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On-Chip Integrated Distributed Amplifier and Antenna Systems in SiGe BiCMOS for Transceivers with Ultra-Large Bandwidth

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Abstract: This paper presents an overview of the research work currently being performed within the frame of project DAAB and its successor DAAB-TX towards the integration of ultra-wideband transceivers operating at mm-wave frequencies and capable of data rates up to 100 Gbits⁻¹. Two basic system architectures are being considered: integrating a broadband antenna with a distributed amplifier and integrate antennas centered at adjacent frequencies with broadband active combiners or dividers. The paper discusses in detail the design of such systems and their components, from the distributed amplifiers and combiners, to the broadband silicon antennas and their single-chip integration. All components are designed for fabrication in a commercially available SiGe:C BiCMOS technology. The presented results represent the state of the art in their respective areas: 170 GHz is the highest reported bandwidth for distributed amplifiers integrated in Silicon; 89 GHz is the widest reported bandwidth for integrated-system antennas; the simulated performance of the two antenna integrated receiver spans 105 GHz centered at 148GHz, which would improve the state of the art by a factor in excess of 4 even against III-V implementations, if confirmed by measurements.

Keywords: mm-wave, wireless communications, BiCMOS, SiGe, SiGe:C, travelling-wave amplifier, distributed amplifier, active combiner, broadband antenna, silicon antenna

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1 Introduction

One fundamental approach to increase the data rate of communication systems towards 100 Gbits⁻¹ consists in increasing the bandwidth of the radio channel in use. One natural path towards achieving very large bandwidths is the exploitation of ultra-high frequencies, e.g. beyond 100 GHz. This consideration motivates research interest on mm-wave electronics for wireless communication in general and broadband implementations in particular. These efforts align very well with the adjacent area of imaging and sensing applications, which share extremely similar requirements for the high-frequency components on the transmitter side – in particular power amplifier and antennas. In fact, while a very large bandwidth can naturally enable data rates in the 100 Gbits⁻¹ range, the same ultra-wideband is necessary for mm-wave imaging to achieve high resolutions, high contrast and operate in a non-invasive nature. This results from a direct relation between the bandwidth of the radiated signals and the achievable spatial resolution. For both mm-wave communications and imaging also high power levels are required to overcome the propagation losses in free space and reach either the receiver or the target objects with sufficient signal power. The generation of high power levels requires large transistors, which are unavoidably associated with large parasitic capacitances and – therefore – not readily compatible with very-high-frequency operation over large bandwidths.

As mentioned above, and in agreement with the basic theorem of Shannon, the data rate of communication systems can be boosted by increasing the bandwidth and carrier frequencies beyond 100 GHz. In general, however, the design of antennas and amplifiers are challenging at such high frequencies. Moreover, the connection between amplifiers and antennas are critical. To decrease the associated connection parasitics, the antennas can be integrated together with the amplifiers on one single chip.

Within the frame of the DFG Schwerpunktprogramm (Special Priority Program, SPP) 1655 *Drahtlose Ultrahochgeschwindigkeitskommunikation für den mobilen*

Internetzugriff Wireless 100 Gbits⁻¹ and beyond [1], project DAAB (On-Chip Integrated Distributed Amplifier and Antenna Systems in Locally-Backside-Etched SiGe BiCMOS for Receivers with Ultra-Large Bandwidth) [2] and its phase-II successor DAAB-Tx (On-Chip Integrated Distributed Amplifier and Antenna Systems in SiGe BiCMOS for Ultra-Large-Bandwidth Transmitters) address the challenges associated with this application and aim at significant improvements over the state of the art.

Typical circuits integrating antenna and amplifier offer a relative bandwidth of about 10%. For example, a center frequency of 170 GHz was reported for a SiGe (Silicon Germanium) transceiver with on-chip dipole antennas [3]. This technology features HBTs (Hetero Bipolar Transistors) with an f_{max} (Maximum Frequency of Oscillation) of 340 GHz. To achieve sufficient gain high-quality resonant structures are used. Hence, the 3 dB gain bandwidth is less than 15 GHz leading to a relative bandwidth¹ of less than 10%.

