A-SSCC
IEEE Asian Solid-State Circuits Conference

SSCS

A 0.7 V-to-1.0 V 10.1 dBm-to-13.2 dBm 60-GHz Power Amplifier Using Digitally-Assisted LDO Considering HCI Issues

Rui Wu, Yuuki Tsukui, Ryo Minami, Kenichi Okada, and Akira Matsuzawa

Tokyo Institute of Technology, Japan

Matsuzawa & Okada Lab.

TOKYO TECH
Pursuing Excellence

Outline

- **Background**
  - 60-GHz field is attractive
- **Hot-Carrier-Induced Issues**
  - HCI influence on circuit reliability
- **Variable-Supply-Voltage PA using Digitally-assisted LDO**
  - Circuit design & Measurement results
- **Conclusions**

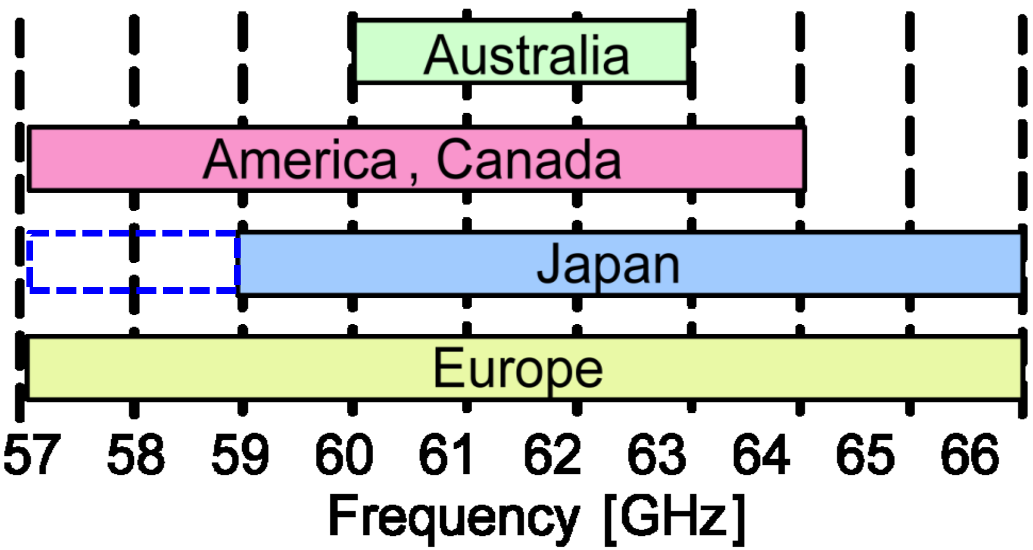
Background

- **9-GHz unlicensed bandwidth**
- **Several Gbps wireless communication**

e.g. IEEE 802.15.3c

QPSK→3.5 Gbps/ch

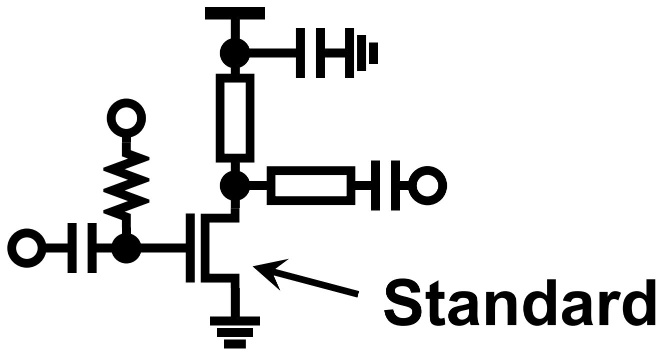
16QAM→7 Gbps/ch



[1] http://www.tele.soumu.go.jp

HCI Issues are Emerging at 60 GHz

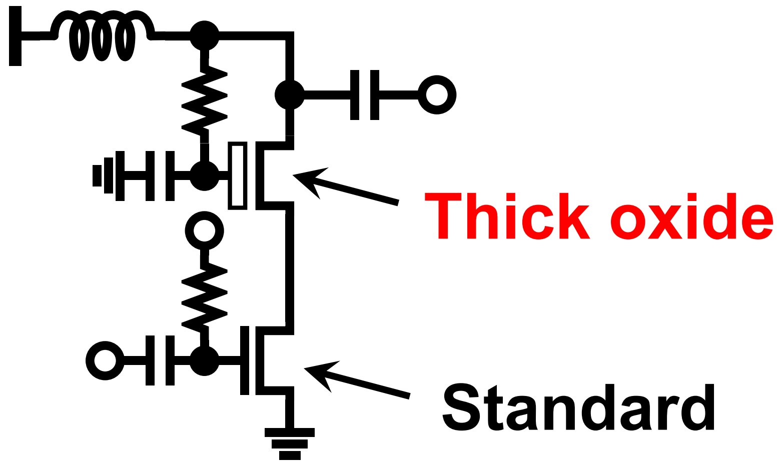
60-GHz power amplifier



☺ High f_{max}, suitable for 60-GHz amplifier

☹ Bad HCI performance

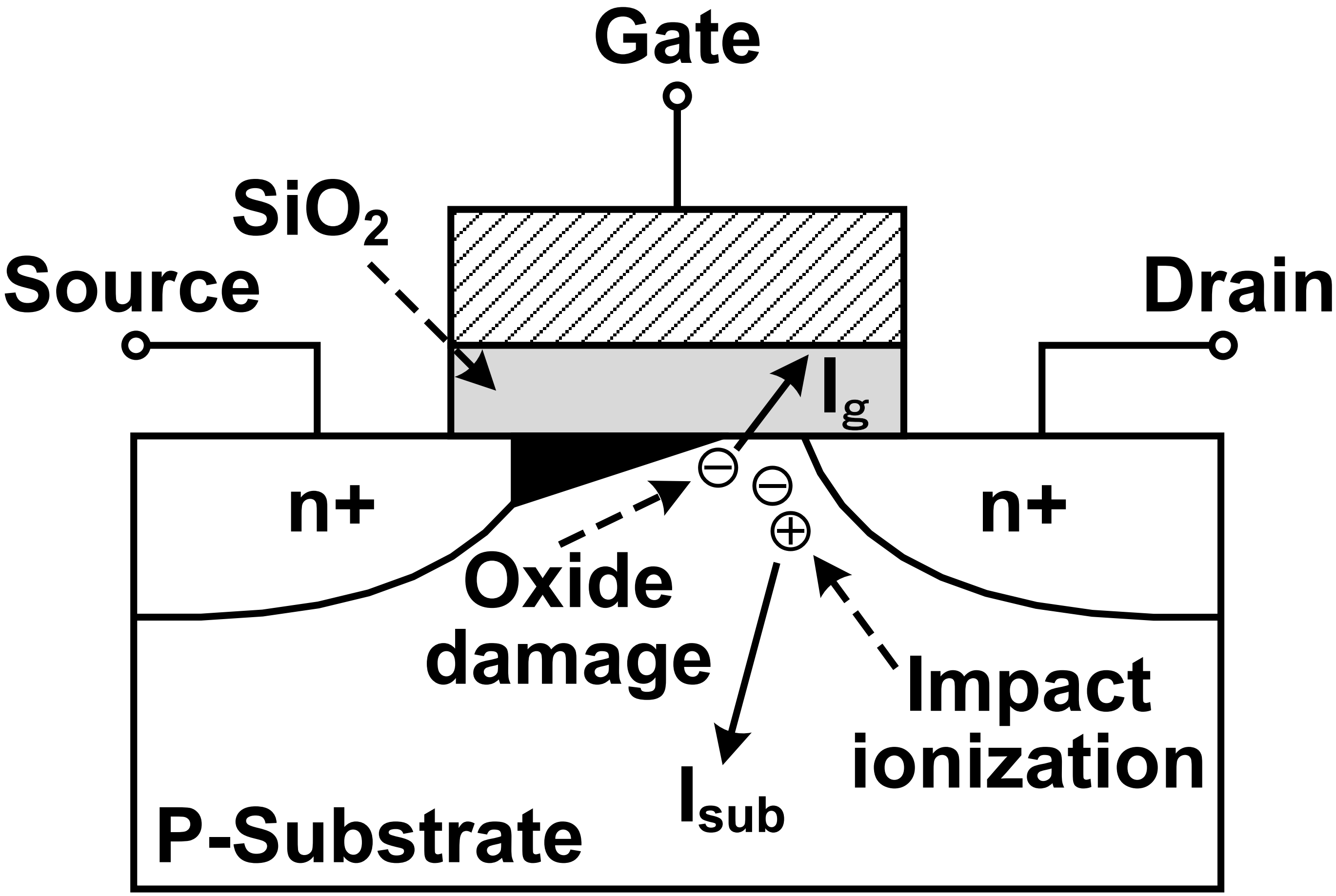
2.4-GHz power amplifier



☺ Good HCI performance

☹ Low f_{max}, can’t be used for 60-GHz amplifier

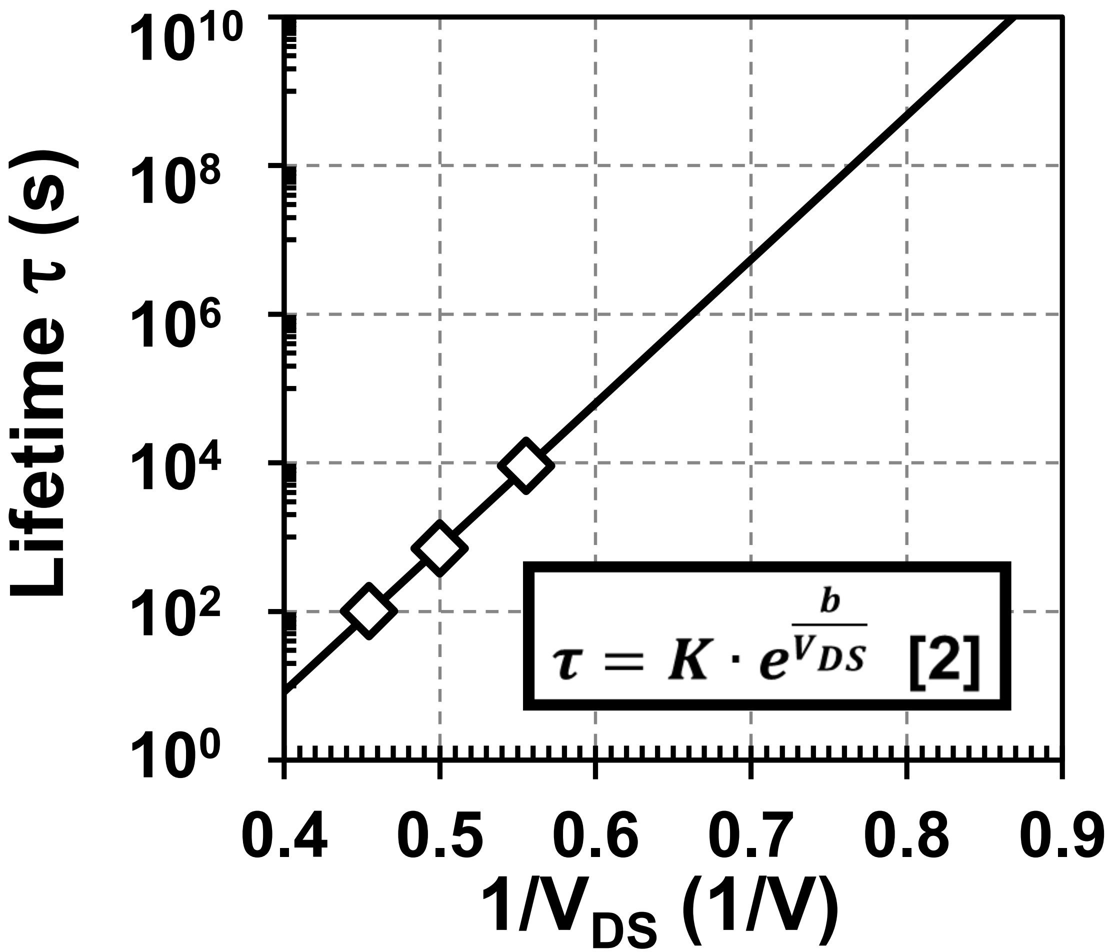
Hot-Carrier-Induced (HCI) Effects



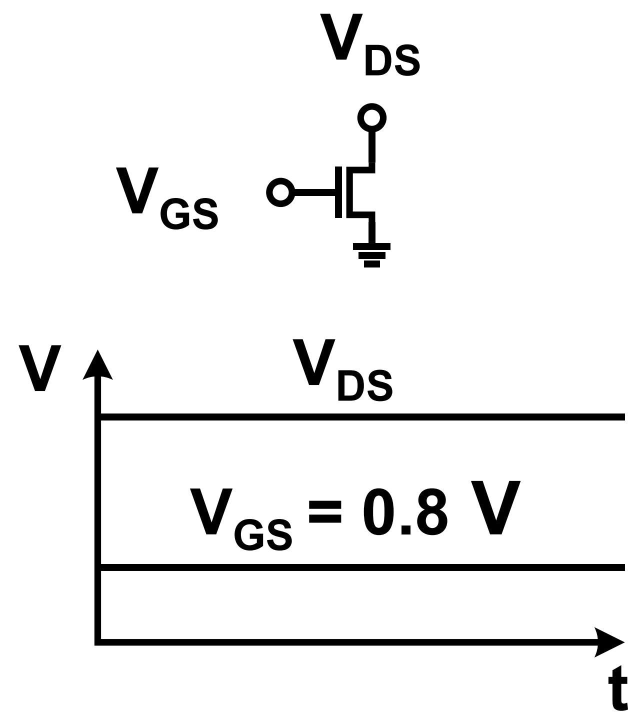
Degrade V_{th}, g_m, drain current, and lifetime

