A Study on Power Line Noise Reduction in Large Scale Integration

半導体集積回路における電源ノイズ低減に関する研究

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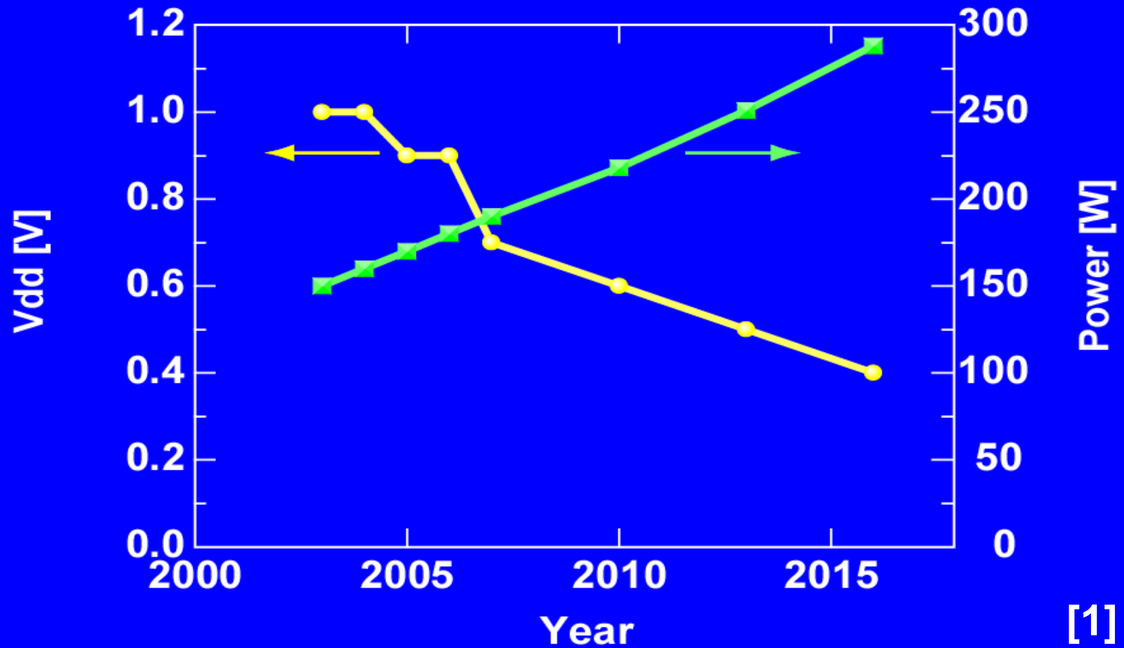
Final Defense for Ph.D

Introduction

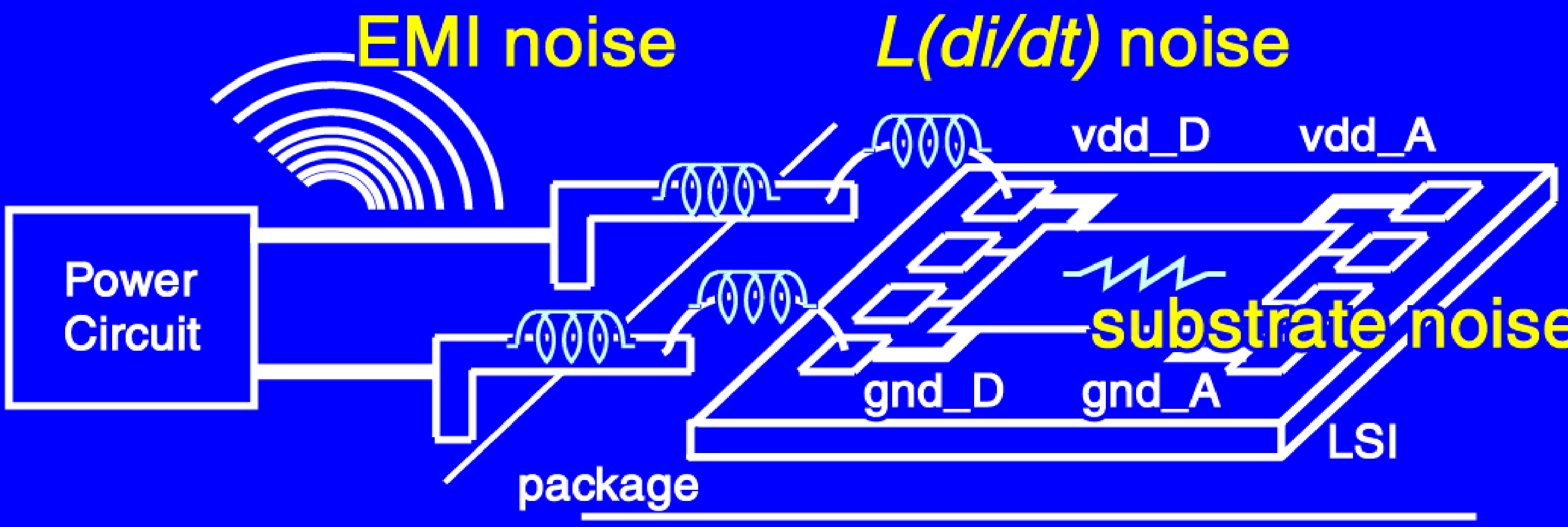
- Power supply voltage will decrease
  - Noise margin will be reduced
- Power and currents will increase
  - Noise amplitude will be increased



[1] *ITRS 2002 Roadmap*

Signal Integrity and di/dt

- Power supply noise : L(di/dt)
- EMI noise : caused by di/dt
- Substrate noise : related to power noise



Signal Integrity Problems

- Power supply noise
  - Timing violation – *delay* $\propto$ *1/(Vdd-Vth)*
  - Logic error
- Substrate noise
  - PLL jitter becomes 10 times bigger by the substrate noise [20]
- EMI noise
  - Operational problems in other devices
  - Regulations has been enforced [2]

[20] *P. Larsson, JSSC July 2001*
[2] *VCCI*

Improve Signal Integrity

- Reduce the di/dt
- Measure the di/dt
- Use the di/dt for substrate noise reduction

Contents

- Introduction
- Comparison of stubs and decoupling capacitor for noise reduction
- Experiments for power supply noise reduction using stubs
- On-chip di/dt detector for power supply
- Feedforward active substrate noise cancelling using the di/dt detector
- Conclusions

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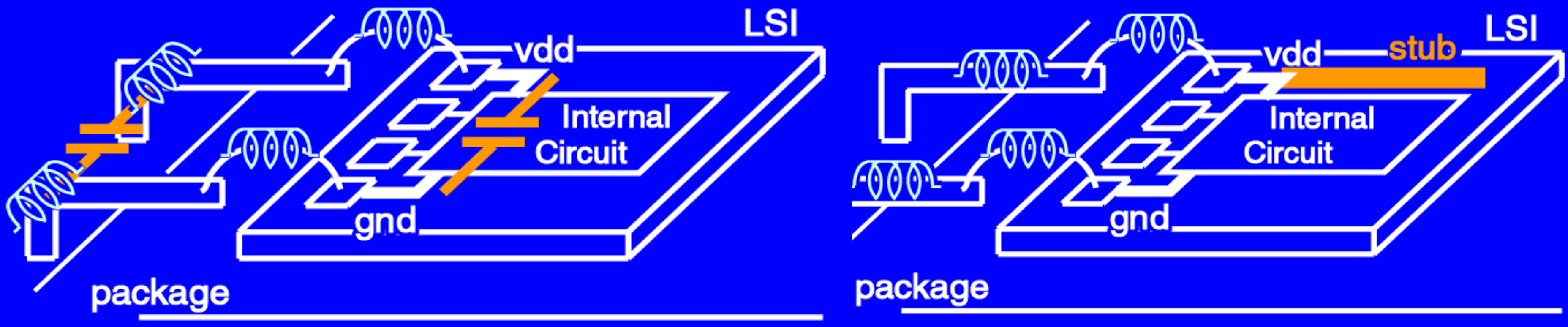
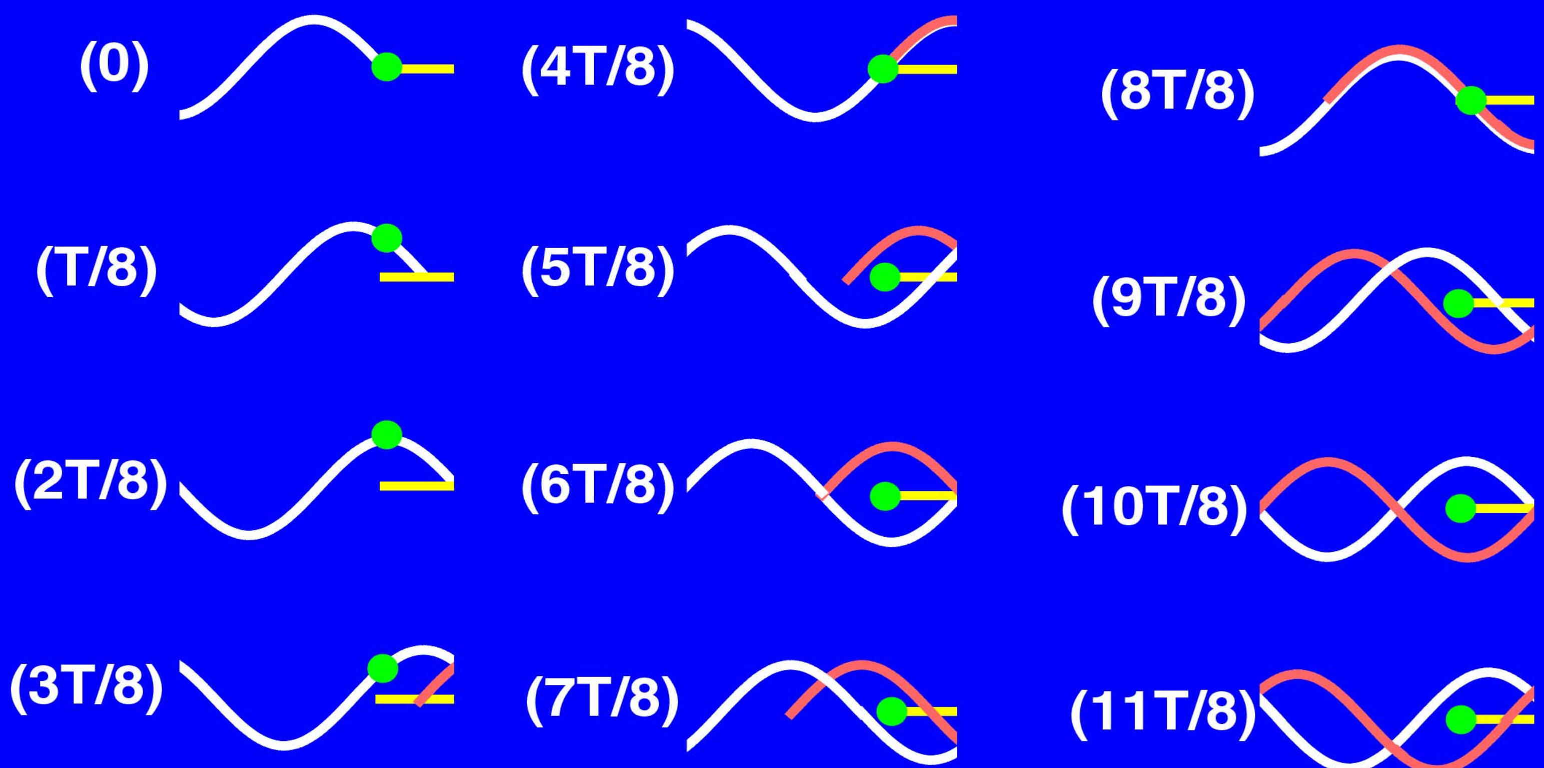
Background – di/dt Reduction –

- Decoupling capacitor
  - Area penalty, parasitic inductance
- Attach the stub to the power line will reduce the power supply noise

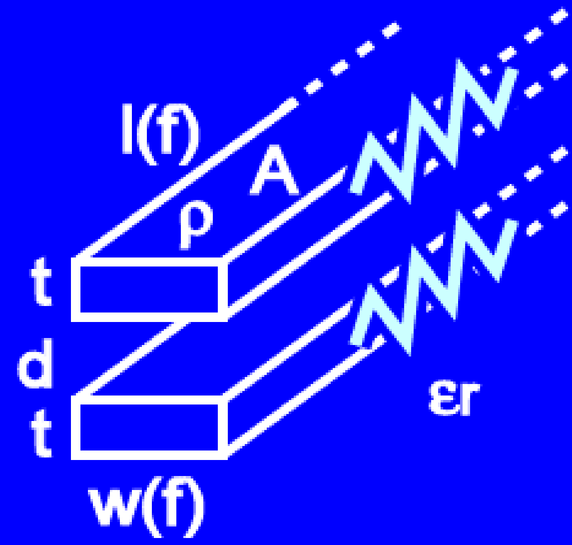


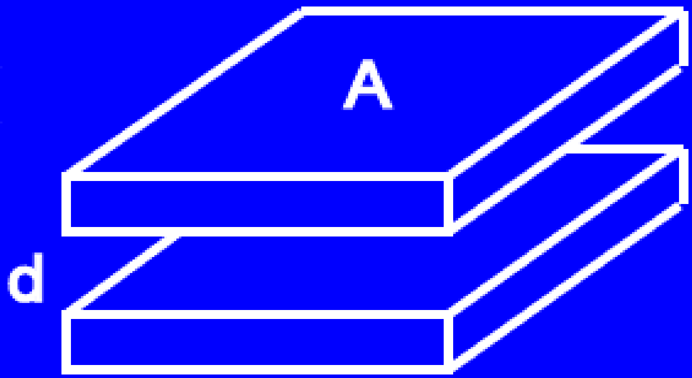
Waveform in Ideal λ/4 Stub

- The forward- and backward-going waves are cancelled



Stub and Capacitor Impedance





$$l = \frac{\lambda}{4} = \frac{c/\sqrt{\varepsilon_r}}{4f}$$

$$Zcap = \frac{1}{j\omega Ctotal} = \frac{d}{2\pi f \varepsilon_r \varepsilon_0 A}$$

$$w = \frac{A}{l} = \frac{4Af\sqrt{\varepsilon_r}}{c}$$

$$Zstub = \ldots$$

Boundary Frequency

- Stub input impedance $Zstub \propto f^{-2}, f^{-1.5}$
- Capacitor input impedance $Zcap \propto f^{-1}$
- Boundary frequency at $Zstub = Zcap$

$$fB = \frac{\pi c^2 \varepsilon_0 \rho}{8td} \qquad \frac{t3}{A} < \frac{16\rho\sqrt{\varepsilon_r}\,\varepsilon_0 c}{\pi} \text{ and } t < \frac{16d}{\pi 2}$$

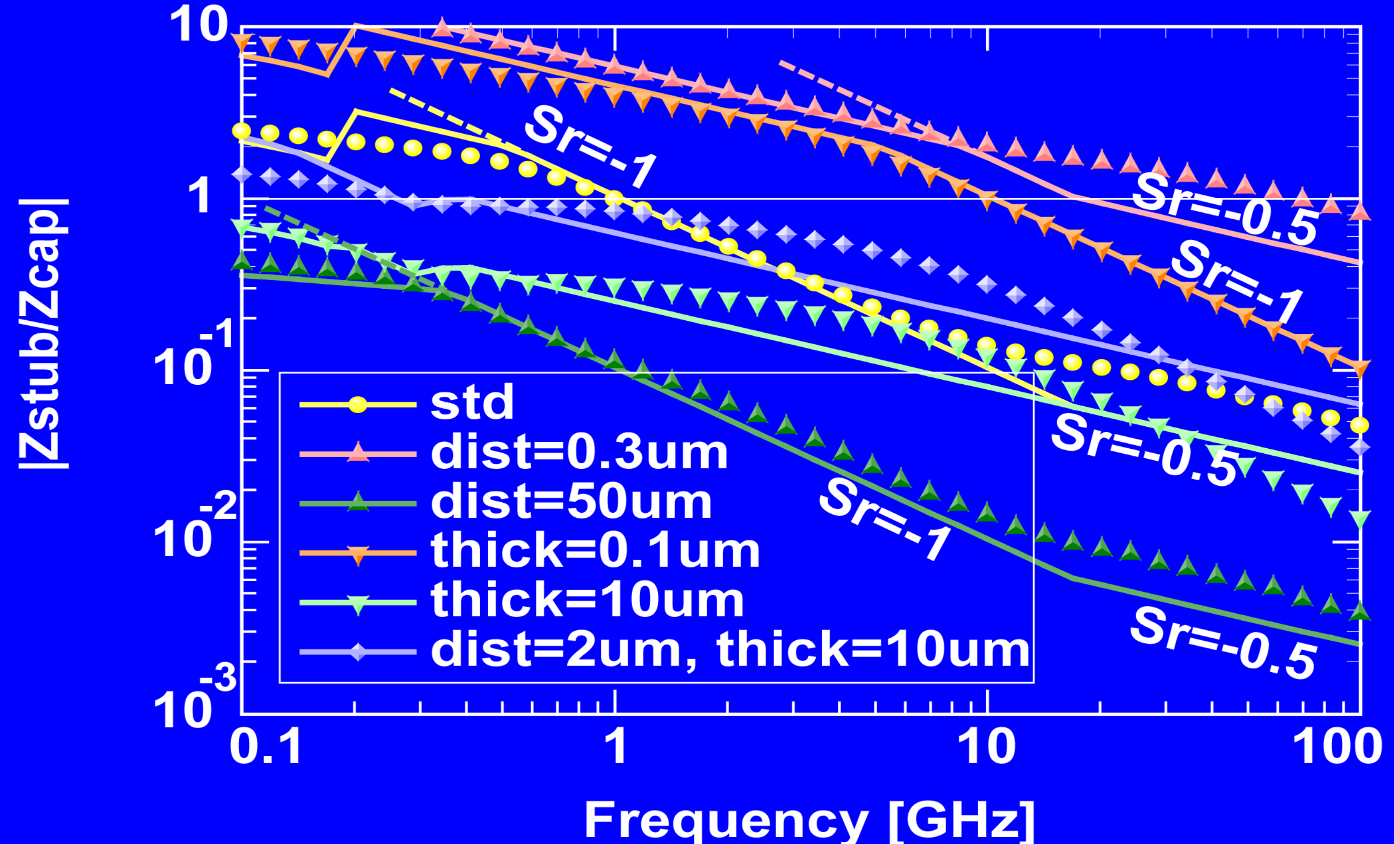
$$\frac{t3}{A} > \frac{16\rho\sqrt{\varepsilon_r}\,\varepsilon_0 c}{\pi} \text{ and } t > \frac{\pi 3 c\sqrt{\varepsilon_r}\,\varepsilon_0 \rho A}{64d2}$$

$$fB = \frac{\pi 3 c^2 \varepsilon_0 \rho}{256d2} \qquad \frac{t3}{A} < \frac{16\rho\sqrt{\varepsilon_r}\,\varepsilon_0 c}{\pi} \text{ and } t > \frac{16d}{\pi 2}$$

$$\frac{t3}{A} > \frac{16\rho\sqrt{\varepsilon_r}\,\varepsilon_0 c}{\pi} \text{ and } t < \frac{\pi 3 c\sqrt{\varepsilon_r}\,\varepsilon_0 \rho A}{64d2}$$

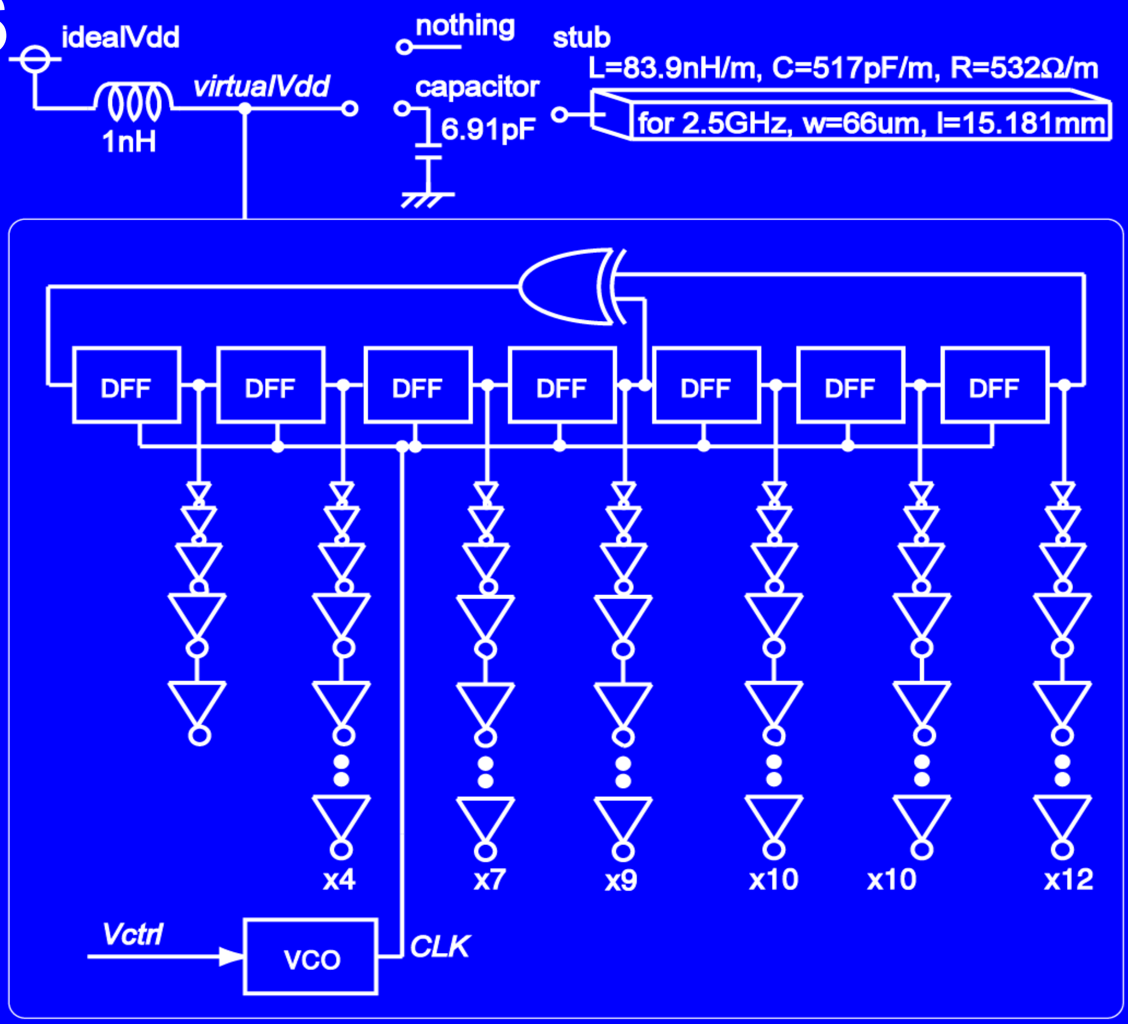
Numerical Analysis

- Raphael(L,C), Fasthenry(R) vs. the model
- d=5um, t=1um, A=1mm2, εr=3.9, ρ=ρCu

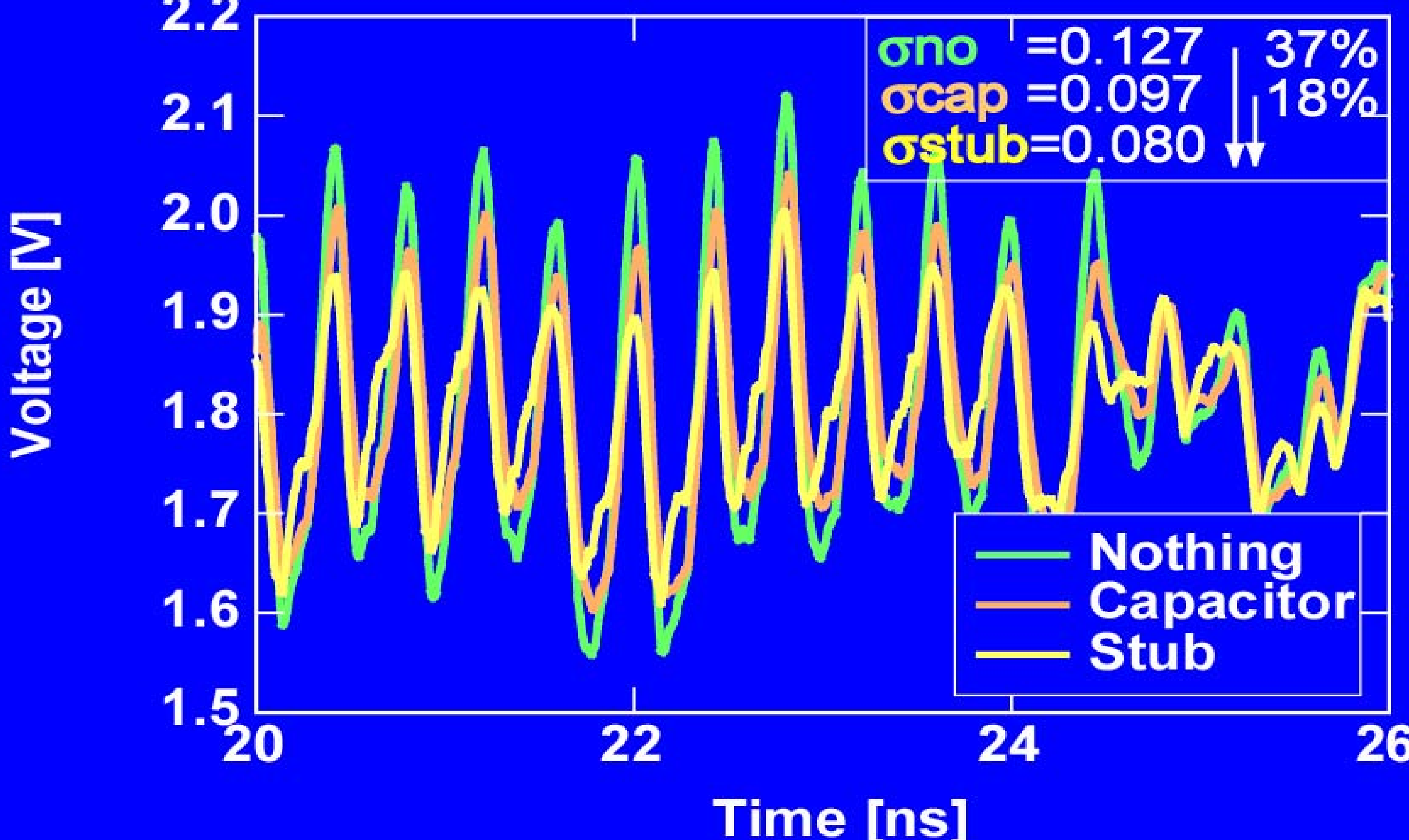


Circuit Simulation

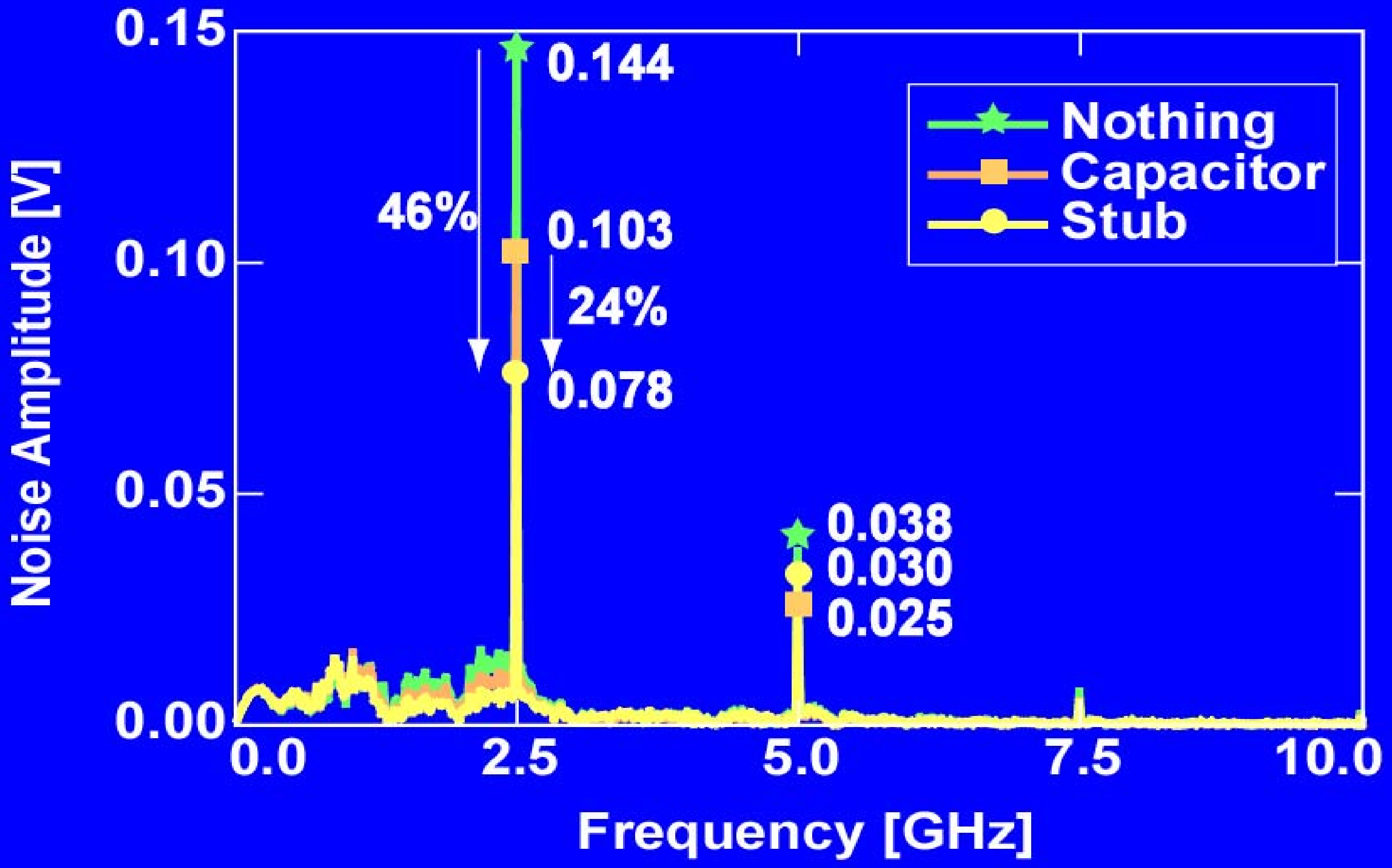
- 0.18um CMOS
- *fop*=2.5GHz



Power Supply Noise Waveform



Power Supply Noise Spectrum



Short Summary

- Stubs and capacitors are compared for power supply noise reduction
- Boundary frequency above which stubs are more effective than decoupling capacitors is clarified
- Circuit simulation shows that the stub reduces 37% and 18% of the power supply noise compared with the nothing and the capacitor case.
- It is theoretically shown that stubs will have more advantage over capacitors for LSIs with higher operating frequency

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- Experiments for power supply noise reduction using stubs
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- Feedforward active substrate noise cancelling using the di/dt detector
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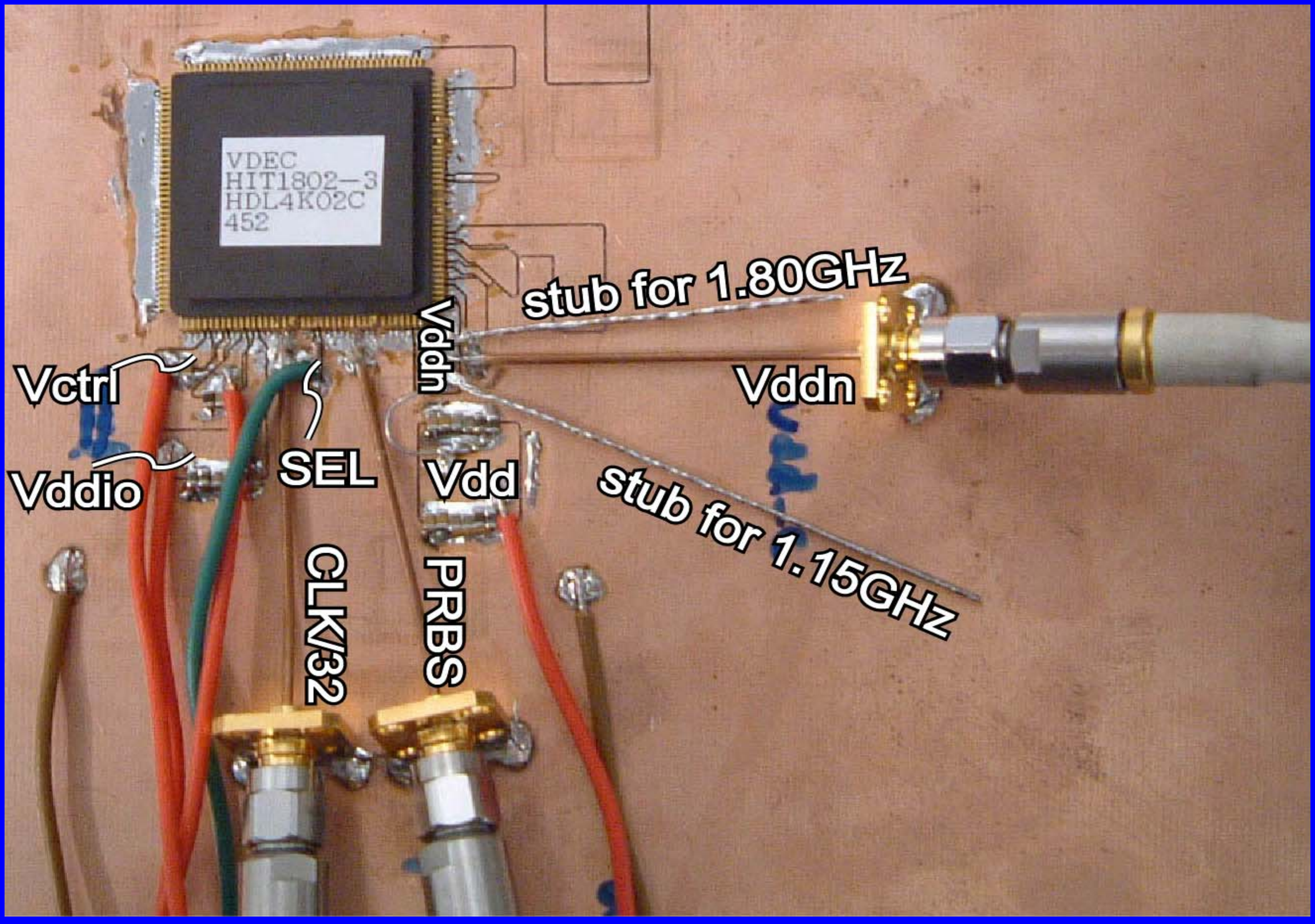
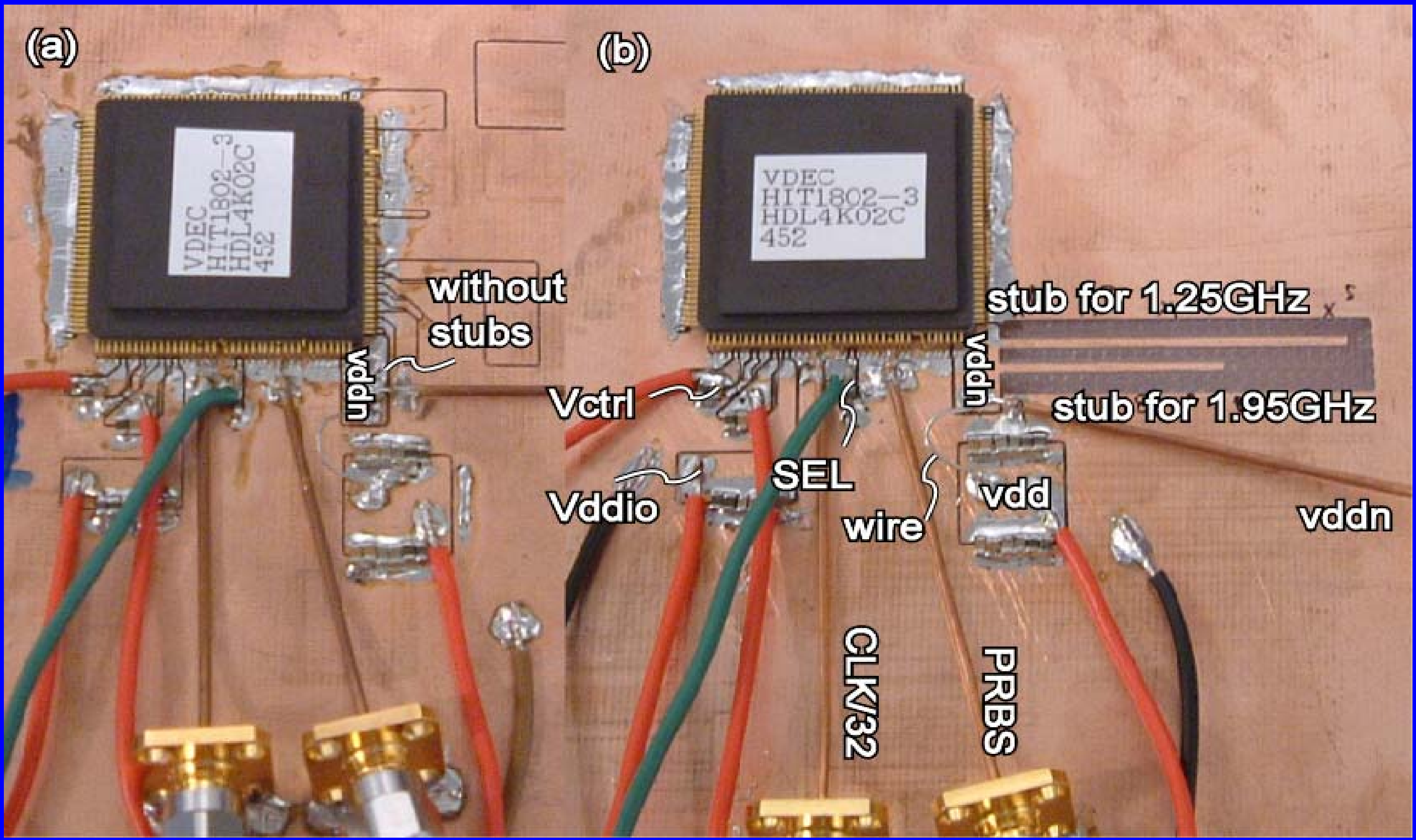
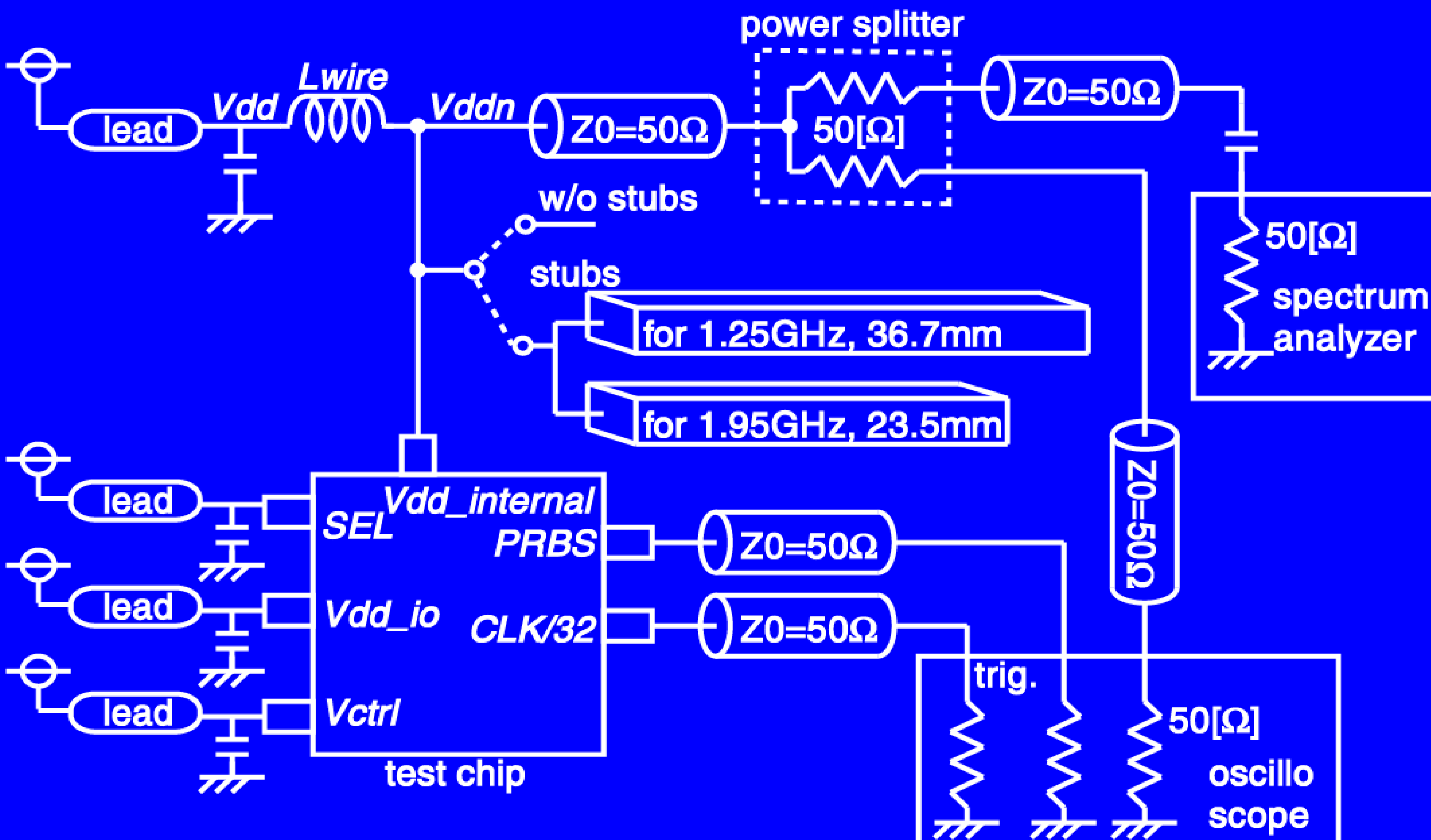
Off-chip Stubs



On-board Stubs

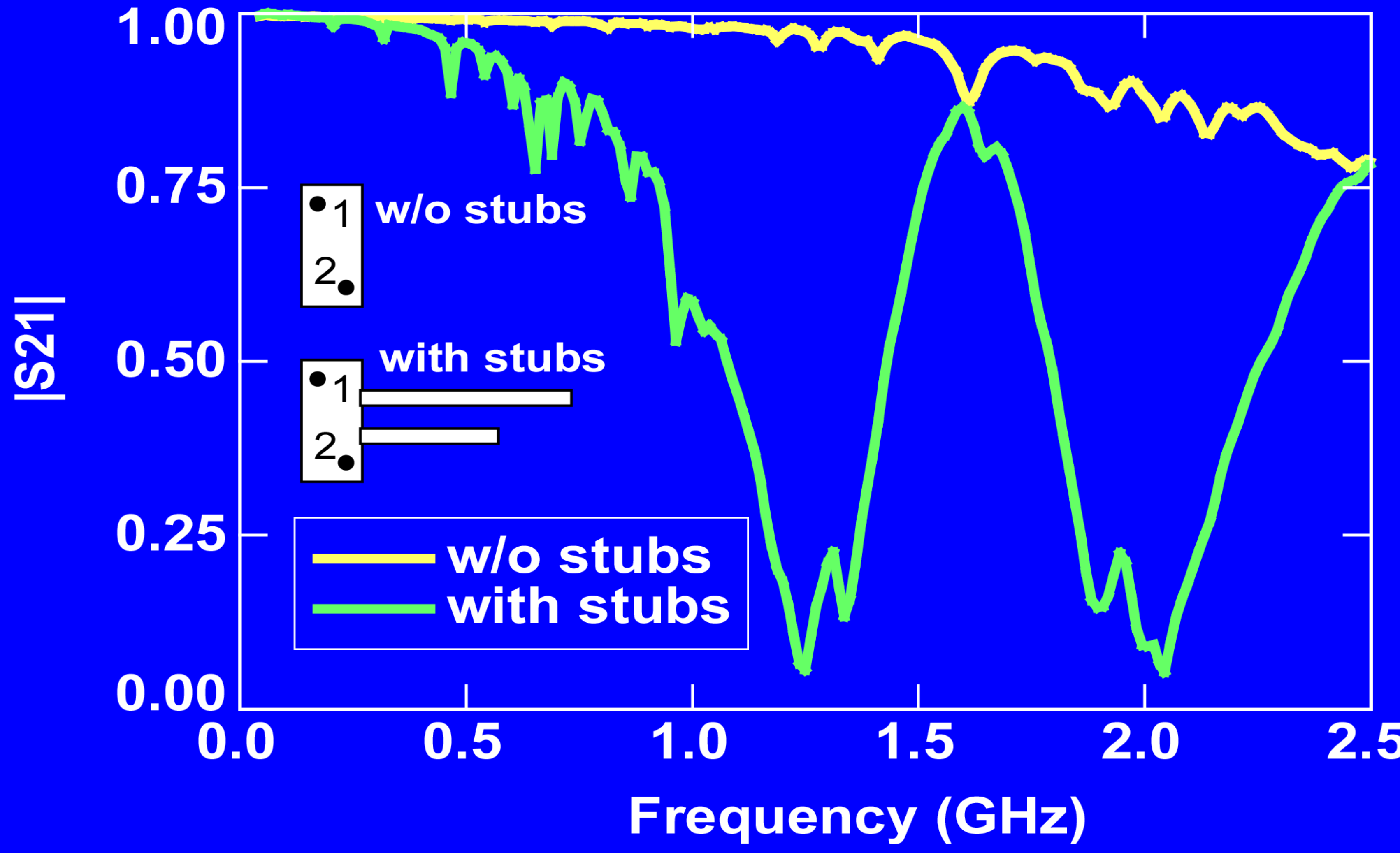


Schematic

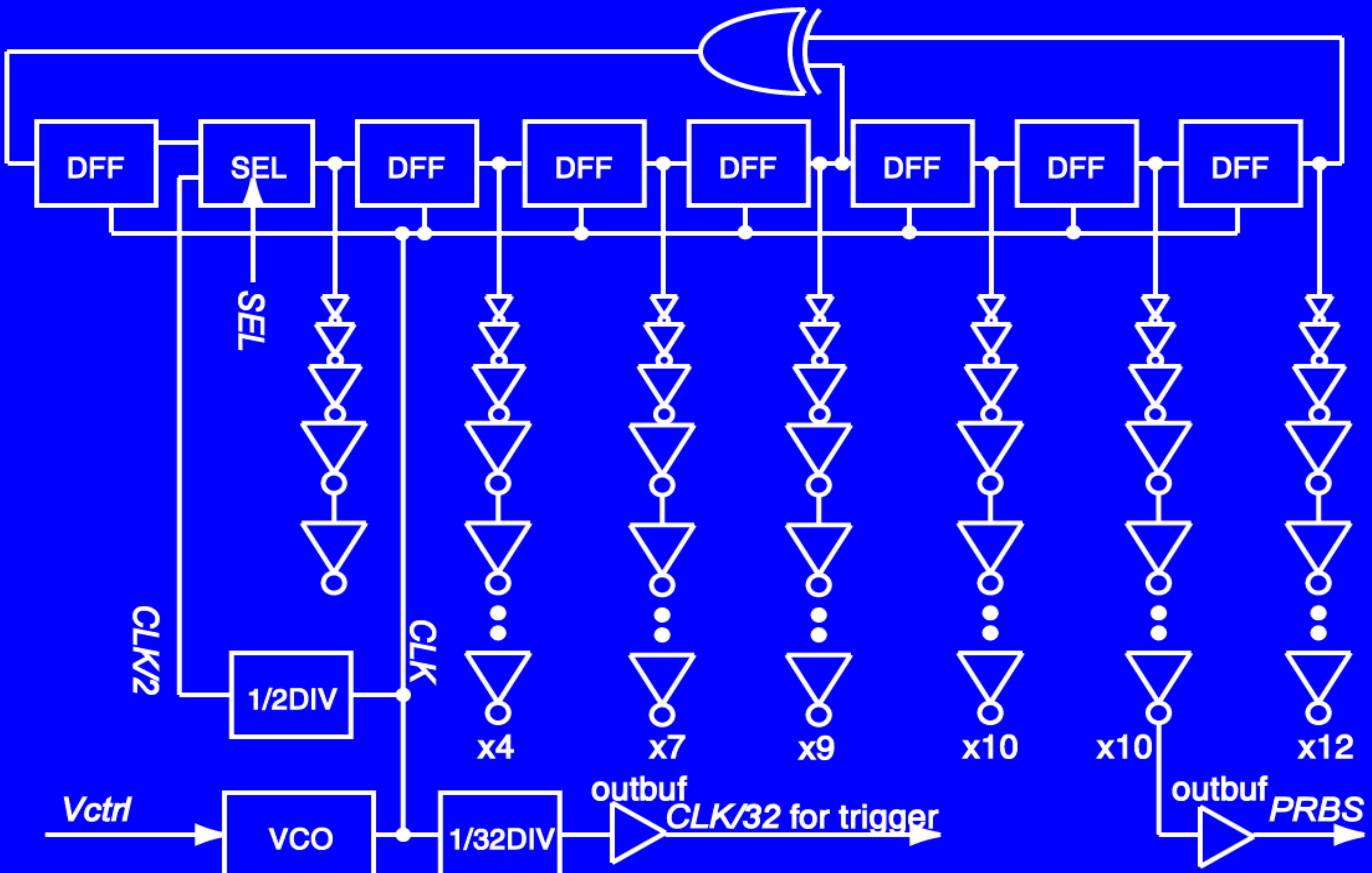


power splitter
lead
Vdd
Lwire
Vddn
Z0=50Ω
50[Ω]
Z0=50Ω
w/o stubs
stubs
50[Ω]
spectrum
analyzer
for 1.25GHz, 36.7mm
for 1.95GHz, 23.5mm
lead
SEL
Vdd_internal
PRBS
Z0=50Ω
Z0=50Ω
lead
Vdd_io
CLK/32
Z0=50Ω
trig.
lead
Vctrl
50[Ω]
oscillo
scope
test chip

