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AlGaN/GaN-based power amplifiers for mobile radio applications: a review from the system supplier's perspective

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This paper gives a summarized overview on the progress and achievements on AlGaN/GaN high electron mobility transistors (HEMT)-based power amplifiers (PAs) for mobile radio applications which have been achieved within two national funded German projects during a period of six years. Starting with a first 34 dBm (2.5 W, peak) amplifier in 2003 the impressive progress toward highly efficient S-band mobile radio PAs with up to >50 dBm (100 W) peak output power is described by means of some selected single- and multiband amplifier demonstrators. This progress has been mainly enabled by clear progress on GaN technology, device packaging, and PA design. Targeting at highly efficient single-band amplifier applications, a 2.7 GHz symmetrical Doherty amplifier with up to 45% drain efficiency at close to 45 dBm average output power under single-carrier W-CDMA (Wideband Code Division Multiple Access) operation using digital predistortion can be highlighted. In case of multiband capable amplifiers addressing software-defined radio applications, a class-AB-based demonstrator covering a frequency range from 1.8 to 2.7 GHz was realized. The amplifier showed >30% drain efficiency up to 2.5 GHz as well as up to 40 dBm average output power under single-carrier W-CDMA operation using proprietary digital predistortion. Finally, Alcatel-Lucent's activities on envelope tracking for future efficiency improved GaN-based amplifiers are described.

Keywords: AlGaN/GaN HEMT, W-CDMA, Power amplifier, Multiband, Doherty, Envelope tracking, Drain efficiency, Digital predistortion

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I. INTRODUCTION

Today's mobile radio communication is characterized by a coexistence of various different communication standards like GSM (second generation of mobile communication), UMTS (third generation of mobile communication), and its potential successor LTE (Long Term Evolution) which will be commercially introduced in near future. These standards exist in different frequency bands distributed in the L- and S-band between approximately 400 MHz up to 4 GHz. The standards have been developed and introduced in order to enable the continuously increasing data rates being necessary to support multimedia applications and mobile internet. UMTS and LTE use complex modulation schemes with non-constant envelopes, characterized by signals exhibiting a high peak-to-average-ratio of e.g. >10 dB and imposing high linearity constraints. When using classical amplifier designs, compliance with these constraints can only be achieved at the expense of power amplifier (PA) efficiency.

In order to afford today's and future mobile radio applications and to increase PA efficiency as well as to enable multiband and multistandard capable solutions like software-defined radio, suitable PA semiconductor technologies enabling performance improvement and supporting new promising circuit concepts are urgently required.

Against this background, Alcatel-Lucent started at an early point in time to evaluate the promising AlGaN/GaN semiconductor technology for future mobile radio PA applications within four national funded projects (GANGLION & ErGaN (2003–2006) and ELBA & Class-S (2006–2009)).

In the following sections, the progress on linear single- and multiband PAs based on AlGaN/GaN semiconductor technology provided by FhG-IAF Freiburg is described and illustrated by selected demonstrators and related characteristic measurement results. The progress has been achieved during a period of six years within GANGLION and ELBA project.

II. GANGLION PROJECT – GaN-BASED MULTIBAND PAs

Main target of GANGLION project was to evaluate the GaN technology for multiband RF PAs featuring a total covered bandwidth of up to 900 MHz and output power levels under UMTS operation of 10 W average and even higher.

A) Basic design considerations

Using established technologies like LDMOS, multiband amplifier design becomes very difficult, especially for high

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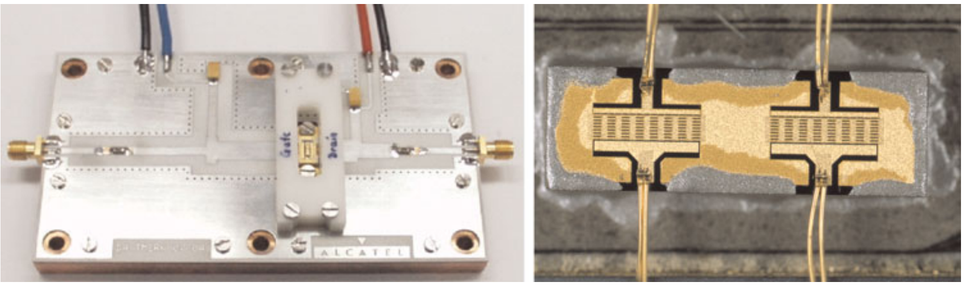


Fig. 1. Photos of an early GANGLION multiband PA and of a packaged $W_G = 2$ mm power cell.

power levels, e.g. due to low impedance levels and thus required internal prematching. Owing to the high power density of GaN high electron mobility transistors (HEMT) devices, GaN technology brings additional possibilities and advantages for the design of amplifiers, especially for wide- and multiband amplifiers. Because to this fact, GaN HEMTs are the best choice when realizing future multiband capable amplifiers and evaluating the limits. In order to support the multiband amplifier design, which requires optimized tuning as well as appropriate parameter trade-off (e.g. gain versus efficiency and power) for different frequencies within the targeted bandwidth, CAD tools and accurate transistor models are essential. Furthermore, different important requirements e.g. coming from the communication standard (e.g. adjacent channel leackage ratio (ACLR)), from the standard related signal (e.g. Peak-to-Average Ratio (PAR)), from the targeted application (output power, frequency range, etc.) and last but not least from the chosen amplifier concept and use of linearization and reduction of signal dynamic, have to be considered when designing mobile radio amplifiers. Based on this background, the following described amplifier demonstrators have been designed.

