A Class F^{-1}/F 24-to-31GHz Power Amplifier with 40.7% Peak PAE, 15dBm OP_{1dB}, and 50mW P_{sat} in 0.13μm SiGe BiCMOS

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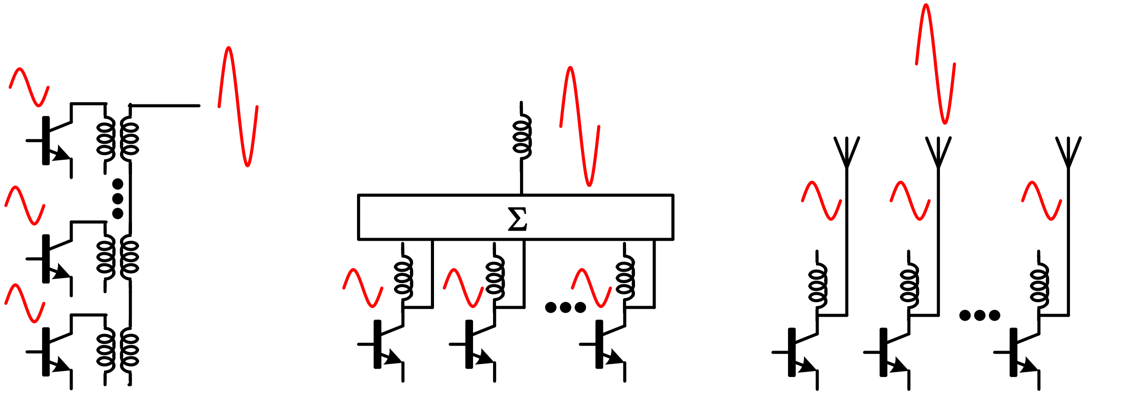
Outline

- Background / Motivation
  - Challenge in Silicon mm-Wave PAs
  - Efficiency of mm-Wave PAs
  - Harmonic Tuned (Class-F^{-1}, Class-F) PAs
- Class-F^{-1} to Class-F Mode-Transition PA Design
- Measurement Results
- Conclusion

Challenge in Silicon mm-Wave PAs

- Speed-breakdown tradeoff
- Not sufficient silicon transistor speed (f_T, f_{max}) for mm-wave

⇨ **Small P_{out} per PA stage**
- Power combining with a PA-array can increase P_{out}.



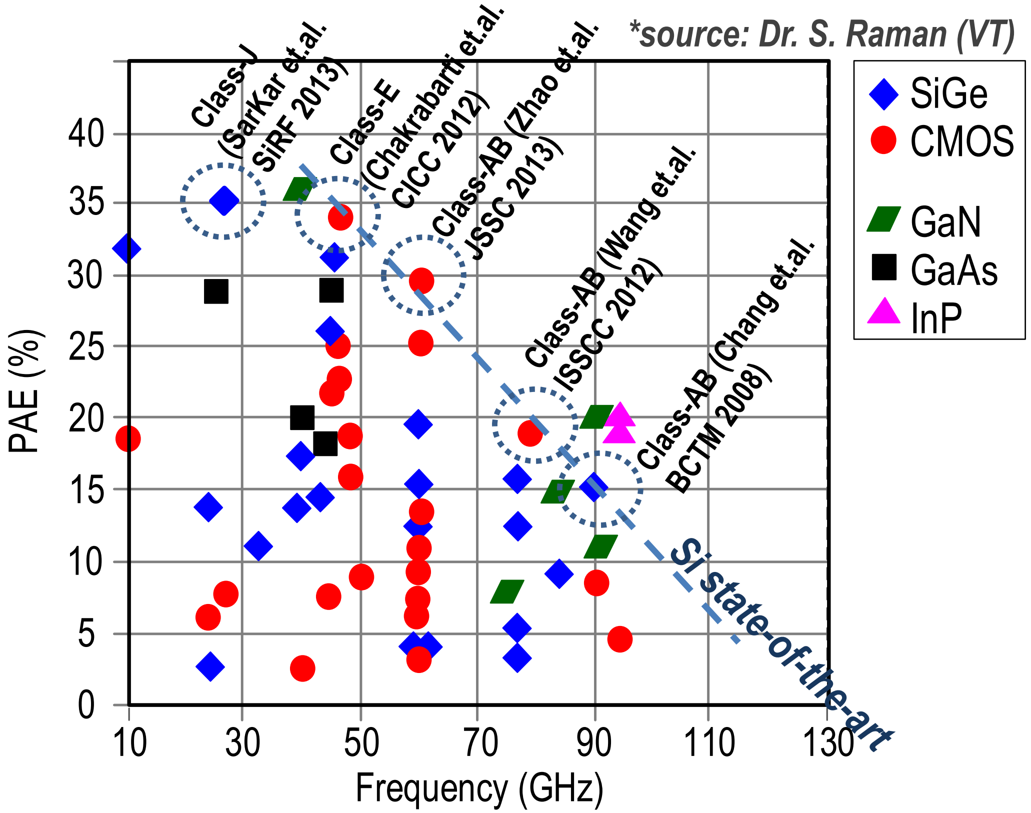
Series combining
(e.g. distributed transformer)

Parallel combining
(e.g. Wilkinson)

Spatial combining
(e.g. phased array)

⇨ **Low power-added efficiency (PAE)**
- It is critical to improve unit PA's PAE to improve overall PAE in a PA-array.
- Relatively, a lack of research on efficient PA topology suitable for mm-wave.

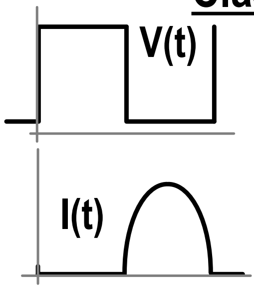
Efficiency of mm-Wave PAs



- With *Class-AB*, ~30% PAE has been reported at 60 GHz in 40 nm CMOS.
- *Class-E* PA has achieved ~30-35% PAE at ~45 GHz in 45 nm SOI CMOS.
- *While potentially viable technology, harmonic-tuned approaches (Class-F, Class-F^{-1}) has not been explored yet at mm-wave.*

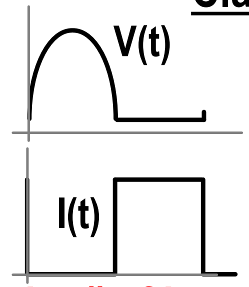
Harmonic Tuned (Class-F, Class-F^{-1}) PAs

Class-F



$Z_L(f_o) = R_{opt}$
$Z_L(2n \cdot f_o) = 0$
$Z_L((2n+1) \cdot f_o) = \infty$

Class-F^{-1}



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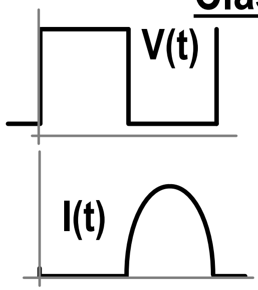
non-overlap V-I: 100% η but infinite # of harmonics control

- In practice, ~ up to the 3rd harmonic power control at mm-wave with a finite V_{knee} (e.g. practical max. η ~90%x(V_{CC}-V_{knee})/V_{CC} =68% if V_{CC}=2V & V_{knee}=0.5V).

Harmonic Tuned (Class-F, Class-F^{-1}) PAs

Class-F



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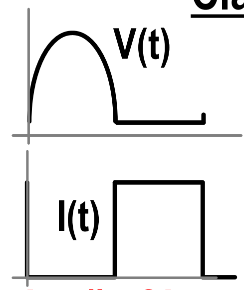
Class-F^{-1}



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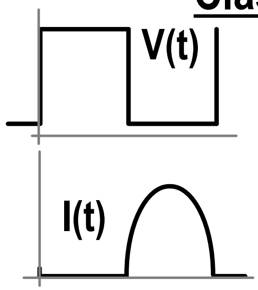
Pros:

- Current-mode: power transistor operates as a current source
- Class-AB biasing: fast speed, high gain
- No switching loss involved
- On-chip high-Q L-C networks are readily available for harmonic-Z control @mm-wave

Harmonic Tuned (Class-F, Class-F^{-1}) PAs

Class-F



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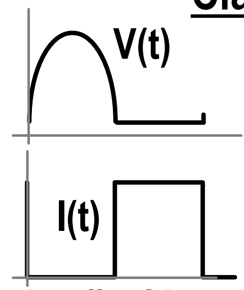
Class-F^{-1}



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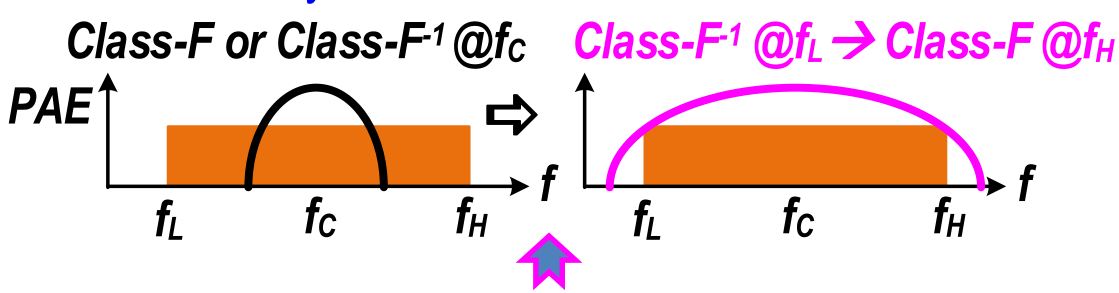
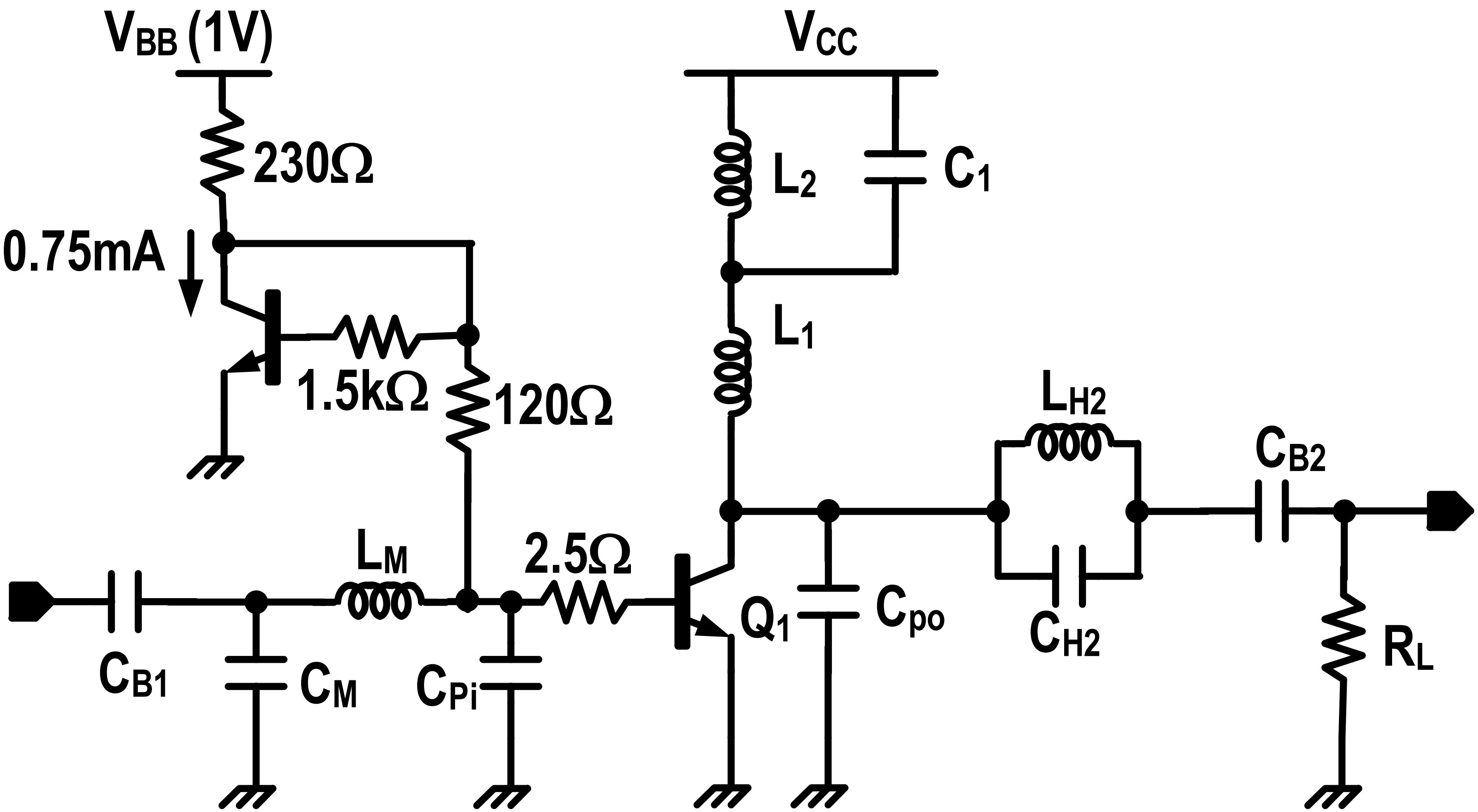


