A GaN Gain Enhancement PA with Peak Power Combining

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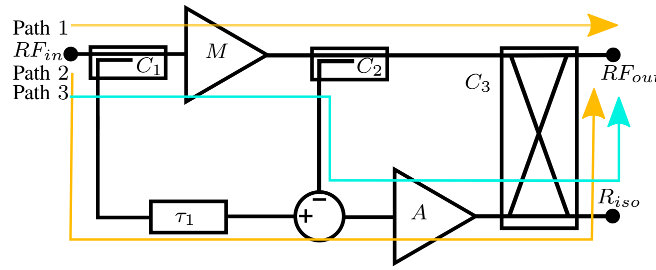
***Abstract*— This paper presents a novel approach for increasing the gain of a pair of parallel amplifiers by introducing a series connection between them on the input side. The resulting structure, referred to here as a gain enhancement PA (GEPA), has higher gain than each individual amplifier while maintaining the output power and efficiency from the parallel combination of the amplifiers. An initial prototype operating at 2.03 GHz with 42.6 dBm output power, 20.1 dB small signal gain, and 57.1% peak PAE is reported. The GEPA is made up of two identically performing amplifiers that have 40.4 dBm output power, 16.0 dB small signal gain, and 59.2% peak PAE. The GEPA has 4 dB higher gain than either component amplifier, the sum of the output powers of the two component amplifiers, and equivalent peak PAE, making this technique valuable for applications where high amplifier gain is required.**

***Keywords*— 5G mobile communication, feedforward, power amplifiers (PAs).**

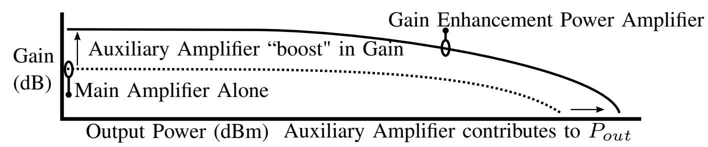
I. Introduction

A core benefit of the transition to 5G systems is the addition of millimeter wave (mmWave) bands that take advantage of fractional bandwidth scaling to open up larger channel bandwidths and enable higher bit rate communication [1]. At higher operating frequencies, the performance a power amplifier (PA) designer can wring from any device is limited as gain, output power, and power added efficiency (PAE) are all lower at mmWave compared to the Sub-6GHz range. Low device gain can be resolved by introducing additional device stages — but at the cost of the increased current draw and device periphery. When multiple, low-gain stages are cascaded, the typical assumption that efficiency is dominated by the final stage becomes invalid. Rather, the individual stages operate at power levels where their current draw is significant, thereby reducing the overall efficiency.

This work presents a novel gain enhancement PA (GEPA) architecture, designed to enhance the gain of an RF PA without sacrificing output power or efficiency and without introducing new gain stages with their associated efficiency penalty. The GEPA block diagram is shown in Fig. 1(a), and consists of two component amplifiers (the main and auxiliary PAs) whose output powers are combined via a structure based on a quadrature hybrid coupler. Whereas the constituent PA outputs are combined in parallel (gold paths 1 and 2), their inputs are effectively series-connected via the coupler and subtractor structure seen in the figure (main to auxiliary path 3, in teal). When the coupling factors of C_1 and C_2 are appropriately selected, the series signal connection will result in a gain boost over all output power levels. As shown in the sketch in Fig. 1(b), the expected GEPA gain performance is not only higher than the gain of the main amplifier alone, but the GEPA will also have higher output power due to the contributions from the auxiliary amplifier.



(a)



(b)

Fig. 1. (a) Architecture of the gain enhancement power amplifier (GEPA) featuring parallel amplifier connections (gold paths 1 and 2) and a series amplifier connection (teal path 3) as implemented in this work. (b) A simplified visualization of how the GEPA gain response over output power improves gain and total output power compared to the main amplifier alone.

The proof-of-concept hybrid GaN prototype in this work is realized at 2.03 GHz and is measured to have a state-of-the art small-signal gain of 20.1 dB. The peak power of 42.6 dBm output power and 57.1% peak PAE are consistent with the state of the art in the selected device technology, confirming that the approach enhances gain without compromising other performance metrics.