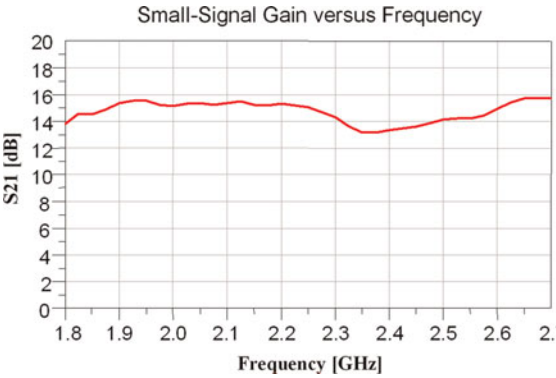


Fig. 2. Measured frequency characteristic of first GANGLION amplifier.

B) First multiband capable amplifier

At the beginning of GANGLION project, a first class-AB-based PA was realized, yielding up to approx. 34 dBm peak output power when using a single-carrier W-CDMA signal. This amplifier was based on a power cell with a gate width of $W_G = 2$ mm. Figure 1 shows a photo of the realized demonstrator and Fig. 2 the related measured small-signal S21 frequency characteristic. The amplifier exhibited a total gain of approximately 15 dB with a gain ripple of about 2 dB in the frequency range between 1.8 and 2.7 GHz.

This multiband amplifier mainly represents the status of technology and multiband RF amplifier design at the beginning of the project. Pushing forward to higher power levels, larger power cells had to be realized and challenges like stability and suitable assembly/packaging technology as well as reliable modeling of transistor and package, respectively, had to be faced.

C) Two-stage traveling-wave amplifier (TWA)

The realization of a two-stage TWA, covering a frequency range from 1.4 to 2.5 GHz was a next important step toward increased output power [2]. The TWA concept has been chosen due to the fact that it is very suited for wideband/multiband applications. The two-stage TWA shown in Fig. 3 consists of a driver stage with a gate width of $W_{GS1} = 4$ mm and a final stage with an all in all gate width

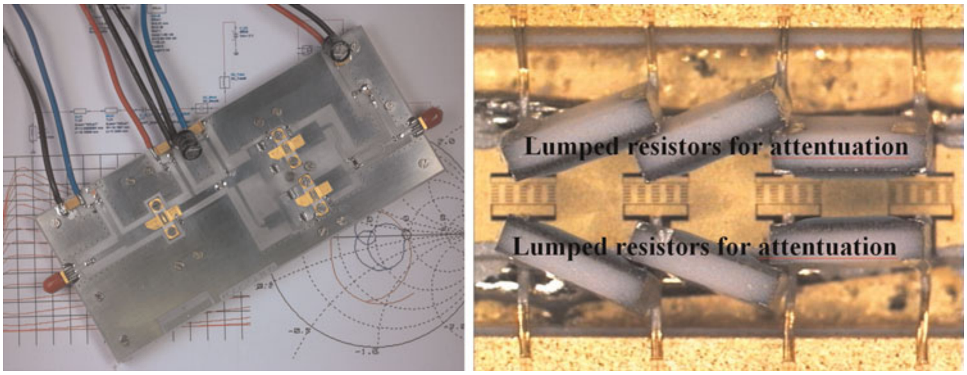


Fig. 3. Photo of the two-stage TWA and of a $W_G = 8$ mm packaged power cell.

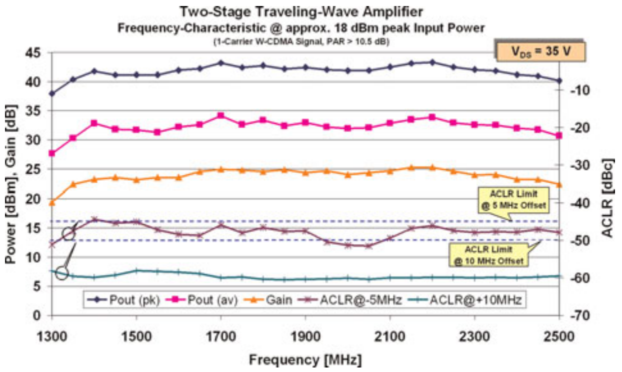
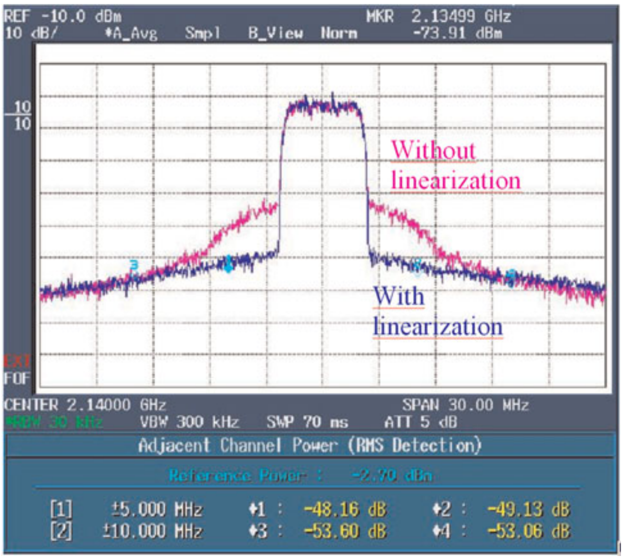


Fig. 4. Frequency characteristic of travelling-wave PA.

of $W_{GS2} = 16$ mm, realized by two $W_G = 8$ mm power cells each in a separate package. After the driver stage, the input power is time delayed fed into the parallel transistors. In order to compensate for this time delay, an equal delay line at the output is necessary. For power combining, a Wilkinson configuration was chosen for the TWA final amplifier stage. On the right-hand side Fig. 3 shows a photo of the employed $W_G = 8$ mm power cell, which has been realized by combination of four $W_G = 2$ mm sub cells. Later on inserted lumped resistors guarantee for stability by stabilizing the sub-cells against each other. This procedure resulted in a stable TWA.