Cons:

- Narrowband PAE

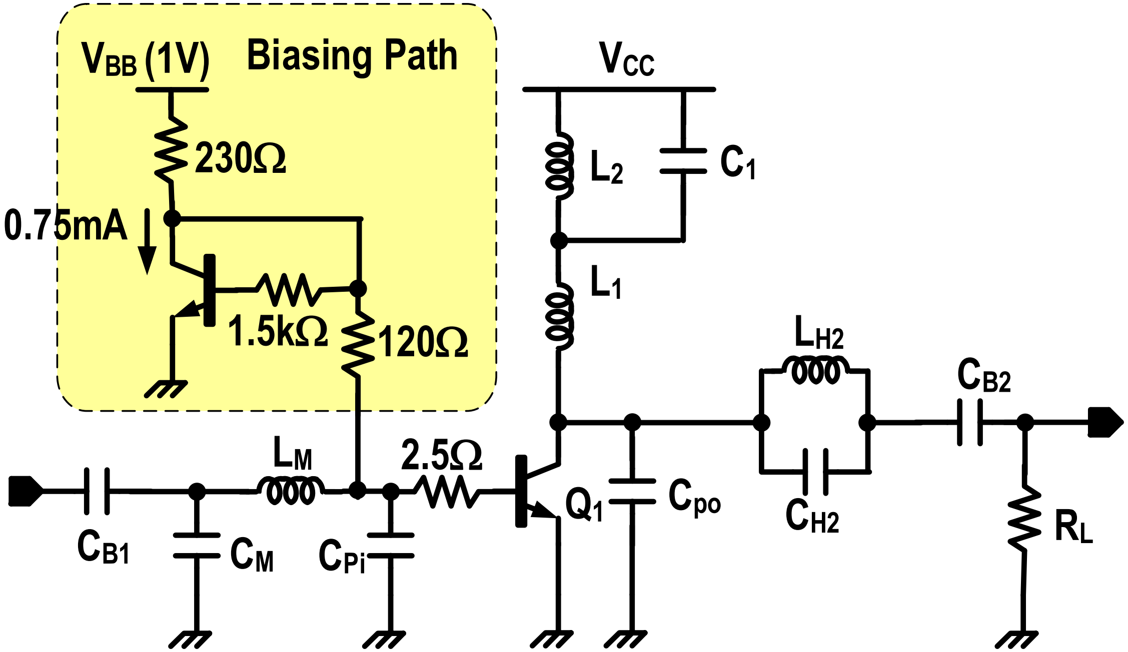
⇨ Need a wideband technique: motivation of *"mode-transition" operation.*

Proposed Class-F^{-1} to Class-F Mode-Transition PA



$C_{B1,2}$:DC decoupling

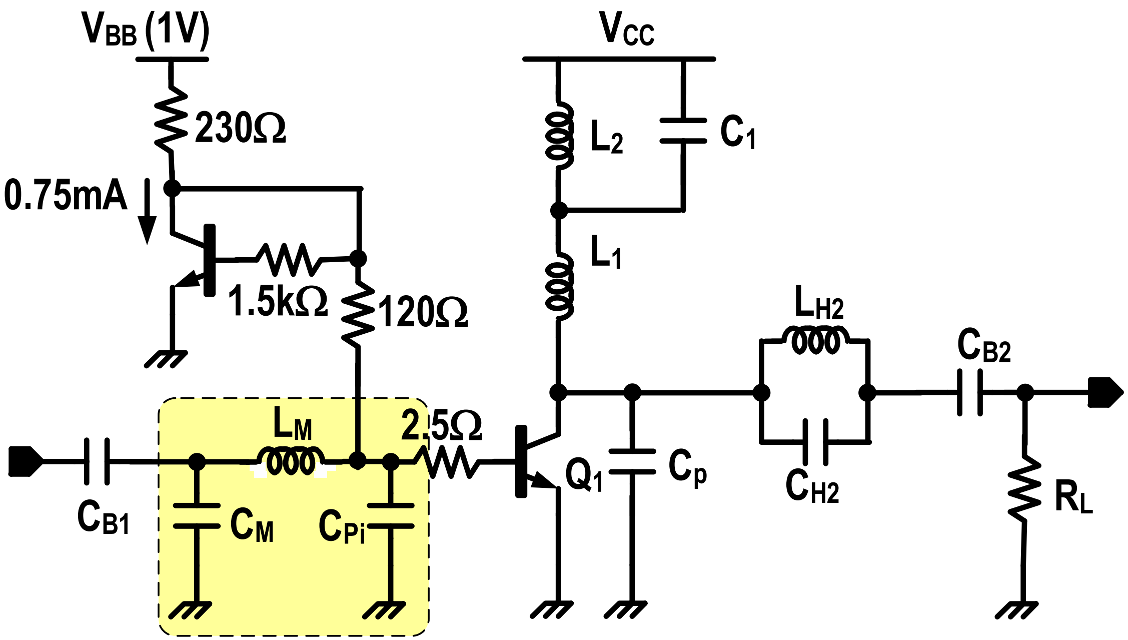
Class-F^{-1} to Class-F Mode-Transition PA (1)



$C_{B1,2}$:DC decoupling

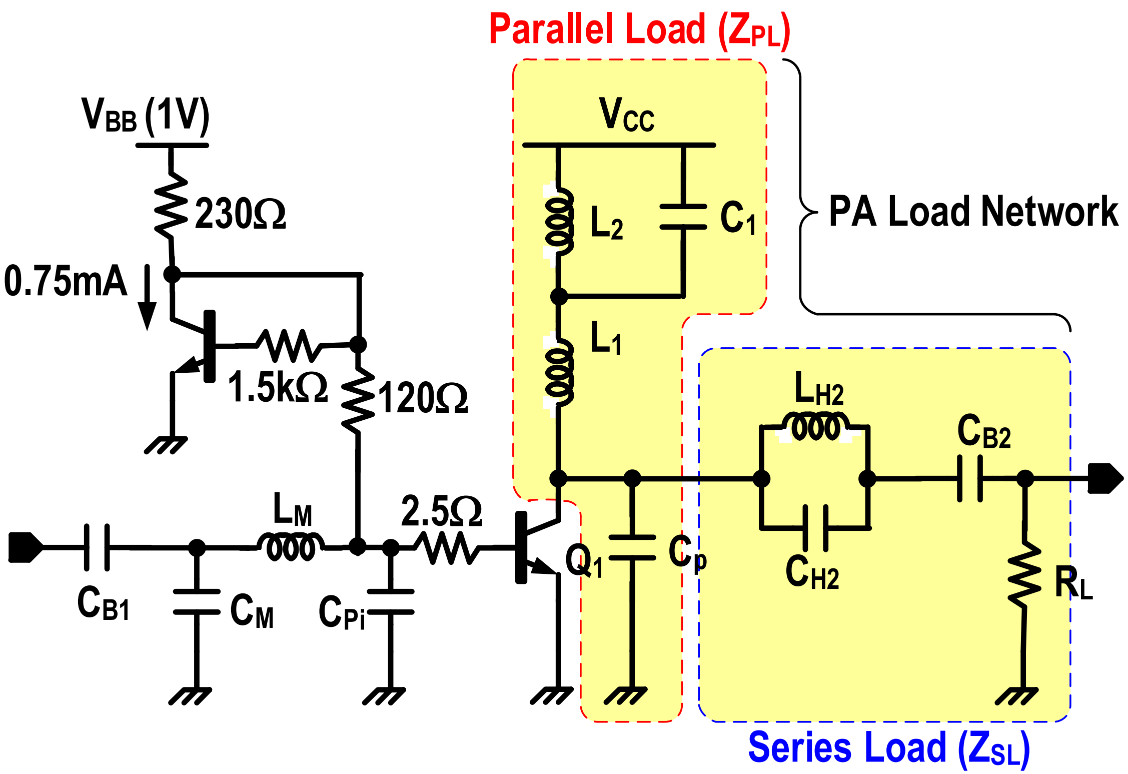
- Class-AB biasing: V_{BE}=0.85 V & I_{CE}=9 mA (V_{CC}=2.2 V, V_{knee}=0.5 V)
- Sizing for peak f_T (~180 GHz) @P_{sat}=50 mW
- Impedance seen from base is < 300-Ω so that $V_{CE, peak}$ ~ 3xBV_{CEO}~5 V @Class-F^{-1} (BV_{CEO}~1.7 V & BV_{CBO}~5.5 V)

Class-F^{-1} to Class-F Mode-Transition PA (2)



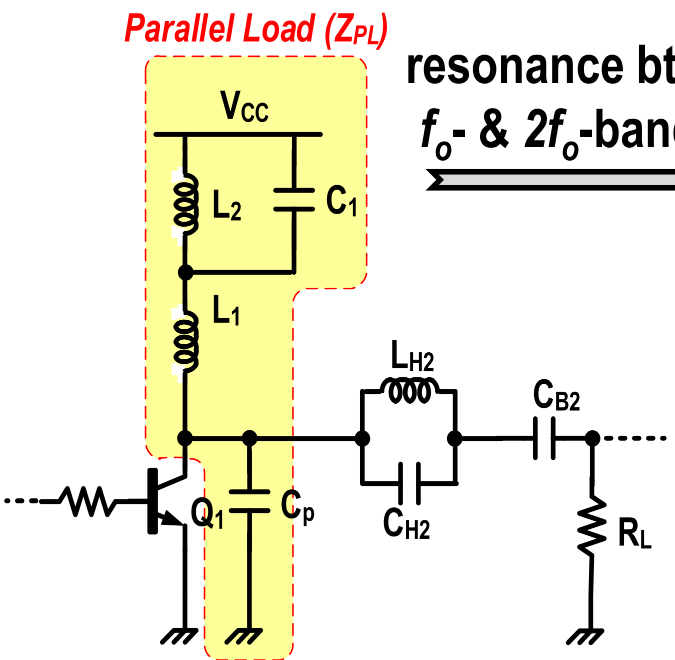
- Π-matching network provides a wideband Z-matching: S_{11} < -10 dB @23-31 GHz (sim.).
- C_{pi} includes base-node parasitic capacitances including layout parasitics.
- 2.5 Ω base resistance stabilizes the PA over all operation frequencies.

