Intermodulation Distortion Mitigation in Microwave Amplifiers and Frequency Converters

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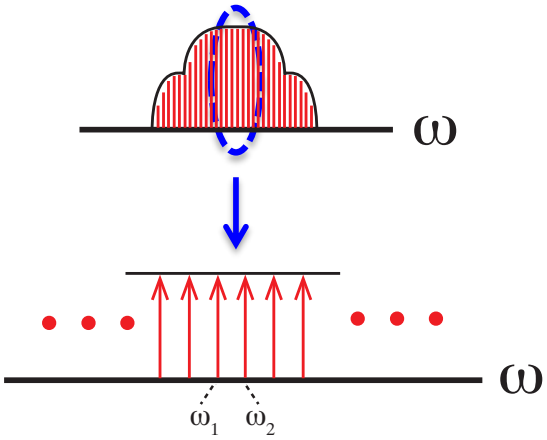
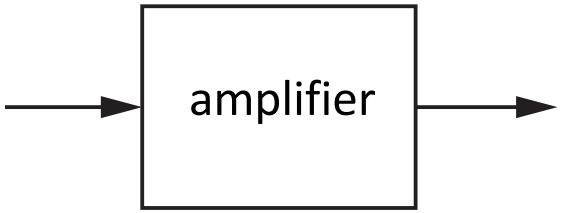
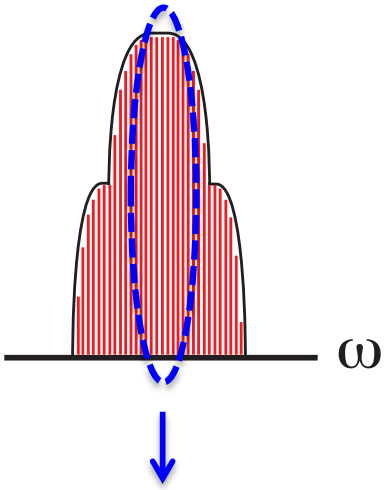
Outline

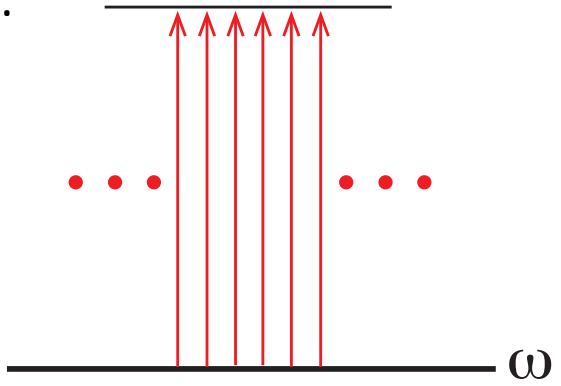
- Concepts/Review
- Broadband GaN power amplifier with distortion cancellation
- Stand-alone distortion cancelling cell
- Distortion cancellation techniques for mixers





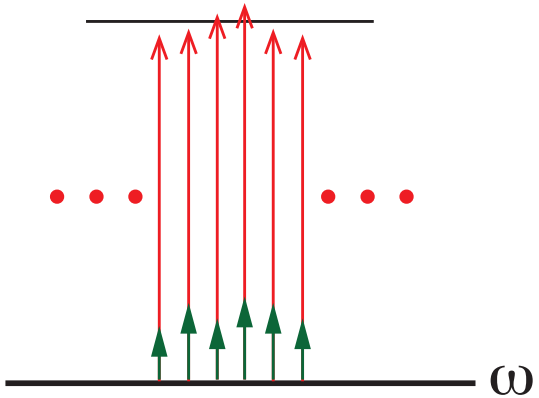


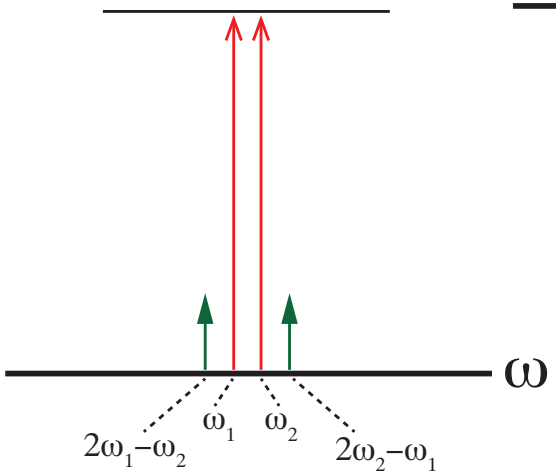
Ideally:

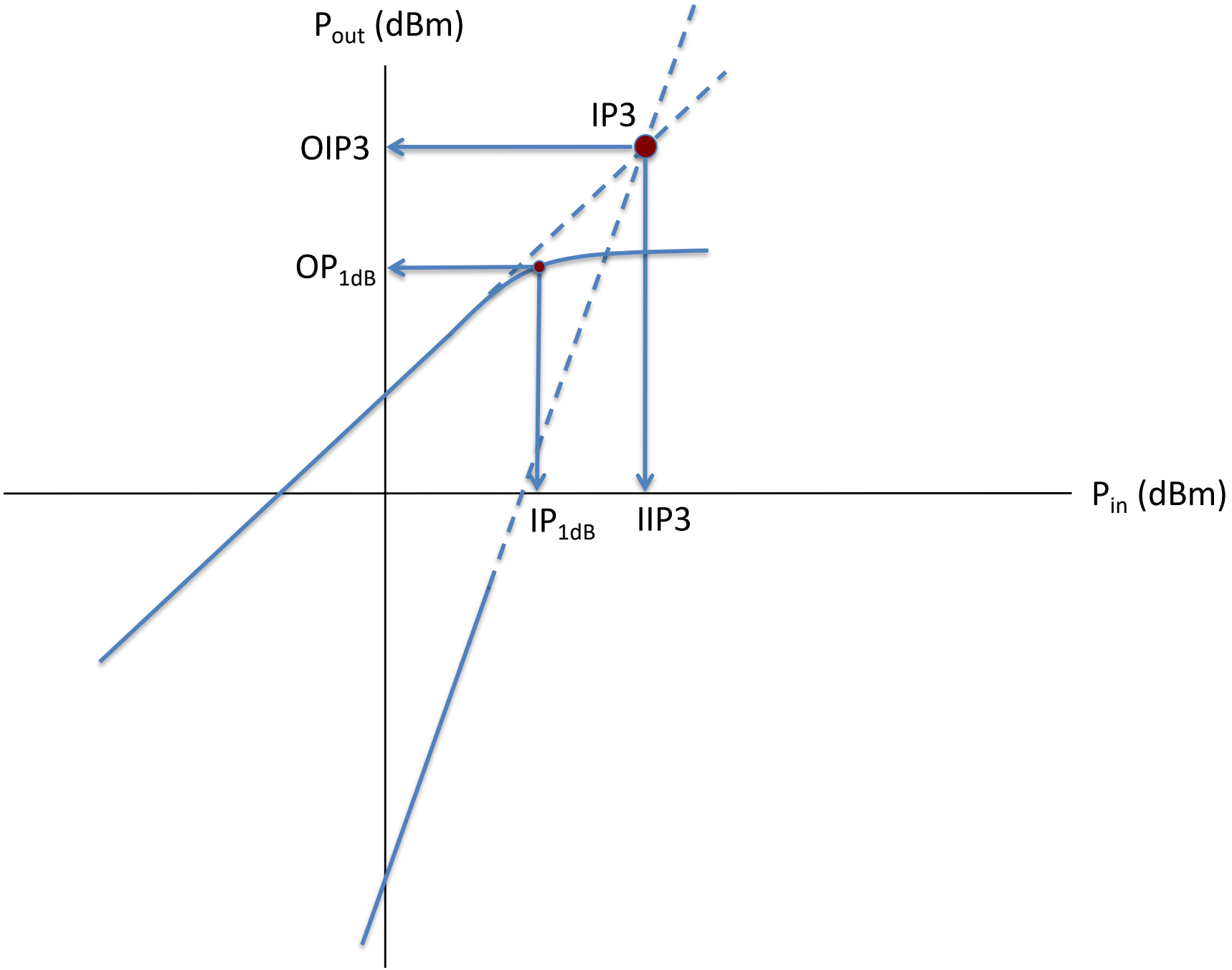


$$[A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t)]^3 = \cdots + 3A_1^2 A_2\cos^2(\omega_1 t)\cos(\omega_2 t) + 3A_1 A_2^2\cos(\omega_1 t)\cos^2(\omega_2 t) + \cdots$$

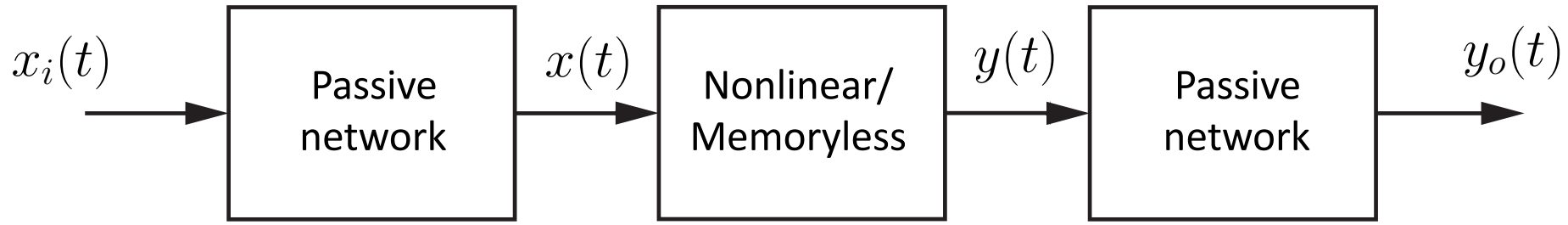
3rd order IMD

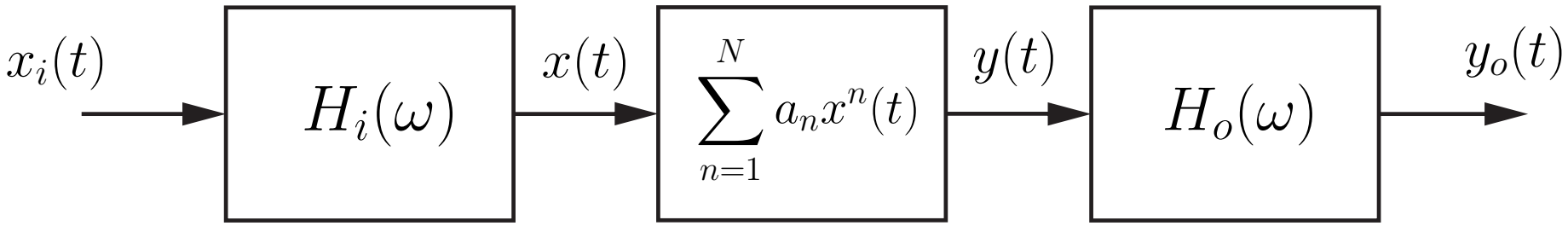


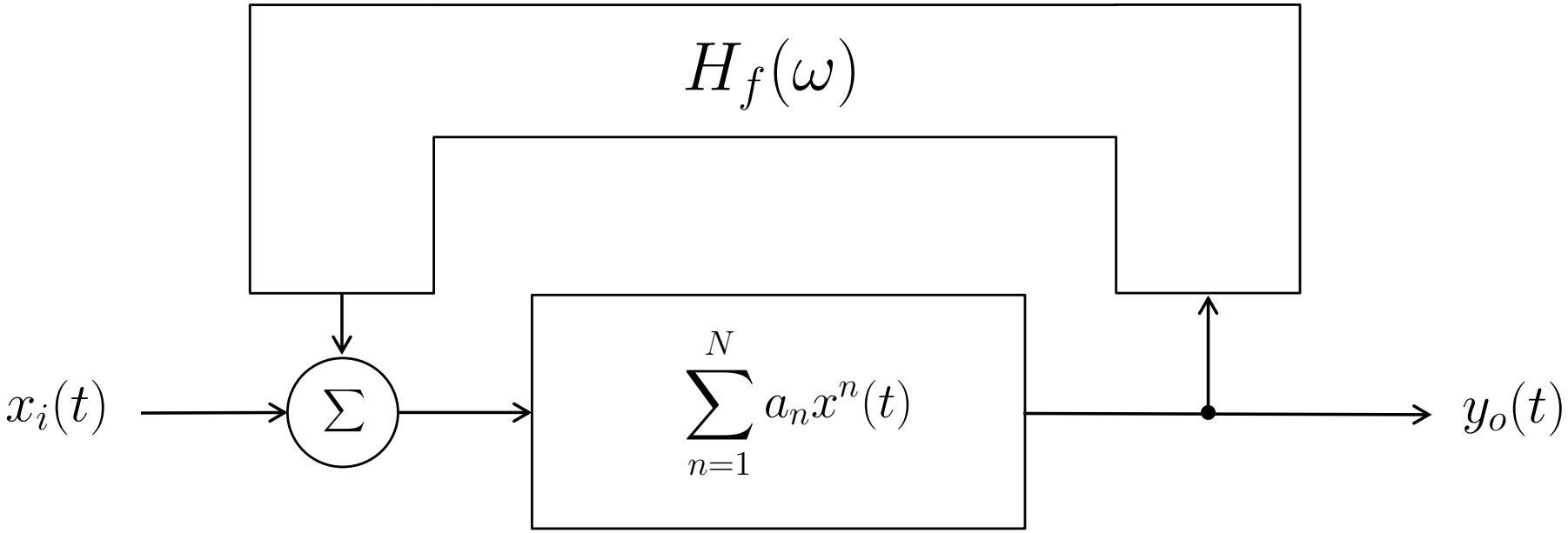



P_{out} (dBm)
IP3
OIP3
OP_{1dB}
IP_{1dB}
IIP3
P_{in} (dBm)