Figure 4 gives the peak and average output power as well as the gain for the TWA module between 1.3 and 2.5 GHz. We observed a 3 dB bandwidth of 1.15 GHz between 1.35 and 2.5 GHz. The ACLR requirements at 5 and 10 MHz offset are met from 1.55 to 2.5 GHz when using a single-carrier W-CDMA signal with 10.5 dB PAR without using digital predistortion. The corresponding measured peak power is clearly beyond 40 dBm with a maximum of 43.2 dBm at 2.2 GHz.

At the end of GANGLION project, a high power multiband amplifier in push–pull configuration has been successfully realized. A photo of the amplifier is shown in Fig. 5. The photo of the packaged $W_G = 32$ mm power bar on the right-hand side impressively demonstrates the progress in sub-cell stabilization. The power cell design has been clearly improved, making above mentioned stabilizing lumped resistors (Fig. 3) obsolete. The push–pull amplifier is based on two of those $W_G = 32$ mm power cells and covers a frequency range from 1.8 to 2.2 GHz. It achieved up to 46.2 dBm average output power at 2.14 GHz meeting 3GPP ACLR specification when applying a single-carrier W-CDMA signal with 5.5 dB PAR and using digital predistortion. The related measured spectrum without (magenta) and with (blue) digital predistortion is shown in Fig. 6. The maximum measured peak output power of the amplifier was 51.9 dBm at 2.14 GHz, as shown in Fig. 7. By this amplifier, the potential of AlGaN/GaN technology for high power multiband amplifiers has been impressively demonstrated.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REF -10.0 dBm                          MKR 2.13499 GHz
10 dB/    *A_Avg   Smpl   B_View  Norm     -73.91 dBm
CENTER 2.14000 GHz                    SPAN 30.00 MHz
*RBW 30 kHz    VBW 300 kHz   SWP 70 ms   ATT 5 dB
           Adjacent Channel Power (RMS Detection)
              Reference Power :   -2.70 dBm
 [1]   ±5.000 MHz   *1 : -48.16 dB   *2 : -49.13 dB
 [2]  ±10.000 MHz   *3 : -53.60 dB   *4 : -53.06 dB
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Fig. 6. Measured output spectrum at 2.14 GHz with and without linearization.

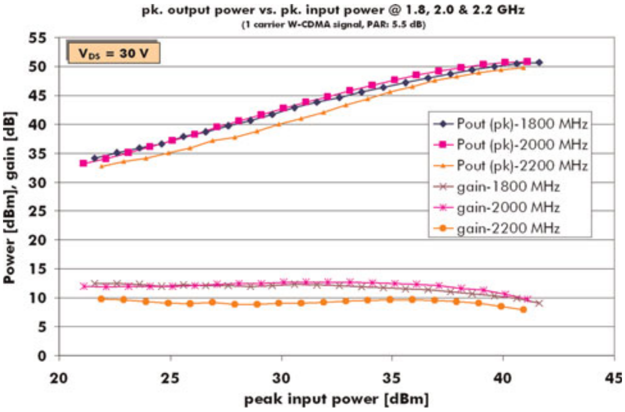

Fig. 7. Measurement result of the push–pull amplifier.

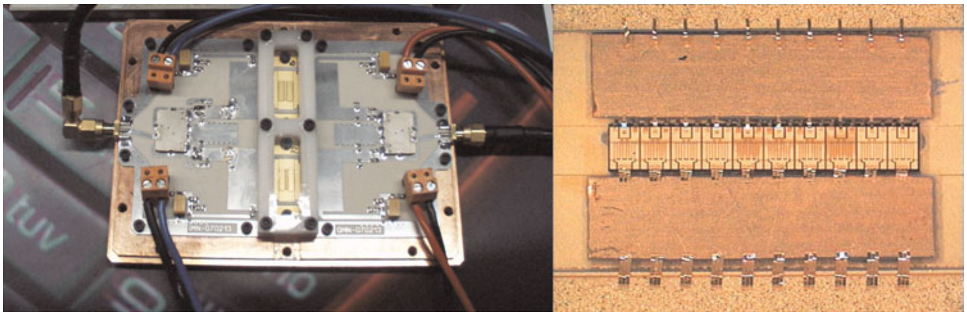

Fig. 5. Photo of the push–pull multiband amplifier and a packaged $W_G = 32$ mm chip.