Class-F^{-1} to Class-F Mode-Transition PA (3)

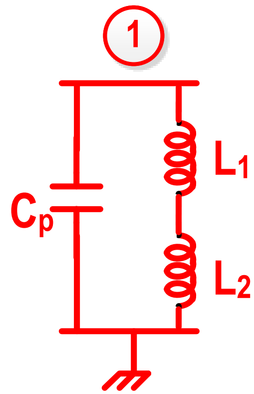


- Z_{PL} & Z_{SL} comprise multi-resonance harmonic tuned load, cooperatively shaping an optimum load impedance for Class-F^{-1} and Class-F operations.
- C_p includes collector-node parasitic capacitances including layout parasitics.
- *L2-C1 tank impedance variation over harmonic frequencies plays a key role in transferring from Class-F^{-1} to Class-F over 24-31 GHz (see next slides).*

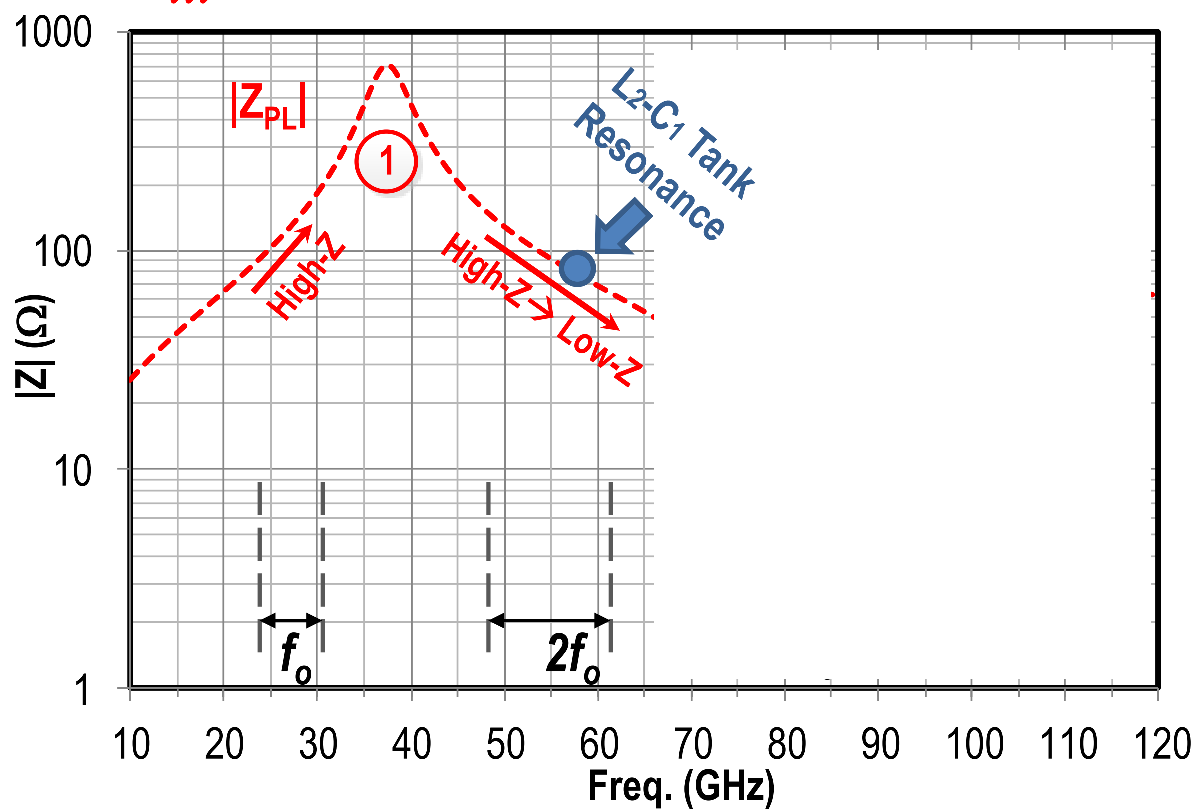
Load Network with F^{-1}/F Mode Transition (1)



resonance btw f_o- & $2f_o$-band



This tank provides relatively high impedance for both fundamental (f_o) and the 2nd harmonic ($2f_o$) bands.

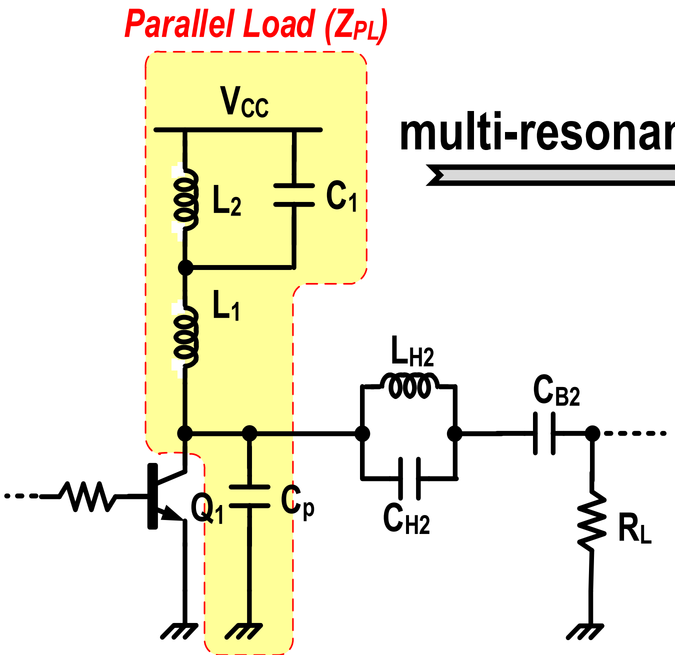


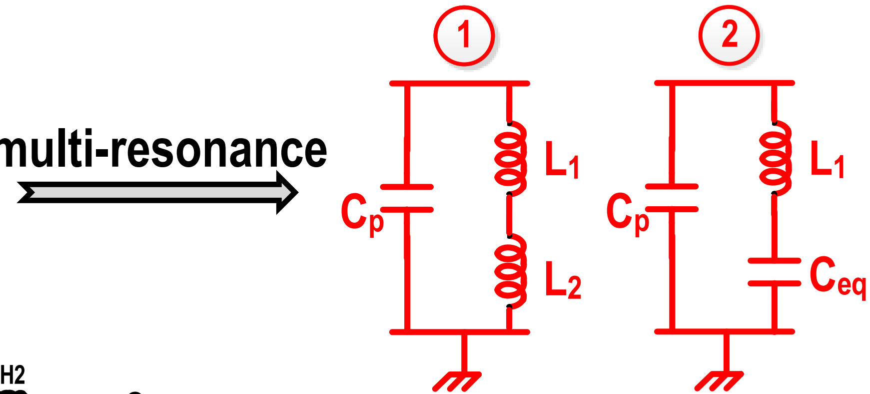
Z_{PL} Modulation by L_2-C_1 Tank

①: $L_2 \,||\, C_1 \sim L_2$

→ $Z_{PL}=s(L_1+L_2) \,||\, 1/sC_P$

Load Network with F^{-1}/F Mode Transition (2)





L_1-C_{eq} series resonance forms a sharp impedance null in the middle of the 3rd harmonic ($3f_o$) band .

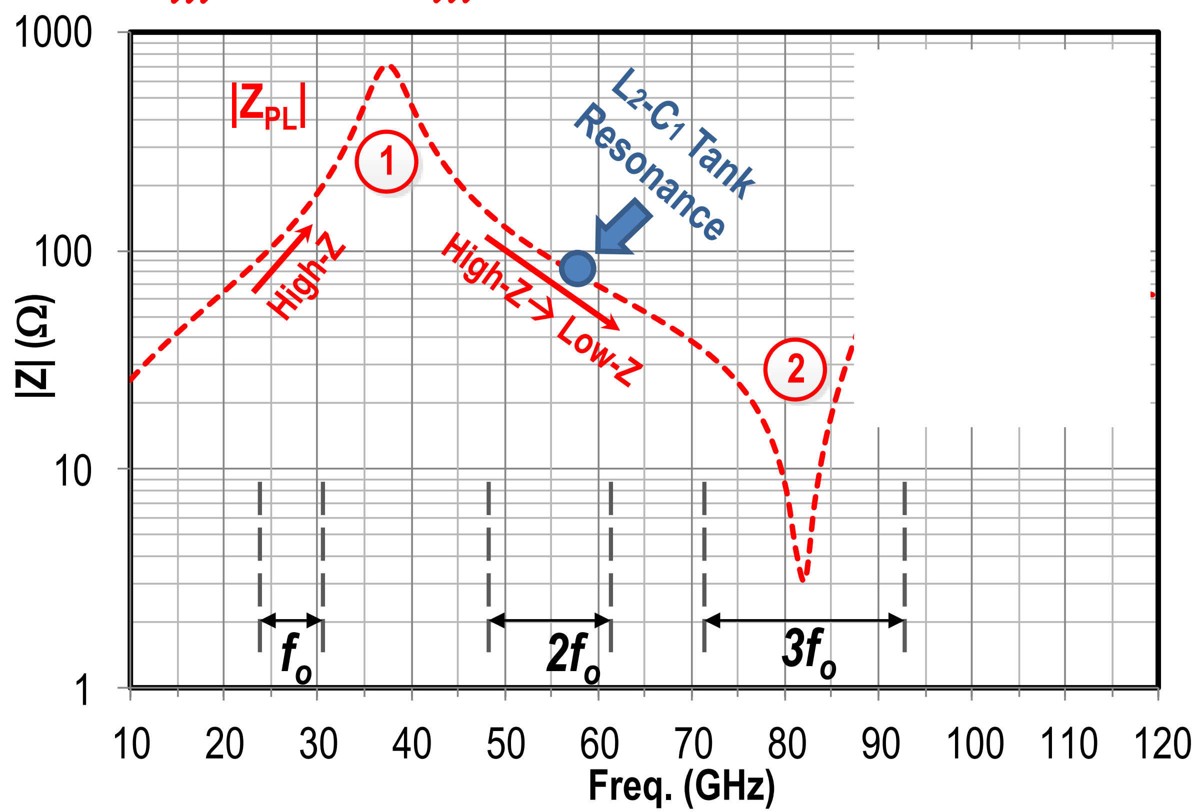
ZPL Modulation by L2-C1 Tank

①: $L_2 \,||\, C_1 \sim L_2$

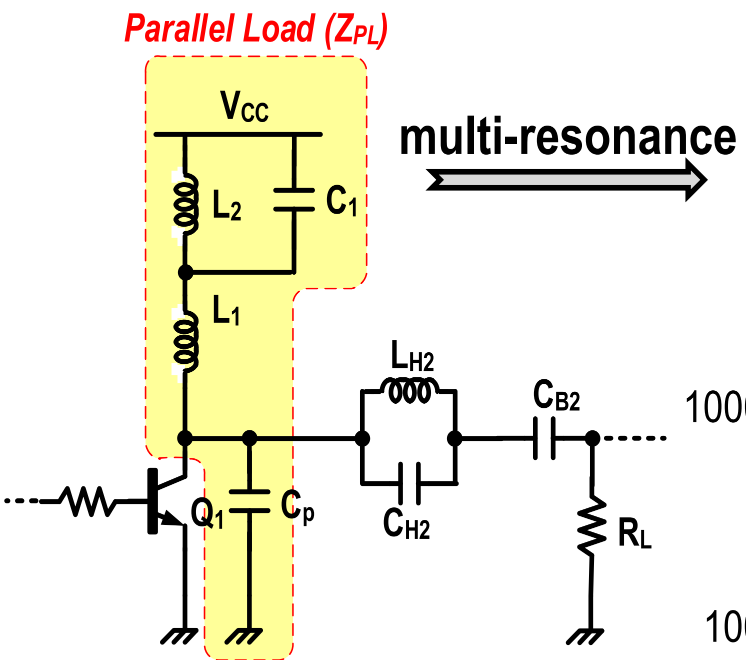
$\rightarrow Z_{PL} = s(L_1+L_2) \,||\, 1/sC_P$

