Early Career Paper Finalist

WE3C-2

# The Role of Nonlinear $C_{out}$ in Continuous Class F PAs

Y. Mary Asha Latha, Luís C. Nunes, Filipe M. Barradas, José C. Pedro

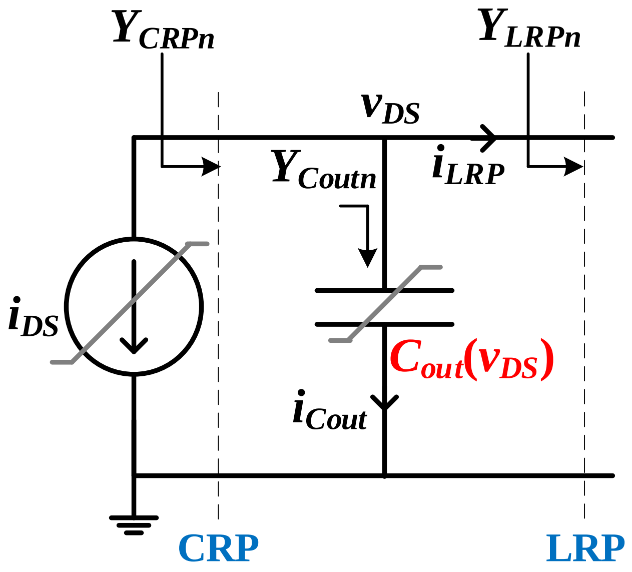
Instituto de Telecomunicações, Campus Universitário de Santiago, Aveiro, Portugal

# Outline

- Introduction
- Theory of Continuous Class F PA
- Continuous Class F PA with nonlinear $C_{out}$
- Design Methodology
- Experimental Validation
- Conclusions

# Introduction

- Continuous Class F (CCF) design equations are defined at the current-source reference plane (CRP).
- These equations do not consider the effect of the non-linear output capacitance ($C_{out}$).



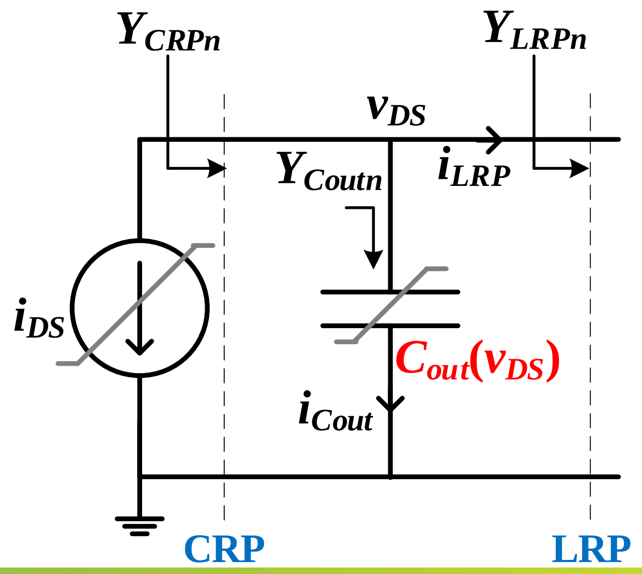

- If conventional equations are used to design PA, the harmonic tuning conditions are altered at the load reference plane (LRP).

# Introduction



- Based on the voltage waveform, the load at CRP sees is either active or passive at second harmonic.

- This work
  - Includes the non-linear $C_{out}$ in the design equations of CCF
  - Analyze its impact on the loads.
  - Analyze its impact on the performance of PA.



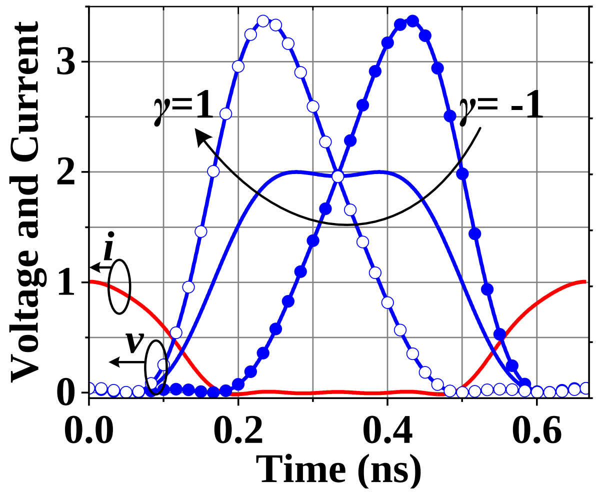
# Theory of Continuous Class F PA

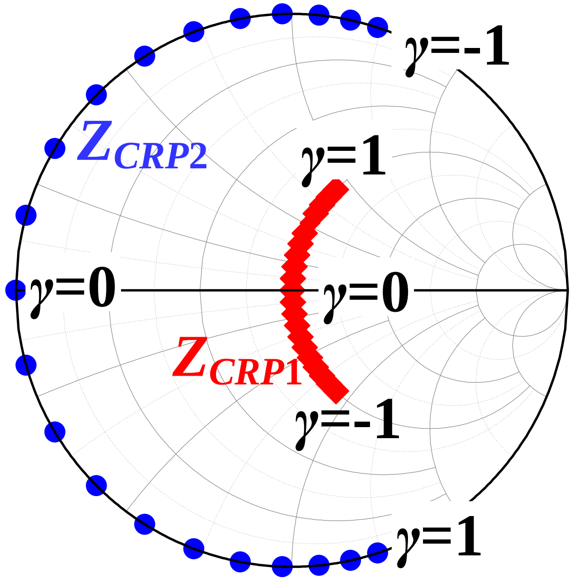


- Voltage equation at CRP is

$$v_{DS}(\theta) = (1 - \alpha\cos\theta)^2(1 + \beta\cos\theta)(1 - \gamma\sin\theta)$$