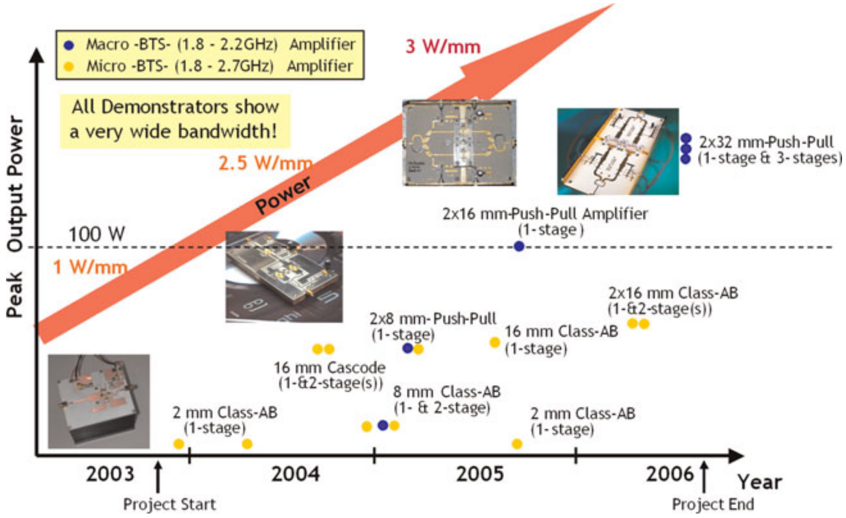

Fig. 8. Overview on GaN multiband amplifiers realized in GANGLION.

In retrospect, an impressive progress for AlGaN/GaN-based multiband PAs has been achieved by the close Alcatel-Lucent/FhG-IAF collaboration within the GANGLION project. Starting with a low power 34 dBm (peak) amplifier, the peak output power has been boosted up to 51.9 dBm – which means by 18 dB! In parallel, all demonstrators exhibited a large bandwidth and have been characterized successfully against 3GPP ACLR specification using a single-carrier W-CDMA signal, partially also using linearization and reduction of signal dynamic. Figure 8 gives a summarized overview on all GaN multiband amplifiers realized within GANGLION. It can be noticed that more than 15 amplifier demos have been commonly realized by Alcatel-Lucent and FhG-IAF within the three years project duration.

III. ELBA PROJECT – EFFICIENCY IMPROVED GaN-BASED PAs

While the main focus in GANGLION was a general investigation of the suitability of GaN technology for mobile radio multiband PA realization up to high output power levels, the main target in ELBA was to investigate promising amplifier concepts for efficiency improvement based on GaN technology. In order to achieve this, demonstrators for single- and multiband amplifiers have been realized and characterized using W-CDMA test signals in combination with reduction of signal dynamic and digital predistortion.

For this purpose, a single-band class-AB GaN amplifier was realized in the beginning in order to determine the current GaN technology status and limits of conventional class-AB amplifiers at the beginning of the project.

A) Single-band class-AB GaN amplifier

Figure 9 shows a photo of the realized 2.7 GHz class-AB amplifier, based on a $W_G = 32$ mm GaN power cell. As shown by Fig. 10 the amplifier yielded up to approximately 49 dBm saturated output power at $V_{DS} = 34$ V, when using a single-carrier W-CDMA signal. The estimated ACLR limit for linearizability of this technology is at about −33 dBc resulting in about 43 dBm average output power with a drain efficiency of 31%. The maximum gain after amplifier tuning is 13 dB.

When using digital predistortion and at a supply voltage of $V_{DS} = 30$ V, the spectrum of the single-carrier W-CDMA meets the 3GPP ACLR specification (−45 dBc at 5 MHz offset and −50 dBc at 10 MHz offset) up to an average

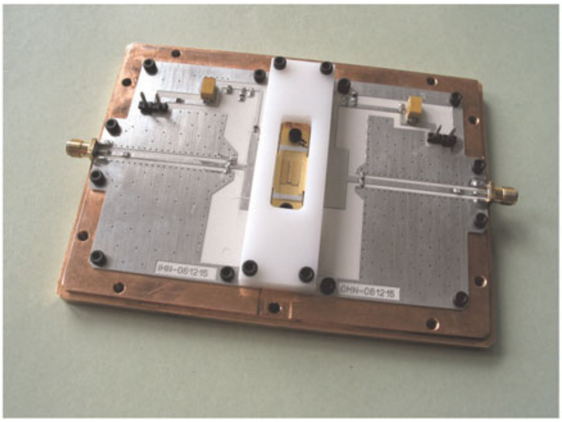

Fig. 9. Photo of 2.7 GHz class-AB amplifier.

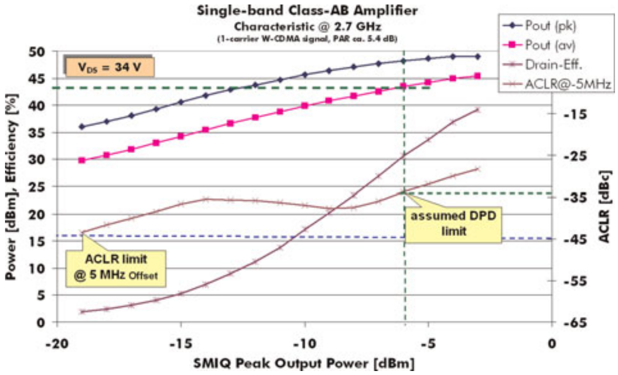

Fig. 10. Measured characteristic of single-band class-AB amplifier.