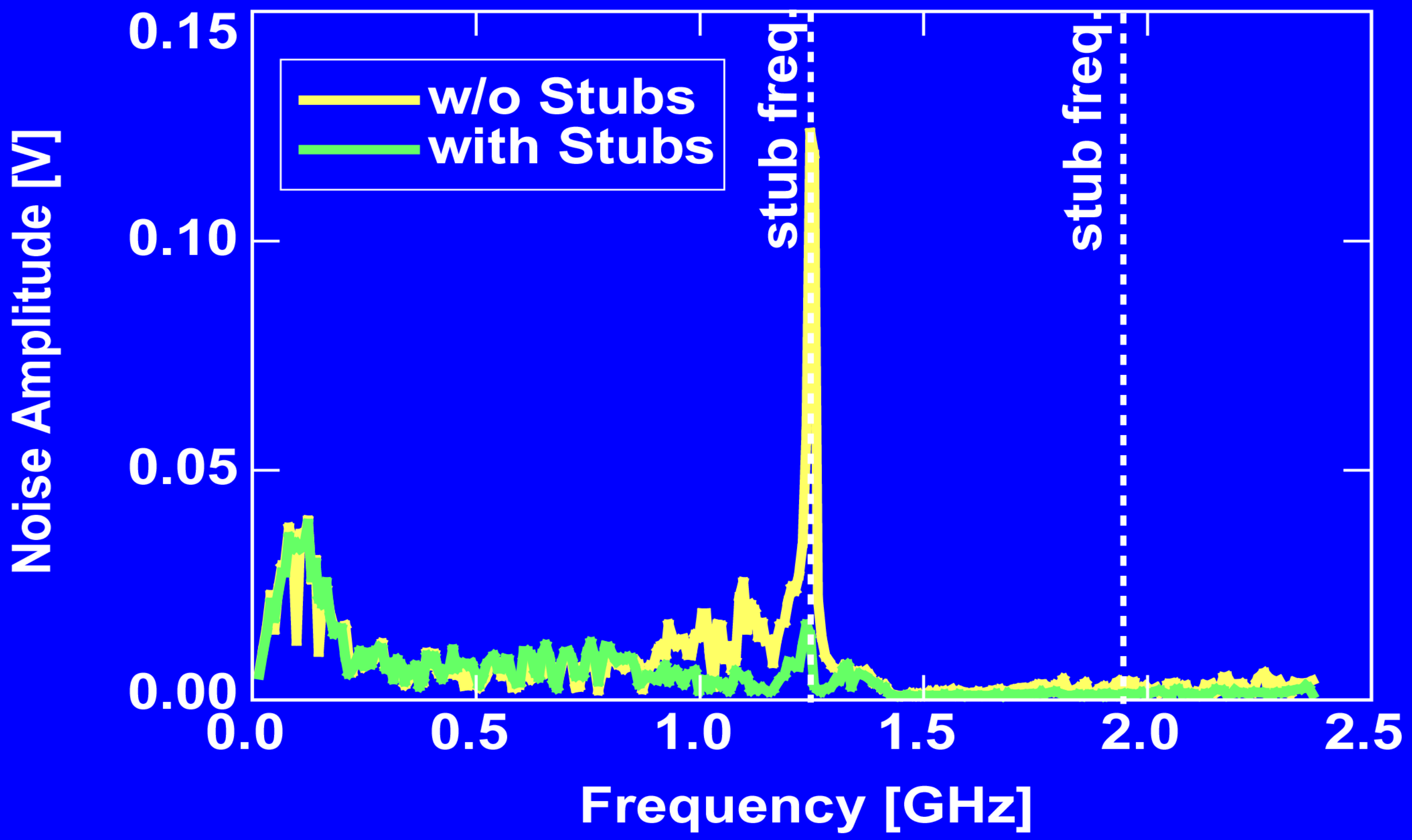
S parameter – |S21|



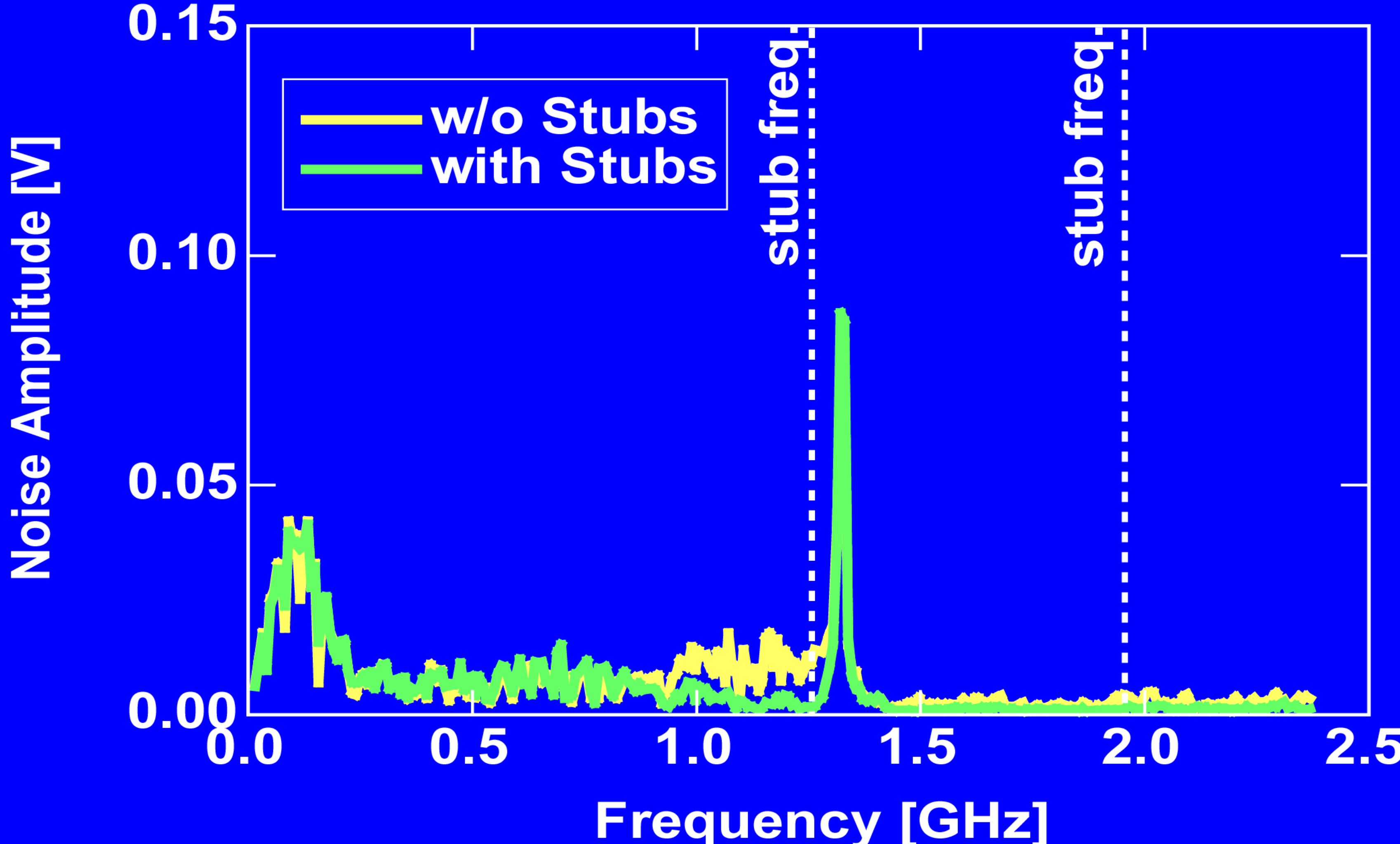
Internal Circuit



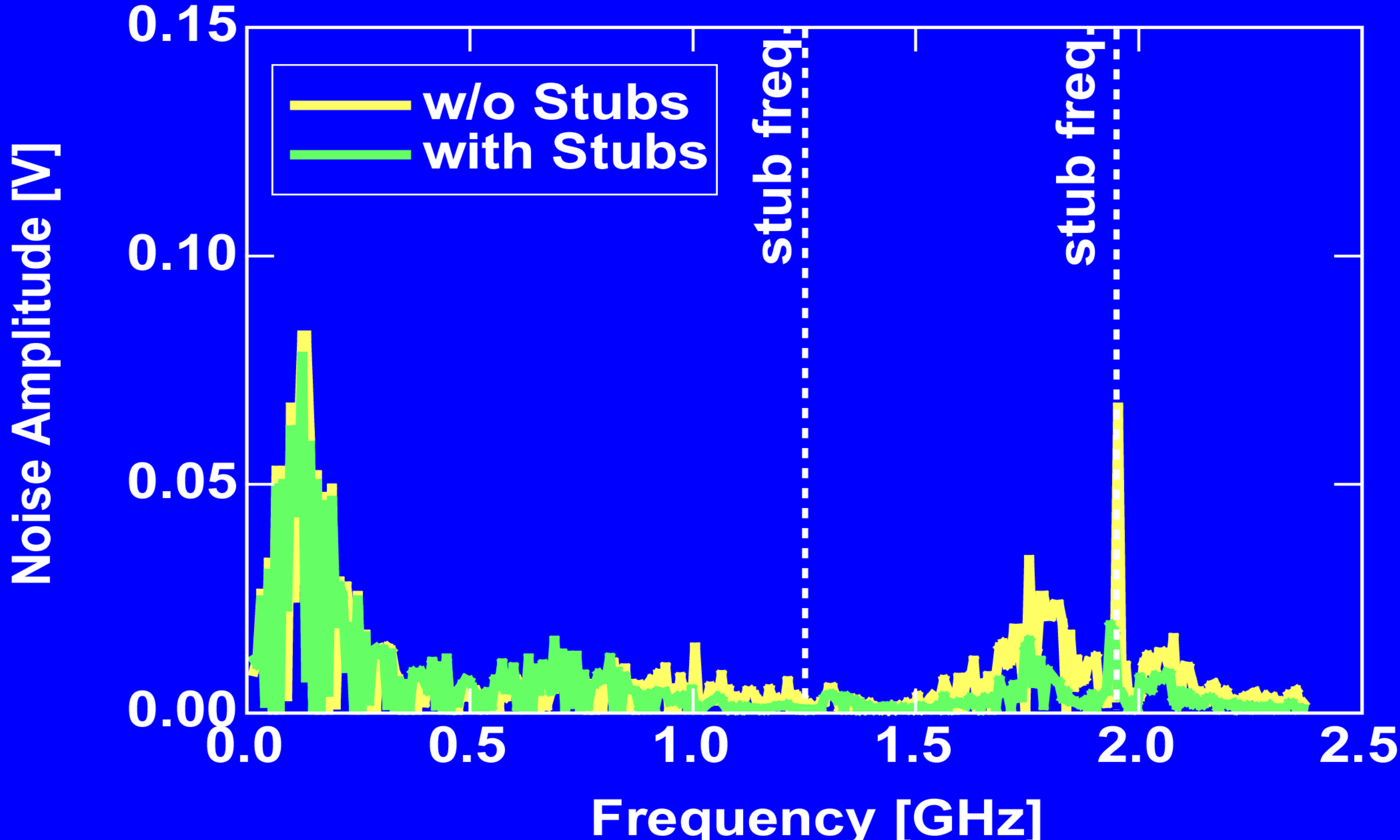
Freq. Dependence @1.25GHz



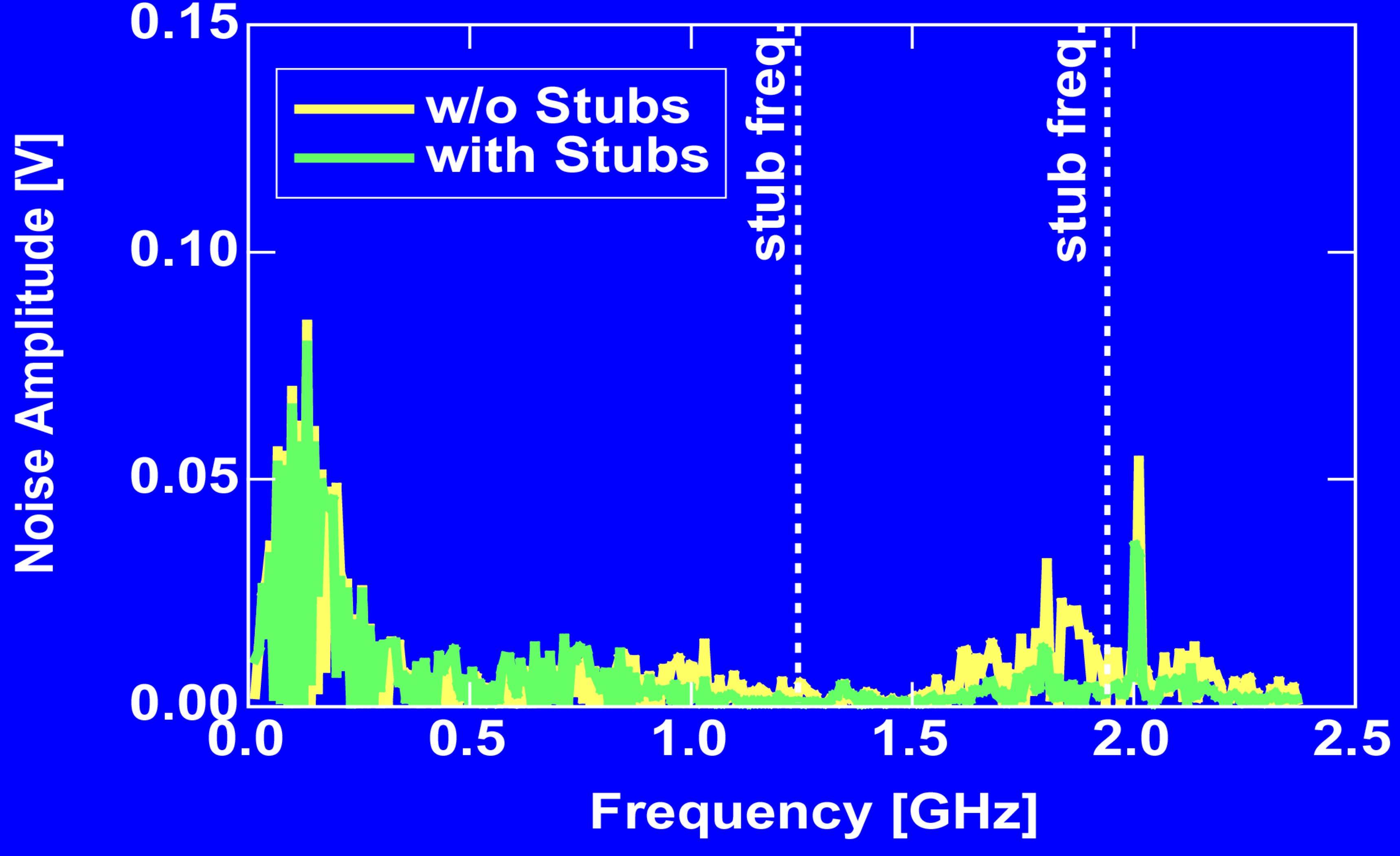
Freq. Dependence @1.32GHz



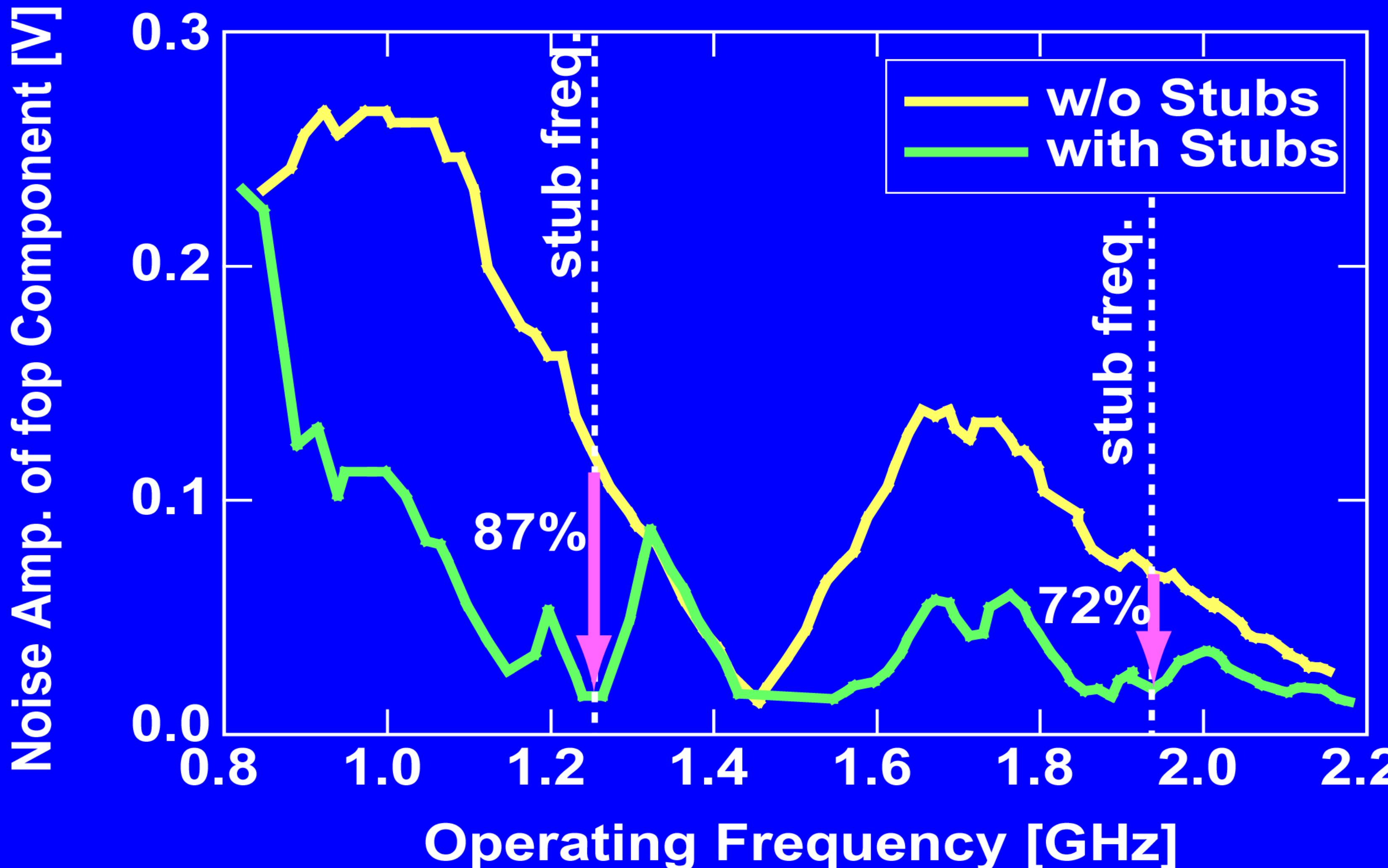
Freq. Dependence @1.95GHz



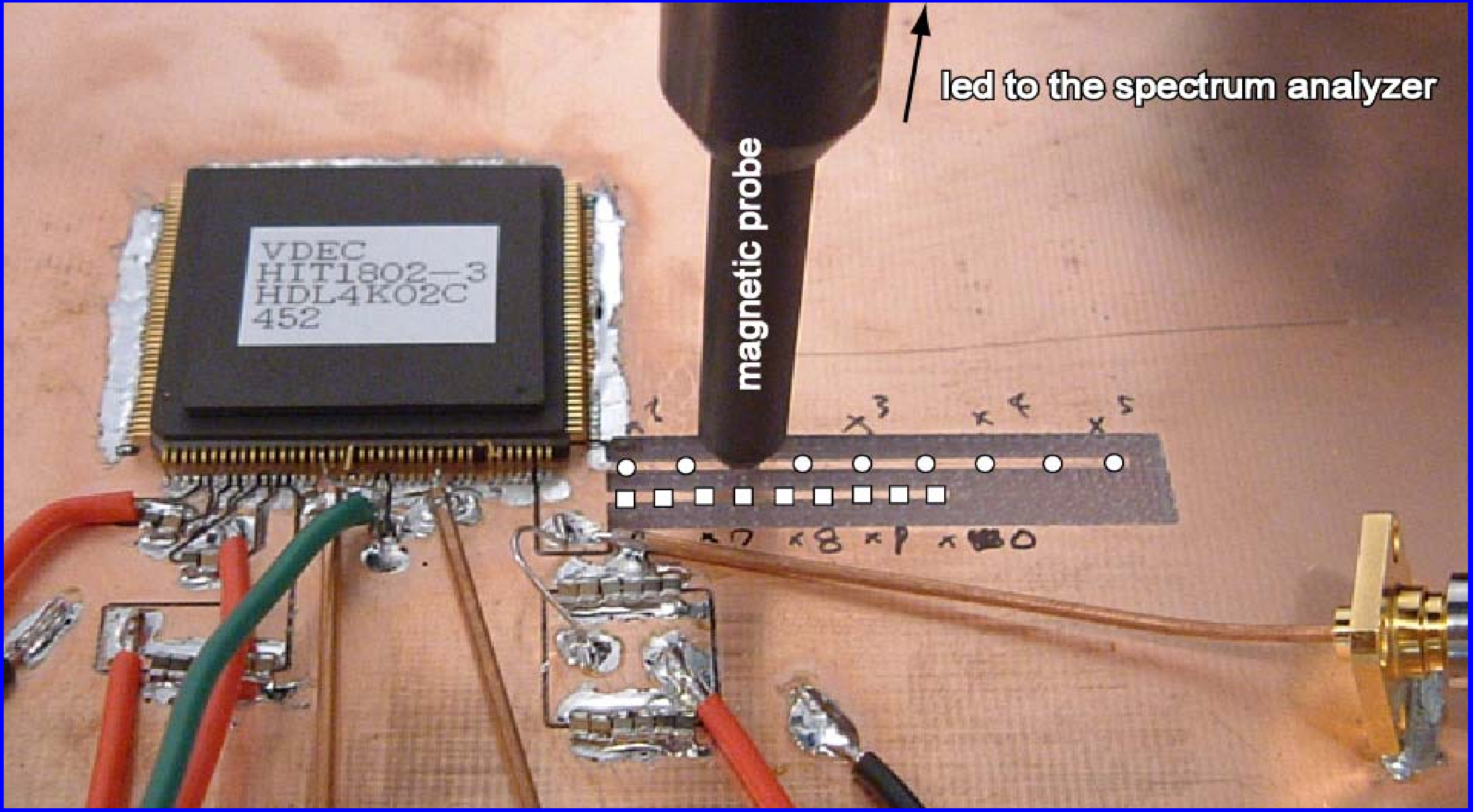
Freq. Dependence @2.00GHz



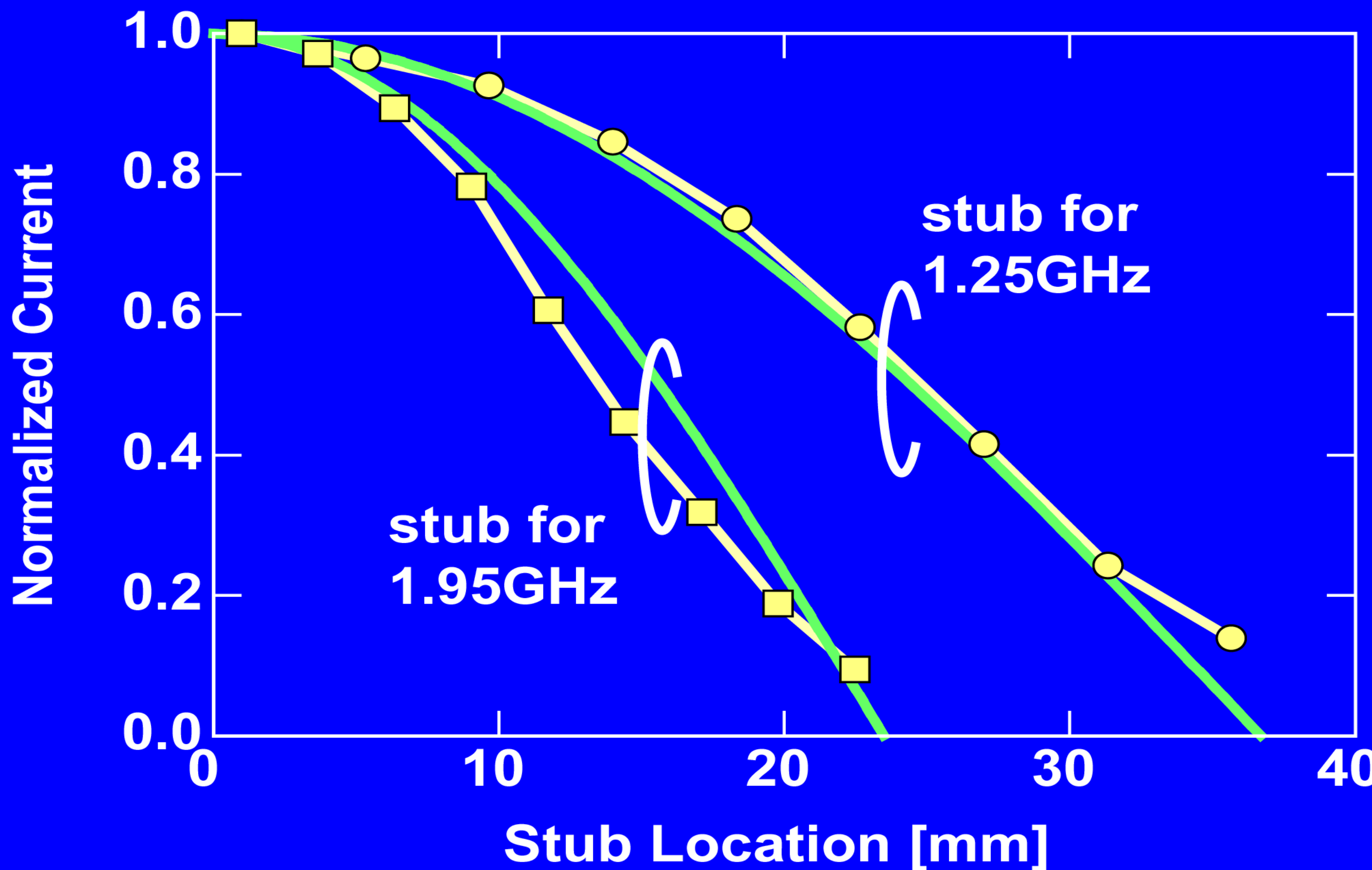
Noise of the *fop* Component



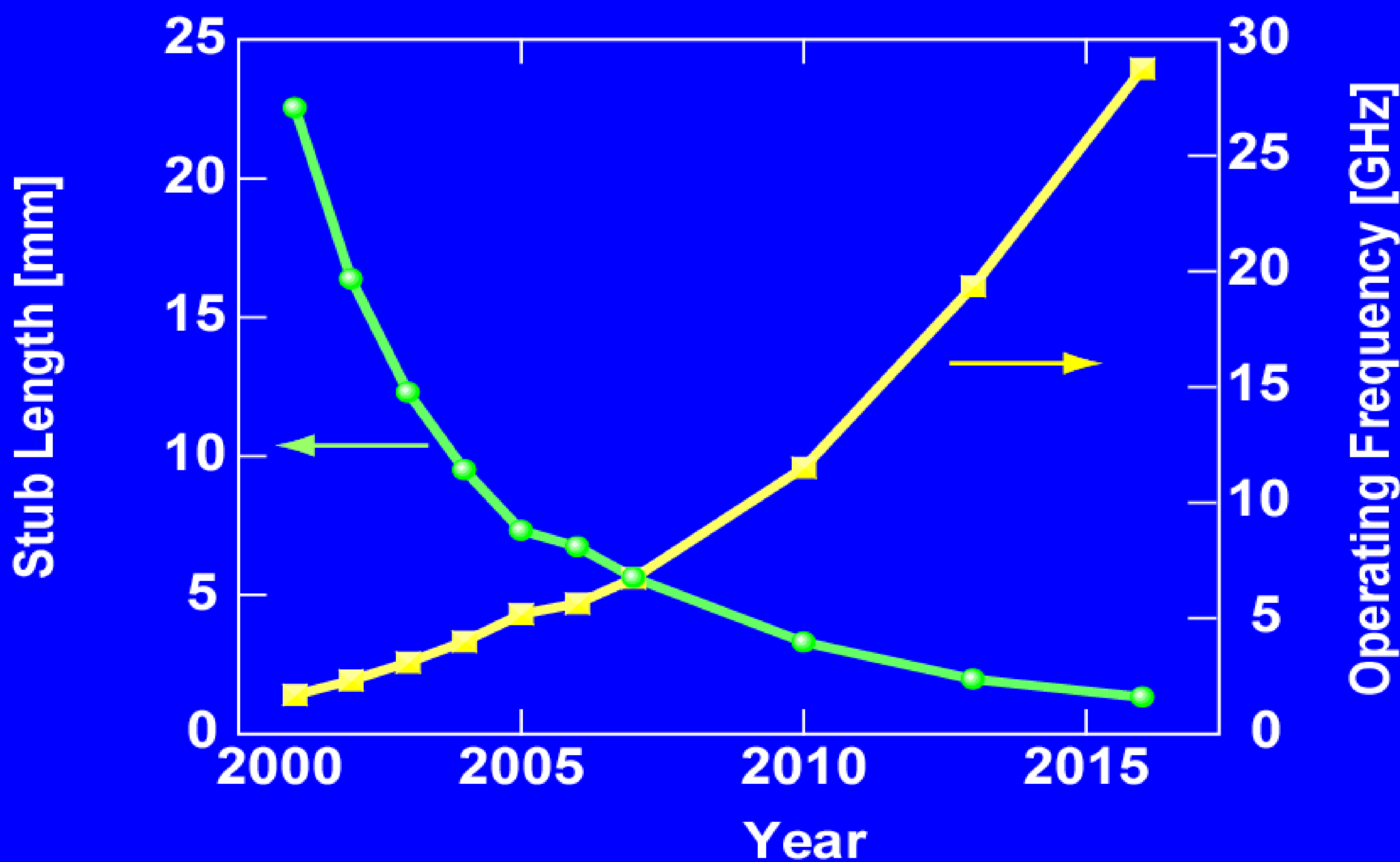
Current Measurement



Current Distribution



Possibility of On-chip Stub



ITRS 2002 Roadmap

Short Summary

- Stub noise reduction is experimented
- The on-board stubs show clear noise reduction
  - 87%, 72% of the operating frequency component at 1.25G, 1.95GHz is suppressed
  - Stub frequency dependence is observed
- On-chip stub integration will be possible in the near future

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- Comparison of stubs and decoupling capacitor for noise reduction
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- On-chip di/dt detector for power supply
- Feedforward active substrate noise cancelling using the di/dt detector
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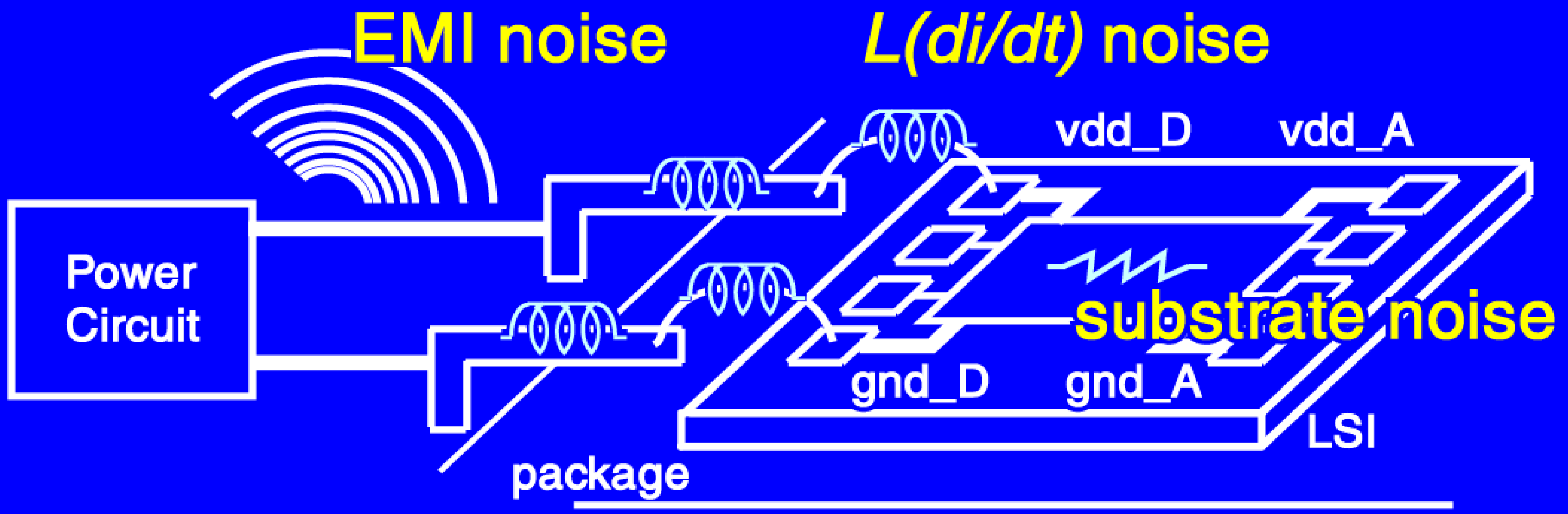
Background

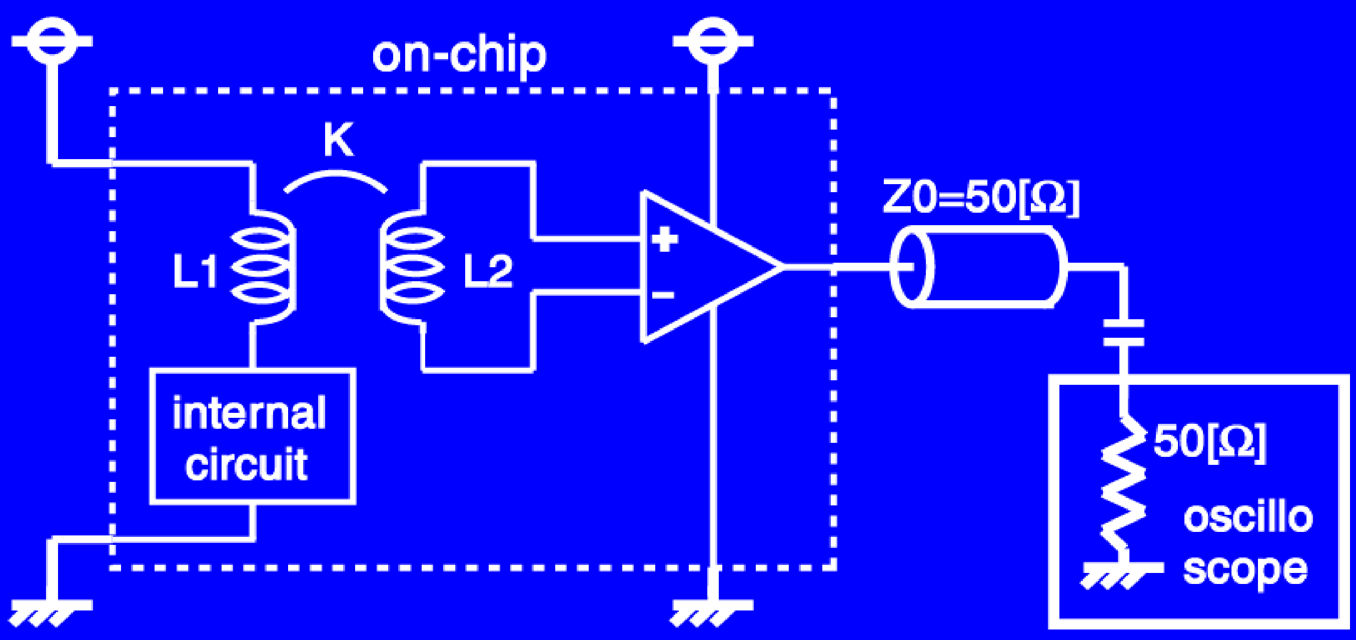
- di/dt is becoming a critical issue
- Need to measure the di/dt



Block Diagram

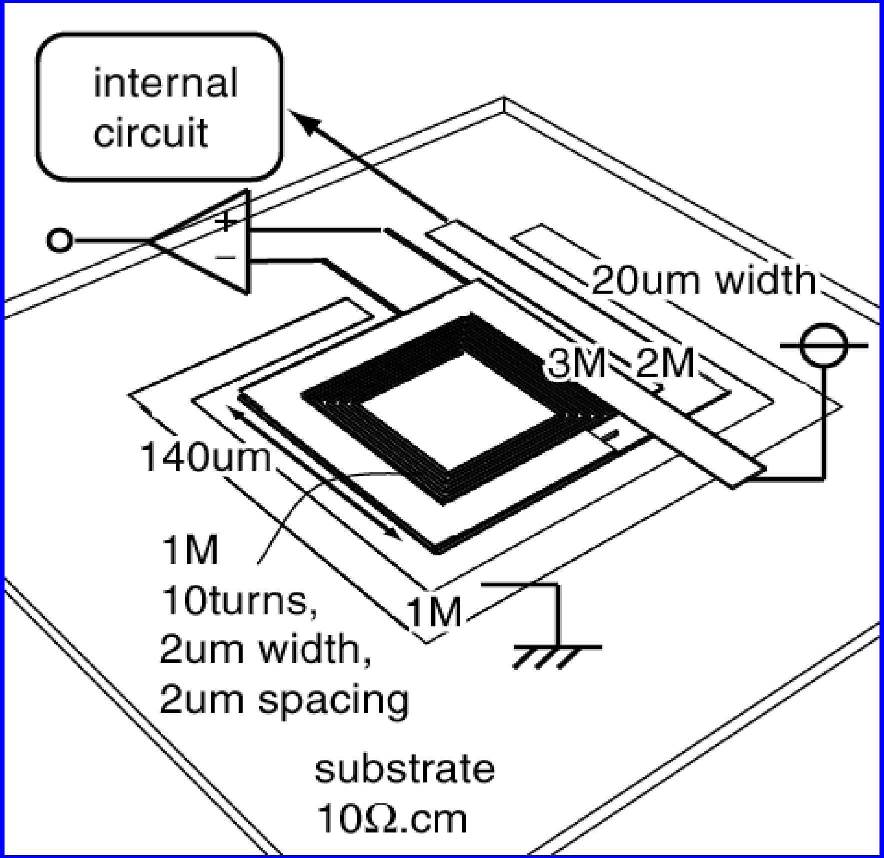
- L2 picks up the di/dt, induce the voltage
- Amplifier amplifies/output the voltage

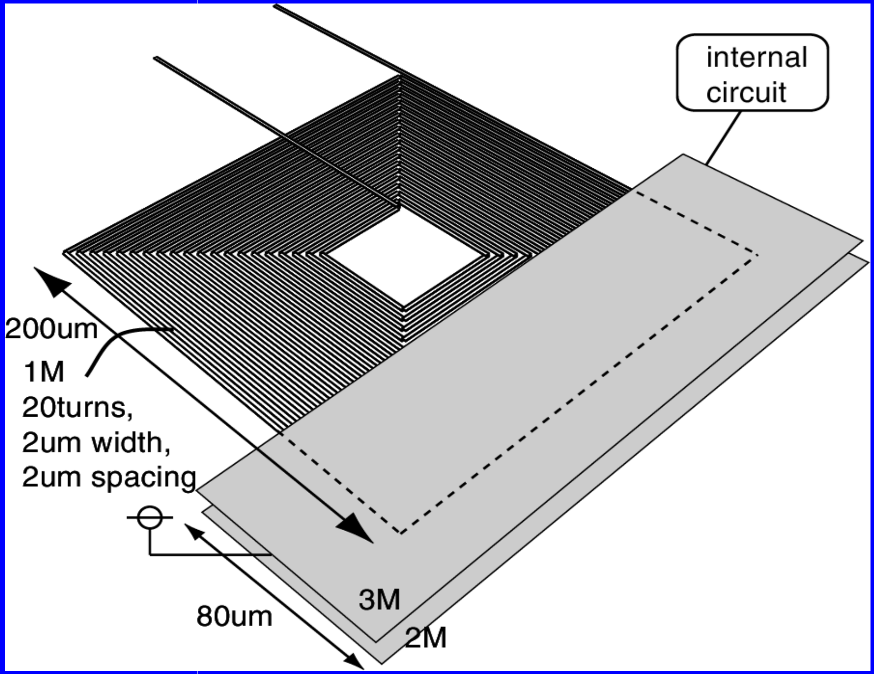
Pros: on-chip, real time, high-bandwidth, no numerical calculation



Improved Mutual Inductor

- Straight layout on the primary part

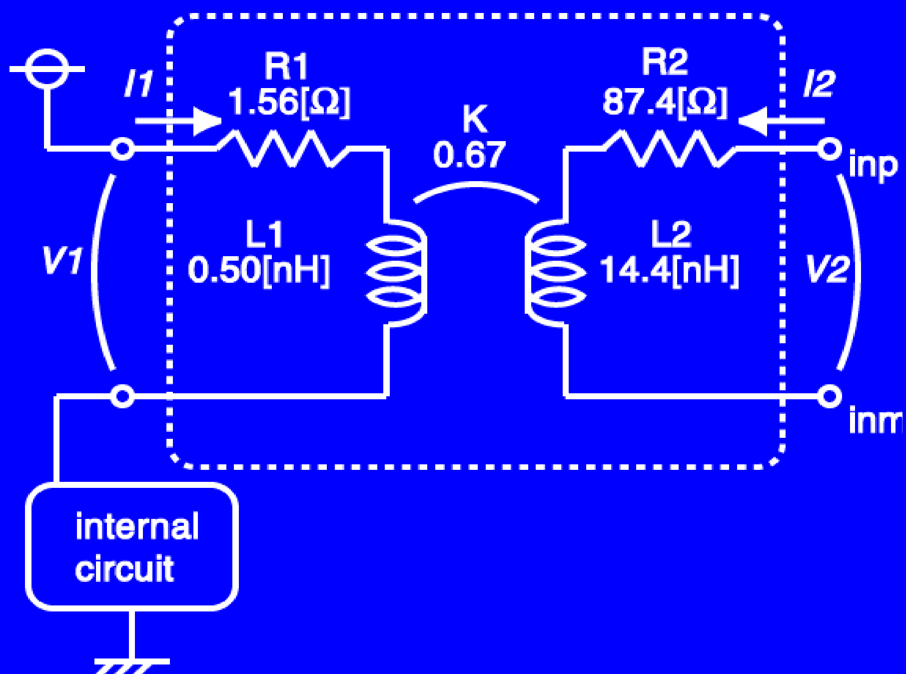


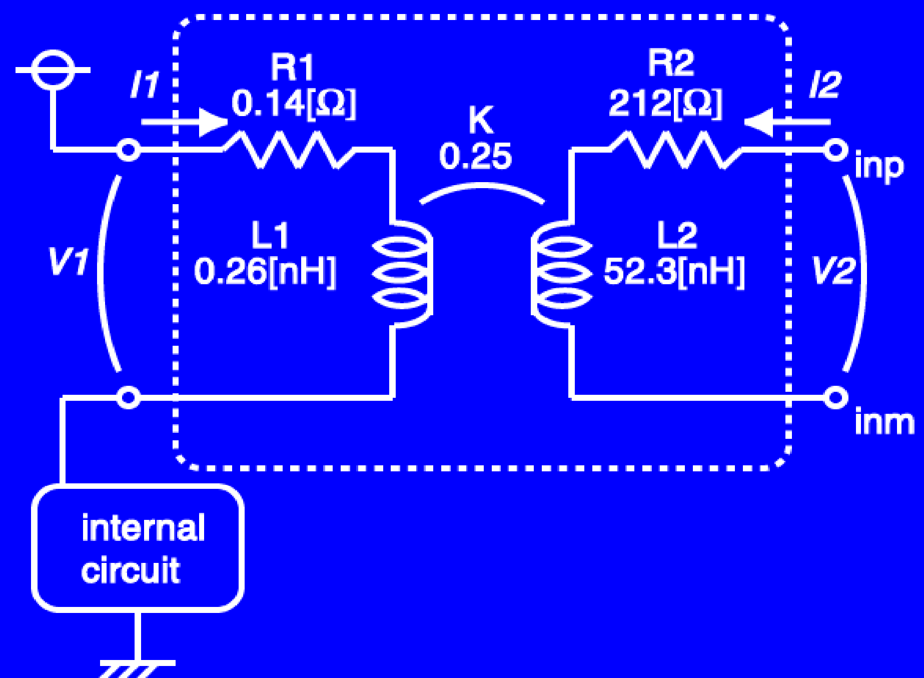


Improved Mutual Inductor

Pros: L1:0.5nH → 0.26nH, R1:1.56Ω → 0.14Ω

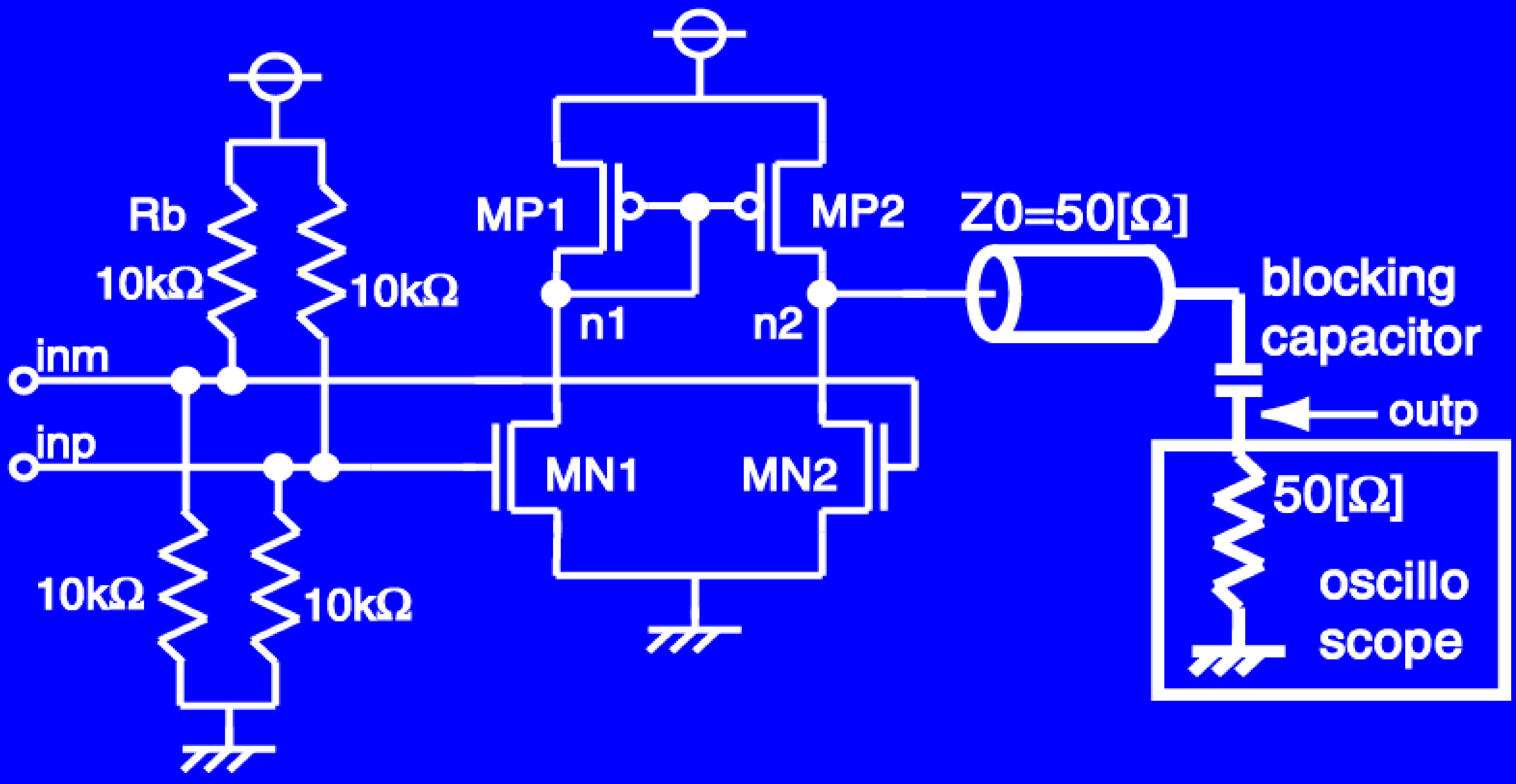
Cons: M :1.80nH → 0.92nH (use large amp.)



