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WE3C-3

A GaN Gain Enhancement PA with Peak Power Combining

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Outline of Discussion

1. Context, Motivation, and Important Design Metrics

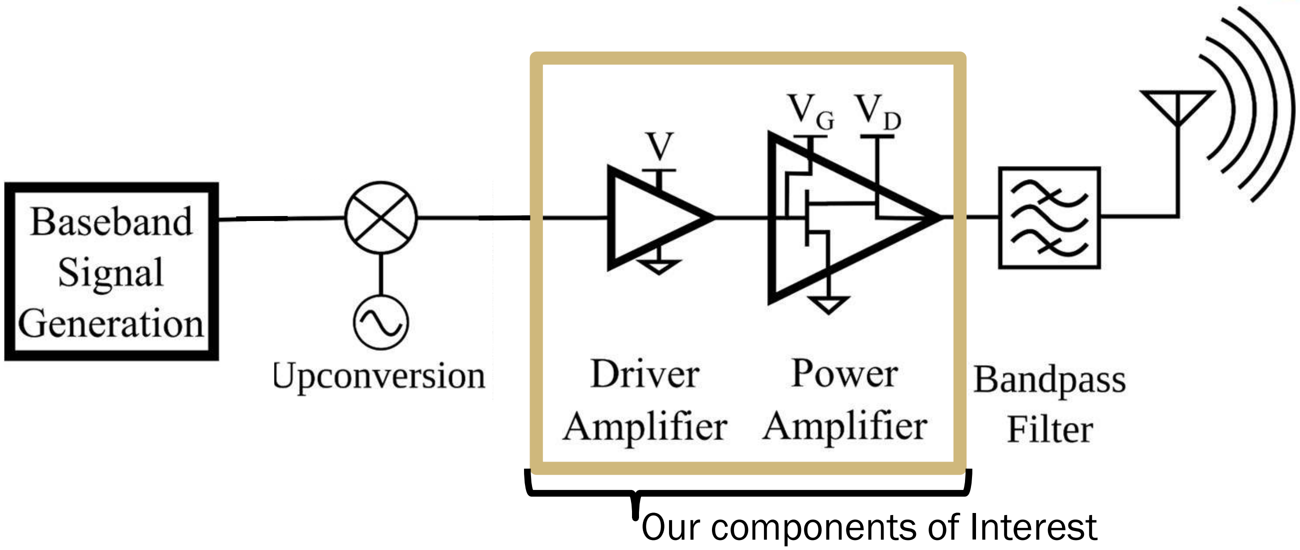
2. Gain Enhancement PA (GEPA) Concept and Theory

3. Initial GEPA Prototype Design and Results

4. Conclusions

RF Communications Transmitter System Context

There are many kinds of transmitter structure depending on the application. This represents a general transmitter, or single element in a phased array.

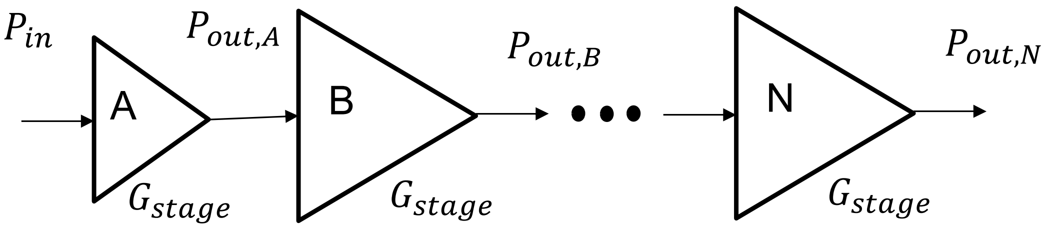


Canonically the performance of Power Amplifier (PA) determines the efficiency as measured by drain efficiency (η_D) or power added efficiency (PAE) of a given transmitter.

HOWEVER, what happens when the PA has low gain and multiple drivers are needed, as in mmWave applications?

Amplifier Cascade Issues – Drain Efficiency

Assume all gain stages have the same peak drain efficiency, identical gain, and that they draw dc power proportional to output power.



$$P_{dc,n} = {P_{dc,n-1}}/{G_{stage}}$$

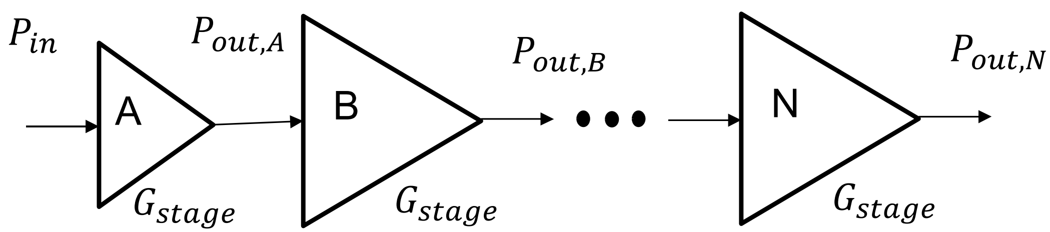
$$\eta_{D,tot,2} = \frac{P_{out,B}}{P_{dc,B} + P_{dc,A}} = \frac{P_{out,B}}{P_{dc,B}\left(1 + {1}/{G_{stage}}\right)} = \eta_{D,B}\frac{G_{stage}}{G_{stage} + 1}$$

$$\eta_{D,tot,3} = \frac{P_{out,C}}{P_{dc,C} + P_{dc,B} + P_{dc,A}} = \frac{P_{out,C}}{P_{dc,C}\left(1 + {1}/{G_{stage}} + {1}/{G_{stage}^2}\right)} = \eta_{D,C}\frac{G_{stage}^2}{G_{stage}^2 + G_{stage} + 1}$$

$$\eta_{D,tot,N} = \frac{P_{out,N}}{\sum_{n=0}^{N} P_{dc,n}} = \frac{P_{out,N}}{P_{dc,N}\sum_{n=0}^{N} {1}/{G_{stage}^n}} = \eta_{D,N}\frac{G_{stage}^N}{\sum_{n=0}^{N} G_{stage}^n} = \eta_{D,N}\frac{\left(G_{stage} - 1\right)G_{stage}^N}{G_{stage}^{N+1} - 1}$$

