A Single-Stage Low-Noise SiGe HBT Distributed Amplifier with 13 dBm Output Power and 20 dB Gain in D-Band and over 170 GHz Bandwidth

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***Abstract*— This paper presents a single-stage distributed amplifier with an average gain of 19 dB and over 170 GHz bandwidth (measurement limited) resulting in >1.5 THz gain-bandwidth product (GBW). The amplifier is composed of 10 gain sections using an emitter follower buffered cascode stage and is implemented in a 130-nm SiGe BiCMOS process with 470 GHz f_T/ 650 GHz f_{max} HBT. The amplifier has over 14 dBm saturated output power (Psat) in W-Band and averages 13 dBm Psat with 20 dB gain in D-Band. Additionally, an average noise figure of 4.7 dB was measured over the complete 75 - 110 GHz range. This amplifier has, to the author's knowledge, the highest single-stage GBW reported to date while at the same time providing high output power and the best reported wideband noise figure for SiGe BiCMOS amplifiers in W-Band.**

***Keywords*— broadband amplifiers, distributed amplifiers, SiGe BiCMOS, sub-THz integrated circuits, mm-wave power amplifiers.**

I. Introduction

Distributed amplifiers (DA's) are the circuit topology of choice for applications requiring ultra-wide bandwidth performance such as optical modulator drivers [1], [2], transimpedance amplifiers, measurement instrumentation and ultra-wideband transceivers for radar and wireless communications. Recently, distributed amplifiers with various topologies and number of stages have been implemented and published in state-of-the-art technologies including SOI CMOS [3], GaAs and InP HEMT [4], InP DHBT [5], [6], [7] and SiGe BiCMOS [8], [9], [10].

However, while having flat gain and excellent matching over an ultra-wide bandwidth, distributed amplifiers typically have limited output power and relatively poor noise figure compared to power amplifiers (PA's) and low-noise amplifiers (LNA's) designed for narrow-band applications.

In this paper, we present a single-stage distributed amplifier with 10 sections with not only a high GBW but also with good output power measured up to 170 GHz and excellent noise performance measured up to 110 GHz.

The design uses a topology originally introduced for optical driver amplifiers [1] and optical receivers [7]. To further lower the noise figure, we take advantage of a state-of-the art SiGe BiCMOS technology with 470 GHz f_T / 650 GHz f_{max} currently under development at IHP. Basic features of the technology called SG13G3 are described in [11], [12]. For comparison, a 7 section amplifier implemented in both SG13G3 and the previous technology generation SG13G2, [13] with peak f_T/f_{max} of 300/500 GHz, is presented.

II. Amplifier Topology and Design

The schematic of the low-noise distributed amplifier is shown in Fig. 1. The amplifier has 10 identical unit sections distributed at both input and output using 90 μm long transmission lines with a characteristic impedance of 70 Ω. The input artificial transmission line is terminated with a 50 Ω resistor connected to the main supply Vcc, while the output line is terminated in 60 Ω, also connected to Vcc.

Each unit cell comprises of a cascode stage buffered at its input by an emitter follower as was introduced in [6]. The emitter follower is biased using a fixed resistor. The biasing and sizing of this emitter follower is a compromise between the amount of loss-compensation provided by the negative resistance created at the input of the emitter follower, its noise matching and the need for high input power compression. A small capacitor (100 fF) is used between the emitter follower and the input of the cascode, both as a DC block and as a capacitive divider, to slightly increase the bandwidth. The value of this capacitor sets the lower frequency 3-dB gain cut-off of the amplifier to about 1 GHz. The cascode stage is biased at its input using a 3 kΩ resistor connected to a current mirror while the voltage on the common-base transistor is set using a resistive divider.

The current to the cascode stages is provided in measurement using an external bias-T connected to the amplifier output. Providing this current (60 mA) through the output termination resistor as was accomplished in [1], would deteriorate the overall efficiency too much. Adding an internal bias-T [8] is possible without too much effect on the mm-wave characteristics and was done in a later version of this amplifier. Such internal bias-T does affect gain, noise and power performance at the lower 10-20 GHz operating range of the amplifier.