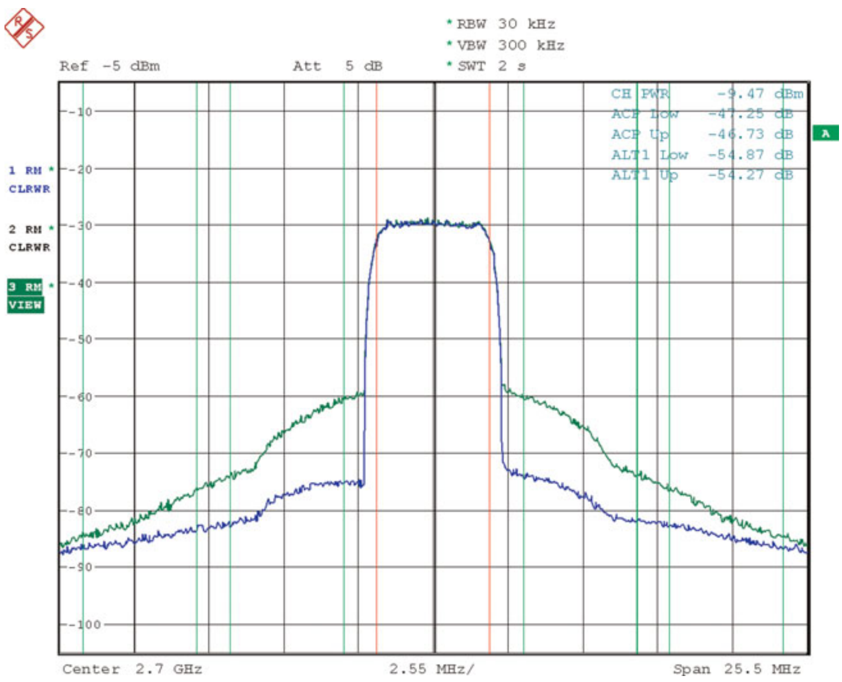

Fig. 11. Measured single-carrier W-CDMA spectrum without and with linearization.

output power of 42.3 dBm and 32.3% drain efficiency, as illustrated by Fig. 11.

B) Single-band symmetrical GaN Doherty amplifier

In order to improve single-band efficiency, the symmetrical Doherty concept was chosen and a GaN-based Doherty amplifier for 2.7 GHz was designed based on a large signal model from FhG-IAF and subsequently realized. Figure 12 shows a photo of this amplifier demonstrator, which is based on two $W_G = 32$ mm power cells. Feeding the signal to the main amplifier and the auxiliary amplifier, a 90°, 3 dB hybrid is used on the input side. In order to increase the bandwidth of the output transformator, a shorted quarter-wave stub has been added.

After manually tuning of the output matching network i.o. to ensure a proper load modulation, the Doherty amplifier yielded a clear efficiency improvement at 2.7 GHz when

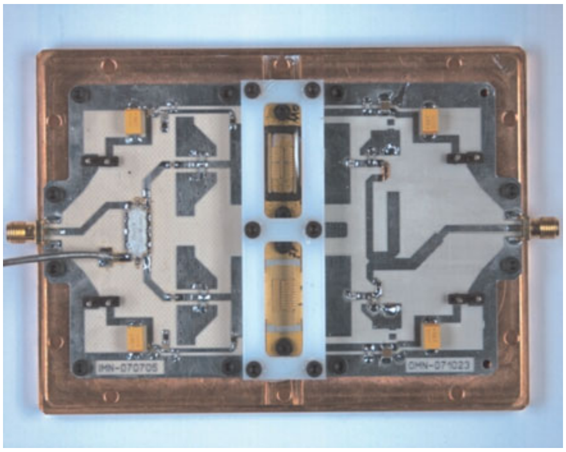

Fig. 12. Photo of a symmetrical Doherty amplifier.

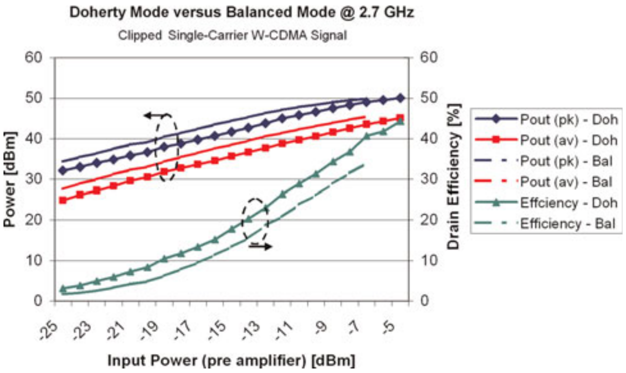

Fig. 13. Measured characteristic in Doherty mode versus balanced mode.

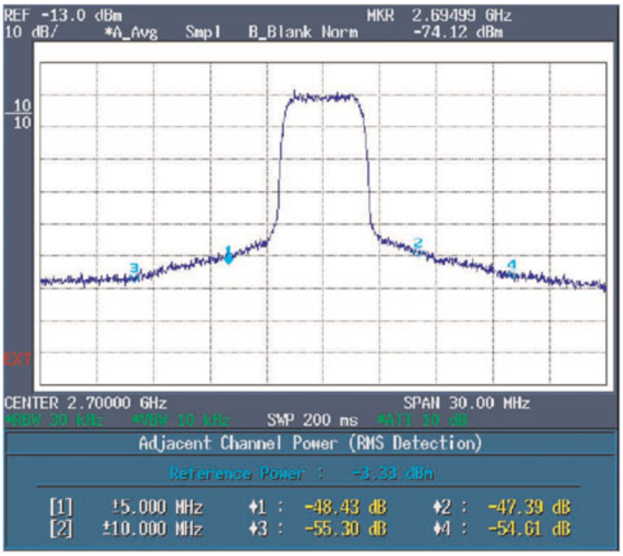

Fig. 14. Measured single-carrier W-CDMA spectrum using digital predistortion.