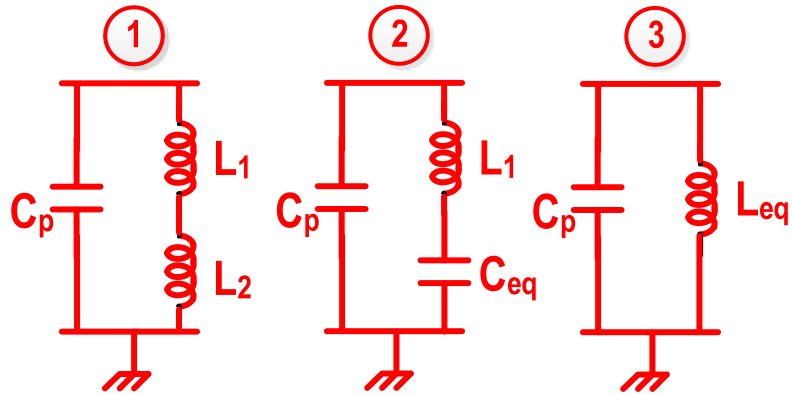
②: $L_2 \,||\, C_1 \sim C_{eq}$

$\rightarrow Z_{PL} = sL_1 + 1/sC_{eq}$

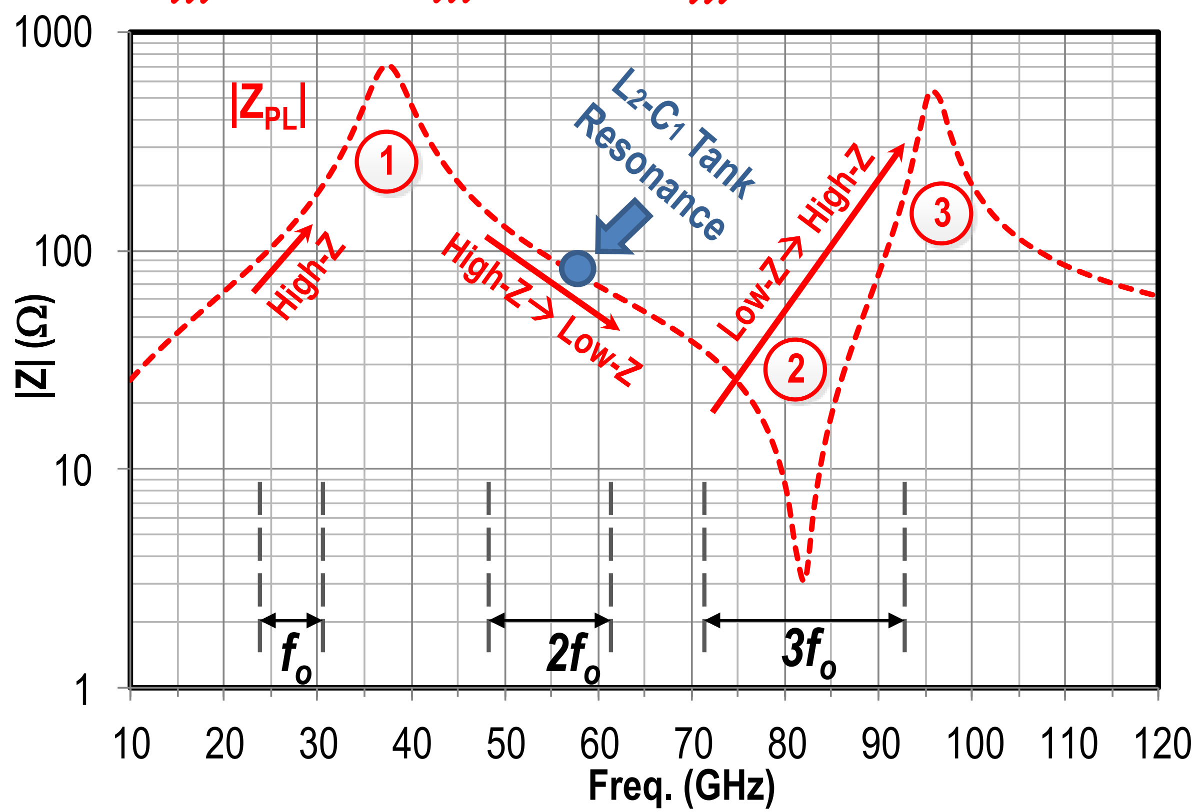


Load Network with F^{-1}/F Mode Transition (3)





L_{eq}-C_P parallel resonance forms an impedance maxima at the edge of the $3f_o$-band.



ZPL Modulation by L2-C1 Tank

①: $L_2 \,||\, C_1 \sim L_2$

→ $Z_{PL}=s(L_1+L_2) \,||\, 1/sC_P$

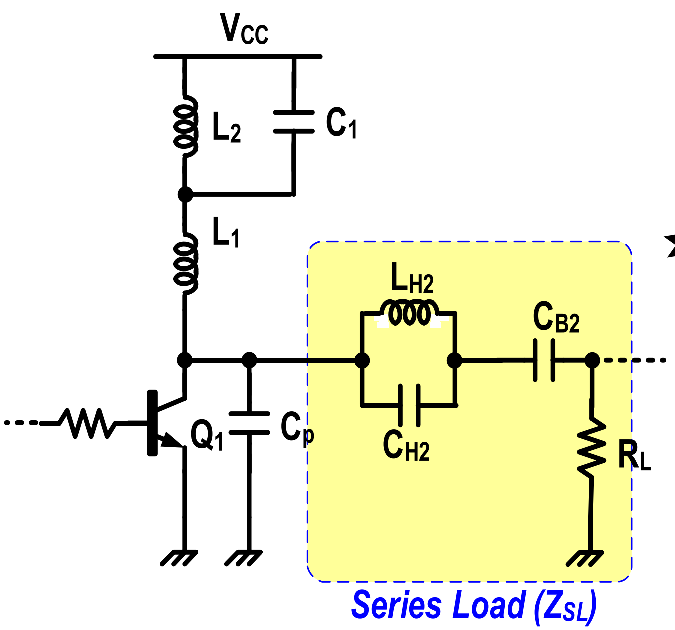
②: $L_2 \,||\, C_1 \sim C_{eq}$

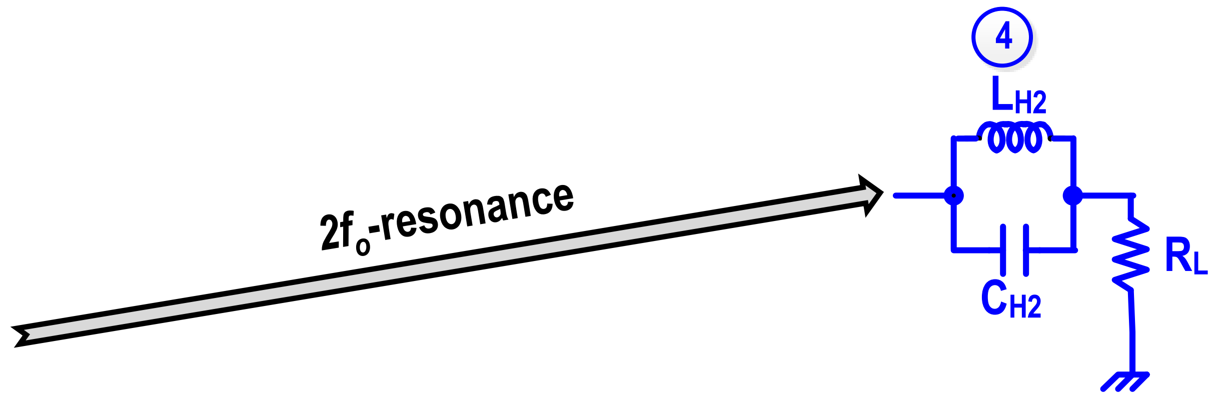
→ $Z_{PL}=sL_1+1/sC_{eq}$

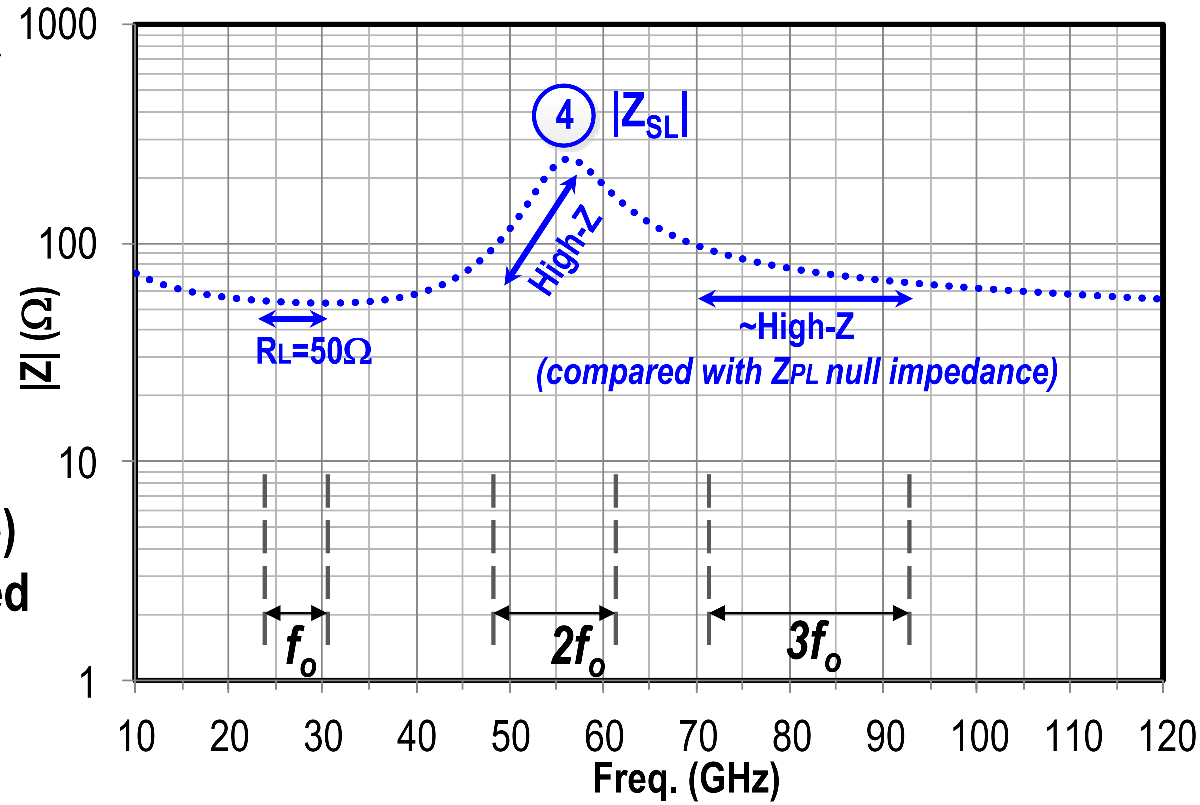
③: L_1–$C_1 \sim L_{eq}$

→ $Z_{PL}=sL_{eq} \,||\, 1/sC_P$

Load Network with F^{-1}/F Mode Transition (4)