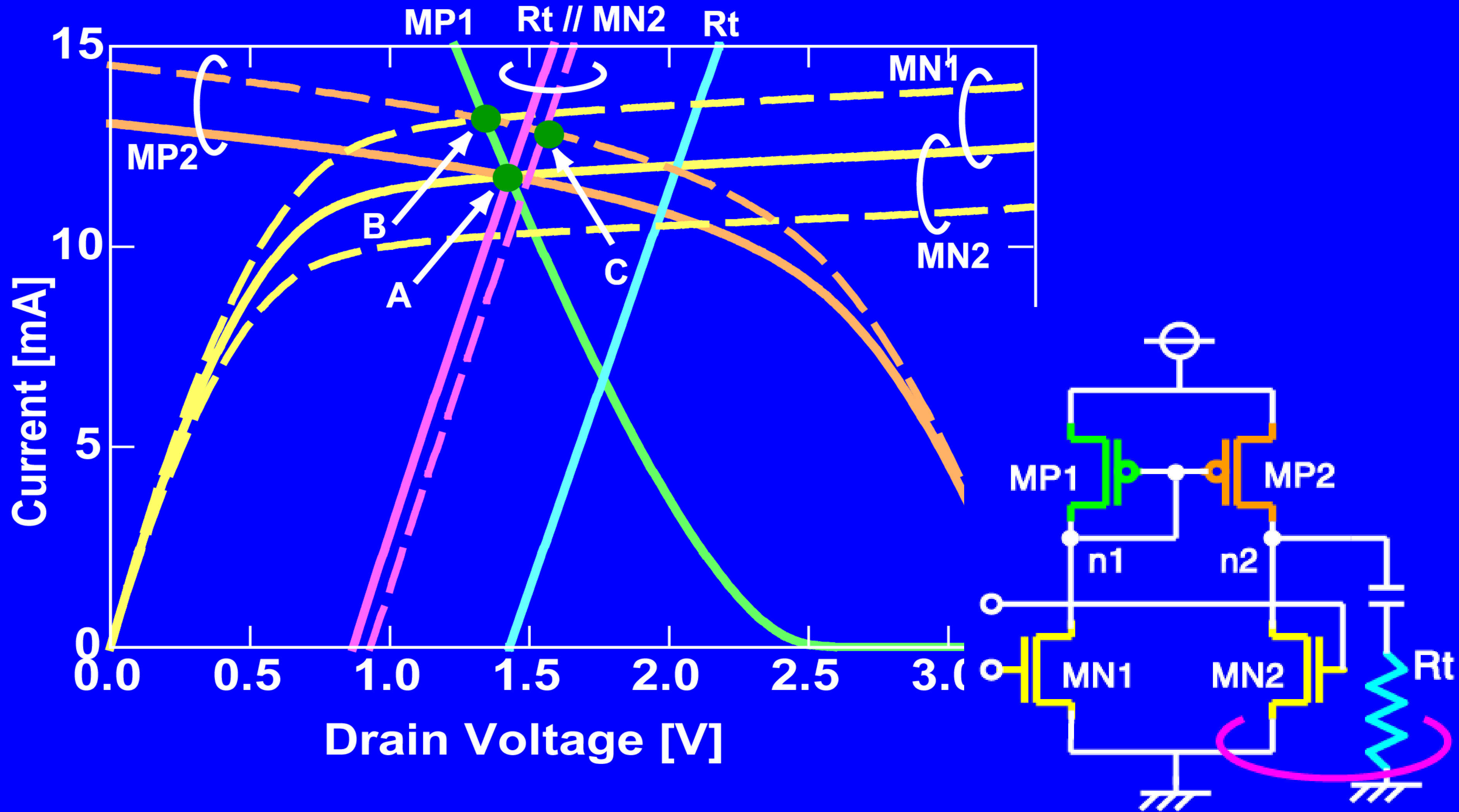


Amplifier/Output buffer

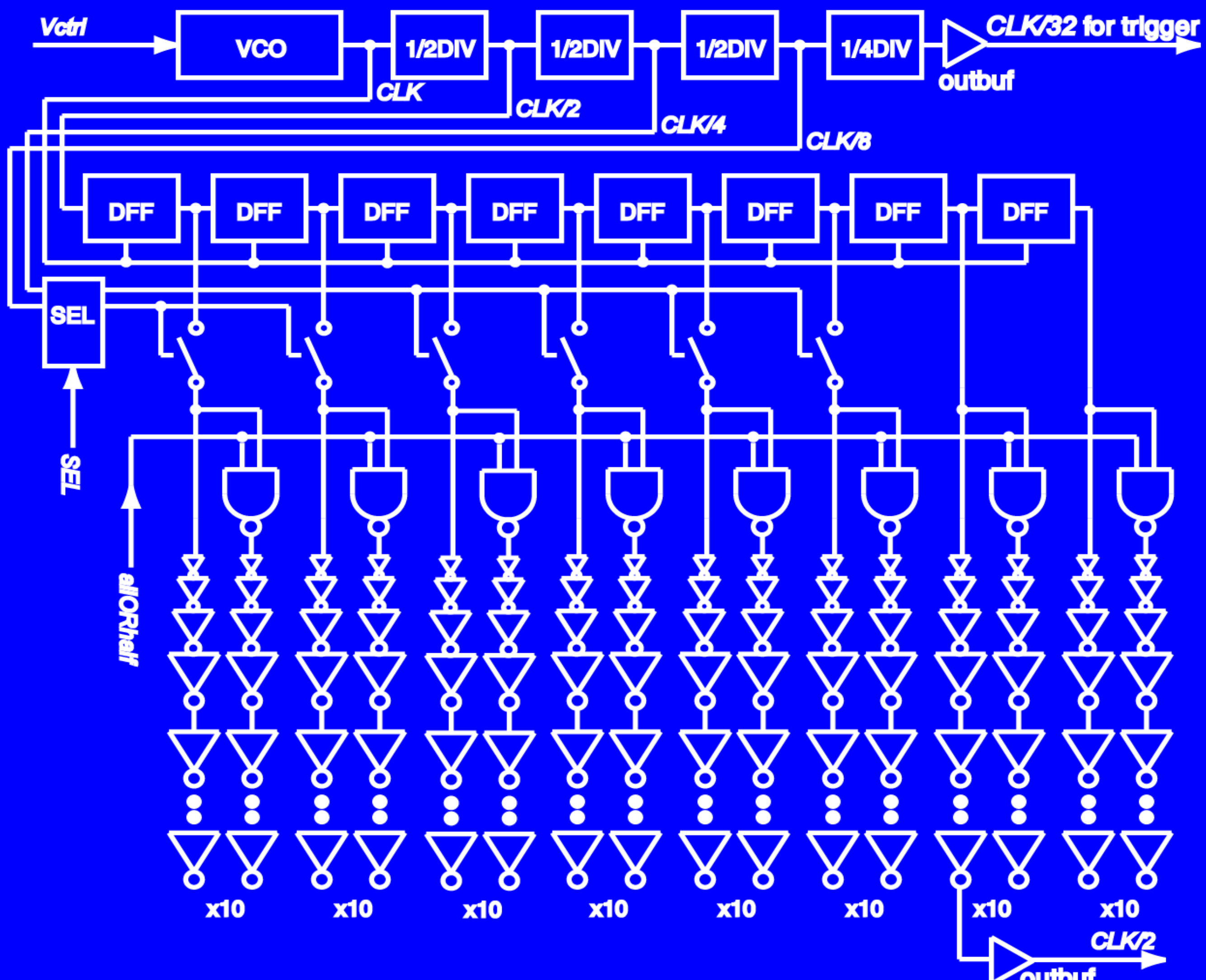
- **Gain: 0.76, fcut-off: 3.3GHz**
  Output linearly: ±0.35V (simulation)



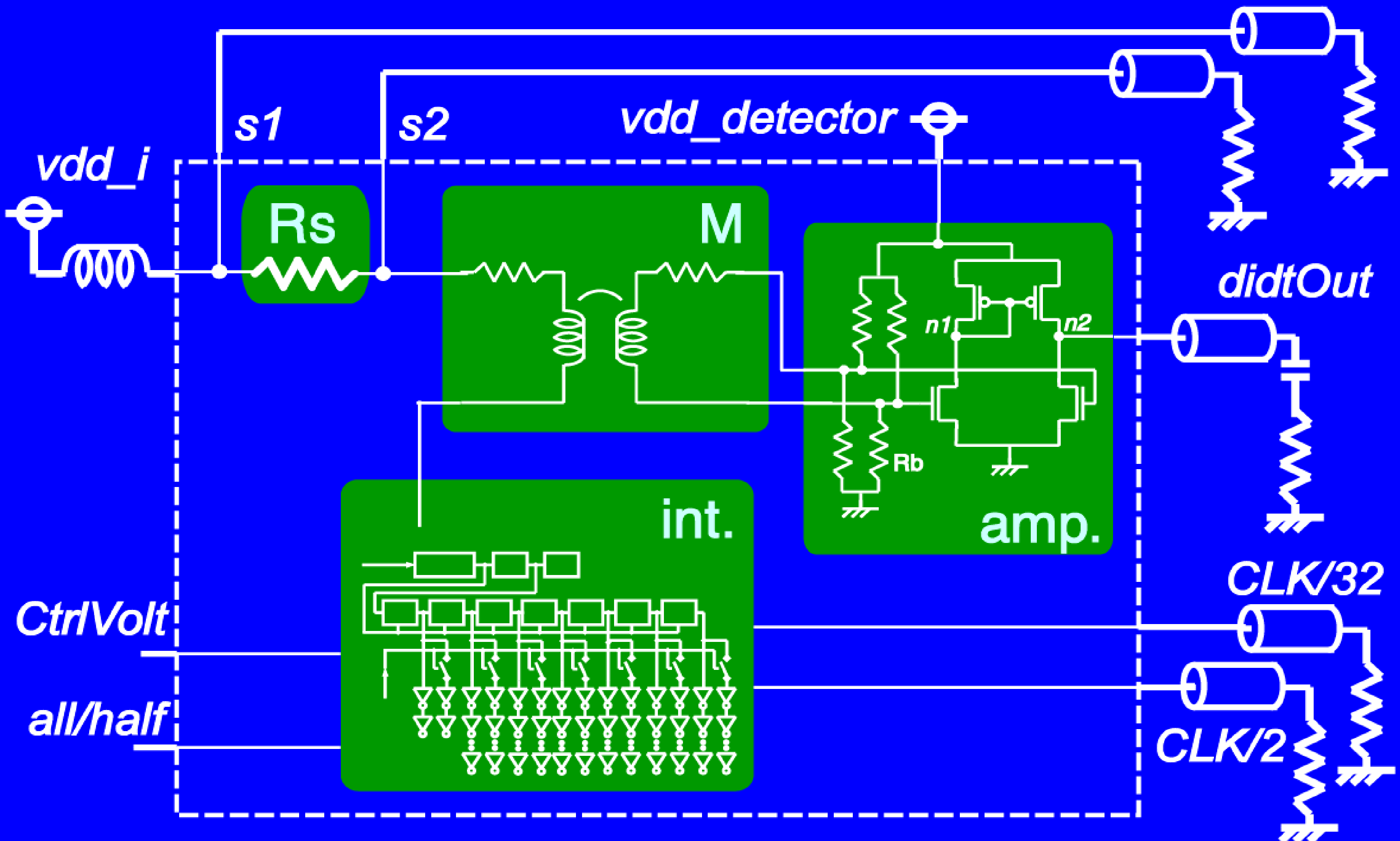
Bias Points of the Amplifier



Internal Circuit as Noise Source

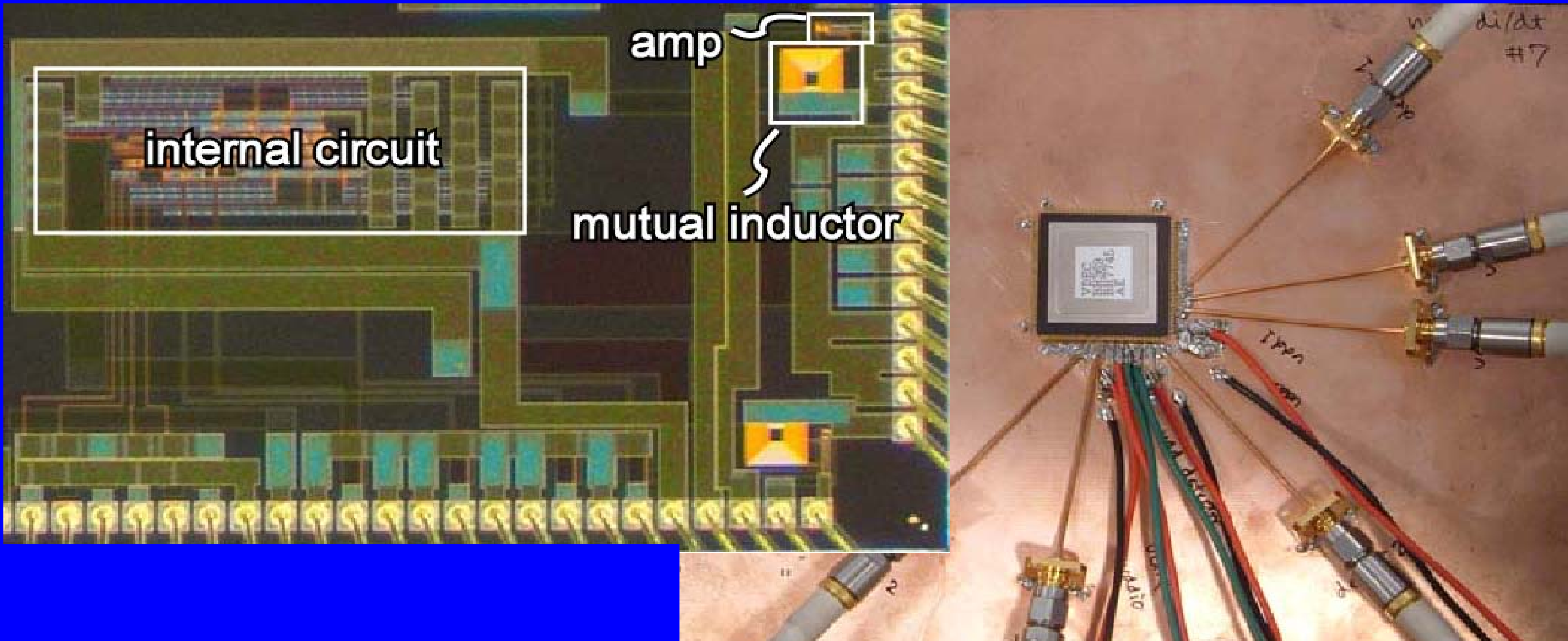


Whole Circuit / Meas. Setup

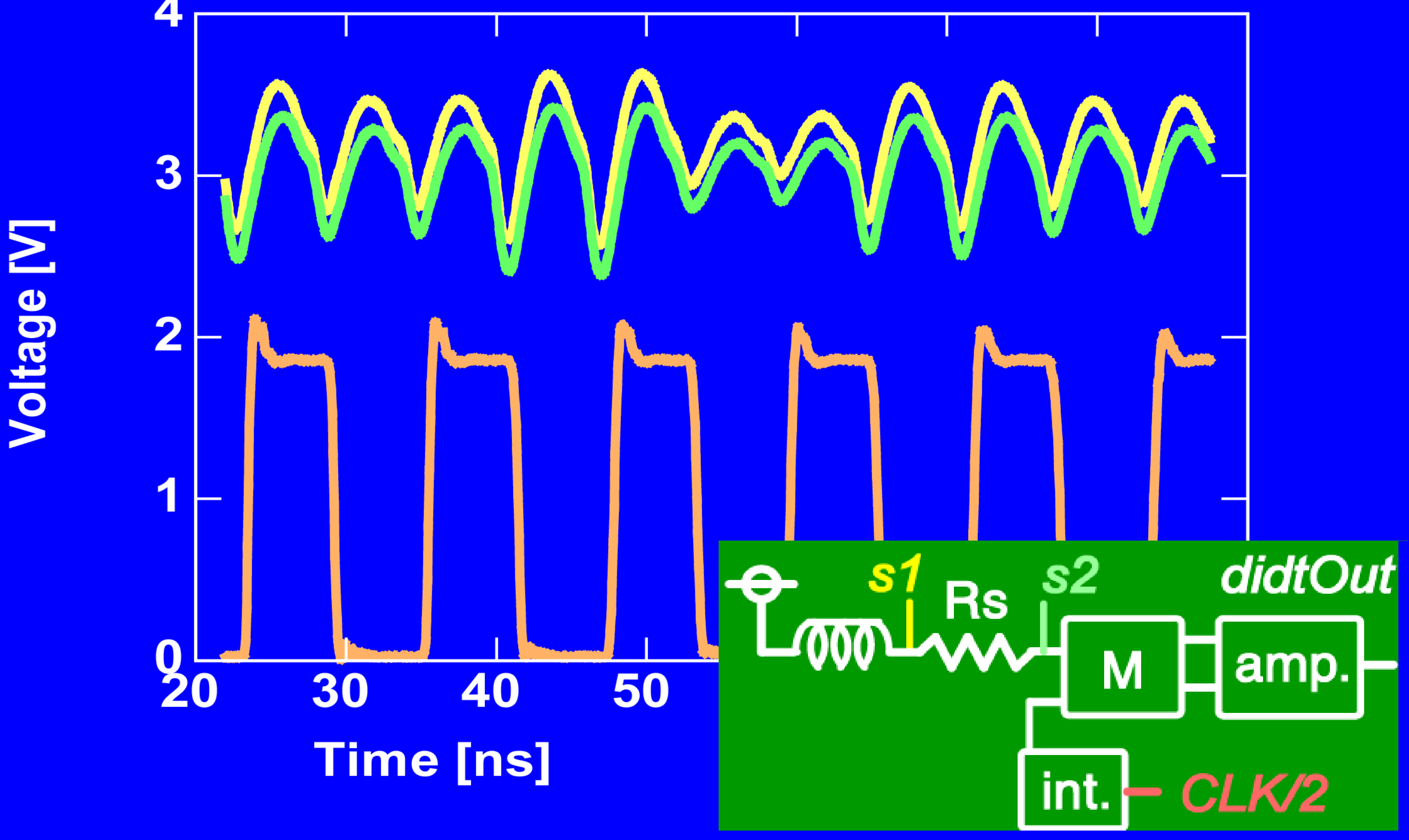


Chip Photograph

- 0.35um 3ML 2P CMOS
  - Chip area : 3.0mm x 1.8mm.
  - di/dt detector : 340um x 280um

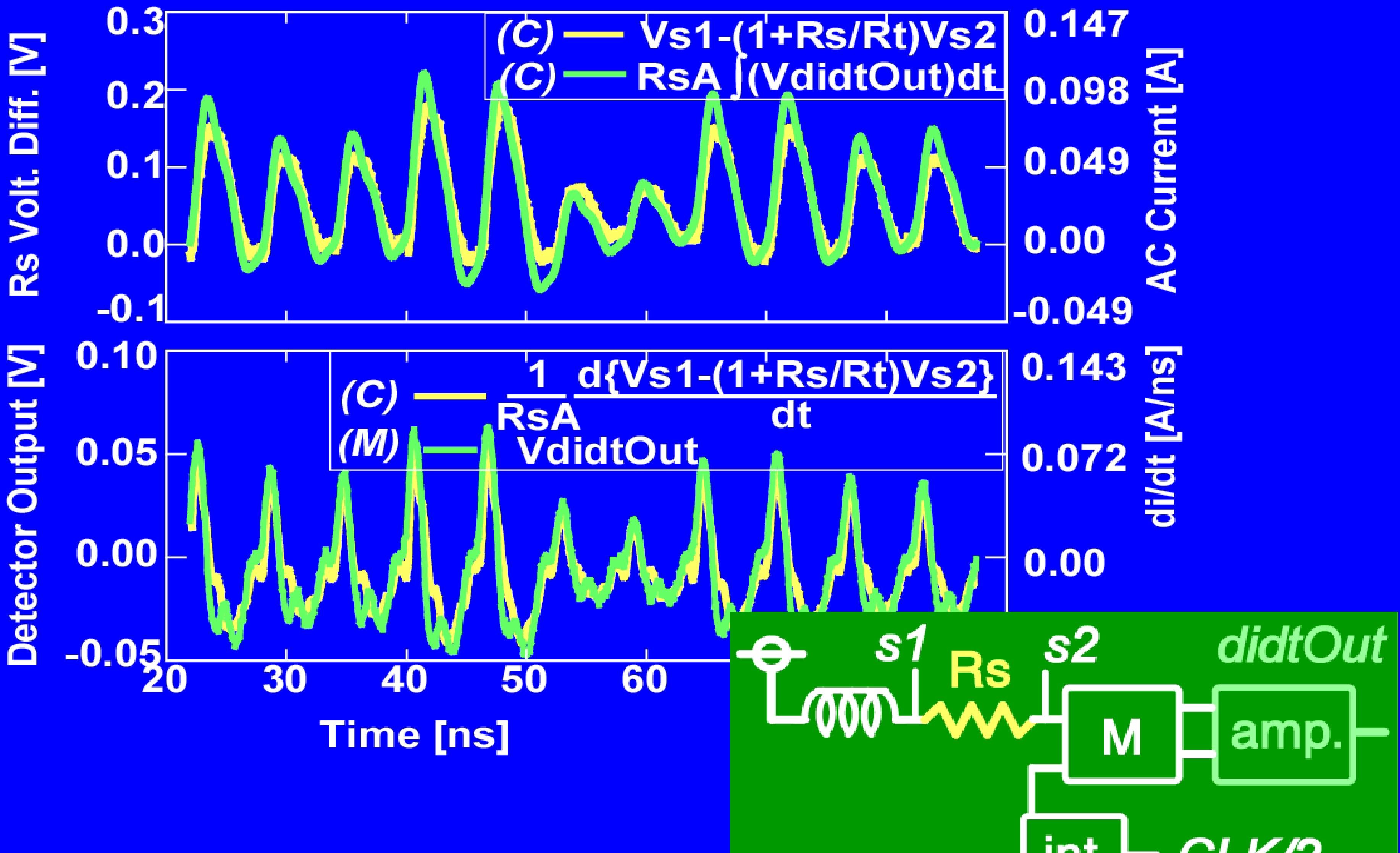


Waveform #1



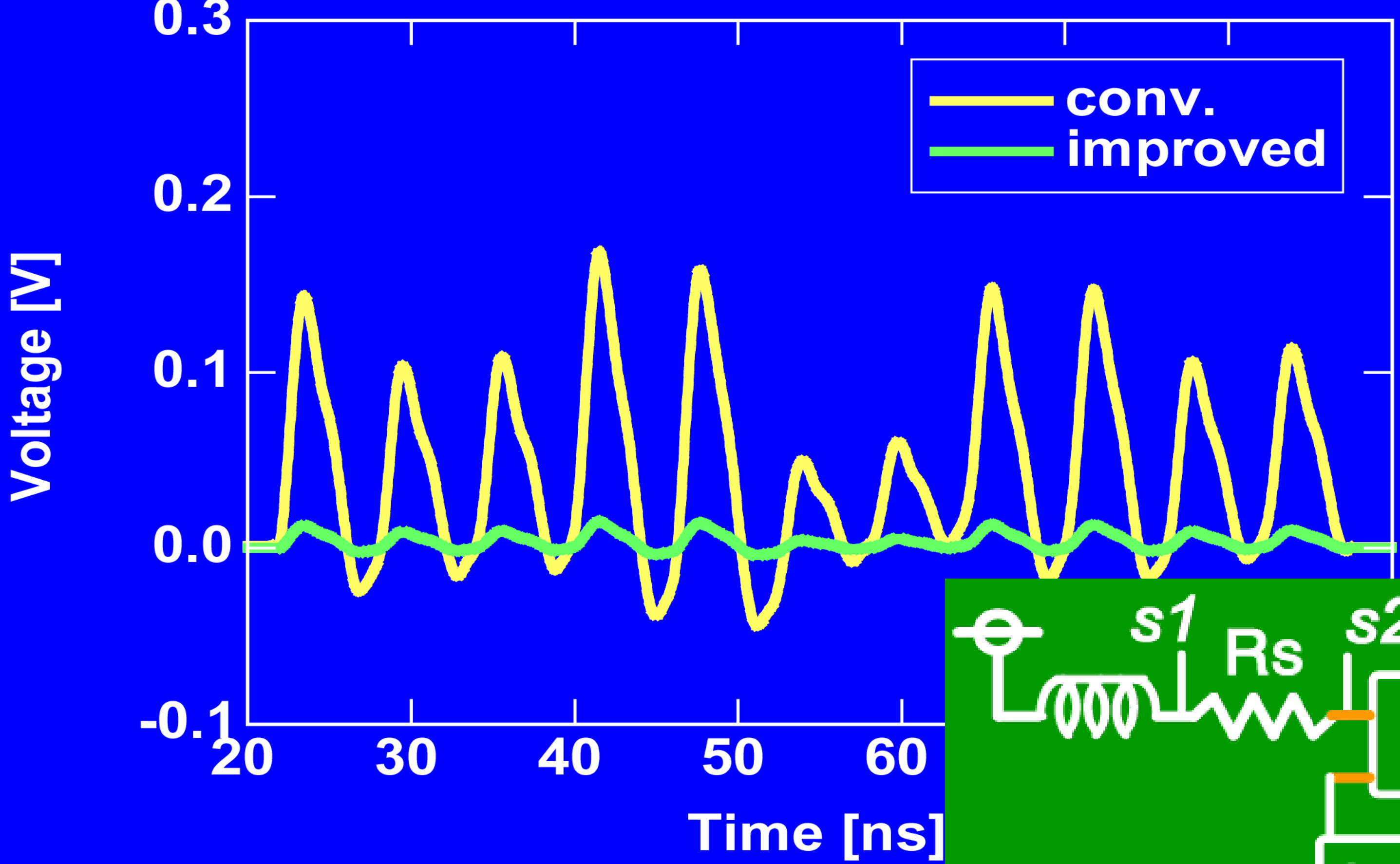
4
3
2
1
0
Voltage [V]
20
30
40
50
Time [ns]
s1
Rs
s2
didtOut
M
amp.
int.
CLK/2

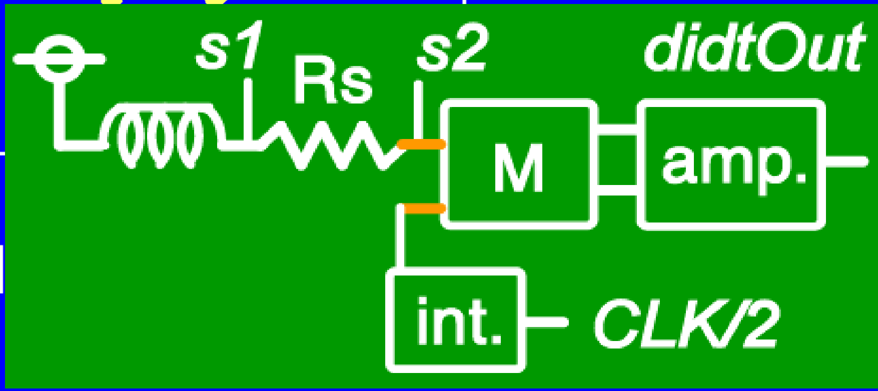
Waveform #2



0.3
0.2
0.1
0.0
-0.1
Rs Volt. Diff. [V]
(C) Vs1-(1+Rs/Rt)Vs2
(C) RsA ∫(VdidtOut)dt
0.147
0.098
0.049
0.00
-0.049
AC Current [A]
0.10
0.05
0.00
-0.05
Detector Output [V]
(C) 1/RsA d{Vs1-(1+Rs/Rt)Vs2}/dt
(M) VdidtOut
0.143
0.072
0.00
di/dt [A/ns]
20
30
40
50
60
Time [ns]
s1
Rs
s2
didtOut
M
amp.

Voltage Drop





- Voltage drop is drastically reduced

Short Summary

- On-chip di/dt detector is demonstrated
- It consists of a power supply line, underlying spiral inductor, an amplifier
- di/dt waveforms obtained from the di/dt detector and the resistor agree well
- Current waveform can be calculated by integrating the detector output by time
- Improved mutual inductor reduces the voltage drop

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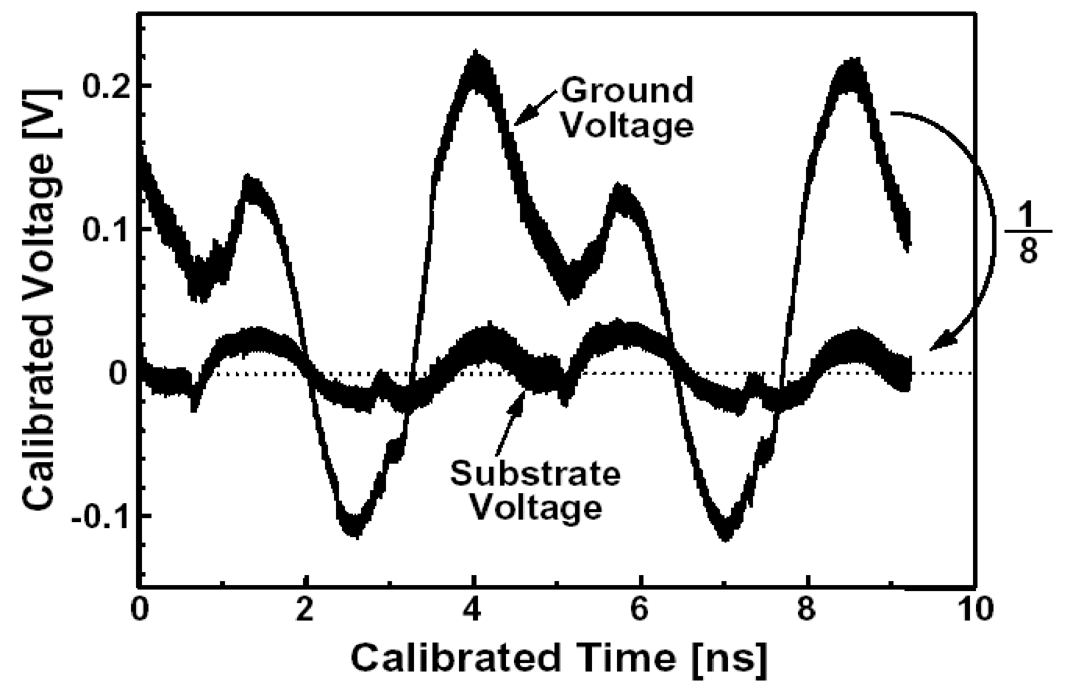
Background – Substrate Noise

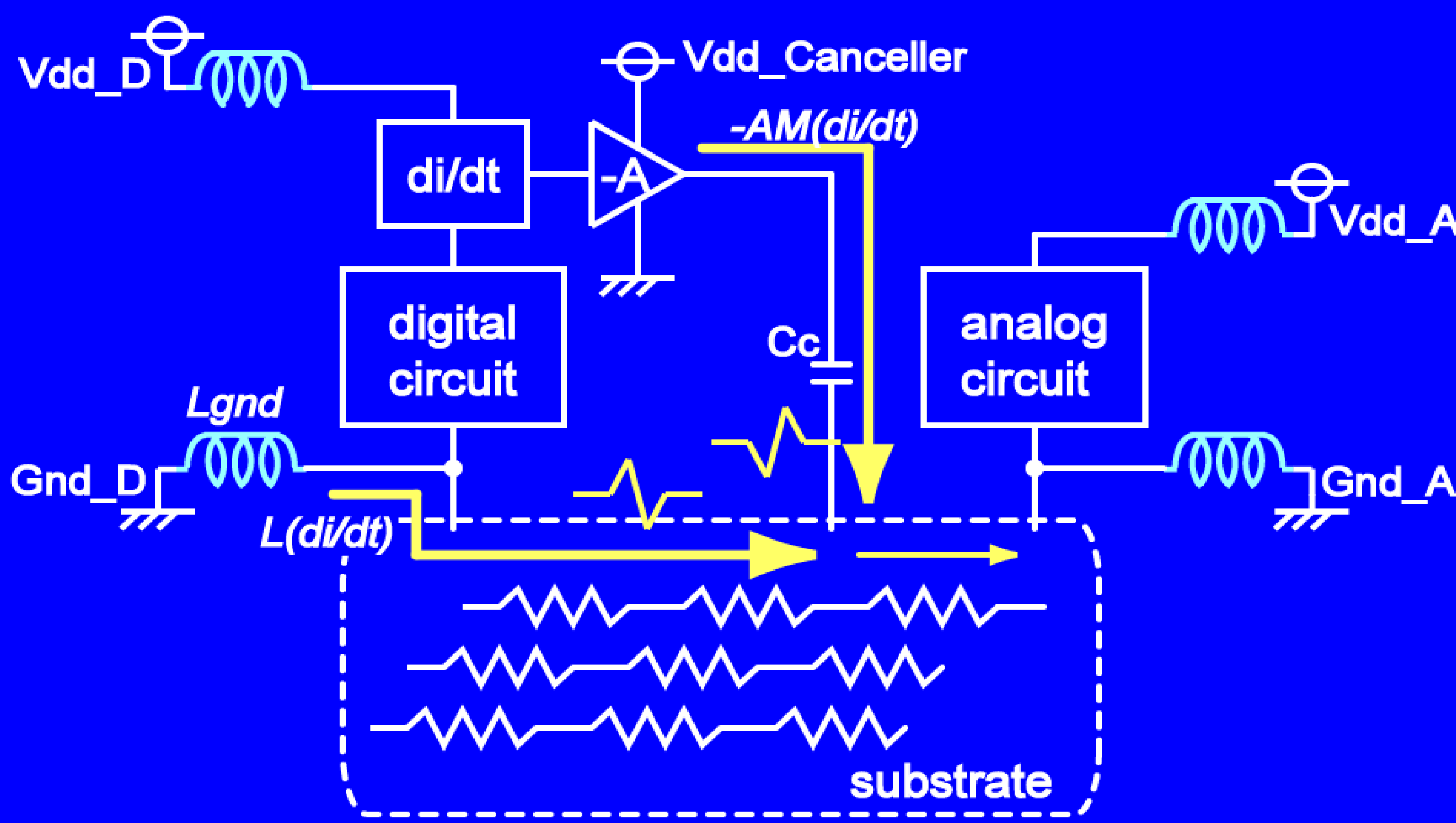
- Guard ring does not work well because of the parasitic impedance
- Substrate noise is related to Gnd noise



[16] *M. Takamiya, et al. ISSCC, Feb., 2002*

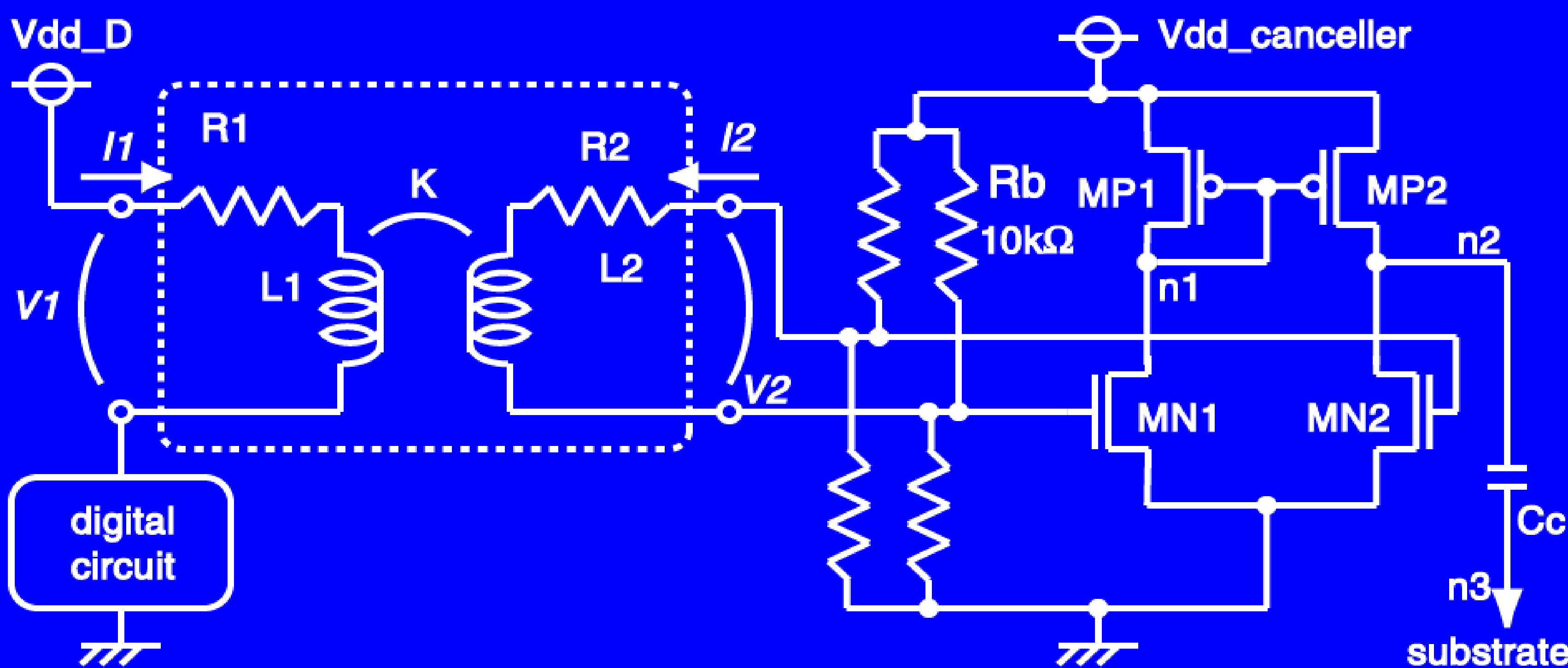
F.F. Active Noise Cancelling

- di/dt detector makes anti-phase signal
  no feedback → high bandwidth



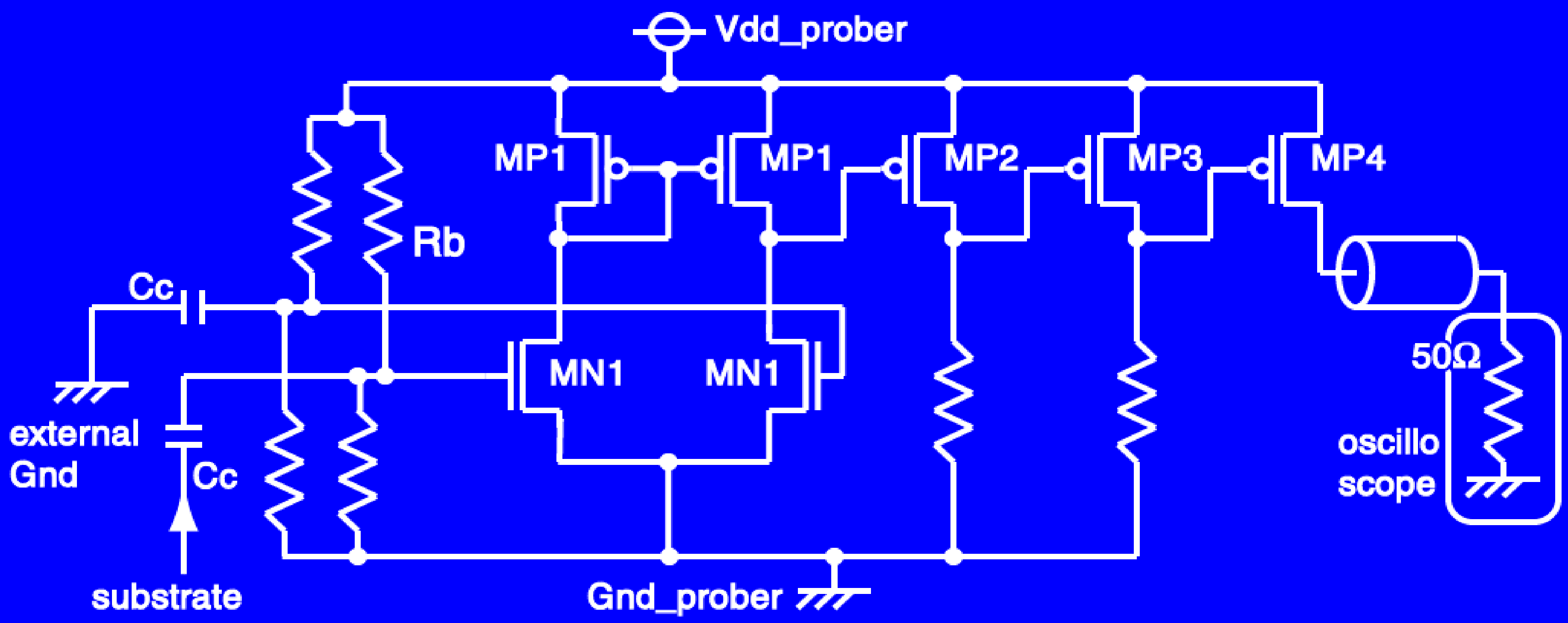
Noise Canceller

- Anti-phase current should be injected
- Cc is large so as to adjust the phase of the original noise and injected currents

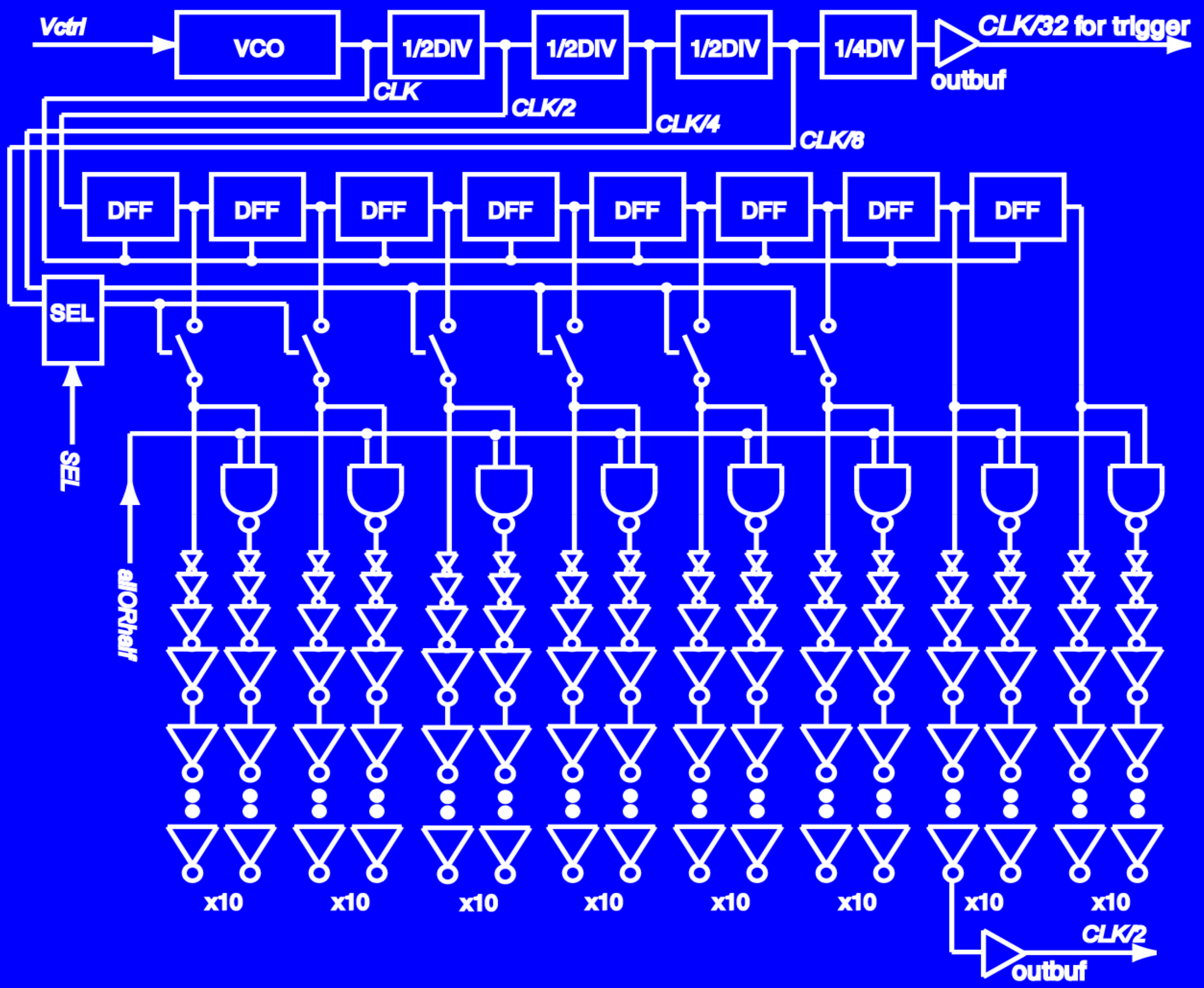


Noise Probing for Verification

- Differential amplifier connected to the substrate and the external Gnd
- No body contact for NMOS (*gm/gbs*=6.0)

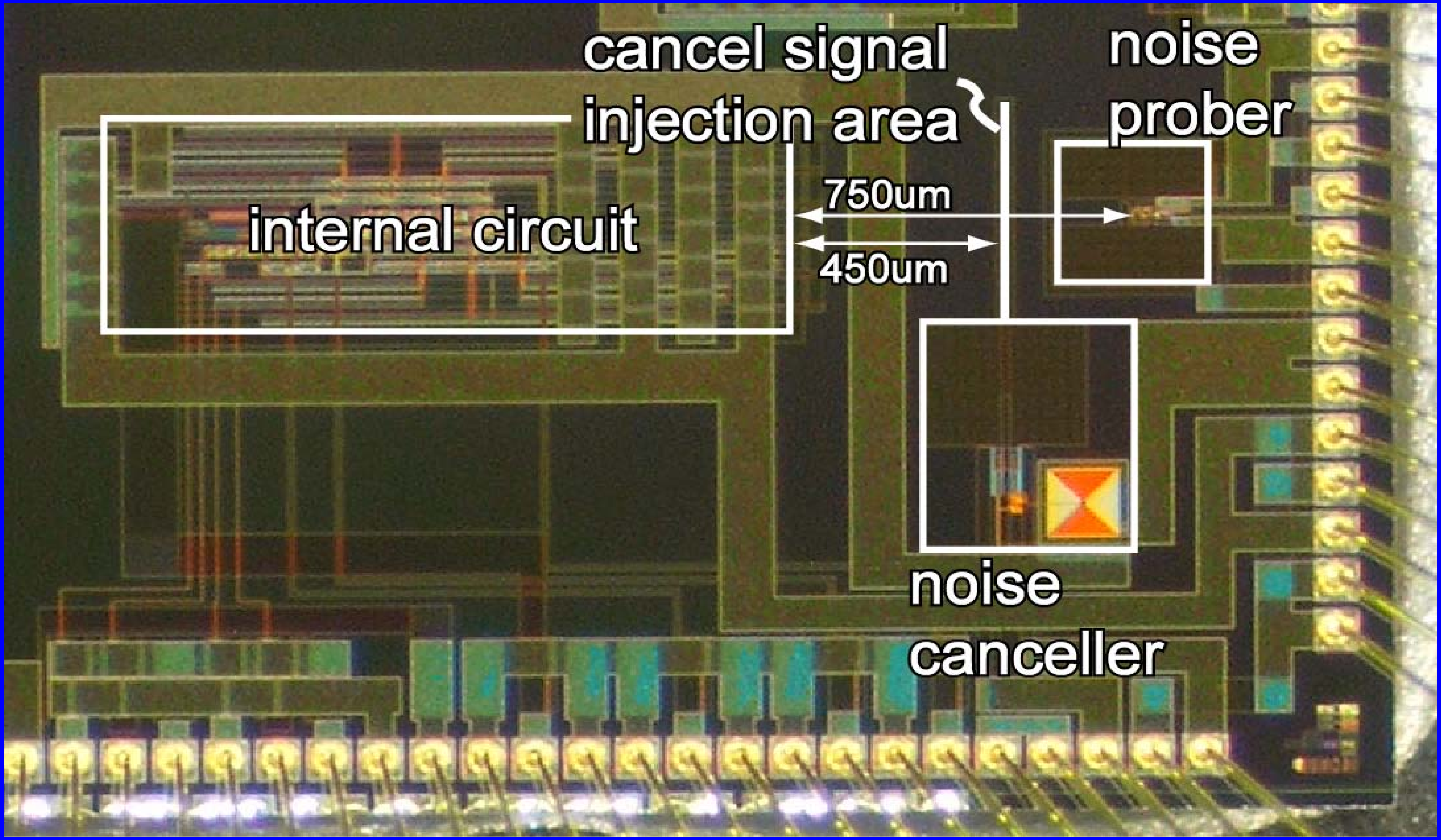


Internal Circuit as Noise Source



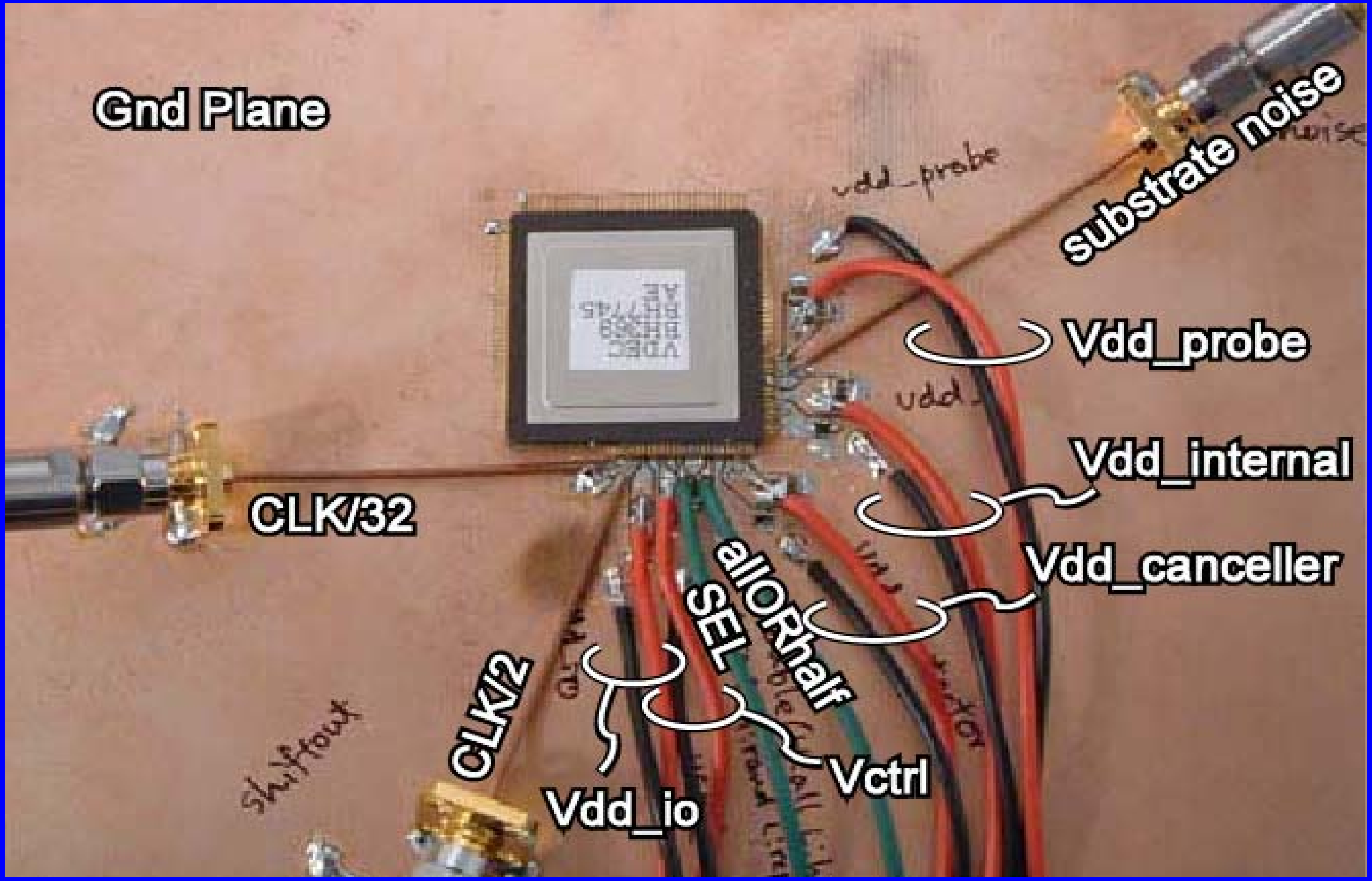
Chip Photograph & Floor Plan

- 0.35um 3ML 2P CMOS (3.0mm x 1.8mm)