II. Gain Enhancement PA Theory and Design

The GEPA operation requires accurate phase alignment in the multiple signal paths indicated in Fig. 1(a) to ensure that the two amplifiers simultaneously add to each other in both gain and power. In other words, the phase delay through path 1 must be equal to the net phase delay from the auxiliary amplifier branch of the circuit, which is the combination of paths 2 and 3.

As seen in Fig. 1(a), the output power combining is realized through a quadrature hybrid combiner, chosen both to support the required phase alignment and to provide some immunity to output impedance variation [2]. This coupler is oriented so that the net quarter wavelength path connects the auxiliary amplifier to the output. With this in mind, the phase delay through path 1 can be written as:

$$\theta_{P1} = \theta_{AC1} + \theta_M + \theta_{AC2} \tag{1}$$

where θ_{ACn} refers to the through phase delay of the n-th coupling elements and θ_M is the phase delay of the main amplifier. The through phase delay of the couplers C_1 and C_2 will be $-\pi/4$ radians when implemented as coupled line couplers as is done here. The phase delay through path 1 then becomes $\theta_{P1} = \theta_M - \pi/2$.

In order to match this phase delay, paths 2 and 3 will be combined through a subtractor as shown in Fig. 1(a). We assume that the phase delay from the GEPA input to the negative terminal of the subtractor and the phase delay from the GEPA input to the positive terminal of the subtractor are made identical through appropriate selection of the delay line τ_1. This leads to the following combined phase response of paths 2 and 3 which create a "pseudo-cascade" (PC) signal path between the amplifiers,

$$\theta_{PC} = \theta_A + \theta_{CC2} + \theta_M + \theta_{AC1} - 3\pi/4 \tag{2}$$

where the additional $-\pi/4$ radians term comes from the phase delay through the quadrature hybrid. Again assuming C_1 and C_2 are implemented as coupled line couplers, and with the further simplifying assumption that that the main and auxiliary amplifiers are identical ($\theta_M = \theta_A$) the pseudo-cascade signal path phase becomes $\theta_{PC} = 2\theta_M - 3\pi/4$. We can then set $\theta_{P1} = \theta_{PC}$ and solve for θ_M:

$$\theta_M = -3\pi/4 \tag{3}$$

We note that the amplifier phase delay $\theta_M = \theta_A$ can be realized either through appropriate design of the amplifier network (as in this work), or by adding other adjustable phase elements in each path to tune the phase response of each path independently of each amplifier.

With the appropriate phase response established, we next consider the relationship between the coupling factors of C_1 and C_2 and the overall system gain. We assume here that the phase conditions described above are met, the main and auxiliary amplifiers are identical (i.e., they have the same small-signal gain $G_M = G_A = G$) and that the GEPA will be designed for maximum gain in the small-signal regime. Then, the the total gain of the GEPA architecture can be found as:

$$G_{GE} = |G(1 - C_{C2} + C_{C1}C_{C2}) + G^2(C_{C1}C_{C2} - C_{C2})| \tag{4}$$

where the coupling factors (C_{Cn}) and amplifier gains (G) are expressed as power quantities. Assuming the small signal gain value G is determined by the available main and auxiliary amplifier technology, there are two design variables available to determine the GEPA architecture's gain: the values of the coupling factors C_1 and C_2.

The component amplifiers in our proof-of-concept design have a gain of $G = 16$ dB at the fundamental frequency of 2.03 GHz. Based on this value, the system gain G_{GE} can be plotted as a function of C_{C1} and C_{C2} as in Fig. 2. The