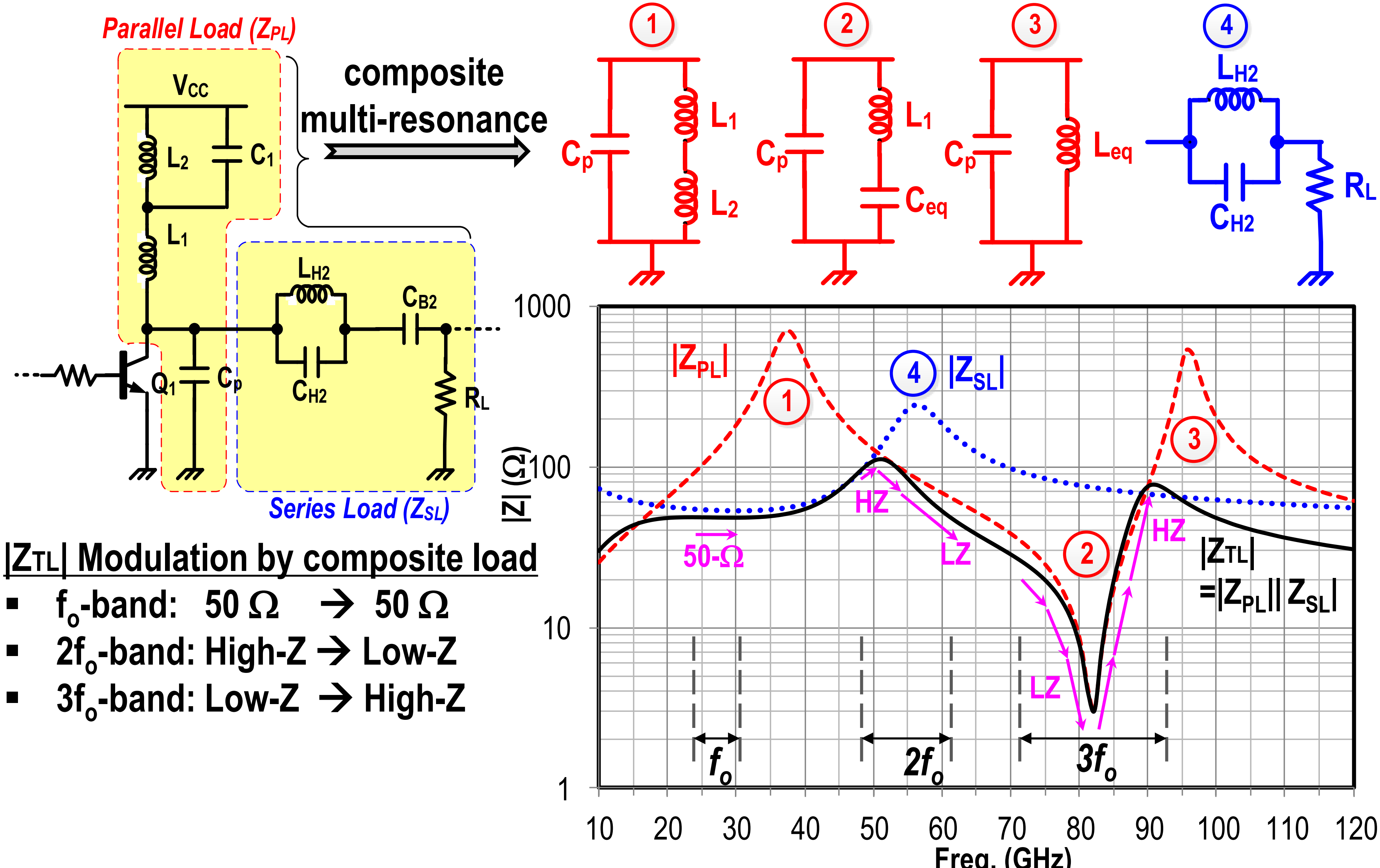




Z_{SL} Modulation by L_{H2}-C_{H2} Tank

- f_o-band: ~ constant 50 Ω
- $2f_o$-band: High-Z (resonance)
- $3f_o$-band: ~ High-Z (compared with Z_{PL} null impedance)

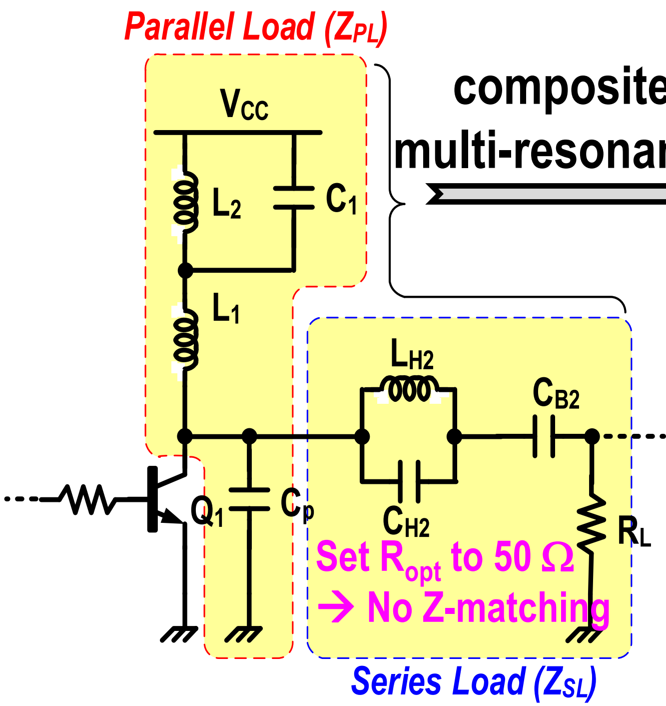
Load Network with F^{-1}/F Mode Transition (5)

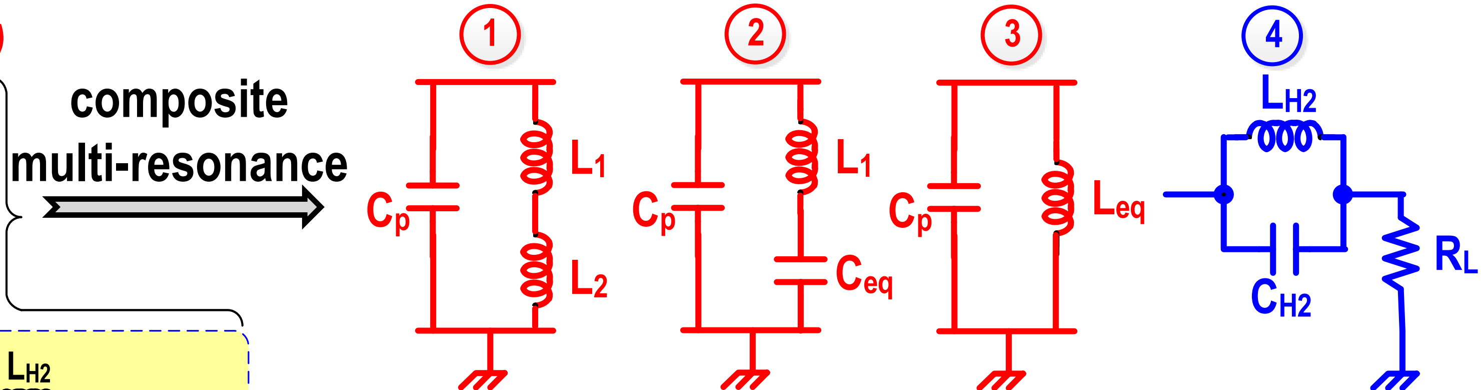


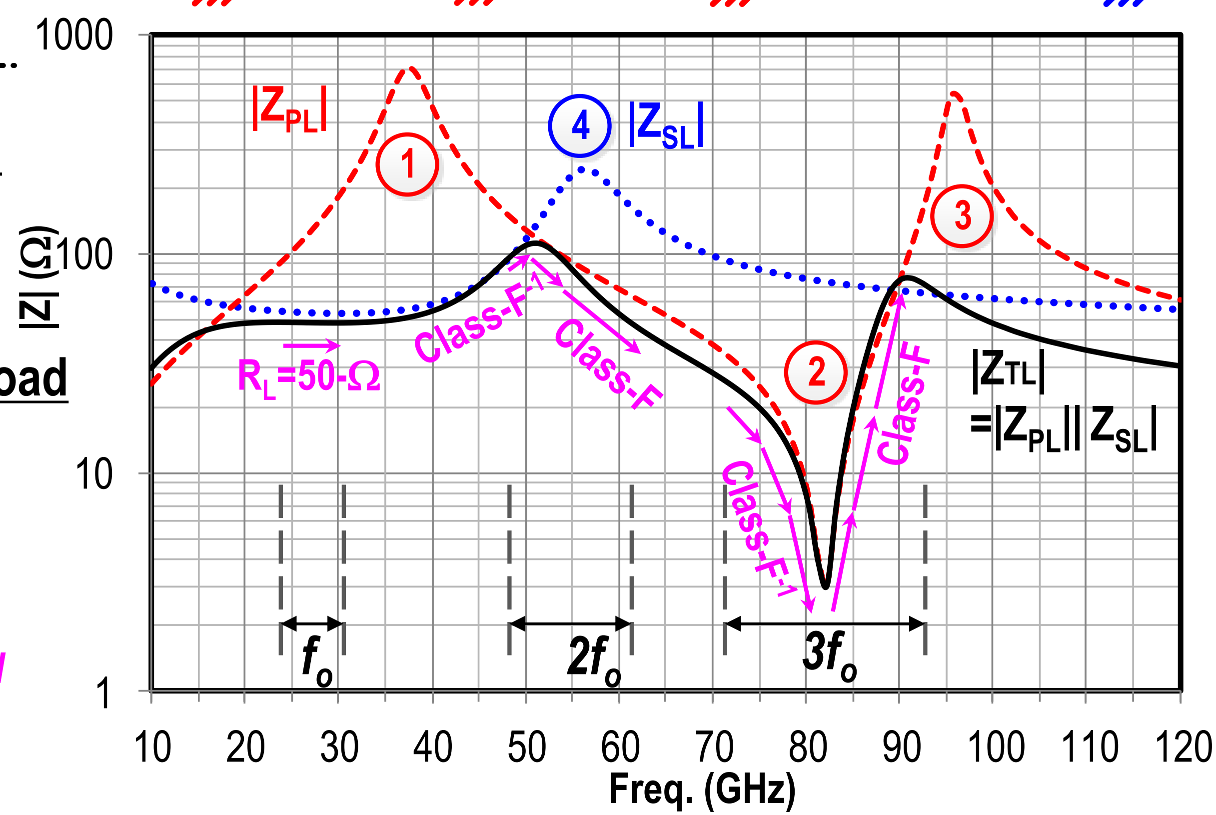
|ZTL| Modulation by composite load

- f_o-band: 50 Ω → 50 Ω
- $2f_o$-band: High-Z → Low-Z
- $3f_o$-band: Low-Z → High-Z