Concerning on-chip antennas, a major challenge is posed by the large substrate losses and the compliance of the antennas with the design rules of modern silicon based technologies, e.g. the metal filling in the isolation layer. A center frequency of 220 GHz and a bandwidth below 30 GHz resulting in less than 15% relative bandwidth were reported in a 0.1 μm GaAs (Gallium Arsenide) HEMT (High Electron Mobility Transistor) technology [4]. A slot-square lens antenna with roughly 40 GHz bandwidth is employed. That means that this design is bandwidth limited by the circuits rather than the antenna.

DAAB research activities aim at significantly increasing the bandwidth of millimeter wave receivers by using distributed (also referred to as traveling wave) concepts for both the amplifiers and the antennas, which are integrated on the same chip. The capacitive parasitics of the amplifiers are incorporated into active transmission lines.

The design of TWAs as stand-alone components has been studied extensively. The typical architecture of such a traveling wave amplifier (here with 3 amplifiers) is shown in Figure 1 [5]. The input signal travels along the input line and feeds the amplifiers, which amplify the signal. Imposing that the delay times $t_i \approx \sqrt{L_i C_i}$ and $t_o \approx \sqrt{L_o C_o}$ are equal, the signals of the amplifier paths are constructively combined at the output resulting in a voltage gain of $a_v \approx \frac{1}{2} n Z_{wo} g_m$. The parameters C_i , C_o , L_i , L_o , n , Z_{wo} and g_m denote the input/output capacitance of the amplifiers, the inductance of the input/output line segments, the number of amplifiers, the impedance of the output line

Figure 1: Architecture of distributed amplifiers.

and the transconductance, respectively. The TWA structure acts as low pass filter with cut-off frequency of the t -lines given by $f_{ci,o} = 1/\pi\sqrt{L_{i,o}C_{i,o}}$. Typically very high cut-off frequencies up to $f_t/2$ can be achieved, while having sufficient/moderate gain. Since there is typically just a low-pass and no high-pass effect, a very large bandwidth can be achieved, being equal to the cut-off frequency of the resulting synthetic lines. At the end of the input and output lines, termination resistors are used to absorb the remaining part of the signal thereby avoiding reflections and yielding a very broadband impedance matching.

By implementing integrated antennas in the overall receiver design, parasitics can be avoided. Nevertheless, their use introduces several challenges. Due to the semiconductor processes used in fabrication, the antenna designs have to deal with some constraints. The silicon substrate with a high relative permittivity of approximately $\epsilon_r = 12$ leads to a high backwards radiation. Consequently, in all the antenna designs described in this paper, a reflector is included at the bottom of the silicon substrate to increase the radiation towards air. Together with the reflector, the stack up of commercial semiconductor processes can be roughly described with a dielectric slab waveguide. Due to this structure substrate modes are able to propagate in the substrate. With the dielectric slab waveguide model, the cut-off frequencies of the substrate modes can be calculated. The number of substrate modes being able to propagate is dependent upon the height of the silicon substrate. Nevertheless, the fundamental TM_0 mode can be excited even when the substrate is thinned. In order to decrease the influence of substrate modes, the substrate is thinned for the antennas presented in this paper. One possible solution to further reduce the mentioned effects is localized backside etching (LBE). Using LBE, parts of the substrate below the antenna are etched away, so the influence of the silicon substrate on the antenna characteristics can be reduced to a high extent. However, the process used is the IHP SG13 process [6] which allows only for a small percentage

¹ Defined as bandwidth over center frequency.

of etched substrate area. For the antenna designs presented, this fraction is too small and therefore, LBE could not be used. Moreover, for the antenna design the necessary metal density set by the foundry has to be fulfilled. Therefore, metal shapes are placed on the metal layers of the process in order to prevent automatic fill by the foundry, which could decrease the antenna performance to a high extent depending where the structures are placed.

By optimizing these fill structures and decreasing the influence of the existing substrate modes, broadband antennas with not only a high impedance bandwidth but sufficient gain as well are designed in DAAB.

Within this context, this paper reviews the results achieved by the end of phase-I of project DAAB, its outlook towards phase-II and its planned improvements of the state-of-the-art in its focus area.