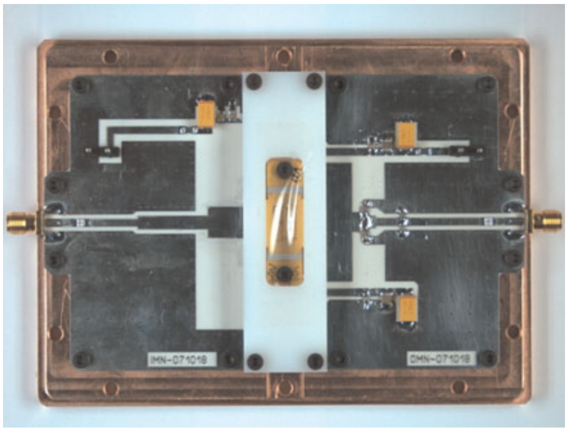

Fig. 15. Photo of highly efficient class-AB multiband amplifier.

compared to the previously presented class-AB amplifier as well as compared to when operating the Doherty in balanced mode. In both cases, a drain efficiency improvement of about 10% has been found. A measured performance comparison between balanced and Doherty mode is given by Fig. 13. The gain of the Doherty is about 9 dB.

Figure 14 shows the measured single-carrier W-CDMA spectrum in Doherty mode, when applying digital predistortion. Meeting 3GPP ACLR specification, the Doherty amplifier achieved up to 44.9 dBm average output power and 45% drain efficiency for $V_{DS} = 30$ V.

In order to investigate multiband PA performance, a class-AB-based demonstrator, covering a frequency range from 1.8 to 2.7 GHz was designed using a packaged $W_G = 32$ mm power cell. A photo of this multiband amplifier is shown in Fig. 15. In the same manner as the previously discussed devices, also this amplifier was characterized using a single-carrier W-CDMA signal with reduced signal dynamic and digital predistortion. Figure 16 shows the measured small signal characteristic of S11 and S21 as well as the linearized single-carrier output spectrum at the three different frequencies 1.8, 2.14 and 2.7 GHz. Up to 2.5 GHz, the multiband amplifier showed very good drain efficiencies of >30%, meeting 3GPP ACLR requirements. The associated average output power is around 40 dBm. At 2.7 GHz the amplifier showed a decrease by ~5% in drain efficiency and 2.5 dBm in output power, while the gain is relatively constant at about 12 dB across the whole frequency range.

C) Envelope tracking (ET) for efficiency improved single- and multiband GaN amplifier

The previously discussed Doherty concept constitutes a good solution to improve single-band PA efficiency at reasonable circuit complexity, but e.g. due to frequency-dependent load modulation and quarter-wave sections, the basic concept is not really suited for efficiency improved multiband amplifier applications.

In contrast to this, the ET concept based on a class-AB RF amplifier is a very promising concept in order to improve efficiency of single- as well as of multiband amplifiers. This is possible due to the fact that the ET modulator is independent from the carrier frequency and a class-AB amplifier can be designed for multiband operation, as shown by the previously described multiband solution. In the following, the ET concept is described in more detail.

The efficiency of linear PAs can be increased by dynamically varying the bias point, thereby reducing the quiescent power dissipation of a PA when the output power decreases. Linear PAs with dynamic supplies have been investigated by means of a bias control applied to the drain terminal of *a*GaN-based HEMT.

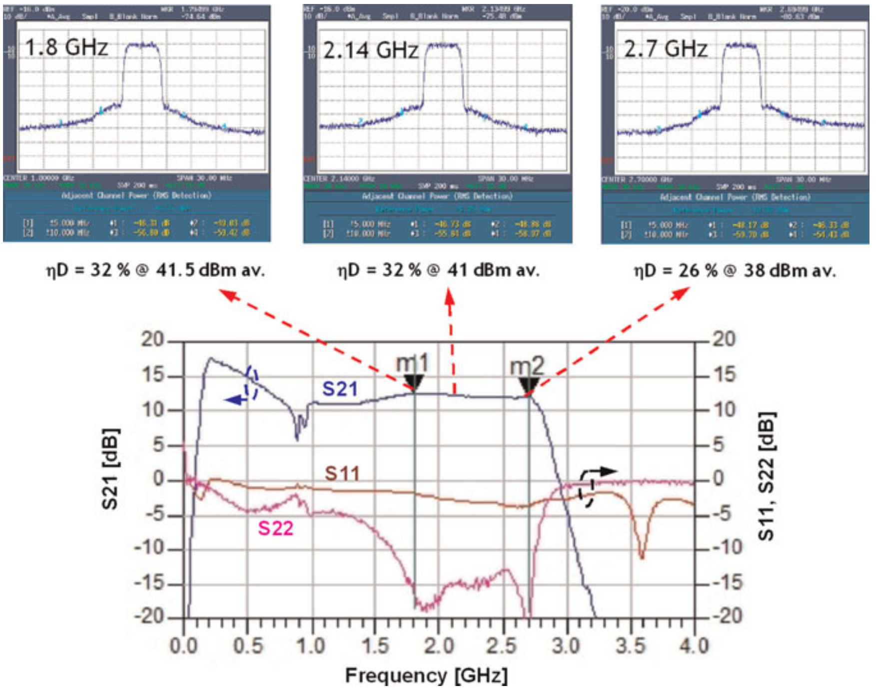

Fig. 16. Measured characteristic of class-AB multiband amplifier.