65 nm NMOSFET DC Stress Lifetime

Lifetime is the time drain current decreases by 10%

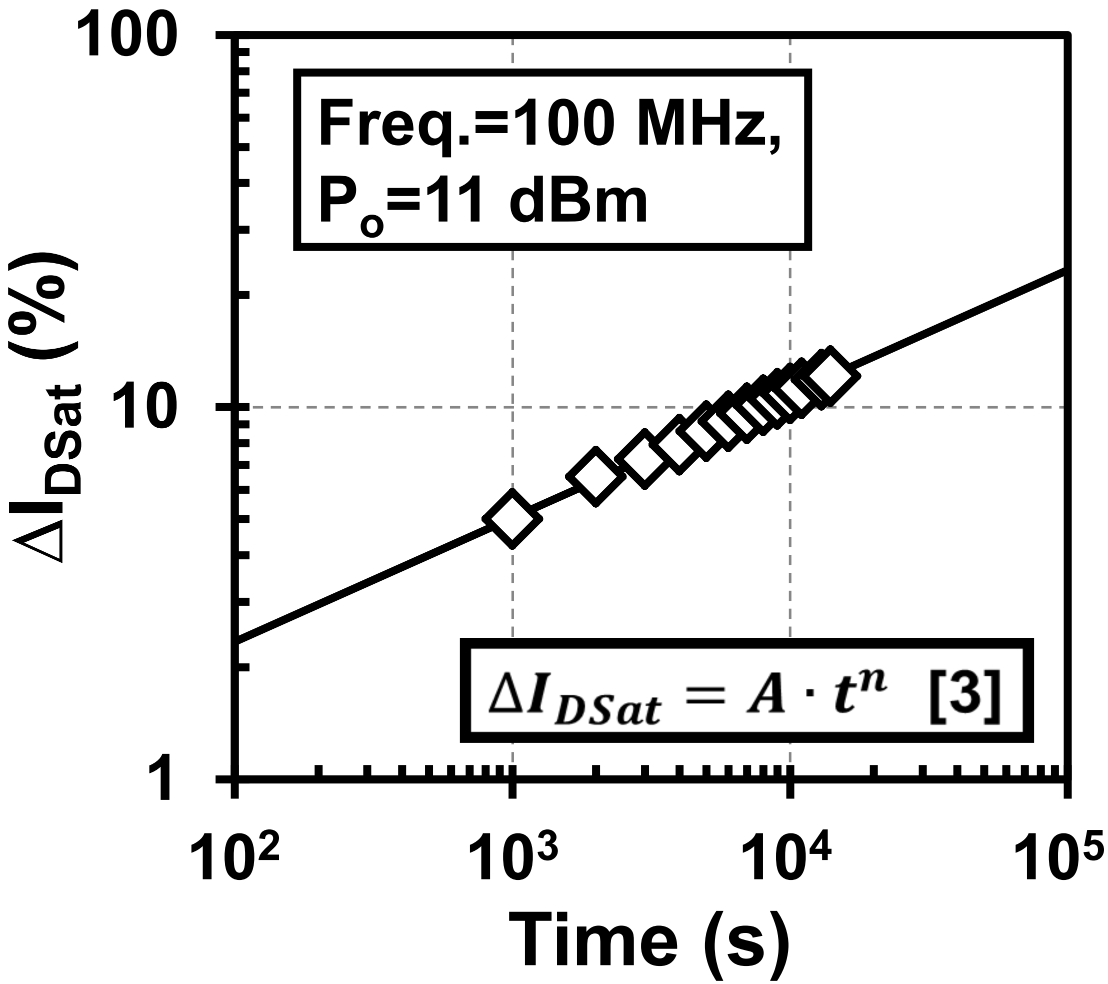


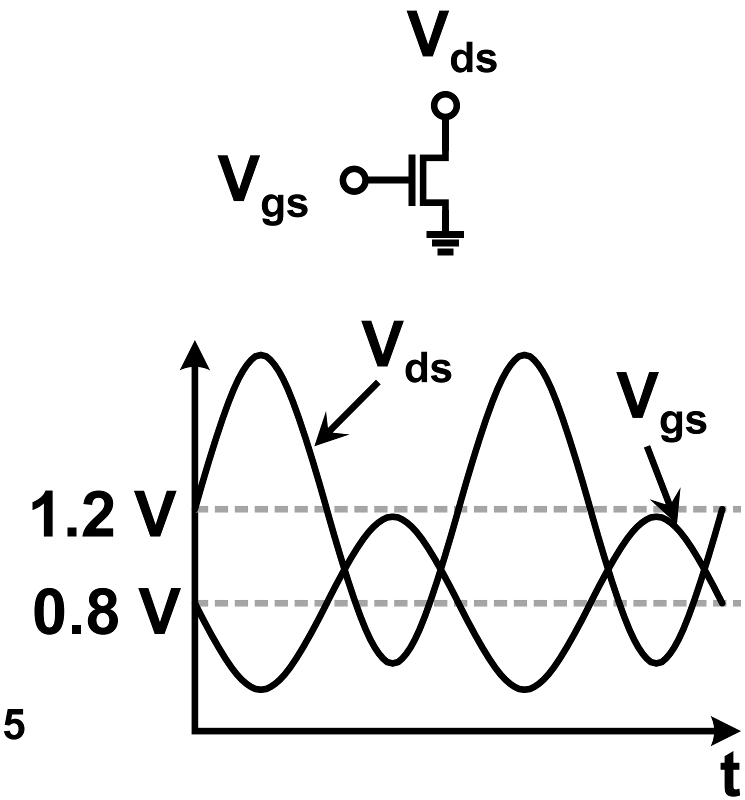
Stress condition



[2] E. Takeda et al., IEDL 1983

65 nm NMOSFET RF Stress Lifetime





[3] L. Negre et al., JSSC 2012

Hot-Carrier Damage Mechanism [4]

- **Single Vibrational Excitation (SVE)** is related to high energetic carrier that has enough energy to break Si-H bond; **(High energy)**
- **Electron Electron Scattering (EES)** is caused by one carrier promotes the other into higher energy and allows Si-H breaking; **(Medium energy)**
- **Multiple Vibrational Excitation (MVE)** is due to a series of low energetic carriers that accumulate enough energy to break Si-H bond. **(Low energy)**

[4] C. Guerin et al., JAP 2009

Hot-Carrier Physical Model [3]

- $\Delta I_{DSat}(t) = A(t) \cdot t^n = \left[\int_0^t A(\tau)^{\frac{1}{n}} d\tau\right]^n$
- $A(t) = [K_{SVE}\left(\frac{I_{DS}(t)}{W}\right)^{\alpha_1}\left(\frac{I_{BS}(t)}{I_{DS}(t)}\right)^m +$

$$K_{EES}\left(\frac{I_{DS}(t)}{W}\right)^{\alpha_2}\left(\frac{I_{BS}(t)}{I_{DS}(t)}\right)^m +$$

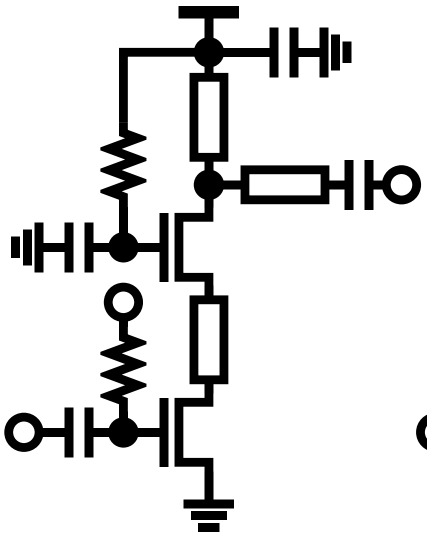
$$K_{MVE}V_{DS}^{\frac{\alpha_3}{2}}(t)\left(\frac{I_{DS}(t)}{W}\right)^{\alpha_3} exp(\frac{-E_{emi}}{kT})]^n$$

I_{DS}(t) is the time-varying drain current which is a function of V_{GS}(t) and V_{DS}(t);
K and α are damage mode dependent constants;
m and *n* are process-related constants.

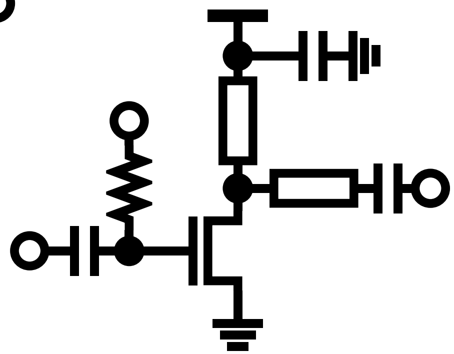
[3] L. Negre et al., JSSC 2012

Conventional Solutions

Cascode [5]



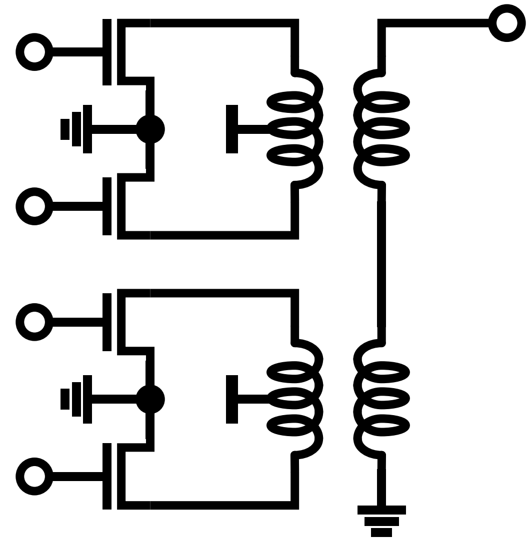
Low V_{dd} [6]



☺ **Better lifetime**

☹ **Degraded output power, efficiency, and linearity**

Power combining [7]