  - $V'_{ds1} = \frac{V_{ds1}}{V_{ds0}} = -\left[\frac{-(3\alpha^2\beta - 8\alpha + 4\beta)}{2\alpha^2 - 4\alpha\beta + 4}\right] - j\gamma\left[\frac{1}{2} + \frac{2}{2\alpha^2 - 4\alpha\beta + 4}\right]$
  - $V'_{ds2} = \frac{V_{ds2}}{V_{ds0}} = -\left[\frac{2}{\alpha^2 - 2\alpha\beta + 2} - 1\right] - j\gamma\left[\frac{(\alpha^2\beta - 4\alpha + 2\beta)}{2\alpha^2 - 4\alpha\beta + 4}\right]$
  - $V'_{ds3} = \frac{V_{ds3}}{V_{ds0}} = \left[\frac{\alpha^2\beta}{2\alpha^2 - 4\alpha\beta + 4}\right] - j\gamma\left[\frac{1}{2} - \frac{2}{2\alpha^2 - 4\alpha\beta + 4}\right]$
  - $V'_{ds4} = \frac{V_{ds4}}{V_{ds0}} = -j\gamma\frac{\alpha^2\beta}{4(\alpha^2 - 2\alpha\beta + 2)}$




- In CCF, $Z_{CRP2}$ is at the edge of the Smith chart.
- $Re\{Z_{CRP2}\} = \frac{Re\{V_{ds2}\}}{I_{ds2}} = 0 \rightarrow \beta = \alpha/2$ (or $\beta = \alpha/\beta_1$, where $\beta_1 = 2$)

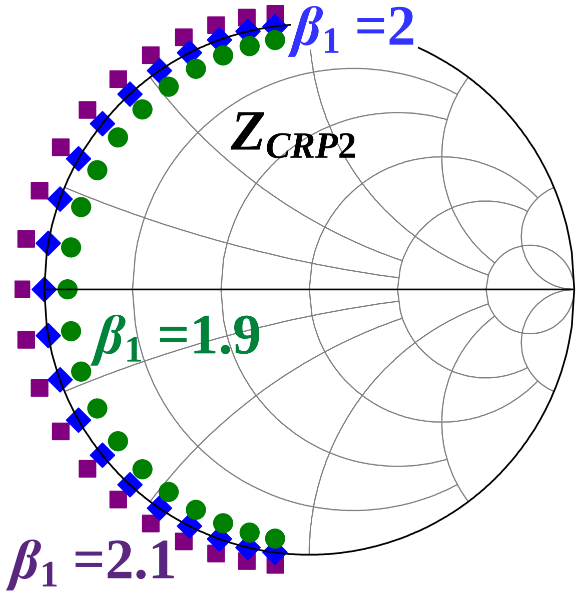
# Theory of Continuous Class F PA

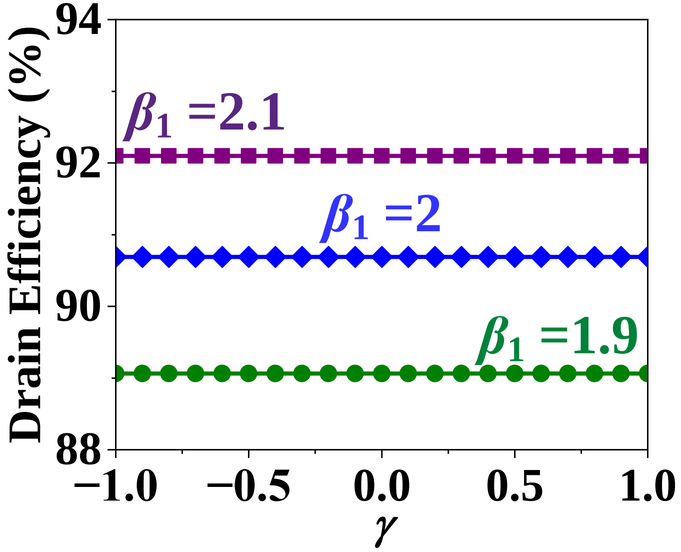
- Maximum DE ⟶ Maximize $Re\{V'_{ds1}\}$ with $\alpha$
- $V'_{ds1} = \frac{V_{ds1}}{V_{ds0}} = -\left[\frac{-(3\alpha^2\beta - 8\alpha + 4\beta)}{2\alpha^2 - 4\alpha\beta + 4}\right] - j\boldsymbol{\gamma}\left[\frac{1}{2} + \frac{2}{2\alpha^2 - 4\alpha\beta + 4}\right]$
- For $\beta_1 \approx 2 \longrightarrow \alpha \approx \frac{2\sqrt{2\boldsymbol{\beta_1} - 1}}{3}$
- $\beta = \alpha/\beta_1 \approx \frac{2\sqrt{2\boldsymbol{\beta_1} - 1}}{3\boldsymbol{\beta_1}}$
- Variables are $\gamma$ and $\beta_1$
- $-1 \leq \gamma \leq 1$
- $|\gamma| > 1 \longrightarrow$ zero-crossing (negative) voltage waveforms

# Theory of Continuous Class F PA



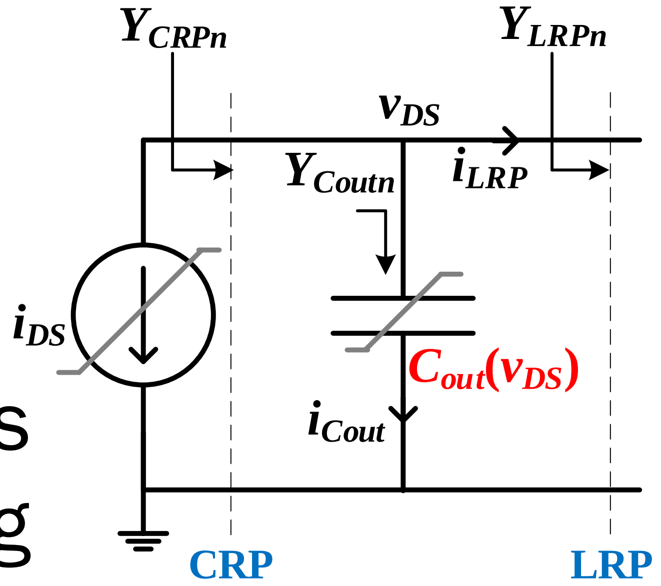
- For $\beta_1 = 2$, Conventional CCF
  - $Z_{CRP2}$ is at the edge of the Smith chart.
  - DE=90.7%
- For $\beta_1 < 2$, Extended CCF
  - $Z_{CRP2}$ is passive i.e., inside the Smith chart.
  - $P_{out}\downarrow$ and DE$\downarrow$.
- For $\beta_1 > 2$,
  - $Z_{CRP2}$ is active i.e., outside the Smith chart.
  - $P_{out}\uparrow$ and DE$\uparrow$.