Power series model



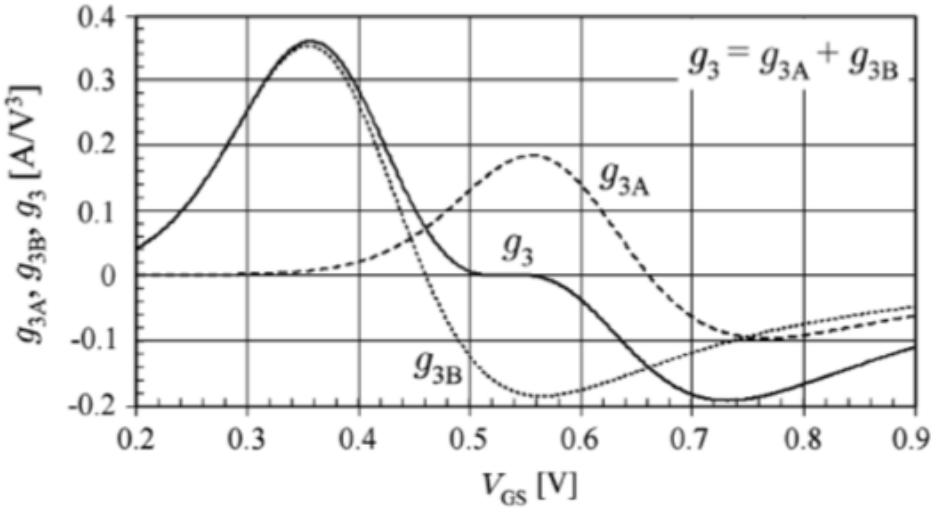


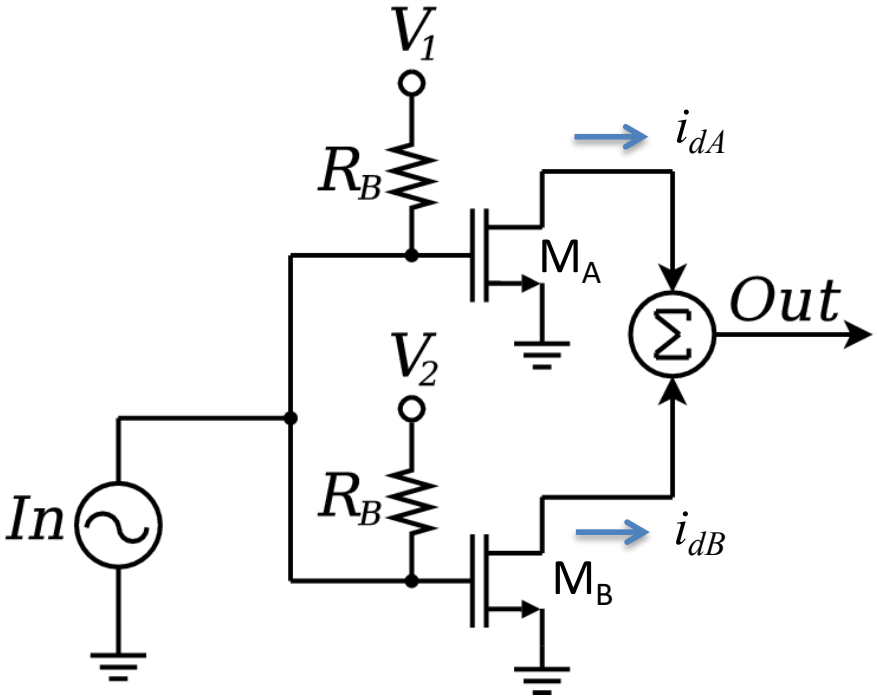

$H_f(\omega)$
$x_i(t)$
Σ
$\sum_{n=1}^{N} a_n x^n(t)$
$y_o(t)$

Derivative superposition [1,2]

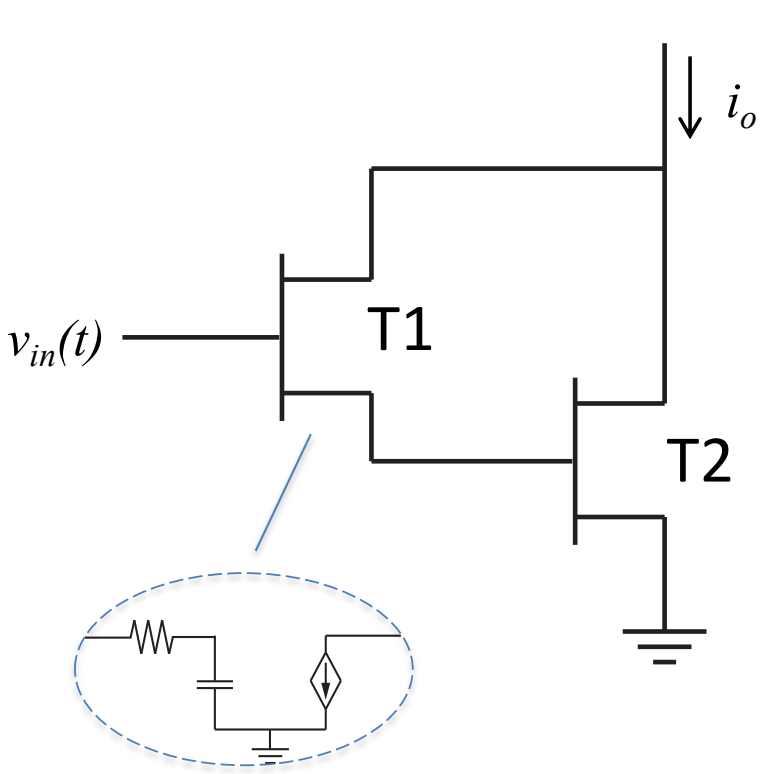
This method to mitigate IMD relies on modeling the FET drain current as a power series:

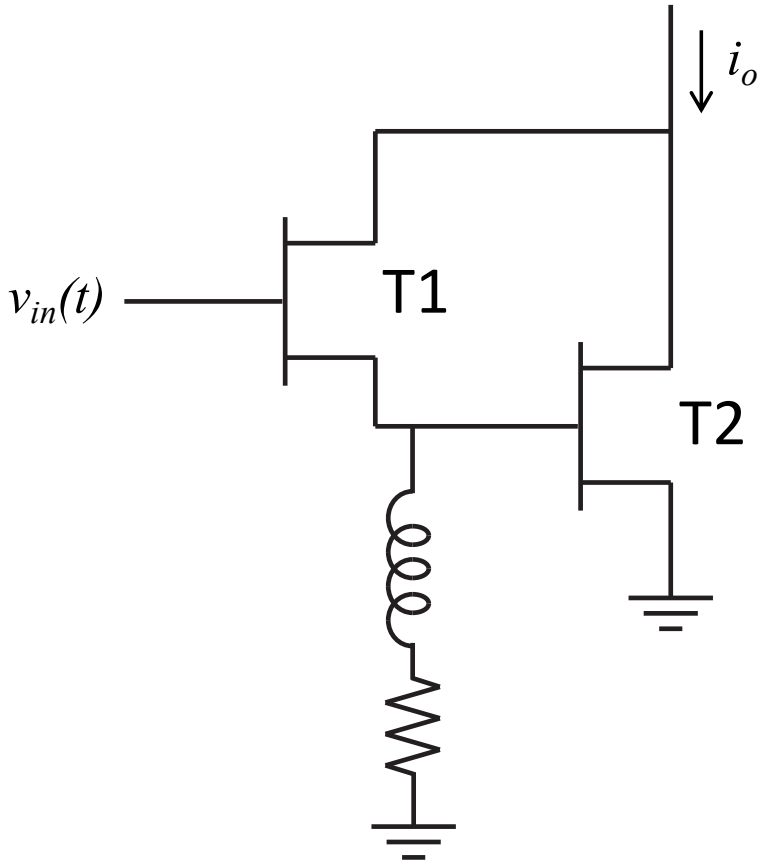
$$i_{ds} = \sum_{n=1}^{N} g_{mn} v_{gs}^{n} \qquad g_{mn} = \frac{\partial^n I_{DS}}{n! \partial V_{GS}^n}$$





HFET f_T doublers [3]





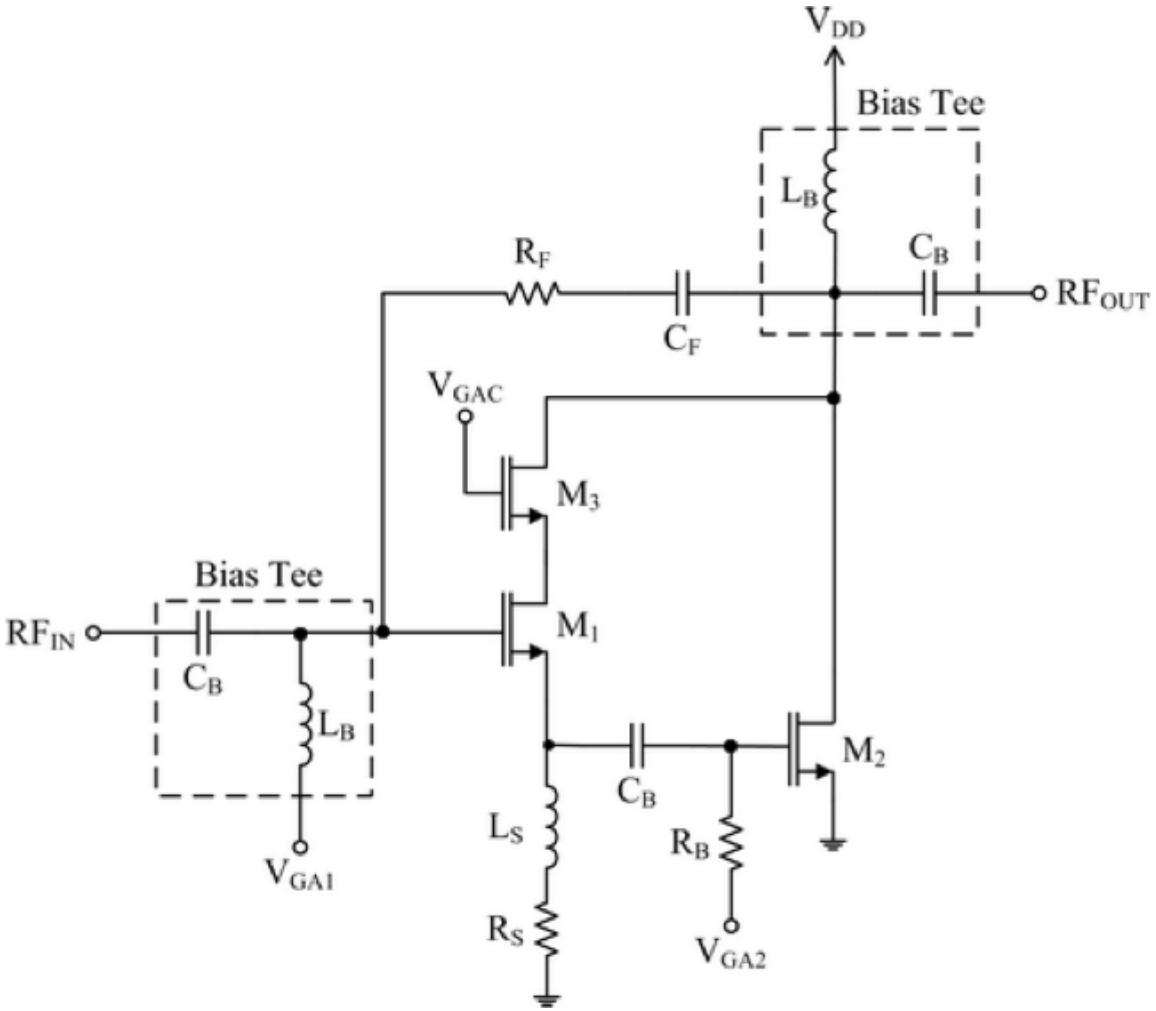
$$Z_{in} = R_{i1}+R_{i2}-\frac{g_{m1}}{\omega^2 C_{gs1}C_{gs2}}+\frac{1}{j\omega}\left(\frac{1+g_{m1}R_{i2}}{C_{gs1}}+\frac{1}{C_{gs2}}\right)$$