☺ **Better lifetime, output power, and linearity**

☹ **Sensitive to process variations**

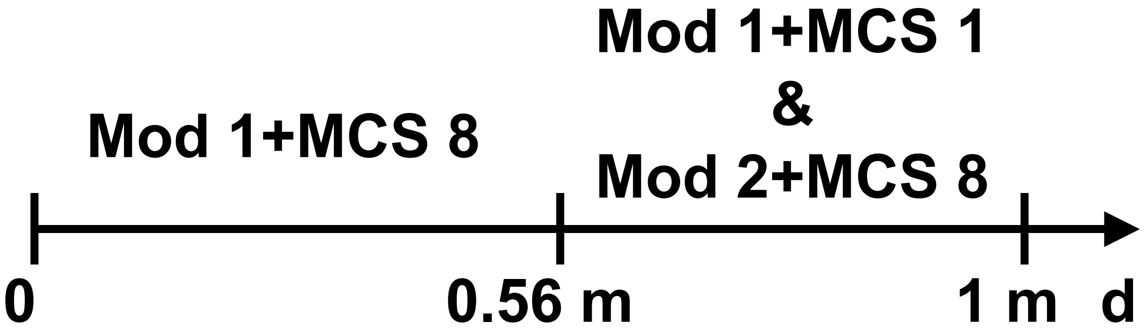
[5] A. Siligaris et al., JSSC 2010

[6] M. Tanomura et al., ISSCC 2008

[7] J. Chen et al., ISSCC 2011

Application Scenario

◆Single Carrier (SC) Mode of IEEE 802.15.3c

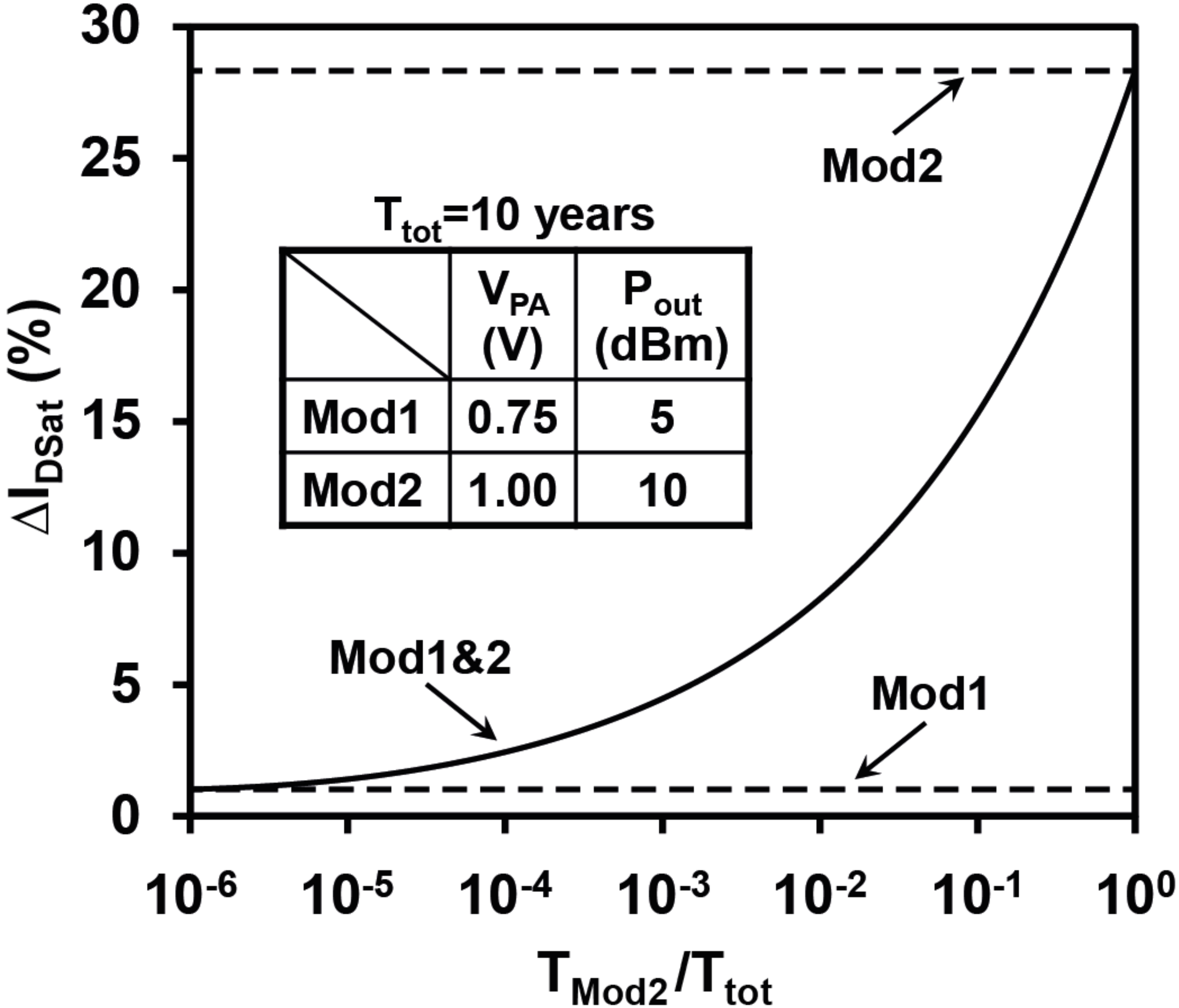


Mod1 low power
Mod2 high power

MCS identifier	8		1
Data rate	2640 Mb/s		412 Mb/s
Rx sensitivity	-56 dBm		-61 dBm
Required CNR	17.5 dB		12.5 dB
Distance	0.56 m	1 m	1 m
Required P_{out}	5 dBm	10 dBm	5 dBm

*NF=8 dB; Thermal noise=-81.5 dBm; Antenna gain=2 dBi; Implementation loss=-2 dB; freq.=60 GHz

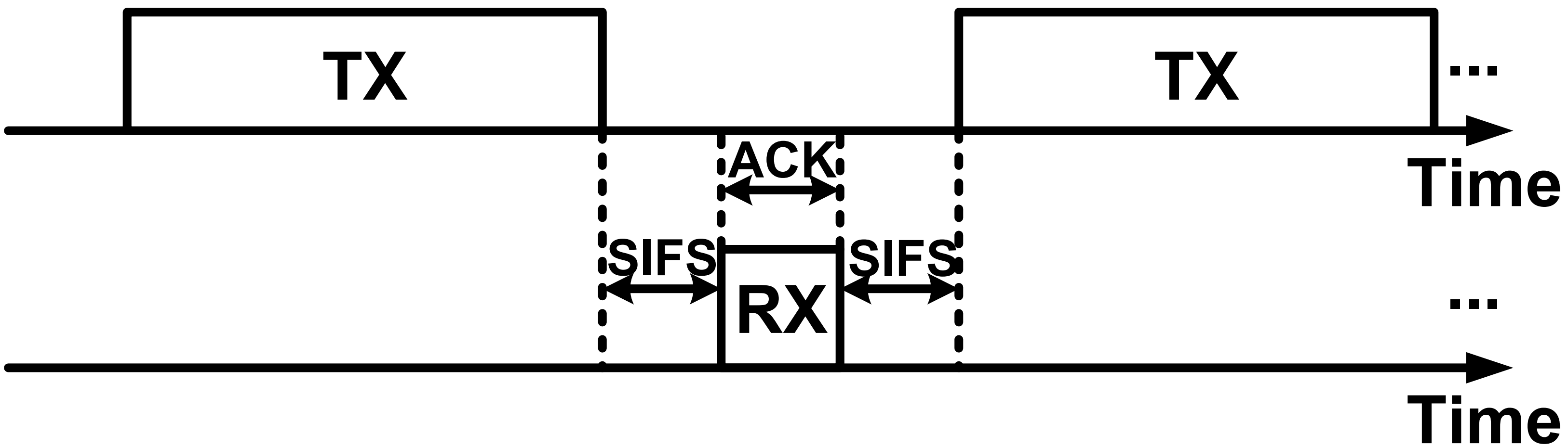
Lifetime estimation



	V_{PA} (V)	P_{out} (dBm)
Mod1	0.75	5
Mod2	1.00	10

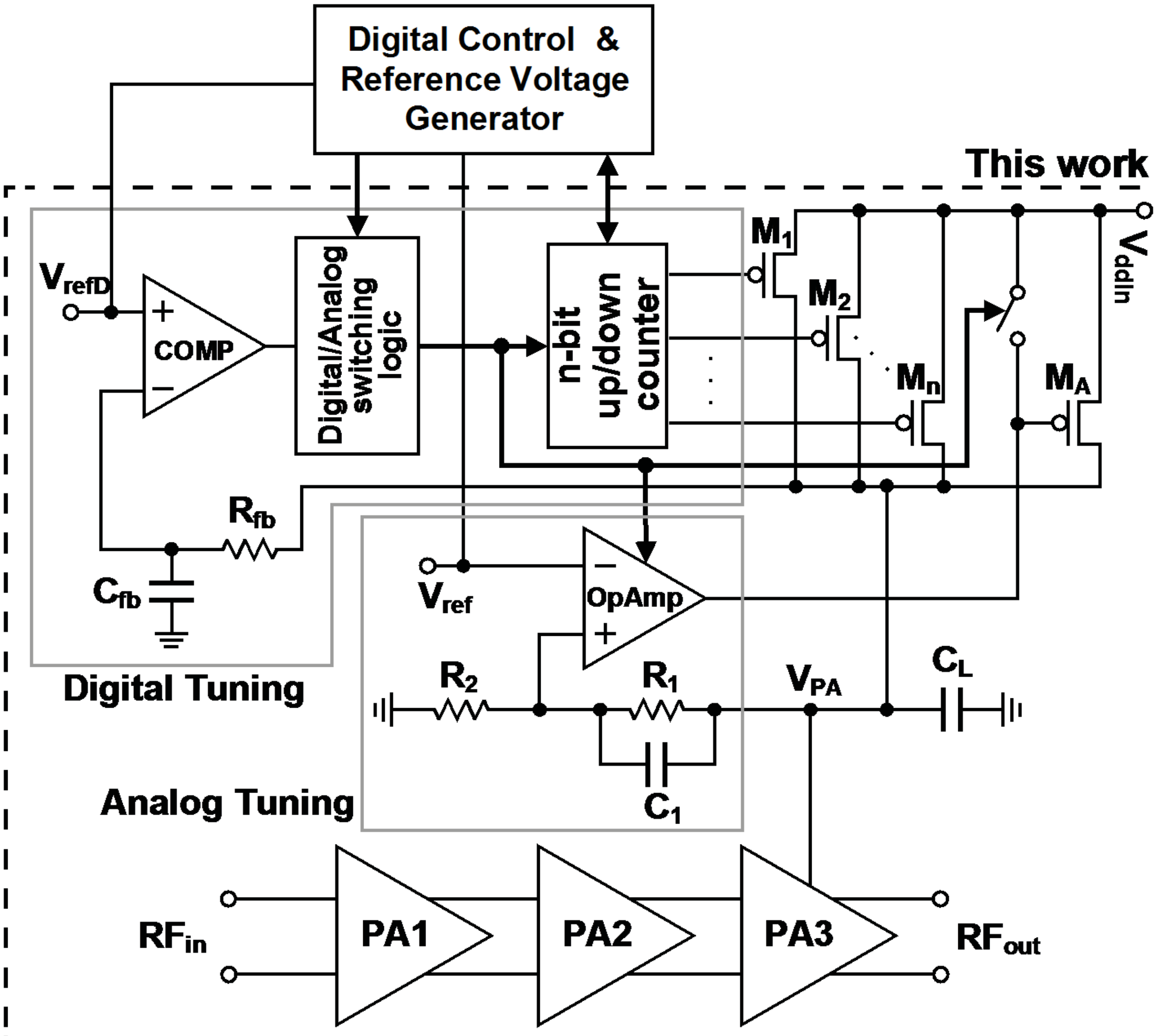
Time-Division Duplex (TDD) Operation

- TDD operation can eliminate the stringent requirement of filtering and extend the available bandwidth for transceivers.