2 Technology

The circuits subject of this work are fabricated in a 0.13 μm SiGe BiCMOS process. At the time of writing, this process is the fastest SiGe BiCMOS commercially available, and it is offered by IHP as SG13G2. Under optimal bias conditions, the f_{max} is 450 GHz, while f_t occurs at 300 GHz. The transistors are well suited for mm-wave design; this feature is further supported by the process back-end, which enables the fabrication of high-quality inductors and transmission lines through the availability of two thick top metal layers on top of five lower layers for dense interconnections. Among them, the lowest metal (M1) has the smallest thickness to enable fine lithographies used for contacting the silicon devices, while the top metals are thicker to sustain higher current densities, and to reduce the sheet resist-

Figure 2: Simplified view of the metal stack used in this work. Two thick metals are above 5 lower ones. The lowest metal (M1) is the thinnest metal layer of the process.

ance. A sketch of the metal stack is in Figure 2. Altogether the seven metal layers enable the design of coplanar, micro-strip and stripline waveguides with a high degree of freedom for the dielectric thickness. This process offers also passive components such as polysilicon resistors and Metal-Insulator-Metal (MIM) capacitors with high quality factors and high resonance frequencies. The substrate of the presented circuit is 300 μm thick.

3 System architecture

As discussed in Section 1, the major motivation to operate at very high frequency – around 170 GHz in SiGe HBT technology [3] or even 220 GHz [4] in GaAs HEMT technology – is the possibility to exploit a very large bandwidth and in turn achieve a high data rate. However, in the conventional architectures – as e.g. in the two state-of-the-art works referenced above – the relative bandwidth is less than 15%. This means that either a very high center frequency is required to achieve a certain high bandwidth, or the bandwidth available around a certain high center frequency is not exploited very efficiently. In conventional architectures, the relative bandwidth is mainly limited by the resonant amplifier impedance matching. DAAB and DAAB-TX study and enhance novel distributed amplifier and broadband antenna system concepts to massively improve the possible relative bandwidth of communication systems at millimeter wave frequencies, e.g. for frequencies above 100 GHz and up to 300 GHz. Leveraging distributed integrated concepts, relative bandwidths of up to 50% are within reach. This would correspond to an improvement by a factor of 3 compared to the state of the art. Hence, data rates beyond 100 Gbits⁻¹ can be processed by the modules.

The DAAB project has focused on receivers for phase I and the transmitters are currently studied in phase II. To minimize the parasitic connections between the traveling wave amplifiers and the antennas, the antennas will be integrated on the amplifier chip. At frequencies above 100 GHz this is possible since the antennas become very compact. There are different promising wideband structures which can radiate RF energy. This includes Vivaldi or linear tapered slot antenna (LTSA) structures, spiral antennas and fractal bowtie antennas. Combinations of orthogonal linear or circular polarizations can be used to build independent channels and to further increase the data rate by about a factor of two.

For both receiver and transmitter two basic approaches have been found to be practical and yet yield very promising results:

1. Integrate a broadband antenna with a distributed amplifier
2. Integrate multiple antennas, centered at adjacent frequencies, and combine their signals with active distributed combiners.

The first approach is limited only by the cutoff frequency of the distributed amplifier at the upper end of the band, and the relative bandwidth achievable by specific antenna types at the lower end of the band. If the antenna and amplifier are integrated in the same substrate, the on-chip impedance can be optimized to values different than 50Ω .

The second approach can relax the design of the antennas, enabling optimization of performance parameters other than the bandwidth and requires the design of very broadband combiners and dividers. Figure 3 shows a system-level schematic with an example of a two-antenna transceiver system, currently being developed for operation at 100 GHz to 200 GHz.

Figure 3: System level schematic of one example of DAAB transceiver architecture. Antennas centered at adjacent frequencies are combined by means of active distributed combiners and dividers. The example shows the case of two antennas, but the approach scales well to larger numbers of antennas, further extending the resulting bandwidth.

4 Distributed circuits

In the first phase of project DAAB, the design of distributed structures suitable for integration with broadband antennas has been studied in detail. In particular, the design approach sought the optimization of the usable bandwidth, in order to support a wider range of antennas. Two prominent examples of the achieved results are presented in this section.

The fastest available BiCMOS technology is being used for the realization of the amplifiers and the integrated antennas require by the project. Currently, this is the IHP SG13G2 technology featuring HBTs (Hetero Bipolar Transistors) with 450 GHz f_{max} , thick top metals and the option for local backside etching of the substrate. Hence, this technology is very well suited for high-Q passive elements required for the distributed concepts, as well as for the antennas.