Load Network with F^{-1}/F Mode Transition (6)





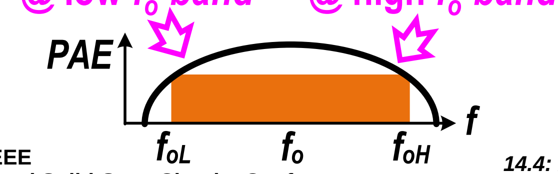


$|Z_{TL}|$ Modulation by composite load

- f_o-band: 50 Ω → 50 Ω
- $2f_o$-band: High-Z → Low-Z
- $3f_o$-band: Low-Z → High-Z

Class-F^{-1} → Class-F

@ low f_o-band @ high f_o-band



Simulated Collector V-I Waveforms (1)

Class-F^{-1} @27-GHz, P_{in}=8-dBm

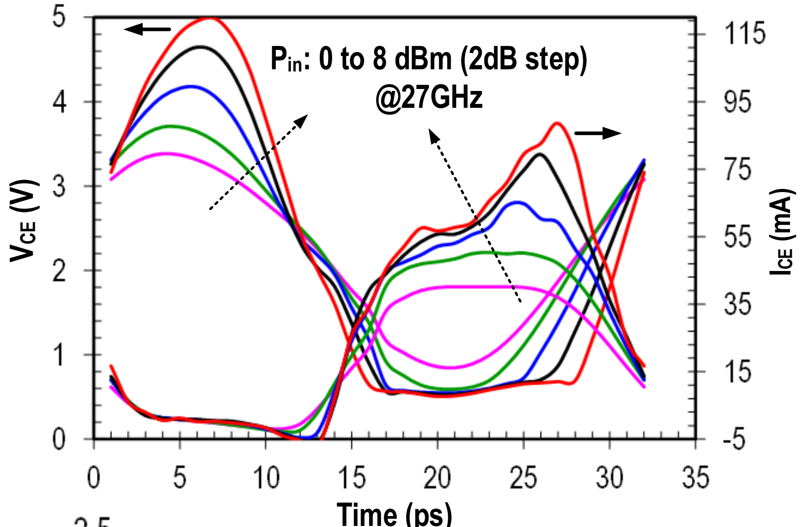
V: Half-sinusoidal peaking

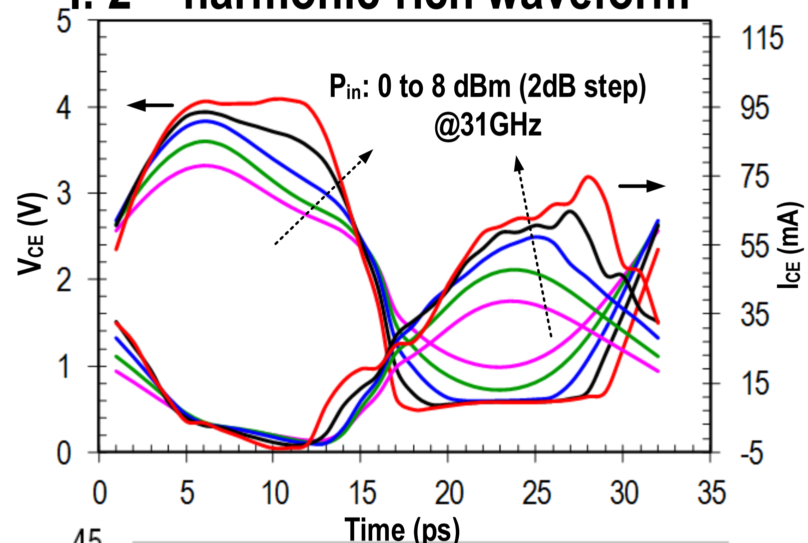
I: 3rd-harmonic-rich waveform

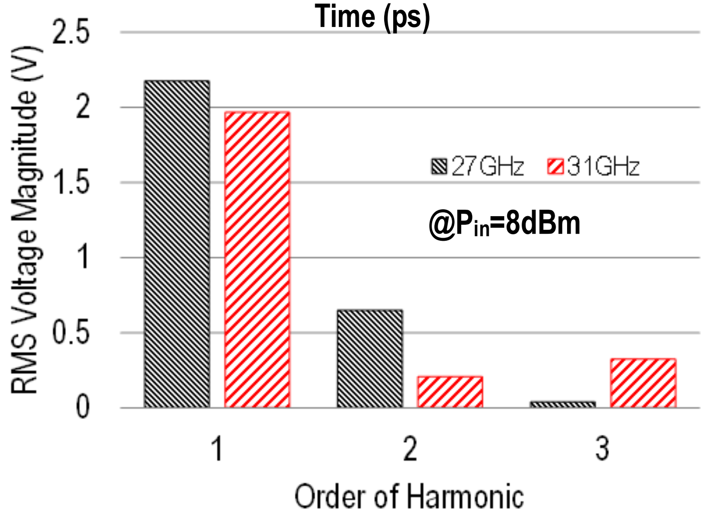
Class-F @31-GHz, P_{in}=8-dBm

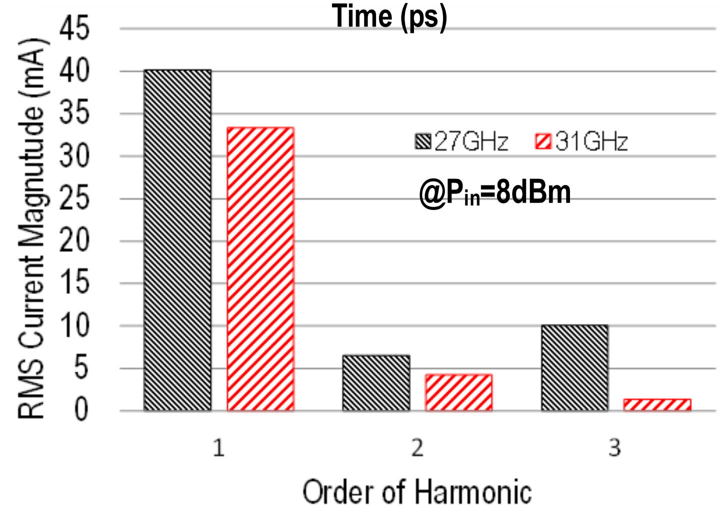
V: Square-wave-like (3rd-harmonic rich)

I: 2nd-harmonic-rich waveform







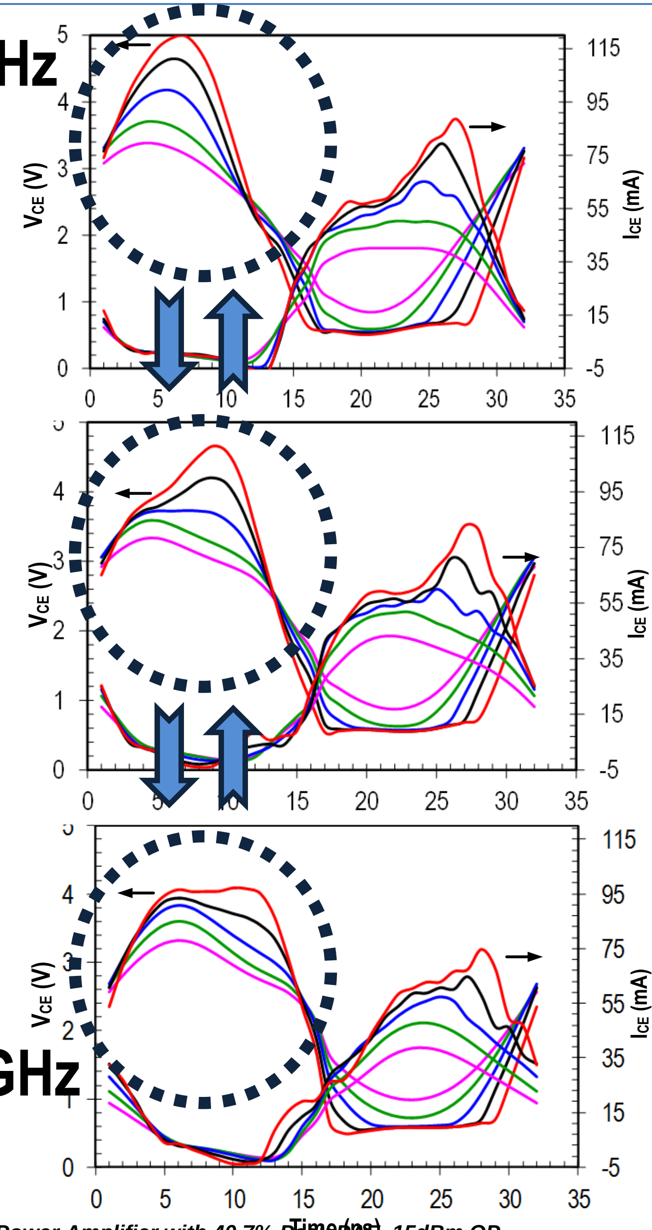


Simulated Collector V-I Waveforms (2)