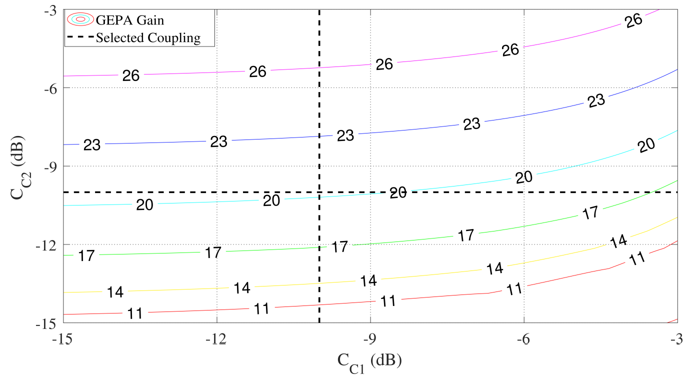
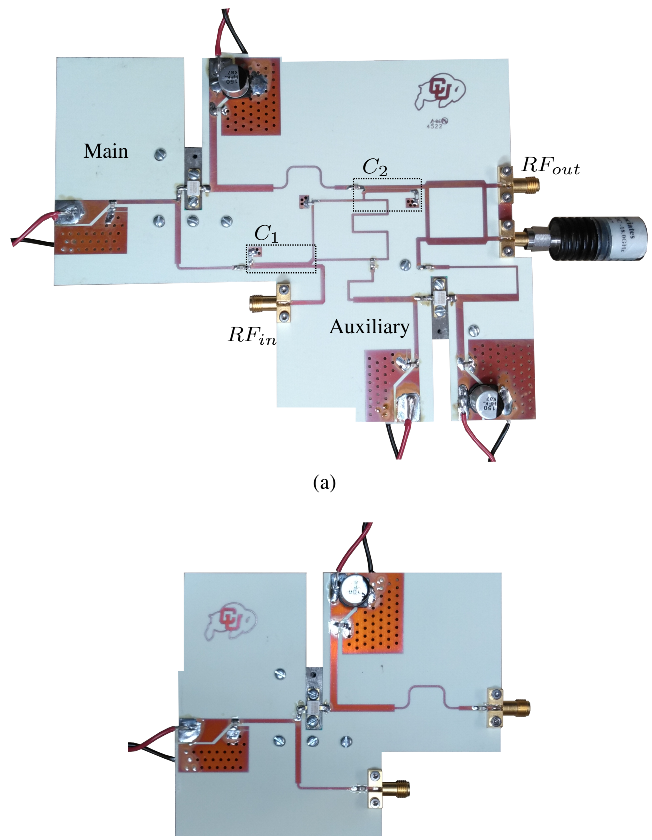


Fig. 2. Contours of GEPA gain (G_{GE}) in dB from (4) as a function of the coupling factors of C_1 (C_{C1}) and C_2 (C_{C2}) assuming the main and auxiliary amplifiers both have 16 dB gain. The selected coupling factors used in the prototype amplifier (-10 dB each) are indicated as the black dashed lines.



(a)

(b)

Fig. 3. Photographs of the (a) GEPA measuring 6.8 inches by 5.2 inches and (b) main amplifier measuring 4.5 inches by 3.5 inches.

highest gain occurs for $C_{C1} < -9$ dB and $C_{C2} > -6$ dB, but for simplicity we implement C_{C1} and C_{C2} with identical coupling factors so the same structure can be used. With this constraint and considering practical values that can be realized on the available RO4350B 30 mil substrate, the highest gain occurs when both couplers have -10 dB coupling factors. The resulting system gain $G_{GE} = 20.3$ dB is 4 dB greater than the 16 dB main and auxiliary amplifier gains.

Photographs of the GEPA prototype and standalone main

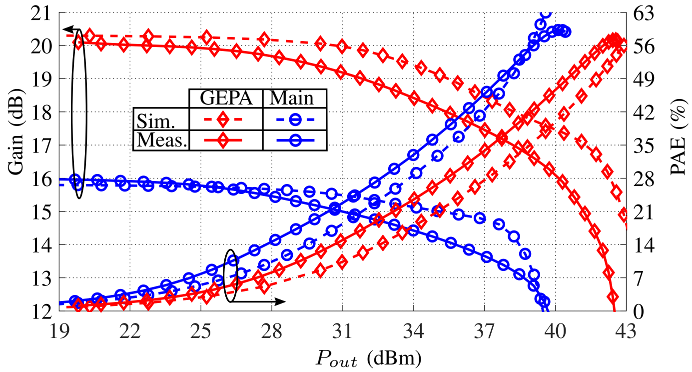


Fig. 4. Simulated (dashed) and measured (solid) CW gain and PAE of the GEPA (diamond) and main amplifier (circle) at 2.03 GHz.