Figures 4–6 present an overview of a 170 GHz distributed amplifier implemented in a SiGe BiCMOS technology [7]. Figure 4 shows the transistor-level schematic of the periodic structure, where the novel triple-cascode topology for the gain cell is presented in detail. It has been shown, that a proper design of this topology can actively compensate the losses in the input transmission line and thus boost the overall bandwidth of the circuit, as discussed in Section 1. Figures 5 and 6 show the measured S-parameters and a photograph of the fabricated IC, respectively. Detailed electromagnetic 3D models were used for the simulation of the gain cell and its interfaces to the input and output transmission lines; the resulting simulations are also shown in Figure 5 and directly compared to measured results with excellent matching. As shown in Table 3 and discussed in Section 7, with a bandwidth of 170 GHz, this amplifier represents the largest bandwidth reported for silicon amplifiers.

Figure 4: Circuit schematic of a loss-compensated distributed amplifier with 170 GHz bandwidth and 10 dB gain implemented in BiCMOS [7].

Figure 5: Measured and simulated S-parameters of the distributed amplifier presented in [7].

Figure 6: Photograph of the loss-compensated distributed amplifier. Area shown measures $850 \mu\text{m} \times 450 \mu\text{m}$.

Figure 7 presents a distributed active combiner implemented in a SiGe BiCMOS process [8]. The circuit provides the power combination through two independent traveling wave amplifiers (TWAs), which share the same output line. The circuit blocks are illustrated in Figure 7. A cascaded single-stage distributed amplifier (CSSDA) [9] is employed after the combiner TWAs to increase the gain of the combining paths. Independent bias of the two combining path allows gain control on the two inputs, easing the interface with antennas of different gain in the incident-wave dir-

ection. Figure 8 shows a picture of the active combiner, while the overall system response is shown in Figure 9. The signal amplification in each combining path is 20 dB from 1 GHz to 170 GHz and it decreases to 15 dB at 220 GHz. This reported bandwidth and gain values are – with a very large margin – the best reported in literature for monolithic active combiner. For example the 170 GHz bandwidth improves by a factor 16 the best reported silicon component [10] and by a factor 4.5 the best III-V component [11].

5 Integrated antennas

For the antenna design, the IHP SG13 process offers seven metal layers, two thick top metal layers (TM_1 ($2 \mu\text{m}$) and TM_2 ($3 \mu\text{m}$)) and five thinner metal layers below. More details on the process can be found in [12]. The bulk silicon substrate has a relative permittivity ϵ_r of 11.9. For the silicon dioxide, an ϵ_r of 4 was assumed. With these inputs, the simulations of the integrated designs have been performed with Ansys HFSS [13].

In order to achieve the high relative bandwidth of approximately 40% at a center frequency around 180 GHz

Figure 7: Simplified schematic view of the active combiner. The circuit input stage consists of two traveling-wave amplifiers, which share their output synthetic line and whose gain cells are indicated with TWA_{GC} . The resulting combined output is based on a multi-stage CSSDA, whose gain stages are labeled with CSSDA_{GC} .

Figure 8: Photograph of the active distributed combiner. The circuit size is 0.57mm^2 . The RF inputs are on the left side of the chip, while the output is on the right.

several antenna designs have been investigated and fabricated, amongst others a slot bow-tie, a fractal bow-tie, half cloverleaf shaped antennas and multiple stacked open slot antennas. Since being used in one of the fabricated receiver chips, a two times stacked vivaldi-shaped open slot antenna will be described in more detail in the following.

5.1 Antenna design

To realize the high antenna bandwidths necessary for implementing a 100 Gbit/s wireless transmission, distributed designs are promising approaches. Therefore, a two times stacked vivaldi-shaped open slot design will be discussed in the following. The name is derived from the exponential vivaldi taper for all the antenna elements. The fabricated chip is shown in Figure 10. Since for the characterization of the single antenna no active parts are

necessary, it was fabricated in a Backend-of-line (BEOL) run, which reduces costs.