Additionally, we implemented a very similar distributed amplifier with 7 identical sections separated by 110 μm long 70 Ω transmission lines. This amplifier was implemented in both IHP SG13G2 and SG13G3 technologies. The die photographs of both the 10-section and 7-section distributed amplifiers are

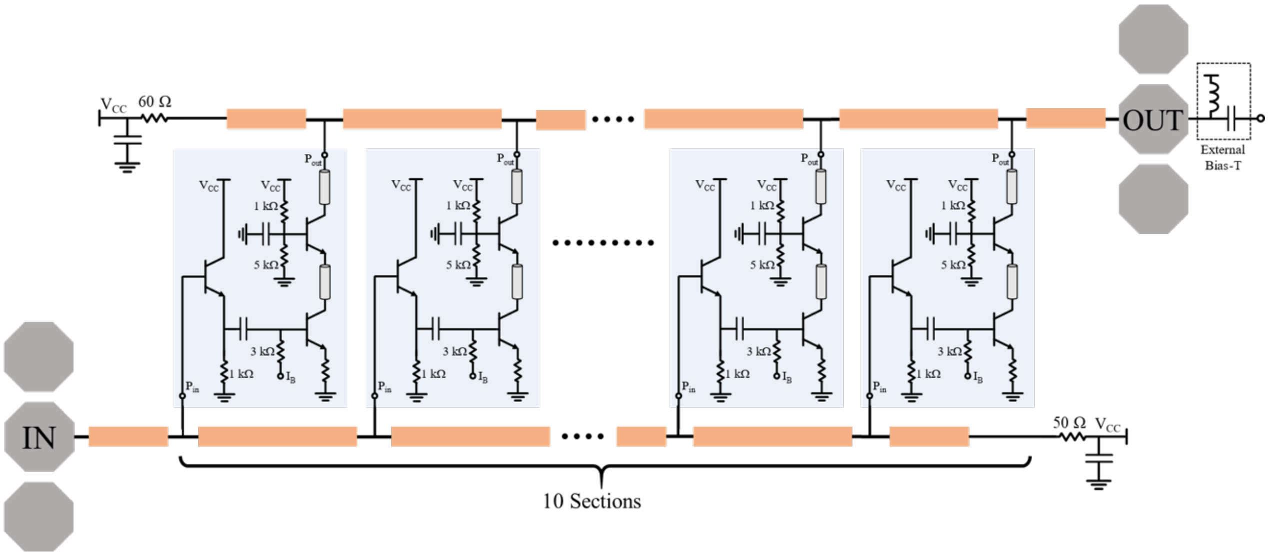

Fig. 1. Schematic diagram of the 10-section low-noise distributed amplifier (DA).

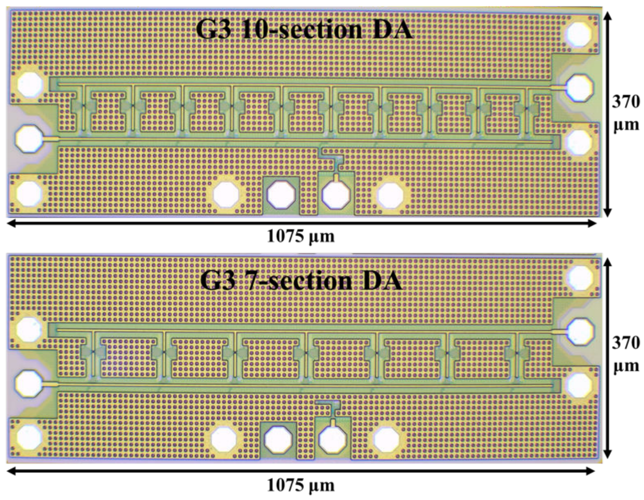

Fig. 2. Chip micrograph of the 10-section (top) and 7-section (bottom) distributed amplifiers.

