provide a solution were the radiating probe/patch can be realized in printed circuit technology and the chip can be embedded underneath the probe. The probes can then be used as either standalone antennas or coupled to a waveguide.

Chapter 4 Summary and Conclusion

A brief introduction to short range radar applications and W-band point-to-point wireless applications were given. Realistic system requirements for a high-performance radar or radio link were then presented. The requirements implies the use of GaN-on-Si mm-wave technology to achieve high-output power, small form factor and high energy efficiency. The requirements were then brought down to the, front-end, sub-system level.

From a front-end perspective it was found that both the shortrange radar and point-to-point communication application have similar requirements. Furthermore, preliminary simulations have shown that the 60 nm GaN-on-Si technology should be capable of reaching the target specifications in the 92 GHz to 95 GHz range. Further work in WP4 are needed to assess if the frequency range can be extended up to 100 GHz (and possibly up to 114 GHz) without significant reduction in performance.

Chapter 5 List of Abbreviations

Abbreviation	Translation
COTS	Commercial off the shelf
CMOS	Complementary metal oxide semiconductor
CW	continuous wave
dB	decibel
dBi	Decibel relative isotropic radiation
dBm	Decibel relative to 1 mW
FDD	frequency division duplex
GaAs	Gallium Arsenide
GaN	Gallium Nitride
Gbps	Giga bits per second
GHz	Giga Hertz
HPA	High power amplifier
IF	Intermediate frequency
LNA	Low noise amplifier
MHz	Mega hertz
MMIC	Microwave monolithic integrated circuit
PA	Power amplifier
PCB	Printed circuit board
QAM	Quadrature amplitude modulation
Si	Silicon
SiC	Silicon carbide
SiGe	Silicon Germanium
TBD	to be determined
TDD	time division duplex
TX	Transmitter
RX	Receiver

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