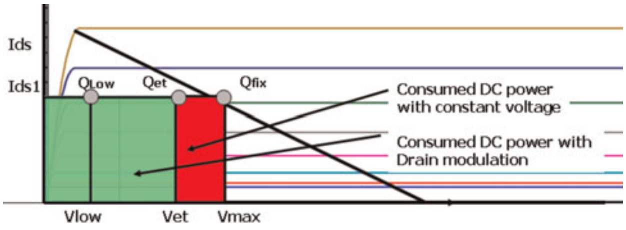

Fig. 17. Drain modulation principle.

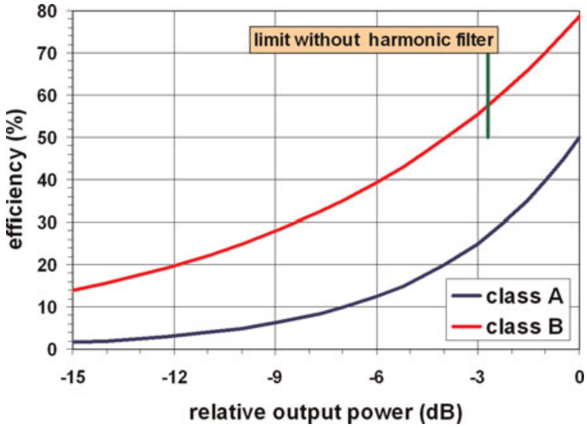

Fig. 18. Efficiency curves of class-A and-B operation.

The RF PA is biased in class-AB mode in order to trade-off linearity and efficiency. With dynamic control of the drain bias voltage, the quiescent point moves horizontally for a fixed drain current (Fig. 17).

The area below Ids1 and Qfix exemplarily represents the consumed DC power if the PA is supplied with a maximum fix supply voltage. *Vlow* is the lower supply voltage limit for the RF amplifier. When applying ET, the supply voltage *Vet* is modulated between *Vlow* and *Vmax*. The consumed DC power for ET operation is thus represented by the area below Ids1 and Qet. Depending on the RF signal, Qet is moving and the consumed power under ET operation is thus changing depending on the RF signal. The power saving for ET is finally represented by the area below Qet and Qfix and can be significant for signals with high PAR.

Figure 18 shows the efficiency of class-A and class-B amplifiers. Both amplifiers are reaching good efficiency figures at full output power, but they are decreasing when using high PAR signals like those used in modern communication schemes.

In order to gain efficiency within the ET architecture, the drain voltage should follow as accurate as possible the envelope signal, so that the RF PA is always operated close to its saturation point. In order to guarantee good overall ET performance, the envelope modulator has to amplify linearly and efficiently the envelope signal.

In the ideal case (theoretically 78% efficiency), a class-B biased RF PA combined with a accurate envelope modulator featuring 90% efficiency could optimally reach 70% overall drain efficiency. In a real application, overall efficiency figures of 50% are more realistic considering a class-B RF amplifier with 60% efficiency and an envelope modulator with 80% efficiency [6].

The block diagram shown in Fig. 19 describes an ET system featuring an envelope amplifier which adjusts the supply voltage (i.e. the drain voltage) of the class-AB stage dynamically by following the signal envelope.

By following the envelope which represents the magnitude of the I&Q – signal vector, the peak load efficiency of the system is improved. However the requirement for high bandwidth high power and linearity to the envelope modulator results in lower overall efficiency at different loads. It is worth noticing the mandatory need to delay the RF input signal in order to synchronize both envelope path and the RF path. Such time mismatch as well as voltage ripple at the DC-feed of the output stage would degrade efficiency and linearity of the ET architecture.

The total efficiency can be calculated by means of the general equation for dynamic biasing schemes [1].

$$\eta_{Env\_Follower} = \eta_{Envelope\_Amplifier} * \eta_{\mathrm{RF\_PA}}. \tag{1}$$

It is evident that the whole stage efficiency is strongly depending on the efficiency of both the envelope modulator and the RF PA.

The envelope modulator has been realized using a common circuit topology which has been inspired from the audio

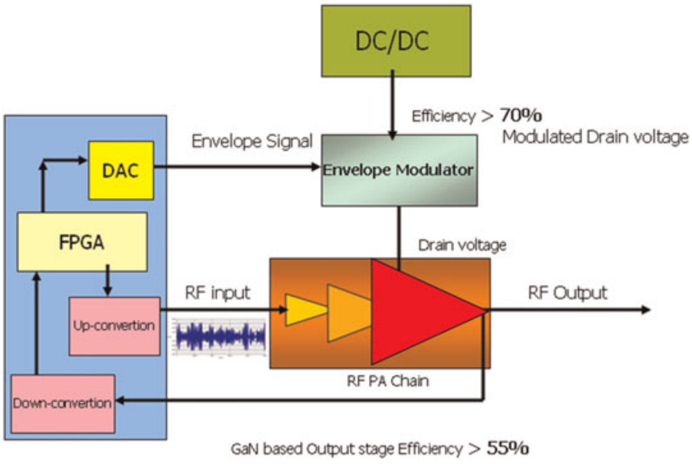

Fig. 19. Block diagram of the ET system for 3-/4-G radio transmitters.