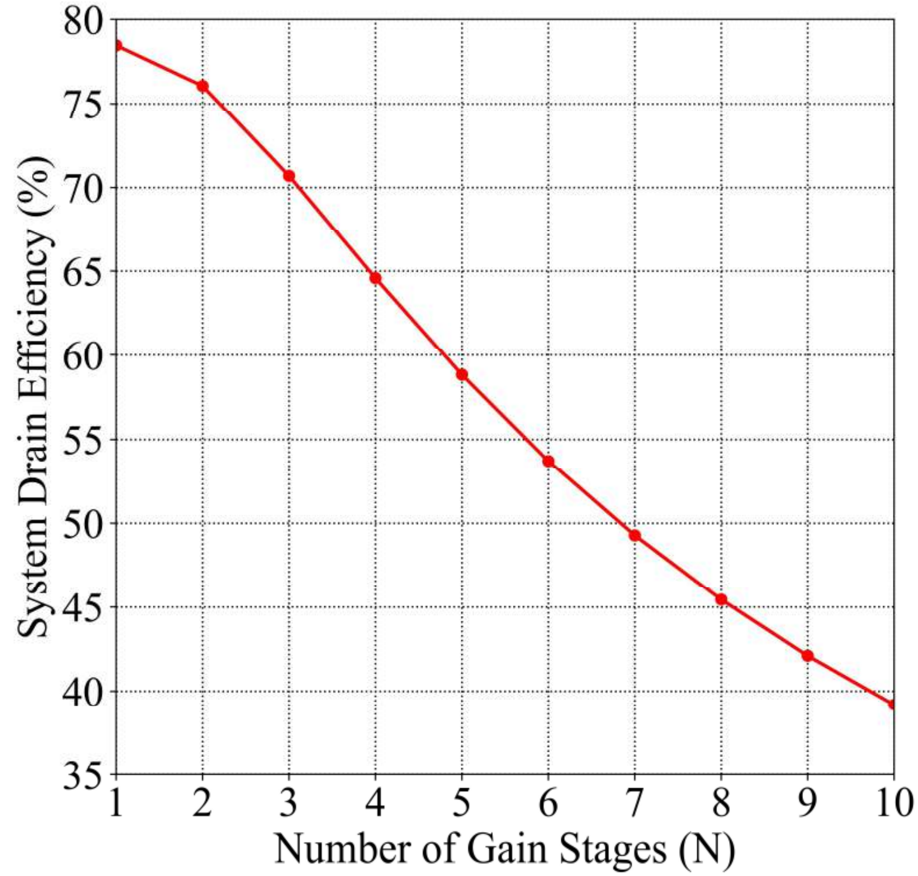
Amplifier Cascade Issues – Drain Efficiency

Assume all gain stages have the same peak drain efficiency, identical gain, and that they draw dc power proportional to output power.



$$\eta_{D,tot} = \eta_{D,N} \frac{(G_{stage} - 1) G_{stage}^{N}}{G_{stage}^{N+1} - 1}$$

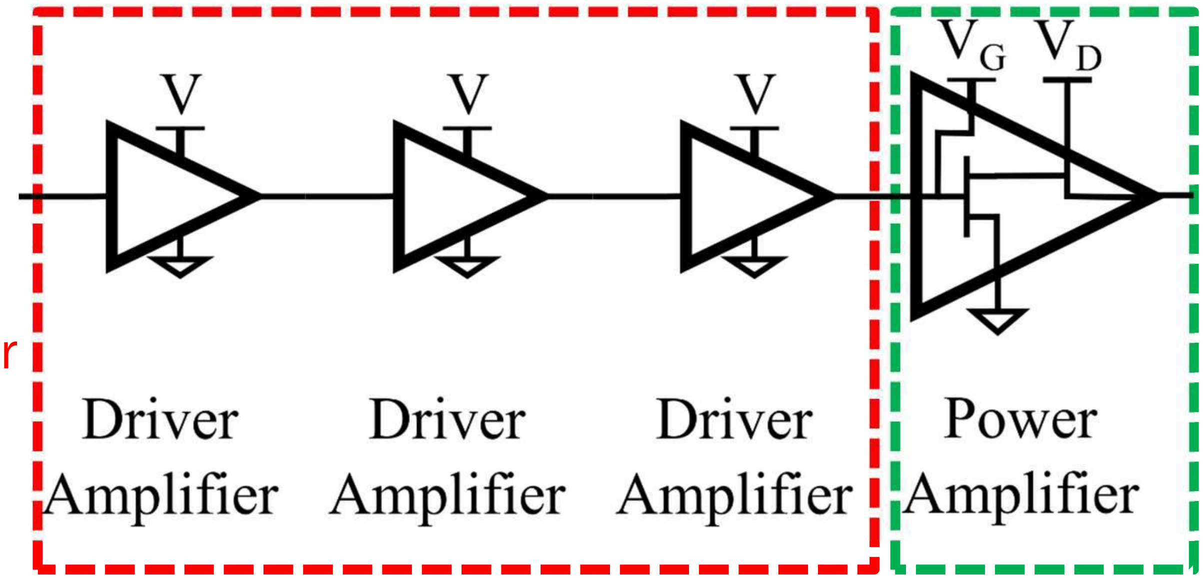
Total cascaded gain: 30 dB



Adding amplifier stages with low gain reduces overall efficiency!
Conventional assumption that final stage is dominant is not true.