# Approach for Analysis

- Conventional theory is defined at CRP.
- Our approach for analysis:
  - CRP to LRP
- Enforce design conditions at CRP and observe its impact at LRP using Non-linear embedding model.




- General approach for design:
  - LRP to CRP.
- Loads are enforced at LRP with OMN which presents a particular load at CRP.

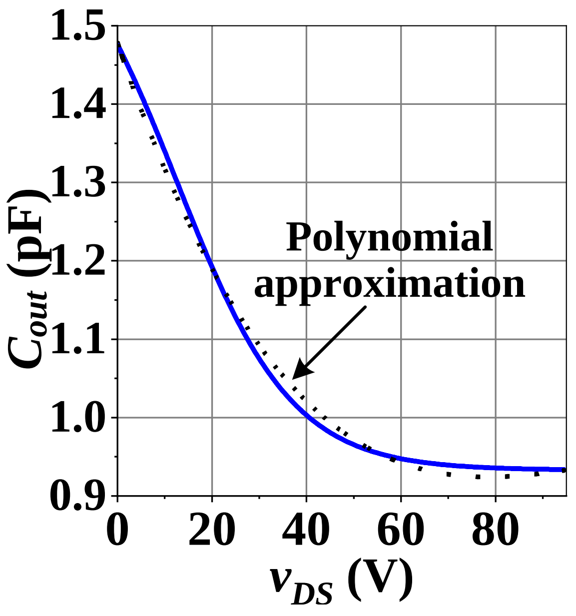
# Theory of CCF PA with Nonlinear $C_{out}$

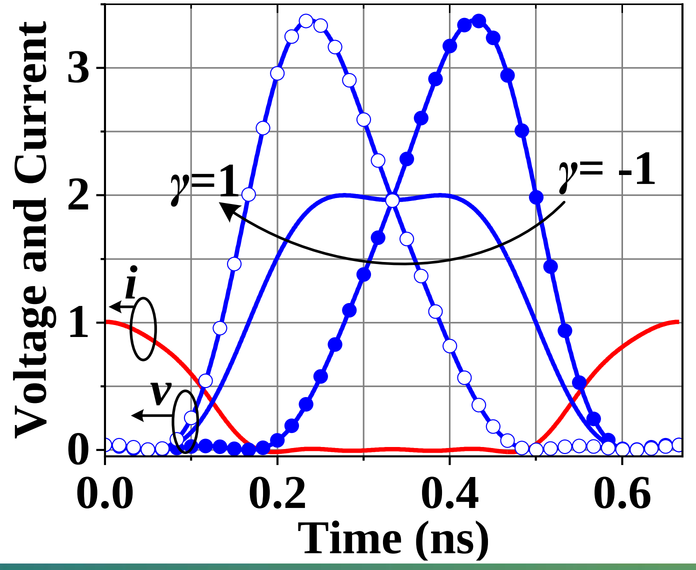


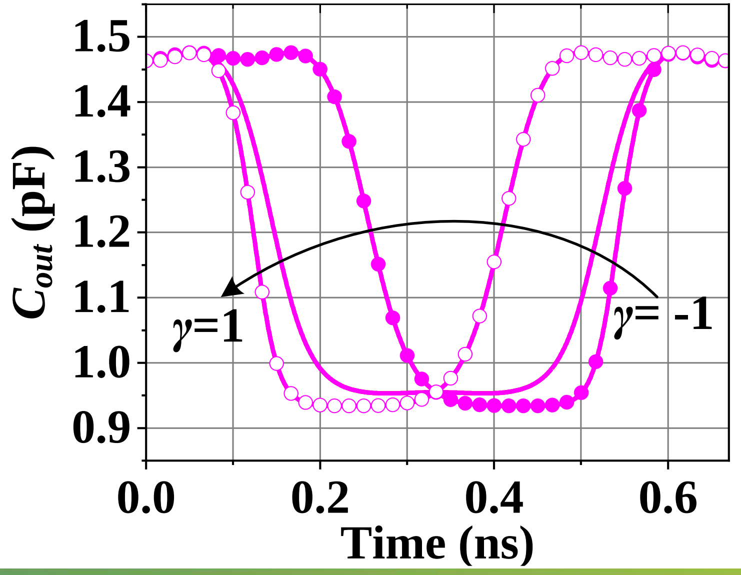
- When the gate is short-circuited at harmonics $C_{out} = C_{ds} \parallel C_{gd}$
- Non-linear output $C_{out}$ can be modelled as,

$$C_{out}[v_{DS}(\theta)] = C_0 + \frac{A_c}{2}\left[1 - \tanh\left(K_c\left(V_c - \boldsymbol{v_{DS}(\theta)}\right)\right)\right]$$

$$v_{DS}(\theta) = (1 - \alpha\cos\theta)^2(1 + \beta\cos\theta)(1 - \gamma\sin\theta)$$



# Theory of CCF PA with Nonlinear $C_{out}$



- Current flowing through non-linear $C_{out}$

$$i_{Cout}(\theta) = C_{out}[v_{DS}(\theta)]\frac{dv_{DS}(\theta)}{d\theta}$$

$$= \frac{1}{2}\left[\sum_{n_1=0}^{N}\left(\boldsymbol{C_{outn_1}}e^{jn_1\theta} + \boldsymbol{C^*_{outn_1}}e^{-jn_1\theta}\right)\right]$$

$$\times \frac{1}{2}\left[\sum_{n_2=0}^{N}\left(jn_2\theta\boldsymbol{V_{dsn_2}}e^{jn_2\theta} - jn_2\theta\boldsymbol{V^*_{dsn_2}}e^{-jn_2\theta}\right)\right]$$