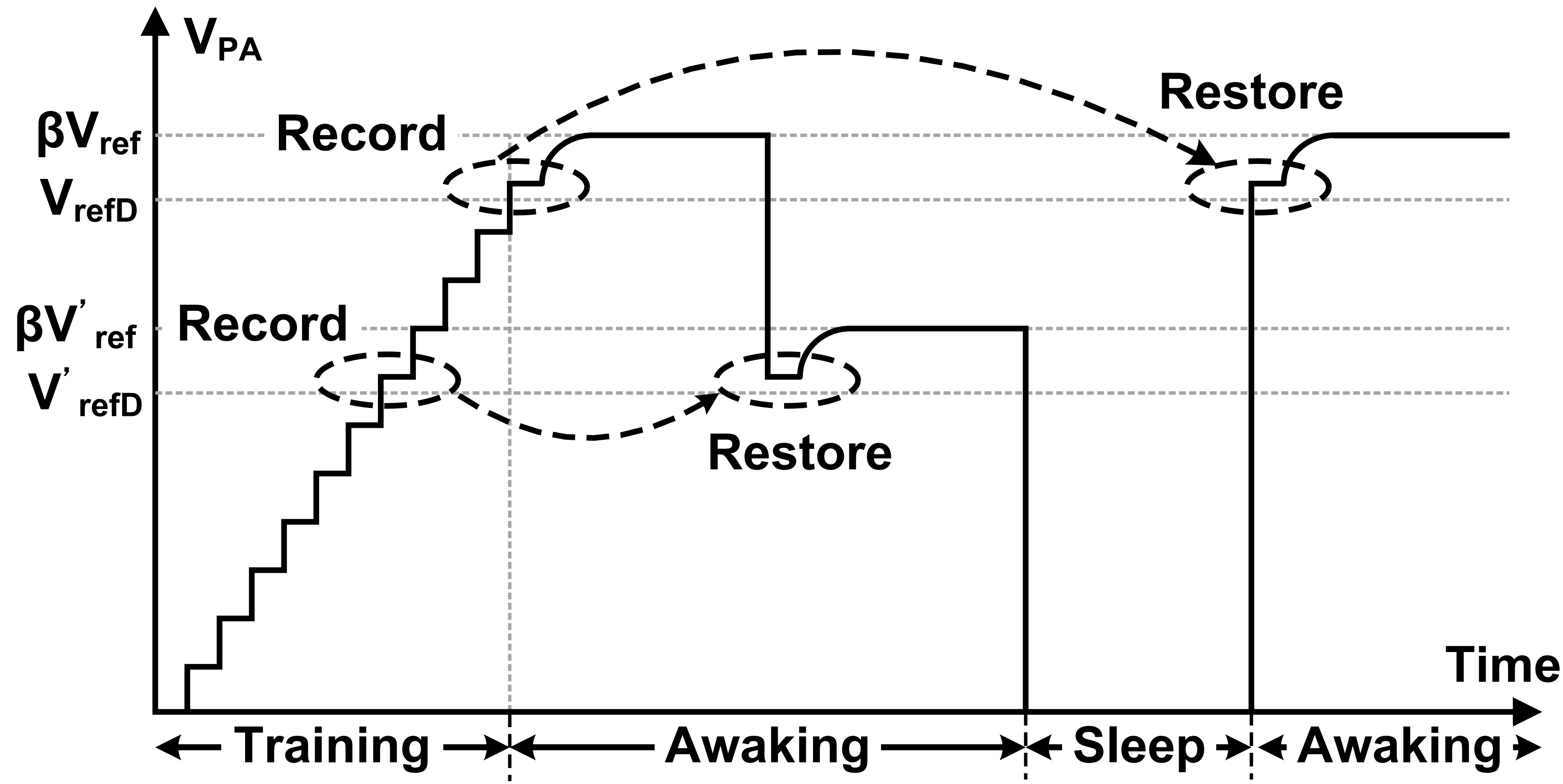


In IEEE 802.11ad, short inter-frame space (SIFS) is indicated to be 3μs

The Proposed Power Amplifier

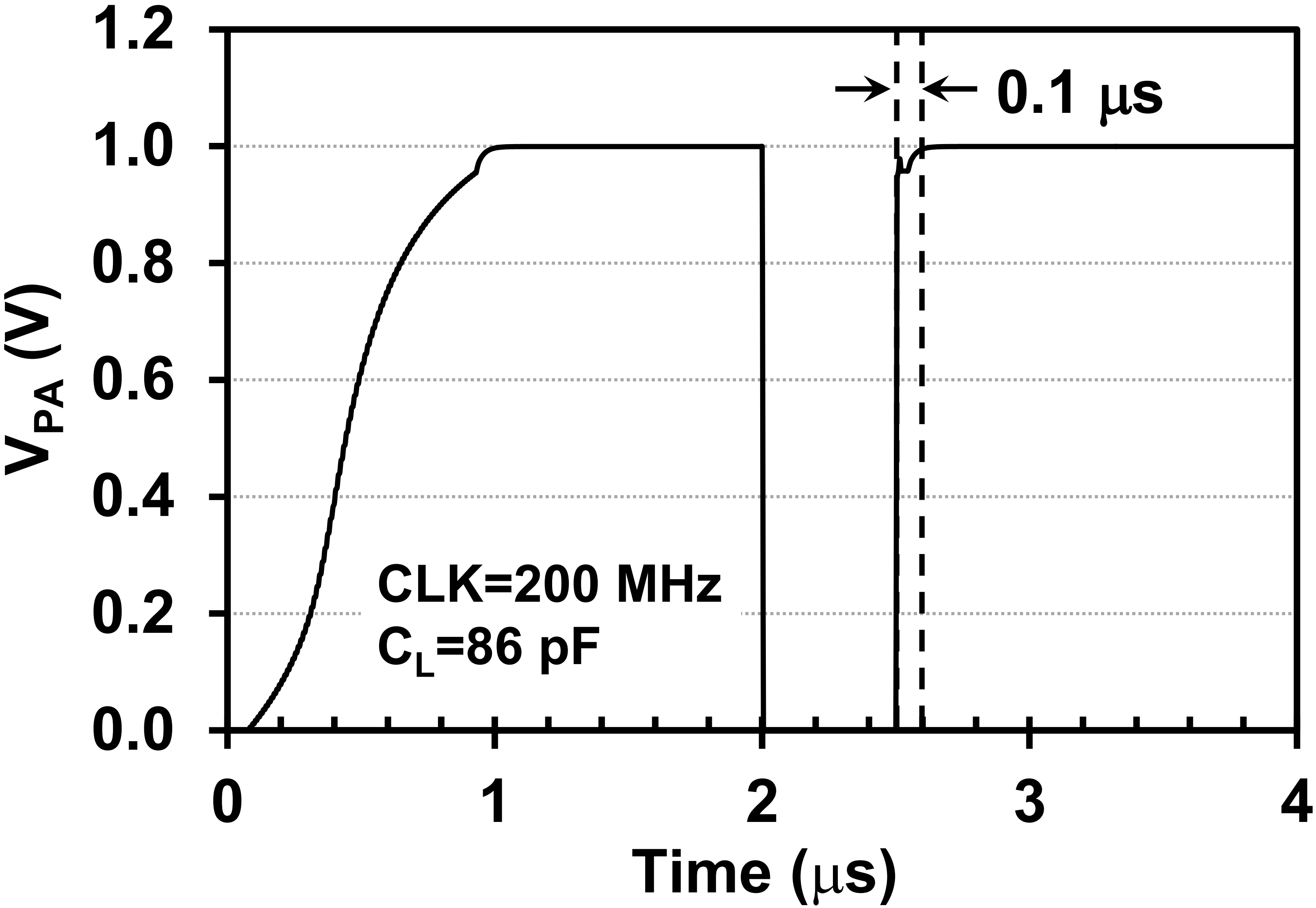


Transient Operation of the LDO

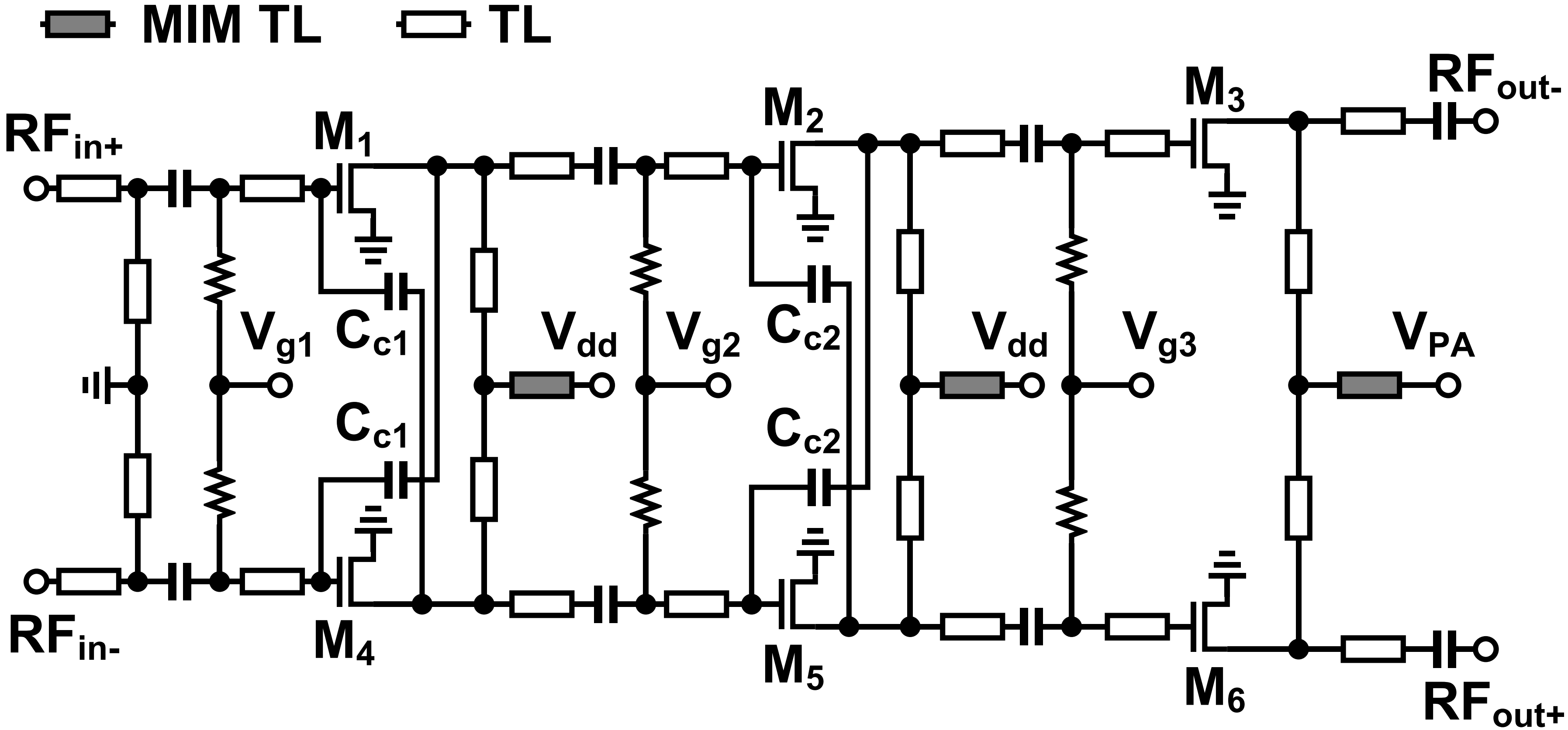


$$\beta = (R_1 + R_2)/R_2$$

Transient Simulation Result

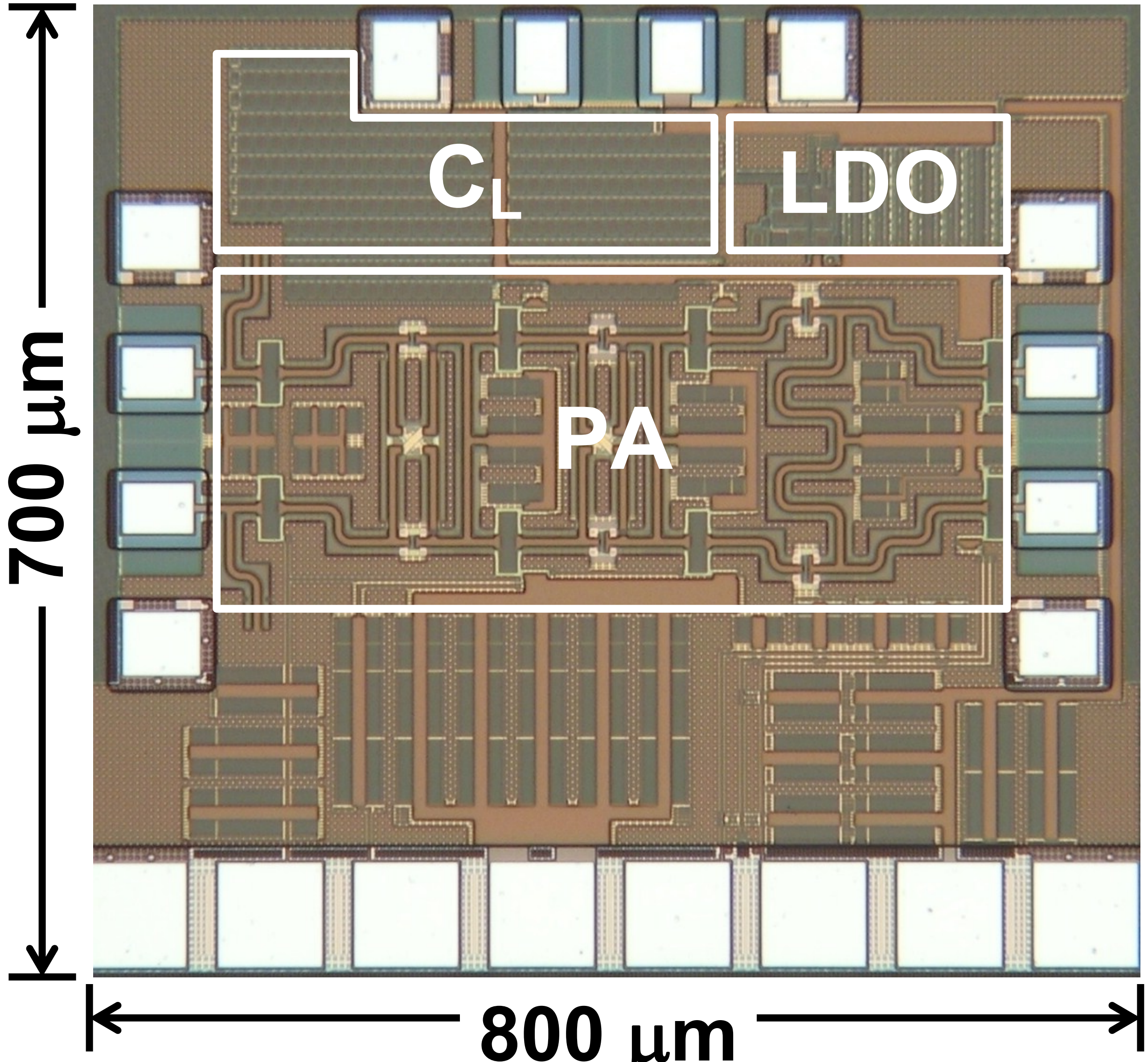


Differential PA Topology

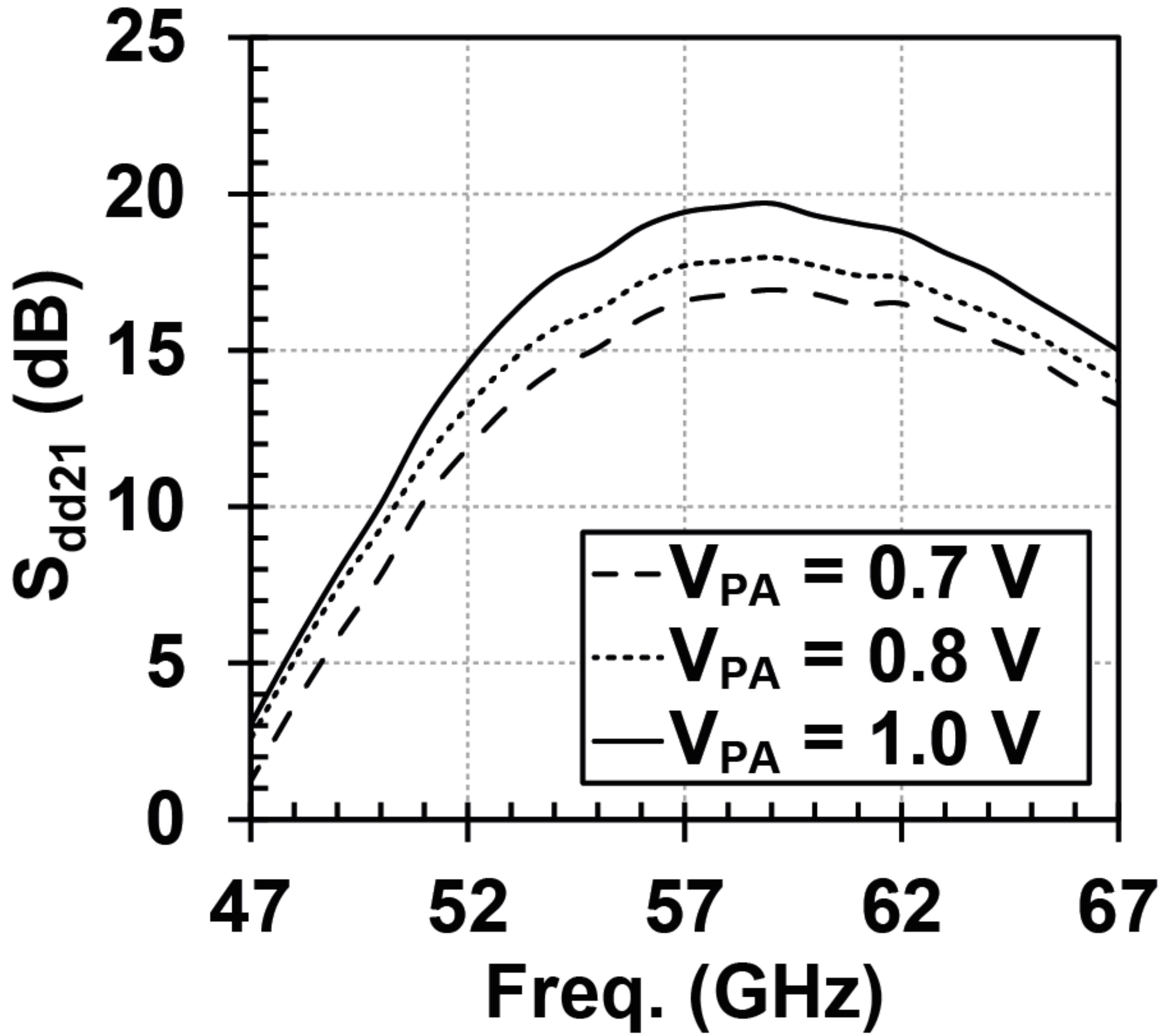


The cross-coupling capacitor technique is adopted to improve the stability and power gain