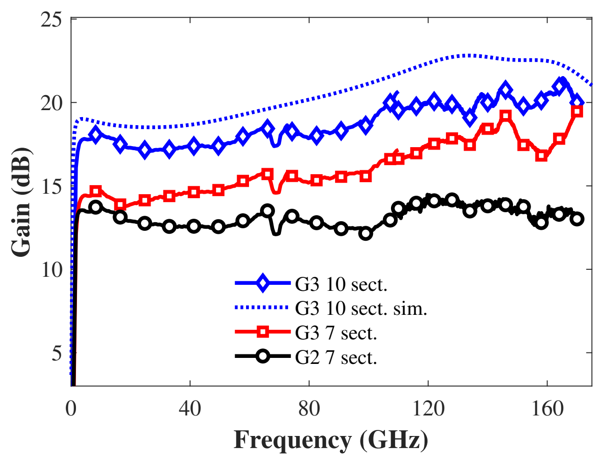

Fig. 3. Measured and simulated insertion gain of the 10-section G3 DA and the measured insertion gain of the 7-section G3 and G2 DAs.

shown in Fig. 2 . The overall size of each amplifier is 1.08 x 0.37 mm^2 which is mainly pad limited, the active area itself is only 0.92 x 0.15 mm^2.

III. Measurements

S-parameter measurements between 10 MHz and 170 GHz were performed using two test benches: from 10 MHz -110 GHz using a 1-mm connectorized Keysight network analyzer and in D-Band (110-170 GHz) using Virginia Diodes (VDI) WR6 waveguide extenders. The measured insertion gains of the 10-section G3 amplifier and the 7-section G2 and G3 amplifiers are shown in Fig. 3. The 10-section amplifier has a lower cut-off frequency of 1 GHz, an average gain of 18 dB in the 1-110 GHz range and over 20 dB average gain in the 110-170 GHz range. The gain is still rising at 170 GHz, and simulations indicate a 3-dB cut-off frequency of over 200 GHz. The 7-section G3 amplifier has a reduced gain averaging 15 dB up to 110 GHz and 17 dB in D-Band, while the identical amplifier implemented in G2 has a very flat gain of 13 dB ($\pm$1 dB, within calibration accuracy) over the complete 1-170 GHz range. All S-parameter measurements were performed at overall bias of 3.3V for both the main and bias-T supply. Total current draw is 85 mA for the 10-section and 65 mA for the 7-section amplifiers.

Thanks to the emitter follower buffer at the input and the cascode topology at the output, providing low capacitive loading on both the input and output artificial transmission lines, good input and output reflection is achieved, as is illustrated in Fig. 4 and 5 respectively . All 3 versions have input reflection of better than -14 dB from 10 MHz up to 110 GHz and better than -10 dB up to 160 GHz. The output reflection is between -25 dB and -10 dB for most of the frequency range. For the 10-stage G3 amplifier an increased

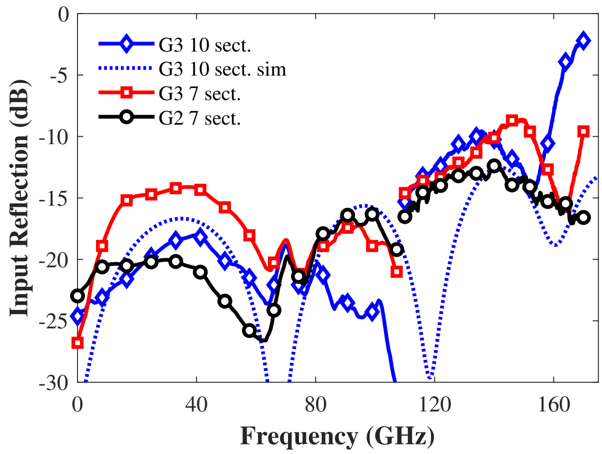

Fig. 4. Measured and simulated input reflection of the 10-section G3 DA and the measured input reflection of the 7-section G3 and G2 DAs.