- Fundamental and second harmonic components of current $i_{Cout}$ are

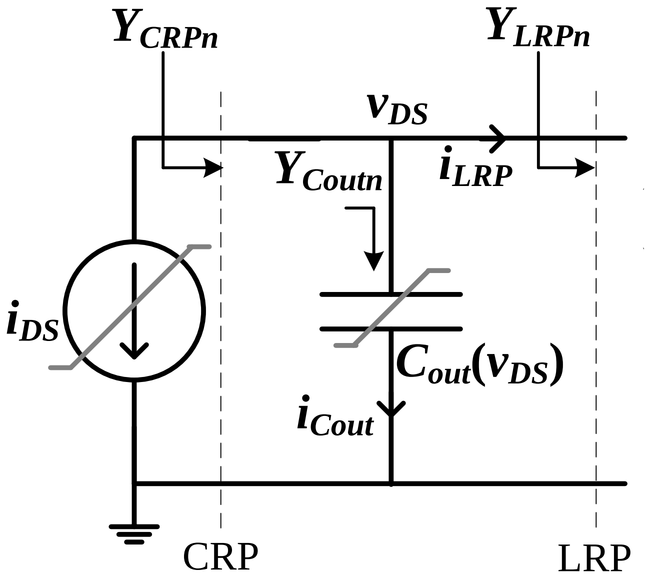
$$I_{Cout1} = j\omega_0 C_{out0}\boldsymbol{V_{ds1}} - \frac{j\omega_0 C_{out2}\boldsymbol{V^*_{ds1}}}{2} + \frac{j2\omega_0 C^*_{out1}\boldsymbol{V_{ds2}}}{2} \ldots$$

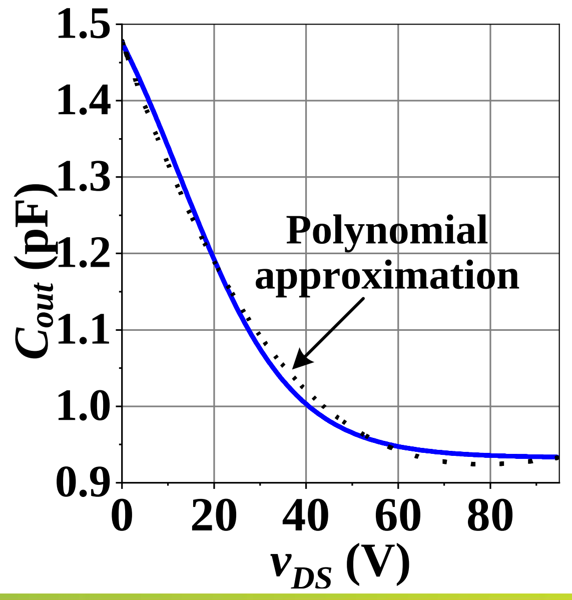
$$I_{Cout2} = \frac{j\omega_0 C_{out1}\boldsymbol{V_{ds1}}}{2} + j2\omega_0 C_{out0}\boldsymbol{V_{ds2}} - \frac{j\omega_0 C_{out3}\boldsymbol{V^*_{ds1}}}{2} \ldots$$

# Theory of CCF PA with Nonlinear $C_{out}$



- $Y_{LRP2} = Y_{CRP2} - \mathbf{Y_{Cout2}}$
- $Y_{Cout2} = \frac{I_{Cout2}}{V_{ds2}} \approx \underbrace{\frac{j\omega_0 \mathbf{C_{out1}}}{2}}_{k_1} \cdot \underbrace{\frac{\mathbf{V_{ds1}}}{\mathbf{V_{ds2}}}}_{k_2} + j2\omega_0 C_{out0}$
- $Re\{Y_{Cout2}\} = Re\{k_1\} \cdot Re\{k_2\} - Im\{k_1\} \cdot Im\{k_2\}$
- $k_1 \propto C_{out1}$
- $C_{out}[v_{DS}(\theta)] = C_0 + \frac{A_c}{2}\left[1 - \tanh\left(K_c\left(V_c - v_{DS}(\theta)\right)\right)\right] \approx p_0 + p_1 v_{DS} + p_2 v_{DS}^2 + p_3 v_{DS}^3$
- $C_{out1} \approx \left[p_1 + 2p_2 V_{ds0} + 3p_3 V_{ds0}^2\right] \times \mathbf{V_{ds1}}$



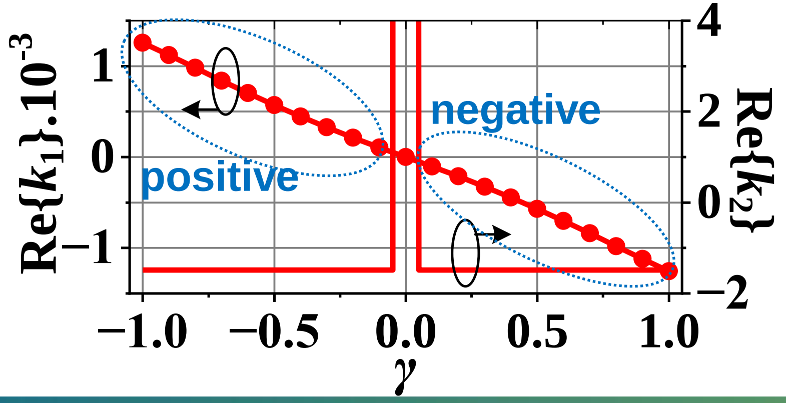



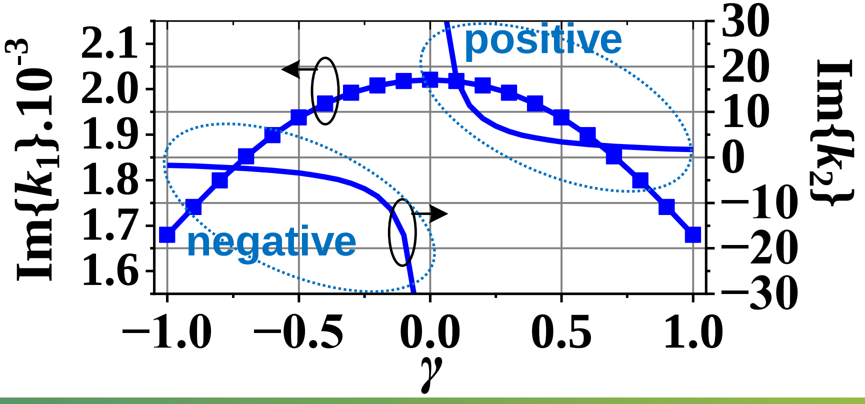
# Theory of CCF PA with Nonlinear $C_{out}$