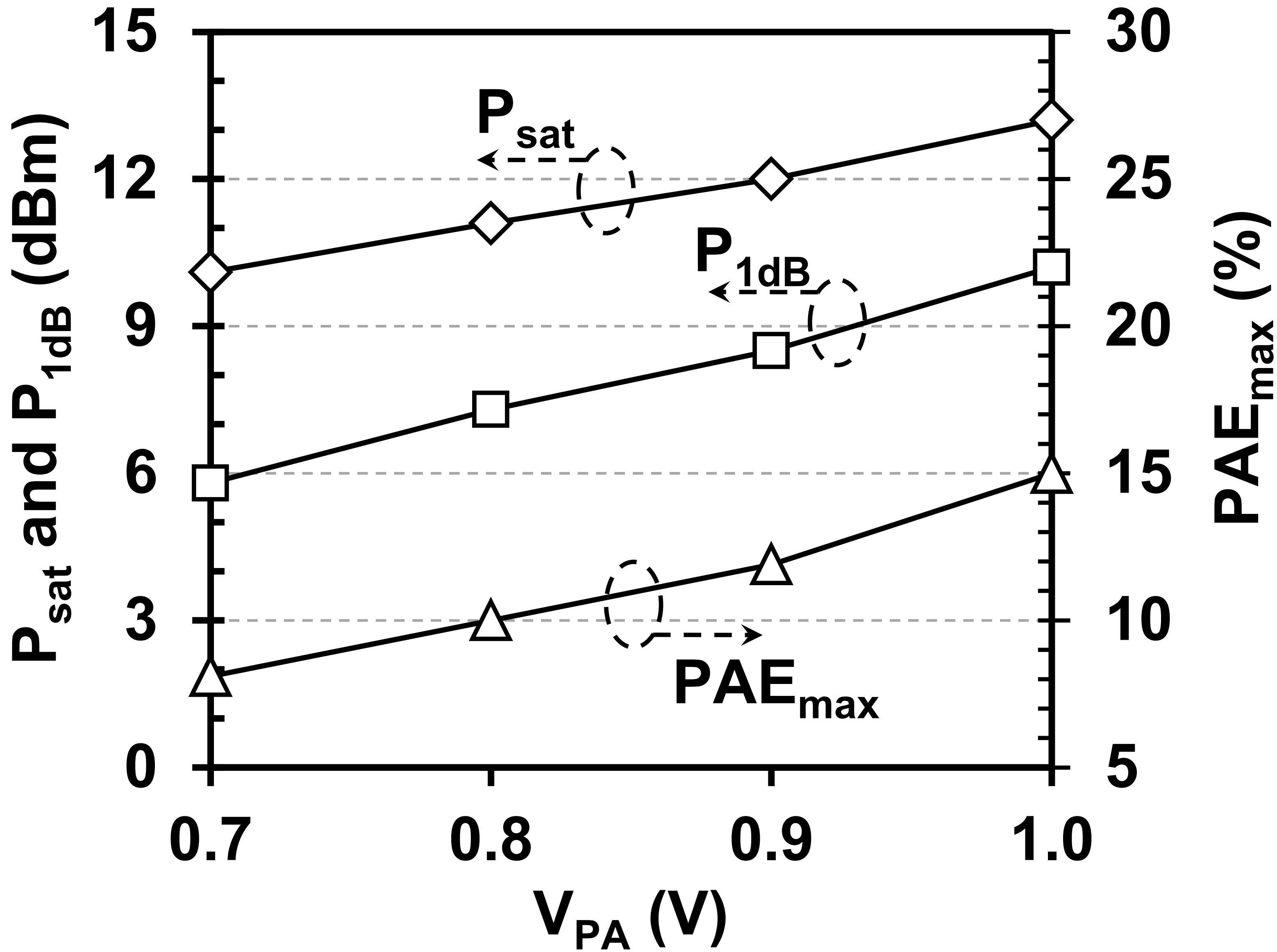
Die Micro-photograph



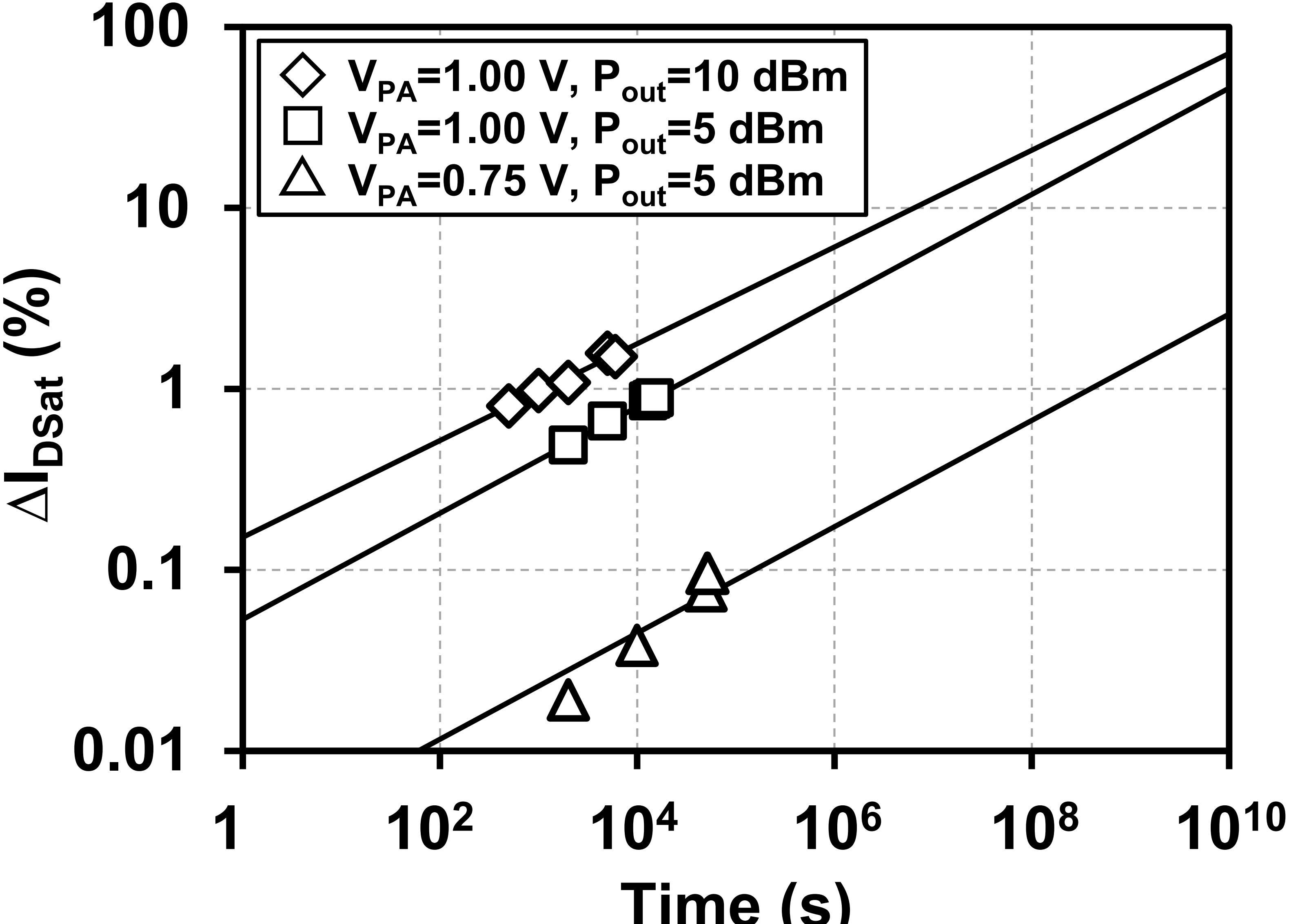
Measured Small-Signal S-parameter



PA Performance vs V_{PA} @60 GHz

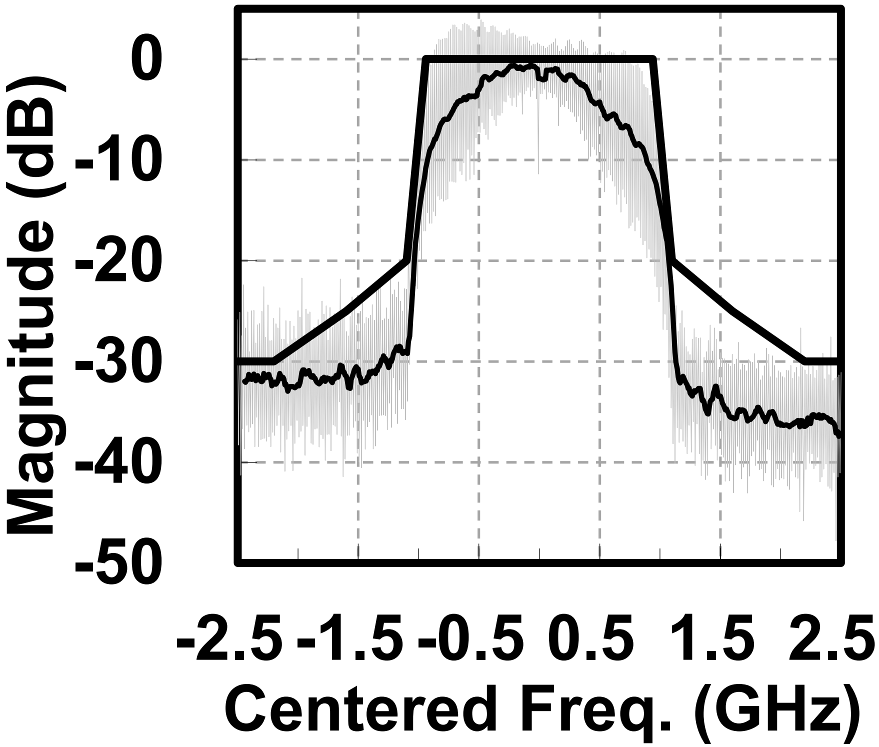


Measured Lifetime of the PA

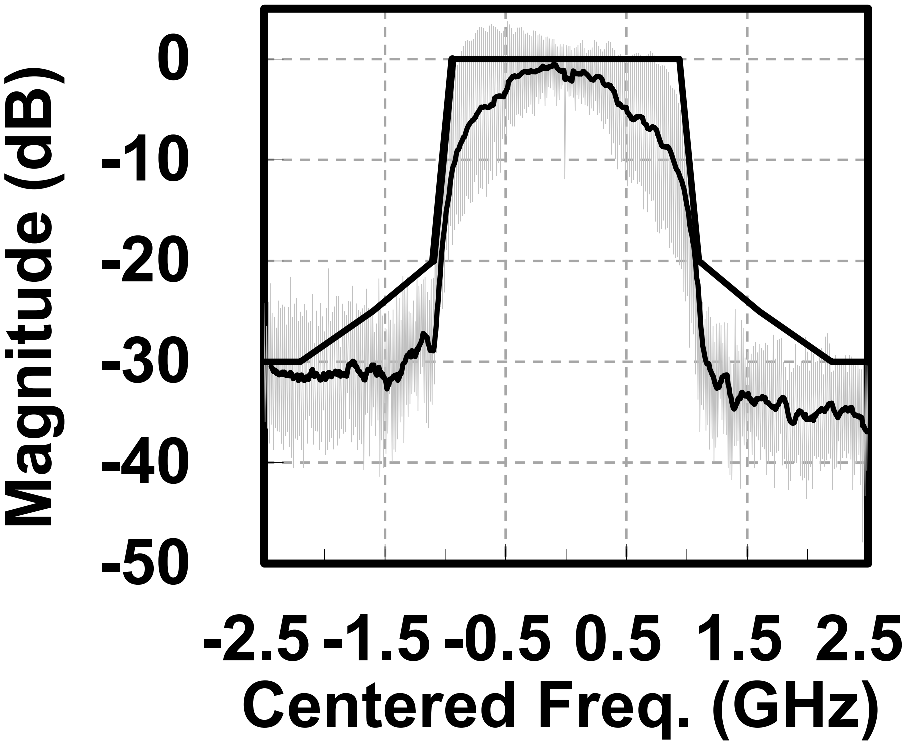


Measured Output Spectrum

IEEE 802.15.3c Spectrum mask



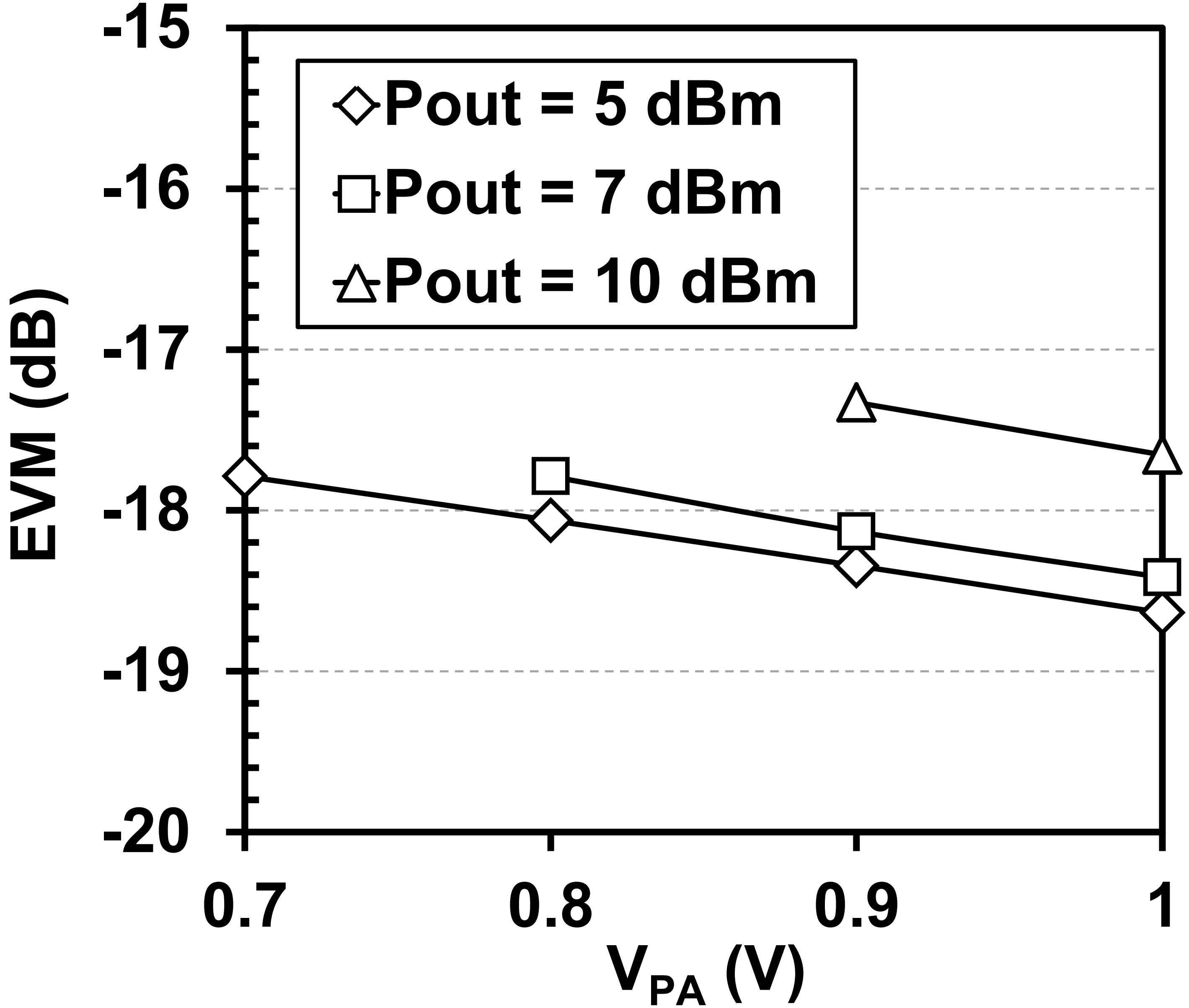
(a)



(b)

Spectrum centered at 62.64 GHz for QPSK modulation
(a) V_{PA}=1.0 V, P_{out}=4 dBm; (b) V_{PA}=0.7 V, P_{out}=3 dBm

Measured EVM for QPSK Modualtion



60 GHz CMOS PA Performance Comparison

Ref.	Process	Vdd (V)	P_{1dB} (dBm)	P_{sat} (dBm)	PAE_{max} (%)	Lifetime (year)
[5]	65 nm SOI	1.2	7.1	10.5	22.3	N/A
		1.8	12.7	14.5	25.7	
		2.6	15.2	16.5	18.2	
[6]	90 nm	0.7	5.2	8.5	7.0	> 10^5*