In Figure 10, the upmost metal layer with the vivaldi tapered open slot can be seen. Moreover, a coplanar waveguide is implemented in order to enable wafer-prober based characterization of the single antenna. The fill structures on TM2 are shown as well.

The concept of the multiple stacked vivaldi-shaped open slot design is based on [14]. In [14], a multilayer design at 60 GHz is presented which enables a small tilt of the radiation characteristics in comparison to a usual vivaldi antenna which radiates towards its sides. However, for the intended application, radiation vertical to the chip surface is desired. Moreover, the frequency range and the processes used are different.

In the design presented here, the radiating elements are implemented in layer TM2, Metal 5 and Metal 4. On

Figure 10: Photograph of the fabricated two times stacked vivaldi-shaped open slot antenna.

Figure 9: Measured and simulated S-parameters of the active distributed combiner.

Table 1: Dimensions of the radiating elements.

	TopMetal 2	Metal 5	Metal 4
Width radiating element	267 μm	267 μm	267 μm
Length radiating element	830 μm	930 μm	1030 μm

each layer, the width of these elements is the same, but the lengths varies. The values are listed in Table 1.

By stacking several radiating elements, the overall antenna bandwidth can be enhanced. However, the limitation towards the lower frequencies is set by the size of the largest antenna. The broadband characteristic of the antenna is achieved by the exponential taper of the open slot. As mentioned before the taper has the same shape like the well known Vivaldi antenna. Due to the stacked approach a common feeding for all the layers has to be implemented. This feeding structure is shown in Figure 11.

A CPW to microstrip (MS) transition is designed and placed at the edge of the radiating element on TM2. Afterwards, the signal line of the MS is implemented on TM1. This layer does not include a radiating element. Each of the three radiating elements is fed by the signal line below/above its slot. Behind the feeding zone, a stub is implemented. In order to characterize the antenna, a ground-signal-ground-structure to contact the chip with microwave probes is included. In Figure 12, the measured and simulated S_{11} of the antenna is shown.

It can be seen, that the simulated and the measured values agree to a high extent. For frequencies above approximately 165 GHz, the S_{11} stays below -10 dB, just the measured values between 180 GHz and 185 GHz show a slightly higher value. The resulting impedance bandwidth is 39%. Minor deviations can be noticed between simulation and measurements, which can be explained first by measurement influences like the positioning and

Figure 11: Schematic of the feeding structure for the stacked vivaldi-shaped open slot antenna. **Figure 12:** Measured and simulated matching of the two times stacked vivaldi-shaped open slot antenna.

contact force of the microwave probes and second by simplifications in the simulation model.

Besides the matching of the antenna, the radiation characteristics are a figure of merit for the antenna design. For the application intended, a radiation vertical to the chip surface is necessary. In Figure 13 radiation patterns of the antenna are shown.

In Figure 13, the realized gain (including matching) is shown exemplarily for four frequencies and two orthogonal antenna planes. For all frequencies shown, a realized gain above 0 dBi can be achieved for the main beam ($\theta = 0^\circ$). The slight asymmetry of the patterns in the xz-plane can be explained by the influence of the feeding structures. A radiation efficiency of 35% has been simulated. The radiation characteristics of the antenna have been measured as well and agree very well with the simulated values. This is shown in Figure 14.

The measured angle depends on the size of the scanned near-field area and due to the near-field measurement, only normalized values are given. The setup used for this measurement is described in the following section. The slight deviations between measured and simulated values can be explained by influences of the microwave probe and the probe antenna during the measurement.

It can be concluded, that by introducing a stacked Vivaldi-shaped open slot antenna, a bandwidth of 39% can be reached with reasonable gain values.

5.2 Pattern measurement setup

In order to verify the simulation of the integrated antennas, measurements are necessary. Usual measurements in antenna measurement chambers are not suitable for integ-

Figure 13: Simulated radiation patterns of the two times stacked vivaldi-shaped open slot antenna for the xz- and yz-plane.

Figure 14: Comparison of simulated and measured radiation pattern of the two times stacked vivaldi-shaped open slot antenna for 180GHz; normalized.

rated antennas due to their size. The contacting of the chips is only possible with microwave probes and not with connectors. Therefore, a measurement setup based on a commercially available wafer-prober has been developed and is shown in Figure 15.