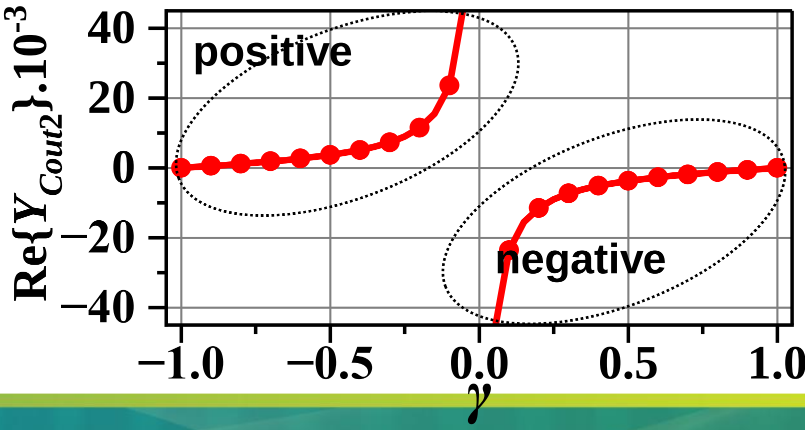


- $Y_{Cout2} \approx \underbrace{\frac{j\omega_0 C_{out1}}{2}}_{k_1} . \underbrace{\frac{V_{ds1}}{V_{ds2}}}_{k_2} + j2\omega_0 C_{out0}$
- $Im\{V_{ds1}\}$ depends on $\gamma$
  - sign of $Im\{C_{out1}\}$ varies with $\gamma$
  - sign of $Re\{k_1\}$ varies with $\gamma$.
- $Im\{V_{ds1}\}$ and $Im\{V_{ds2}\}$ depends on $\gamma$
  - sign of $Im\{k_2\}$ varies with $\gamma$.

- $k_1 \propto C_{out1} \propto V_{ds1}$
  - $Re\{Y_{Cout2}\}$
    - positive for $-1 \le \gamma < 0$
    - negative for $0 < \gamma \le 1$
  - $Y_{Cout2}$
    - passive for $-1 \le \gamma < 0$
    - active for $0 < \gamma \le 1$.