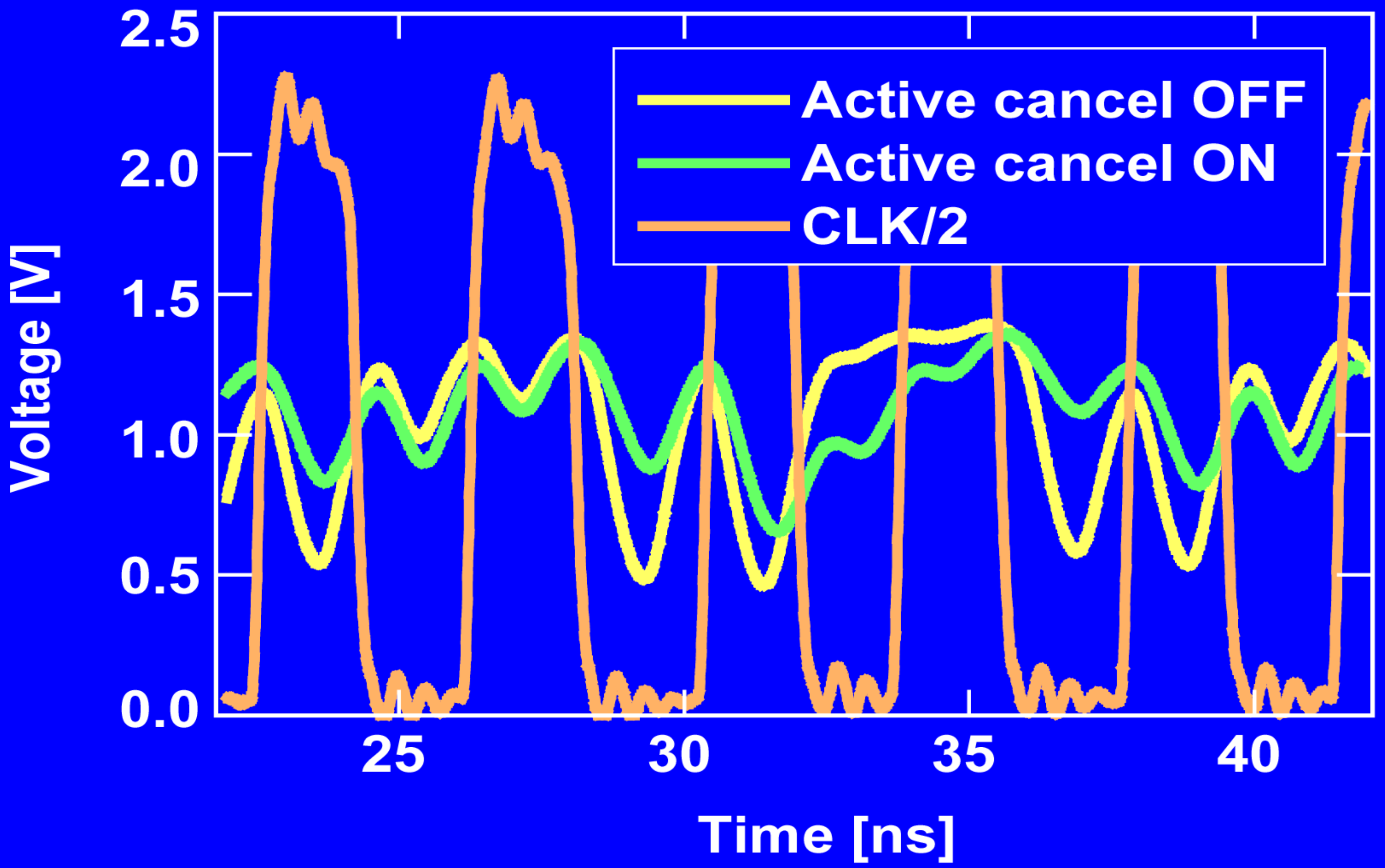


Chip Mount

- The test chip is mounted on a Cu board

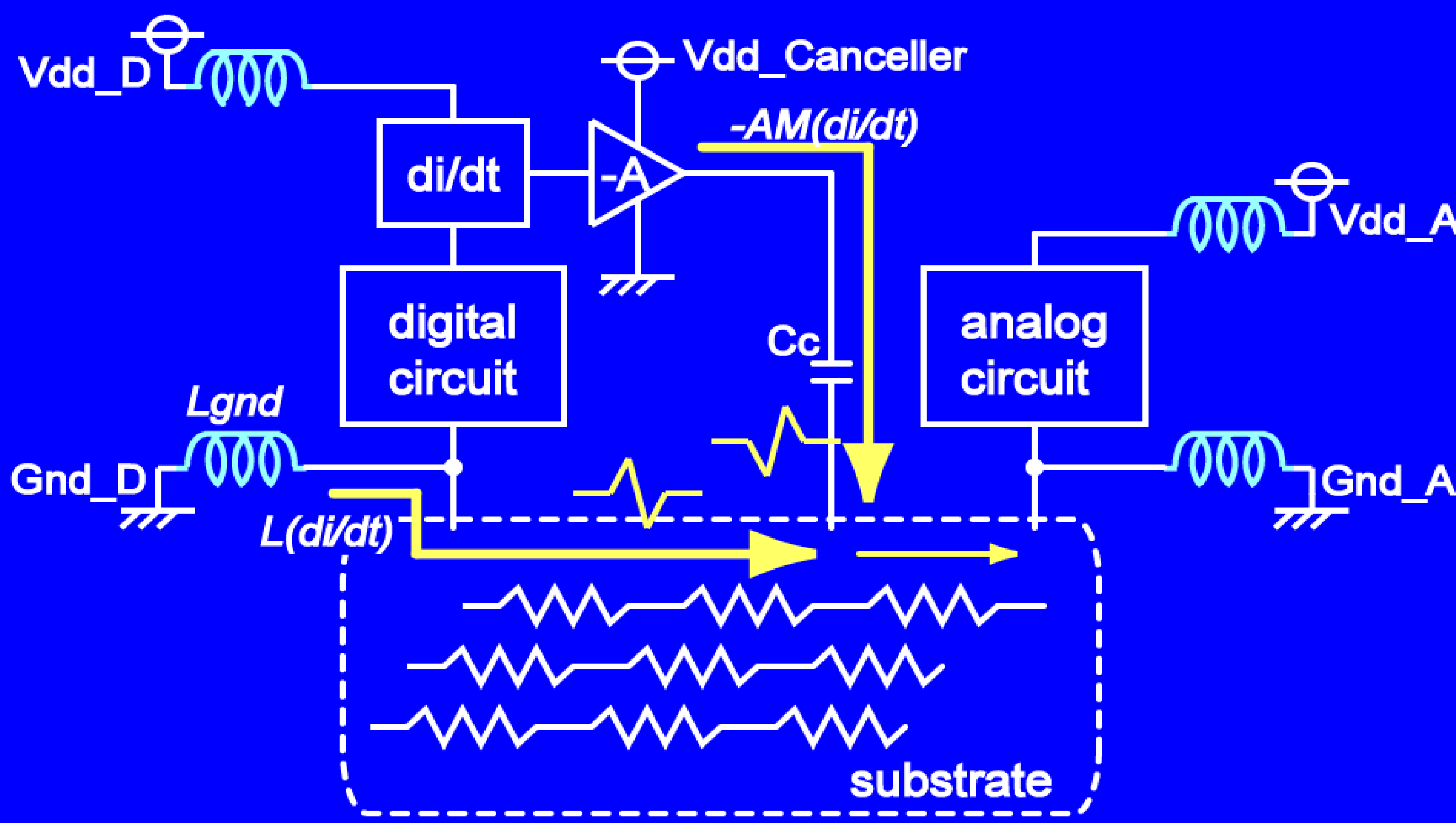


Waveform (Random@500MHz)

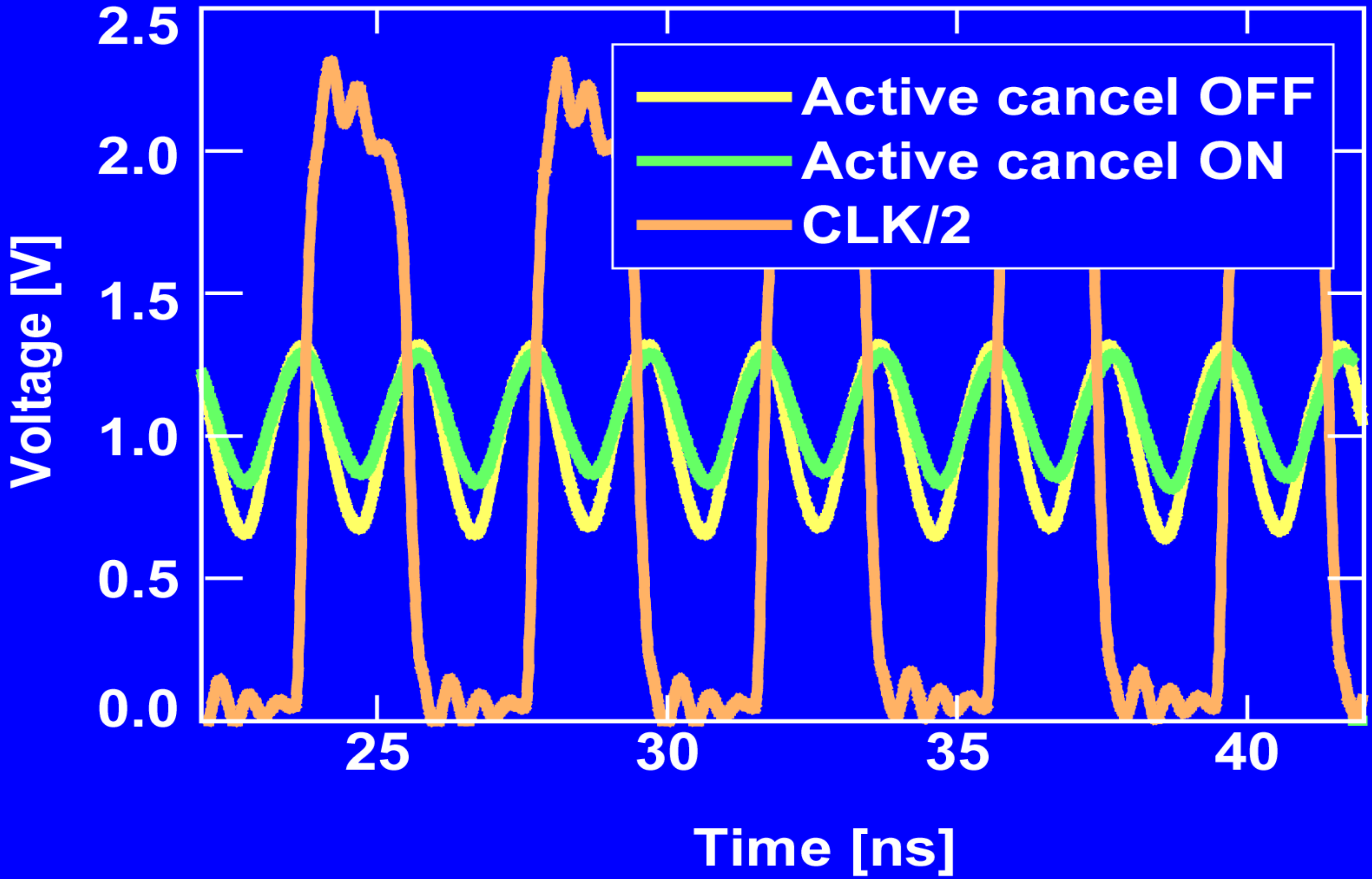


Active Cancel ON/OFF

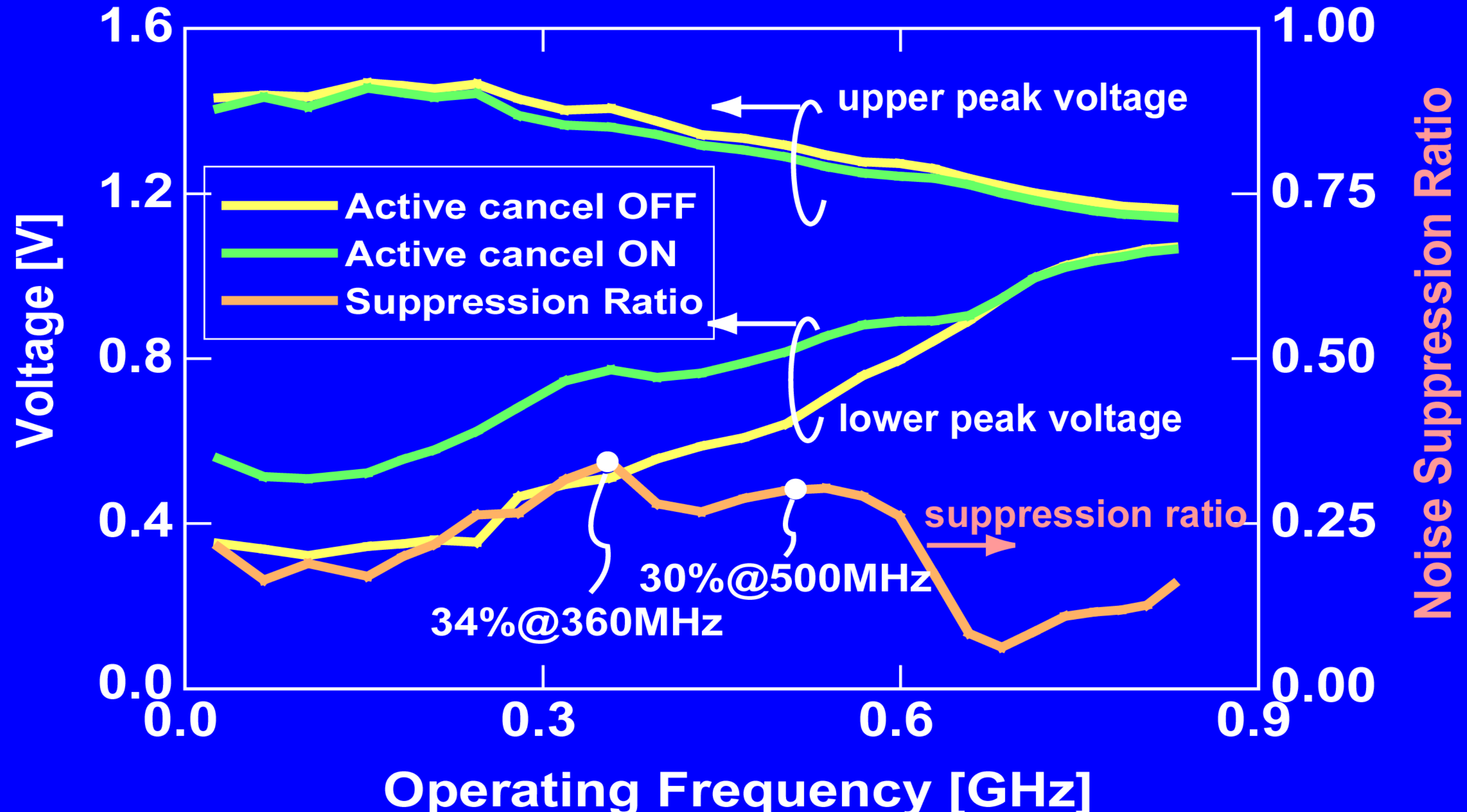
- ON, OFF means Vdd_Canceller=3.3V, 0V



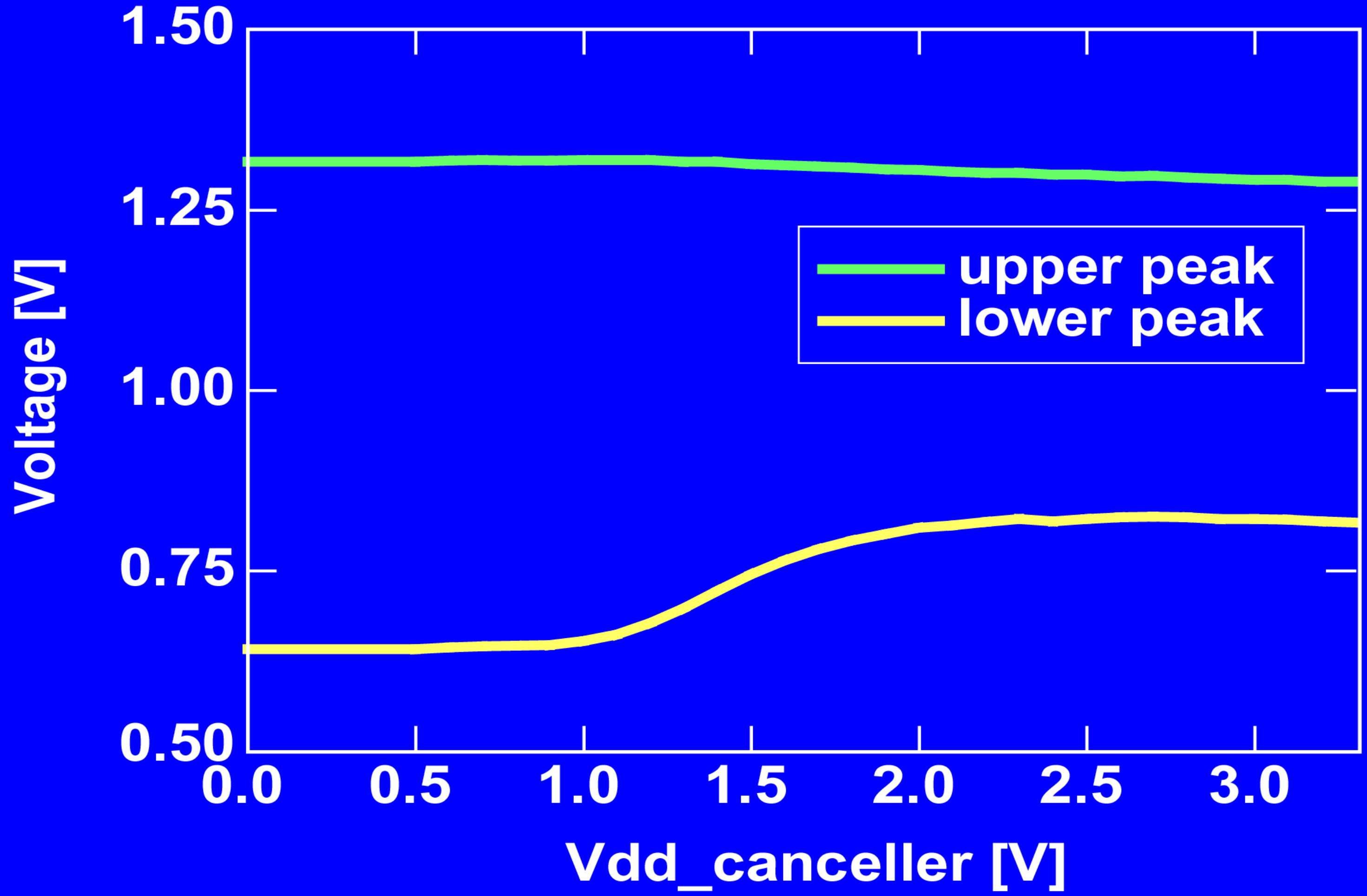
Waveform (Repeat@500MHz)



Frequency Dependence (repeat)



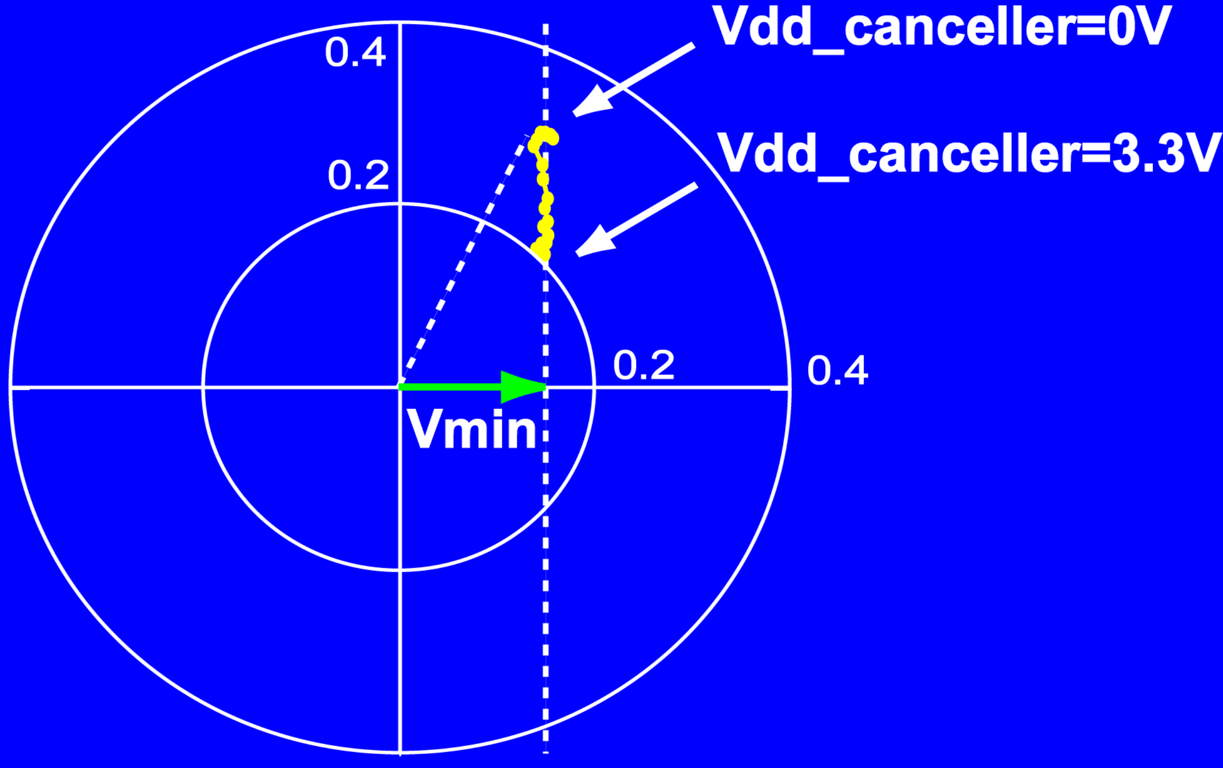
Noise Amplitude Change



- @500MHz operation, repeat mode

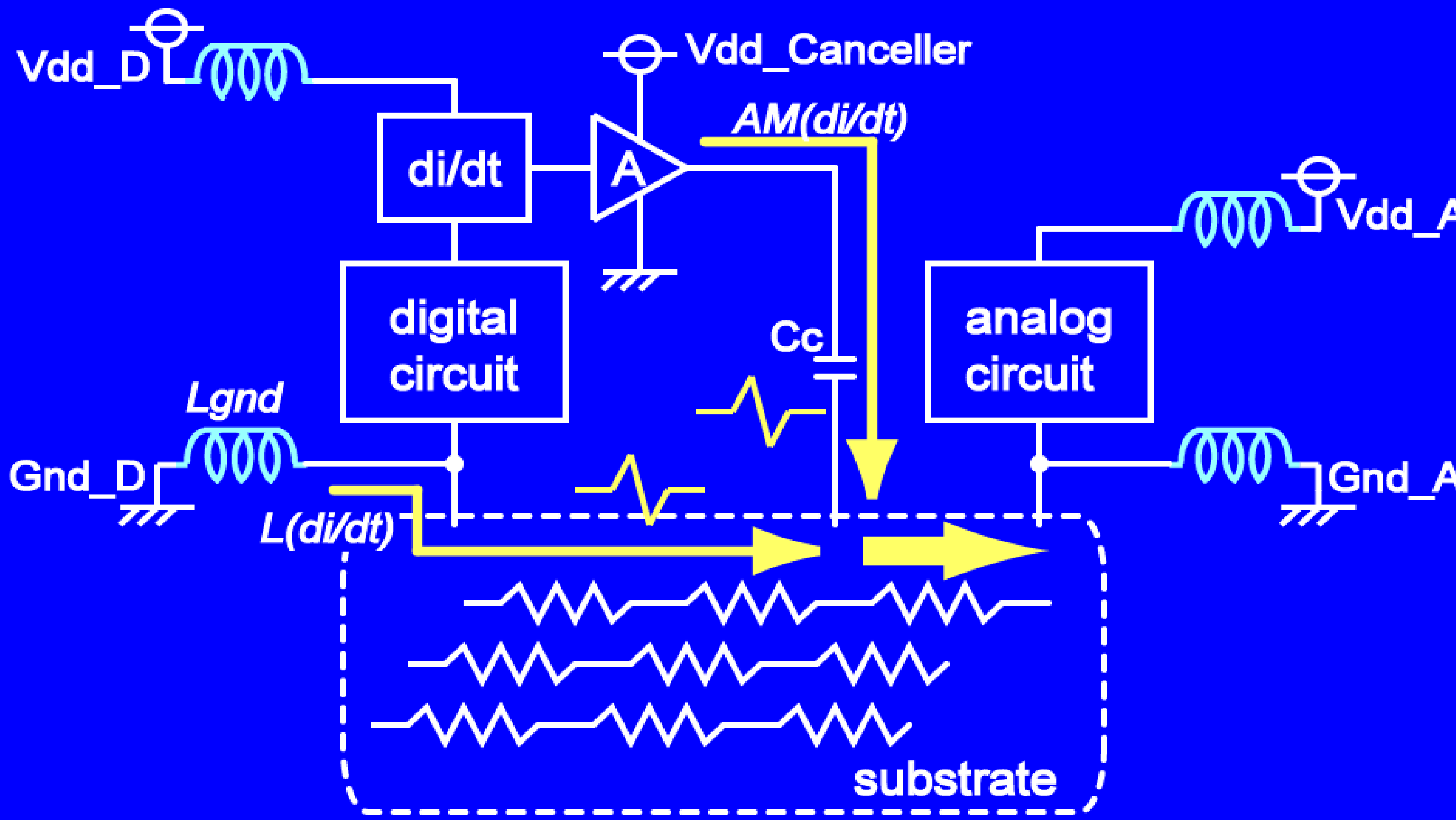
Phasor of the Substrate Noise

- Phase of the injected current is $-\pi/2$
- 54% noise reduction would be achieved by optimizing the amplifier design

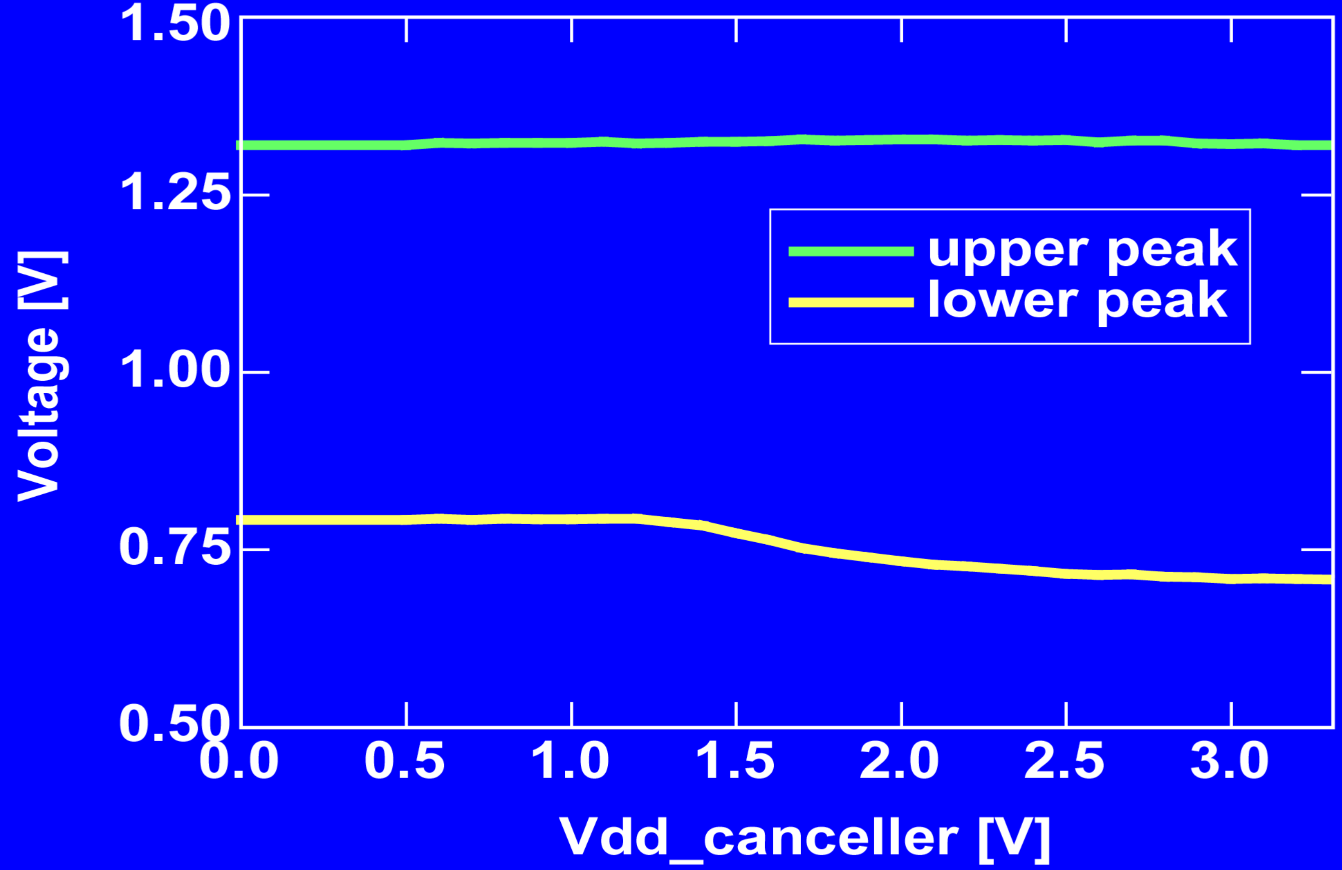


In-phase Current Injection

- In-phase injection increase the noise



In-phase Current Injection



- This result supports our model

Short Summary

- Feedforward active substrate noise cancelling technique is demonstrated
- A di/dt detector generates anti-phase signals, and injected into the substrate
- Measurement results show that 17% to 34% of the substrate noise reduction is achieved from 100MHz to 600MHz range
- Optimized injector design will enhance the noise suppression ratio up to 56%

Contents

- Introduction
- Comparison of stubs and decoupling capacitor for noise reduction
- Experiments for power supply noise reduction using stubs
- On-chip di/dt detector for power supply
- Feedforward active substrate noise cancelling using the di/dt detector
- Conclusions

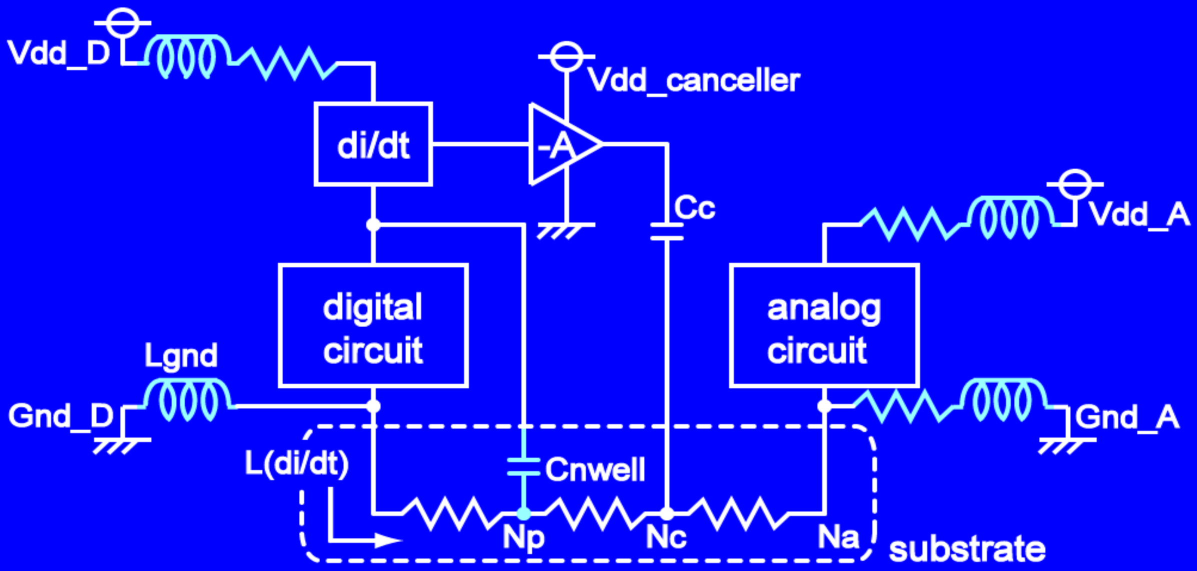
Conclusions

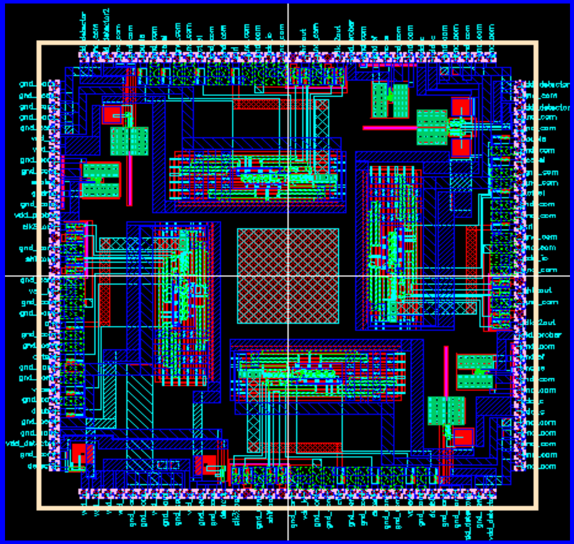
- Stubs and capacitors are compared for power supply noise reduction
  - Boundary frequency is clarified
  - Stubs have advantage for high-frequency
- Clear supply noise reduction effects were observed with on-board stubs
- On-chip di/dt detector was demonstrated
  - on-chip and real time di/dt measurement
- Feedforward active substrate noise cancelling was demonstrated
  - Use the di/dt detector

Q&A

Future Works (1/4)

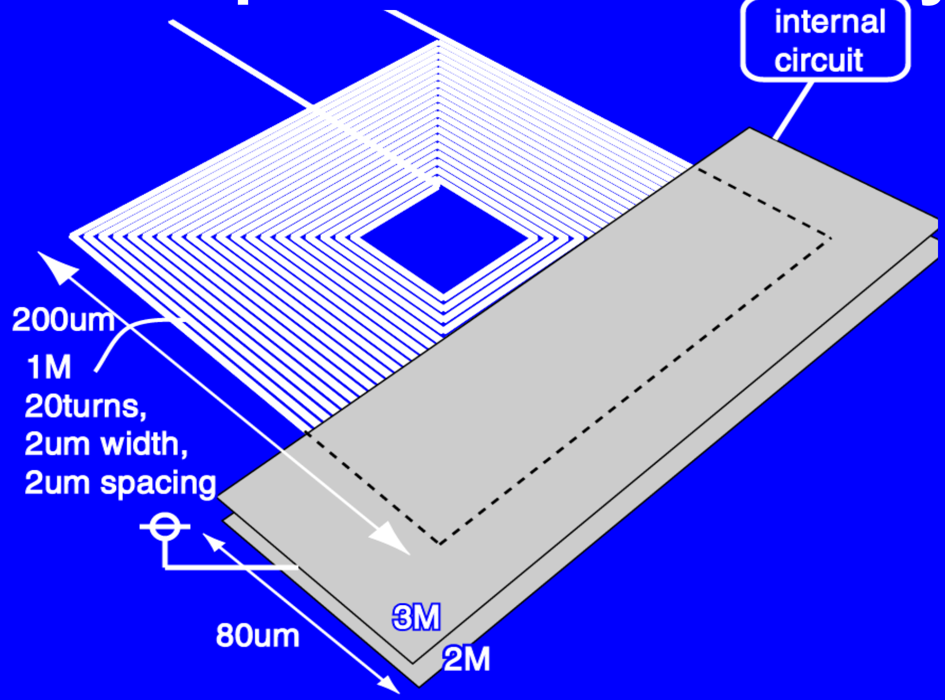
- Measure the substrate noise cancelling circuit (chip delivery 10/8)

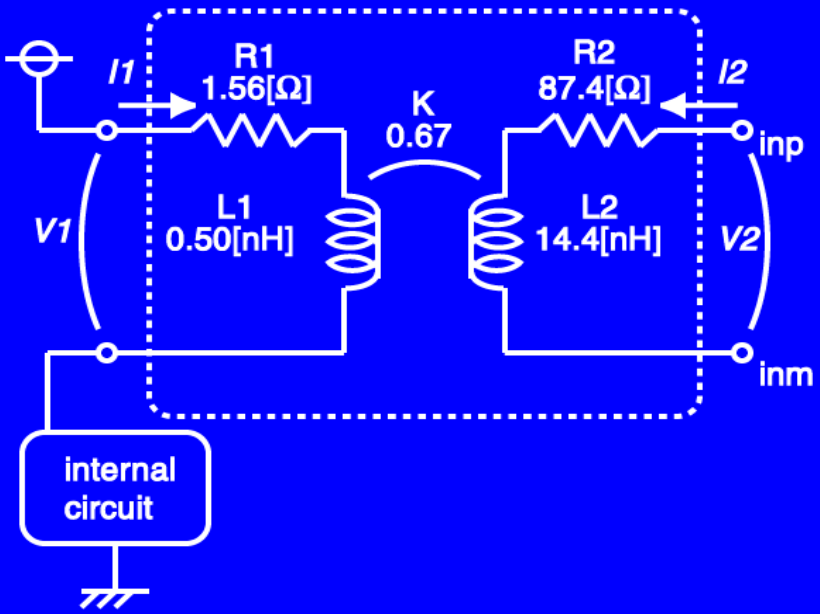




Future Works (2/4)

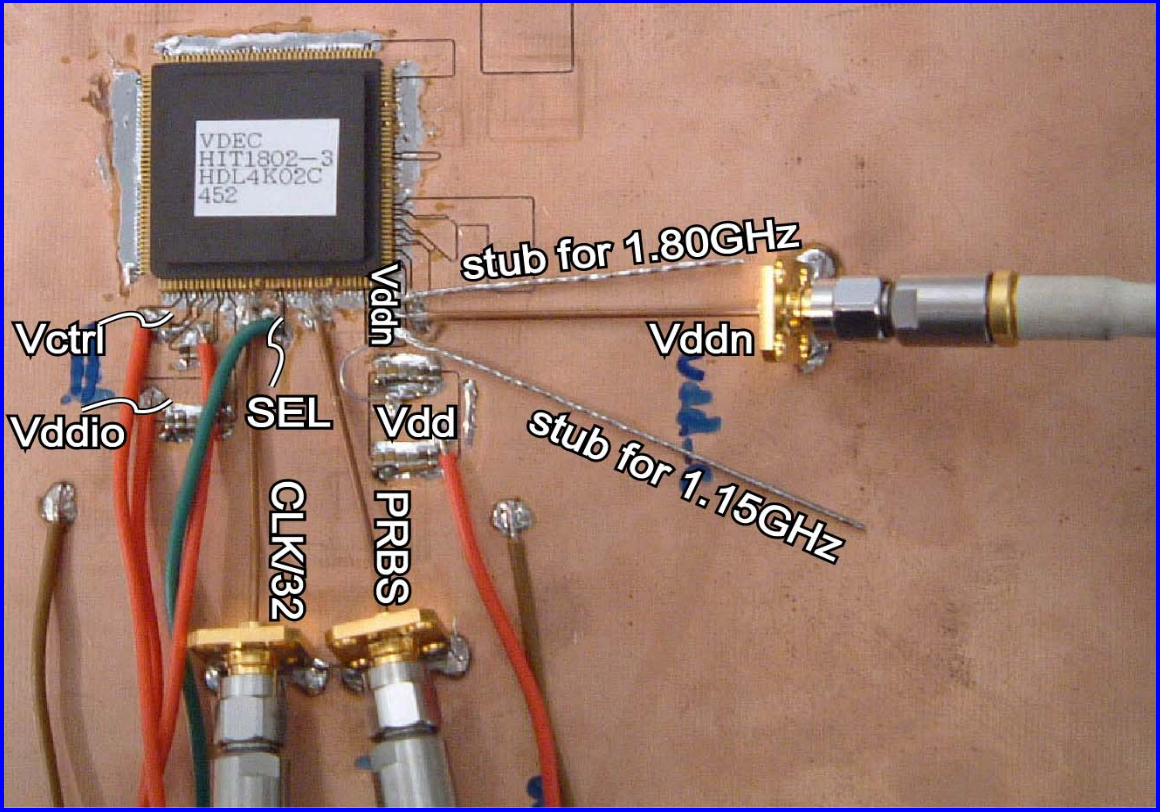
- **Measure an improved di/dt detector**
  - Pros: L1:0.5nH → 0.26nH, R1:1.56Ω → 0.25Ω
  - Cons: M :1.80nH → 0.92nH
  - – Depend on the delivery date (10/8???)





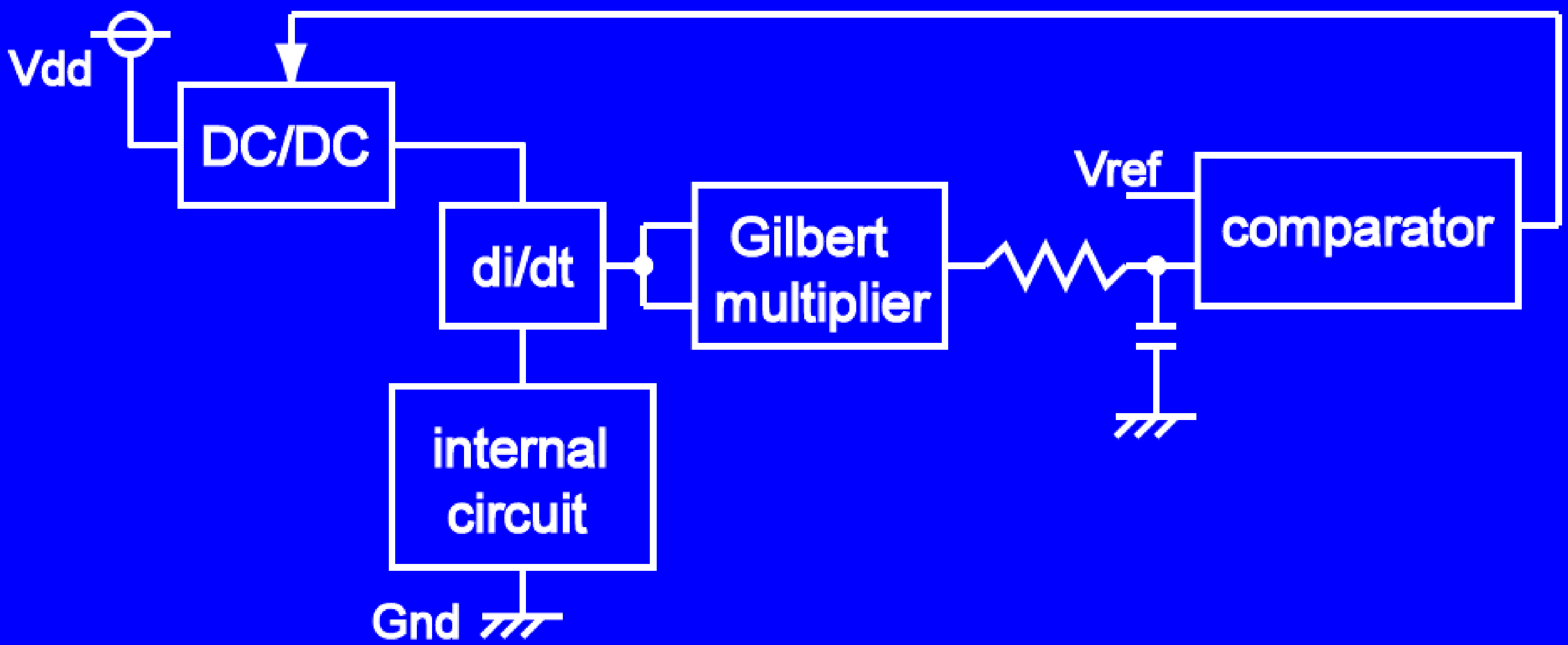
Future Works (3/4)

- Off-chip stub vs off-chip capacitor
  - Write stub and capacitor patterns with the same area on PCB



Future Works (4/4)

- Simulate a feedback di/dt control system



Introduction

Power Supply Noise

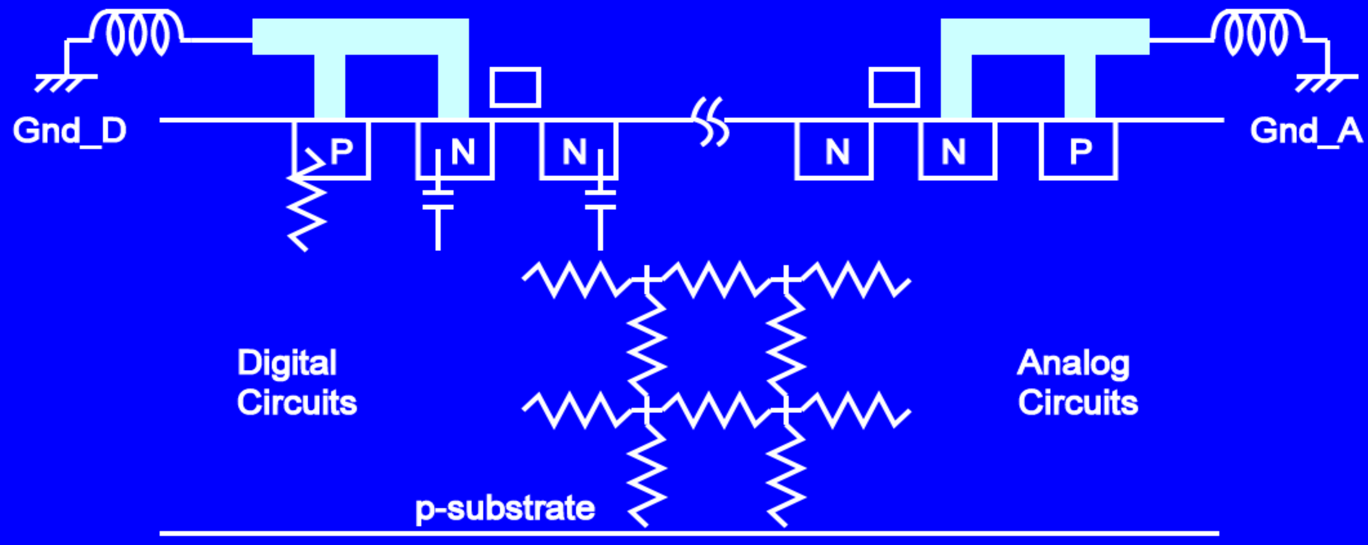
- As the Vdd decrease, the noise margin is reduced
  - Timing violation – *delay* $\propto$ *1/(Vdd-Vth)*
  - Logic error
- L(di/dt)+RI causes the noise
  - L(di/dt) is dominant in high-speed LSIs
  - Decoupling capacitor reduce the di/dt
    - ▶ Requires more die area for on-chip capacitor
    - ▶ Parasitic inductance disturbs for off-chip capacitor

Power Supply Noise

- As the Vdd decrease, the noise margin is reduced
  - Timing violation – *delay* $\propto$ *1/(Vdd-Vth)*
  - Logic error
- L(di/dt)+RI causes the noise
  - L(di/dt) is dominant in high-speed LSIs

Substrate Noise

- PLL jitter becomes 10 times bigger by the substrate noise [16]
- Coupling from power supply noise is the main source → di/dt is important



[16] *P. Larsson, JSSC July 2001*

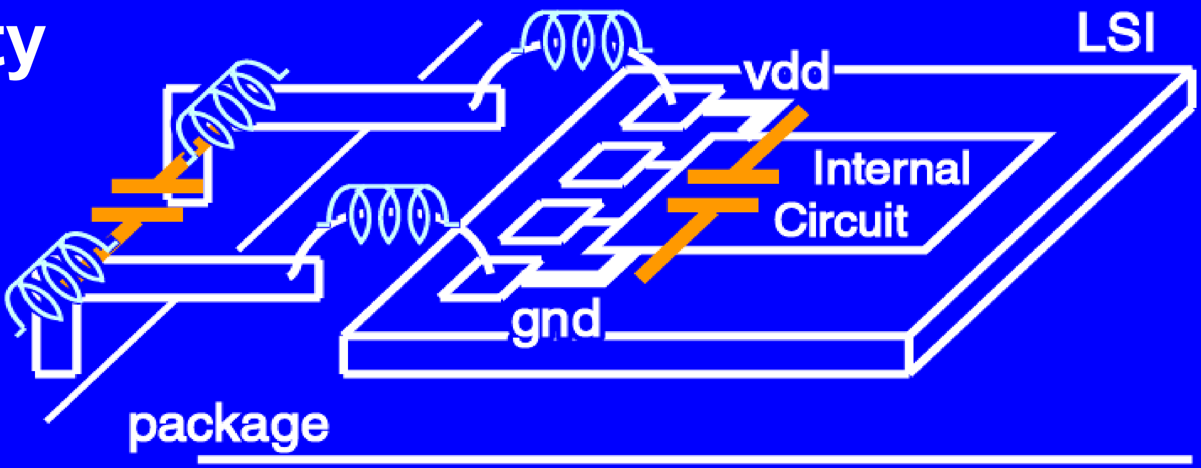
EMI noise

- EMI radiation can cause operational problems in other devices
- EMI radiation occurs from cables, connectors, PBC, package ...
- Ultimate noise source is di/dt caused by gate switching in LSIs
- EMI radiation is caused by di/dt, not by voltage perturbation

Theoretical Study of Stubs vs Capacitors

Background

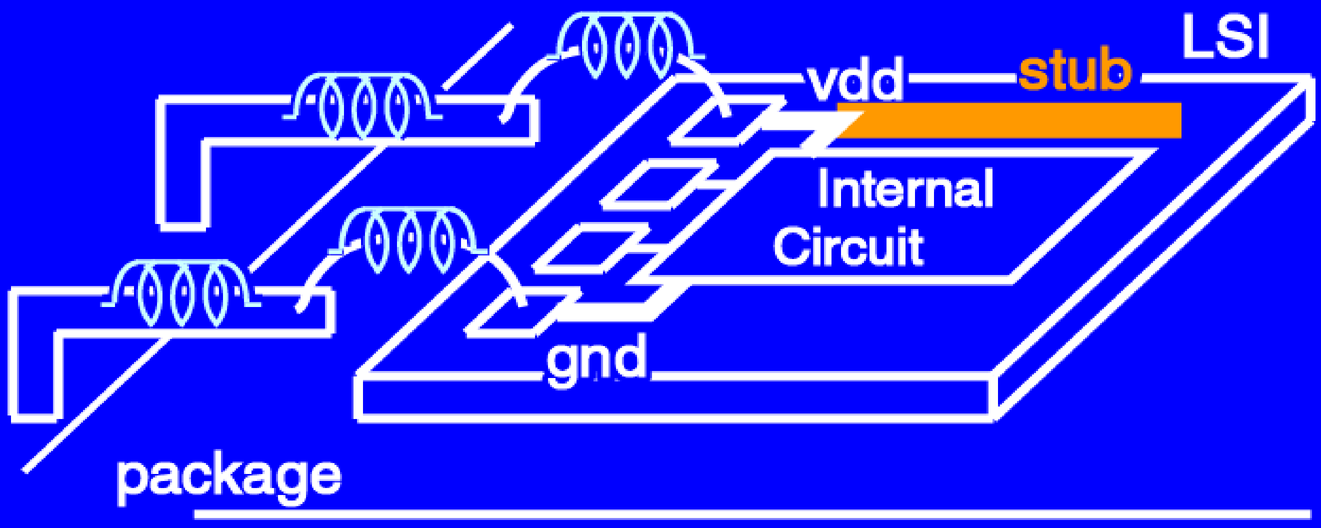
- Decoupling capacitor
  - Area penalty
  - Parasitic inductance



- Semi-asynchronous architecture
  - Complicated design
- Spiral power line on PCB board
  - Complicated design

Power Line Noise Reduction

- Attach the stub to the power line will reduce the power supply noise



Stub Theorem

- Input impedance of the transmission line of Z0, β, l, and ZL termination :

$$Zstub = Z0\frac{ZL\cos\beta l + Z0\sin\beta l}{Z0\cos\beta l + ZL\sin\beta l}$$

- When open termination (ZL=infty)

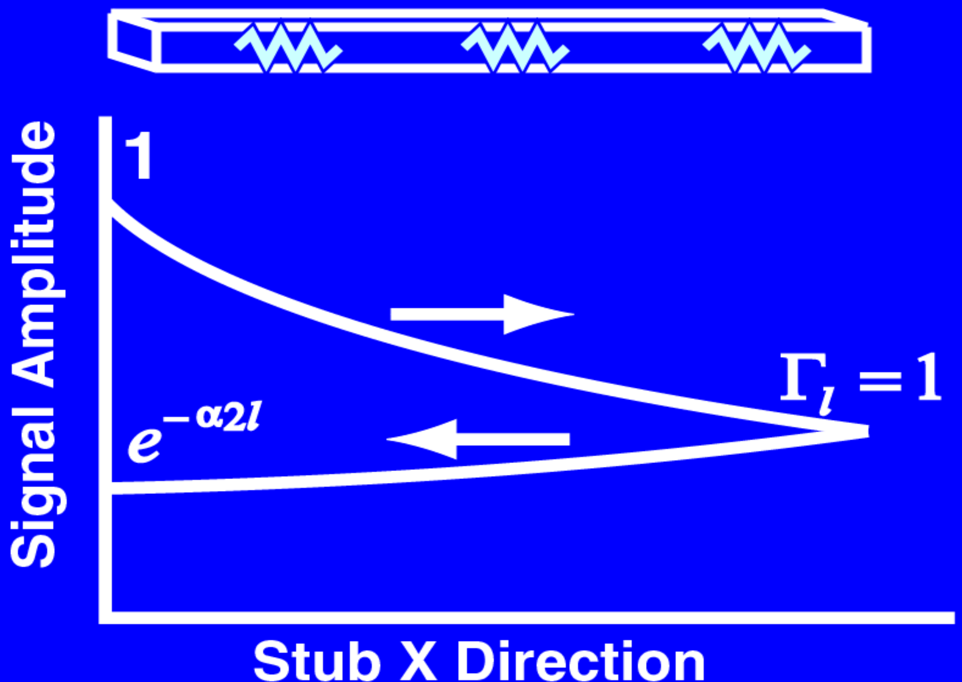
$$Zstub = Z0\frac{\cos\beta l}{j\sin\beta l}$$