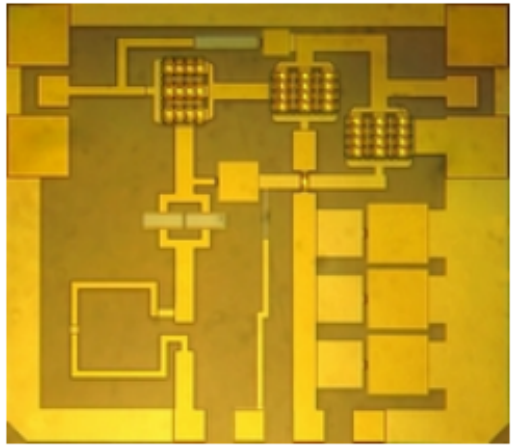
$$h_{21} = \frac{1+j2f/f_T}{(jf/f_T)^2}$$

$$Z_{in} = R_{i1}+R_{i2}+\frac{1}{j\omega}\left(\frac{1}{C_{gs1}}+\frac{1}{C_{gs2}}\right)$$

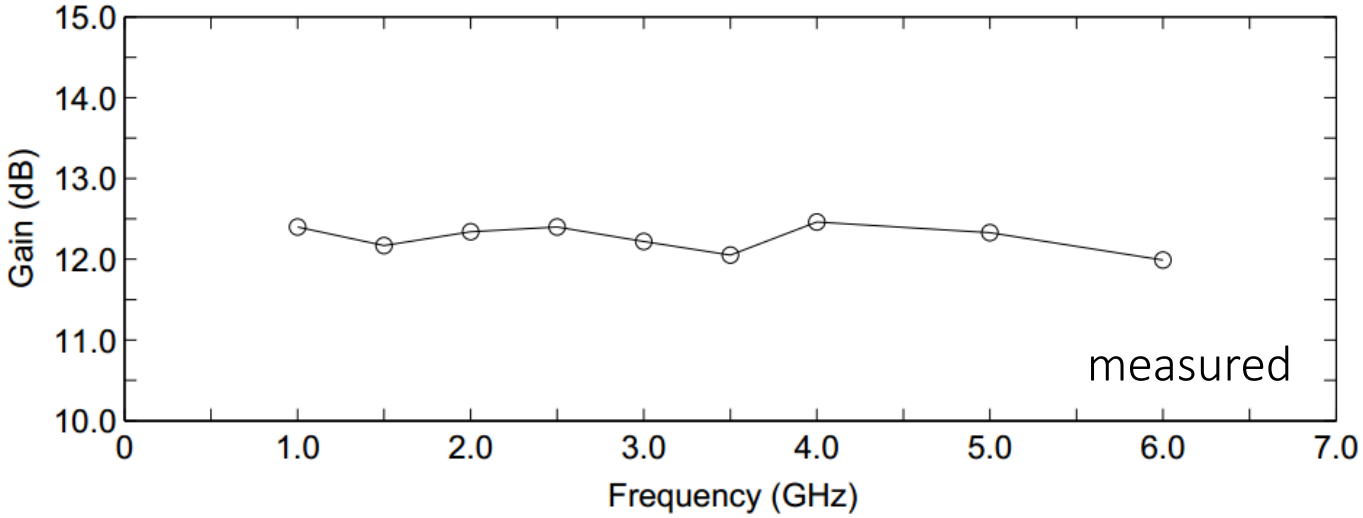
$$h_{21} = \frac{2f_T}{jf}$$

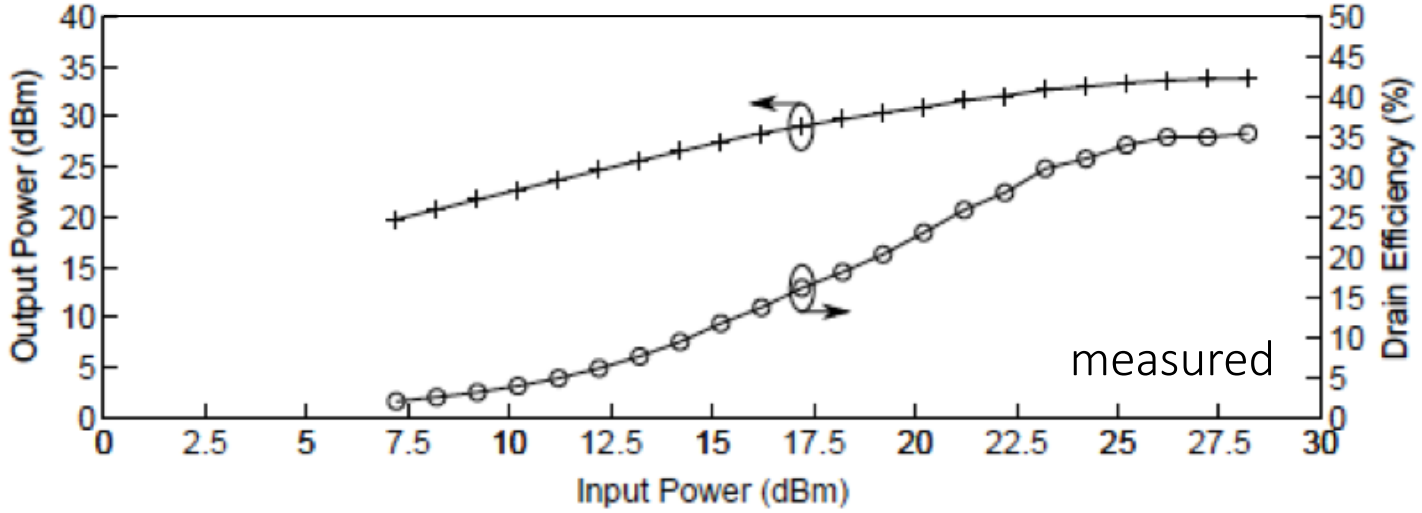
1-6 GHz, 2-Watt GaN baseline amplifier

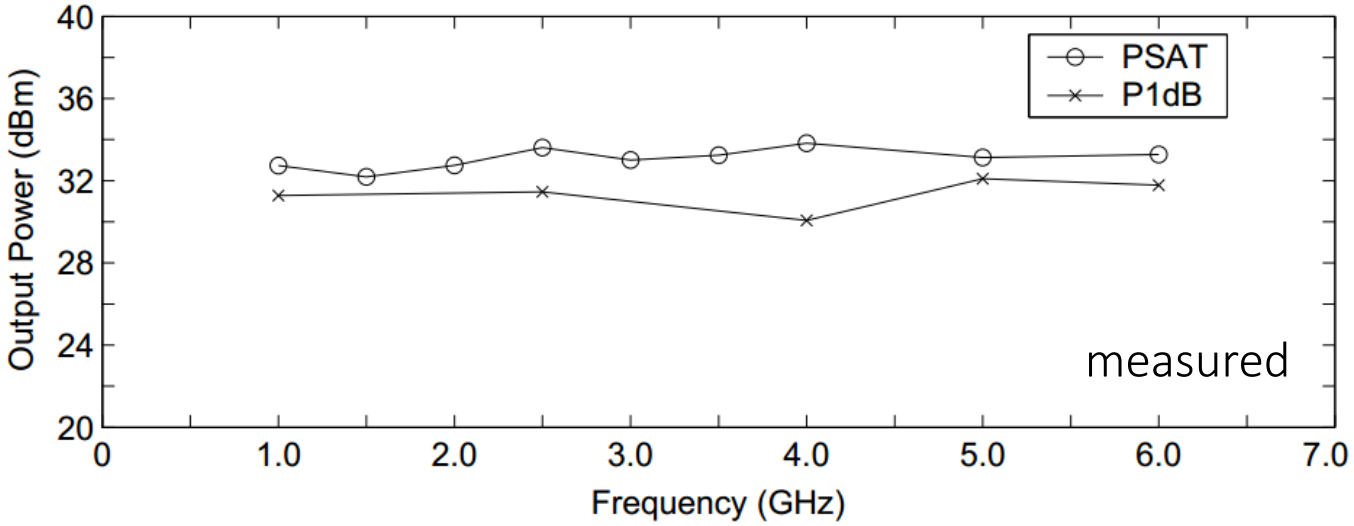


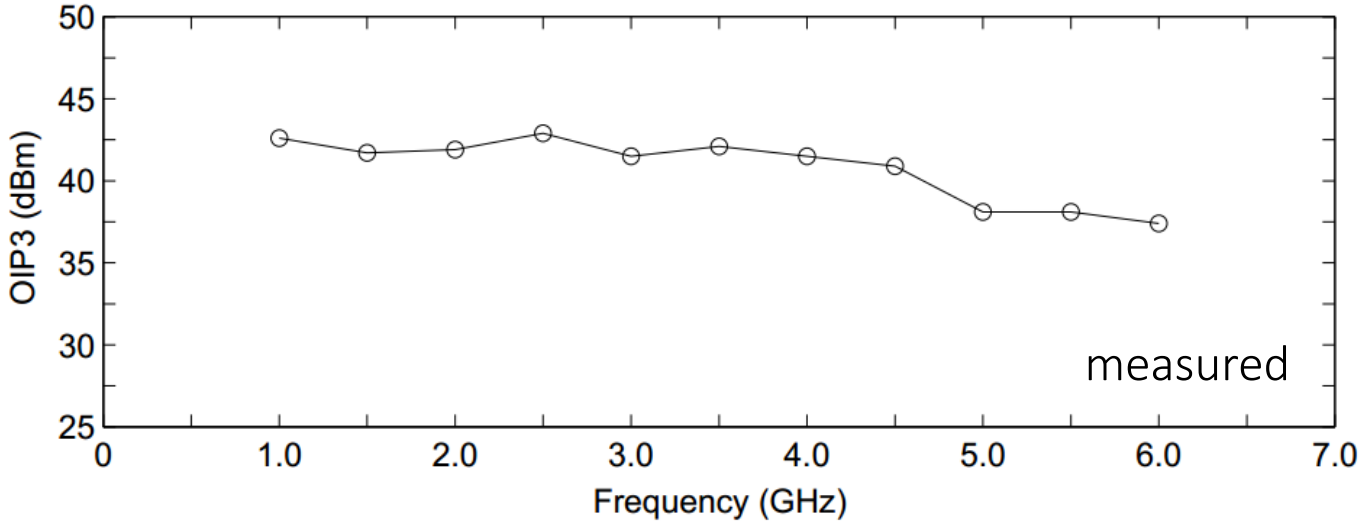


$(W/L)_{1,2,3}$	L_S	R_S	R_F	R_B	C_F	C_B
600/0.8	0.3 nH	8 Ω	255 Ω	1.2 kΩ	2.5 pF	6 pF

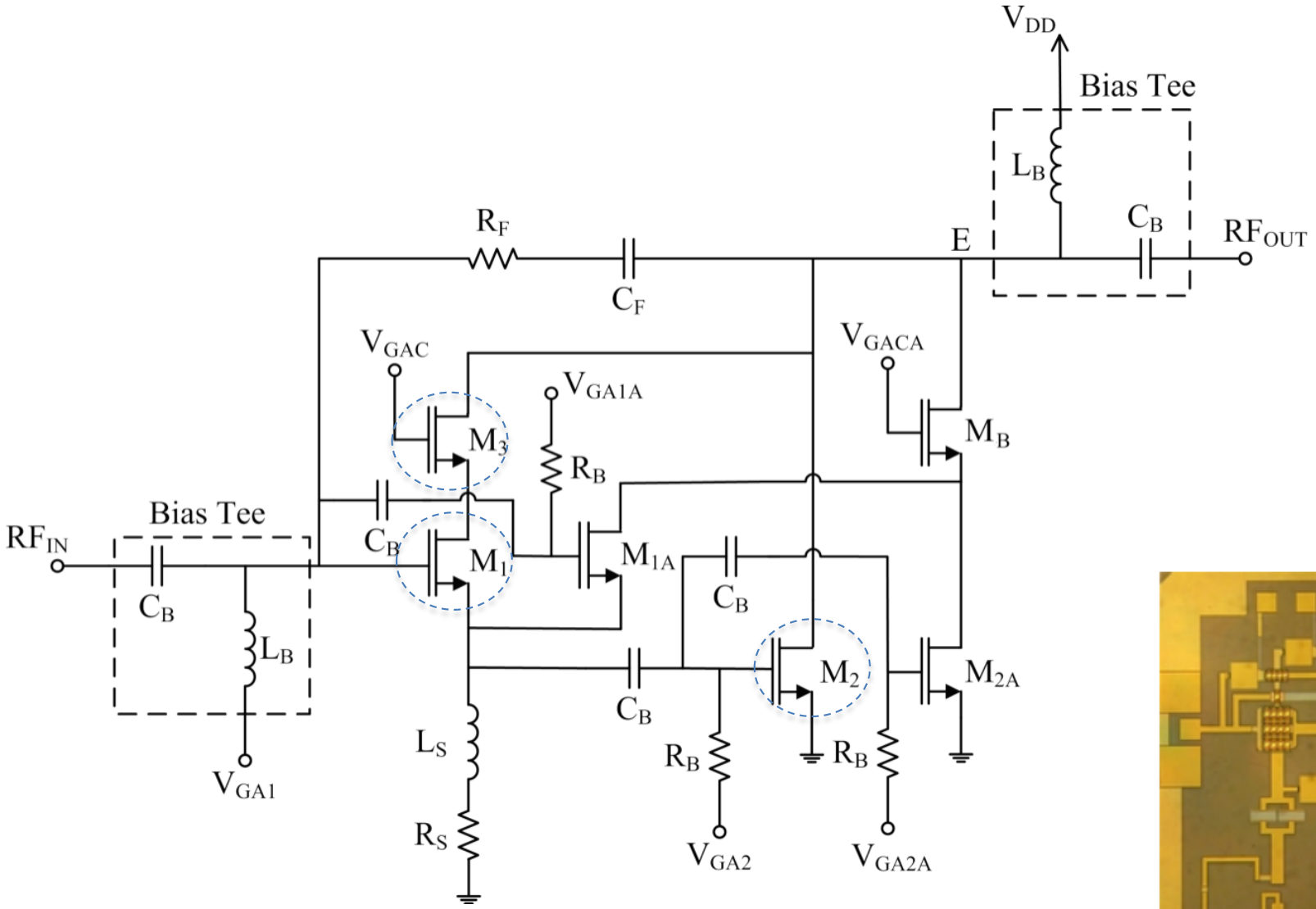

15.0
14.0
13.0
12.0
11.0
10.0
Gain (dB)
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Frequency (GHz)
measured