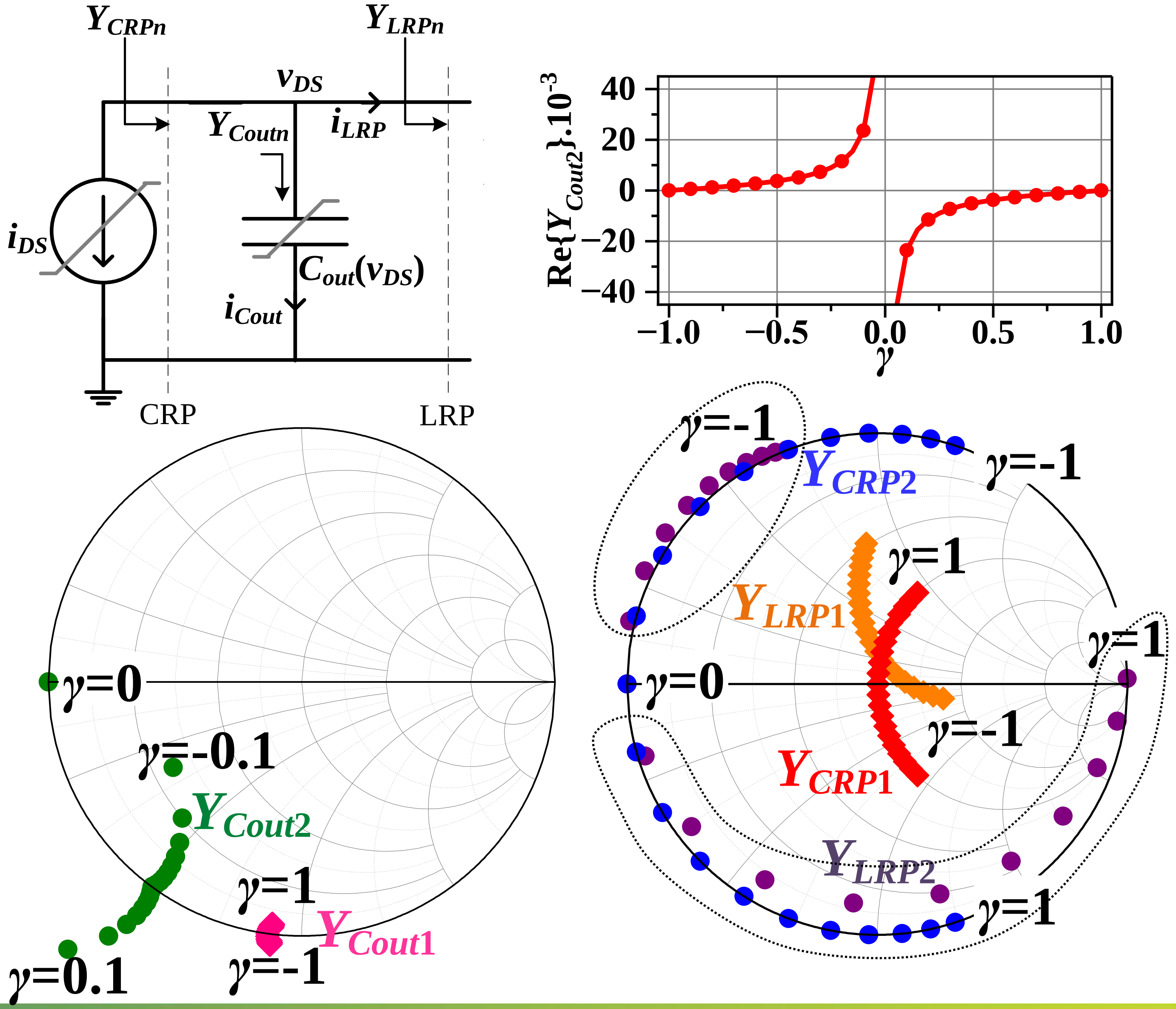


# Active and passive nature of LRP loads

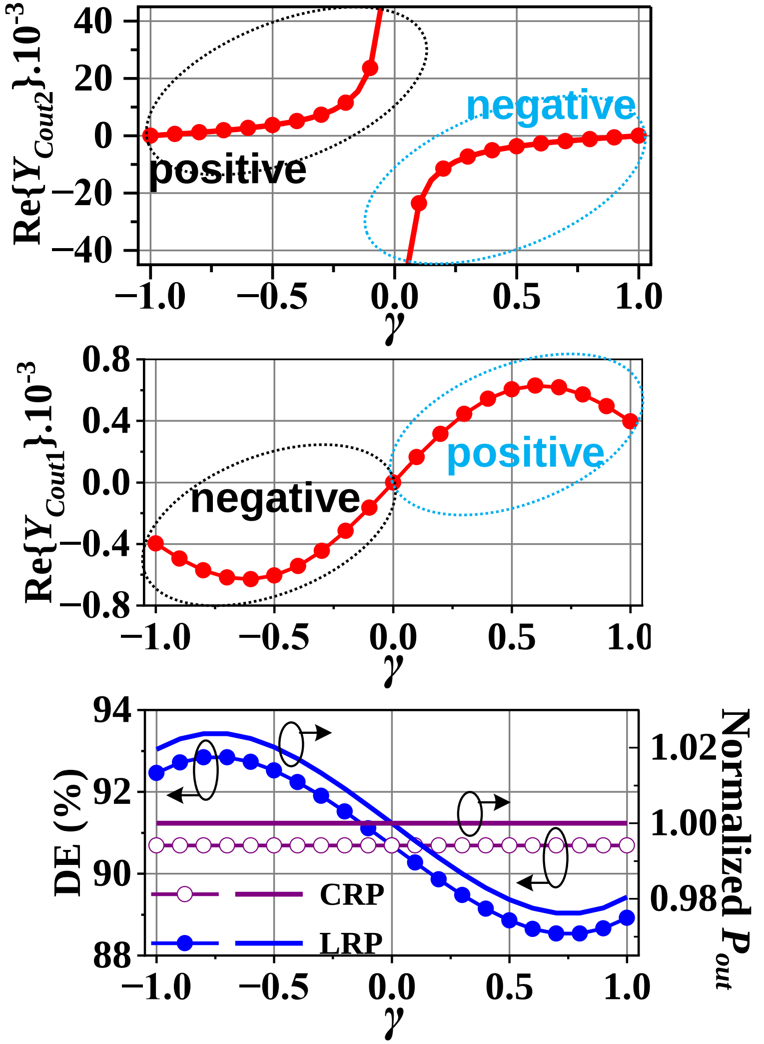
- $Y_{CRP2} = Y_{LRP2} + Y_{Cout2}$
- For $-1 \leq \gamma < 0$
  - $Y_{Cout2}$ is passive
  - $Y_{LRP2}$ is active
- For $0 < \gamma \leq 1$
  - $Y_{Cout2}$ is active
  - $Y_{LRP2}$ is passive



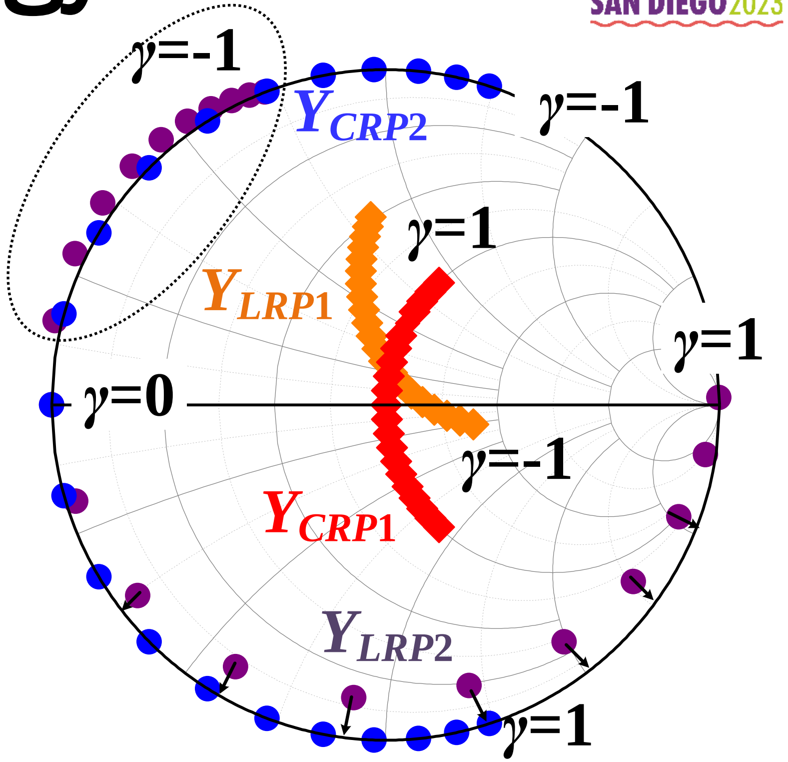
# Performance at LRP



- The performance of PA at LRP will be different from CRP due to non−linear $C_{out}$.
- $P_{out,LRP} = 0.5\mathrm{Re}\{V_{ds1} \times -(I_{ds1} + \boldsymbol{I_{Cout1}})^*\}$
- $DE_{LRP} = \frac{P_{out,LRP}}{P_{DC}} = \frac{0.5\mathrm{Re}\{V_{ds1}\times-(I_{ds1}+\boldsymbol{I_{Cout1}})^*\}}{V_{DD}I_{ds0}}$
- For $-1 \le \gamma < 0$
  - Power conversion from $2f_0$ to $f_0$
  - $P_{out}\uparrow$ and DE↑ at LRP compared to CRP.
- For $0 < \gamma \le 1$
  - Power conversion from $f_0$ to $2f_0$
  - $P_{out}\downarrow$ and DE↓ at LRP compared to CRP.