		1.0	10.5	11.5	8.5	> 10*
[7]	65 nm	1.0	15.0	18.6	15.1	N/A
[8]	65 nm	1.0	8.0	11.5	15.2	> 10*
This work	65 nm	0.7†	5.8	10.1	8.1	> 10^2
		1.0†	10.2	13.2	15.0	> 0.2

† Only for the last stage V_{PA}

* Non-measured results

[5] A. Siligaris et. al, JSSC 2010

[6] M. Tanomura et. al, ISSCC 2008

[7] J. Chen et. al, ISSCC 2011

[8] W. L. Chan et. al, JSSC 2010

Conclusions

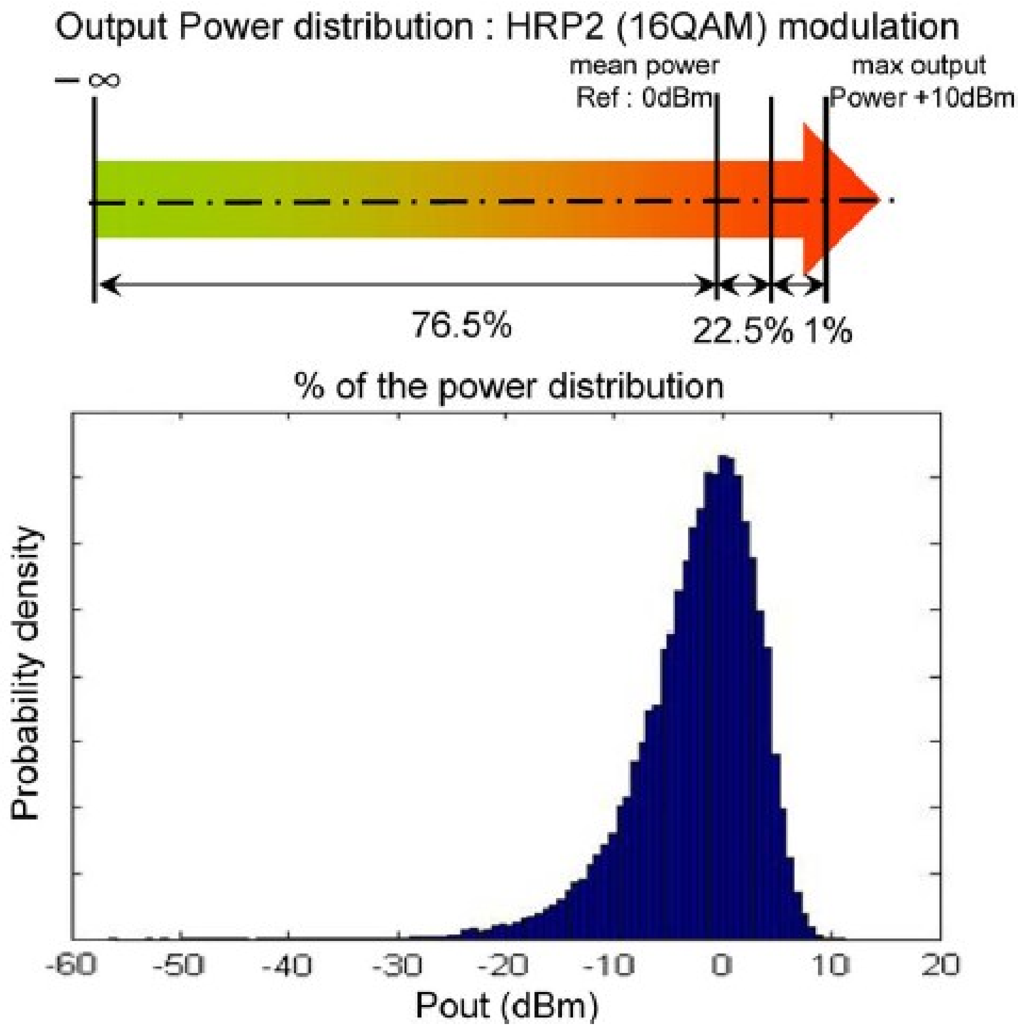
– The lifetime of the proposed PA can be improved dramatically by dynamic operation.

– The tunable supply offers a possibility to meet different linearity, efficiency, output power and lifetime requirements in actual applications.

– The PA is insensitive to the process variations thanks to the tunable supply voltage.

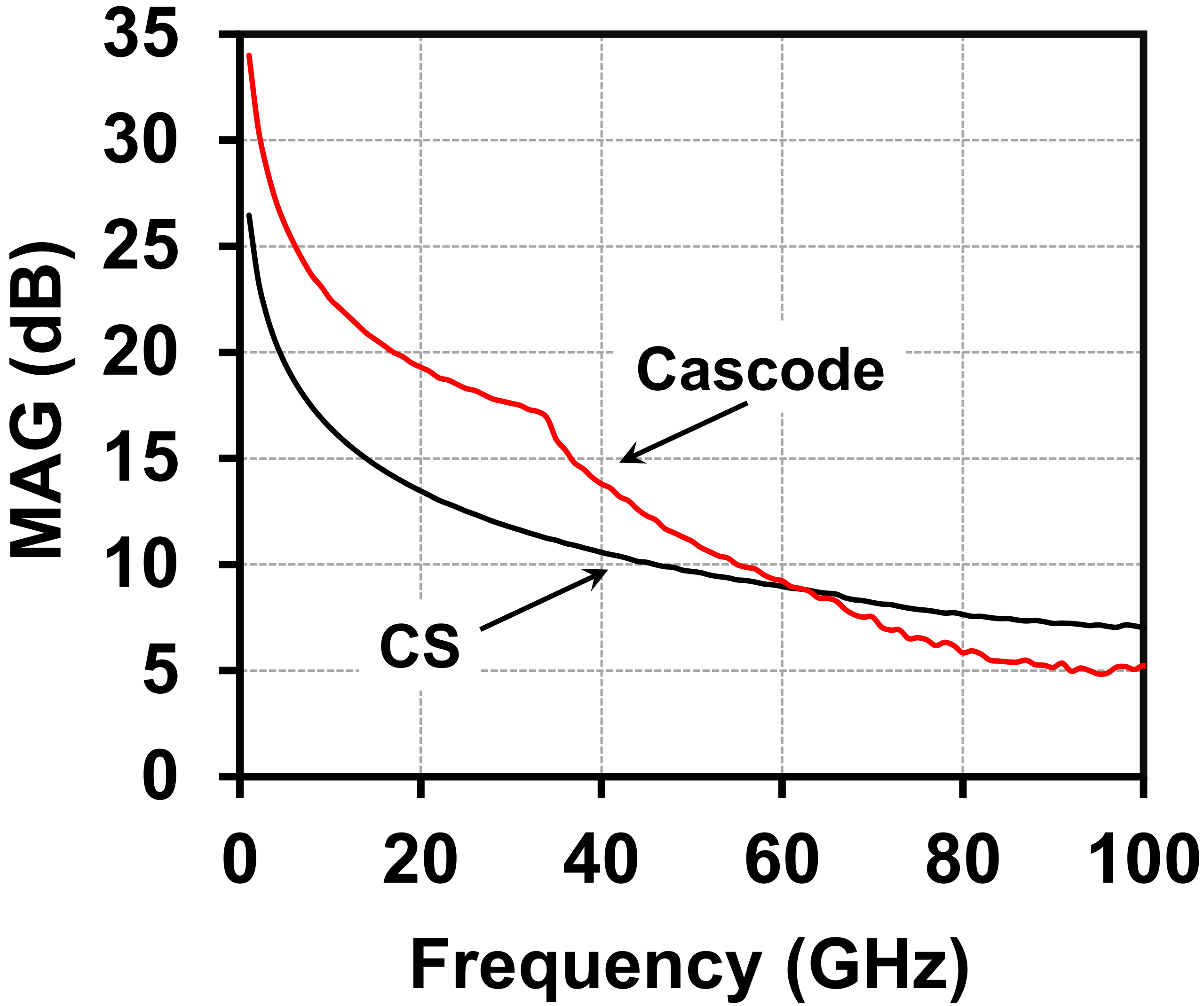
Thank you for your attention!