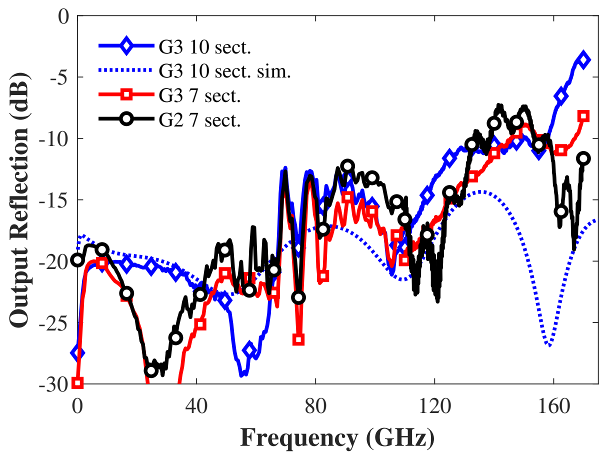

Fig. 5. Measured and simulated output reflection of the 10 section G3 DA and the measured output reflection of the 7 section G3 and G2 DAs.

input and output reflection is observed close to 170 GHz. This may indicate that this amplifier is close to its cut-off frequency or can also be due to the very high gain (22 dB) at 170 GHz in the small singulated die.

Output power measurements were performed using three test benches, one from 1-70 GHz using a 1.85mm source, one in W-Band (75-110 GHz) using a WR-10 frequency multiplier and driver amplifier and one in D-Band using only a WR-6 multiplier. To fully maximize the output power, the main supply was increased to 3.6 V and the bias-T voltage to 3.8 V, resulting in 100 and 75 mA current draw for the 10 and 7-section amplifiers respectively. The measured and simulated saturated output power (Psat) of the 10-section G3 amplifier is shown in Fig. 6. At low frequencies, over 17 dBm output power is achieved. At 60 GHz, a 1-dB compression point (P1dB) of 14 dBm and a saturated output power of 16.3 dBm was measured. In W-Band, a Psat between 14 and 15 dBm is measured over the whole frequency range, while in D-Band, an average output power of 13 dBm is achieved from 110 to

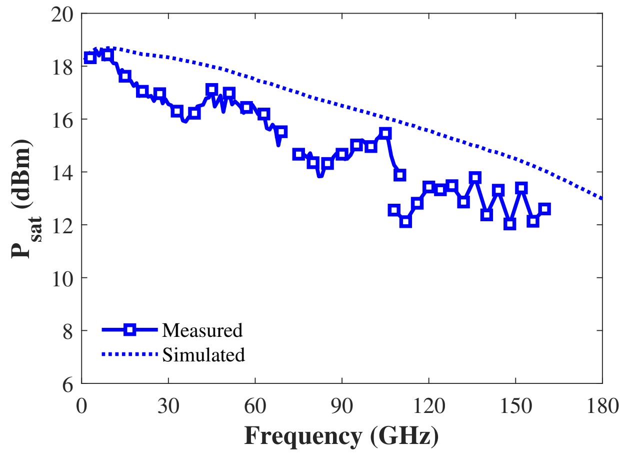

Fig. 6. Simulated and measured saturated output power (P_{sat}) of the 10 section G3 distributed amplifier.

160 GHz, partly limited by the input power available from the frequency multiplier source at these frequencies. The 7-section G3 amplifier provides about 1.5 dB lower output power in both W and D-Band.

Noise measurements were performed from 75-110 GHz using a W-Band waveguide set-up consisting of a Quinstar low ENR WR-10 waveguide noise source and a receiver consisting of a W-Band LNA module, a fundamental WR-10 mixer fed by a Millitech x6 active multiplier and a Keysight PXA spectrum analyzer with integrated low-noise preamplifier. Additionally, noise figure measurements were also performed in a narrow band around 60 GHz. As shown in Figure 6, the 10-section G3 amplifier achieves an outstanding average noise figure of 4.7 dB across the entire 75-110 GHz frequency range and around 4 dB at 60 GHz. This is only slightly higher than the simulated noise figure, which did not include the loss in the RF-pads and some of the extracted layout parasitics. The measured noise figure is close to the 3 dB minimum noise figure for the G3 SiGe HBT's in W-Band, demonstrating the capability of this distributed topology for achieving ultra-wideband low noise figure. For the 7-section G3 amplifier an average noise figure of 5.1 dB was measured in W-band, while the noise in the G2 version was about 1.3 dB higher at 6.4 dB.