- When the line length is quarter of the wavelength (βl=π/2), no loss (R=G=0)

$$Zstub = 0$$

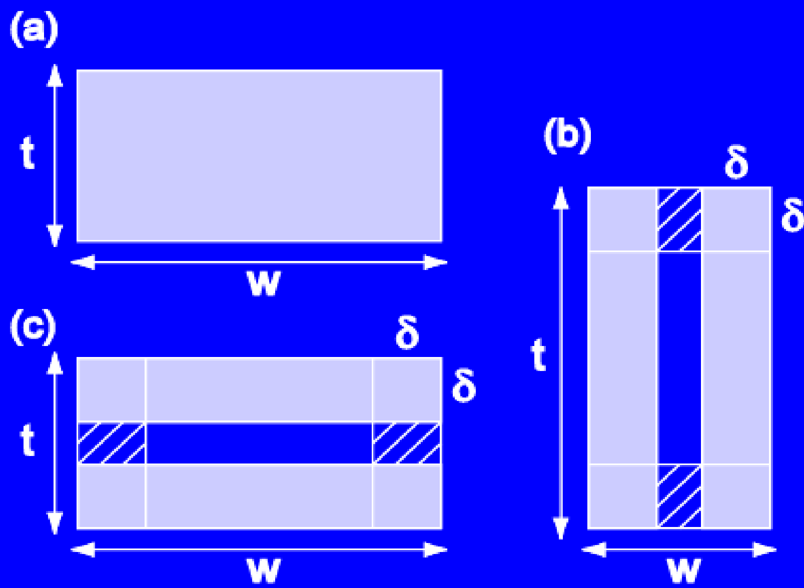
Stub Resistance

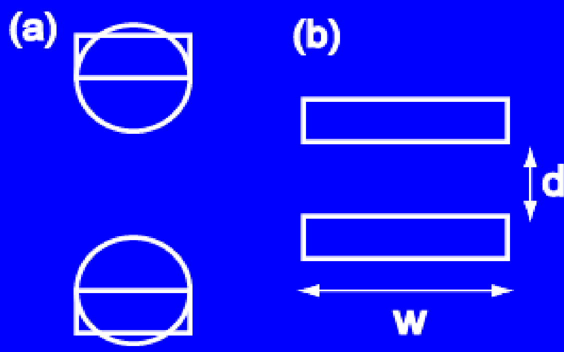
- **The resistance of the stub degrade the noise reduction effect**
  - **Round trip attenuation factor $\eta = e^{-\alpha 2l}$**



Transmission Line Parameters

- Resistance
  - Skin effects $\delta = \sqrt{\frac{2p}{\omega\mu 0}}$
- Capacitance
  - Parallel plate
    for d<w
  - Parallel cylinder
    for w<d
- Inductance
  - $c^2/\varepsilon_r = 1/LC$





Boundary Frequency

- Stub input impedance $Zstub \propto f^{-2}, f^{-1.5}$
  - $l \propto f^{-1}, w \propto f, \delta \propto f^{-0.5}, Zstub = Rl/2$
- Capacitor input impedance $Zcap \propto f^{-1}$
- Boundary frequency at $Zstub = Zcap$

$$f_B = \frac{\pi c^2 \varepsilon_0 \rho}{8td} \qquad \frac{t^3}{A} < \frac{16\rho\sqrt{\varepsilon_r}\,\varepsilon_0 c}{\pi} \text{ and } t < \frac{16d}{\pi^2}$$

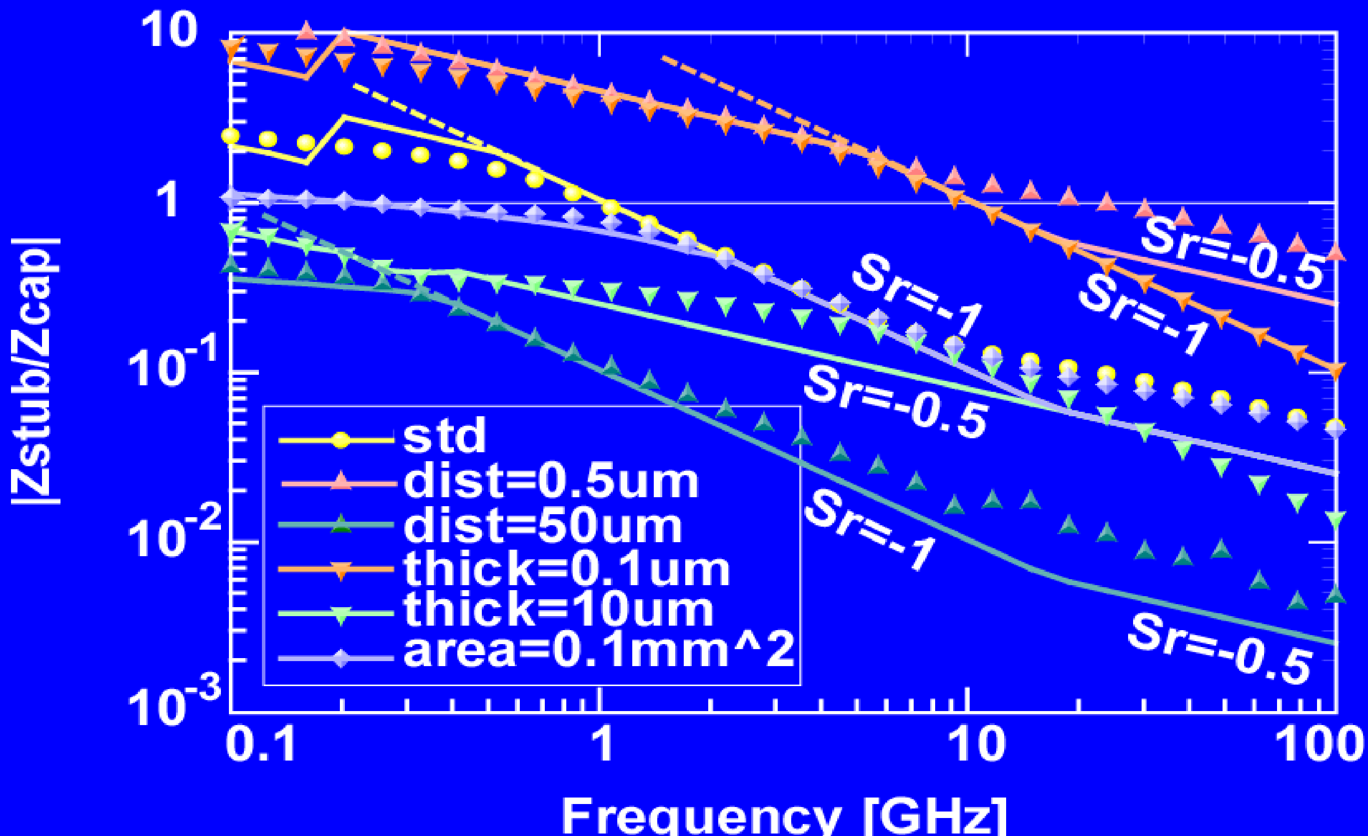
$$\frac{t^3}{A} > \frac{16\rho\sqrt{\varepsilon_r}\,\varepsilon_0 c}{\pi} \text{ and } t > \frac{\pi^3 c\sqrt{\varepsilon_r}\,\varepsilon_0 \rho A}{64d^2}$$

$$f_B = \frac{\pi^3 c^2 \varepsilon_0 \rho}{256d^2} \qquad \frac{t^3}{A} < \frac{16\rho\sqrt{\varepsilon_r}\,\varepsilon_0 c}{\pi} \text{ and } t > \frac{16d}{\pi^2}$$

$$\frac{t^3}{A} > \frac{16\rho\sqrt{\varepsilon_r}\,\varepsilon_0 c}{\pi} \text{ and } t < \frac{\pi^3 c\sqrt{\varepsilon_r}\,\varepsilon_0 \rho A}{64d^2}$$

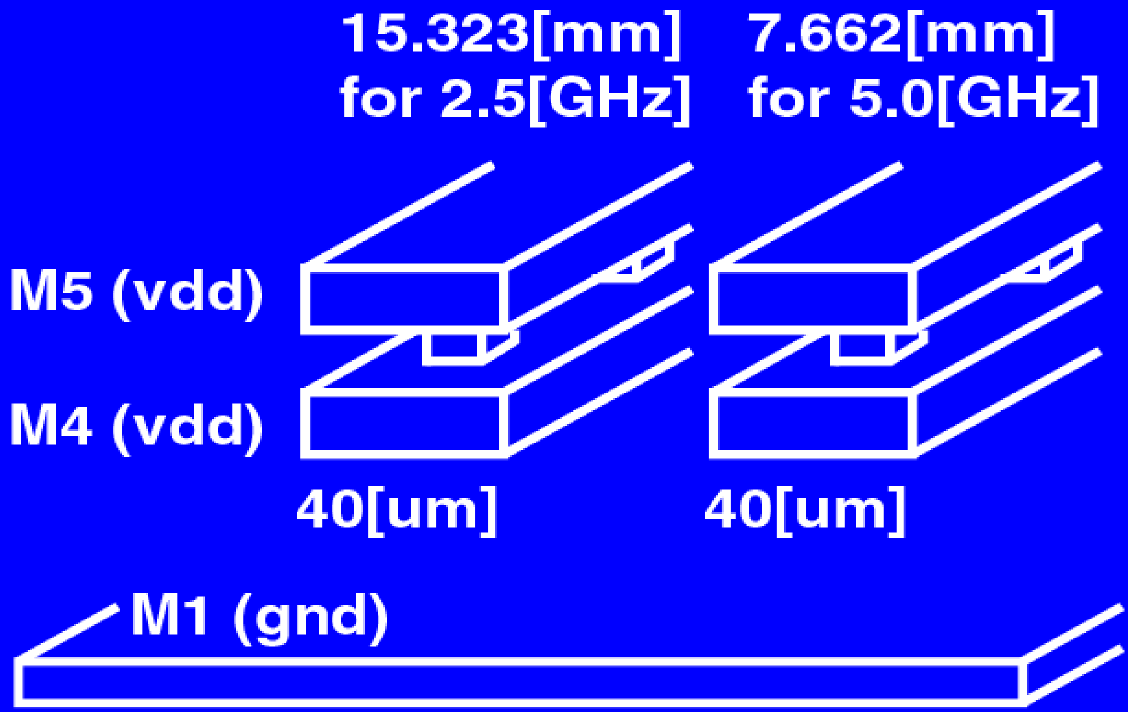
Numerical Analysis

- Raphael(L,C), Fasthenry(R) vs. the model
- d=5um, t=1um, A=1mm2, εr=3.9, ρ=ρCu

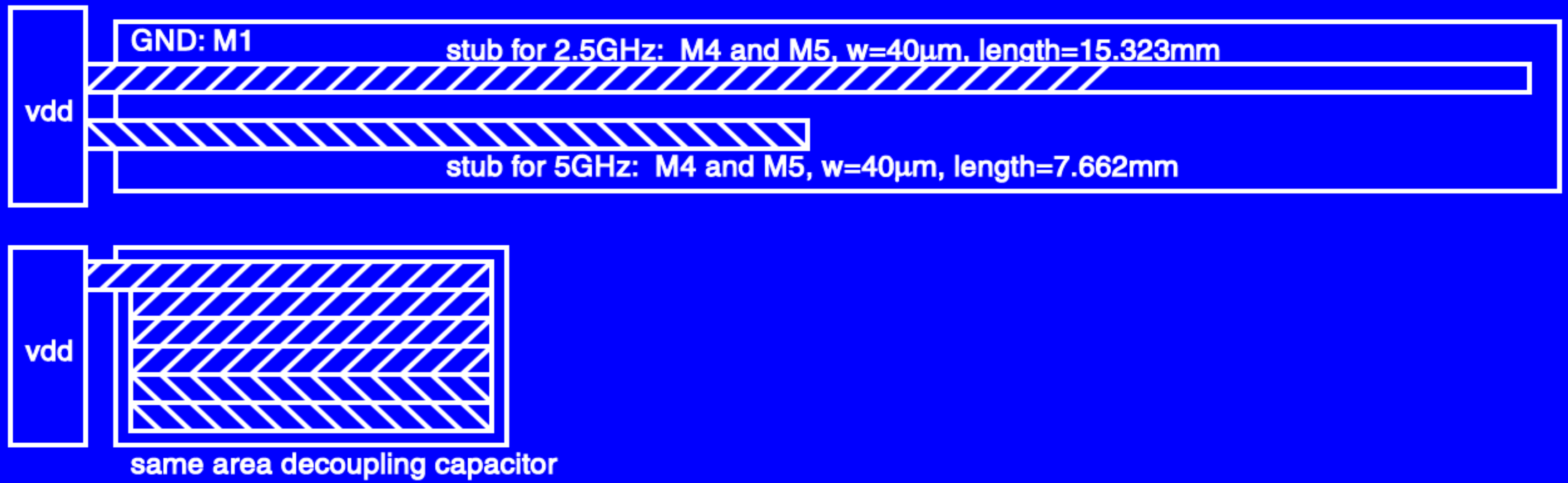


Stub Structure

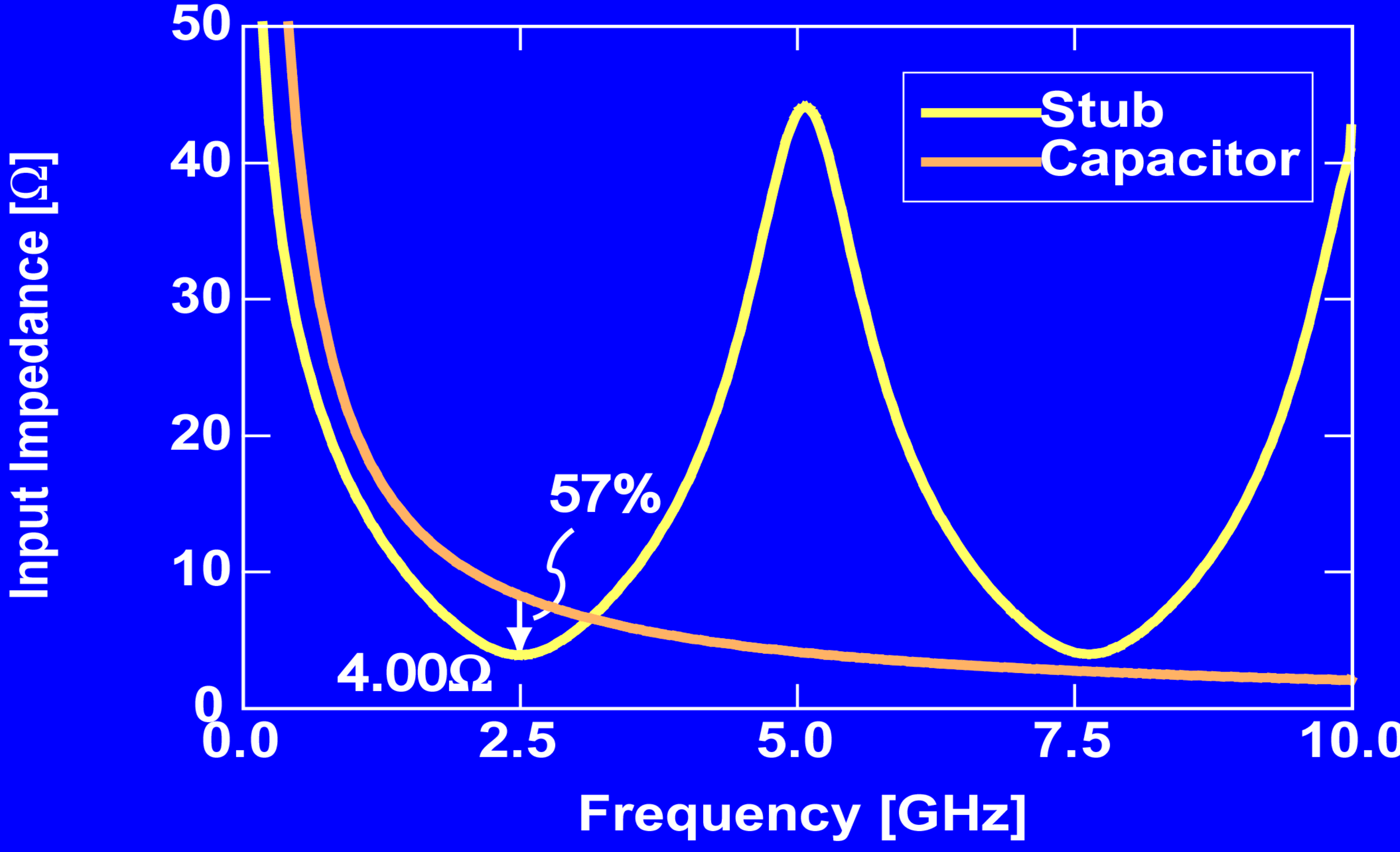
- 0.18um 5M CMOS of company “H”
- For a 2.5GHz operation circuit



Stub and Same-Area Capacitor

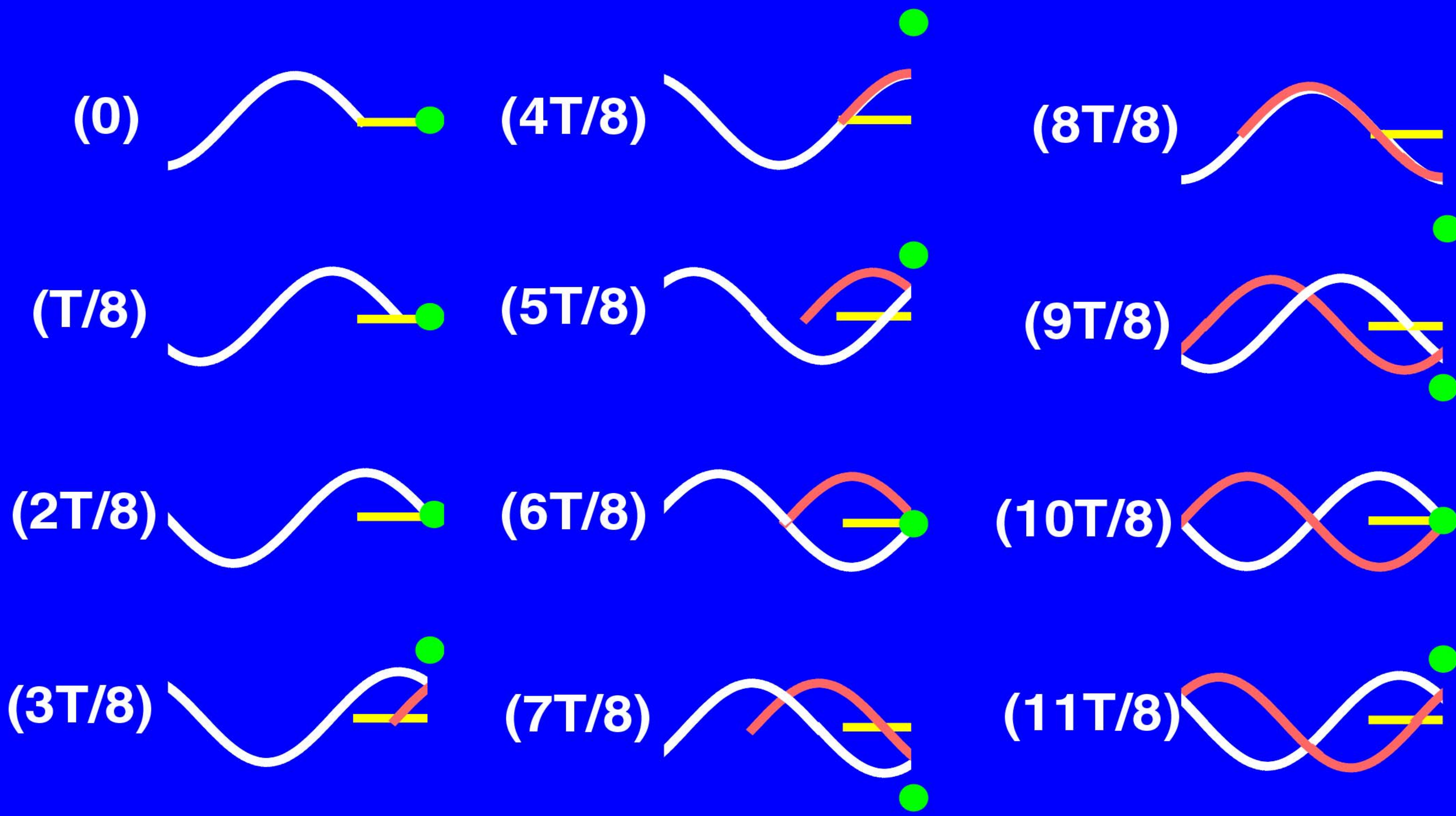


Stub Input Impedance vs. Freq

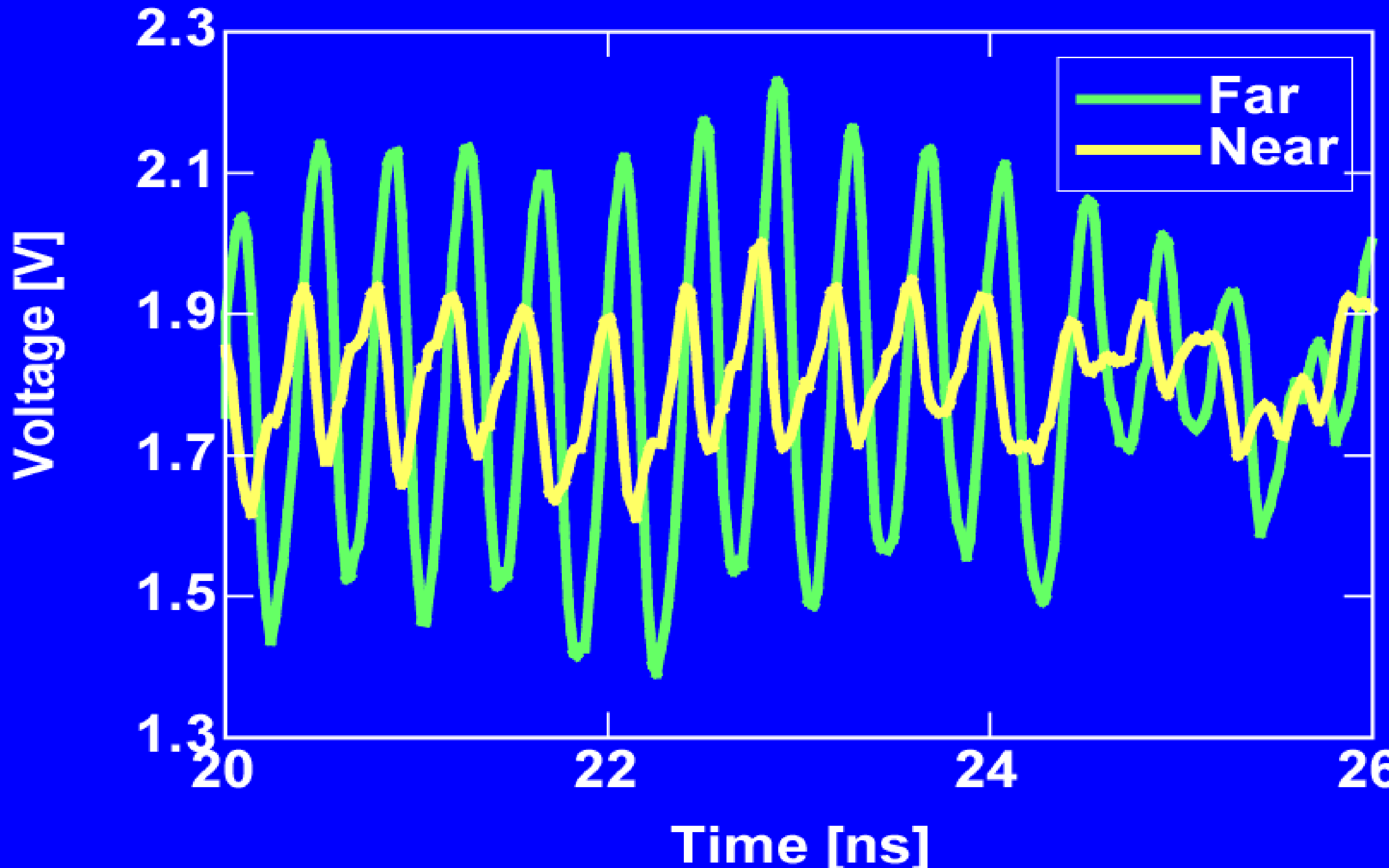


Voltage Swing at Far End

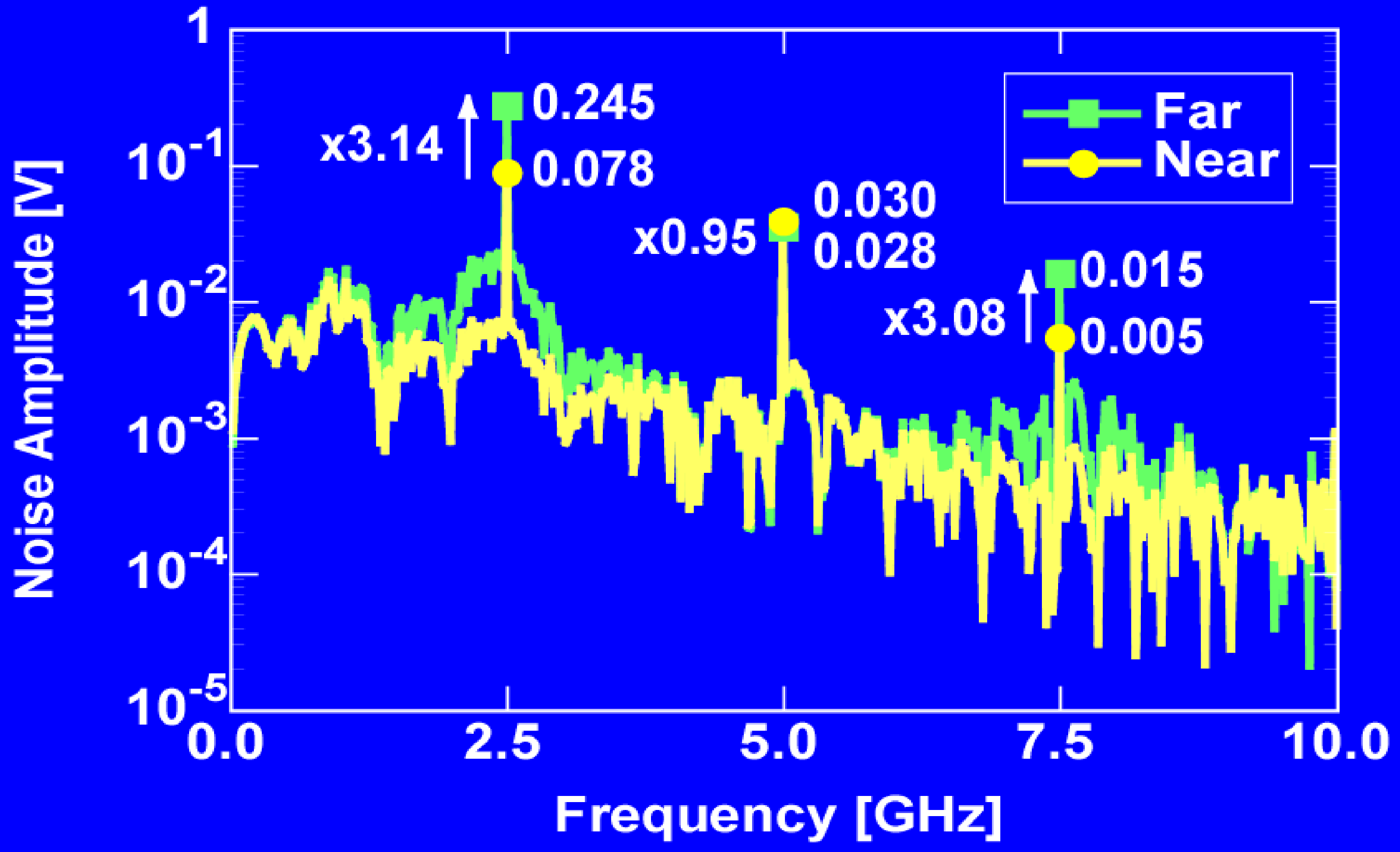
- The voltage swing at far end is bigger



Waveform of Near/Far End



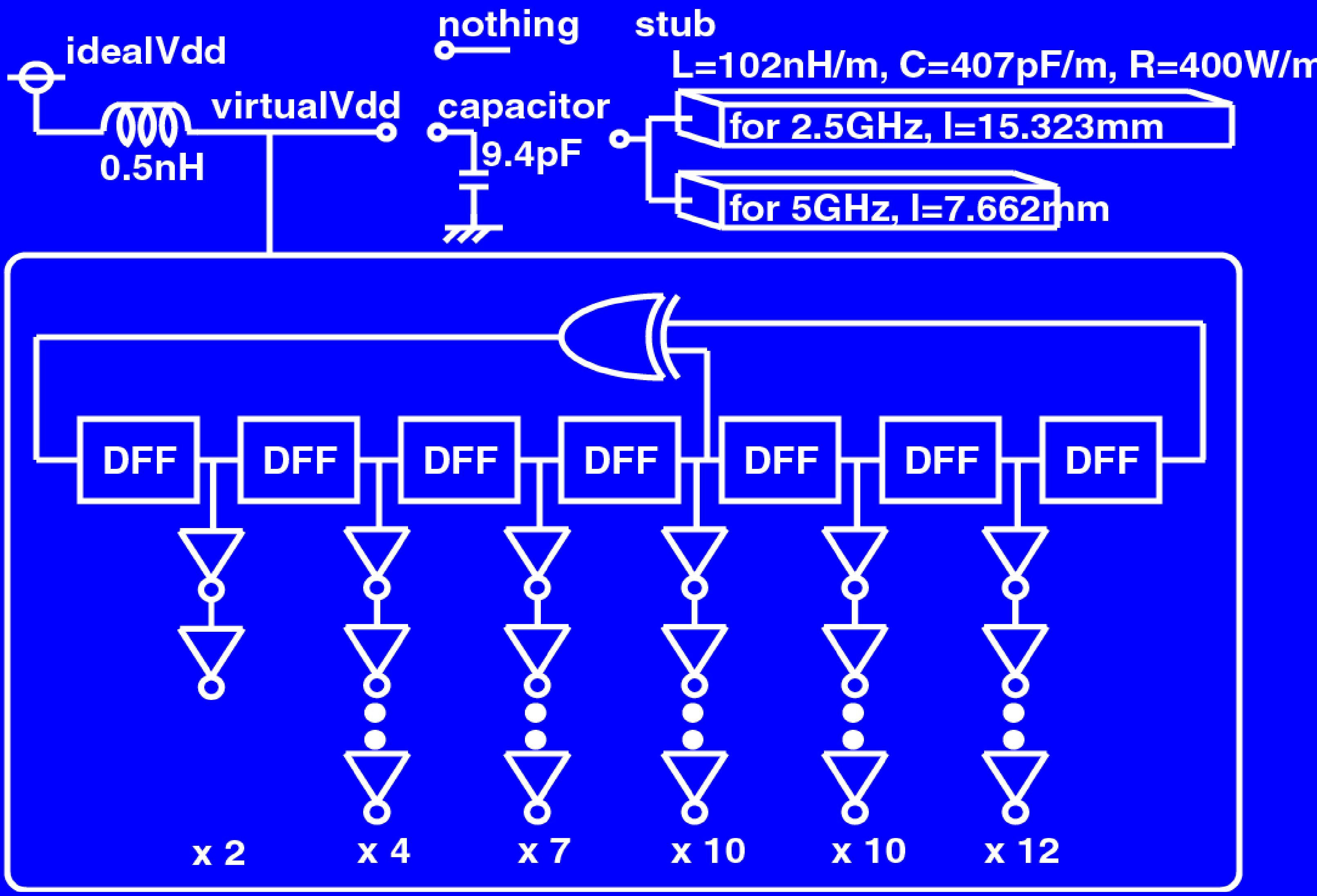
Spectrum of Near/Far End



Stub Design

- **Stub length: quarter wavelength of the operating frequency**
  - **Stub input impedance has frequency dependence**
  - **Operating frequency is the dominant component of the power supply noise**
- **Width: Wider is better for noise reduction**
  - **Smaller resistance, (bigger capacitance)**
- ***Target of this study***
  - ***Observe the noise difference between a stub and the same space decoupling capacitor***

Test Circuit

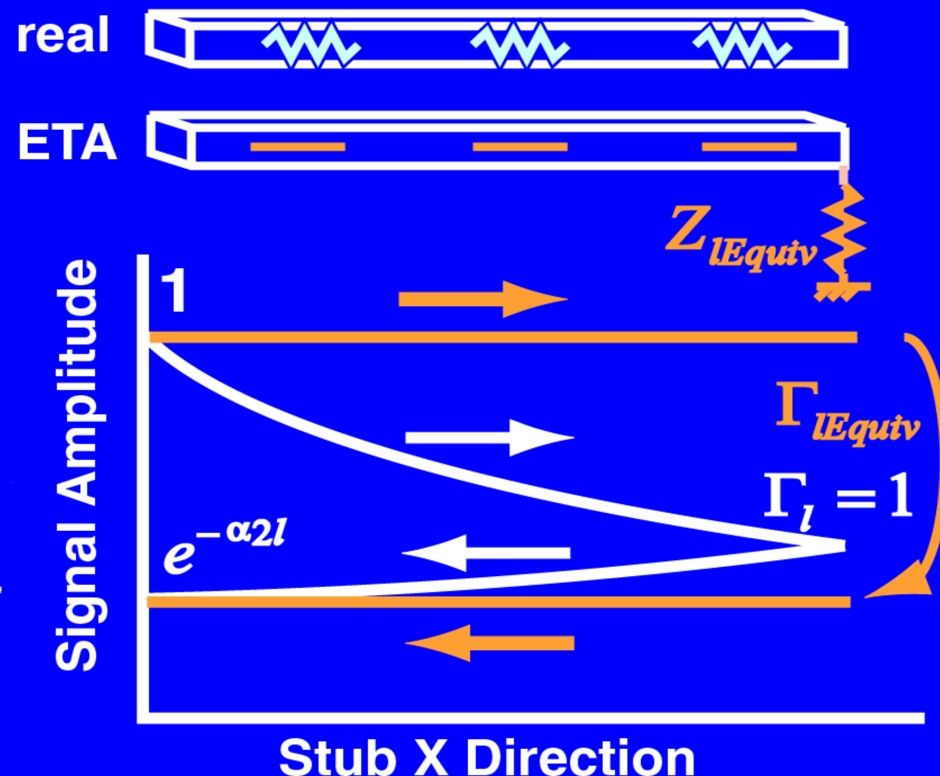


Equivalent Termination Approx.

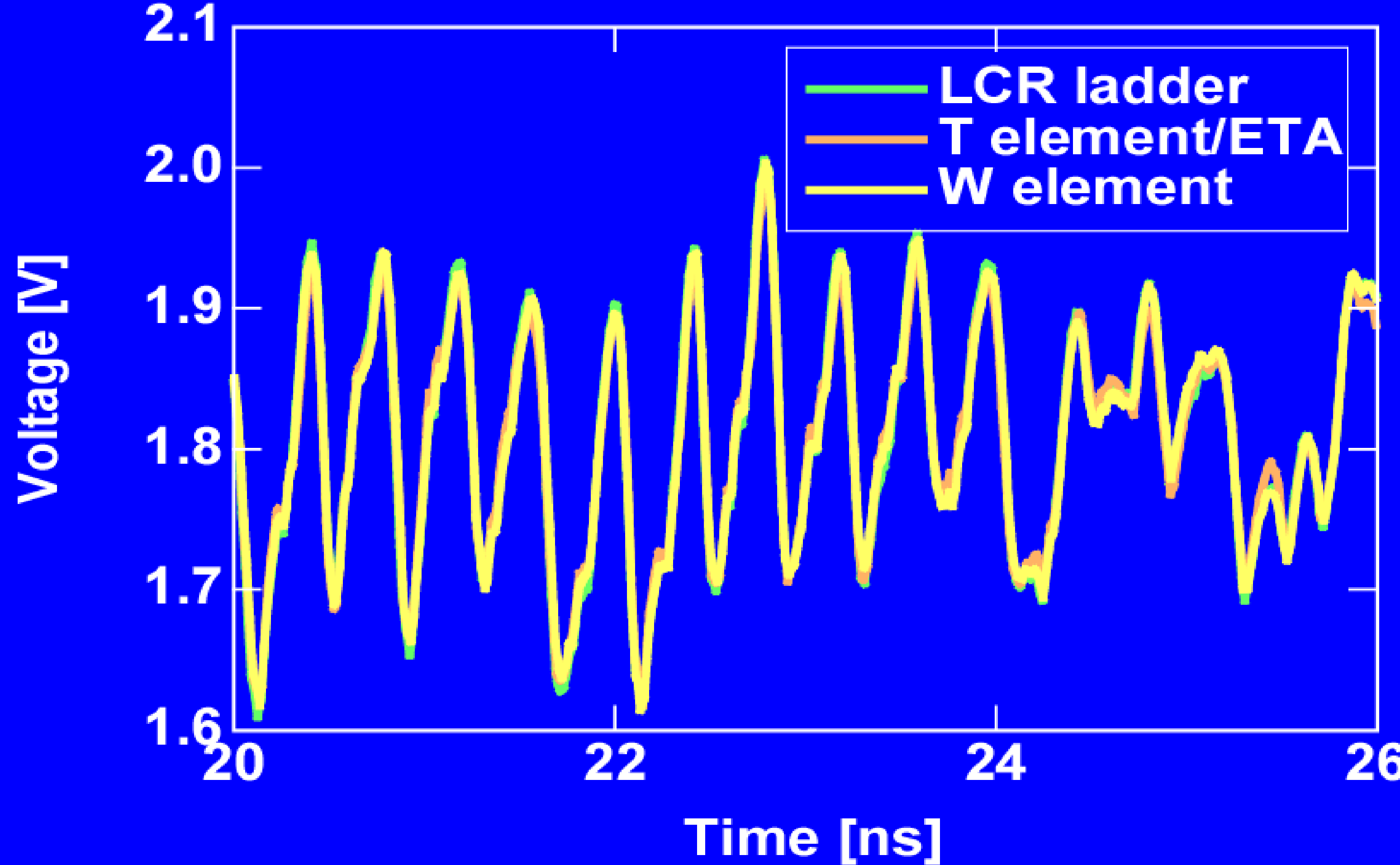
	loss	reflectivity
Real:	α	1
ETA:	0	Γ_{lEquiv}

$$\Gamma_{lEquiv} = \eta = e^{-\alpha 2l}$$

$$Z_{lEquiv} = Z_{0Ideal}\frac{1+\eta}{1-\eta}$$



ETA Waveforms



Analytical Models using ETA (1)

- The stub input impedance

$$ZstubEquiv = \sqrt{\frac{L}{C}\frac{1-\eta}{1+\eta}}$$

- The voltage ratio of the near and far end

$$\frac{Vfar}{Vnear} = -j\frac{1+\eta}{1-\eta}$$

Analytical Models using ETA (2)

- Time constant for stub impedance change
  - At the initial state, stub input impedance is the same as the characteristic impedance

$$Z_{stub} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad \text{(initial)}$$

$$\downarrow \qquad \tau = \frac{1}{-2f \log |\eta \Gamma_s|}$$

$$\frac{\cos\beta l}{j \sin\beta l} \approx \sqrt{\frac{L}{C}} \frac{1-\eta}{1+\eta} \quad \text{(steady)}$$

Lump or Distributed Element?

- Signal propagation time through a wire, compared with the cycle time:

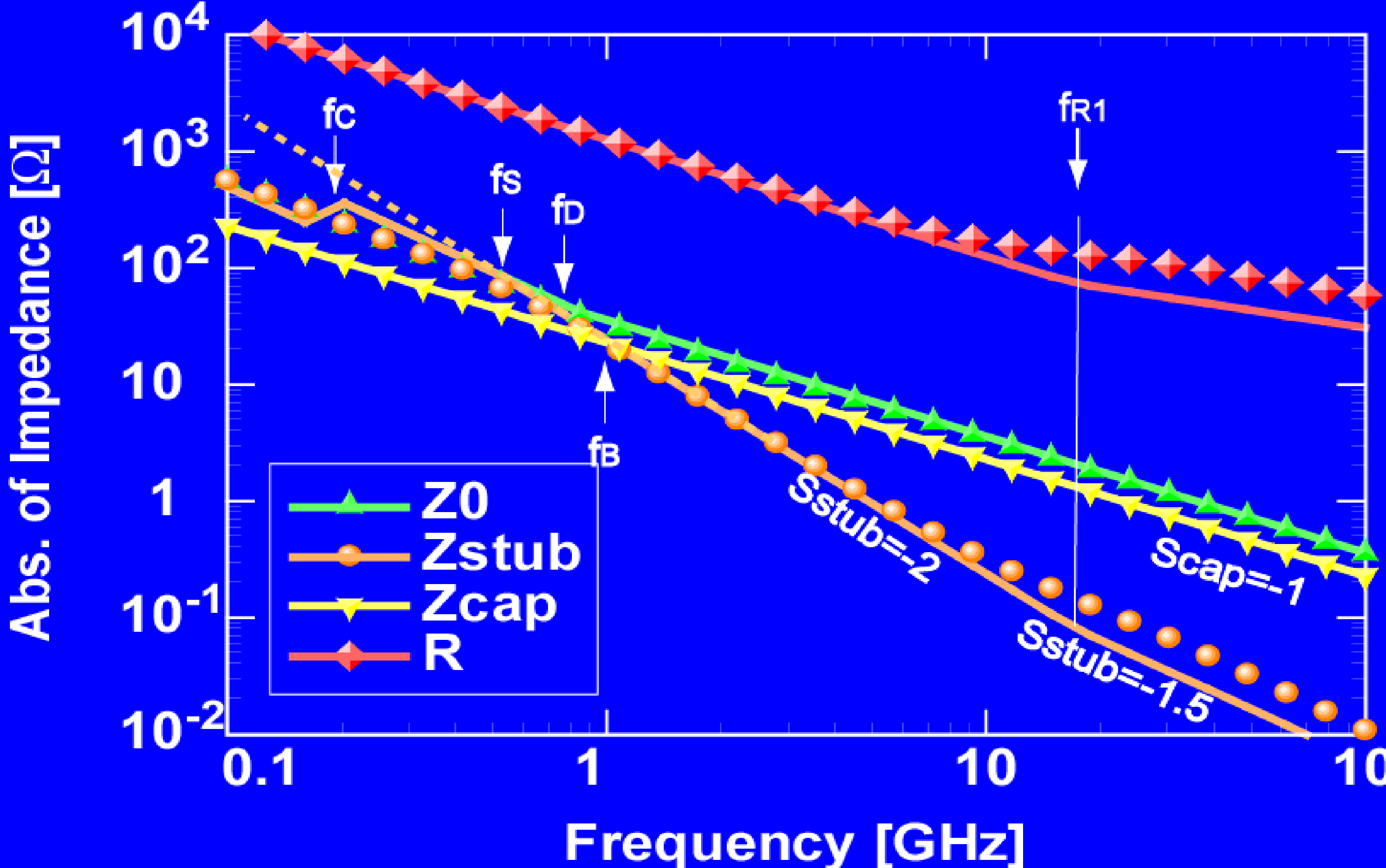
  Negligibly small → lump element (R, C ladder)

  Comparable → distributed element (transmission line)

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad , \quad \textit{length}$$

$$\beta_c = -j\sqrt{(R + j\omega L)(G + j\omega C)} = \beta_r - j\alpha$$

Numerical Analysis

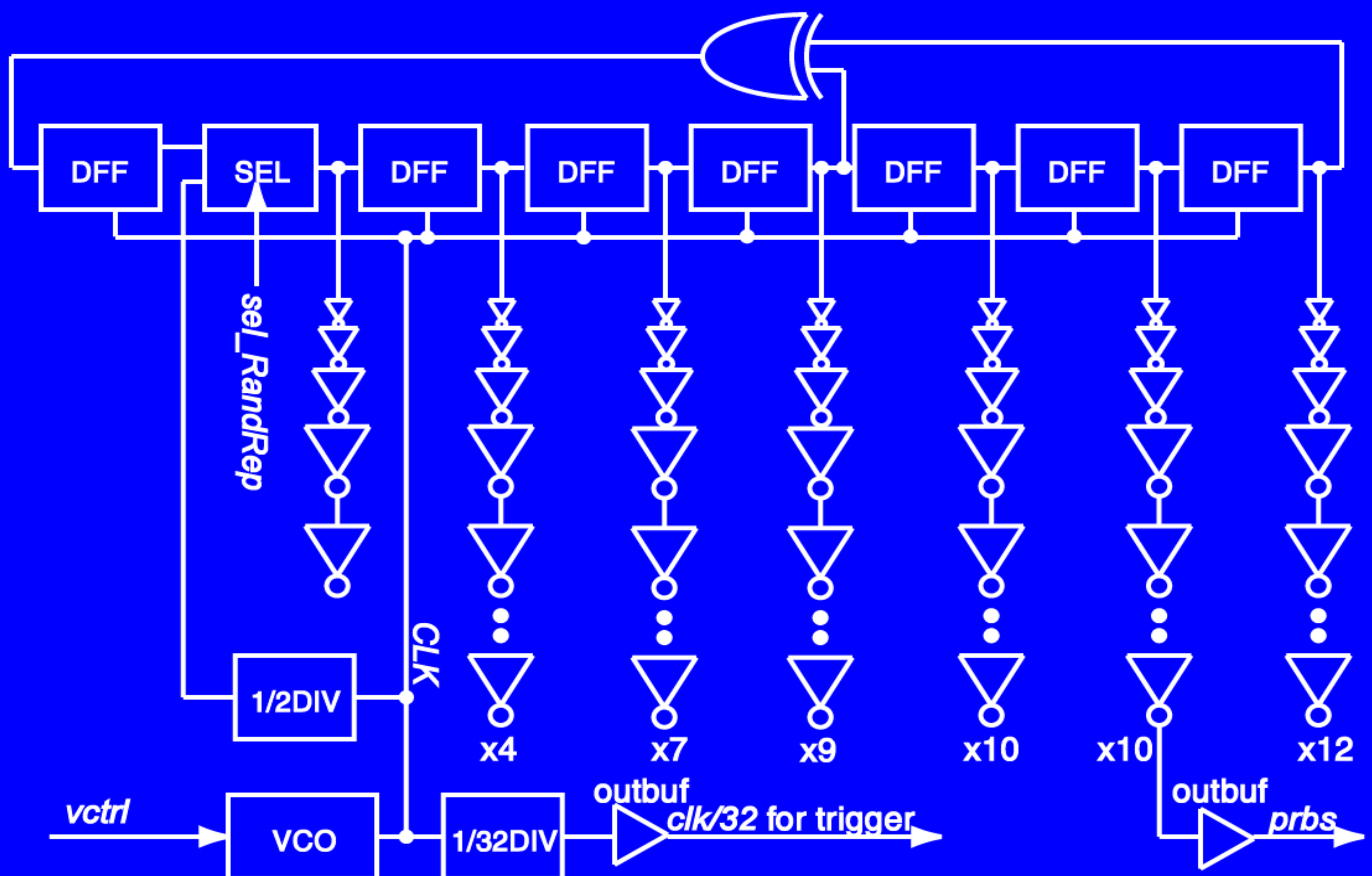


Stub Measurement

Background

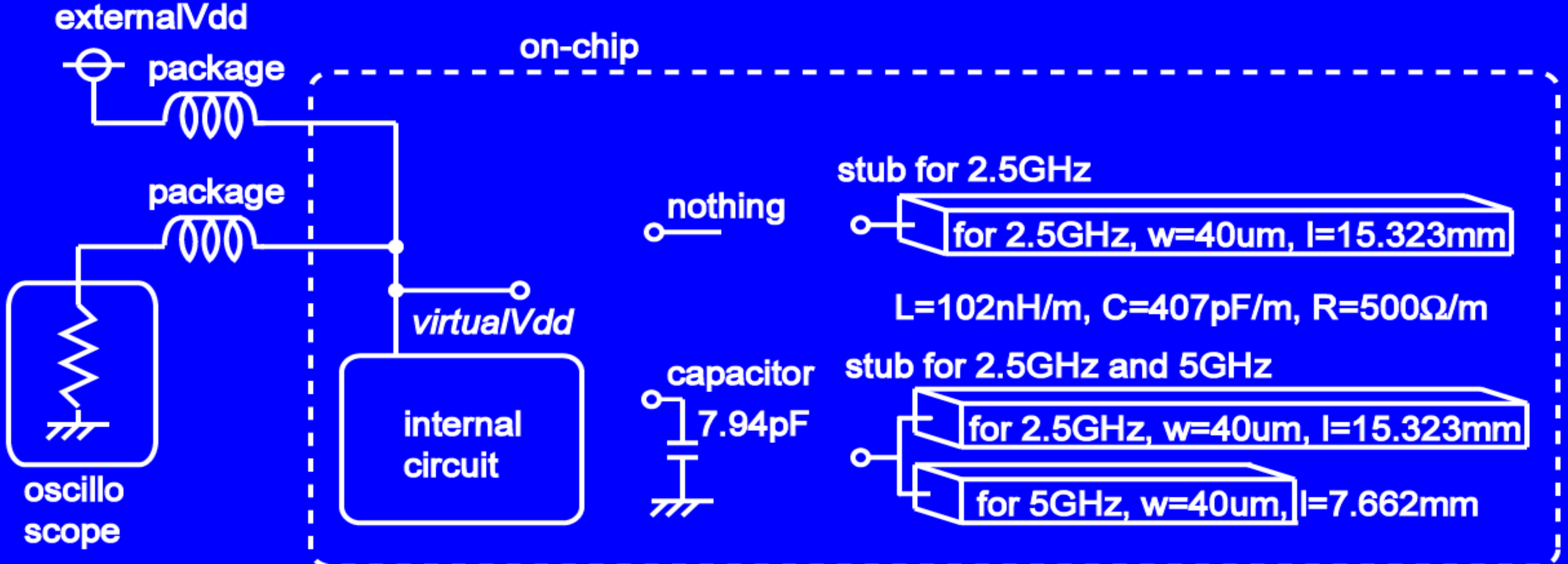
- Theoretical study predicts that stubs can reduce the power supply noise better than decoupling capacitor
- Let's verify the stub noise reduction by experiments