# Design Methodology



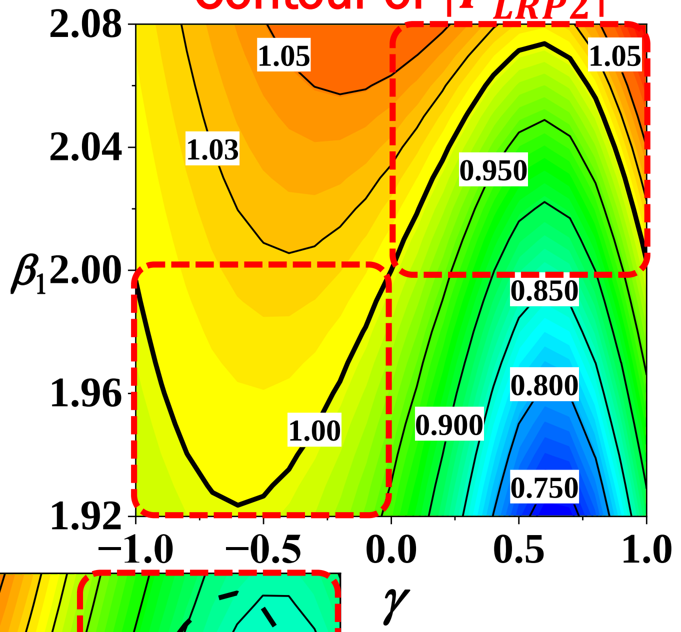

- For $-1 \le \gamma < 0$
  - $P_{out}\uparrow$ and DE↑ at LRP
  - $Y_{LRP2}$ is active
  - can't achieve with passive OMN
  - $\beta_1 = 2$ is not optimum
- For $0 < \gamma \le 1$
  - $Y_{LRP2}$ is passive i.e., inside the Smith chart
  - can be pushed to edge of Smith chart to increase DE at LRP
  - other values of $\beta_1$ should be explored
- $\gamma$ and $\beta_1$ should be carefully mapped to achieve optimum $Y_{LRP2}$ for best DE at LRP.

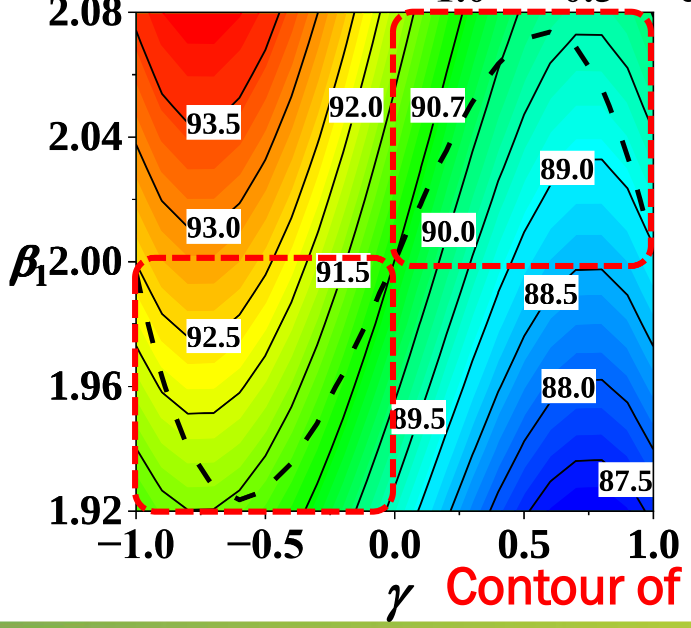
# Design Methodology



- $\gamma$ and $\beta_1$ are simultaneously varied
- Best $DE_{LRP}$ with passive matching
  - $|\Gamma_{LRP2}| = 1$ i.e., $Y_{LRP2}$ at edge of Smith chart.
- For $-1 \leq \gamma < 0 \rightarrow$
  - $|\Gamma_{LRP2}| = 1$ corresponds to $\beta_1 < 2$
  - $DE_{LRP} > 90.7\%$
- For $0 < \gamma \leq 1$
  - $|\Gamma_{LRP2}| = 1$ corresponds to $\beta_1 > 2$
  - $DE_{LRP} < 90.7\%$