Our results are summarized in Table I and compared with the recent state-of-the-art in distributed amplifiers. As can be observed our design achieves an excellent gain-bandwidth product for a single stage amplifier. It also achieves the highest W-band and D-band output power and lowest reported W-Band noise figure for recent distributed amplifiers.

IV. Conclusion

In this paper, we described a distributed amplifier with a record gain-bandwidth for a single stage DA and high output power up to 170 GHz. Its noise figure rivals some of the best W-Band SiGe narrowband LNA's published in literature and thanks to the relatively high input power compression (-5..-10 dBm), the design delivers a high dynamic range over most of

Table 1. Comparison with state of the art distributed amplifiers.

Ref.	Technology	f_t/f_{max} (GHz)	Gain (dB)	BW (GHz)	P_{sat}* (dBm)	GBW (GHz)	Noise Figure* (dB)	P_{DC} (mW)	Area (mm^2)	Topology
[8]	90nm SiGe	255/-	27	120	10 @ 100GHz	2577	-	-	1.25	3 cascaded stages
[3]	45nm SOI	290/250	16	120	21.6 @ 60GHz	757	6.2 @ 50GHz	-	0.51	single stage stacked PA
[9]	130nm SiGe	300/500	10	170	7.5 @20GHz†	537	-	108	0.38	single stage DA
[5]	250nm InP HBT	375/650	10	182	8.5 @ 134GHz	575	-	105	0.33	single stage
[14]	700nm InP DHBT	265/305	21	120	-	1350	-	610	2.0‡	single stage
[15]	500nm InP DHBT	350/400	10	145	10 @ 160GHz	458	8.0 @ 105GHz	96	0.6‡	single stage
[10]	130nm SiGe	300/500	15.3	87	-	508	-	499	0.86‡	single stage differential
		470/700	16.9	>110	-	>770	-	509		
This work	130nm SiGe	470/650	19	>170	13 @150GHz	>1515	4.7 @ 100GHz	350	0.14	single stage 10 sections
		470/650	16	>170	11 @150GHz	>1072	5.2 @ 100GHz	250		single stage 7 sections
		300/500	13.5	>170	11.5 @100GHz	>804	6.4 @100GHz	250		single stage 7 sections

* at highest measured frequency. † P1dB. ‡ including pads.

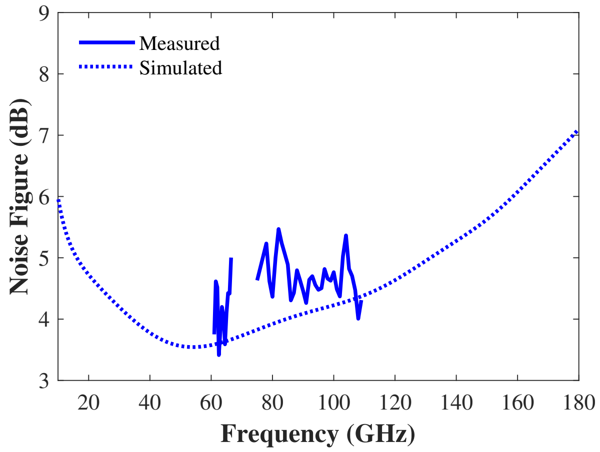

Fig. 7. Simulated and measured noise figure of the 10-section G3 distributed amplifier.

its 170 GHz bandwidth. Additional measurements including S-parameters beyond 170 GHz and noise figure measurements in D-Band will be performed and may be presented at the conference.

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References

[1] Y. Baeyens, N. Weimann, P. Roux, A. Leven, V. Houtsma, R. Kopf, Y. Yang, J. Frackoviak, A. Tate, J. Weiner, P. Paschke, and Y.-K. Chen, "High gain-bandwidth differential distributed InP D-HBT driver amplifiers with large (11.3 Vpp) output swing at 40 Gb/s," *IEEE J. Solid-State Circuits*, vol. 39, no. 10, pp. 1697–1705, Oct. 2004.