Figure 15: Photograph of near-field measurement setup for integrated antennas [15].

The measurements are performed in the near-field of the Antenna Under Test (AUT) and a near-field to far-field transformation is performed afterwards in order to achieve the far-field quantities like the radiation patterns of the AUT. More details on the transformation, which is based on the Plane-Wave Spectrum theory of Kerns can be found in [16]. In the setup, the AUT is contacted directly by microwave probes and connected with a vector network analyzer (VNA). The probe antenna measuring the electric near-field is positioned on a positioning stage and connected with the VNA as well. Both, the positioning stages, as well as the VNA can be controlled by a PC which enables an automatic measurement. For the probe antenna, a plastic open-ended waveguide (OEWG) has been selected to reduce multiple reflections in the setup.

6 Integrated systems

As discussed in Section 3, within the frame of SPP 1655 project DAAB, broadband antenna and amplifier integrated systems are being designed following two approaches: integrate a broadband antenna with a distributed amplifier and integrate antennas centered at adjacent frequencies with a broadband active combiner.

In Figure 16 a layout screenshot of the first example is presented: a broadband Cascaded Single-Stage Distributed Amplifier (CSSDA) [9] is integrated with a three-time-stacked Vivaldi-shaped open-slot antenna and the interface impedance is adjusted for bandwidth optimization. The designed distributed circuit provides amplification from 90 GHz to 250 GHz, sacrificing gain in the lower band to reach frequencies well above the 170 GHz of the TWA state-of-art [7]. This has been crucial

Figure 16: Layout screenshot of the integrated antenna and amplifier.

to exploit at full the bandwidth of the available on-chip antennas, and reduce their chip areas. Figure 17 shows the simulated frequency response of the combined gain from the direction of peak gain of the antenna. The achieved 3 dB bandwidth exceeds 150 GHz to 230 GHz.

Figure 18 presents a second – more complex – example of integration. In order to boost the bandwidth, two antennas centered at adjacent bands – 90 GHz to 140 GHz and 140 GHz to 220 GHz – are integrated in the same die and combined with an active broadband 2:1 power combiner [8]. The antennas are a two-time-stacked

Figure 18: System-level schematic of the integrated antennas and active combiner circuit. The two antennas are centered at adjacent bands – f_1 and f_2 – while their frequency response is merged in the active broadband combiner.

Vivaldi-shaped open-slot antenna and a fractal bowtie. The fractal bowtie antenna is a bandwidth enhanced version of the one presented in [17]. The system-level schematic is shown in Figure 18, while the resulting frequency response of the gain is shown in Figure 19: the system provides useful gain from 95 GHz to 200 GHz. Figure 20 shows a layout screenshot of the IC, currently being fabricated.

The presented circuits compare very well against the state-of-the-art presented in Table 2: with bandwidths of 80 GHz and 105 GHz both circuits improve significantly the best reported values for single- and multi-antenna integrated systems.

Figure 17: Frequency response of the system gain for the integrated antenna and amplifier IC. The frequency response is simulated for the direction of peak gain.

Figure 19: The simulated frequency response of the system gain as a function of frequency for signals received from the direction of peak gain.

Figure 20: Layout screenshot of the integrated antennas and active combiner.

Table 2: State of the art for integrated amplifier and antennas operating above 120GHz.

Center Frequency	Cumulative BW	Amp. Gain	Ant. Gain	Tech.	Ref.
120 GHz	12 GHz	n.a.	4.4 dBi	CMOS and bond wire	[18]
170 GHz	10 GHz	15 dB	-8 dBi	SiGe HBT	[3]
220 GHz	24 GHz	3.5 dB	20 dBi(2)	GaAs HEMT	[19]
240 GHz	20 GHz	5 dB(1)	2 dBi(2)	SiGe:C HBT	[20]
180 GHz	80 GHz	20 dB	n.a. (3)	SiGe BiCMOS	DAAB
148 GHz	105 GHz(2)	20 dB	n.a. (3)	SiGe BiCMOS	DAAB

Notes: (1) Conversion gain of the active mixer; (2) Simulated; (3) Over such a broad bandwidth, the cumulative gain cannot be defined unequivocally.