Contour of $|\Gamma_{LRP2}|$



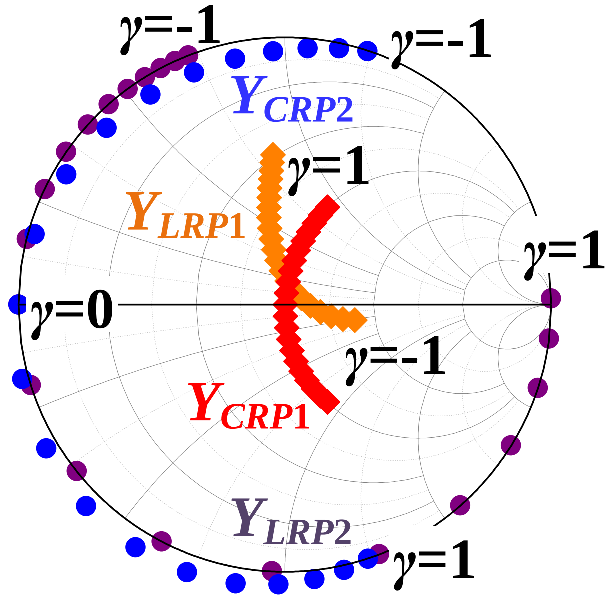



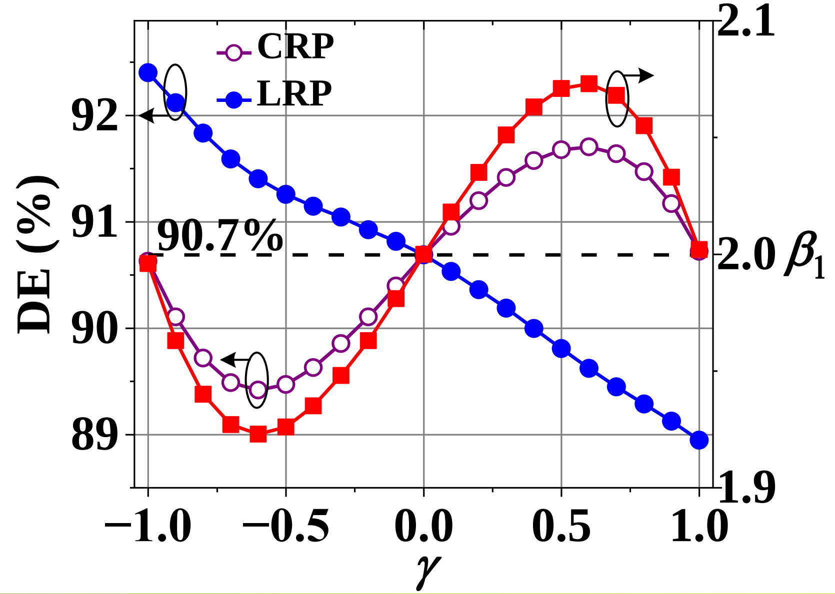

Contour of $DE_{LRP}$

# Design Methodology



- $\gamma$ is mapped to $\beta_1 \in |\Gamma_{LRP2}| = 1$
- For $-1 \leq \gamma < 0$
  - $|\Gamma_{LRP2}| = 1 \in \beta_1 < 2$
  - $Z_{CRP2}$ is passive i.e., $DE_{CRP} < 90.7\%$
  - $DE_{LRP} > 90.7\%$ due to non-linear $C_{out}$.
- For $0 < \gamma \leq 1$
  - $|\Gamma_{LRP2}| = 1 \in \beta_1 > 2$
  - $Z_{CRP2}$ is active i.e., $DE_{CRP} > 90.7\%$
  - $DE_{LRP}$ has improved from $\beta_1 = 2$ case.

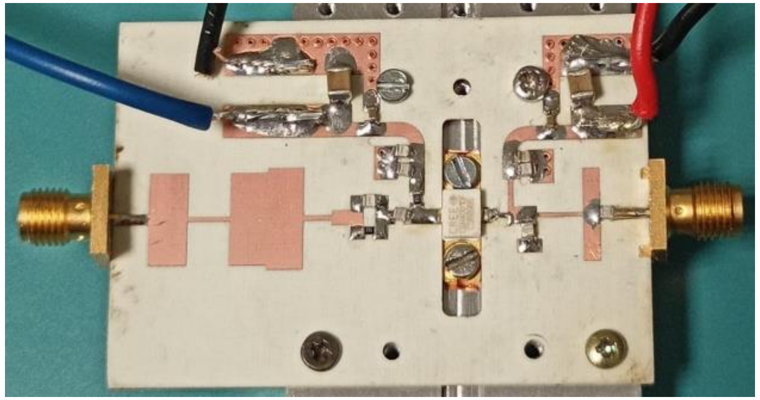


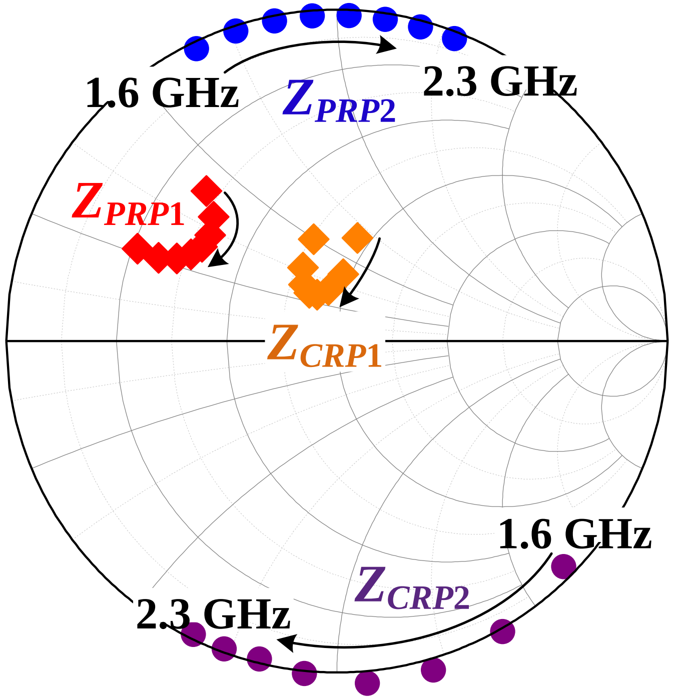



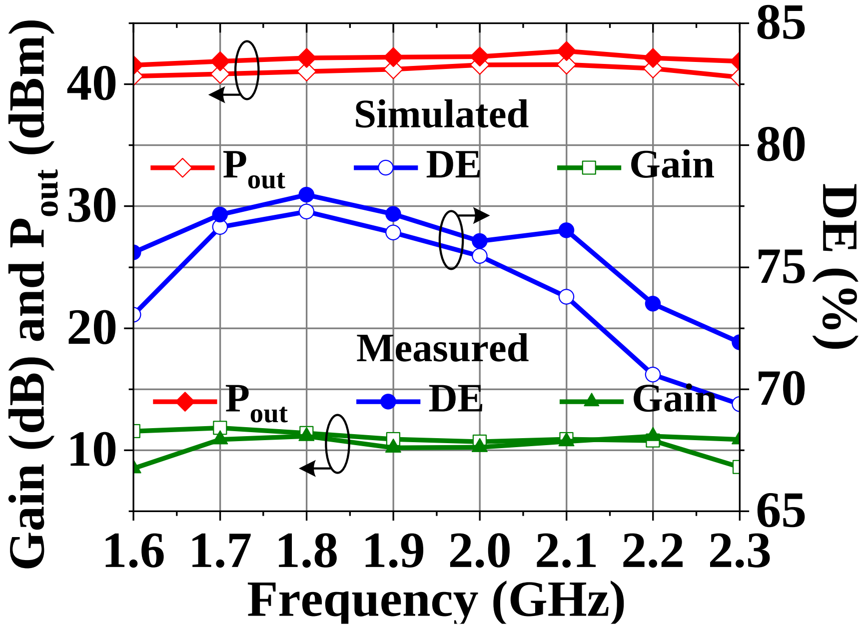
# Experimental Validation



- Loads for $\beta_1 > 2$ and $0.5 \le \gamma \le 1 \rightarrow$ 1.6 to 2.3 GHz
- Active $Z_{CRP2}$ with passive matching network.






| Freq. (GHz) | Power (dBm) | Efficiency (%) | Gain (dB) | Gain Compression (dB) |
|---|---|---|---|---|
| 1.6 - 2.3 | 41.6 - 42.7 | 72 - 78 | 8.6 - 11 | 3 |

# Conclusions



- Non-linear $C_{out}$ impacts the performance of CCF PA.
- Based on the CCF voltage, power conversion takes place from $2f_0$ to $f_0$ , and vice-versa.
- Efficiency higher than conventional CCF can be achieved by wisely mapping $\gamma$ and $\beta_1$.
- An active $2f_0$ load can be achieved at CRP with passive OMN.

# Thank You