Amplifier Cascade Issues - Drivers

Must be designed with drive margin to ensure the PA reaches peak output power – guaranteed lower efficiency!



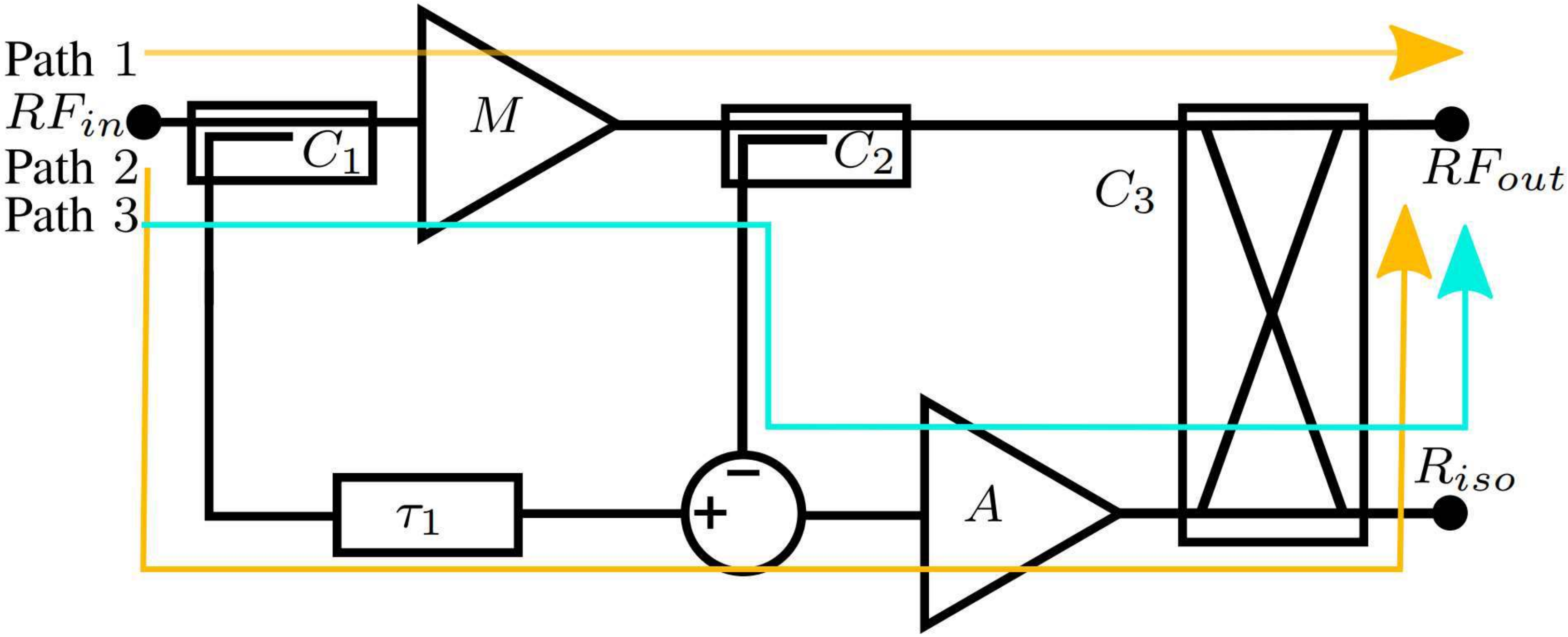
Optimized for efficiency at peak output power

Each additional driver amplifier stage adds:

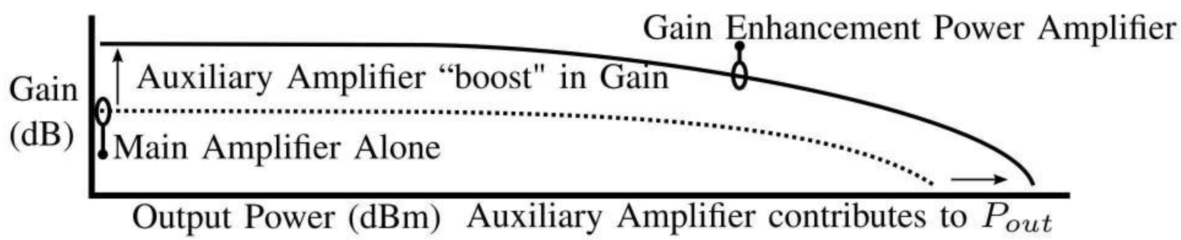
- Increases Gain
- Increases Current Draw (decreasing efficiency)
- Adds Additional Failure Points

How can we minimize the number of driver amplifiers without harming PA efficiency?