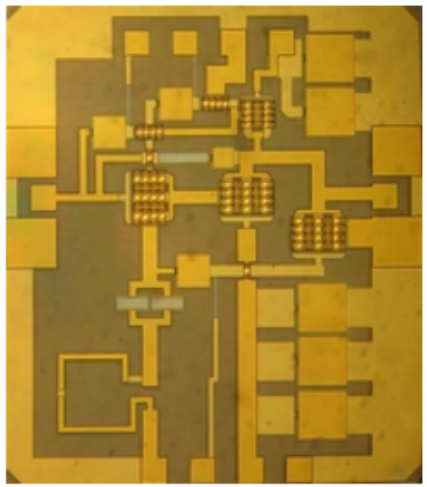

40
35
30
25
20
15
10
5
0
Output Power (dBm)
50
45
40
35
30
25
20
15
10
5
0
Drain Efficiency (%)
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
Input Power (dBm)
measured


PSAT
P1dB
measured
Output Power (dBm)
Frequency (GHz)
40
36
32
28
24
20
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0


measured
OIP3 (dBm)
Frequency (GHz)
50
45
40
35
30
25
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0

Distortion-cancelling GaN amplifier

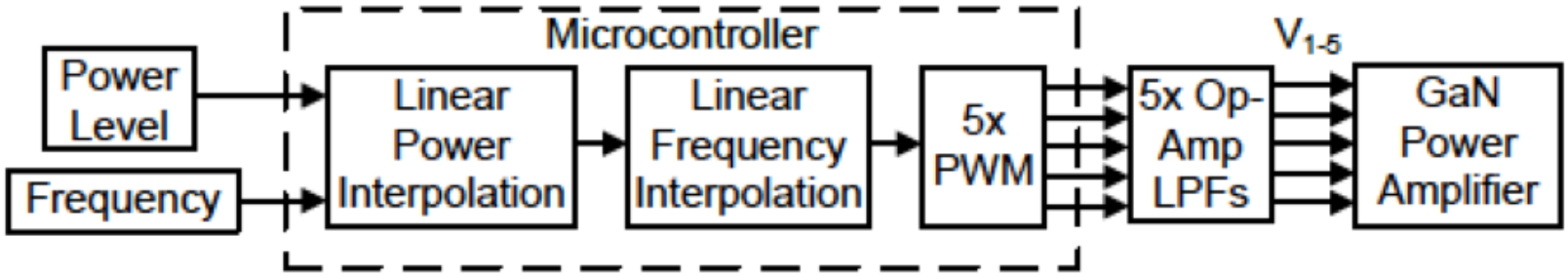


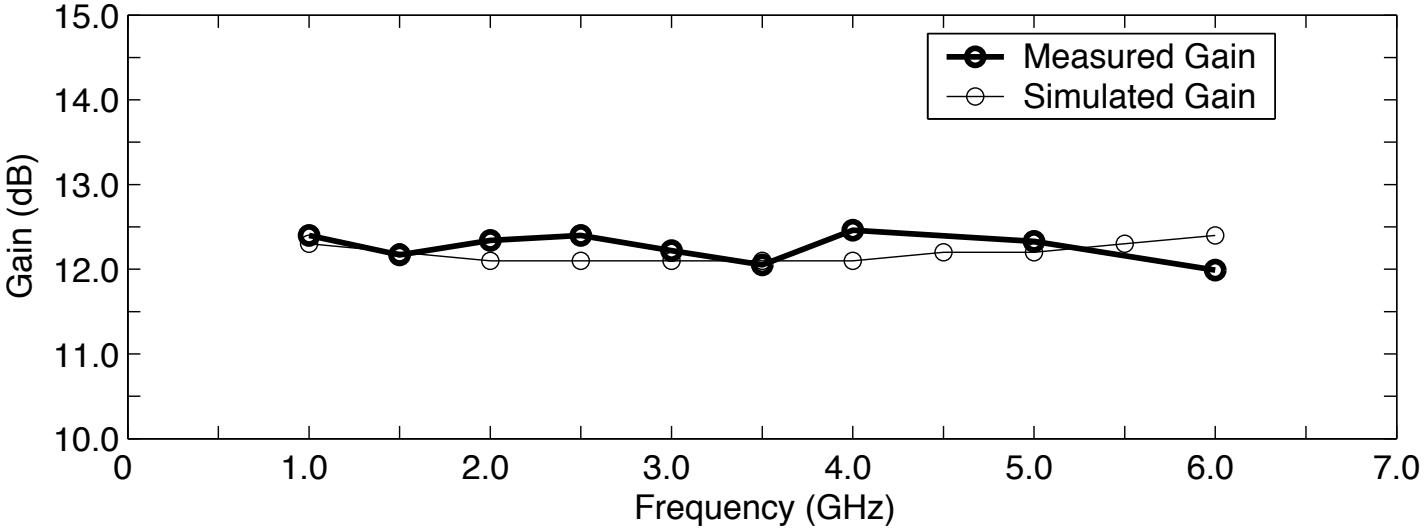


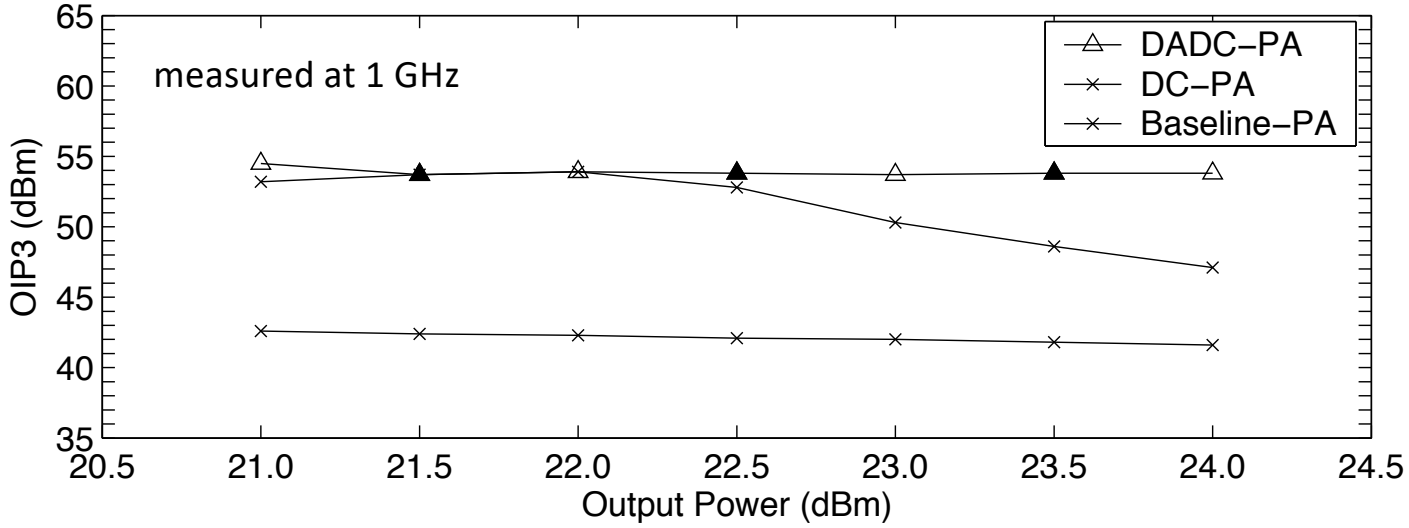
Transistor	$(W/L)_{1,2}$	$(W/L)_3$	$(W/L)_{1A,2A}$	$(W/L)_{3A}$
Size (μm)	600/0.8	600/0.8	160/0.8	320/0.8

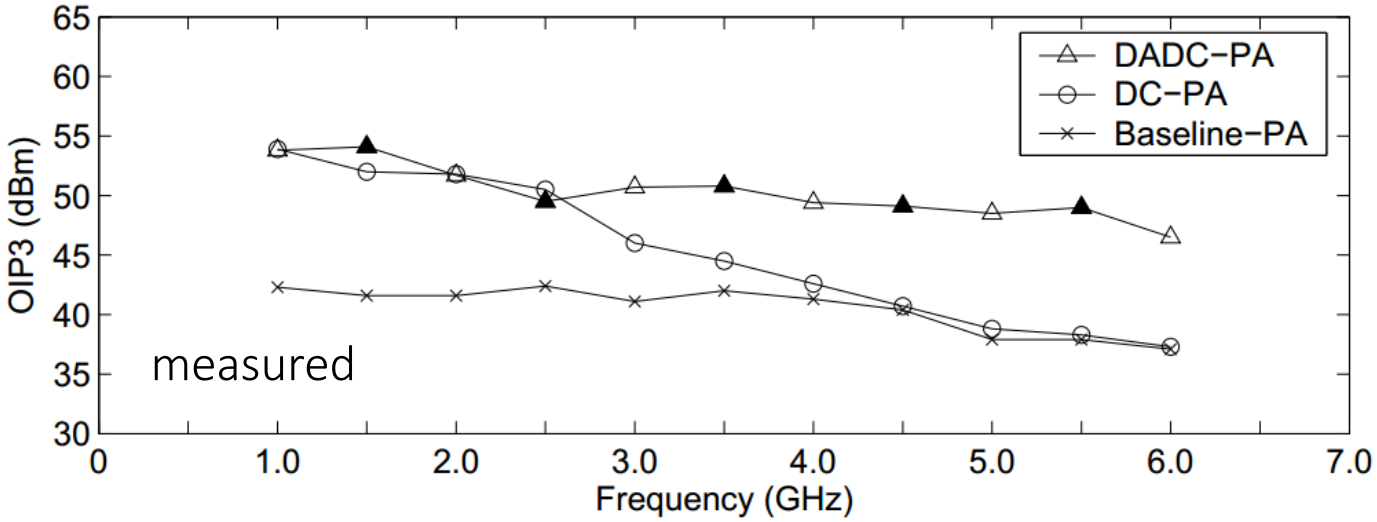
recall the approximation,

$$i_{ds} = \sum_{n=1}^{N} g_{mn} v_{gs}^{n} \qquad g_{mn} = \frac{\partial^n I_{DS}}{n! \partial V_{GS}^{n}}$$




Measured Gain
Simulated Gain
Gain (dB)
Frequency (GHz)
15.0
14.0
13.0
12.0
11.0
10.0
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0

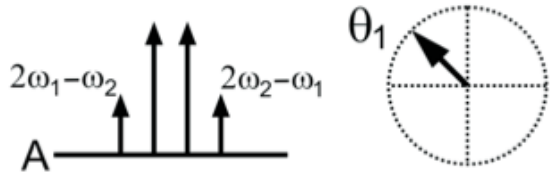

measured at 1 GHz
DADC–PA
DC–PA
Baseline–PA
OIP3 (dBm)
Output Power (dBm)
65
60
55
50
45
40
35
20.5
21.0
21.5
22.0
22.5
23.0
23.5
24.0
24.5

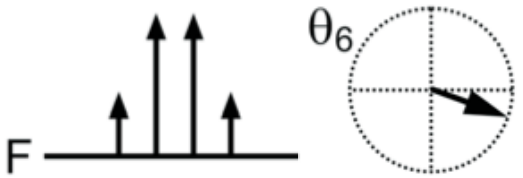


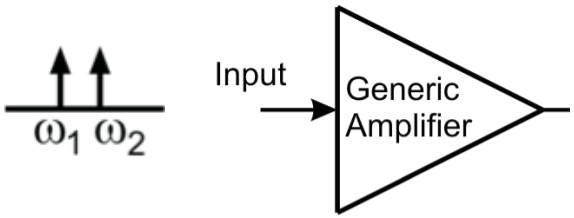
Characteristic	**This work**	[28]	[29]	[30]	[31]	[32]
GaN Technology	**0.8 μm**	0.2 μm	N/A	0.25 μm	0.15 μm	0.2 μm
Circuit Area (mm^2)	**1.03**	4.8	N/A	2.08	6	2.89
Supply Voltage (V)	**20**	30	28	40	20	15
Bandwidth (GHz)	**1−6**	DC−20	0.35−8	0.25−3	9−19	1−4
P_{SAT} (dBm)	**33 $\pm$ 0.8**	30 to 36	38.2	39.2	–	32
Gain (dB)	**12.2 $\pm$ 0.2**	12	9 $\pm$ 1	20	13	14.5
OP_{1dB} (dBm)	**31.3**	32.5	37.1	38.5	27	31
OIP3 (dBm)	**50.25**	42.6	49	51	see note[1]	44.3
Efficiency	**Max: 37% (η)**	10–15% (PAE)	20% (PAE)	see note[2]	–	see note[3]

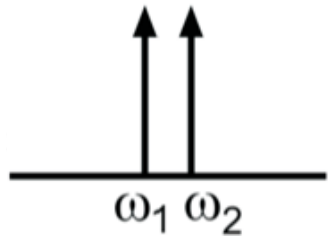
A. M. El-Gabaly, D. Stewart and C. E. Saavedra, "2-Watt Broadband GaN Power Amplifier RFIC using the fT Doubling Technique and Digitally-Assisted Distortion Cancellation", *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 1, pp. 525-532, 2013.