Class-F^{-1} @27-GHz

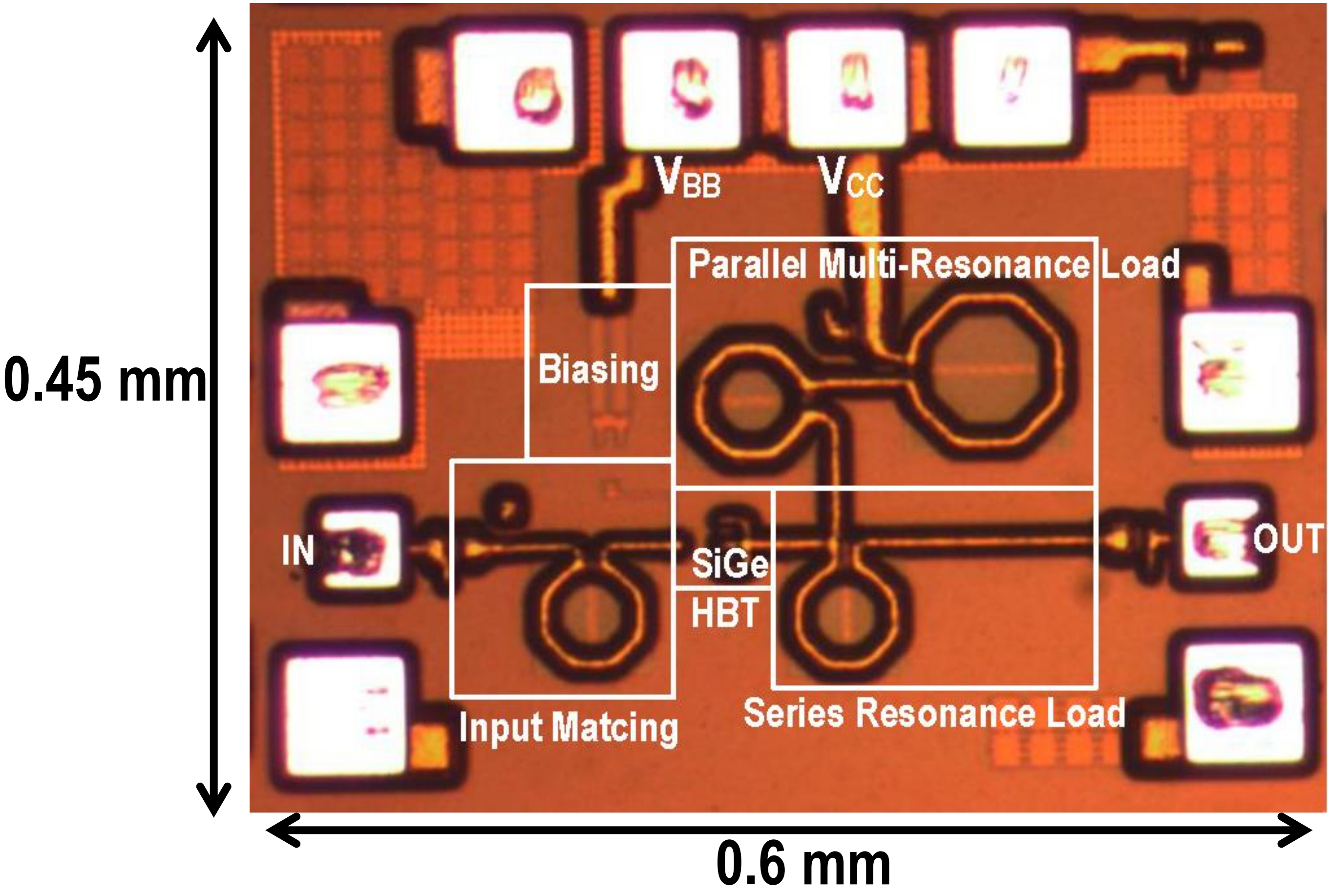
Transition mode @29-GHz

- Transitional ambivalent voltage waveforms between Class-F^{-1} & Class-F.
- Still can maintain a high-efficiency (similar to "*continuous Class-F*").



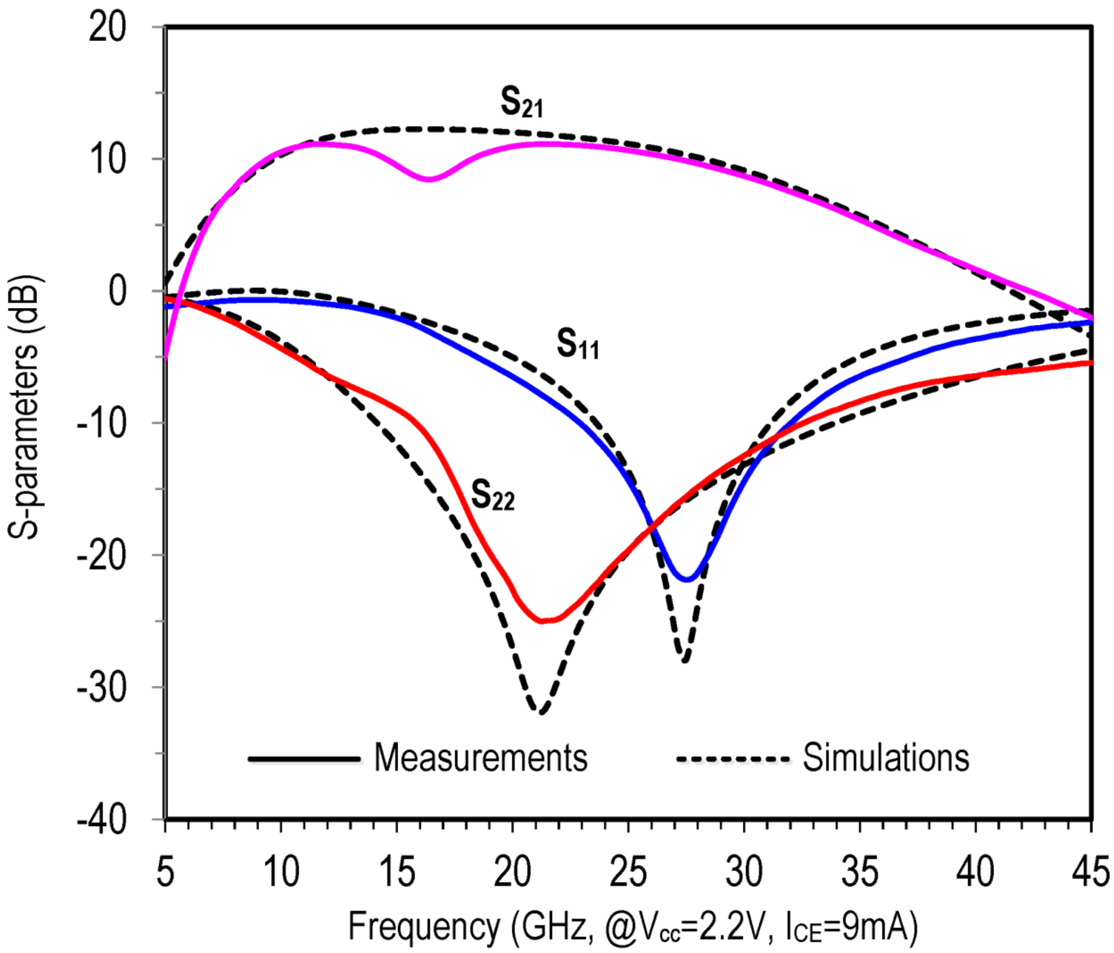
Class-F @31-GHz

Chip Photograph

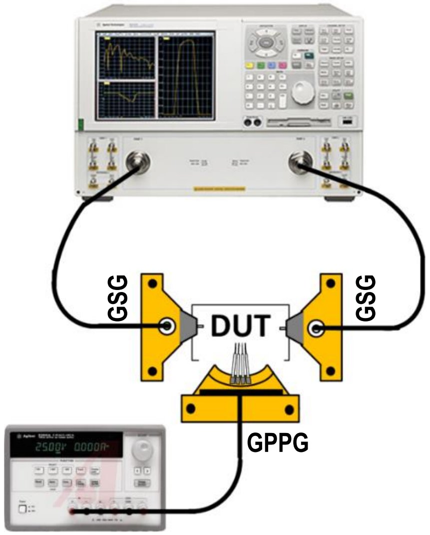


- IBM 8HP SiGe BiCMOS (f_T=180 GHz, f_{max}=200 GHz)
- Chip area: 0.6x0.45 mm^2 (w/i pads), 0.48x0.3 mm^2 (w/o pads)

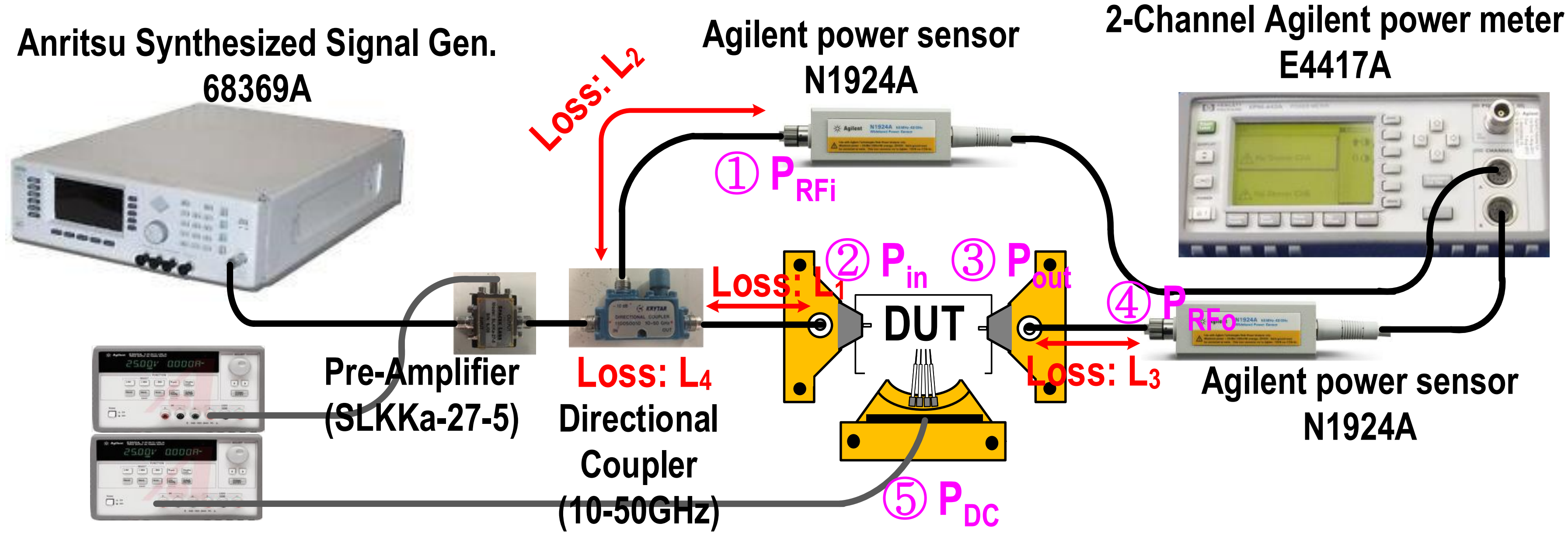
Small-Signal S-Parameters



- SOLT calibration
- Class-AB biasing (V_{CC}=2.2, I_{CE}=9mA)
- S_{21} = 9-10.8 dB : 24~31 GHz
- S_{11} < -10 dB : 22.5~32 GHz
- S_{22} < -10 dB : 15~33 GHz
- K-factor > 1