Gain Enhancement PA Concept

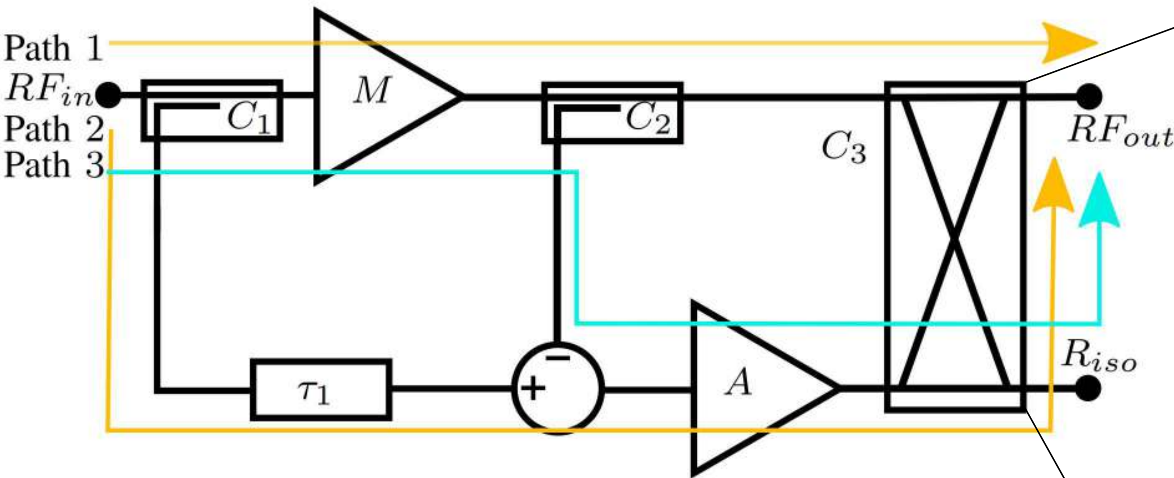


<u>Series connection</u> increases gain of GEPA structure!



<u>Parallel connection</u> ensures output of both amplifiers contributes to overall output!

Design Assumptions and Coupler C_3



Coupler C_3 is implemented as a 3dB quadrature hybrid.

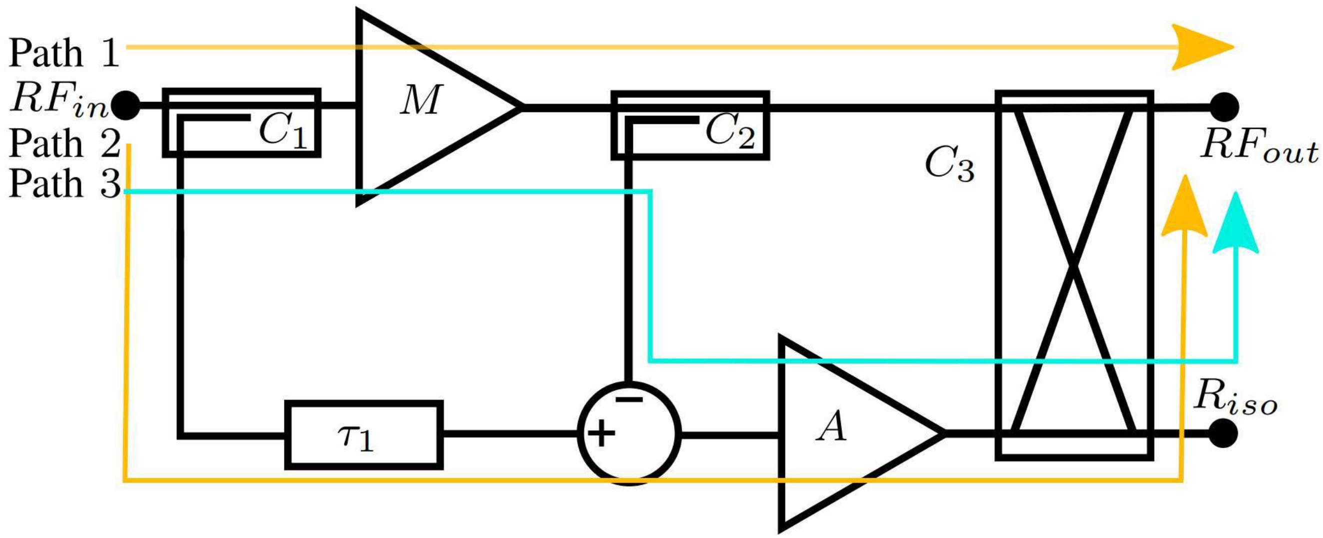
C_3 has a coupling factor of 3dB as the main and auxiliary amplifiers are identical output power.

C_3 is a quadrature coupler to take advantage of that structure's natural resilience to impedance variation, a useful property in phased array applications.

Core Design Assumptions:

- The Main and Auxiliary amplifiers are identical ($G = G_M = G_A$), ($P_{out,max} = P_{out,max,M} = P_{out,max,A}$)
- Subtractor element is ideal (non-idealities absorbed into surrounding components)