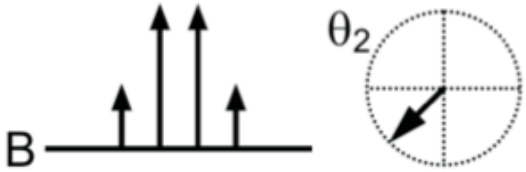
Stand-alone Distortion Cancelling Cell

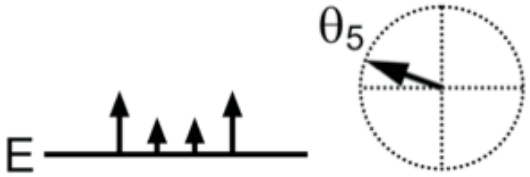

$2\omega_1-\omega_2$
$2\omega_2-\omega_1$
A
θ_1

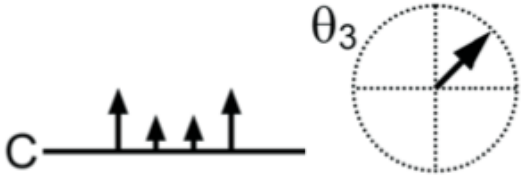

F
θ_6

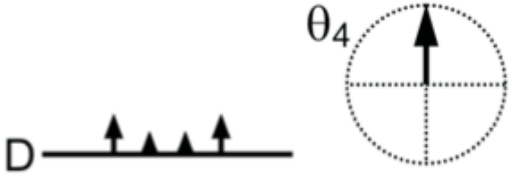

ω_1 ω_2
Input
Generic
Amplifier

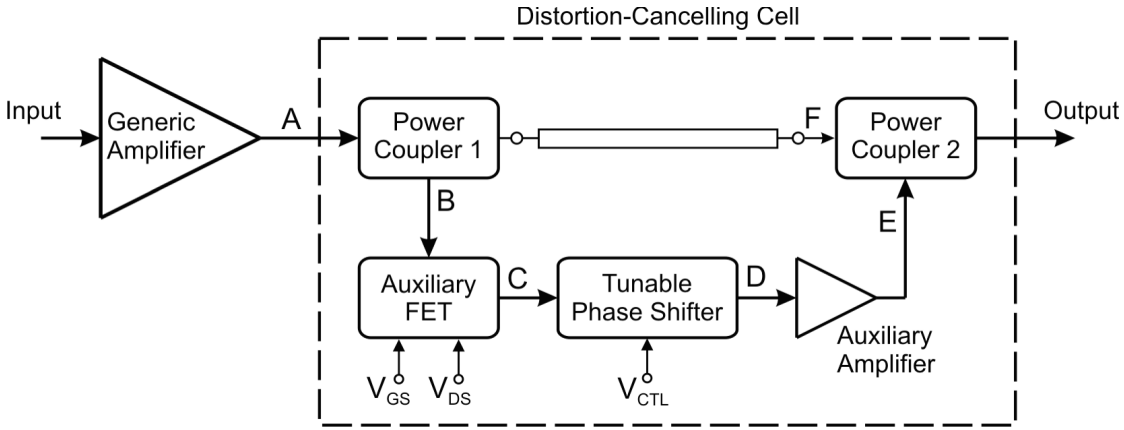

ω_1 ω_2

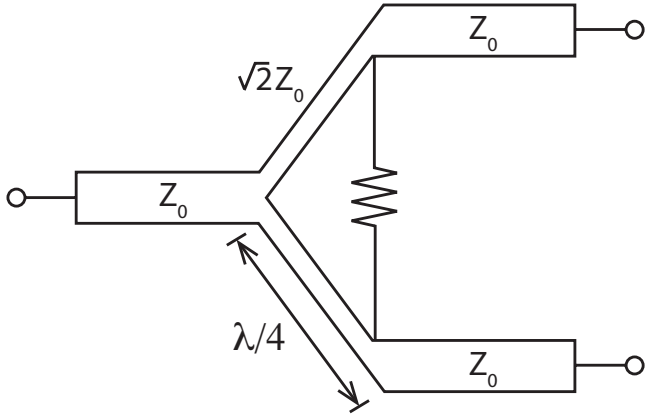

B
θ_2


E
θ_5

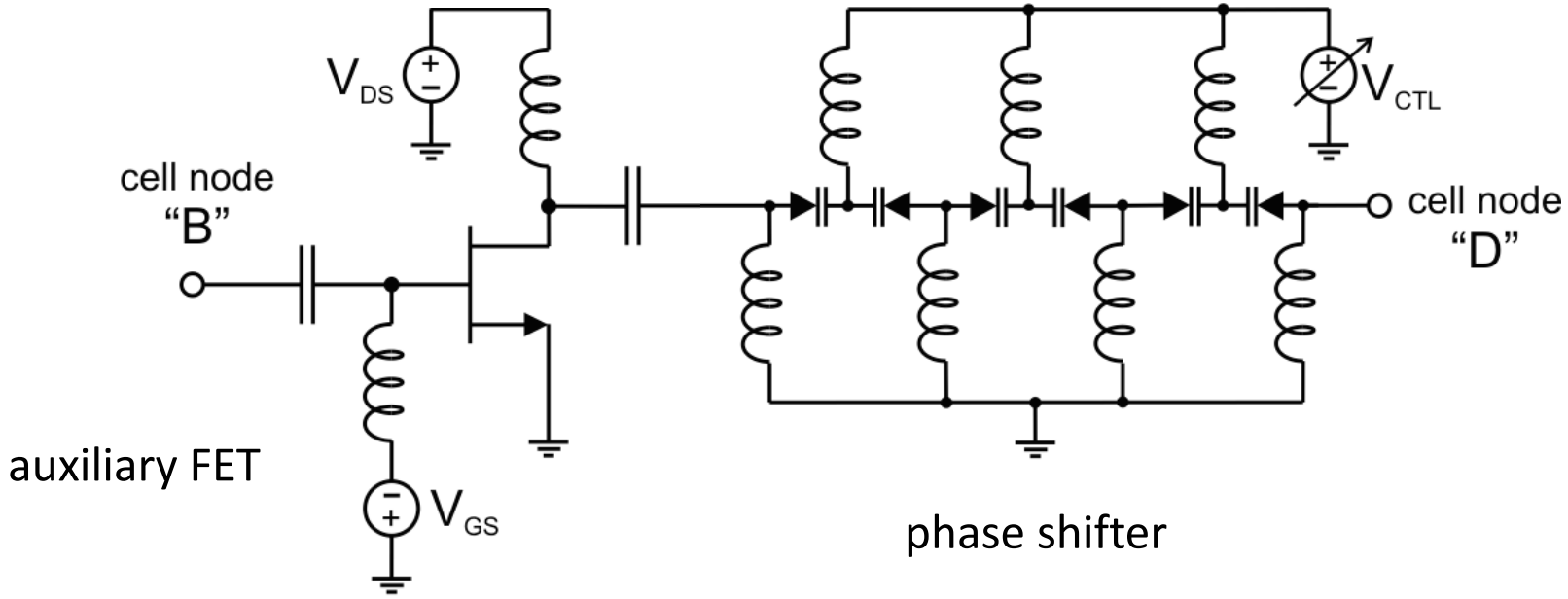

C
θ_3


D
θ_4



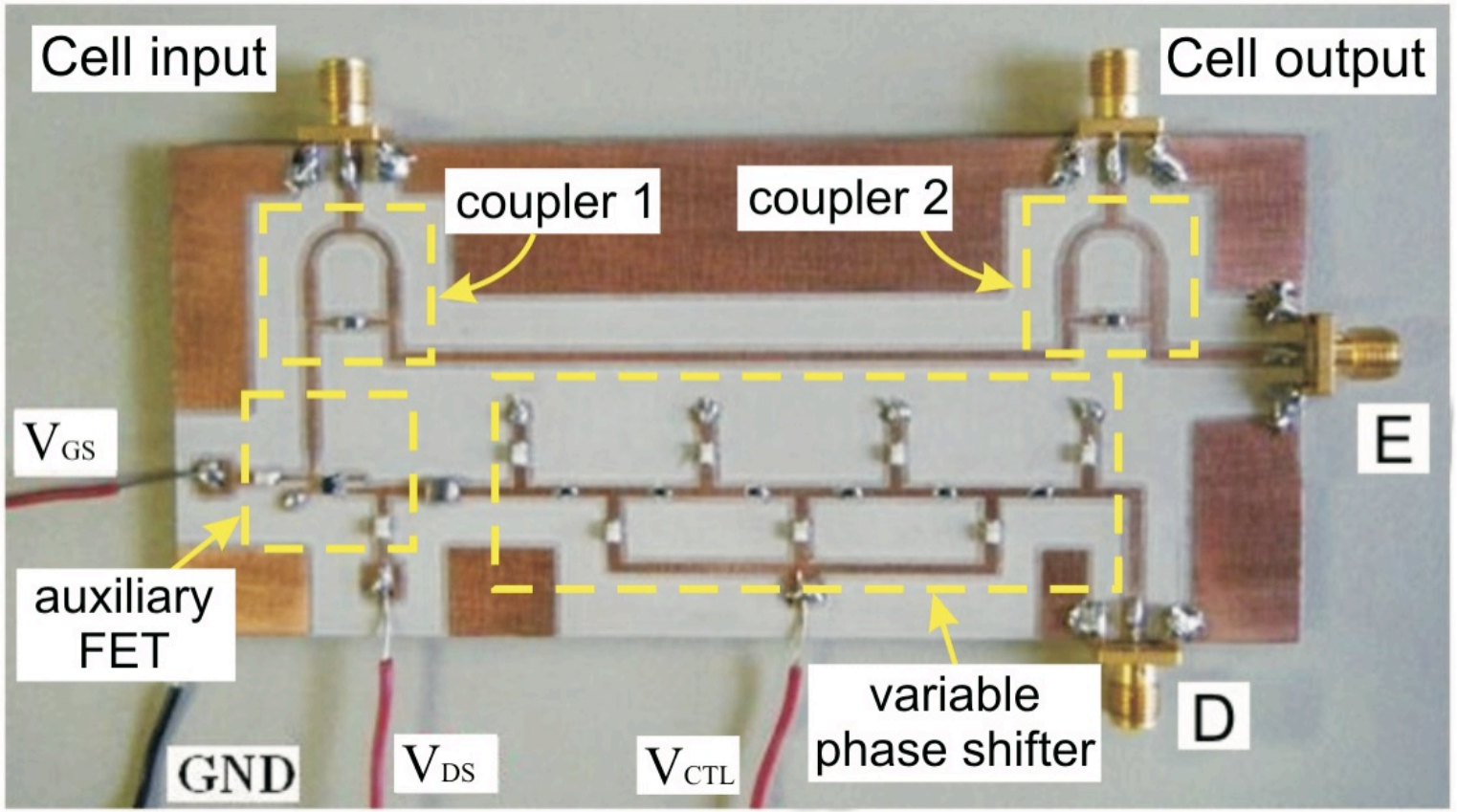


power coupler

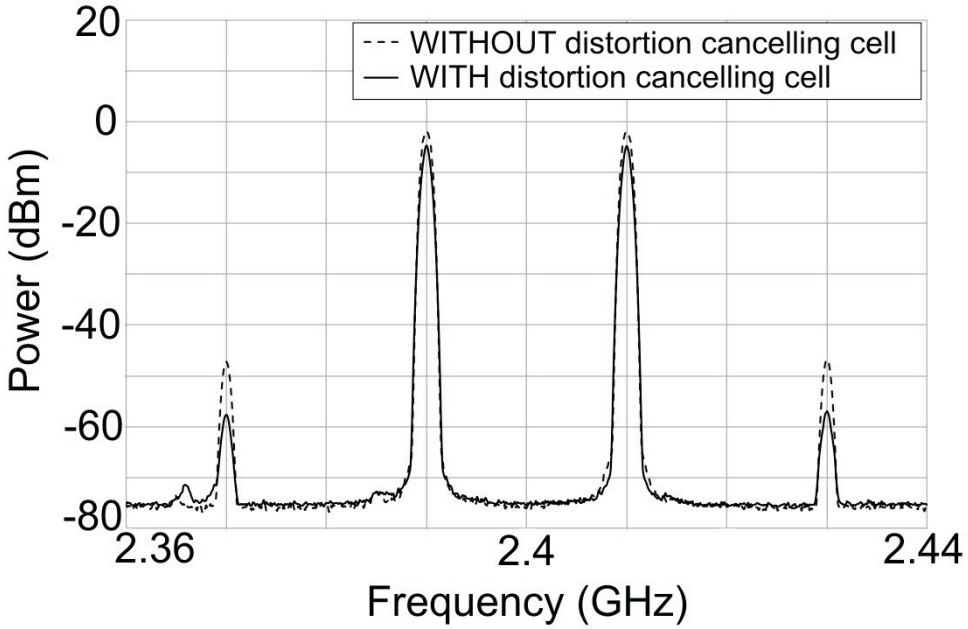


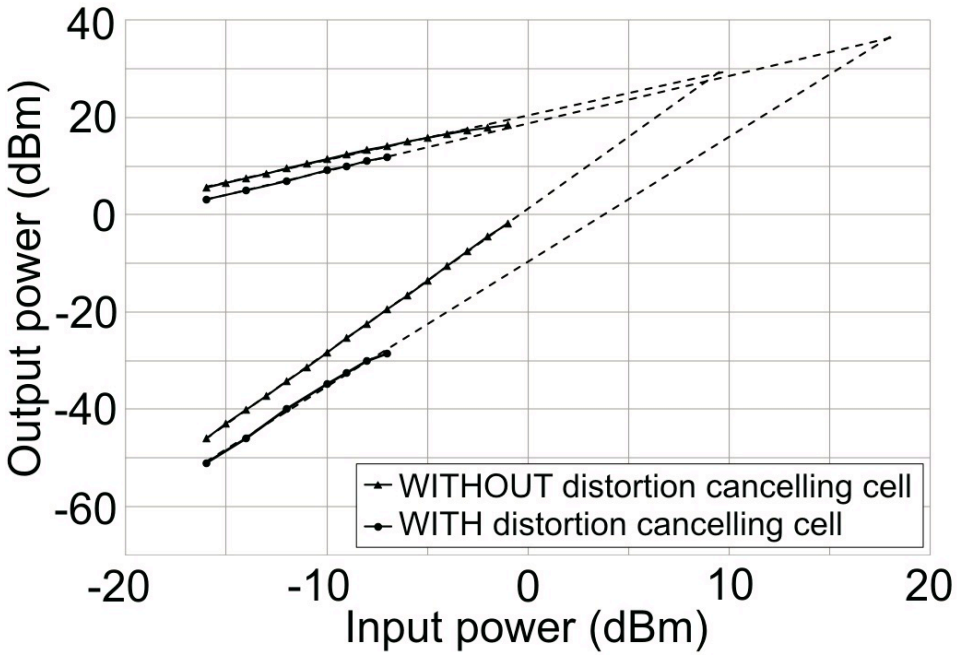
auxiliary FET

phase shifter