Output Power Distribution [5]



[5] A. Siligaris et. al, JSSC 2010

Transistor Measurement Data

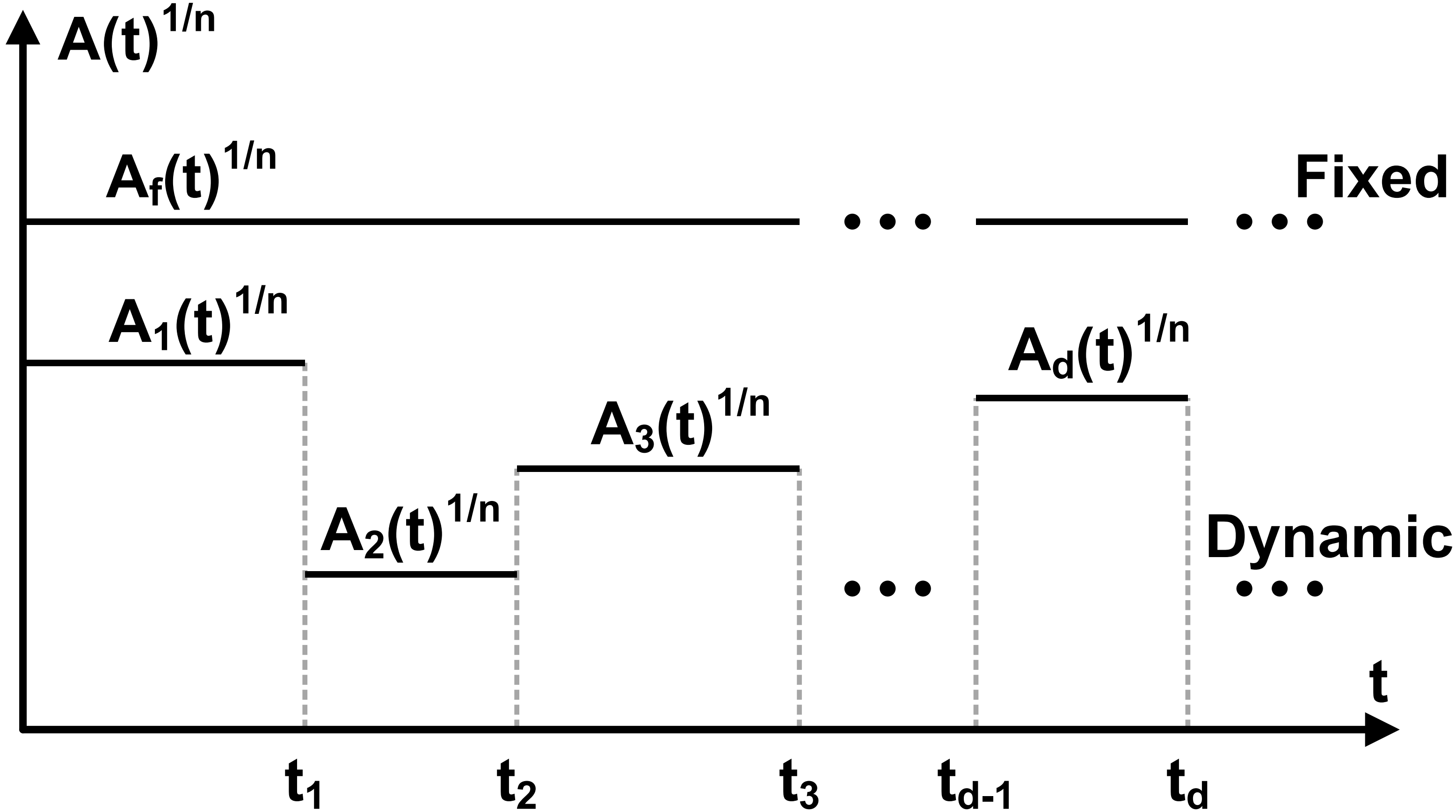


[9] Q. Bu et. al, SSDM 2012

Power Consumption

V_{PA}	$I_{Digital}$	I_{Analog}	I_{PA}
1.0 V	64 μA	312 μA	130 mA
0.7 V	64 μA	312 μA	120 mA

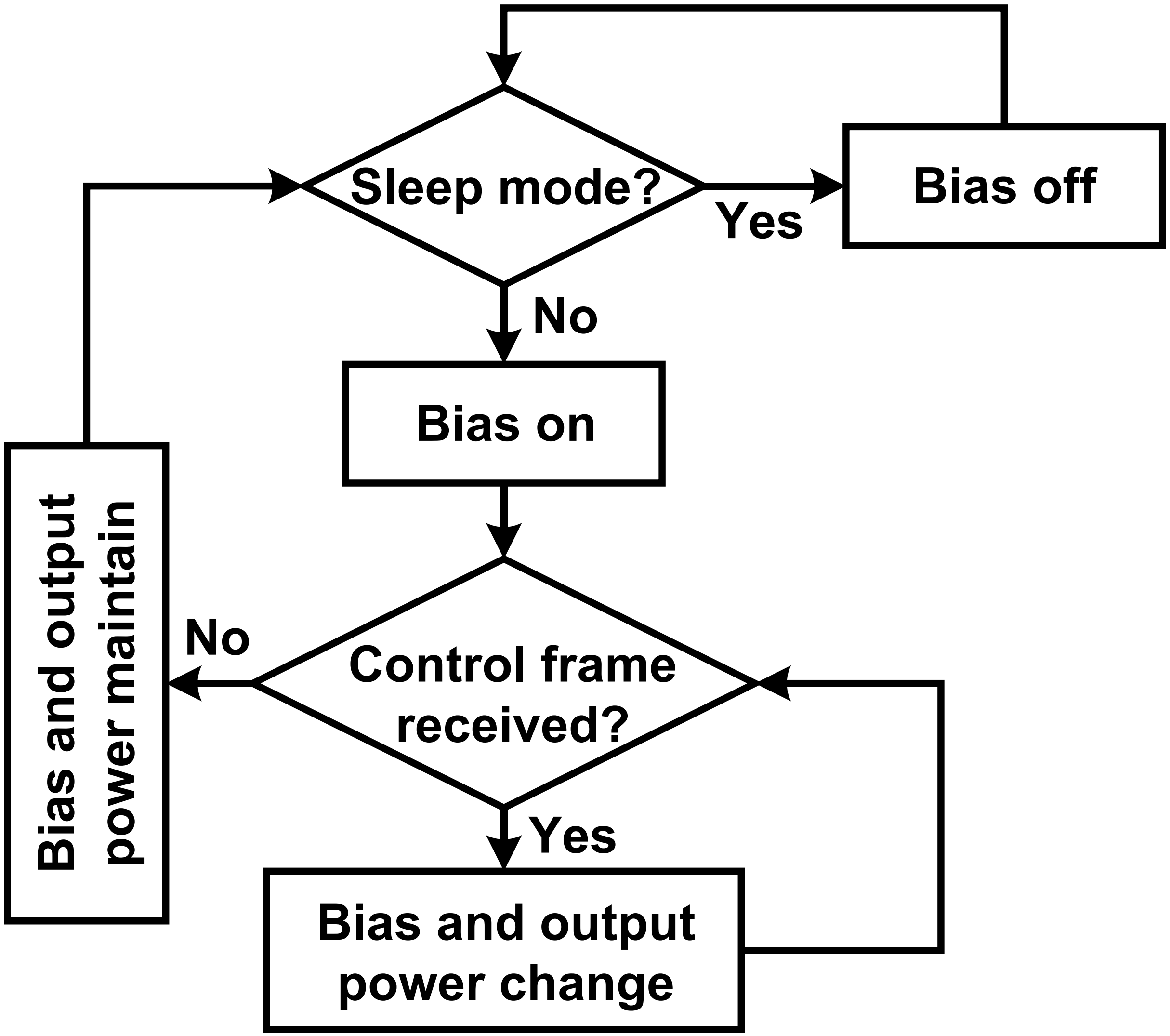
Lifetime Improvement of the PA



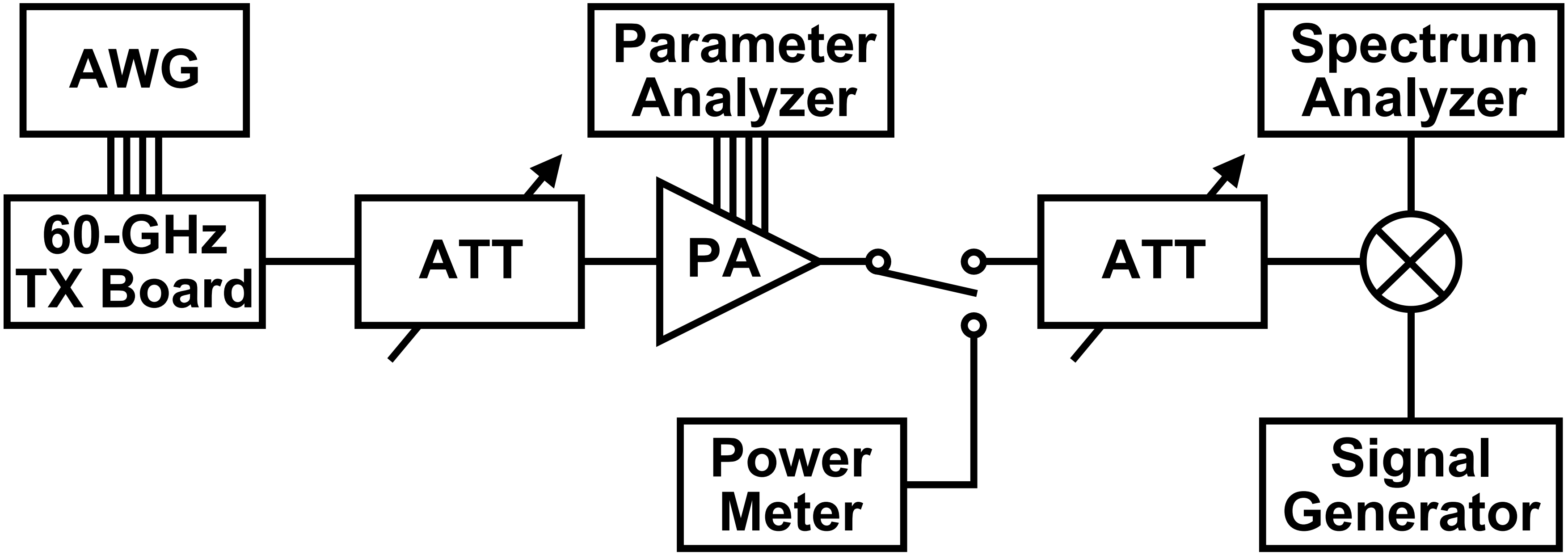
$$\Delta I_{DSat}(t) = \left[\int_0^t A(\tau)^{\frac{1}{n}} d\tau\right]^n = \left[\int_0^{t_1} A_1^{\frac{1}{n}}(\tau)d\tau + \int_{t_1}^{t_2} A_2^{\frac{1}{n}}(\tau)d\tau \cdots + \int_{t_{d-1}}^{t_d} A_d^{\frac{1}{n}}(\tau)d\tau \cdots\right]^n$$