Internal Circuit



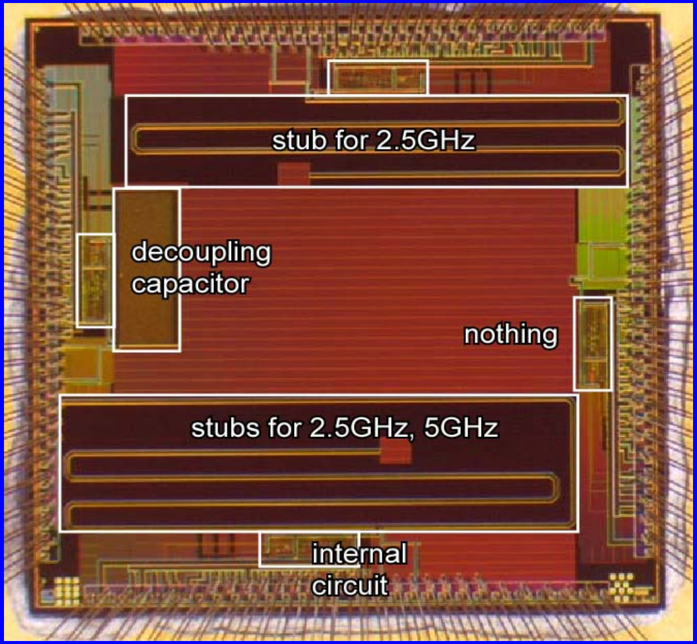
Power Line Structures

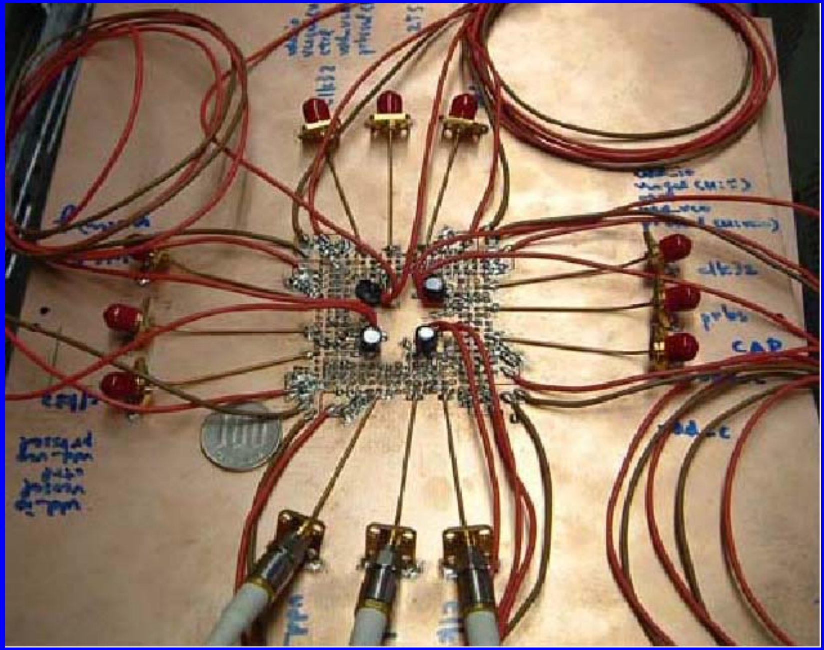
- nothing, capacitor, stub for 2.5GHz, stub for 2.5GHz and 5GHz



On-chip Stub Does Not Work

- 0.18um 5ML standard CMOS (5.9mm x 5.9mm)
- The chip is mounted on a Cu board

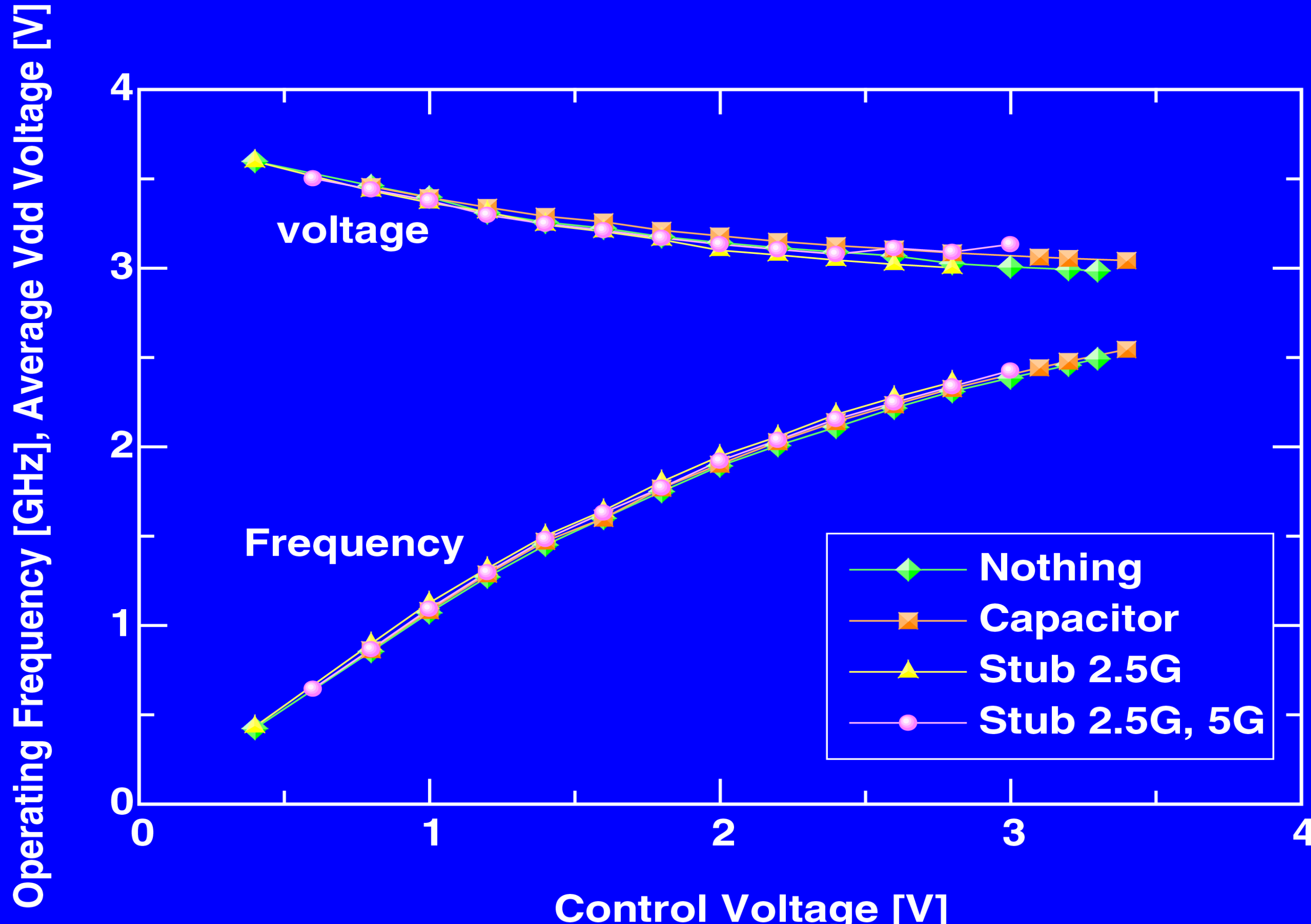




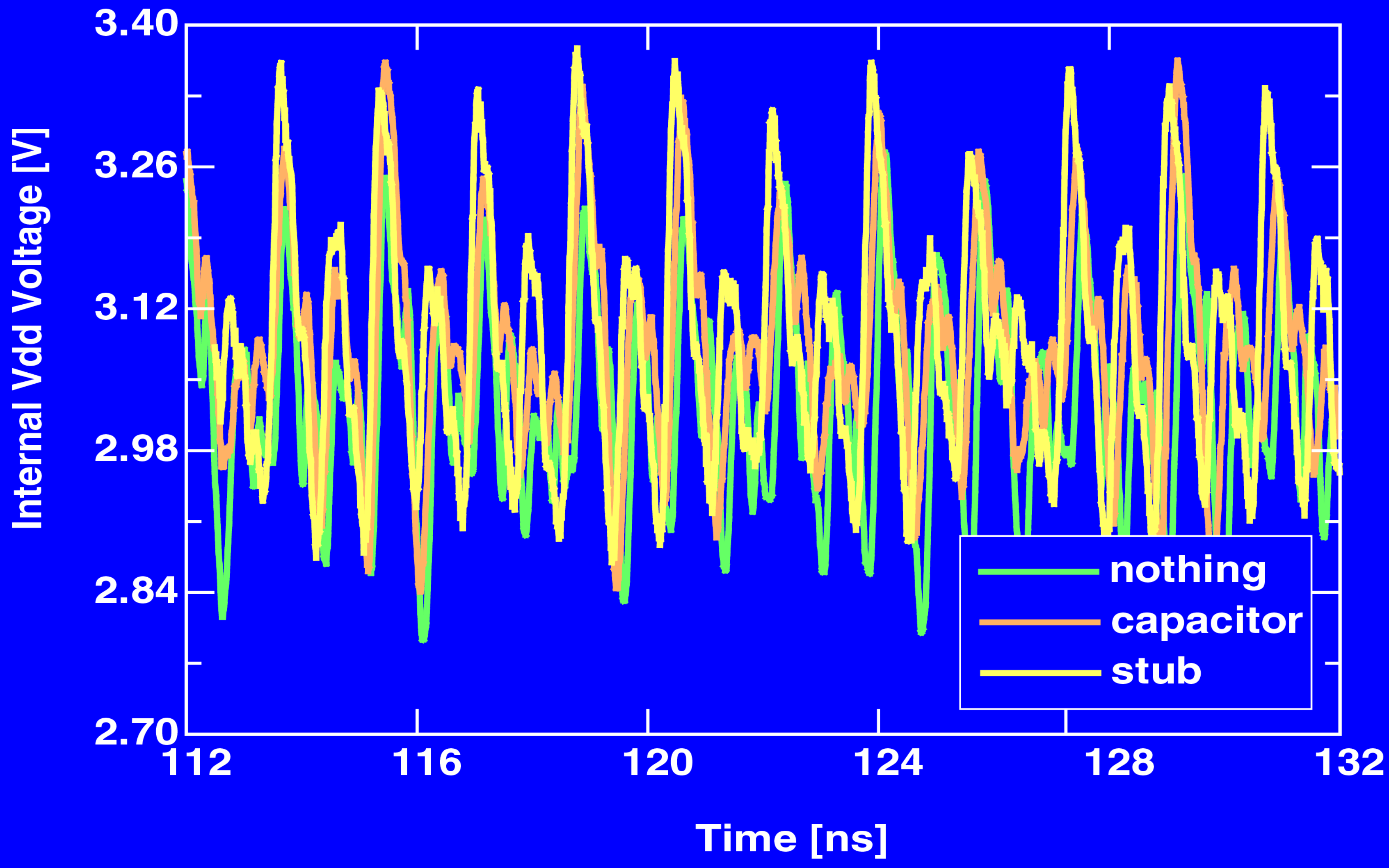
- Reflection at the bent (length>15mm @2.5GHz)
- Resistance is bigger than the estimated value

VCO characteristics, IR drop

- Intra-chip fluctuation is small

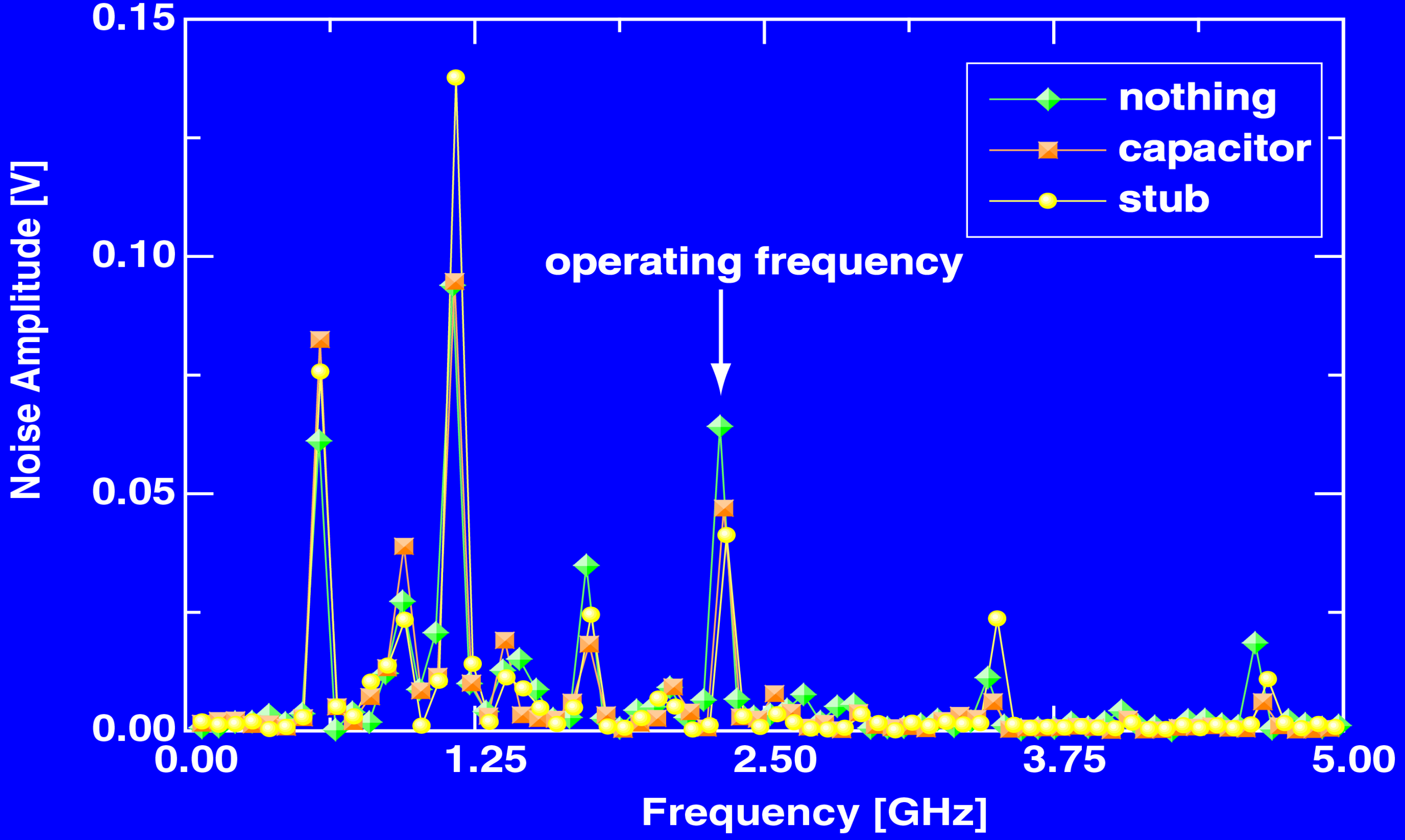


Measured Vdd Waveforms



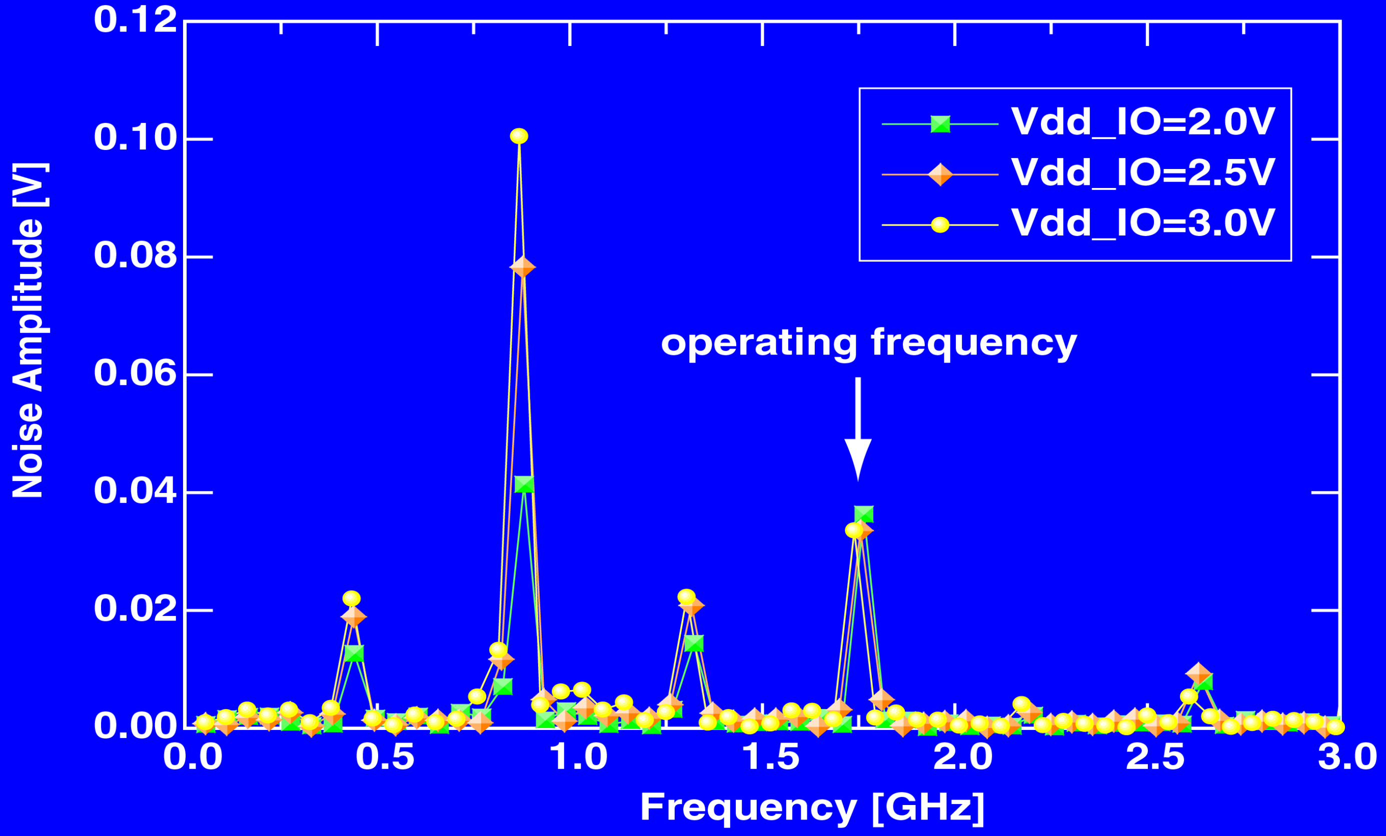
Measured Vdd Spectrum

- Noise peak at f/2, f/4



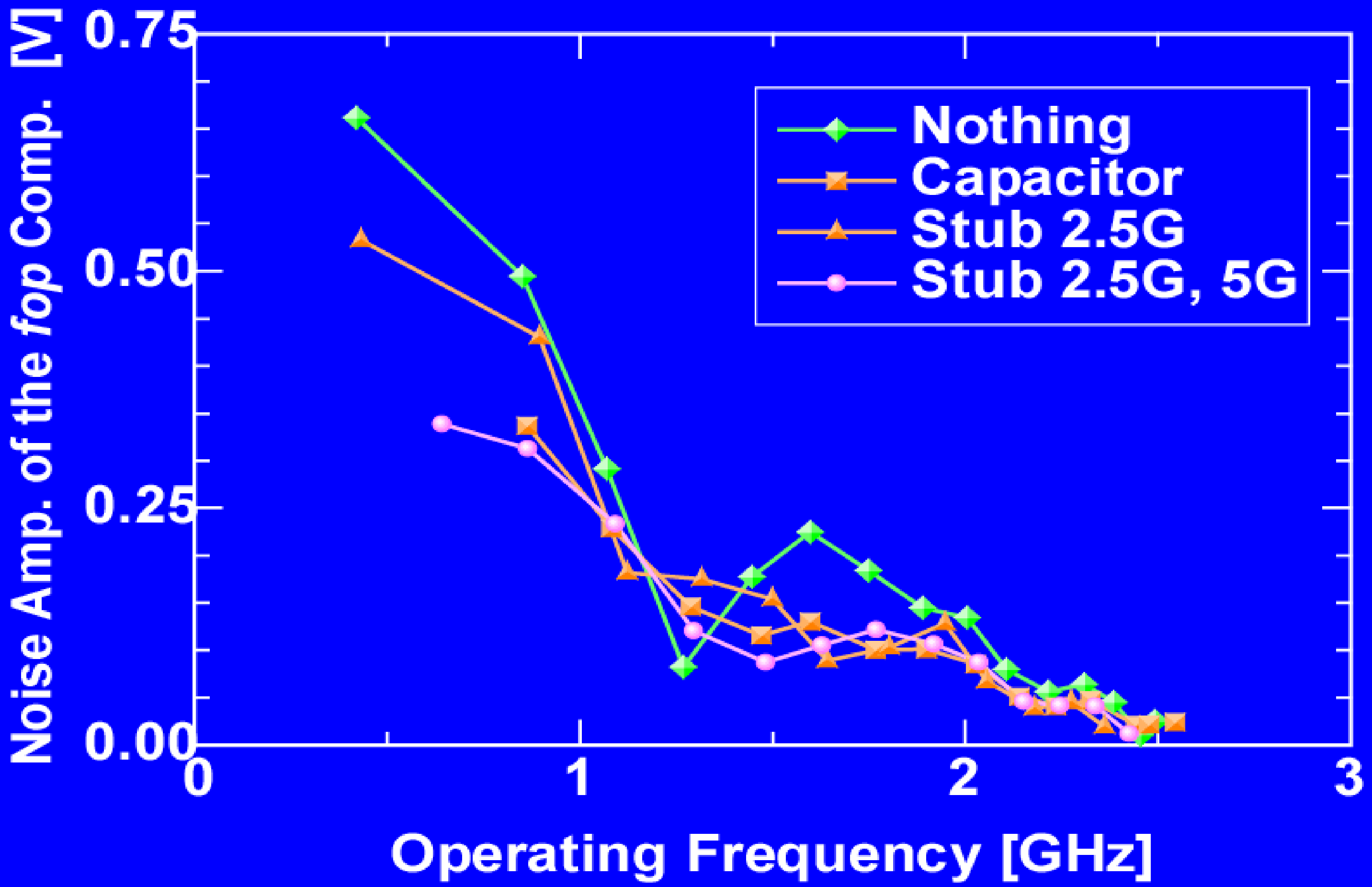
VddIO dependece of Vdd Noise

- Substrate/package coupling of Vdd-IO and Vdd-core



Operating Freq. vs. Noise

- The difference is not clear

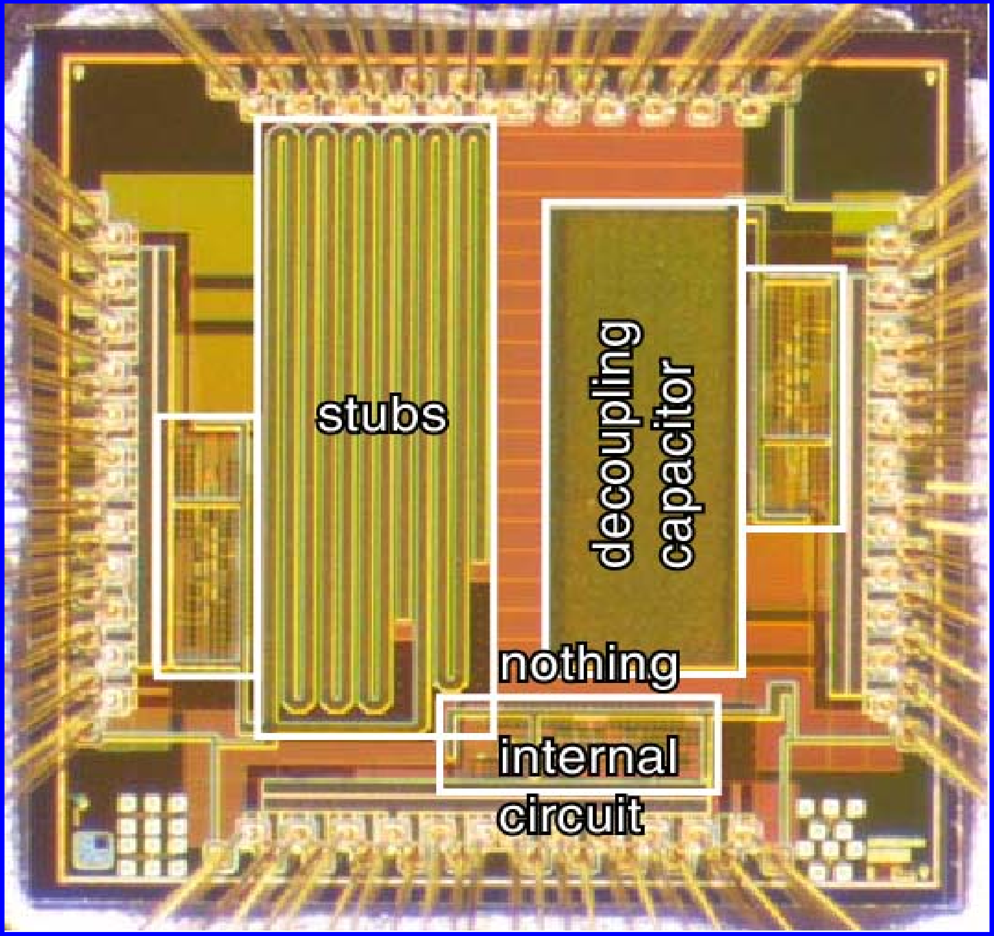


Why the Difference is Small?

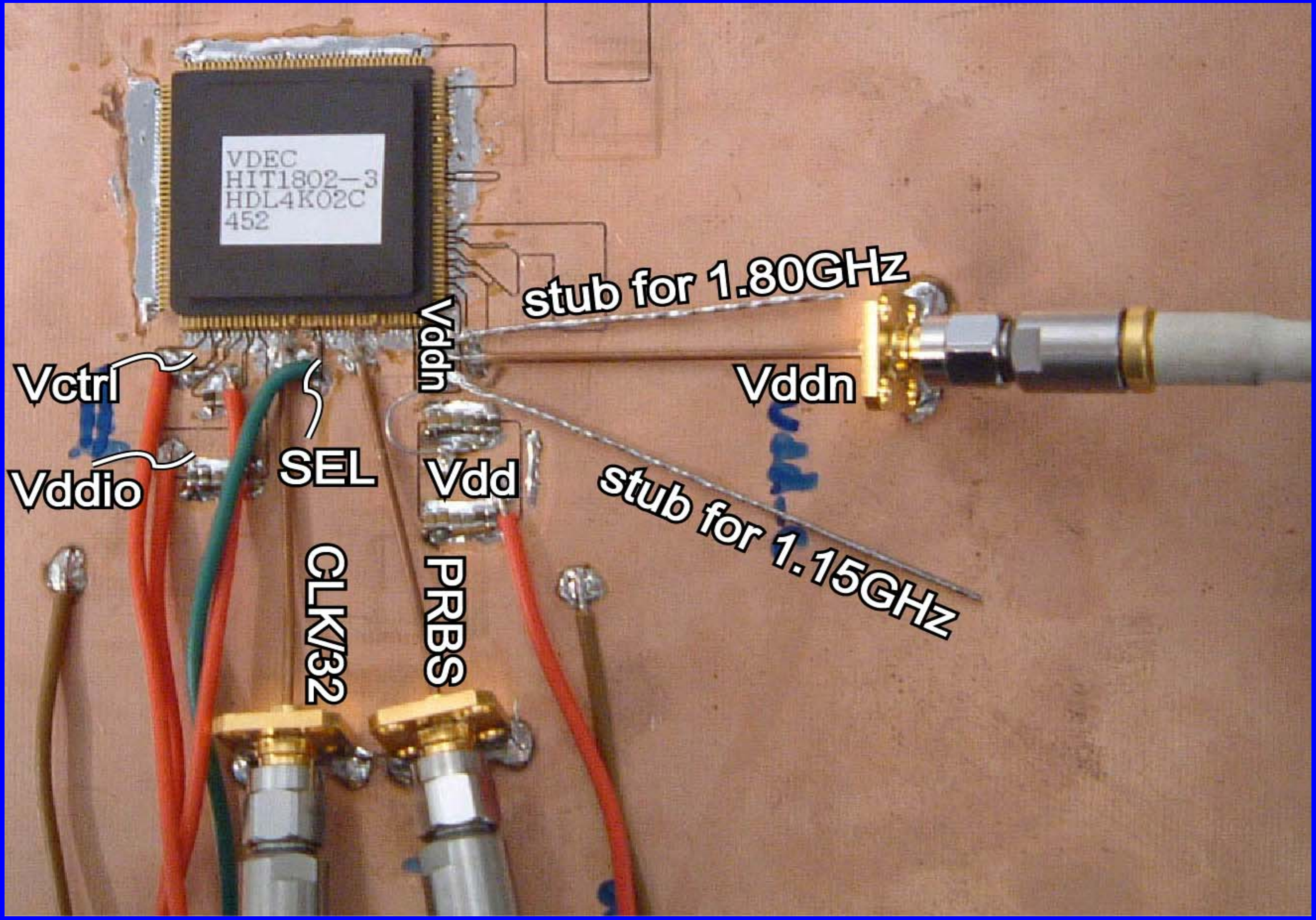
- Stubs are bent in the chip and reflection occurs
- The resistance is much bigger than the estimated value
  - The provided resistance value seems to be a measured sheet resistance at DC
- Package impedance is so big that the noise signal cannot come out

Chip Photograph

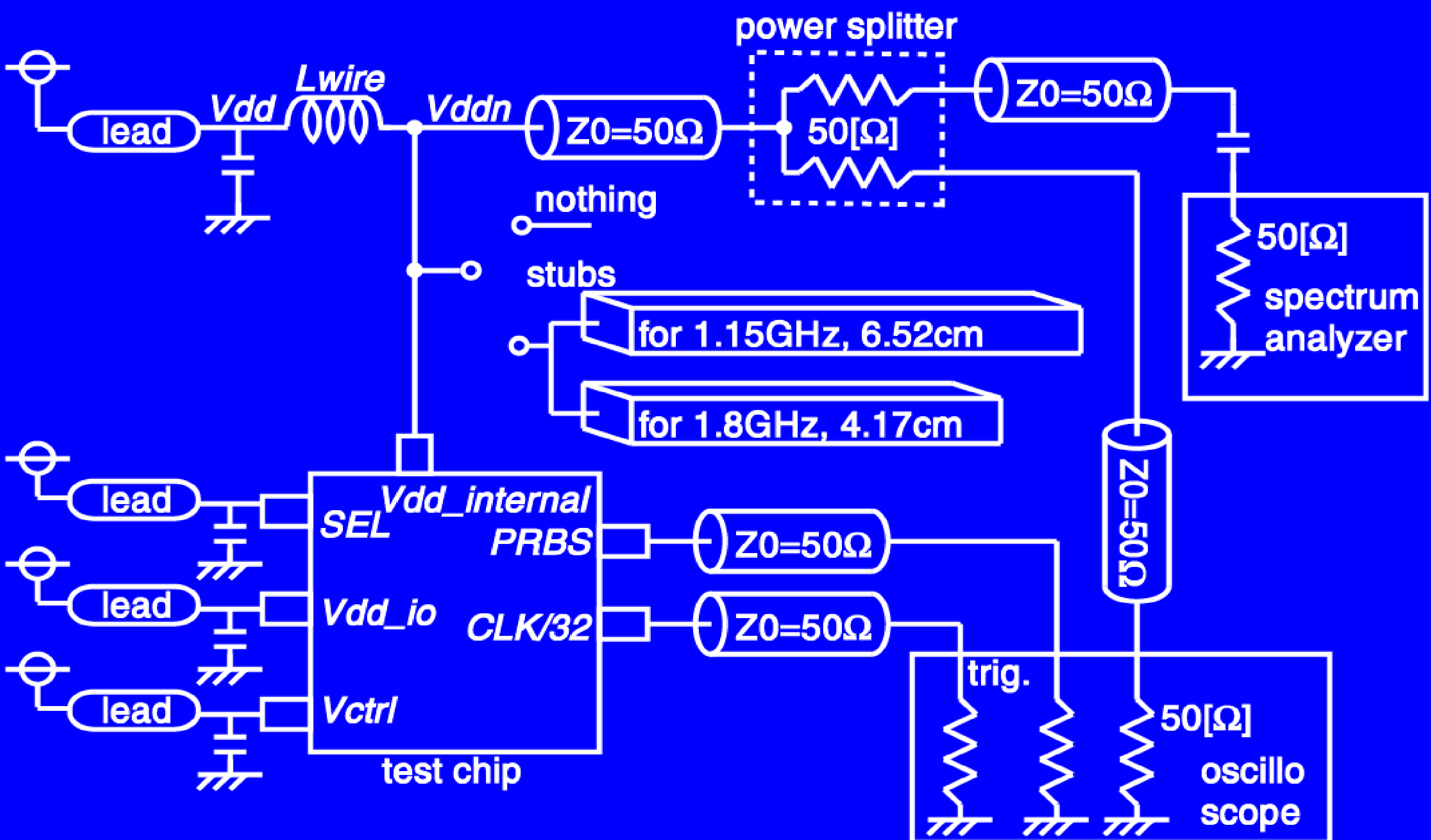
- 0.18um 5ML CMOS (2.4mm x 2.4mm)



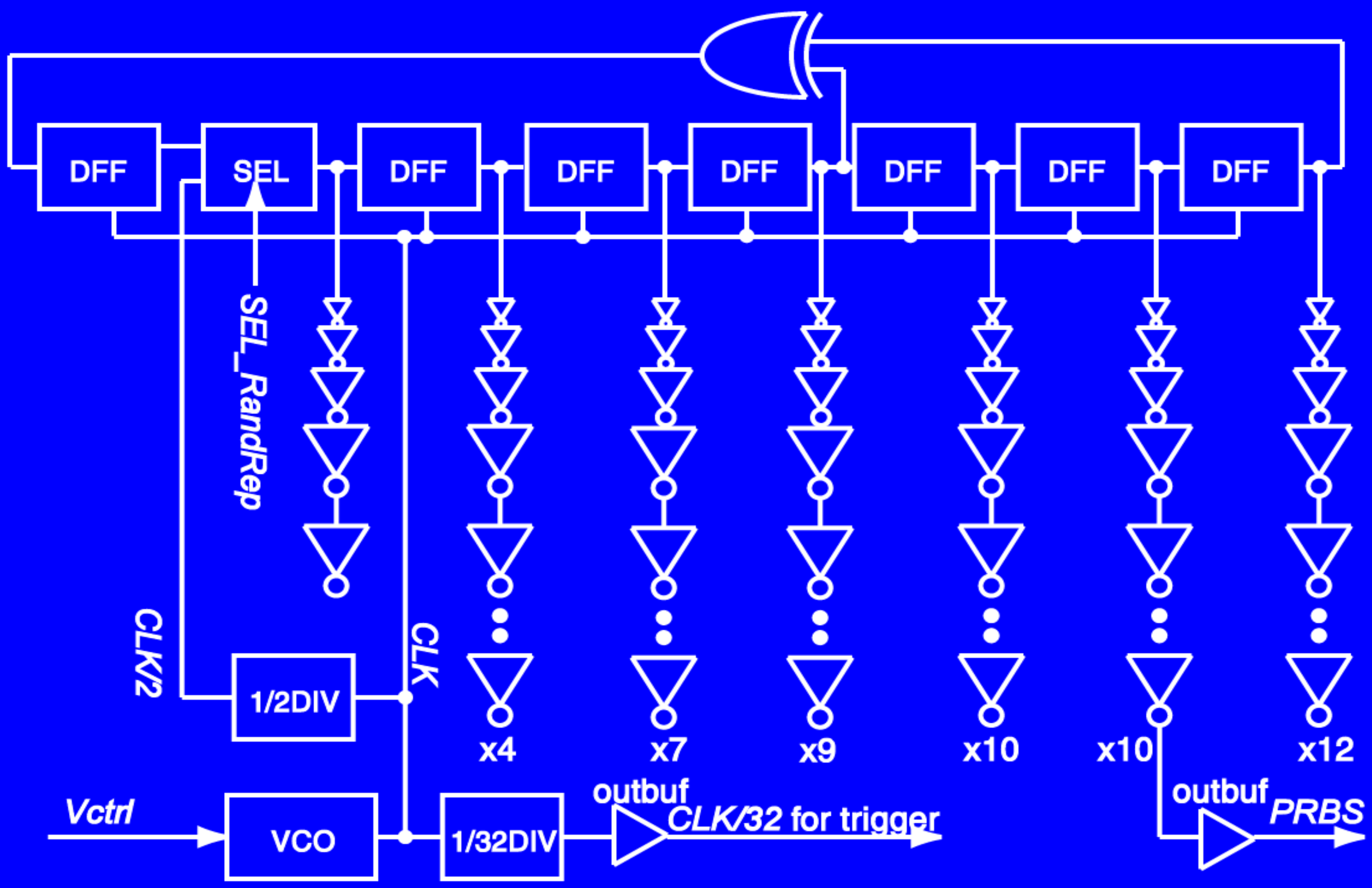
Off-chip Stubs



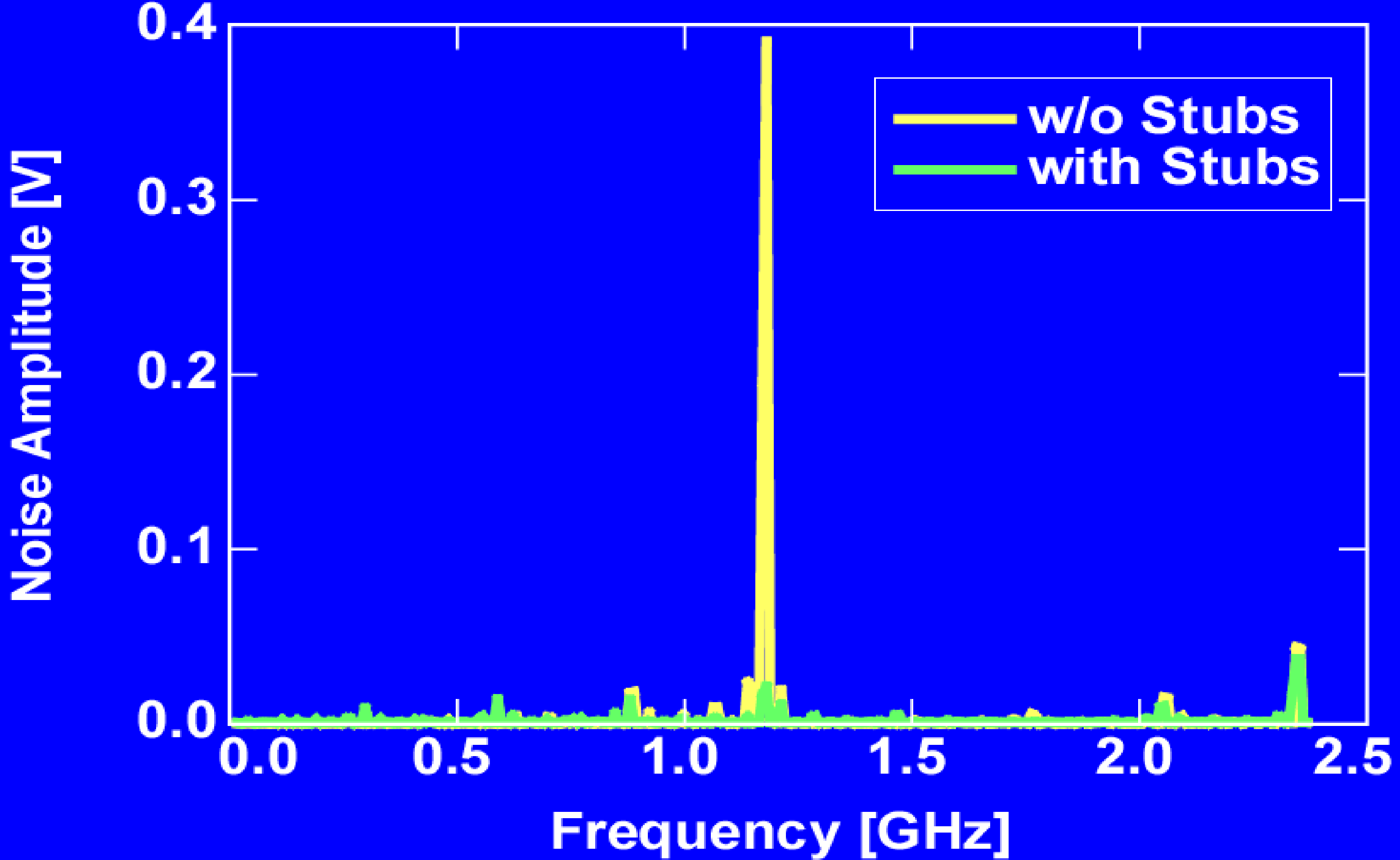
Schematic


power splitter
Lwire
Vdd
Vddn
lead
Z0=50Ω
50[Ω]
Z0=50Ω
nothing
stubs
50[Ω]
spectrum analyzer
for 1.15GHz, 6.52cm
for 1.8GHz, 4.17cm
lead
SEL
Vdd_internal
PRBS
Z0=50Ω
Z0=50Ω
lead
Vdd_io
CLK/32
Z0=50Ω
lead
Vctrl
trig.
50[Ω]
oscillo scope
test chip