General purpose amp:	CSA-880912, Celeritek
Auxiliary FET:	NE34018, NEC GaAs HFET
Auxiliary amp:	ABP1200, Wenteq Corp.
Varactors:	SMV1405-079LF, Skyworks
Substrate:	RO3010, er = 10.2

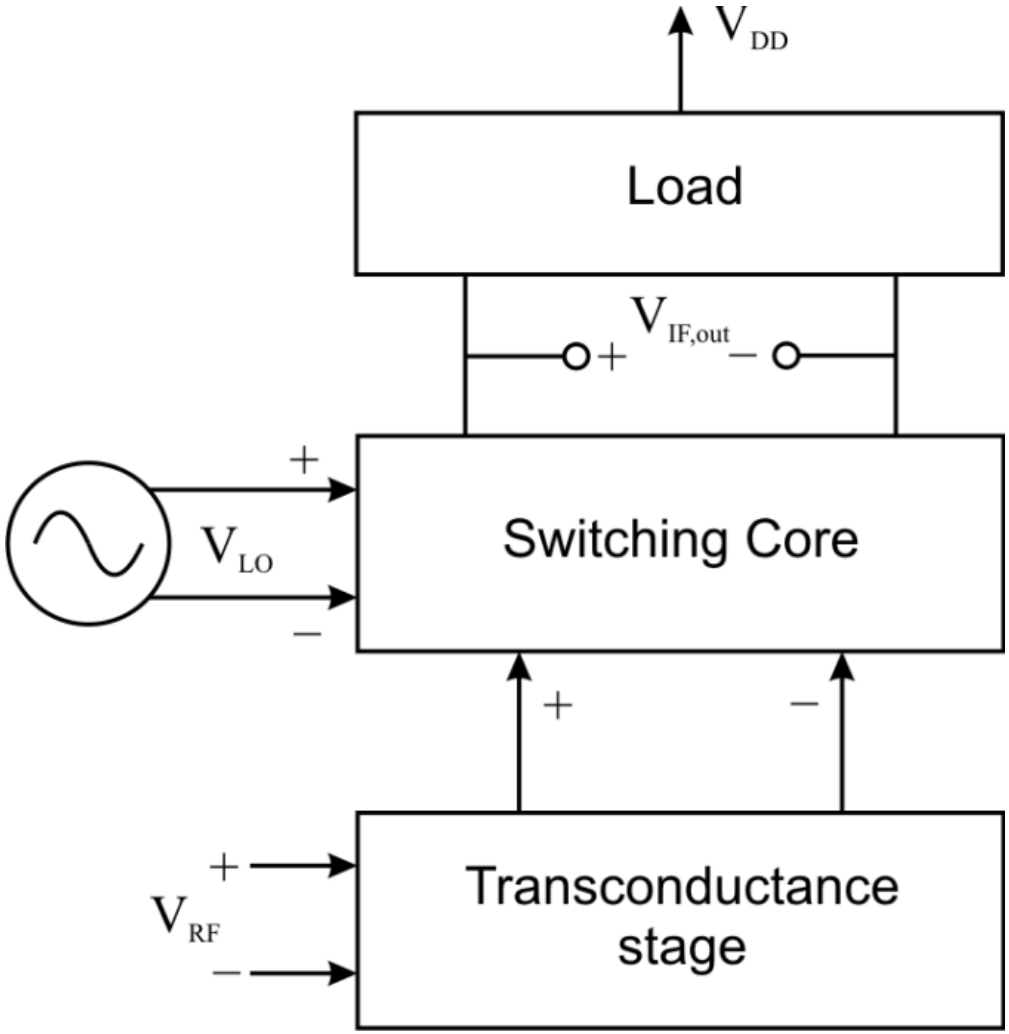


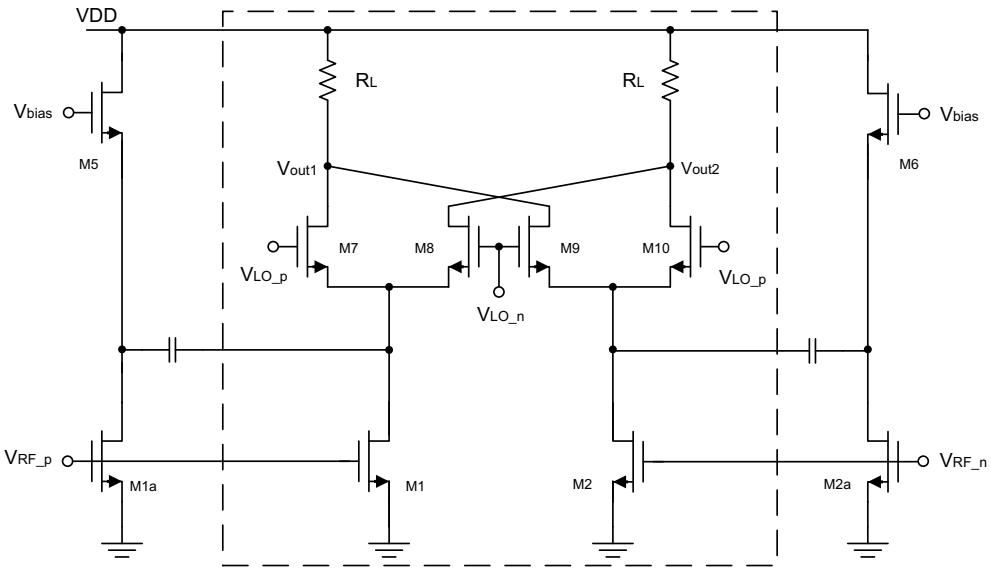


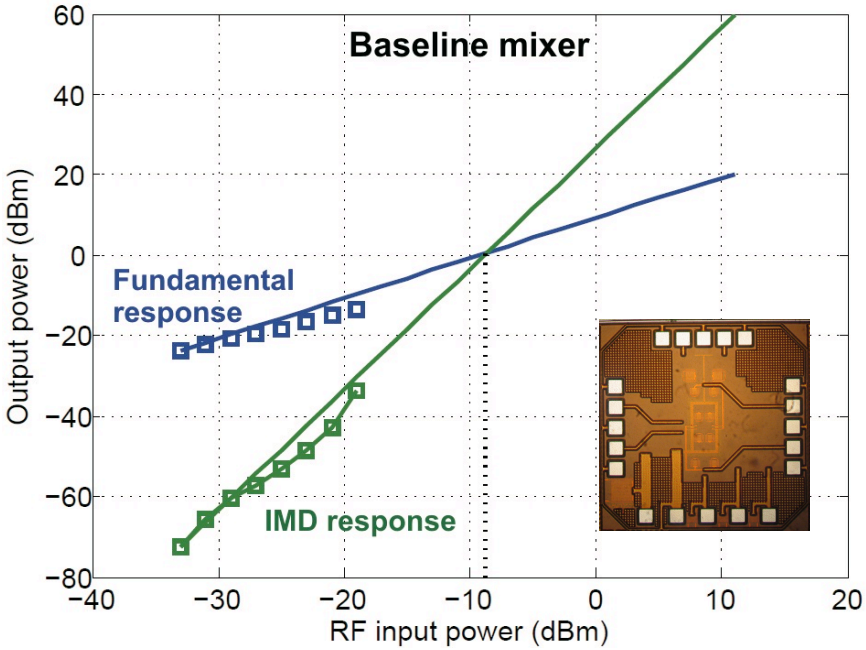
Amplifier	Without DCC	**With DCC**	Change
IIP_3	9.5 dBm	**17.5 dBm**	+8 dB
OIP_3	29.5 dBm	**37 dBm**	+7.5 dB
Power gain	21 dB	**19 dB**	-2 dB

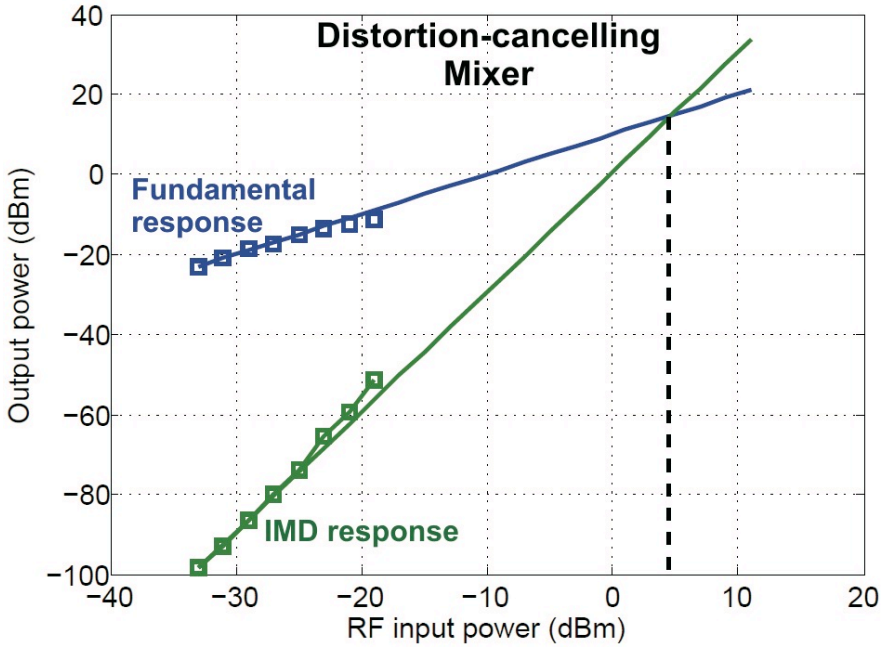
Wen Li and C. E. Saavedra, "A Stand-Alone Distortion-Cancelling Cell for Microwave Amplifiers", *IEEE Microwave and Wireless Components Letters*, vol. 23, no. 4, pp. 205-207, 2013.