Age function

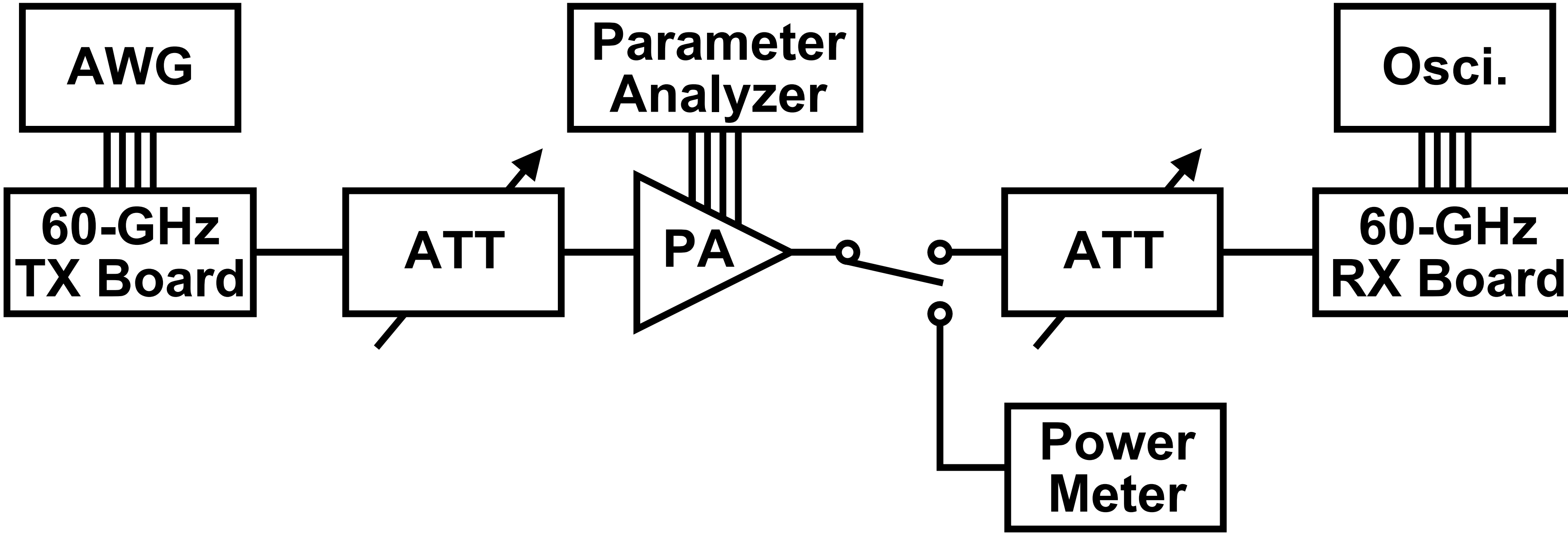
The Flow Chart of Dynamic Operation



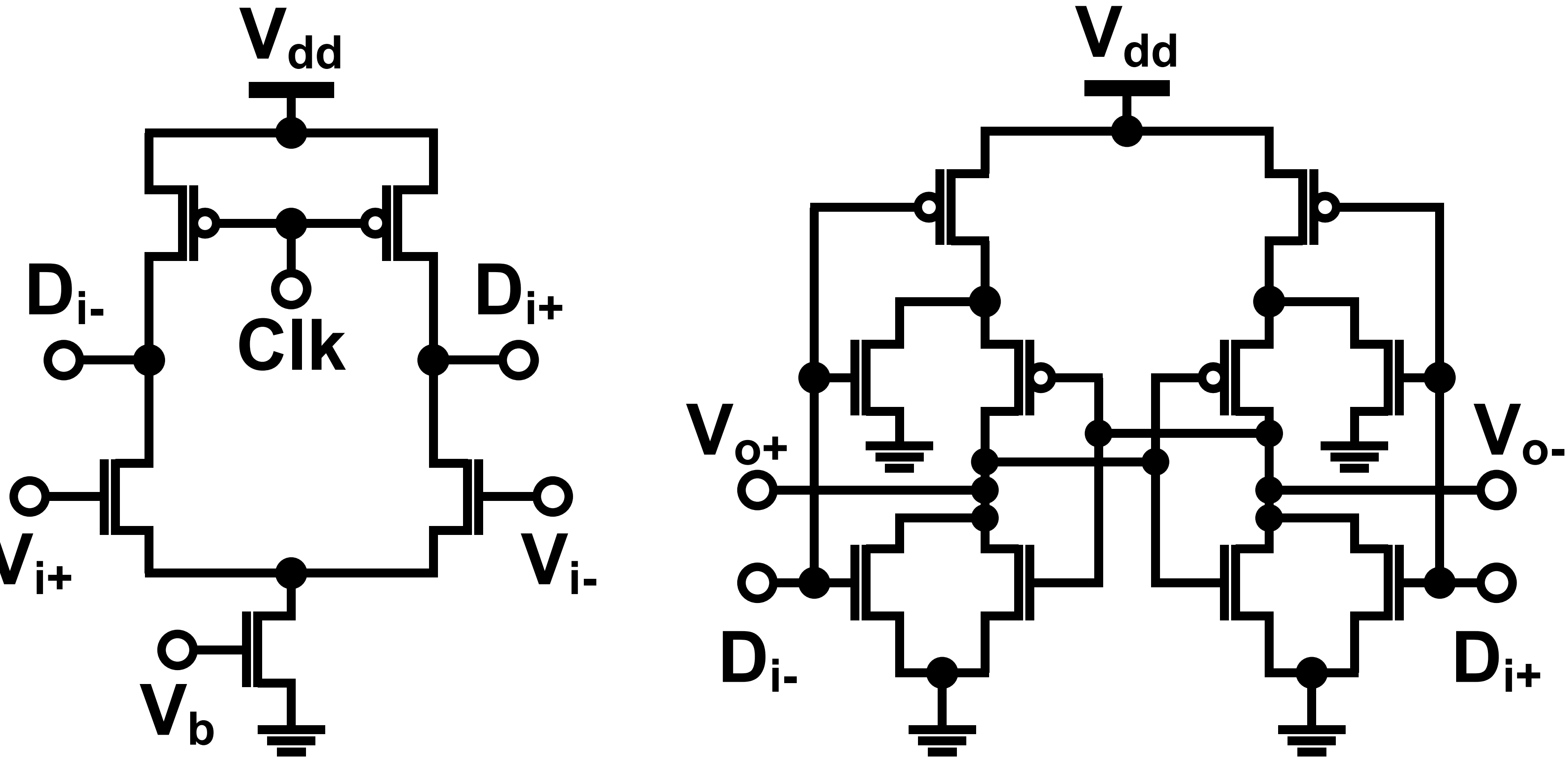
Spectrum Measurement Setup



EVM Measurement Setup



Dynamic Comparator Schematic [9]



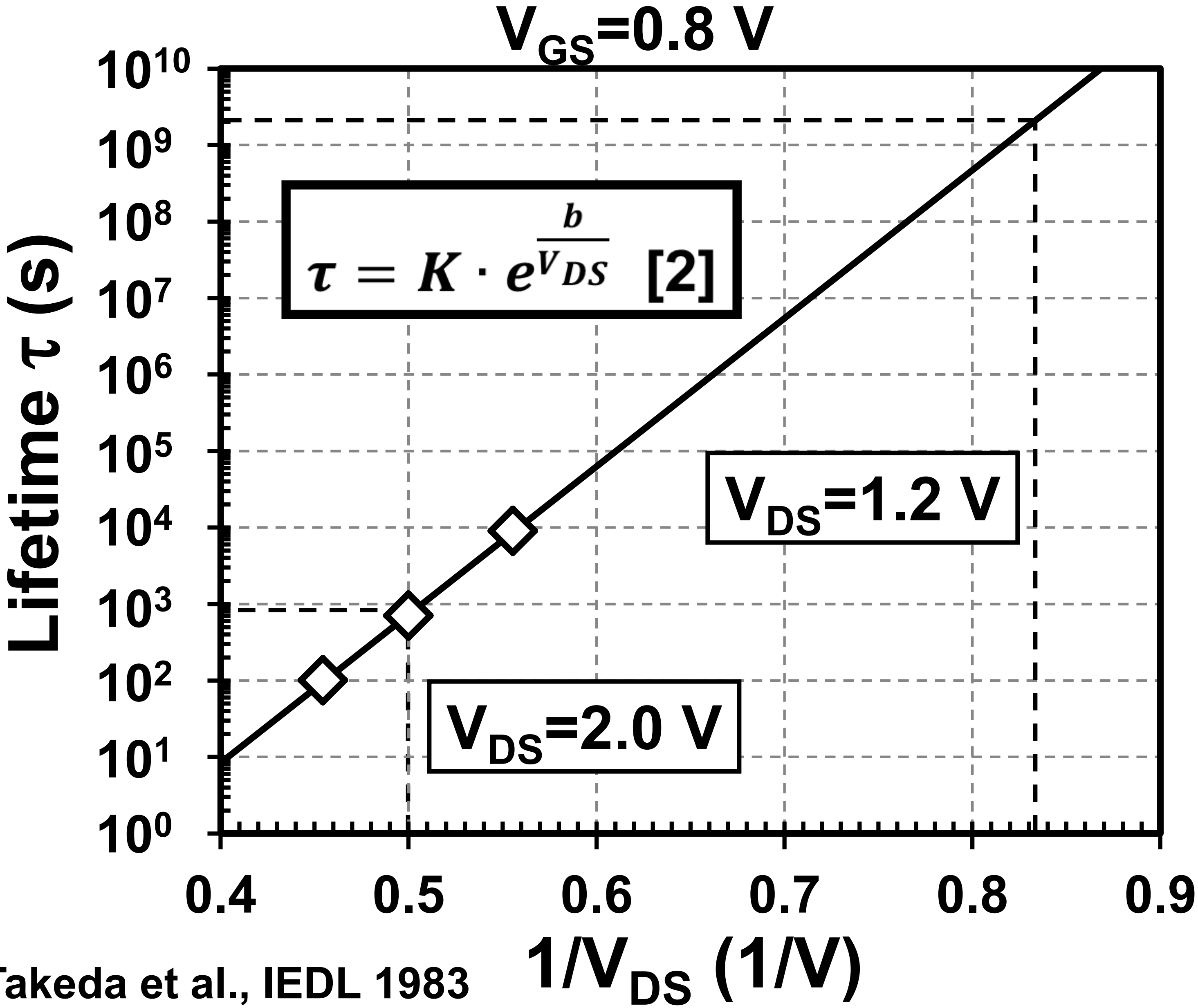
(a) First stage (b) Second stage

[9] M. Miyahara et. al, ASSCC 2008

- $V_{eff} = V_0 + V_{DS} - V_{dsat}$
- $V_{dsat} = \frac{2(V_{GS}-V_{tat})/m}{1+\sqrt{1+\frac{2(V_{GS}-V_{tat})}{mE_CL}}}$

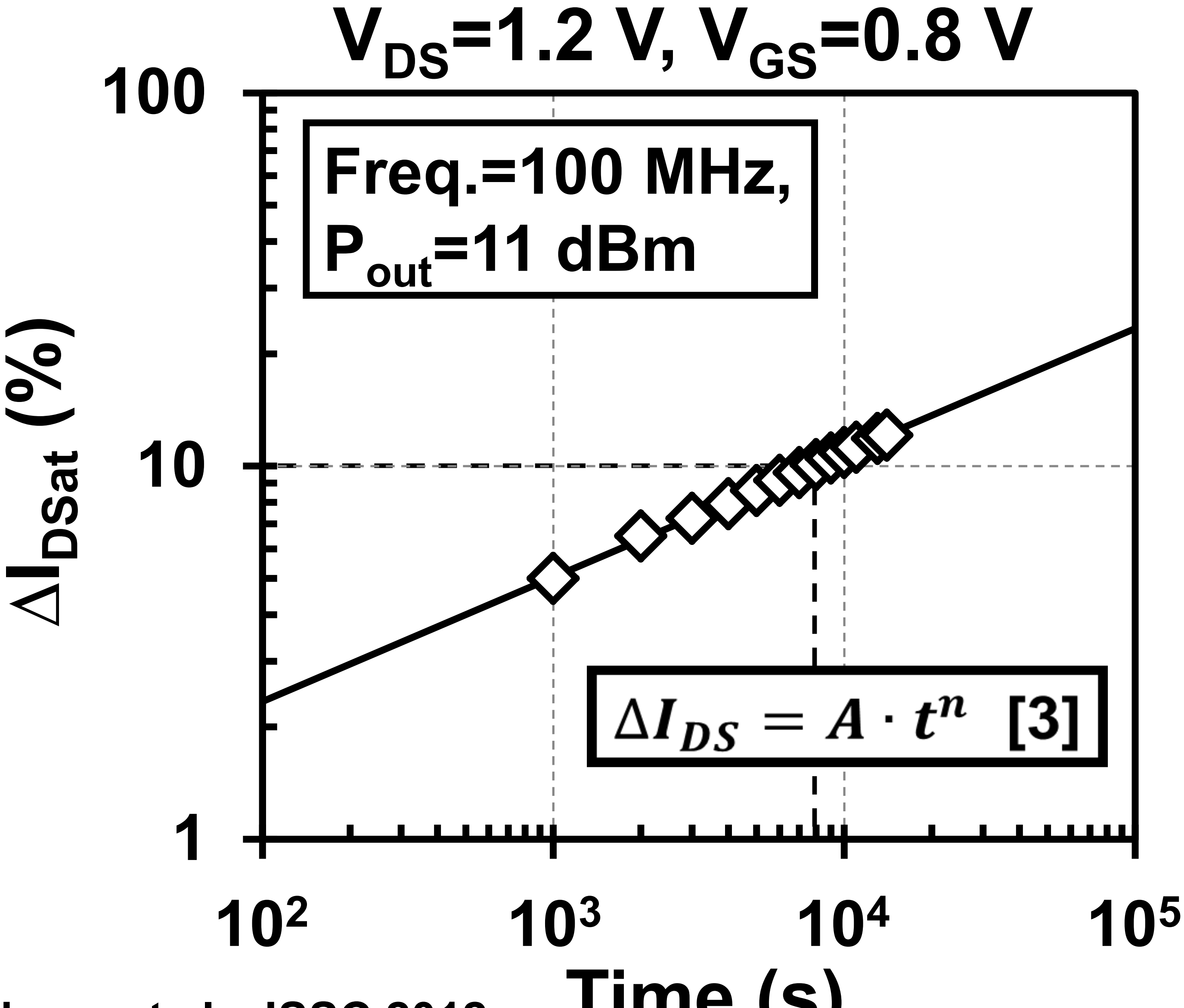
V_{eff} is the effective potential from the drain to channel pinch-off point;
V_0 is a halo-based potential, E_c is the critical field for velocity saturation, and m is a coefficient related to the body effect.
V_{GS} increases, I_{DS} and V_{dsat} increase which leads to V_{eff} decrease.

65 nm NMOSFET DC Stress Lifetime



[2] E. Takeda et al., IEDL 1983

65 nm NMOSFET RF Stress Lifetime



[3] L. Negre et al., JSSC 2012

CMOS PA Performance Comparison

Ref.	Process	Freq. (GHz)	Vdd (V)	P_{1dB} (dBm)	P_{sat} (dBm)	PAE_{max} (%)
[5]	65 nm SOI	60	1.2	7.1	10.5	22.3
			1.8	12.7	14.5	25.7
			2.6	15.2	16.5	18.2
[6]	90 nm	60	0.7	5.2	8.5	7.0
			1.0	10.5	11.5	8.5
[7]	65 nm	60	1.0	15.0	18.6	15.1
[8]	65 nm	60	1.0	8.0	11.5	15.2
This work	65 nm	60	0.7†	5.8	10.1	8.1
			1.0†	10.2	13.2	15.0

† Only for the last stage V_{PA}

[5] A. Siligaris et. al, JSSC 2010

[6] M. Tanomura et. al, ISSCC 2008

[7] J. Chen et. al, ISSCC 2011

[8] W. L. Chan et. al, JSSC 2010

CMOS PA Performance Comparison

Ref.	Process	Vdd (V)	P_{1dB} (dBm)	P_{sat} (dBm)	PAE_{max} (%)	Lifetime (year)
[5]	65 nm SOI	1.2	7.1	10.5	22.3	N/A
		1.8	12.7	14.5	25.7	
		2.6	15.2	16.5	18.2	
[6]	90 nm	0.7	5.2	8.5	7.0	> 10^{5}*
		1.0	10.5	11.5	8.5	> 10*
[7]	65 nm	1.0	15.0	18.6	15.1	N/A
[8]	65 nm	1.0	8.0	11.5	15.2	> 10*
This work	65 nm	0.7†	5.8	10.1	8.1	> 10^{2}
		1.0†	10.2	13.2	15.0	> 0.2

† Only for the last stage V_{PA}

* Estimation results

[5] A. Siligaris et. al, JSSC 2010

[6] M. Tanomura et. al, ISSCC 2008

[7] J. Chen et. al, ISSCC 2011

[8] W. L. Chan et. al, JSSC 2010