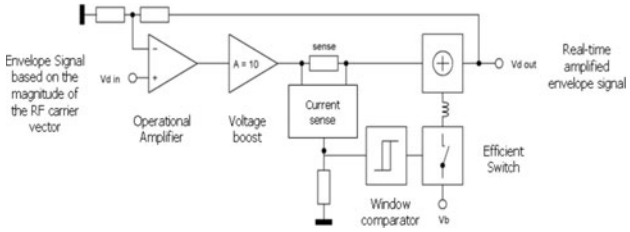

Fig. 20. Block diagram of the in Bell Labs realized ET modulator.

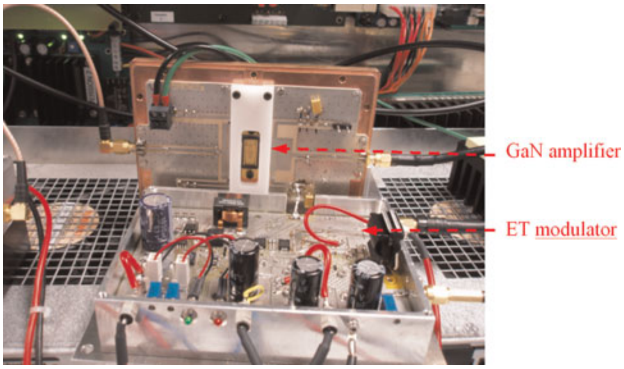

Fig. 21. Photo of an exemplarily ET modulator and PA.

domain and is called switch mode assisted linear amplifier [1]. The DC-coupled envelope amplifier comprises a wide bandwidth class-AB linear stage to provide a wideband voltage source by linearly following the envelope signal and, in parallel, a switching stage to provide an efficient current supply (see Fig. 20). The current is supplied to the drain of the RF amplifier from both the switching stage and the linear stage controlled by the current sensor which senses the error current flowing out of the linear stage and turns on/off the efficient power switch.

The closed-loop linear stage provides the difference between the desired output current and the current provided by the switched MOSFET stage, such that the overall error is minimized.

Following this concept an ET system setup based on GaN-HEMT devices from FhG-IAF Freiburg has been built at Bell Labs Germany. A photo of an exemplarily ET modulator combined with an RF PA as well as a measured single-carrier output spectrum measured with the ET system is shown in Figs 21 and 22, respectively.

IV. SUMMARY

Summarizing six years of GaN technology development and GaN-based PA design AlGaN/GaN-based RF power HEMTs turned out to be the enabling technology for realization of highly efficient single- as well as multiband RF PAs. Within GANGLION and ELBA project, various RF PA demonstrators have been designed and realized addressing single- and multiband applications. Peak output power levels up to 51.9 dBm achieved with a GaN-based multiband amplifier as well as high drain efficiency up to 45% using a single-carrier W-CDMA signal in combination with clipping and digital predistortion based on a symmetrical Doherty are some highlights of the projects indicating the potential of GaN technology. Finally, the current work at Bell Labs on ET based on GaN technology, has been described, targeting at future highly efficient multiband PAs.

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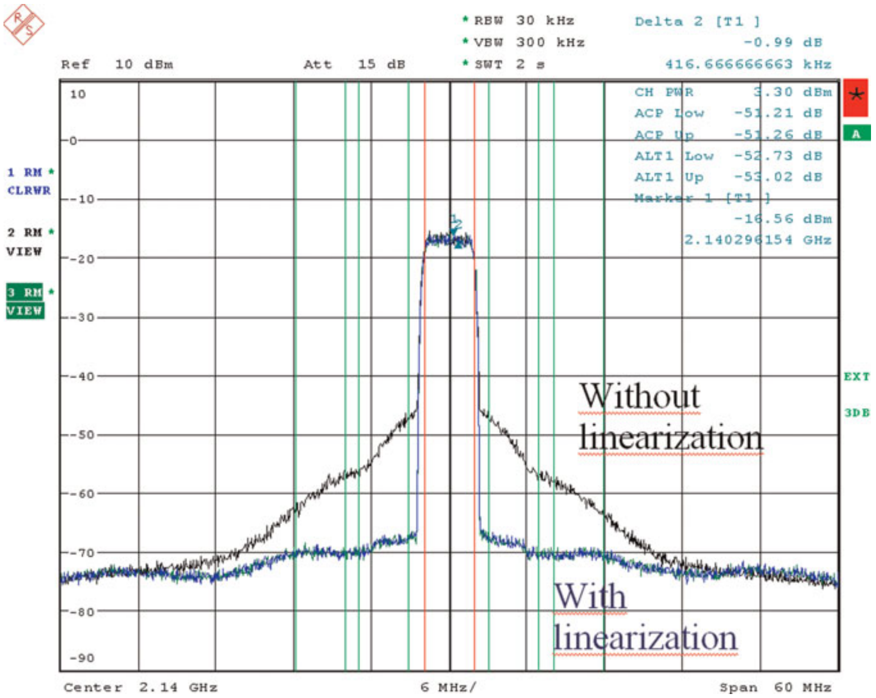

Fig. 22. Exemplariliy measured single-carrier W-CDMA spectrum.

and 01BU600 in the context of ‘mobileGaN’ and ‘mobileInternet’, respectively. The continuous support by the epitaxial and technology department at Fraunhofer IAF and of the Alcatel-Lucent model shop is gratefully acknowledged.

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