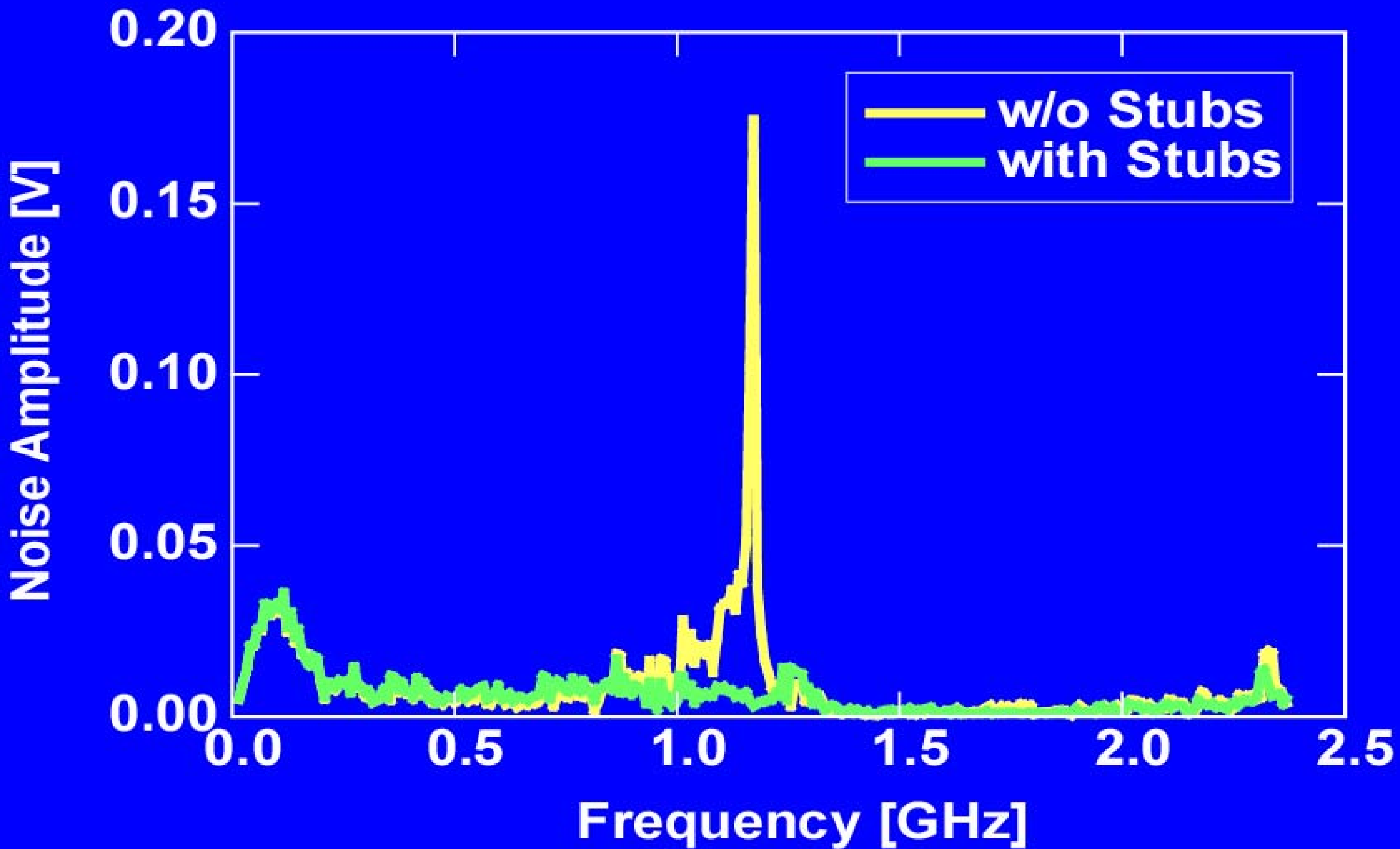
Internal Circuit



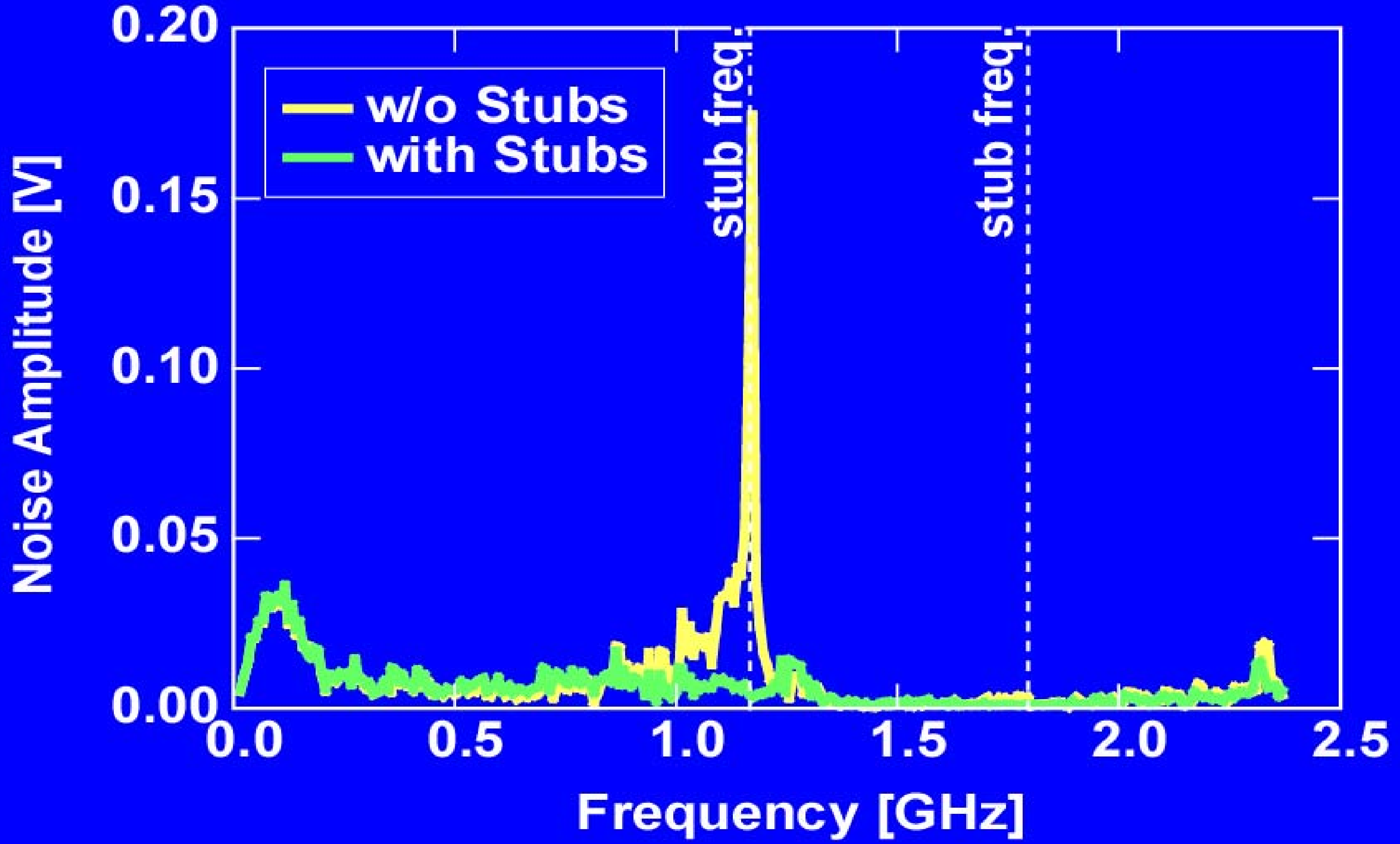
Spectrum @1.15GHz Repeat



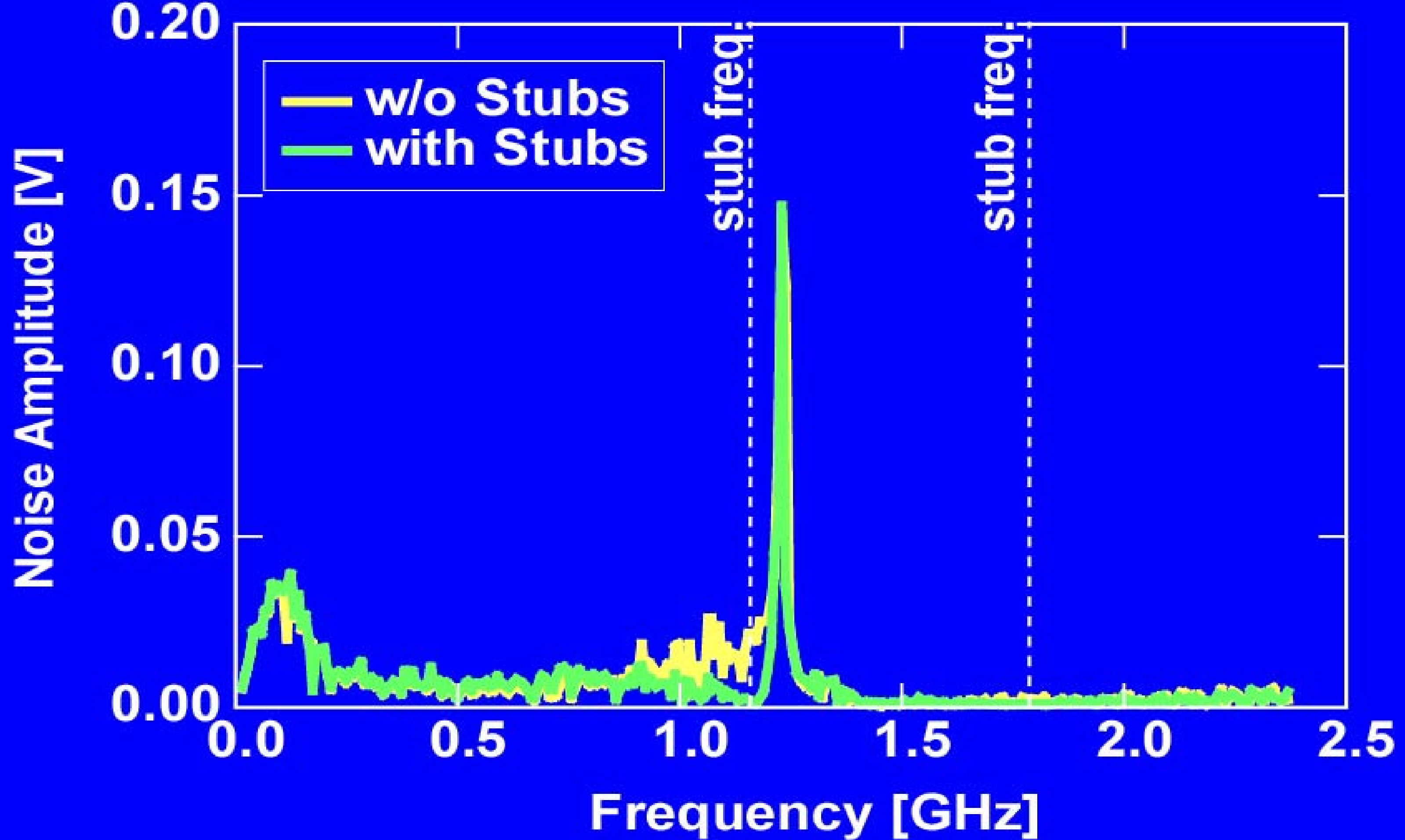
Spectrum @1.15GHz Random



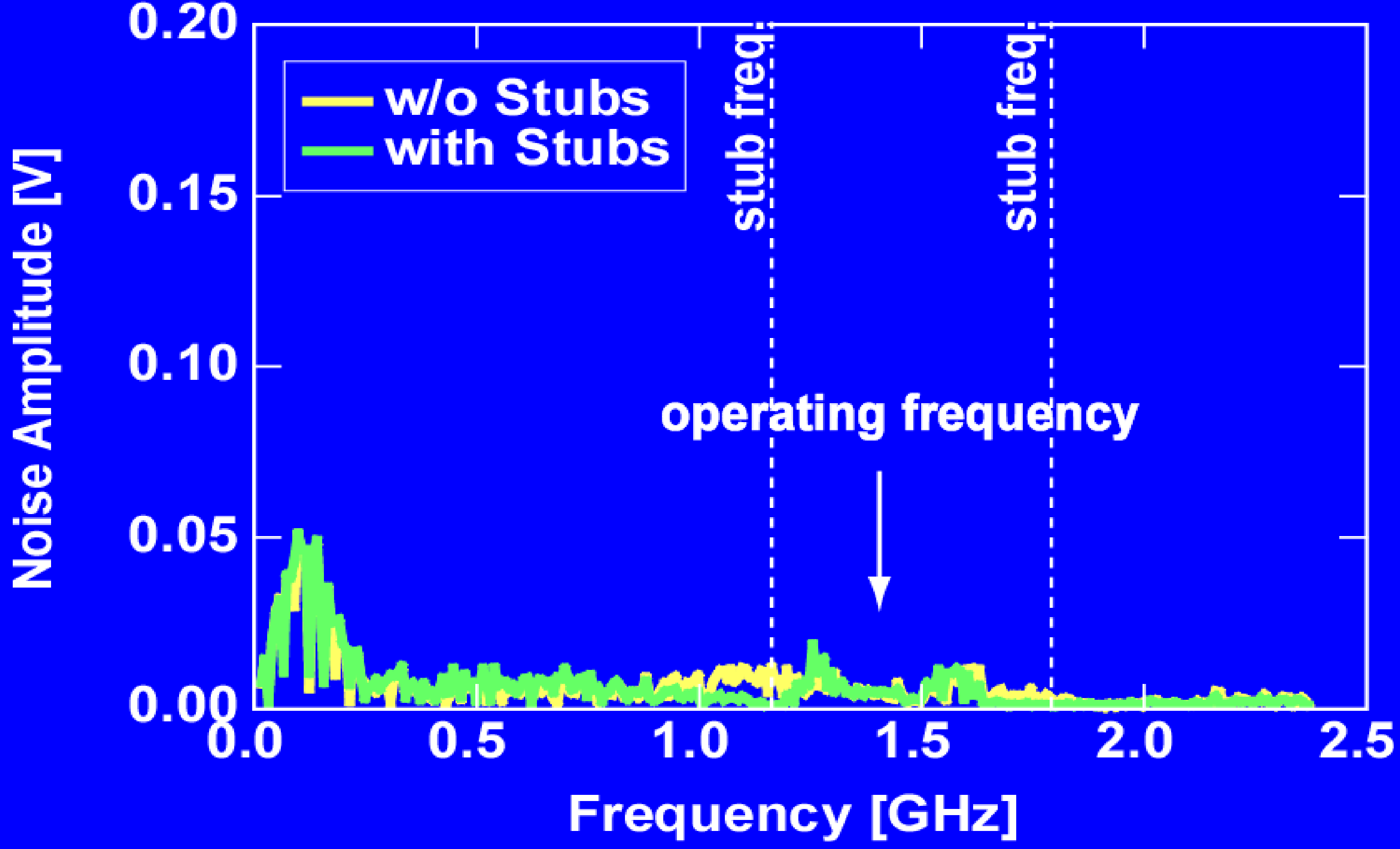
Freq. Dependence @1.15GHz



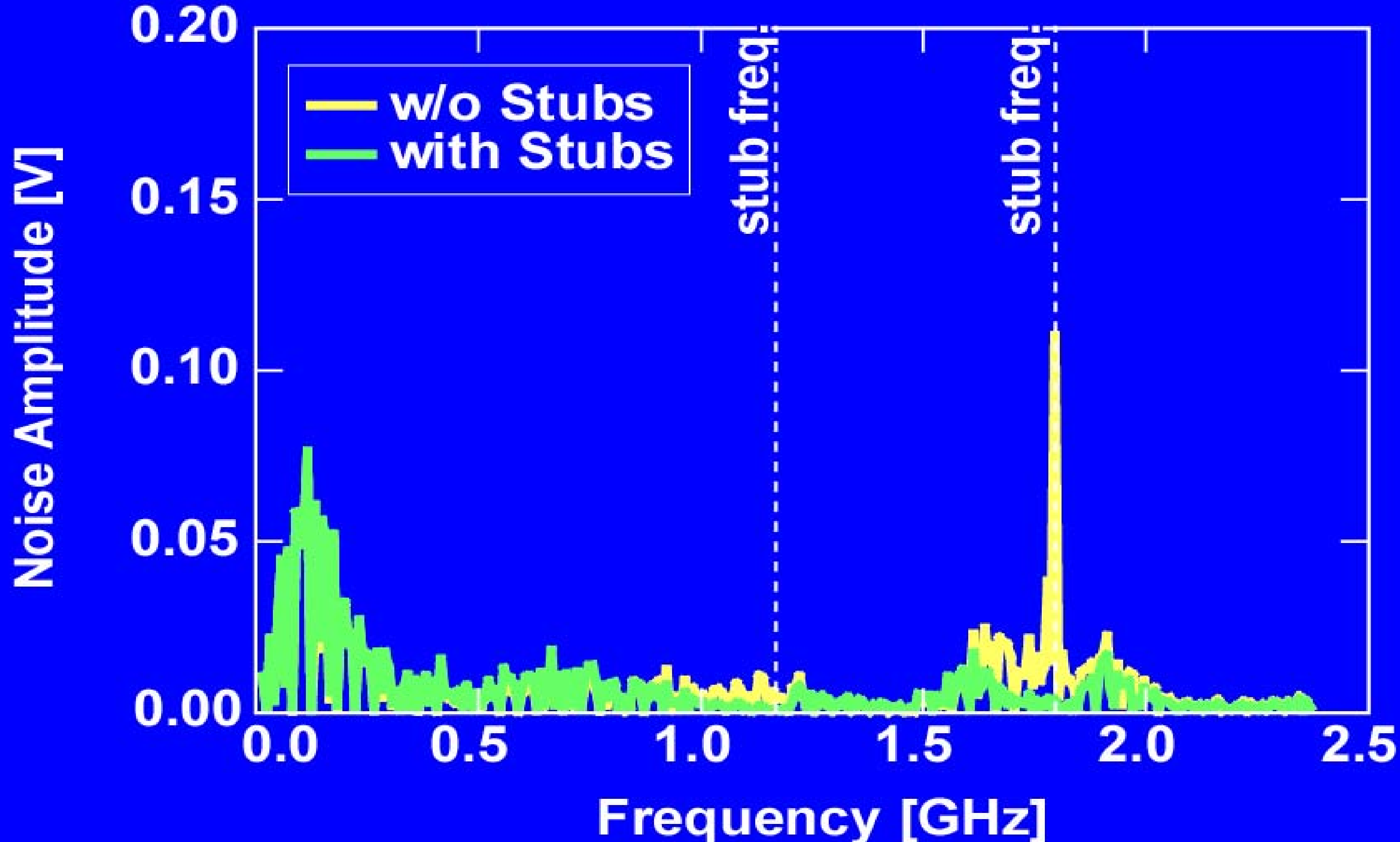
Freq. Dependence @1.25GHz



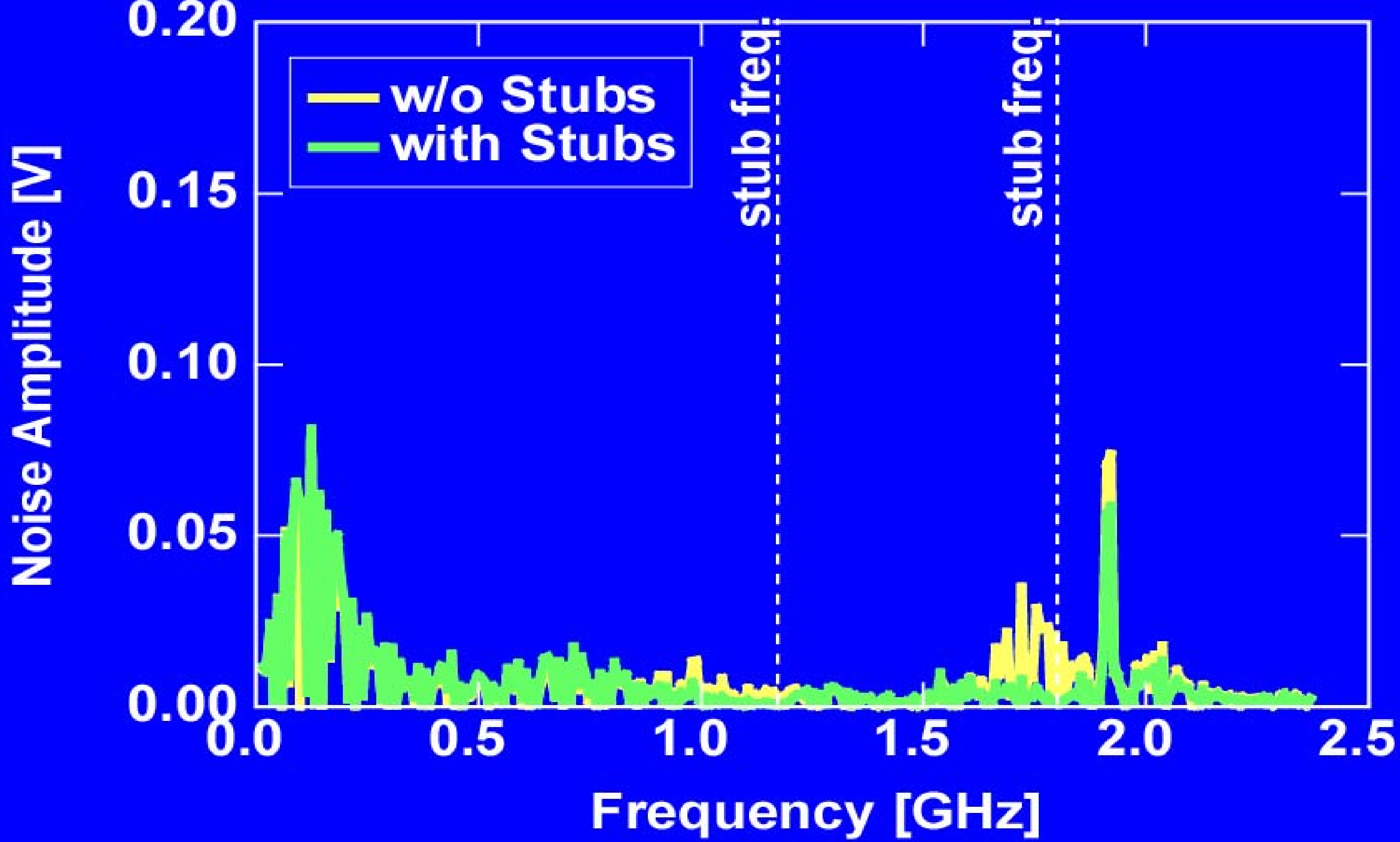
Freq. Dependence @1.45GHz



Freq. Dependence @1.80GHz

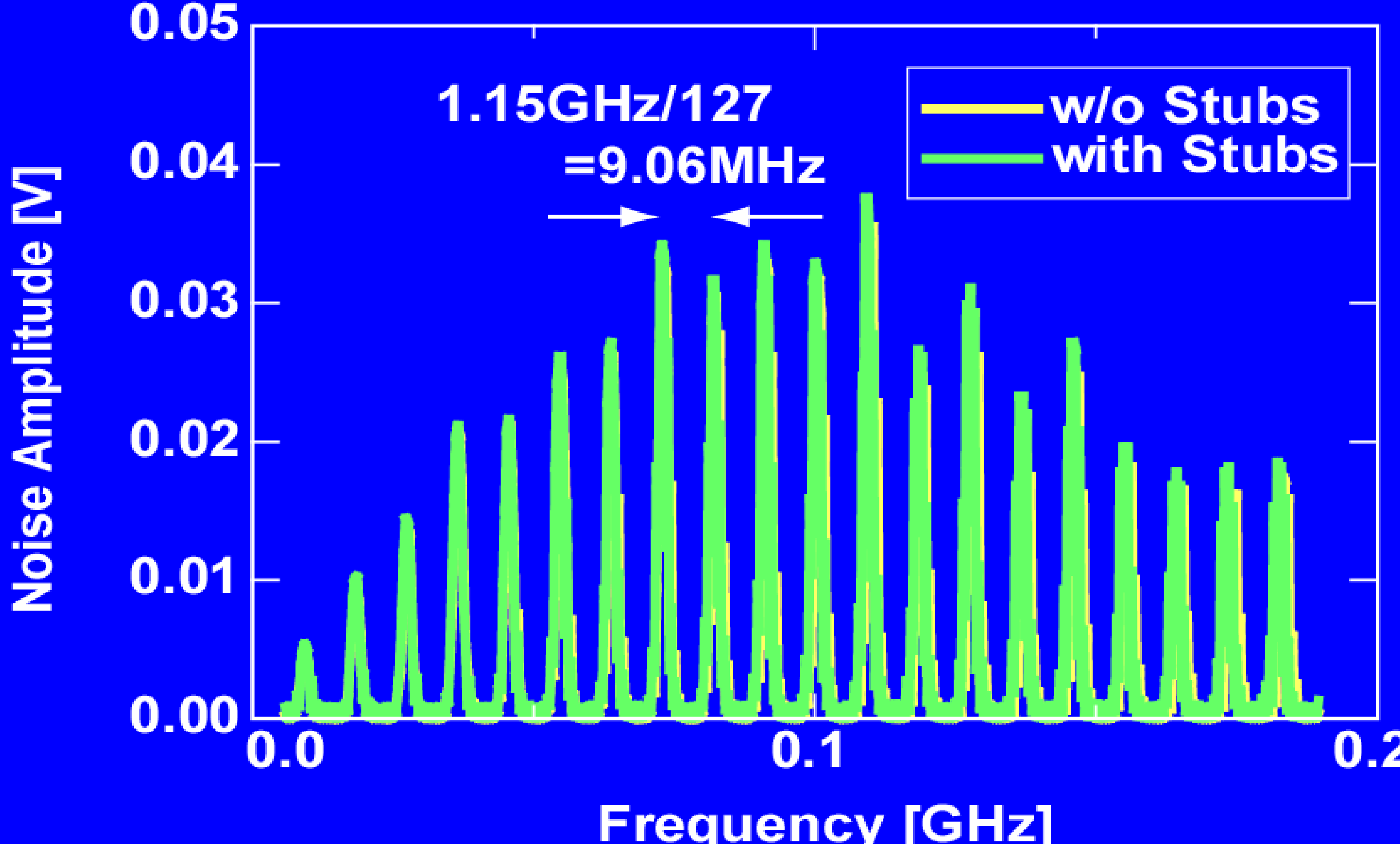


Freq. Dependence @1.85GHz



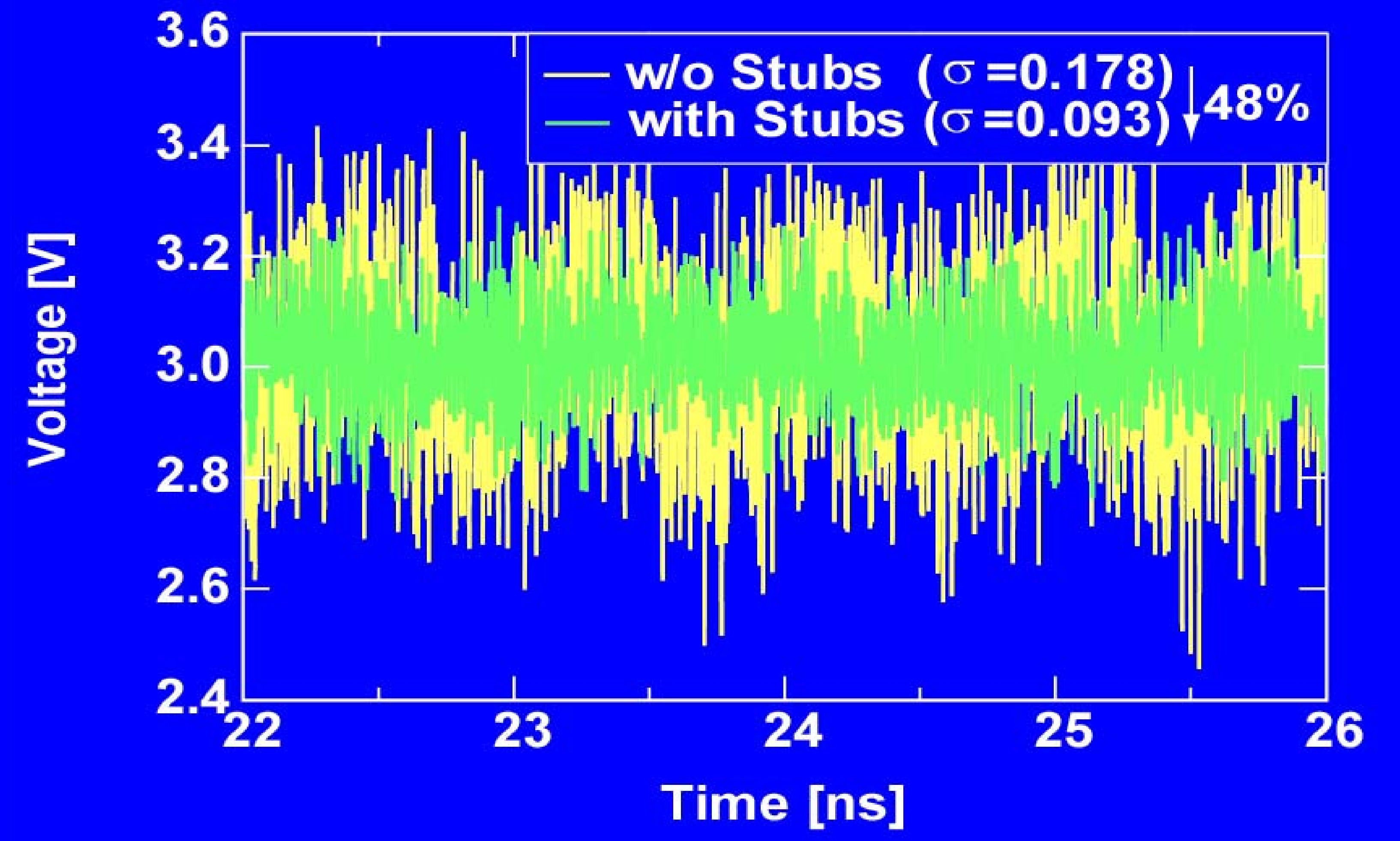
Spectrum of Lower Frequency

- PRBS 2^7-1 characteristics

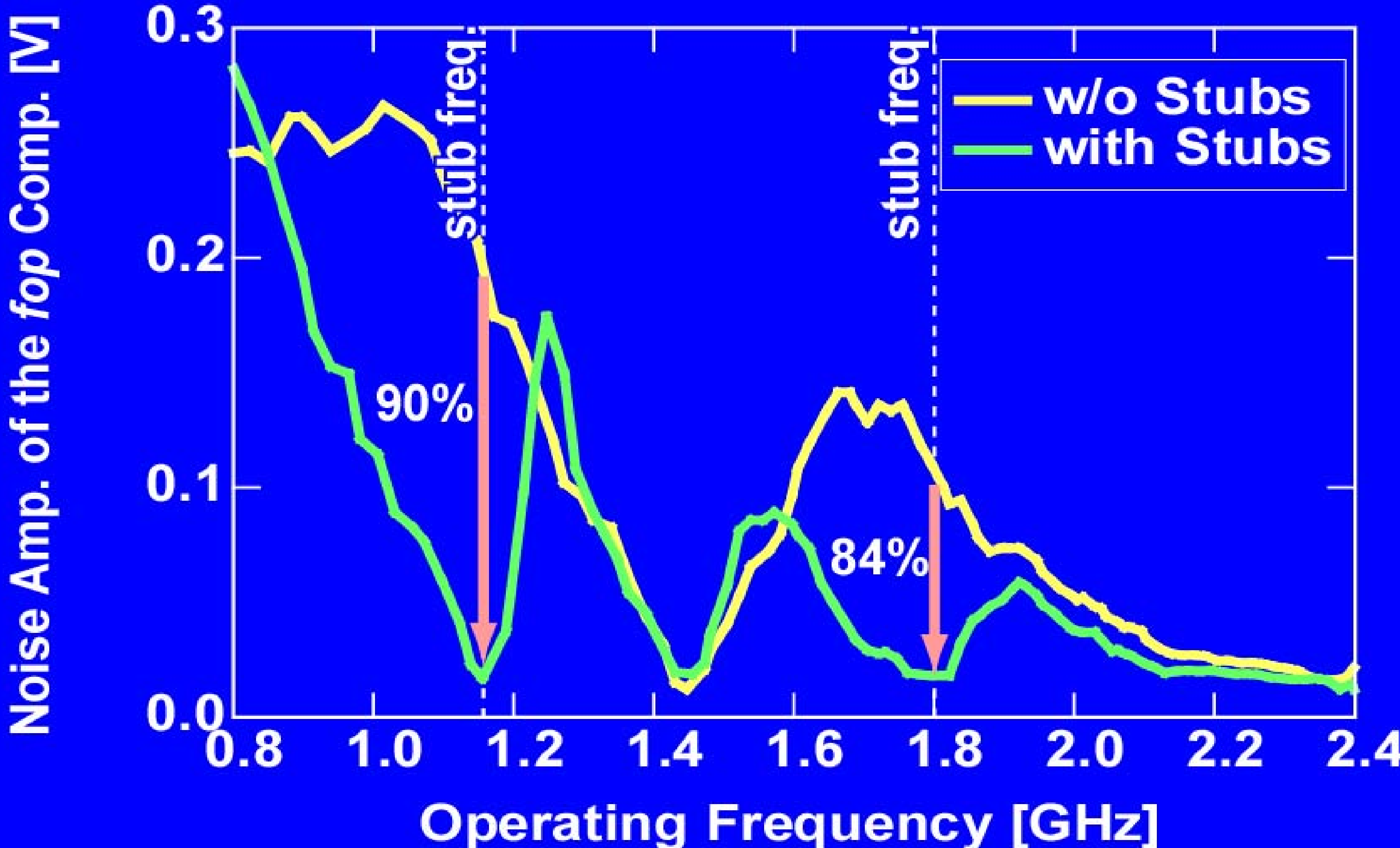


Waveforms @1.15GHz Random

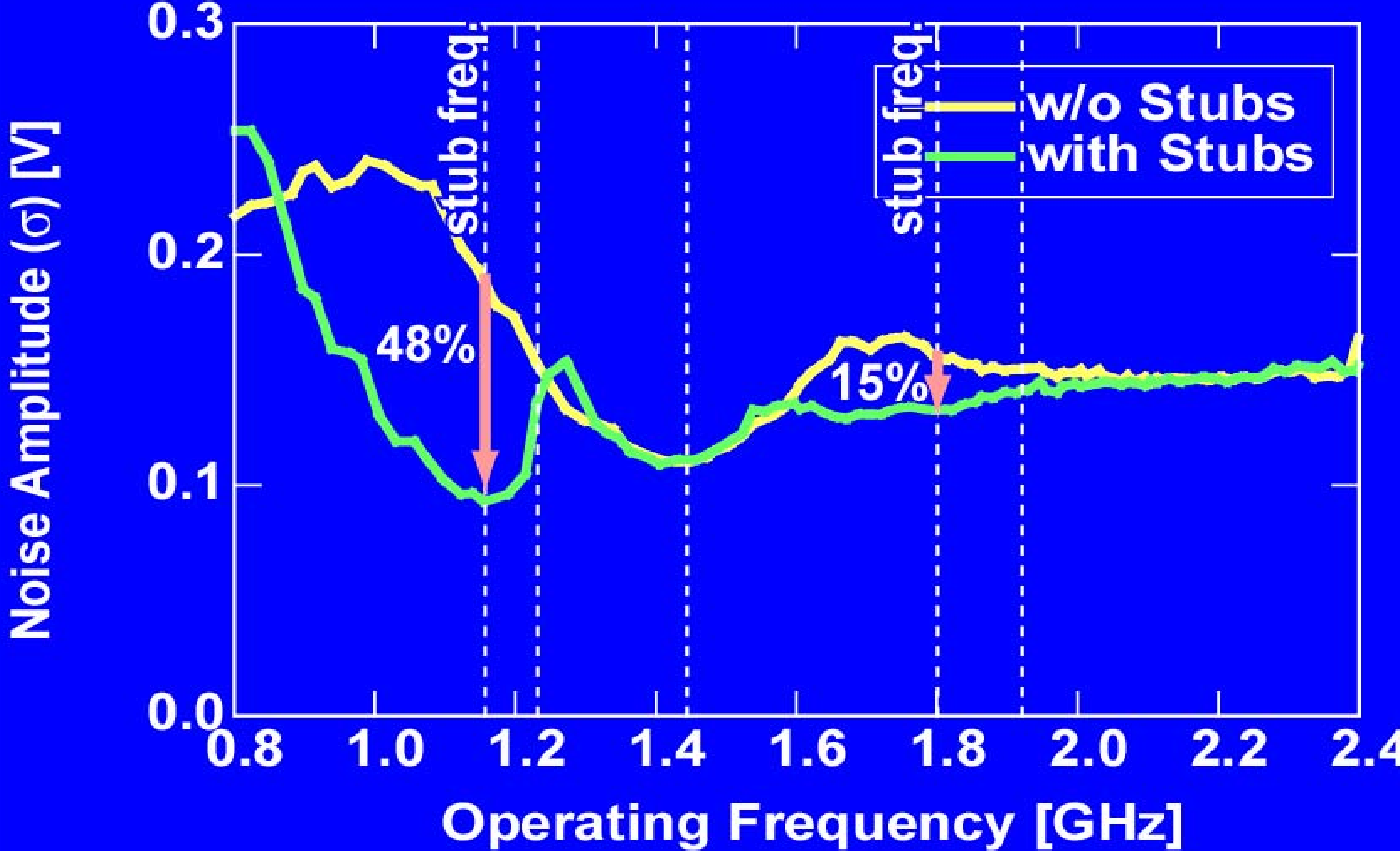
- Noise amplitude is evaluated by σ



Noise of the *fop* Component

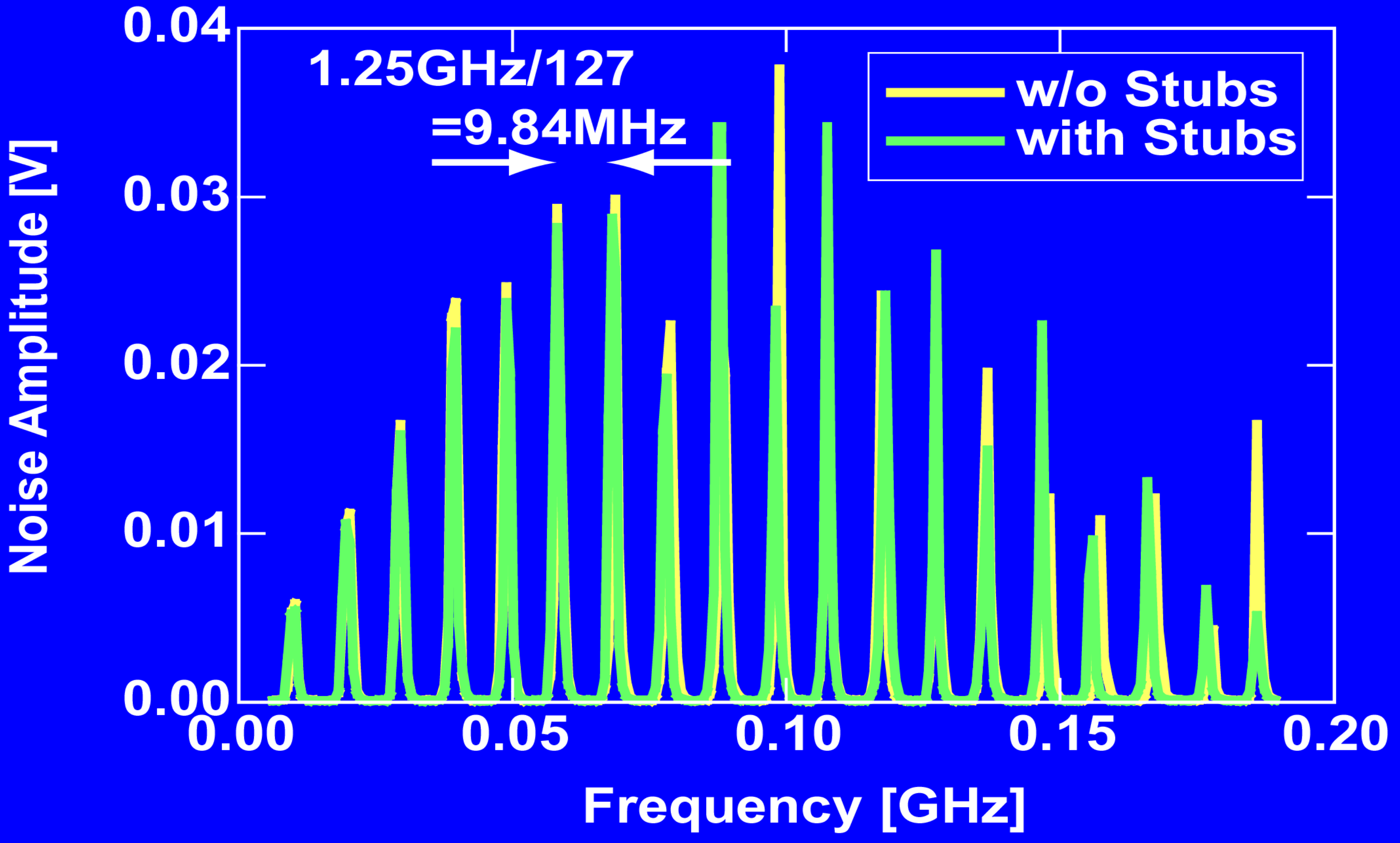


Total Noise Amplitude (σ)



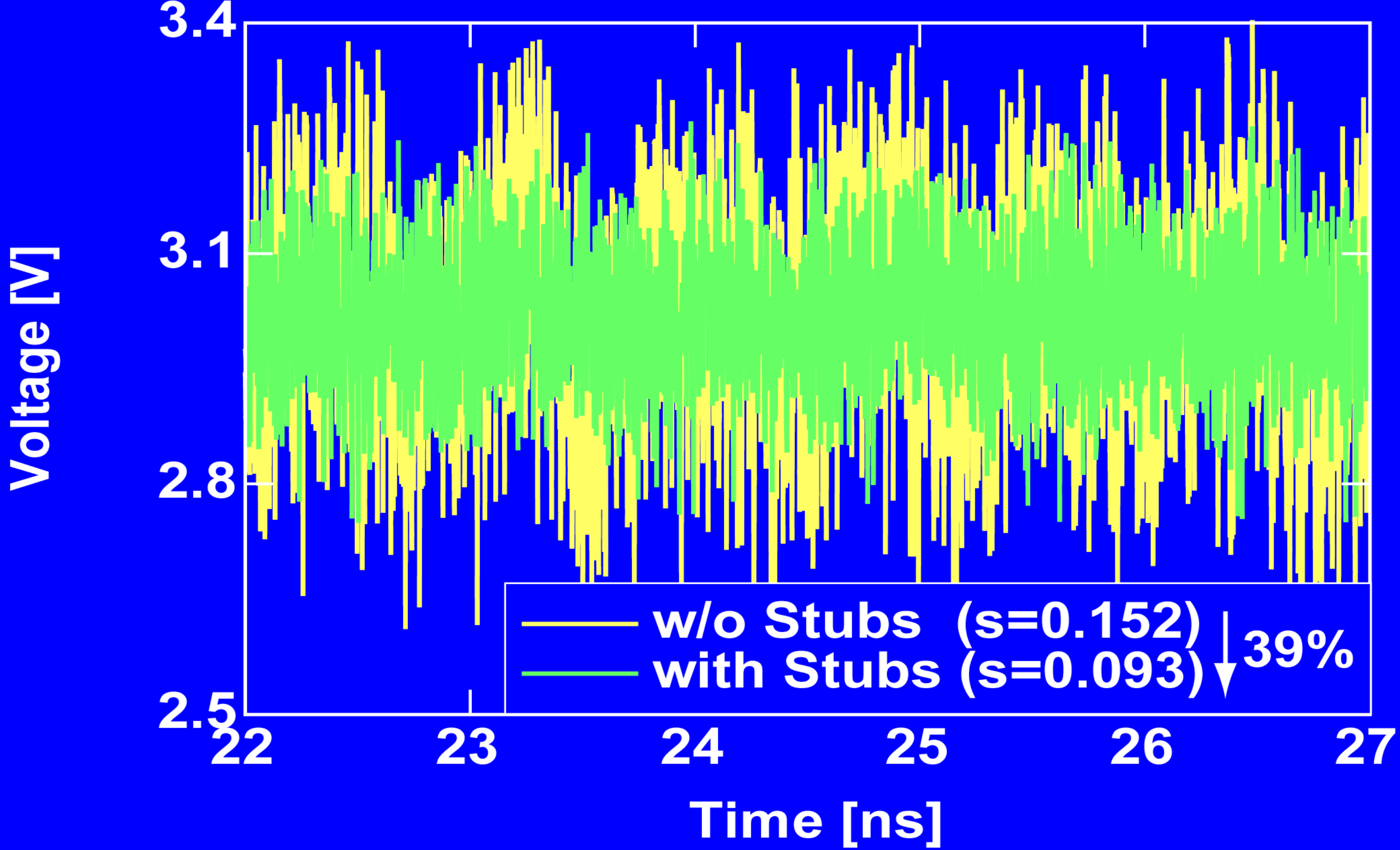
Spectrum of Lower Frequency

- **PRBS 2^7-1 characteristics**

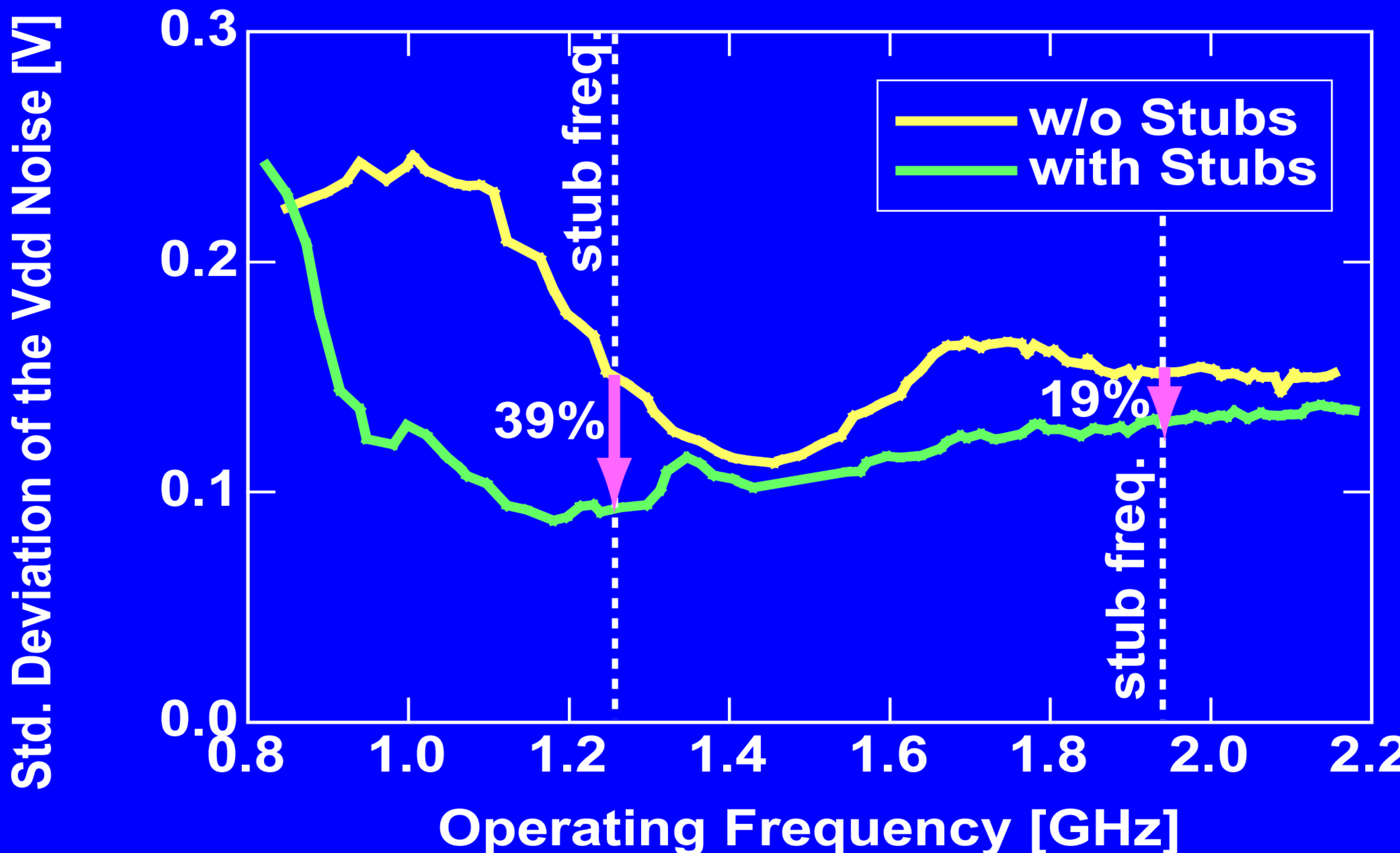


Waveforms @1.25GHz Random

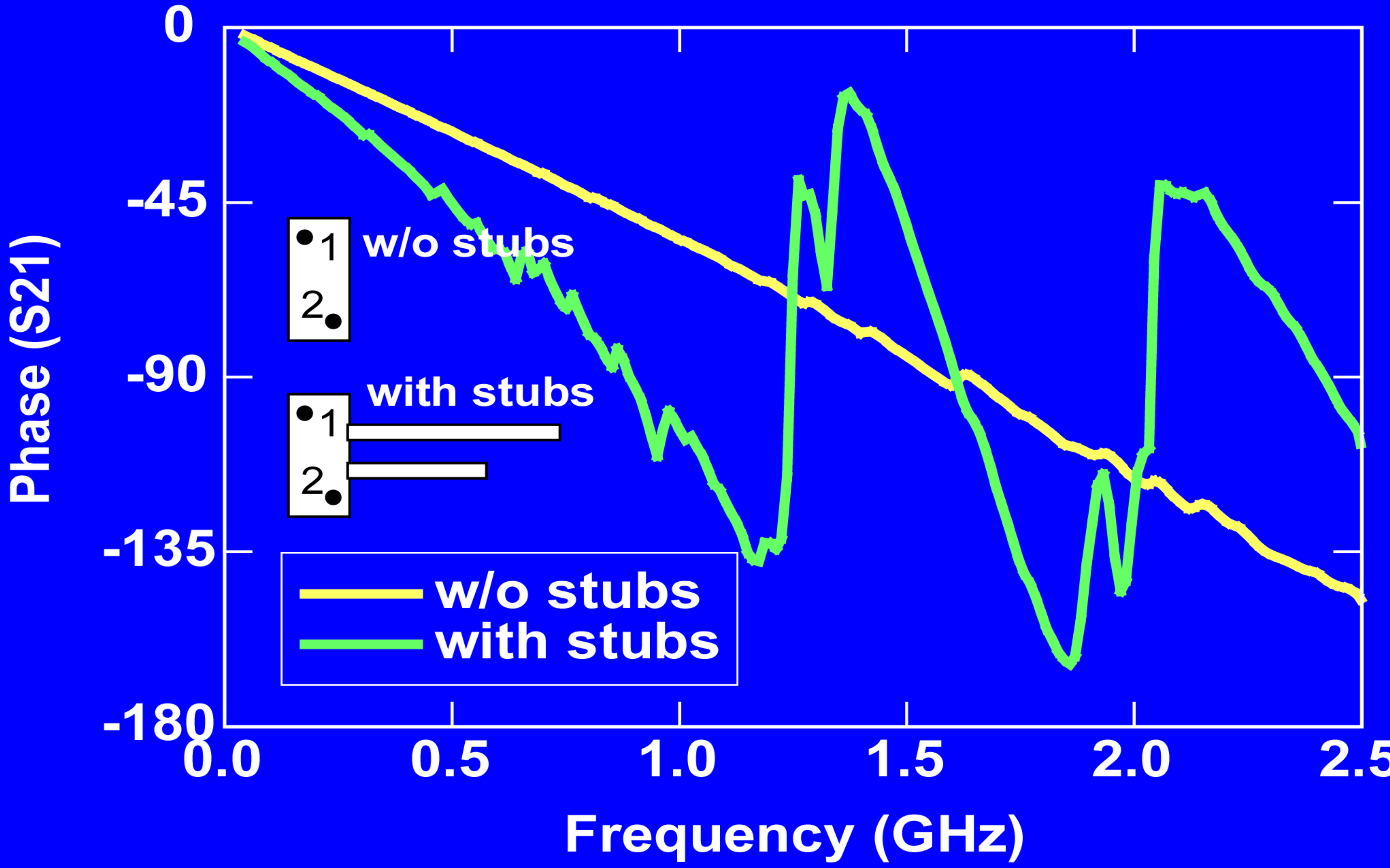
- Noise amplitude is evaluated by σ



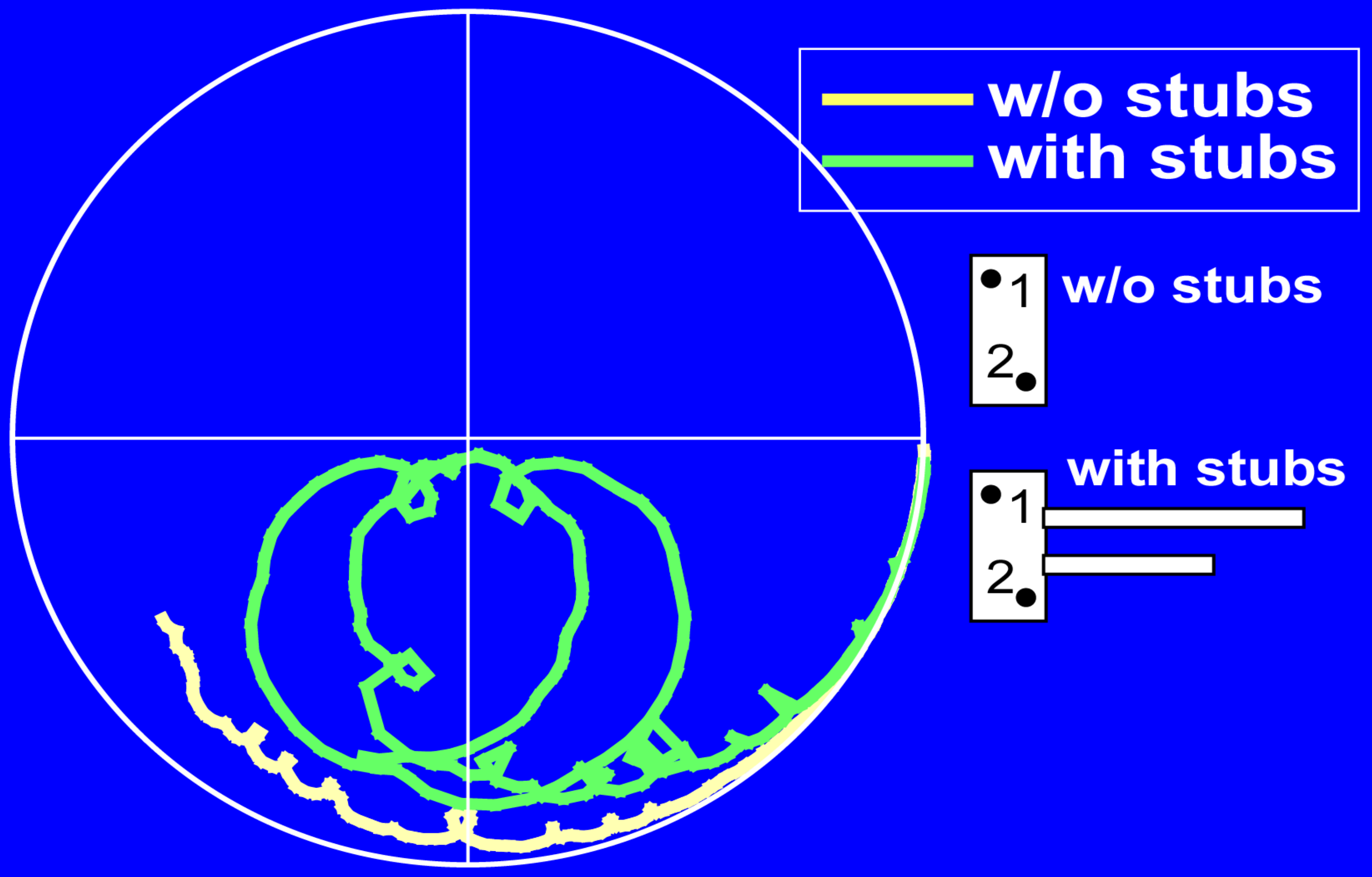
Total Noise Amplitude (σ)



S parameter – arg(S21)



S parameter – S21



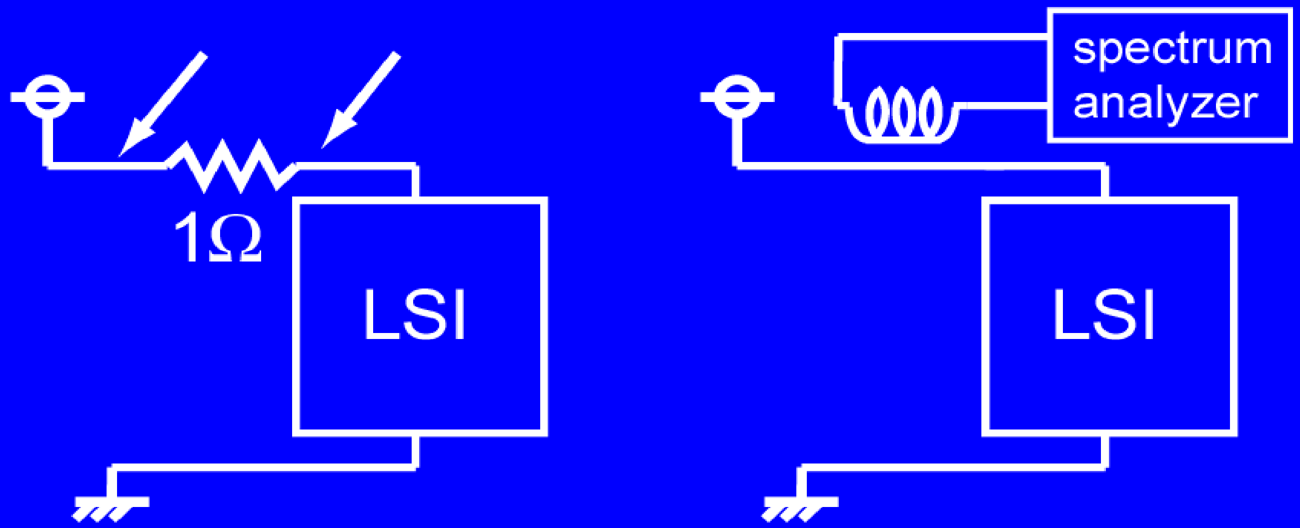
Short Summary

- The on-chip stub does not show the power supply reduction effects
  - Many bents, large resistance
- The off-chip stubs show clear noise reduction
  - 90% of the operating frequency component, 48% total noise is suppressed
  - Stub frequency dependence is observed
- Straight on-chip stub will be possible in the near future (～4mm@10GHz)

On-chip di/dt Detector

Conventional Current Meas.