Phase Alignment

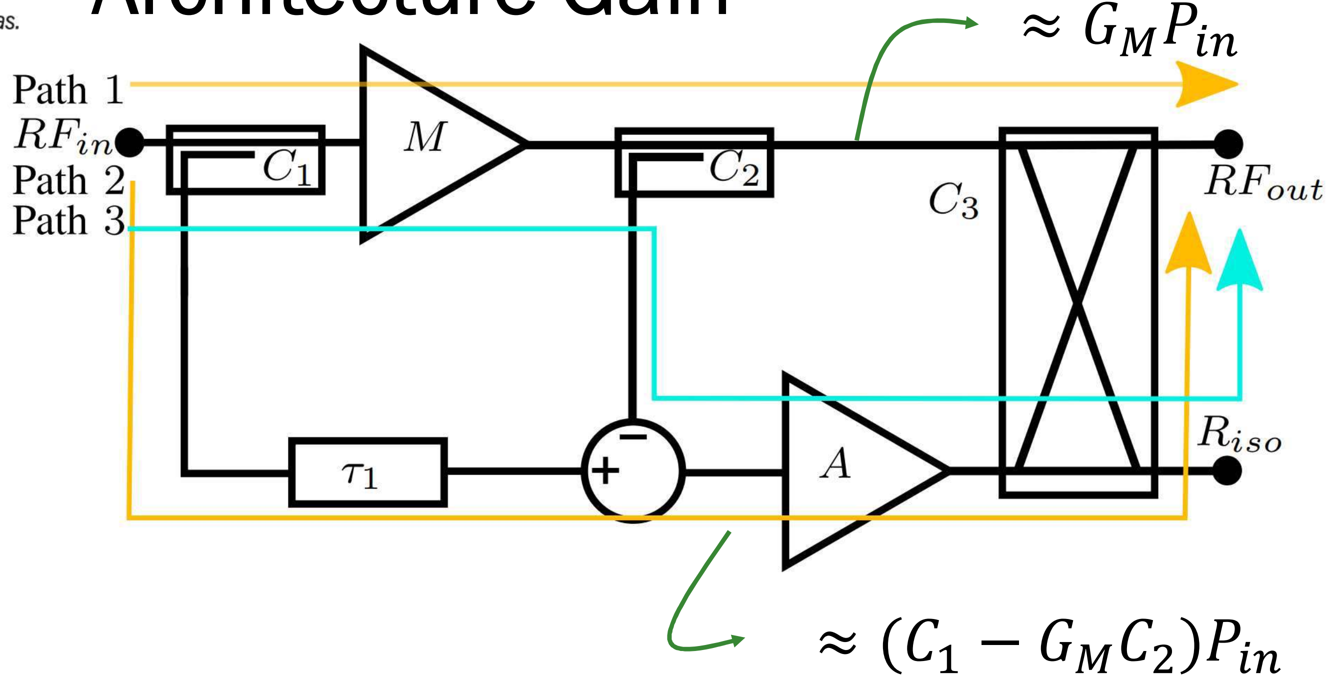


Path 1 and 2 must have equal phase to add at the output
Path 3 must differ from Path 2 by 180^o

$$\theta_{P1} = \theta_{P2}$$

$$\theta_{P2} = \theta_{P3} - \pi$$

Architecture Gain

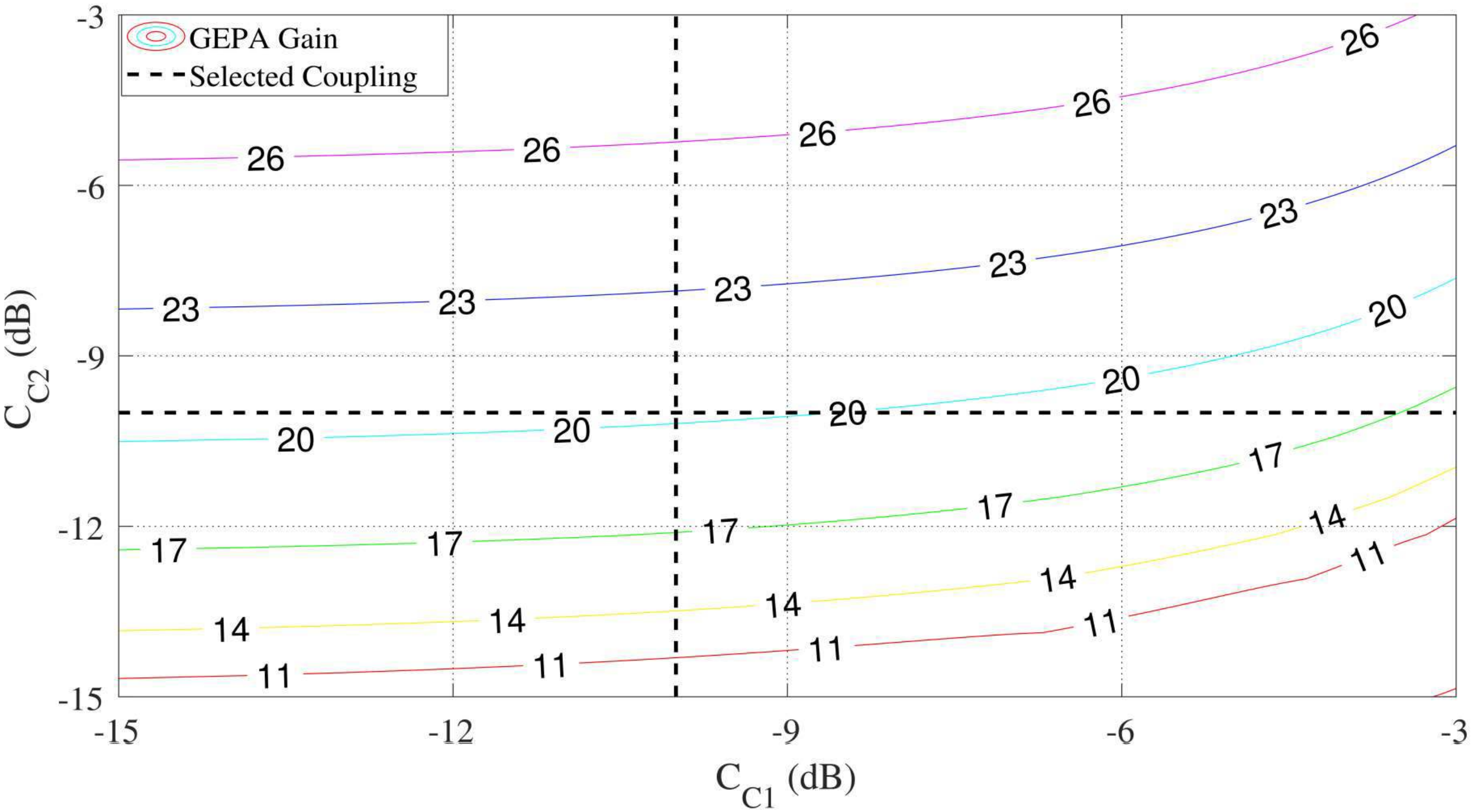


Full gain expression:

$$G_{GEPA} = |G(1 - C_{C2} + C_{C1}C_{C2}) + G^2(C_{C1}C_{C2} - C_{C2})|$$

Selection of Couplers C_1 and C_2

Branch Amplifier Gain of 16 dB:



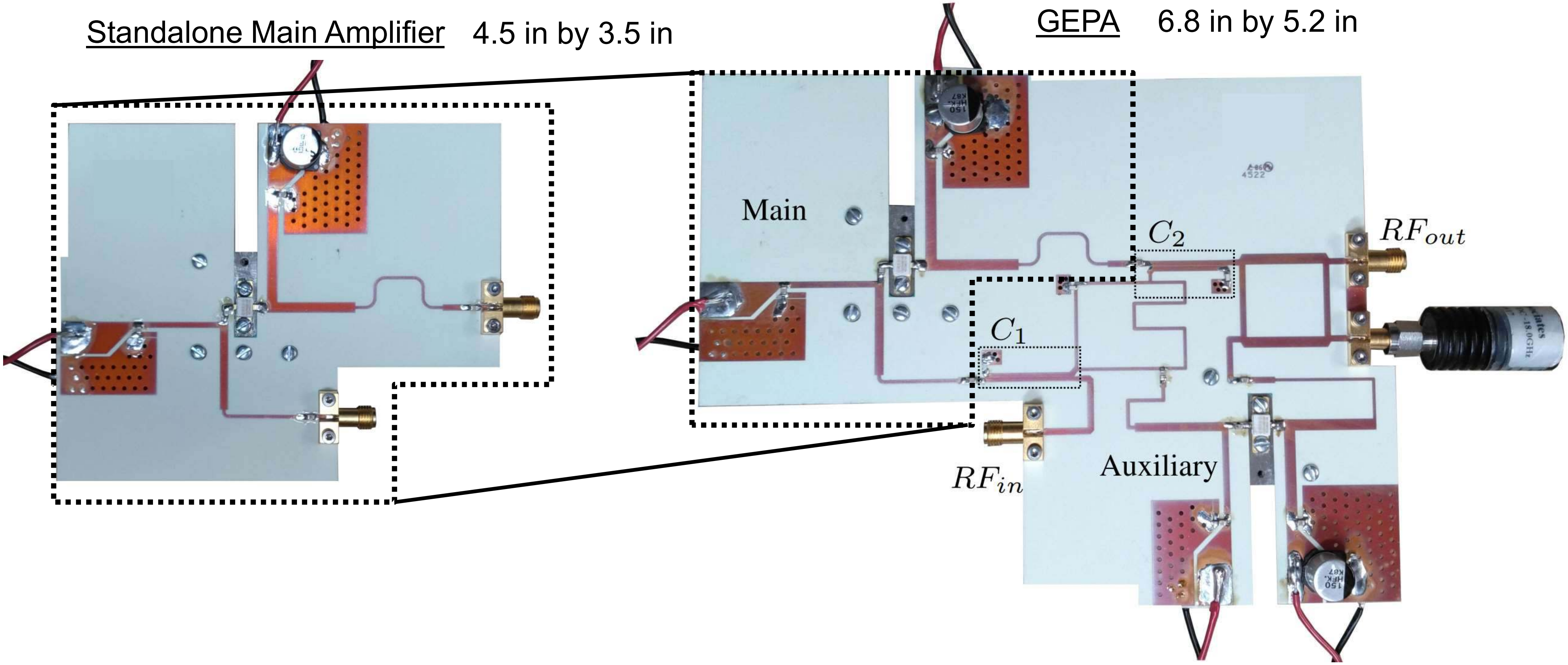
10 dB coupling factors selected in this work such that $C_{C1} = C_{C2}$ and to ensure realizability in RO4350B.