7 Conclusion

This paper presented an overview of the work being performed within projects DAAB and DAAB-Tx towards enabling wireless data rates up to 100 Gbits⁻¹ through the exploitation of distributed structures for operation over very large bandwidths centered at mm-wave frequencies. In particular, work has been and is currently being performed at the circuit design level, the antenna design level and the integration of the two components. In all areas, state-of-the-art results are being achieved.

Table 3 presents an overview of the state of the art for broadband integrated amplifiers operating at frequencies above 100 GHz and delivering moderate to high power levels. It can be noted that the performance of SiGe BiCMOS amplifiers is very close to the III-V technologies in terms of bandwidth. In particular, the best reported III-V

amplifiers are matched in output power and bandwidth by recent results reported for silicon implementations. However, silicon circuits do not deliver the highest output power over the largest bandwidth, motivating research work in this area. The amplifier in [7], outcome of DAAB, represents with 170 GHz the highest reported bandwidth for silicon integrated amplifiers. This is achieved by optimizing the gain cells of the distributed amplifiers to compensate the dominant losses in the input line. Other solutions have been explored to extend the natural bandwidth of well-designed TWA. The work in [24] presents a tapered output line, which is an interesting approach for minimizing the losses and delivered more power to the load. However, the application of the method to higher frequencies needs to be studied.

In Table 4, an overview of broadband millimeter wave antenna designs is given. Most designs capable to achieve

Table 3: State of the art of traveling wave amplifiers at millimeter-wave frequencies, P_{1dB} : 1-dB compression point at the output, P_{dc} : dc power consumption.

Frequency	Gain	P_{1dB}	P_{dc}	Technology	Ref
0 GHz to 95 GHz	21 dB	16 dBm at 20 GHz	700 mW	InP DHBT	[21]
0 GHz to 180 GHz	5 dB	n.a.	n.a.	InP HEMT	[22]
0 GHz to 110 GHz	11 dB	7 dBm	450	GaAs HEMT	[23]
1 GHz to 110 GHz	10 dB	16 dBm at 40 GHz	360 mW	0.13 μ m SiGe HBT	[24]
1 GHz to 170 GHz	10 dB	7.5 dBm at 20 GHz	108 mW	0.13 μ m SiGe HBT	[7], DAAB

Table 4: State of the art for antennas for integrated systems. Results marked with (*) are simulated.

Center Frequency	Gain	Bandwidth ($S_{11} < -10$ dB)	Radiation Efficiency	Substrate Conductivity	Tech.	Ref.
140 GHz	7.7 dBi	n.a.	63%	n.a.	65 nm CMOS	[25]
160 GHz	8.8 dBi	20GHz	n.a.	n.a.	65 nm CMOS, FR4	[26]
230 GHz	6 dBi	37 GHz	n.a.	n.a.	Silicon, Rogers 3850/3908	[27]
130 GHz	-2 dBi(*)	5 GHz(*)	18%(*)	12 Ω cm	Silicon	[28]
194 GHz	3 dBi(*)	89 GHz(*)	n.a.	2 Sm^{-1}	130 nm BiCMOS	[29], DAAB

those high bandwidths include different materials for the antenna designs and therefore introduce connection parasitics. Moreover, the designs in [26, 27] require additional post-processing efforts. The stacked Vivaldi-shaped open slot antenna in [29], outcome of DAAB, fully integrated in a semiconductor process, enables the highest bandwidth reported in silicon.

A critical aspect of wireless communication systems is the connection between amplifiers and antennas. To limit the impact connection parasitics, the antennas can be integrated together with the amplifiers on one single chip. Several different transmitters and receivers with integrated electronics and antennas have been demonstrated in the past for operation frequencies up to 240 GHz. Table 2 presents an overview of the systems presented in literature and operating above 120 GHz. The main drawback of these systems is the relatively narrow band of operation. For example in [19] a bandwidth of 24 GHz is demonstrated for a center frequency of 220 GHz. The main bandwidth limitation of the state of the art arises from the employed narrow band power amplifiers and narrowband dipole antennas. In contrast, the latest chip sent to fabrication in SPP1655 project DAAB, by merging one active combiner [8] and two broadband antennas covering the bands 90 GHz to 140 GHz and 140 GHz to 220 GHz achieves 105 GHz of bandwidth centered at 155 GHz.

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