Mixers


V_{DD}
Load
$V_{IF,out}$
+
−
+
V_{LO}
−
Switching Core
+
−
+
V_{RF}
−
Transconductance stage





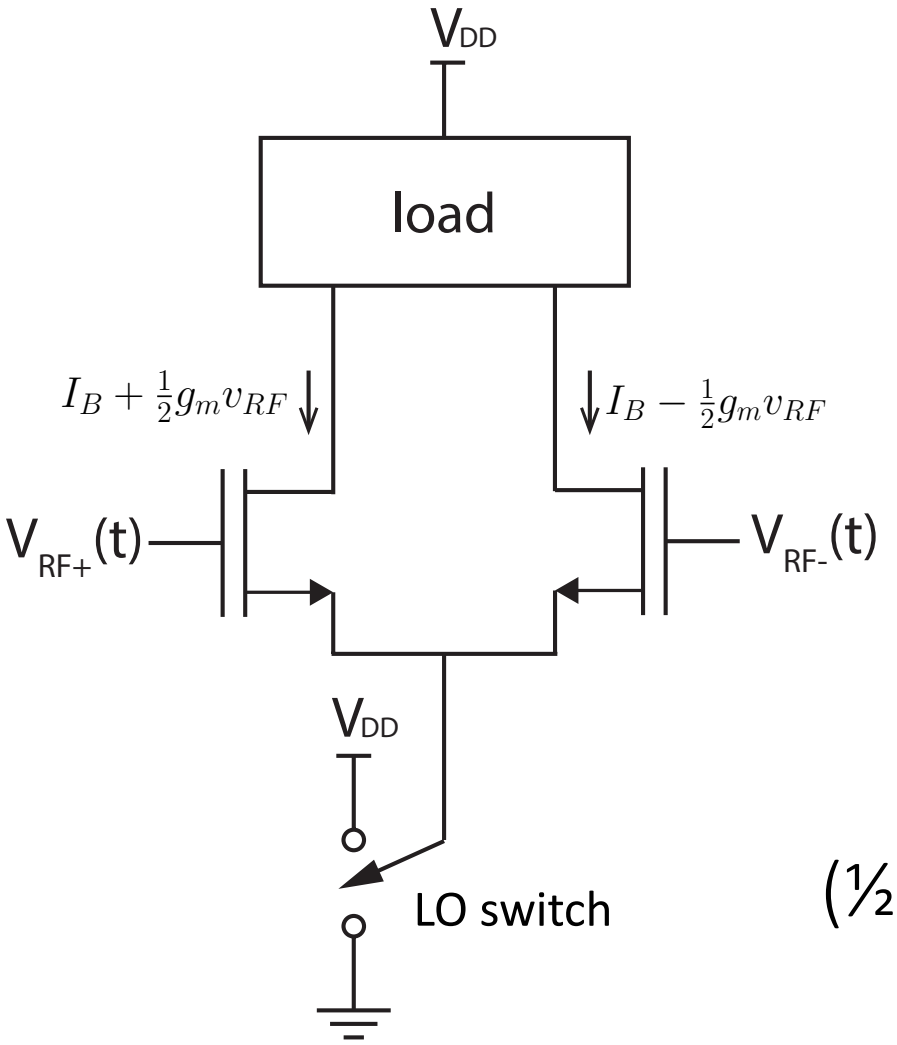


Metric/parameter	value	units	
RF frequency	1.0	GHz	
LO frequency	0.8	GHz	
Chip core area	0.1	mm^2	
CMOS node	130	nm	
IIP_3	-9	dBm	baseline mixer
	5	dBm	dist. cancelling mixer
	+14	dB	change
Conversion gain	11.7	dB	baseline mixer
	11	dB	dist. cancelling mixer
	-0.7	dB	change

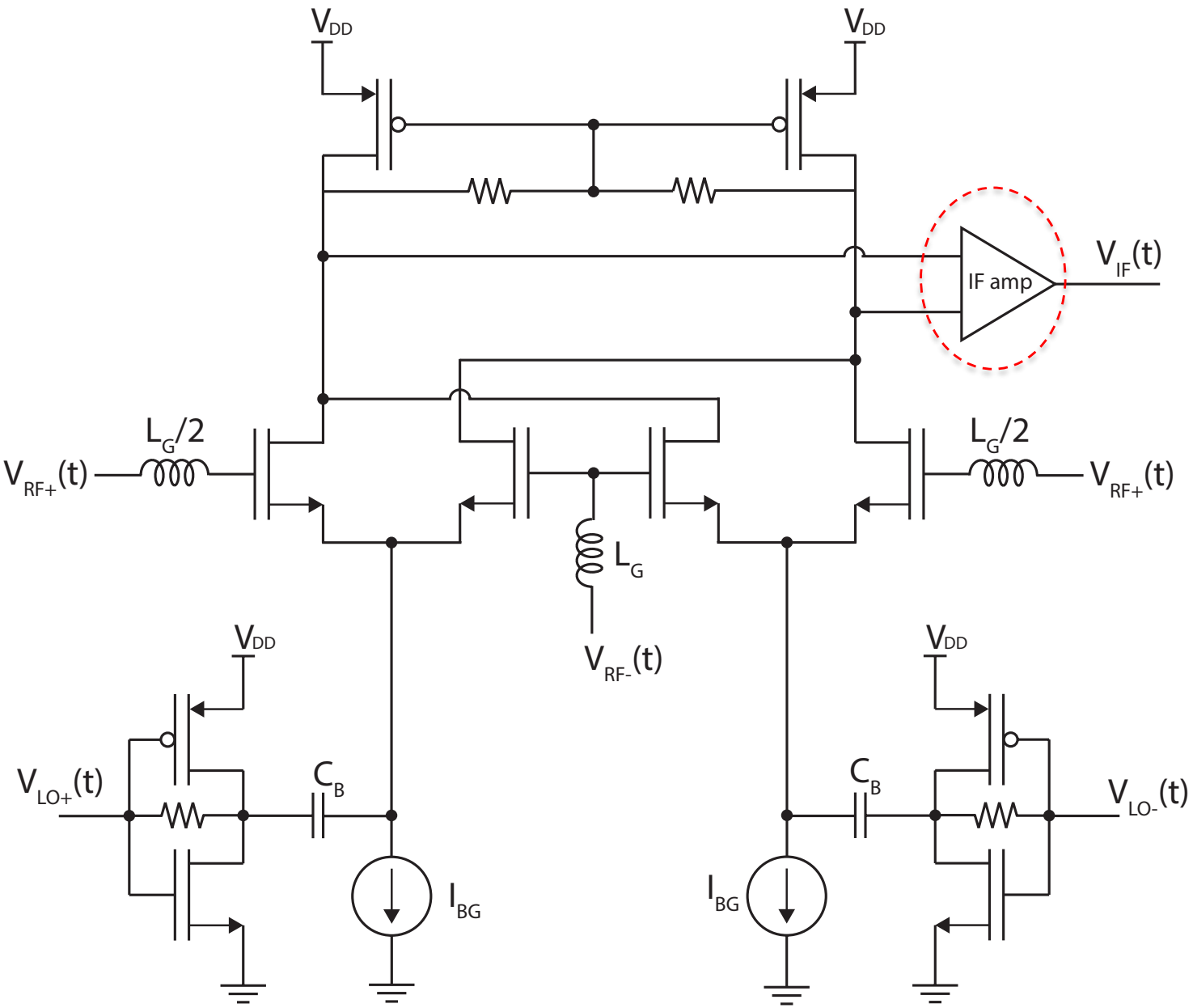
NF = 15.9 dB!

M. Wang, Shan He, C. E. Saavedra, "+14 dB Improvement in the IIP3 of a CMOS Active Mixer Through Distortion Cancellation", *IEEE MTT-S International Wireless Symposium*, Beijing, China, April 2013.

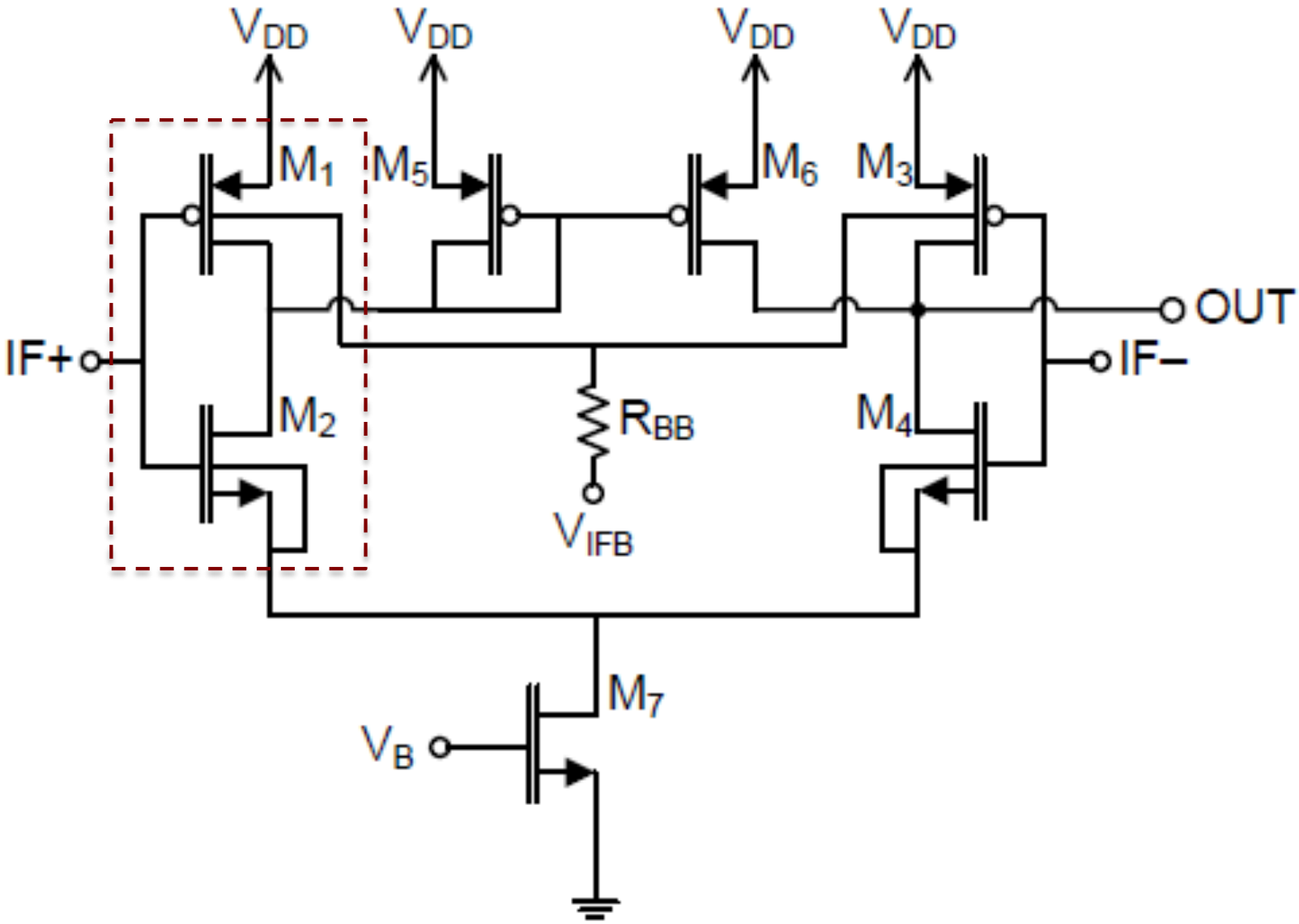
Switched Gm mixer [4]