$$G_{GEPA} = |G(1 - C_{C2} + C_{C1}C_{C2}) + G^2(C_{C1}C_{C2} - C_{C2})|$$

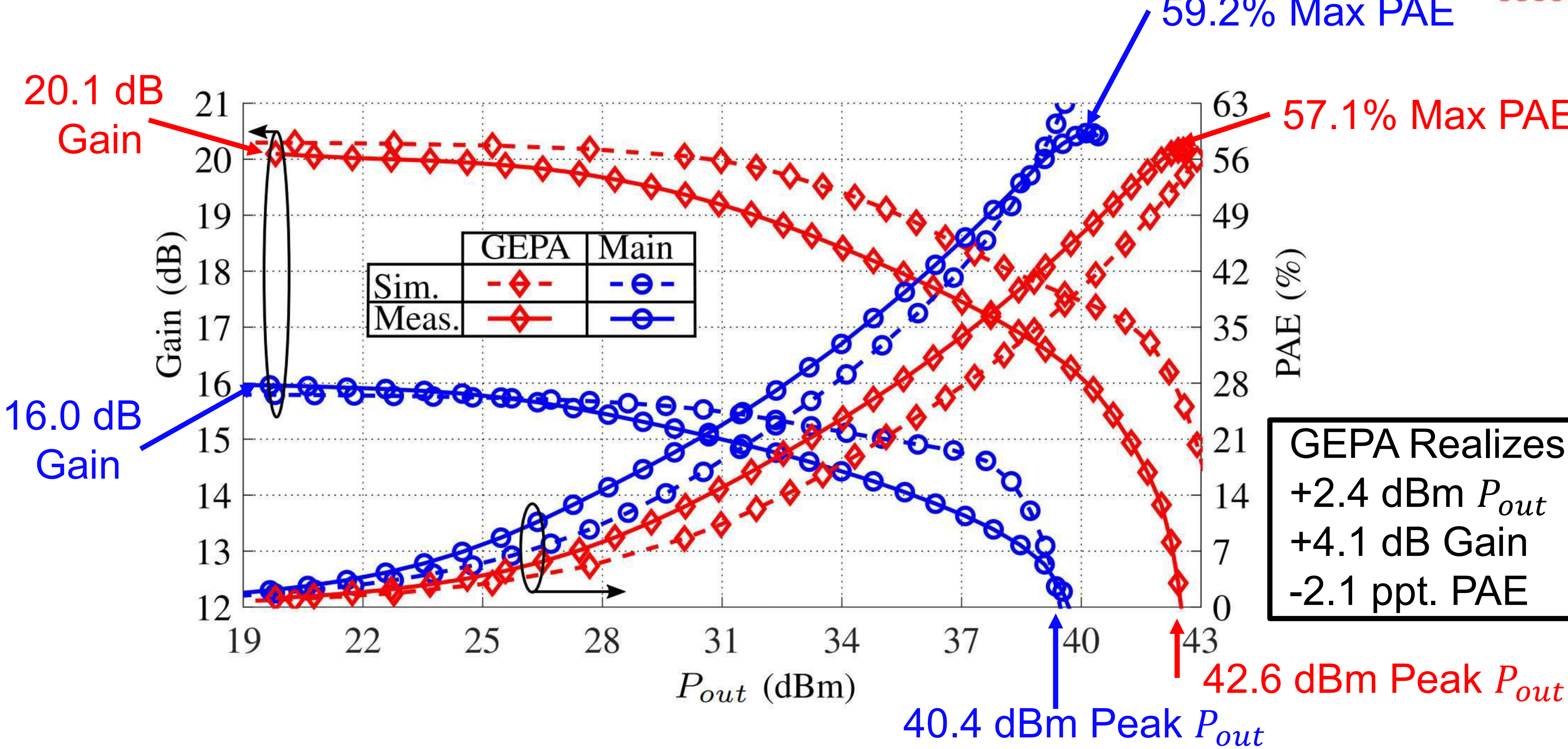
Final Prototype at 2.03 GHz

Standalone Main Amplifier 4.5 in by 3.5 in

GEPA 6.8 in by 5.2 in

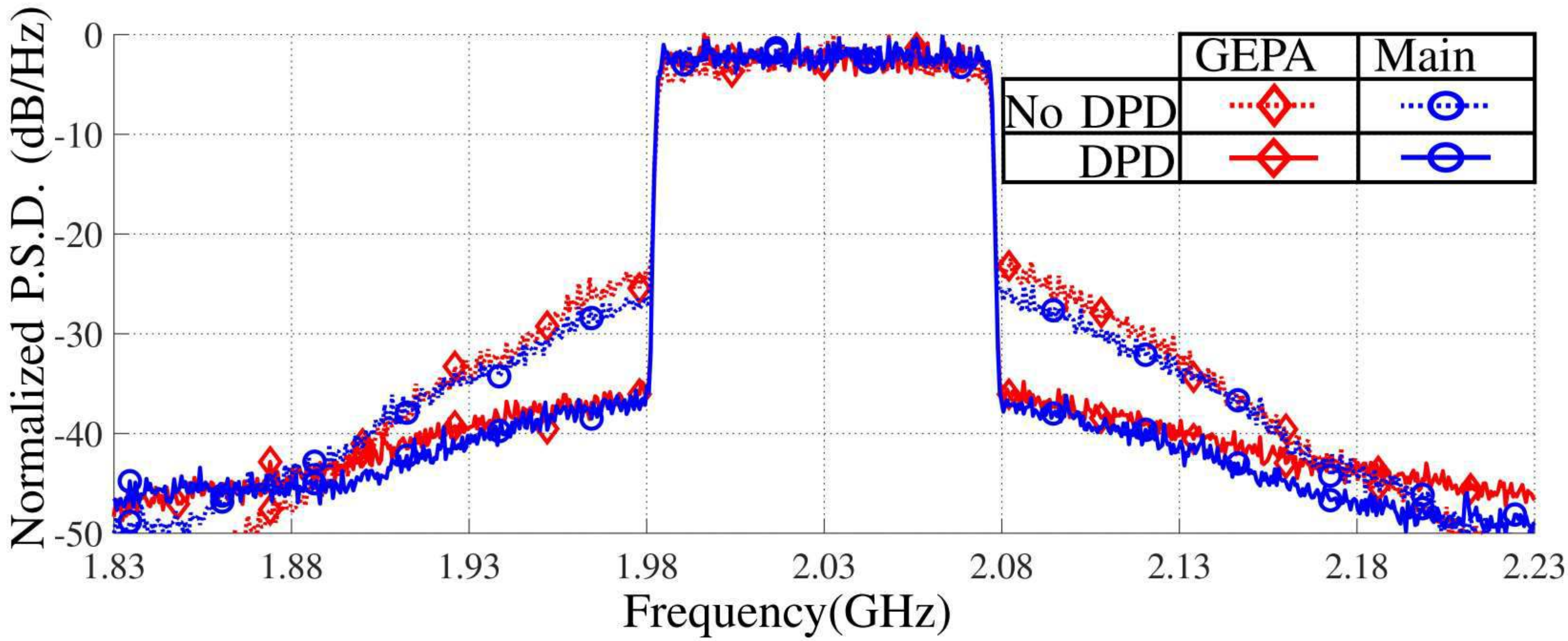


CW Measured Results at 2.03 GHz



GEPA Realizes:
+2.4 dBm P_{out}
+4.1 dB Gain
-2.1 ppt. PAE

LTE Measured Results at 2.03 GHz



Measured output spectrum for a 100 MHz wide LTE-like signal with 10 dB PAPR

	Peak Output Power (dBm)	Average Drain Efficiency (%)	Average Input Power (dBm)
GEPA (w/DPD)	42.2	26.7	14.5
Standalone Main (w/DPD)	39.9	29.2	18.5