[2] P. Rito, I. García López, A. Awny, M. Ko, A. C. Ulusoy, and D. Kissinger, "A DC-90-GHz 4-V_{pp} modulator driver in a 0.13- μm SiGe:C BiCMOS process," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 12, pp. 5192–5202, Dec. 2017.

[3] O. El-Aassar and G. M. Rebeiz, "A 120-GHz bandwidth cmos distributed power amplifier with multi-drive intra-stack coupling," *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 8, pp. 782–785, Aug. 2020.

[4] B. Agarwal, A. Schmitz, J. Brown, M. Matloubian, M. Case, M. Le, M. Lui, and M. Rodwell, "112-GHz, 157-GHz, and 180-GHz InP HEMT traveling-wave amplifiers," *IEEE Trans. Microw. Theory and Techn.*, vol. 46, no. 12, pp. 2553–2559, Dec. 1998.

[5] S. Yoon, I. Lee, M. Urteaga, M. Kim, and S. Jeon, "A fully-integrated 40–222 GHz InP HBT distributed amplifier," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 7, pp. 460–462, Jul. 2014.

[6] Y. Baeyens, N. Weimann, V. Houtsma, J. Weiner, Y. Yang, J. Frackoviak, P. Roux, A. Tate, and Y. K. Chen, "Submicron InP D-HBT single-stage distributed amplifier with 17 dB gain and over 110 GHz bandwidth," in *2006 IEEE MTT-S Int. Microw. Symp. (IMS) Dig.*, 2006, pp. 818–821.

[7] T. Swahn, Y. Baeyens, and M. Meghelli, "ICs for 100-Gb/s serial operation," *IEEE Microw. Mag.*, vol. 10, no. 2, pp. 58–67, Apr. 2009.

[8] O. Kazan and G. M. Rebeiz, "A 10-130 GHz distributed power amplifier achieving 2.6 THz GBW with peak 13.1 dBm output P1dB for ultra-wideband applications in 90nm SiGe HBT technology," in *2021 IEEE BiCMOS Compound Semicond. Integr. Circuits Technol. Symp. (BCICTS)*, 2021, pp. 1–4.

[9] P. V. Testa, G. Belfiore, R. Paulo, C. Carta, and F. Ellinger, "170 GHz SiGe-BiCMOS loss-compensated distributed amplifier," *IEEE J. Solid-State Circuits*, vol. 50, no. 10, pp. 2228–2238, 2015.

[10] M. Inac, A. Fatemi, F. Korndörfer, H. Rücker, F. Gerfers, and A. Malignaggi, "Performance comparison of broadband traveling wave amplifiers in 130-nm SiGe:C SG13G2 and SG13G3 BiCMOS technologies," *IEEE Microw. Wireless Compon. Lett.*, vol. 31, no. 6, pp. 744–747, Jun. 2021.

[11] B. Heinemann *et al.*, "SiGe HBT with fx/fmax of 505 GHz/720 GHz," in *2016 IEEE Int. Electron Devices Meeting (IEDM)*, 2016, pp. 3.1.1–3.1.4.

[12] H. Rücker and B. Heinemann, "Device architectures for high-speed SiGe HBTs," in *2019 IEEE BiCMOS Compound Semicond. Integr. Circuits Technol. Symp. (BCICTS)*, 2019, pp. 1–7.

[13] H. Rücker, B. Heinemann, and A. Fox, "Half-terahertz SiGe BiCMOS technology," in *2012 IEEE 12th Topical Meeting Silicon Monolithic Integr. Circuits in RF Syst.*, 2012, pp. 133–136.

[14] V. Hurm *et al.*, "InP DHBT-based distributed amplifier for 100Gbit/s modulator driver operation," *Electron. Lett.*, vol. 44, pp. 705–706(1), Jun. 2008.

[15] T. Shivan, M. Hossain, D. Stoppel, N. Weimann, S. Schulz, R. Doerner, V. Krozer, and W. Heinrich, "An ultra-broadband low-noise distributed amplifier in InP DHBT technology," in *2018 13th European Microw. Integr. Circuits Conf. (EuMIC)*, 2018, pp. 241–244.