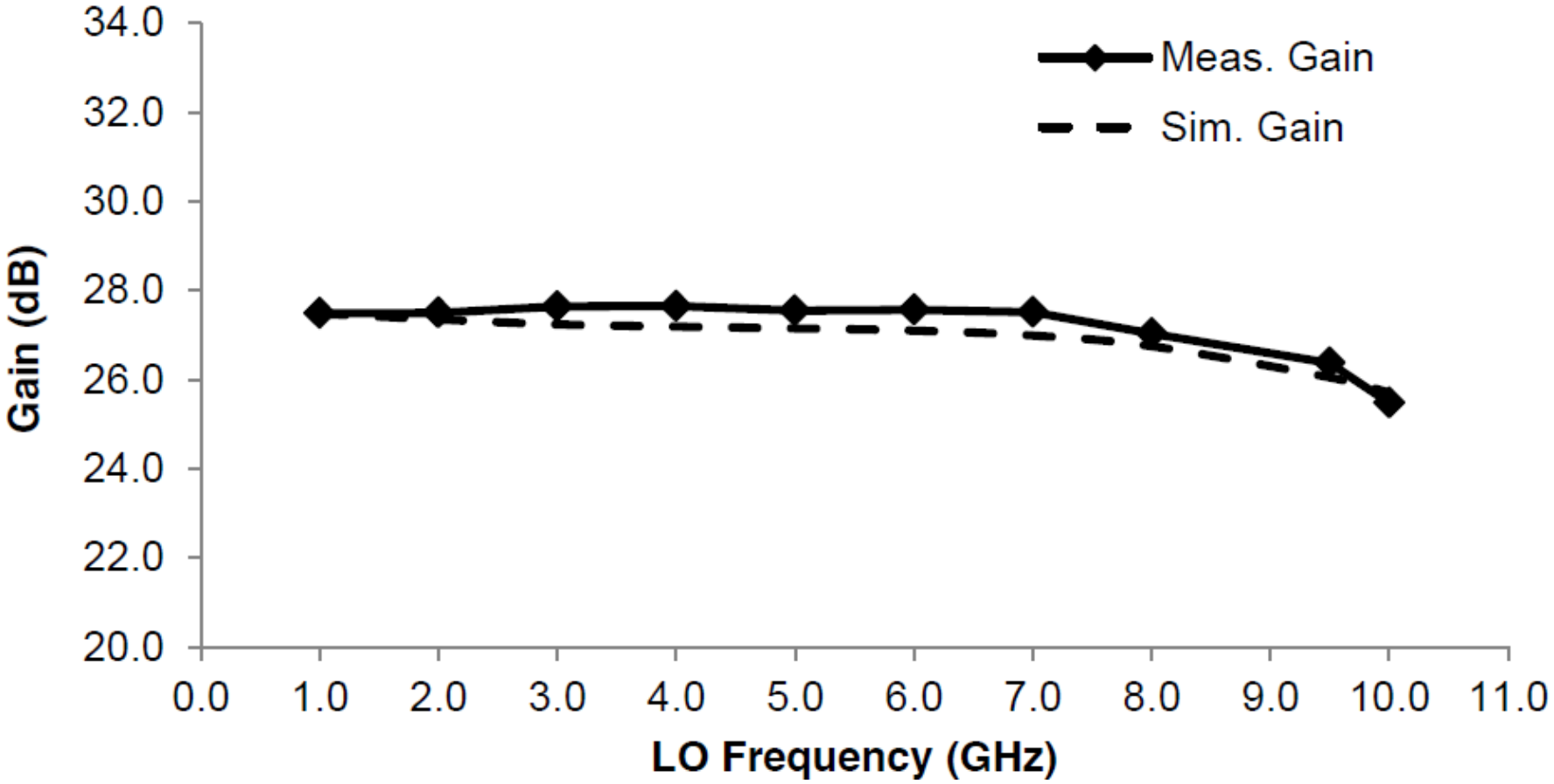
(½ circuit)


VDD
VDD
IF amp
VIF(t)
LG/2
VRF+(t)
LG/2
VRF+(t)
LG
VRF-(t)
VDD
VDD
VLO+(t)
CB
CB
VLO-(t)
IBG
IBG

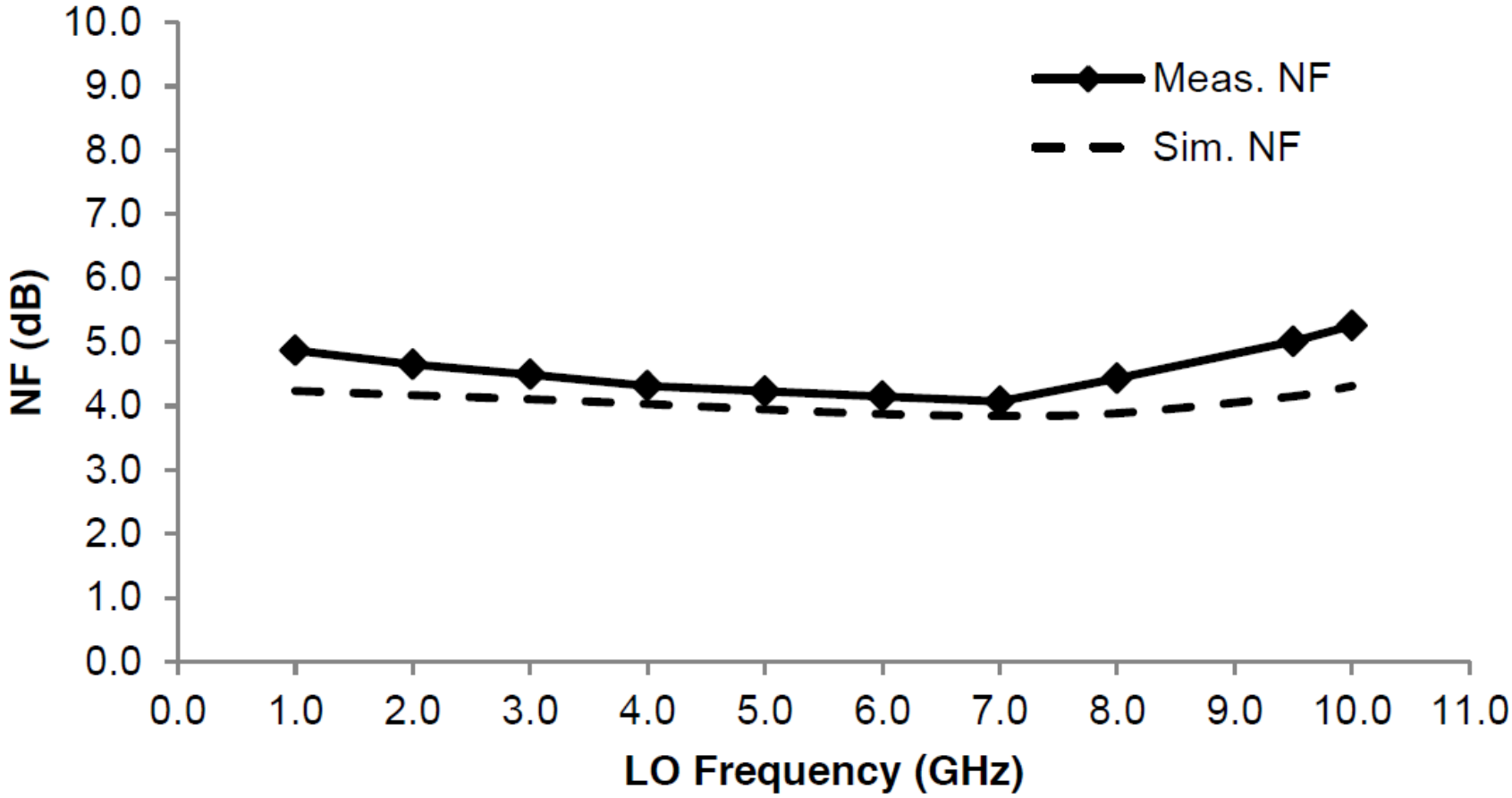
IF output stage



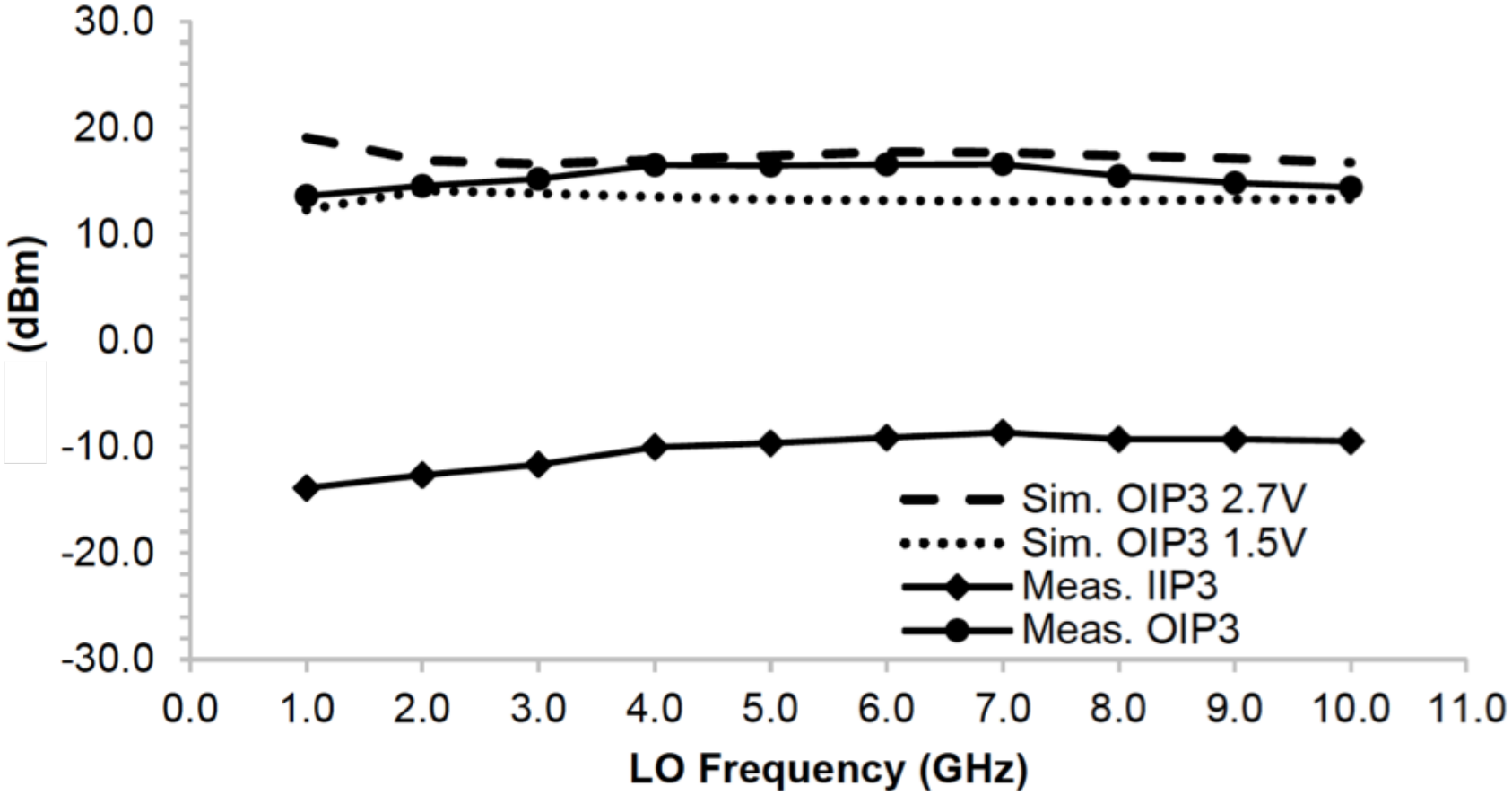
Experimental results



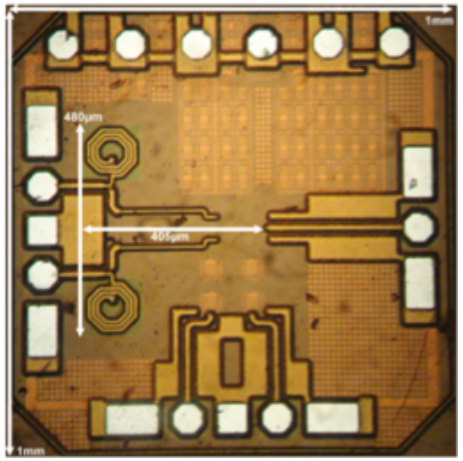
Experimental results



Experimental results



Characteristic	This work	[3]	[8]	[5]
Chip Area (mm^2)	**0.2**	0.315	0.10	1.21
DC Power (mW)	**20**	34.5	20	25.5
Gain (dB)	**26.5**	17.5	11	15
Bandwidth (GHz)	**1–10**	1–5.5	1	0.5–5.8
DSB NF (dB)	**4.6±0.6**	3.9	15.9	4.2
OIP3	**16.5**	15.6	17.5	–



A. M. El-Gabaly, H. Li and C. E. Saavedra, "A Decade-Bandwidth Low-Noise Mixer RFIC with a Distortion-Cancelling Output Amplifier", *IEEE Symposium on Radio Frequency Integration*, Taipei, Taiwan, 2016.

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[8] A. M. El-Gabaly, H. Li and C. E. Saavedra, "A Decade-Bandwidth Low-Noise Mixer RFIC with a Distortion-Cancelling Output Amplifier", *IEEE Symposium on Radio Frequency Integration*, Taipei, Taiwan, 2016.

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