Comparison to State-of-the-Art

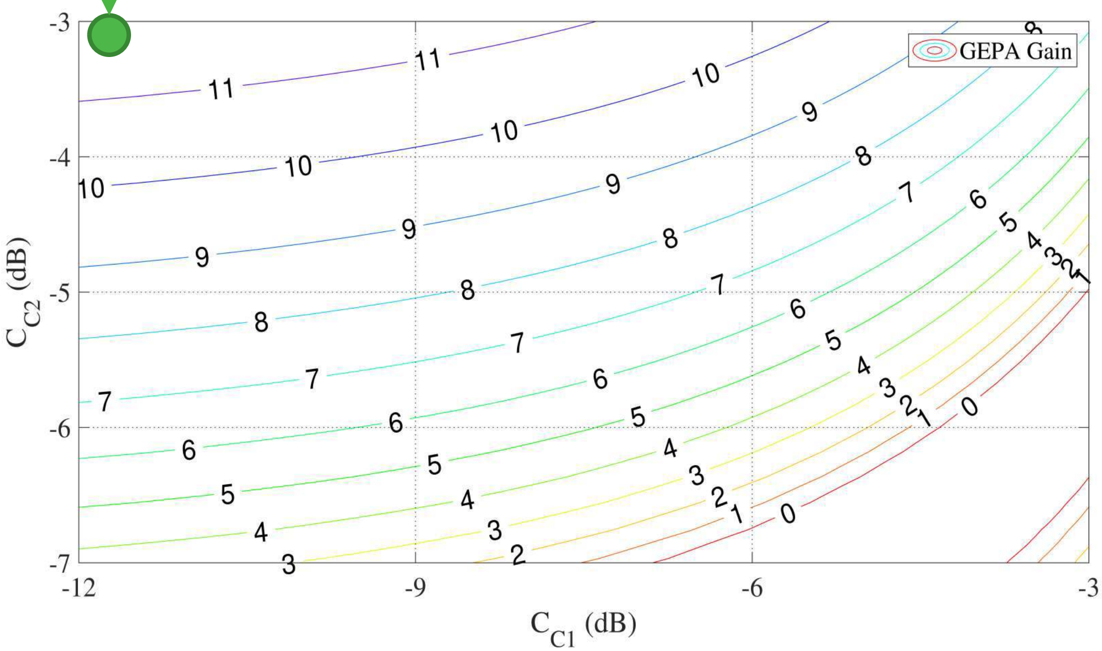
Ref.	Year	Arch.	Freq. (GHz)	Gain (dB)	P_{out} (dBm)	Peak PAE (%)
W. Hallberg, M. Özen, and C. Fager, "Current scaled Doherty amplifier for high efficiency and high linearity," in IEEE MTT-S International Microwave Symposium, 2016, pp. 1–4.	2016	Doherty	2.14	11*	43.0	50*
P. H. Pednekar, W. Hallberg, C. Fager, and T. W. Barton, "Analysis and design of a Doherty-like RF-input load modulated balanced amplifier," IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 12, pp. 5322–5335, 2018.	2018	LMBA	2.4	12*	45.6	60.0
C. Shen, S. He, and X. Zhu, "Design of broadband high-efficiency Doherty power amplifier using post-matching network," in Asia-Pacific Microwave Conference, 2018, pp. 464–466.	2018	Doherty	2.1	12*	44*	57*
M. Jung, S. Min, and B.-W. Min, "A quasi-balanced power amplifier with feedforward linearization," IEEE Microwave and Wireless Components Letters, vol. 32, no. 4, pp. 312–315, 2022	2022	Balanced-FFA	3.5	16.5*	30.8	27.2
W. Sear, D. T. Donahue, M. Pirrone, and T. W. Barton, "Bias and bias line effects on wideband RF power amplifier performance," in IEEE Wireless and Microwave Technology Conference, 2022.	2022	Class-AB	2.2	14*	40.0	50*
This Work		Main Amplifier	2.03	16.0	40.4	59.2
This Work		GEPA	2.03	20.1	42.6	57.1

* - read from graph

Application to mmWave PAs

Optimal GEPA

Branch Amplifier Gain of 8 dB:



Consider the following Amplifier:

A. Der, W. Sear, Z. Popovic, G. Lasser, and T. Barton, "A S-C- / K-band reconfigurable GaAs MMIC power amplifier for 5G applications," in IEEE MTT-S International Microwave Symposium, 2021, pp. 873–876.

Operation at 22 GHz:

	Single Amplifier	2-Stage Cascade	Optimal GEPA*	GEPA-Cascade Δ
P_{out} (dBm)	20.7	20.7	23.7	+3
Gain (dB)	8	16	11.9	-3.1
PAE (%)	30	20.5	30	+9.5

*The optimal GEPA targets maximal gain and assumes no combining loss.

mmWave PAs feature characteristically low per-stage gain, the perfect target for this technique!

Summary of GEPA Performance

- ☑ Compound RF PA's connected simultaneously in parallel and in series (GEPA) can realize increased gain and output power compared to a single RF PA.
- ☑ This connection adds driver (main) amplifier power directly to the output at saturation,
- ☑ If both main and aux. amplifiers have identical RF performance the overall efficiency of the structure will be that efficiency, minus combining losses.
- ☑ The structure is linearizable with DPD.

Questions?

Thank you all for your time and attention!

Questions and comments are appreciated!

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