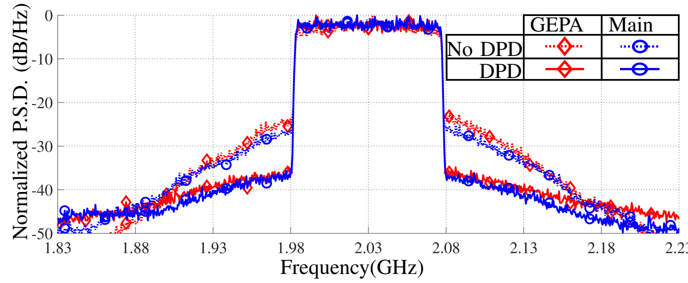


Fig. 5. Measured normalized P.S.D. for a 100 MHz LTE-like signal with 10 dB PAPR EVM at 2.03 GHz for the GEPA and its main amplifier with and without DPD. The GEPA operates at a peak output power of 42.2 dBm and average drain efficiency of 26.7% with 14.5 dBm average input power while the main amplifier operates at a peak output power of 39.9 dBm and average drain efficiency of 29.22% with 18.5 dBm average input power.

amplifier are shown in Fig. 3. The main and auxiliary amplifiers are based on a CG2H40010 GaN HEMT from Wolfspeed that is output matched through a shunt shorted stub that controls the second harmonic impedance termination and a stepped impedance series connection that controls the impedance presented to the fundamental. The input matching networks are designed similarly, with a parallel RC stability network at the device package gate tab and a series RC stability network that terminates the shunt, shorted stub. In our prototype, the couplers C_1 and C_2 are implemented using edge-coupled quarter wave coupled line structures and coupler C_3 is a quarter-wave hybrid implemented as a branch-line coupler. The subtractor element in the GEPA is implemented as a ring hybrid or rat-race coupler, so as to best fit in the available space while maintaining a good match to each branch component. The GEPA theory does not limit the designer to this specific implementation; rather, these components were selected for ease of implementation in a printed circuit board (PCB). If implemented in MMIC form factor, the components of the GEPA stucture should be optimized to take advantage of the capabilities of each process.

III. Measured Performance

The CW simulated and measured performance for the GEPA and main amplifiers is reported in Fig. 4. The main amplifier has a measured 40.4 dBm output power, 16.0 dB small signal gain, and 59.2 % peak PAE while the GEPA realizes 42.6 dBm output power, 20.1 dB small signal gain, and 57.1 % peak PAE. Overall, both amplifiers show agreement between measurements and simulation in back-off, and higher gain compression than expected in the "soft" compression regime. The GEPA furthermore demonstrates the 20-dB gain predicted by GEPA theory. Measured PAE is consistent with the predicted result although slightly higher in measurement than in simulation.

The GEPA and standalone main amplifier were compared in terms of modulated performance by exciting each with a 100 MHz LTE-like signal with 10 dB peak to average power ratio (PAPR). The measured output spectrums are shown in Fig. 5 with and without digital pre-distortion (DPD), applied through the Rohde & Schwarz FSW K-18 amplifier measurement bench. For this comparison, the two amplifiers are excited so that the peak signal output power is close to the saturated output power of the amplifier: 42.2 dBm for the GEPA and 39.9 dBm for the standalone main PA. We can see that both amplifiers linearize equivalently, with average error vector magnitudes below 3% and adjacent channel leakage ratio (ACLR) below -38 dBc with DPD. The GEPA reports an average drain efficiency of 26.7%, while the main reports 29.2%. Notably, the main required an additional 4 dB of input power to reach its 2.3 dB lower peak operating power, consistent with the gain enhancement reported in the CW results. In other words, the GEPA provides gain enhancement and increased output power, demonstrated with a realistic 100-MHz signal, with only a modest reduction in average efficiency and with equivalent linearized ACPR.

Table 1. Comparison to state-of-the-art packaged device GaN PAs.