Large-Signal Measurement Setup

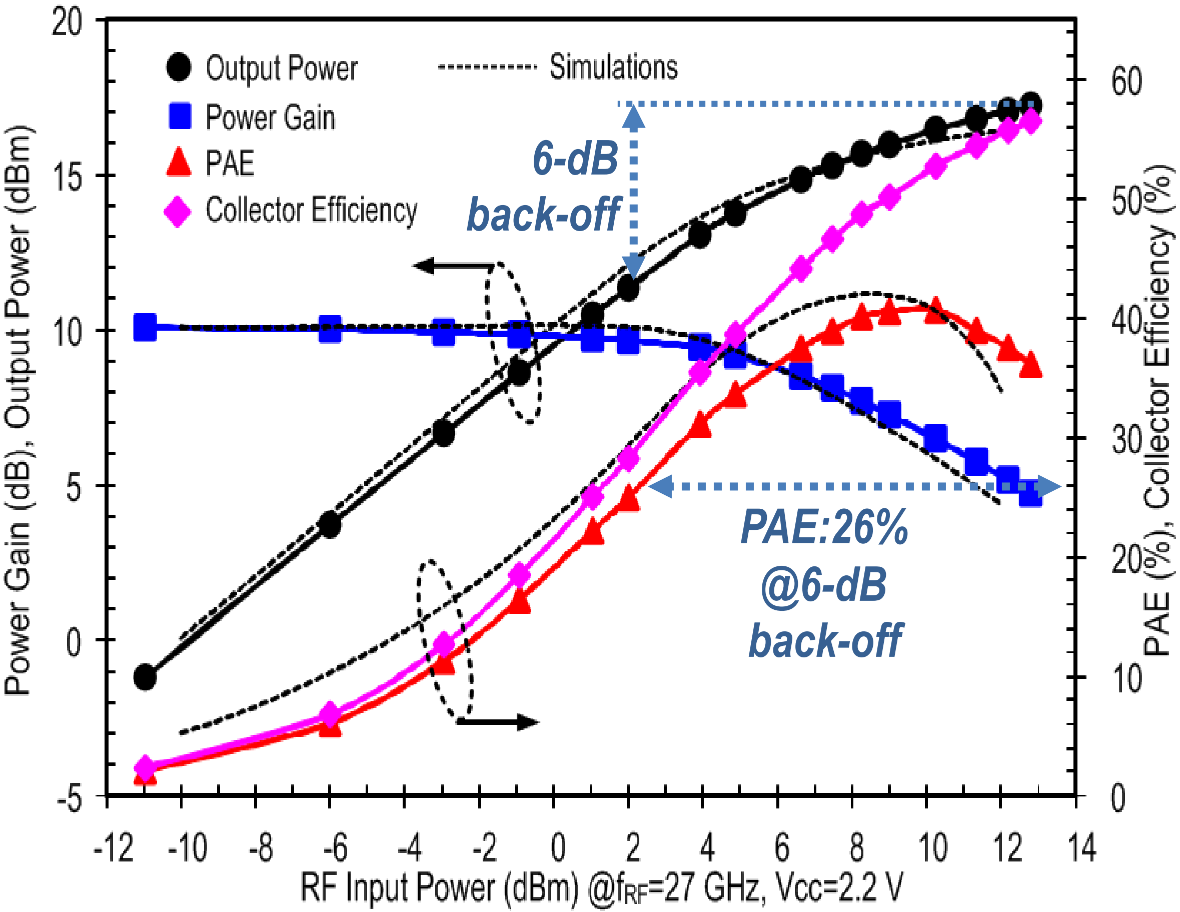


Power Calibration

- L_1, L_2 & L_3 : cable losses, L_4: coupler loss (typ. 10 dB @24-31 GHz)
- $P_{in} = P_{RFi} - L_1 + L_2 + L_4$ (dB)
- $P_{out} = P_{RFo} + L_3$ (dB)

$$PAE = (P_{out} - P_{in}) / P_{DC}$$

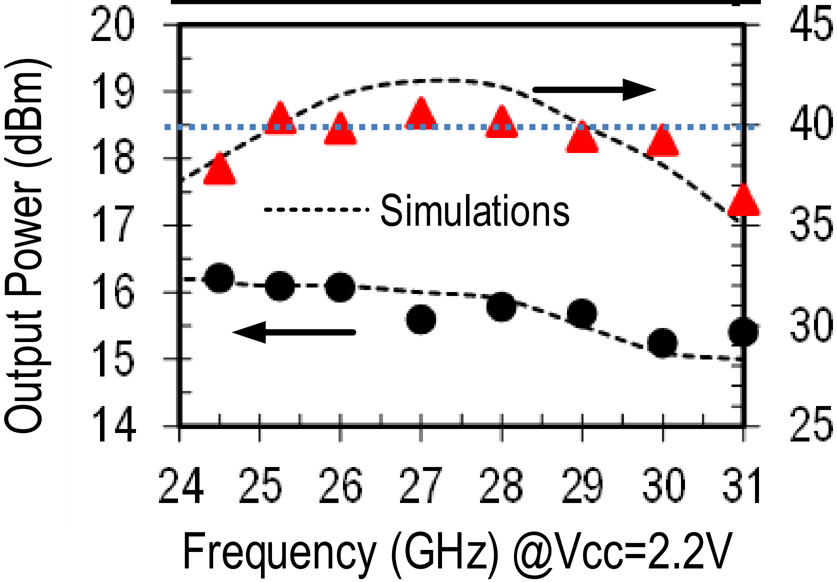
Large-Signal Performance (1)

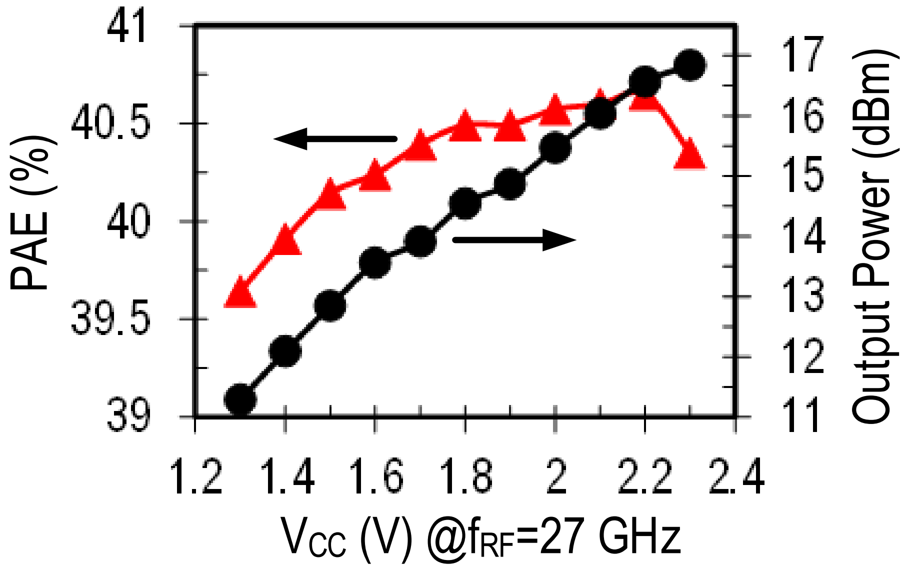


Measurement @27 GHz

- Class-AB biasing (V_{CC}=2.2, I_{CE}=9mA)
- Peak PAE: 40.7% (Drain η: 52.7%)
- P_{sat}: 17.1 dBm (50 mW)
- OP_{-1dB}: 15 dBm

Large-Signal Performance (2)





- **PAE: 39.3-40.7% @ 25-30 GHz**
- **PAE > 36% @24-31 GHz**

Note: due to mode-transition, the PA can maintain ~40% PAE over 25-30 GHz.

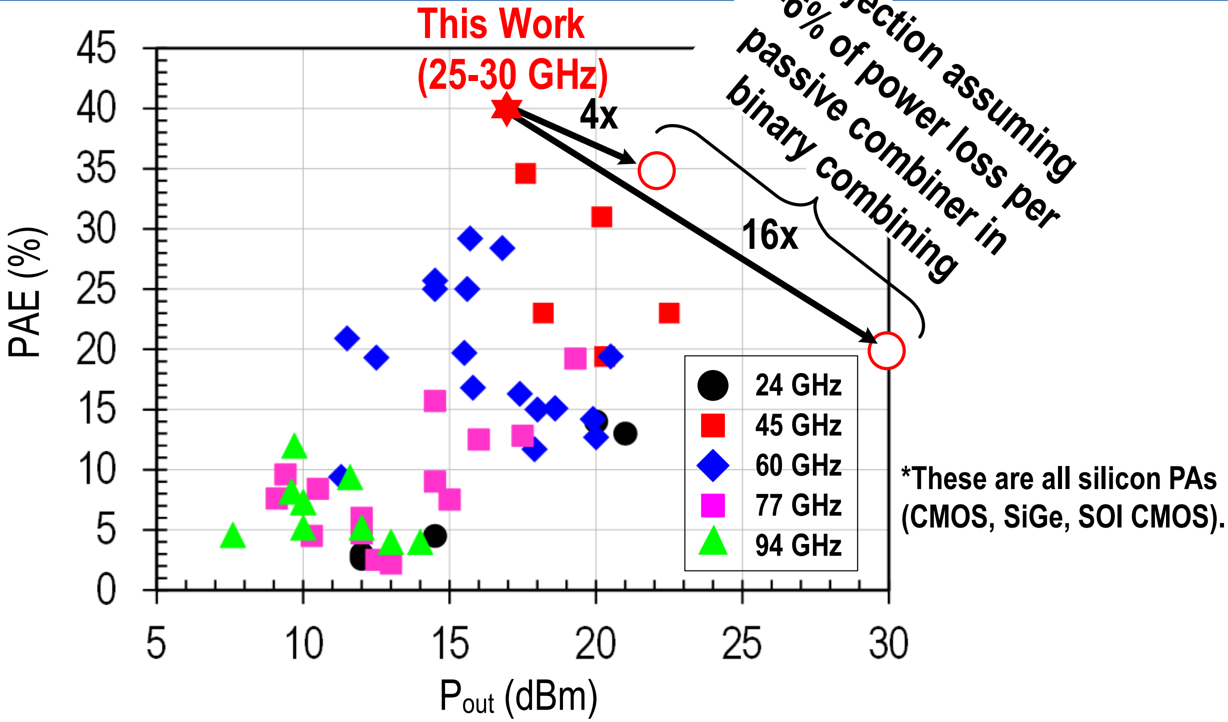
- **PAE: 39.6-40.7% @ V_{CC}=1.3-2.3 V**

Note: it can maintain ~40% PAE over 1-V V_{CC} variations with ~6-dB P_{out} variations.

Performance Summary & Comparison

Authors	Freq.(GHz)	PAE (%)	P_{sat} (dBm)	OP_{-1dB}(dBm)	Gain (dB)	Size (mm^2)	Supply(V)	Process
This Work	**25-30** **24-31**	**39.3-40.7** **36.3-40.7**	**17.1**	**15**	**10.3**	**0.27(0.14*)** *** w/o pad**	**2.2**	**0.13μm SiGe**
JSSC 2005 A. Komijani, *et al.*	24	6.5	14.5	11	7	1.26	2.8	0.18μm CMOS
RFIC 2007 M. Chang, *et al.*	33	11.2	17	15.5	13	1.83	1.4	0.13μm SiGe
JSSC 2005 T.S.D. Cheung, *et al.*	22 24	19.7 13	20-23	NA	15-19	6	1.8	0.2μm SiGe
RFIC 2005 N. Kinayman, *et al.*	24	2.9	12	11	18	1.1	5	0.5μm SiGe
T-MTT 2012 N. Kalantari, *et al.*	38	20	23	NA	18.7	1.04	3	0.12μm SiGe
CICC 2012 A. Chakrabarti, *et al.*	47	34.6	17.6	NA	13	0.12	2.5	45nm SOI CMOS
CICC 2012 K. Datta, *et al.*	45	31.5	20.2	NA	10.5	1.3	2.4	0.13μm SiGe
T-MTT 2012 P.-C. Huang, *et al.*	24-26	40	23.5	22	9	1.5	4	GaAs HEMT
RFIC 2013 N. Kinayman, *et al.*	26.4	38	25.3	NA	10.3	25	5	GaAs HEMT
MTTs 2012 C.F. Campbell, *et al.*	29	30	37	NA	25	4.8	20	GaN HEMT

Conclusion



- First successful silicon PA in Class-F^{-1} and Class-F at mm-wave with a record ~40% peak PAE at 25-30 GHz.
- First successful realization of a mode-transition mm-wave PA to achieve a high PAE over a wideband: 24-31 GHz (25.5% fractional BW) with PAE > 36%.
- A linear mode (Class-AB) PAE with 6-dB back-off is ~26%, still comparable to peak PAE of state-of-the-art silicon PAs.
- With 16x power combining, potentially it can achieve > 20% PAE with Watt-level P_{out}.

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