Ref.	Year	Arch.	Freq. (GHz)	Gain (dB)	Pout (dBm)	Peak PAE (%)
[3]	2016	Doherty	2.14	11*	43.0	50*
[4]	2018	LMBA	2.4	12*	45.6	60.0
[5]	2018	Doherty	2.1	12*	44*	57*
[6]	2021	Balanced-FFA	3.5	16.5*	30.8	27.2
[7]	2022	Class-AB	2.2	14*	40.0	50*
This Work		Main Amp.	2.03	16.0	40.4	59.2
		GEPA	2.03	20.1	42.6	57.1

* — read from graph; † — Drain Efficiency

The GEPA PA is compared to similar works based on GaN packaged devices in Table 1. We find that the GEPA reports higher single-stage gain than any other reported design, while maintaining the power combining and peak PAE shown by parallel connection PA architectures such as Doherty and conventional balanced amplifiers.

IV. Discussion of Scaling

The gain of the consituent PAs in our proof-of-concept demonstrator is relatively high at 16-dB due to the low operating frequency of this hybrid prototype. If we instead consider a case where the gain per stage is assumed to be 8 dB, the GEPA gain can be boosted to a total 11.9 dB gain as seen in the contour plot in Fig. 6. We note that in this case the coupling factors must be chosen asymmetrically, for

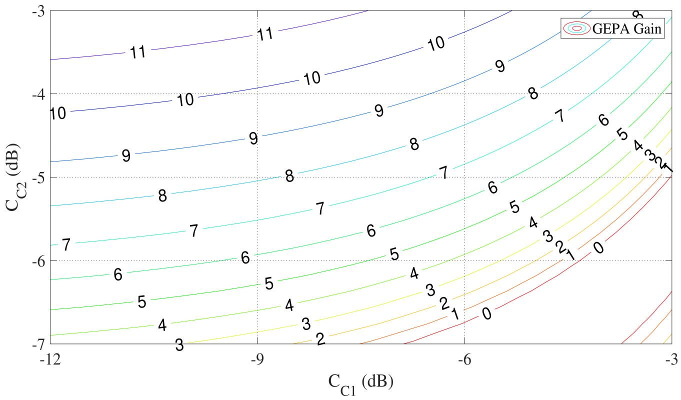


Fig. 6. Contours of GEPA gain (G_{GE}) in dB from (4) as a function of the coupling factors of C_1 (C_{C1}) and C_2 (C_{C2}) assuming the main and auxiliary amplifiers both have 8 dB gain (as in [8]).

example with $C_{C1} = -9$ dB and $C_{C2} = -3$ dB. A point of diminishing returns can be evaluated from (4) to correspond roughly to a gain-per-stage of 6 dB. At this gain level, the GEPA gain boost is only around 1 dB and the added system complexity and realistic loss in the combining network limits the value of the GEPA approach.

We consider as an example the single-stage GaAs MMIC reported in [8], which has an 8 dB small-signal gain, saturated output power of 20.7 dBm and peak PAE of approximately 30% at 22 GHz. Based on the agreement in our proof-of-concept demonstrator between theory and measurement, we can estimate that this PA would exhibit 11.9 dB gain (as seen in Fig. 6) and 23.7 dBm output power when used in a GEPA configuration, with 30% PAE if the combining network is assumed lossless. In contrast, a cascade of two such PAs would have a predicted 16 dB gain, the same 20.7 dBm saturated output power as in [8], and a cascaded PAE of 20.5%. For applications where efficiency and output power is important, the GEPA is clearly advantageous.

V. Discussion and Conclusion

The proof-of-concept gain enhancement feedforward amplifier (GEPA) is demonstrated in this work to realize a gain and output power improvement via a series-and-parallel connection of two amplifier stages. The performance of the demonstrator PA is on par with the state of the art in terms of output power and efficiency, but with higher gain. While the prototype amplifier is here designed at 2.03 GHz, a design example based on a single-stage MMIC PA from the literature indicates that the technique will be especially beneficial at frequencies close to the maximum frequency of the selected technology, where realizable gains are lower.

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