- Probe the voltage difference of the R
  - Needs numerical calculation
- Probe the magnetic field by pickup coil
  - Phase information is lost

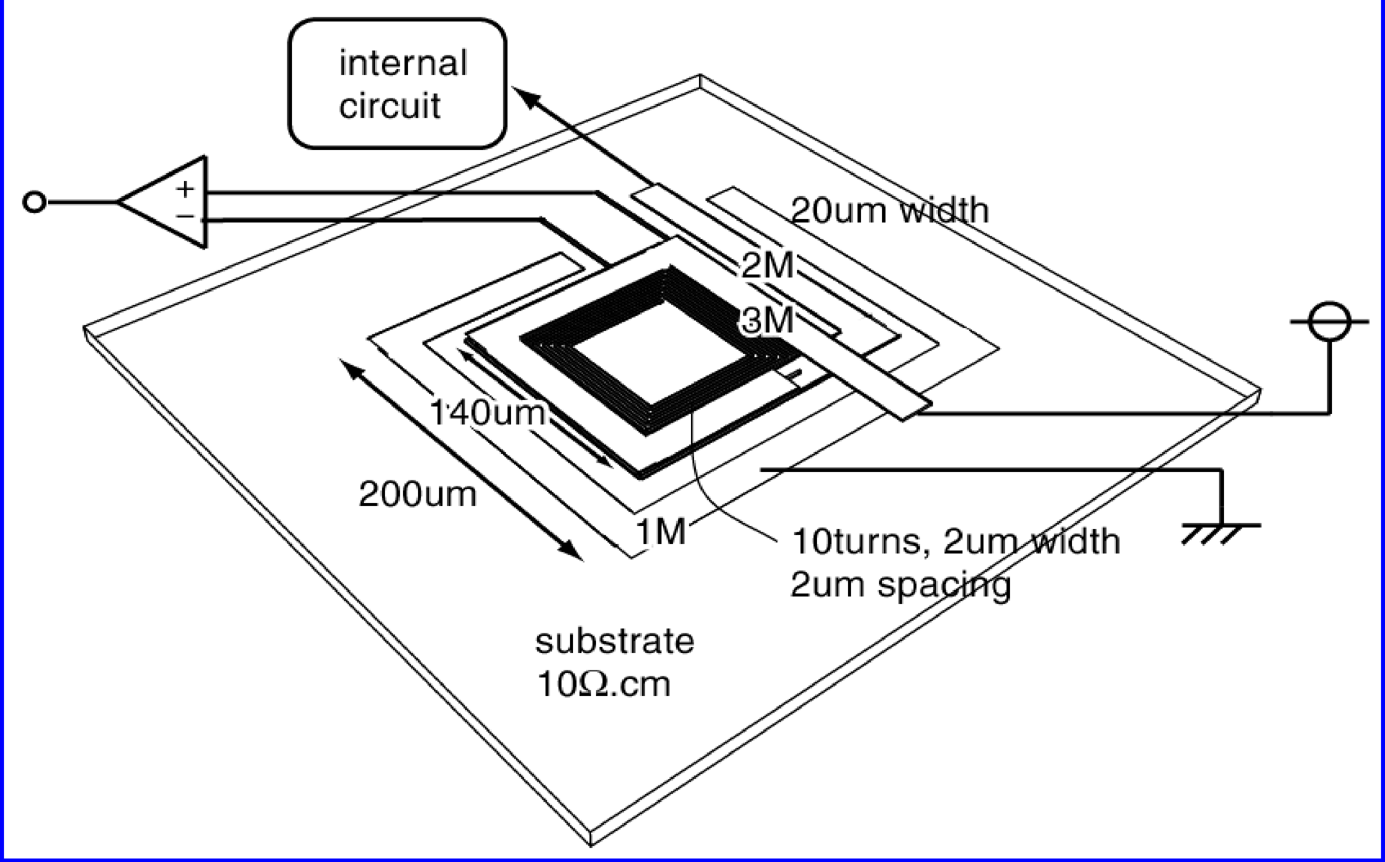


Advantage

- On-chip
- di/dt waveform without numerical calculation
- Real time
- Feedback di/dt control is possible

Mutual Inductor

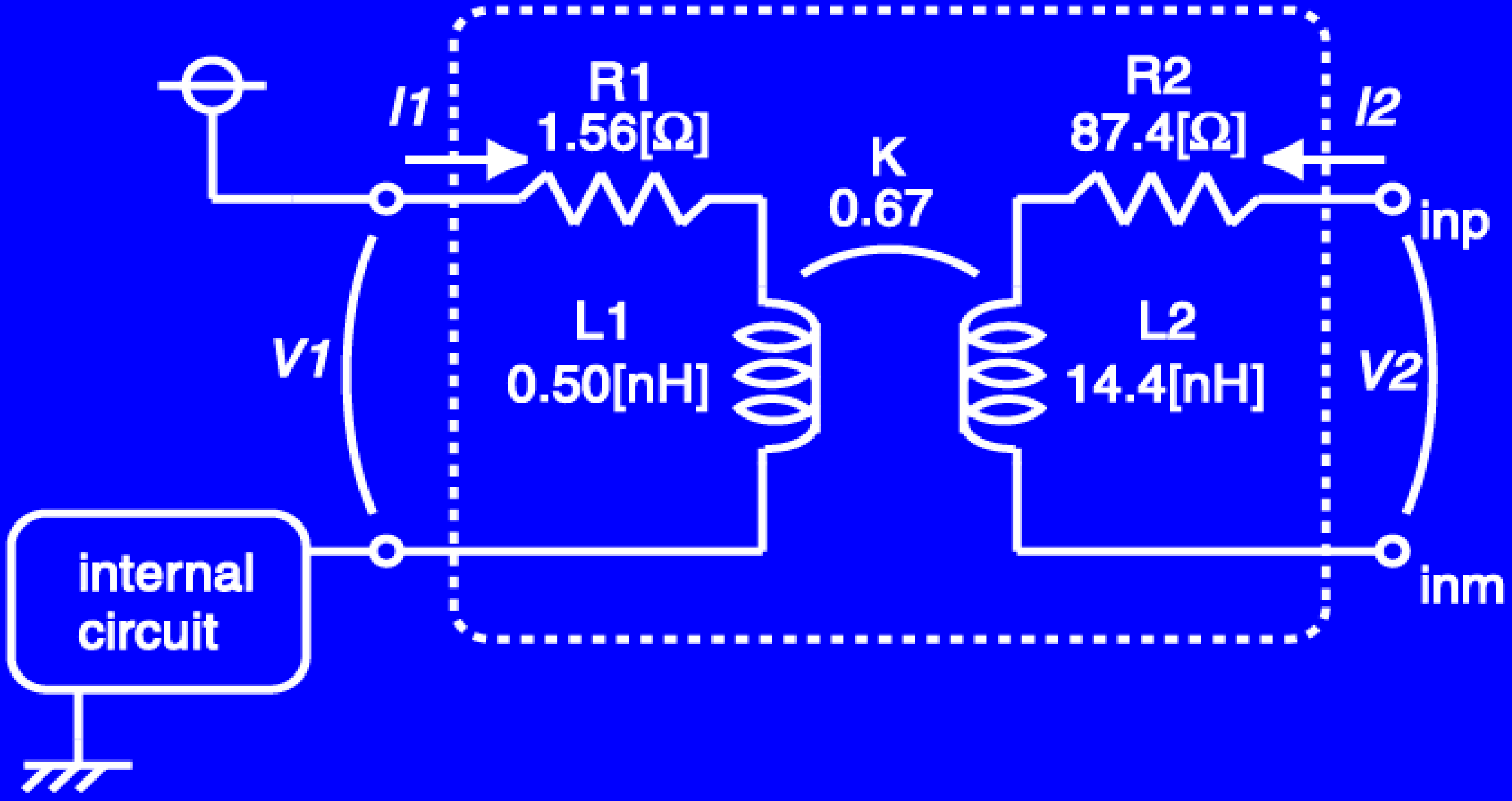
- 0.35um, 3ML standard CMOS process



- Large: 200um diameter, 24 turns

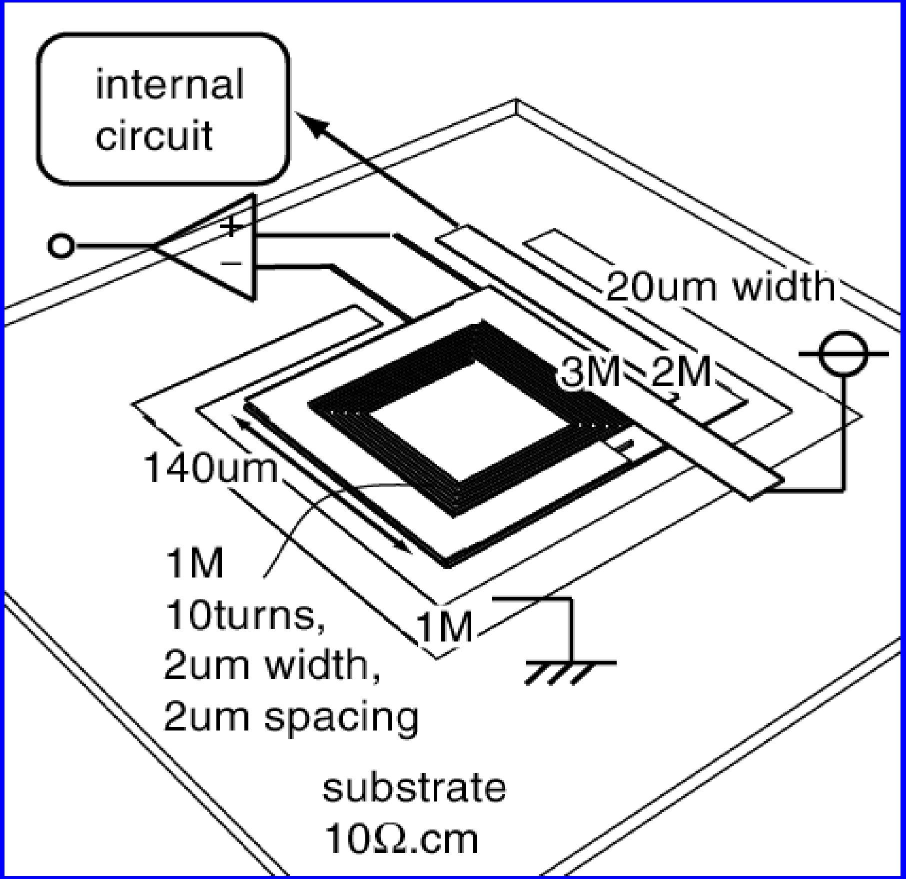
Equivalent Circuit

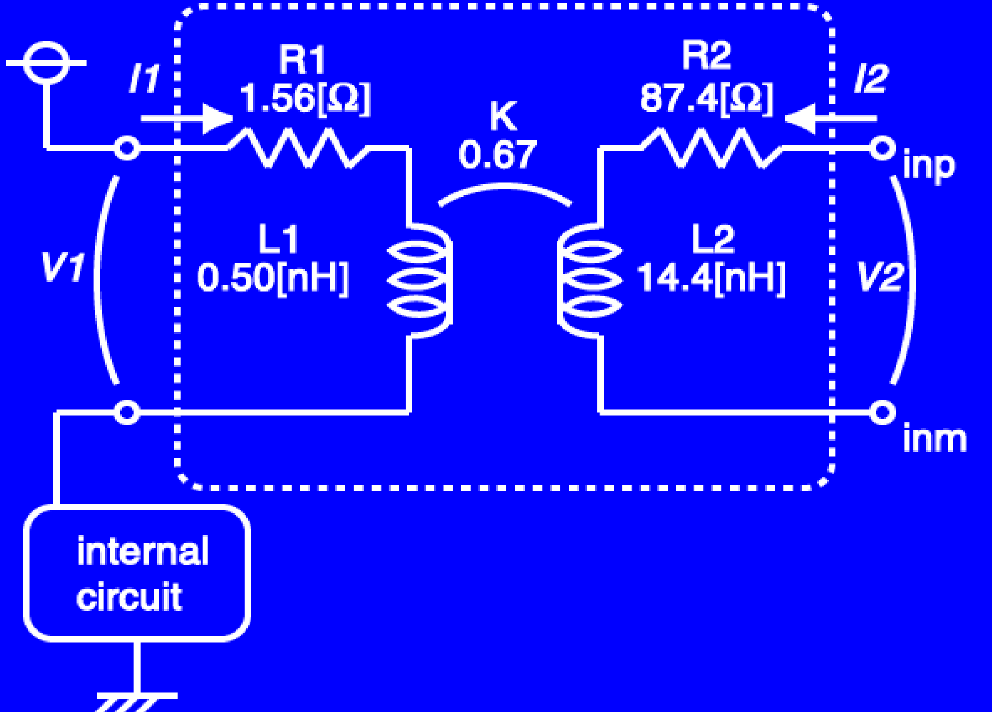
- **Extracted by FastHenry**



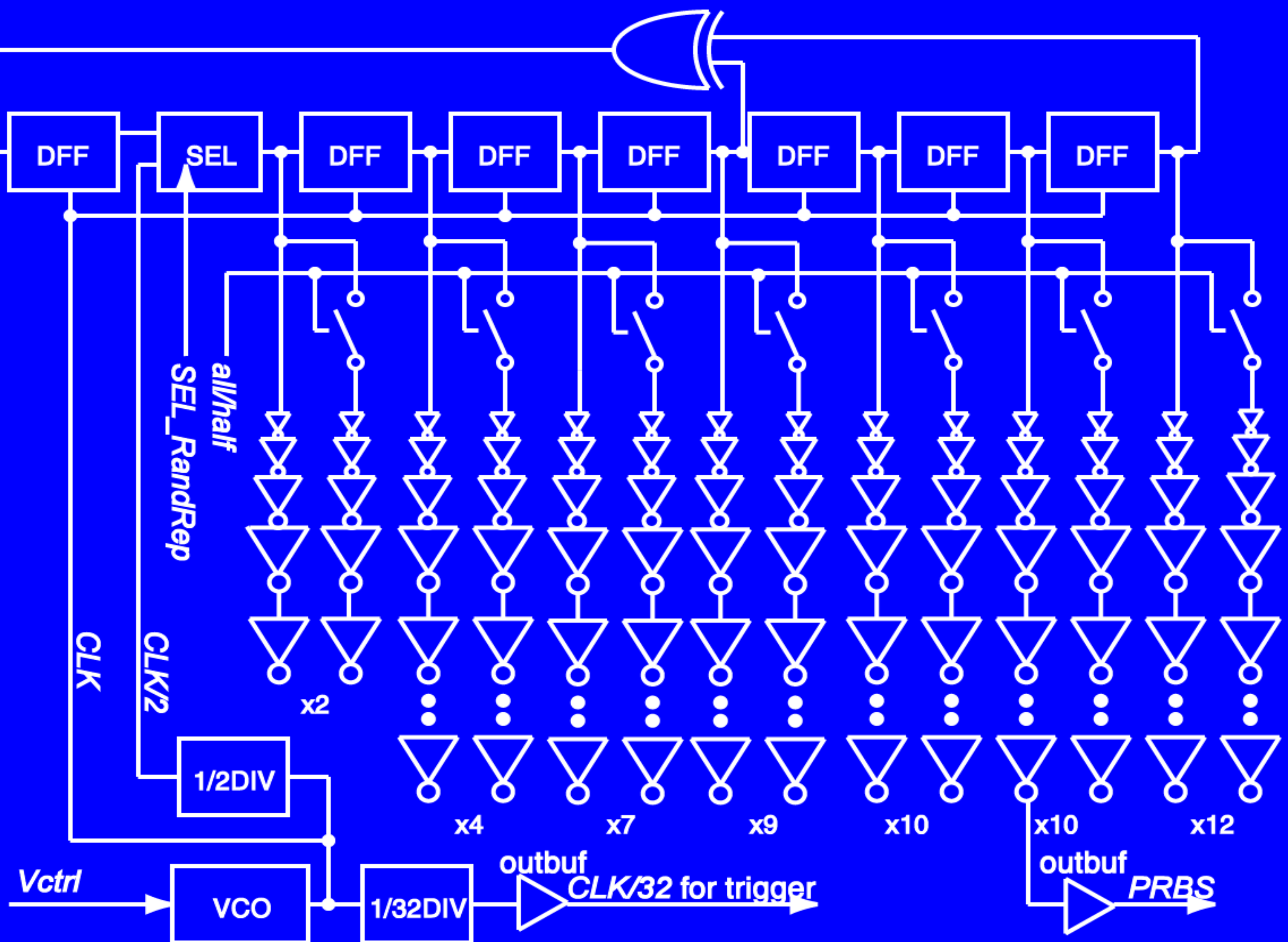
Mutual Inductor

- 0.35um, 3ML standard CMOS process
- FastHenry extracts the equivalent circuit



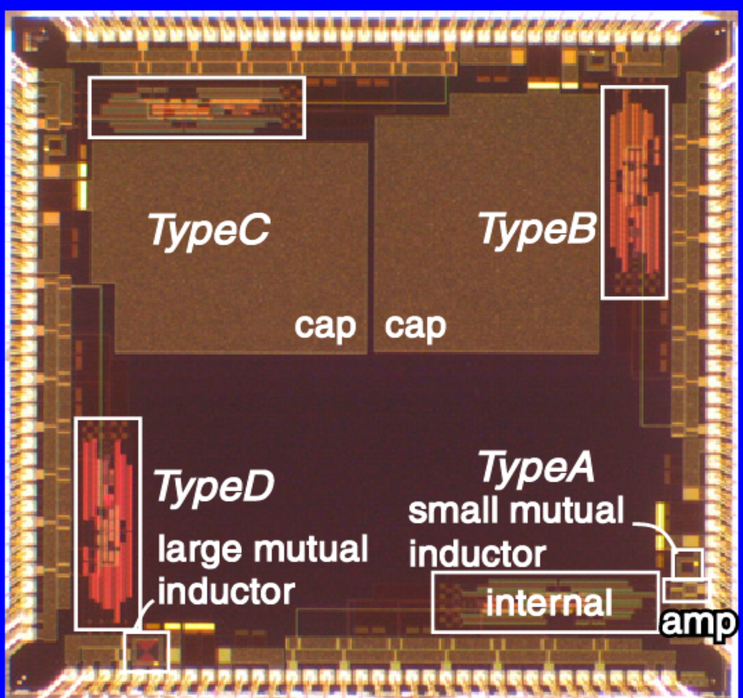


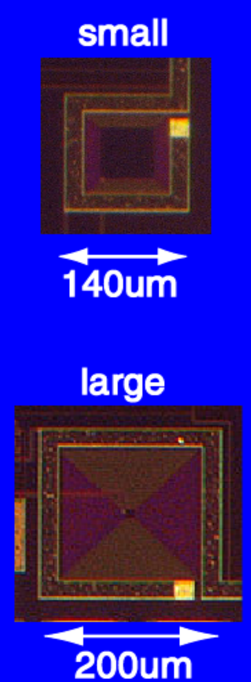
Internal Circuit as Noise Source

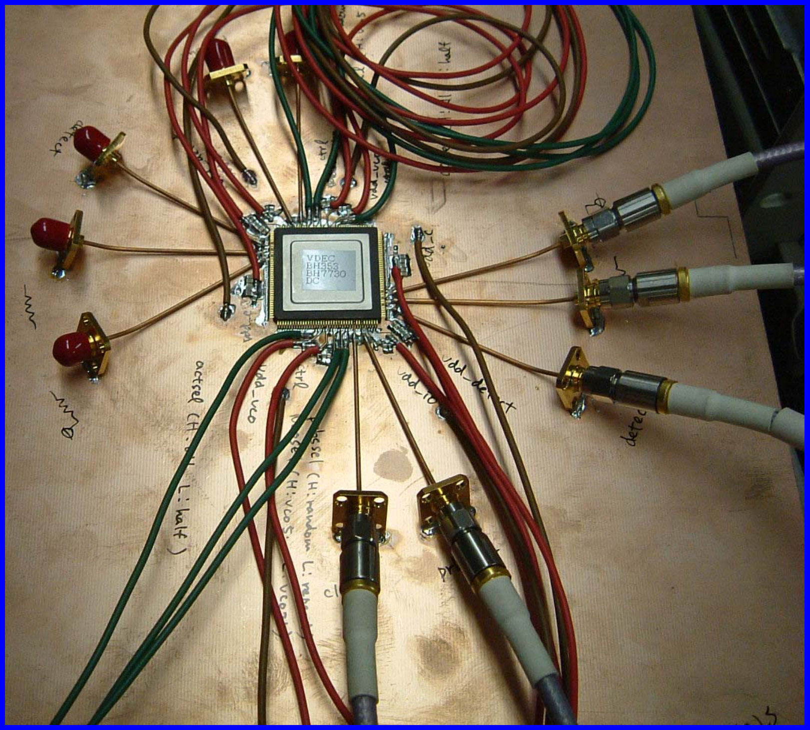


Chip Photograph

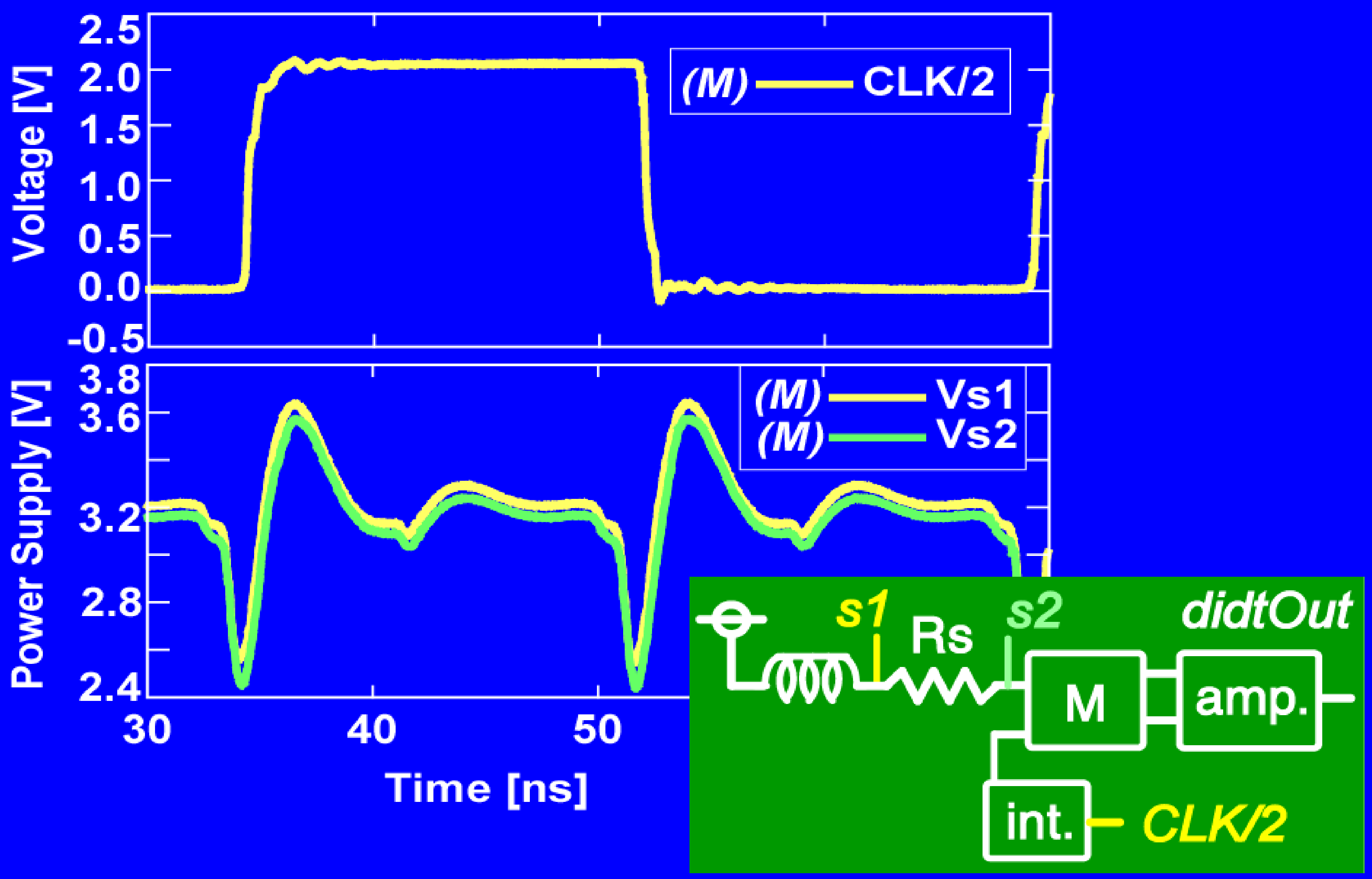
- 0.35um 3ML 2P CMOS (4.9mm x 4.9mm)
- The chip is mounted on a Cu board





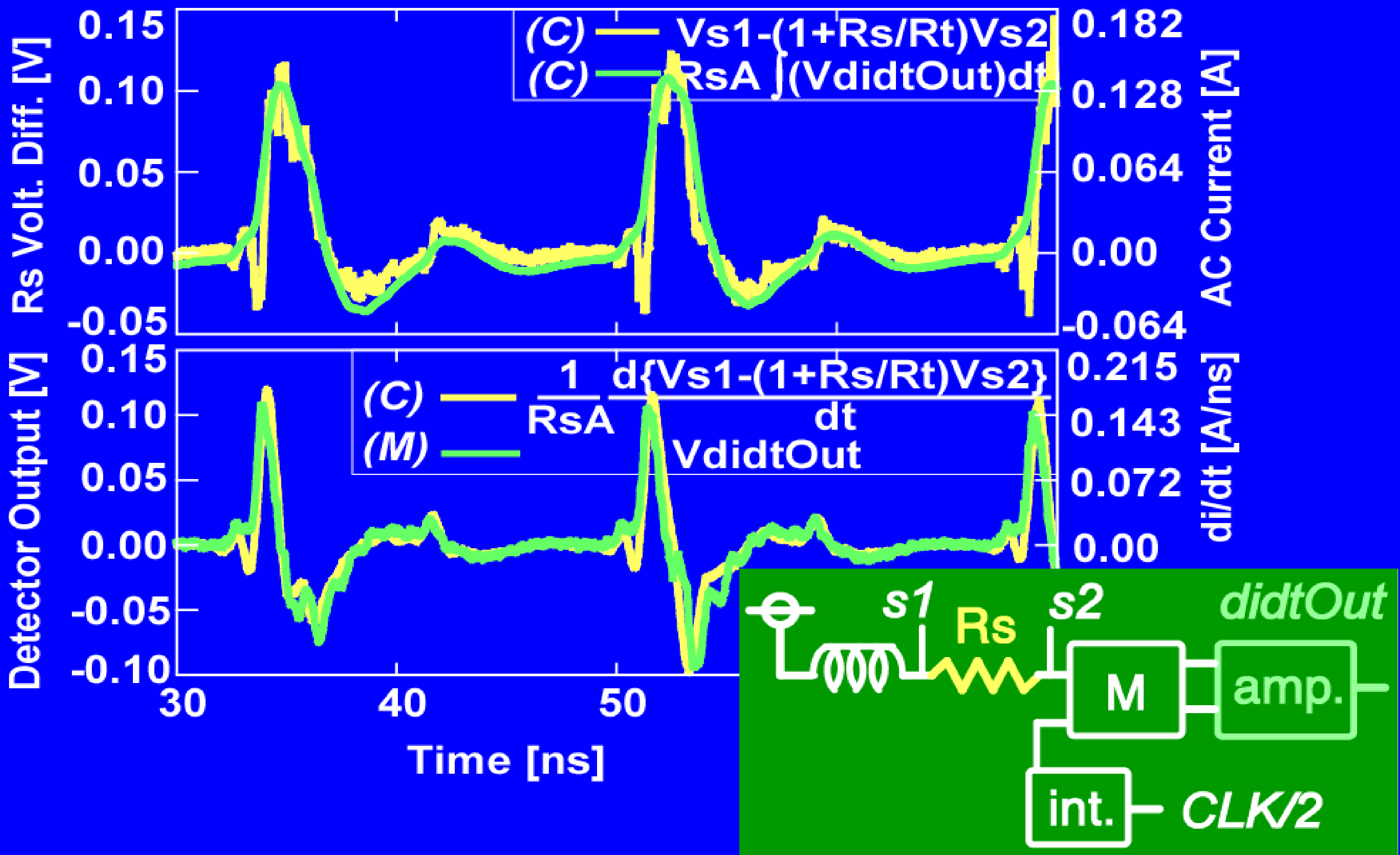


Waveforms #1



Voltage [V]
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
(M) CLK/2
Power Supply [V]
3.8
3.6
3.2
2.8
2.4
(M) Vs1
(M) Vs2
30
40
50
Time [ns]
s1
Rs
s2
didtOut
M
amp.
int.
CLK/2

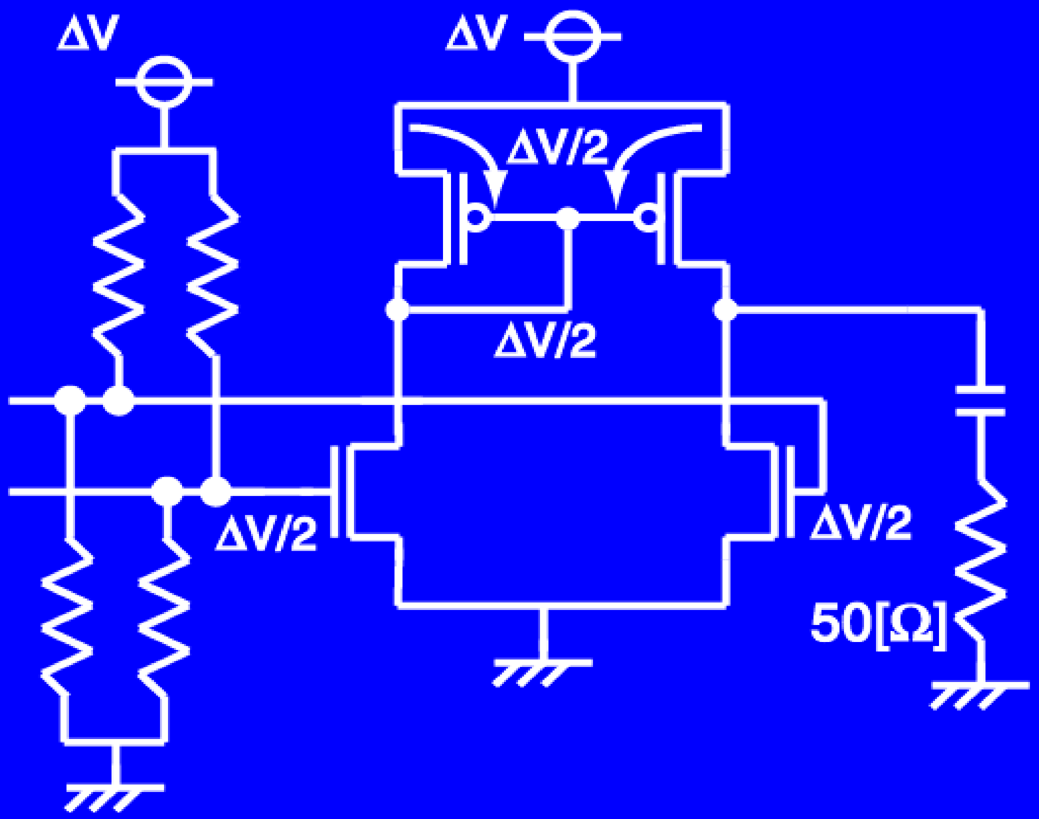
Waveforms #2

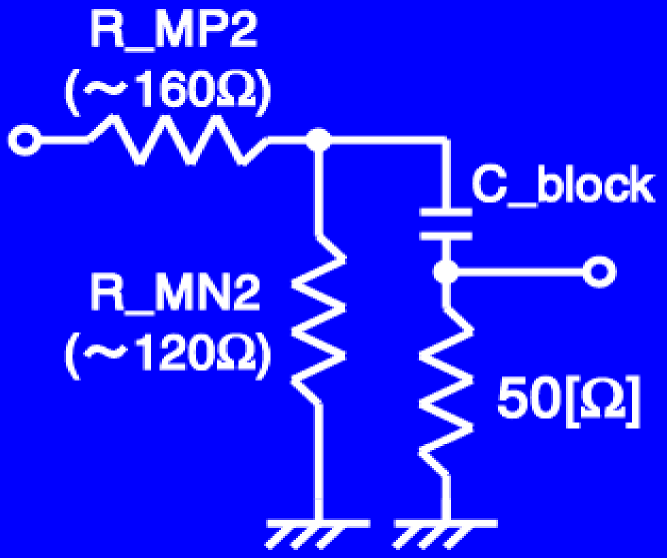


(C) Vs1-(1+Rs/Rt)Vs2
(C) RsA ∫(VdidtOut)dt
Rs Volt. Diff. [V]
AC Current [A]
0.15
0.10
0.05
0.00
-0.05
0.182
0.128
0.064
0.00
-0.064
(C) 1/RsA d{Vs1-(1+Rs/Rt)Vs2}/dt
(M) VdidtOut
Detector Output [V]
di/dt [A/ns]
0.15
0.10
0.05
0.00
-0.05
-0.10
0.215
0.143
0.072
0.00
30
40
50
Time [ns]
s1
Rs
s2
didtOut
M
amp.
int.
CLK/2

Noise Tolerance

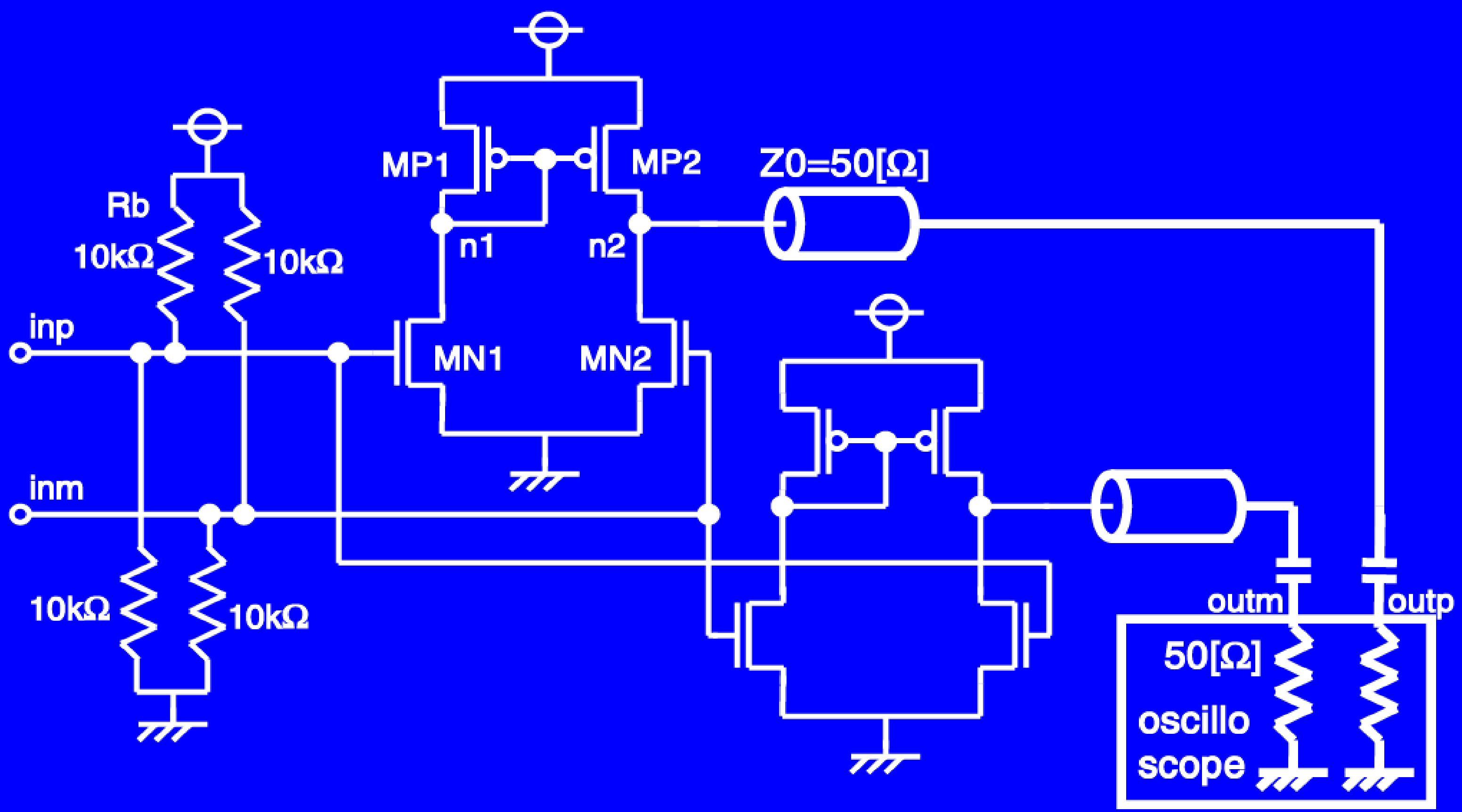
- Common mode noise is eliminated
- Vdd noise is suppressed to 18% (by 82%)





Single or Dual?

- Noise immunity, Sensitivity, Symmetric
- Require two pins, numerical calculation



Equations

$$V_2 = K\sqrt{L_1 L_2}\frac{dI_1}{dt}$$

$$V_{s1} - \left(1+\frac{R_S}{R_t}\right)V_{s2} = R_S I_1$$

$$V_{didtOut} = GV_2 = GK\sqrt{L_1 L_2}\frac{dI_1}{dt}$$

$$\frac{dI_1}{dt} = \frac{1}{GK\sqrt{L_1 L_2}} V_{didtOut} = A_{v2didt} V_{didtOut}$$

$$A_{v2didt} = \frac{1}{GK\sqrt{L_1 L_2}}$$

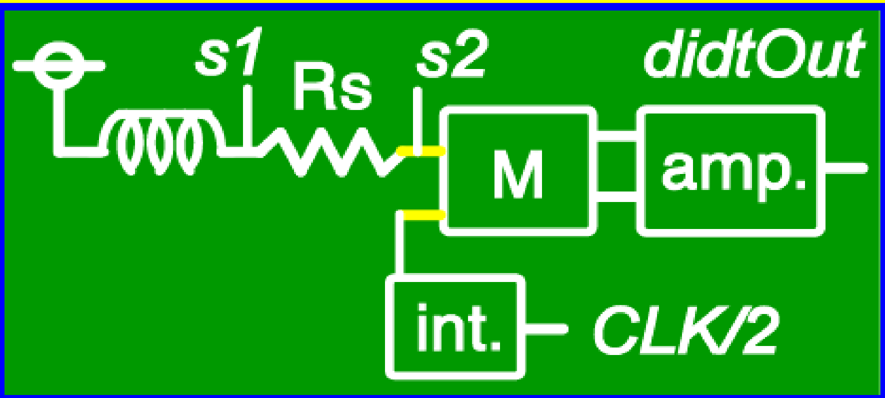
$$\frac{dI_1}{dt}_{range} = A_{v2didt} V_{amp\_outRange\_lin}$$

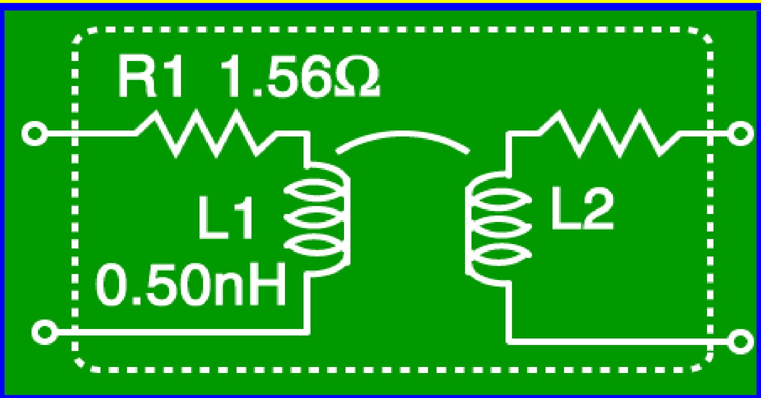
$$I_1 = A_{v2didt}\int V_{didtOut}\, dt + C$$

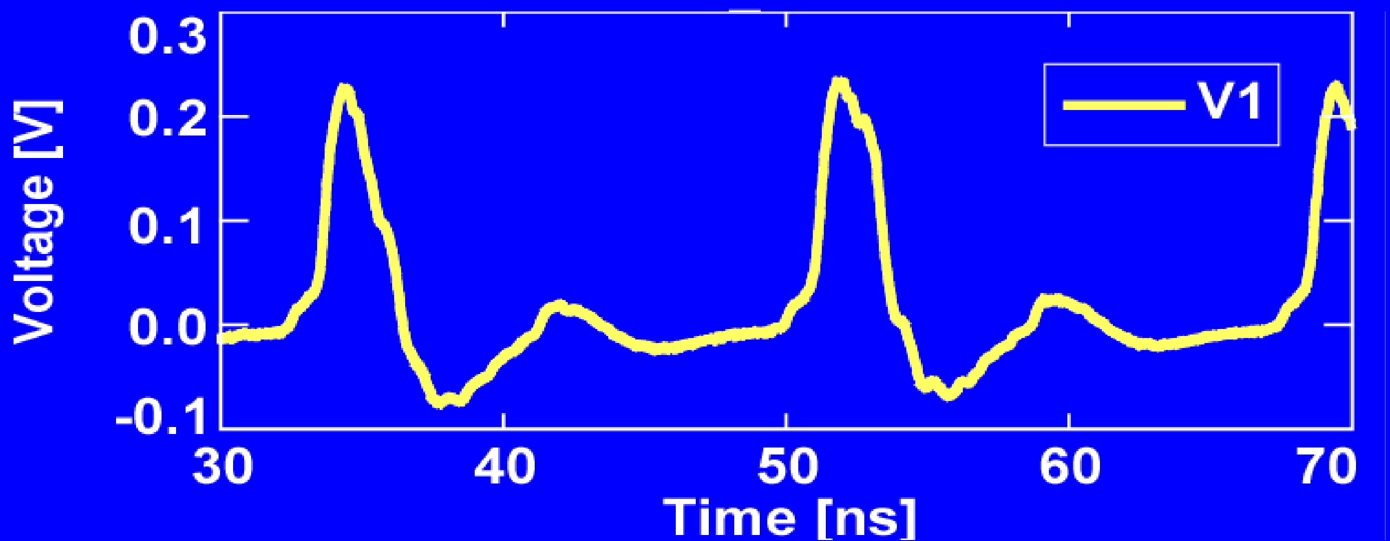
$$\frac{dI_1}{dt}_{res} = A_{v2didt} V_{didtOut\_res}$$

- **L1=0.5nH, L2=14.4nH, K=0.67, G=0.385,**
- **Rs=0.78Ω, Rt=50Ω**
- **Vamp_lin=±0.35V, di/dt_range=±0.5x10^{9}A/s**

di/dt Detector Impedance

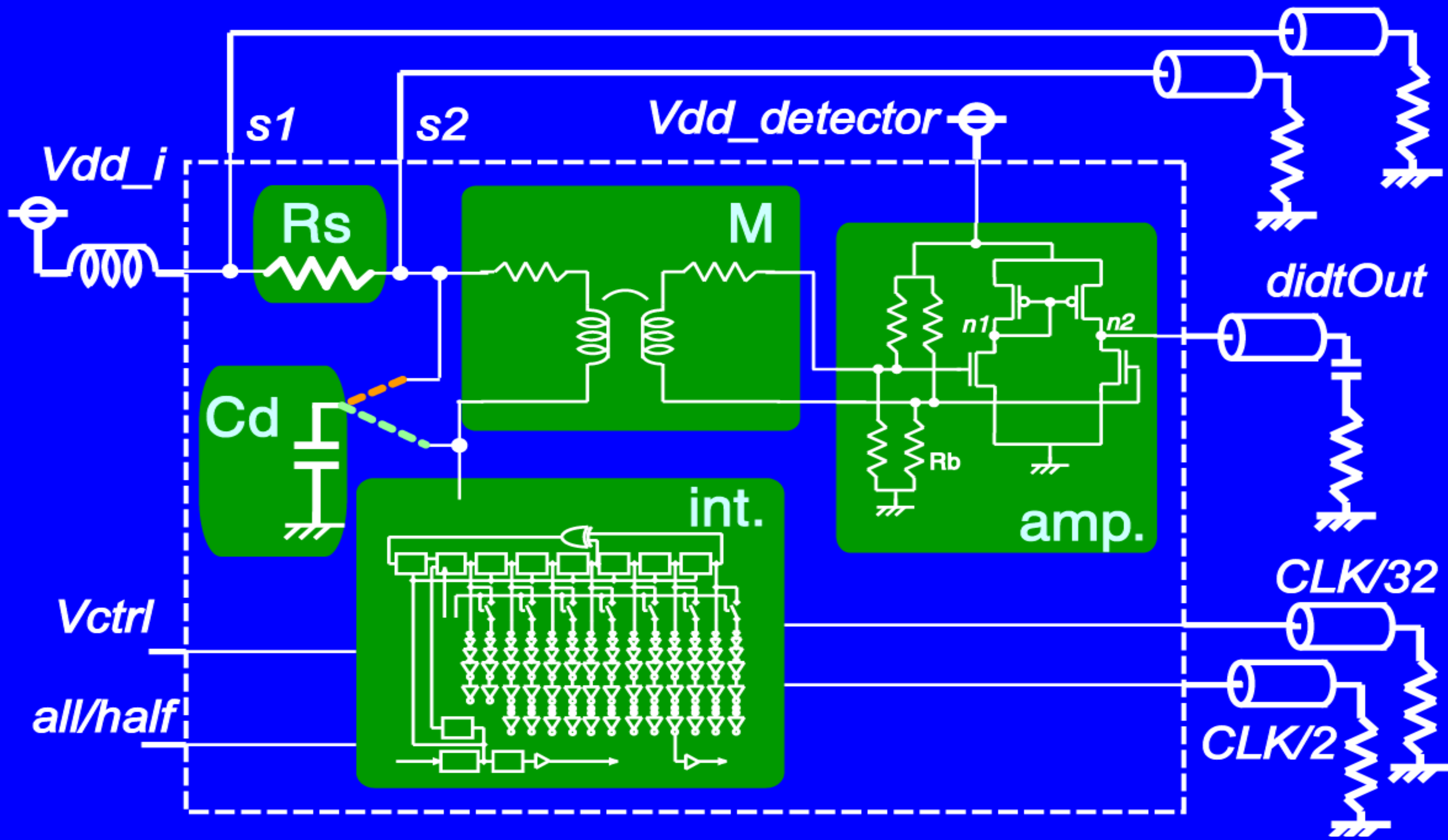




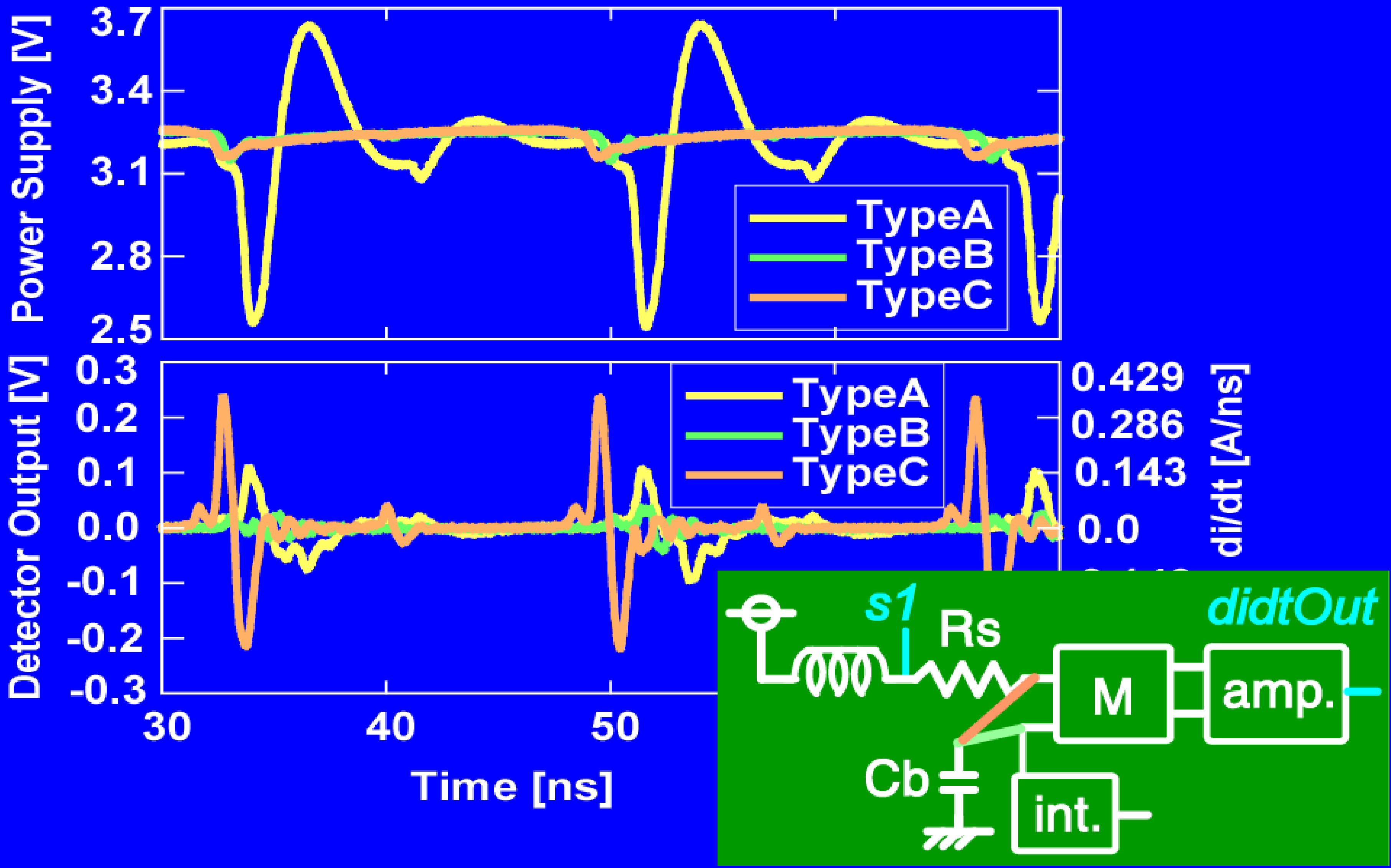


- **Multi-layer metal, wider line or low sensitivity can reduce the voltage drop**

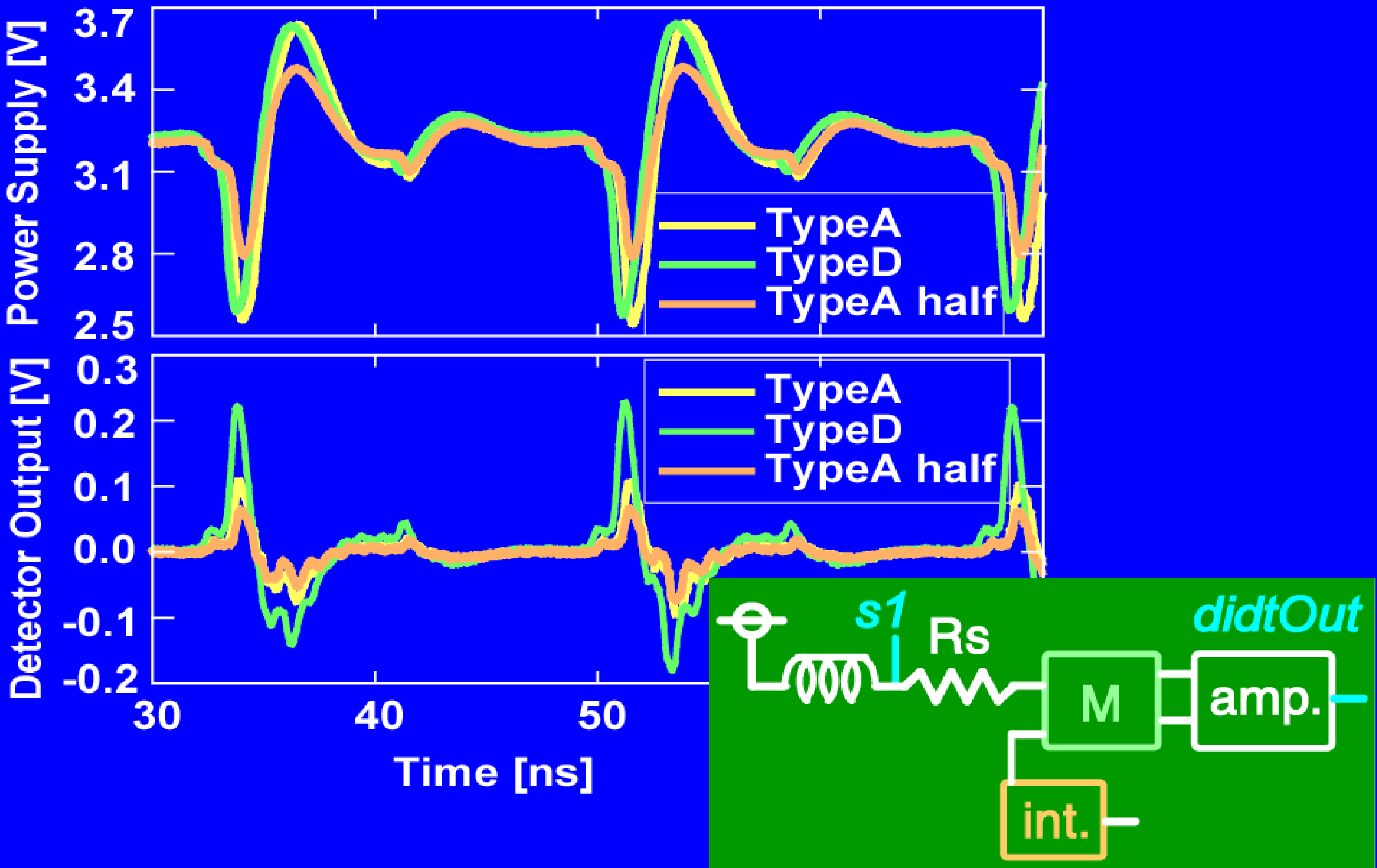
Whole Circuit / Meas. Setup



Decoupling Capacitor Effects

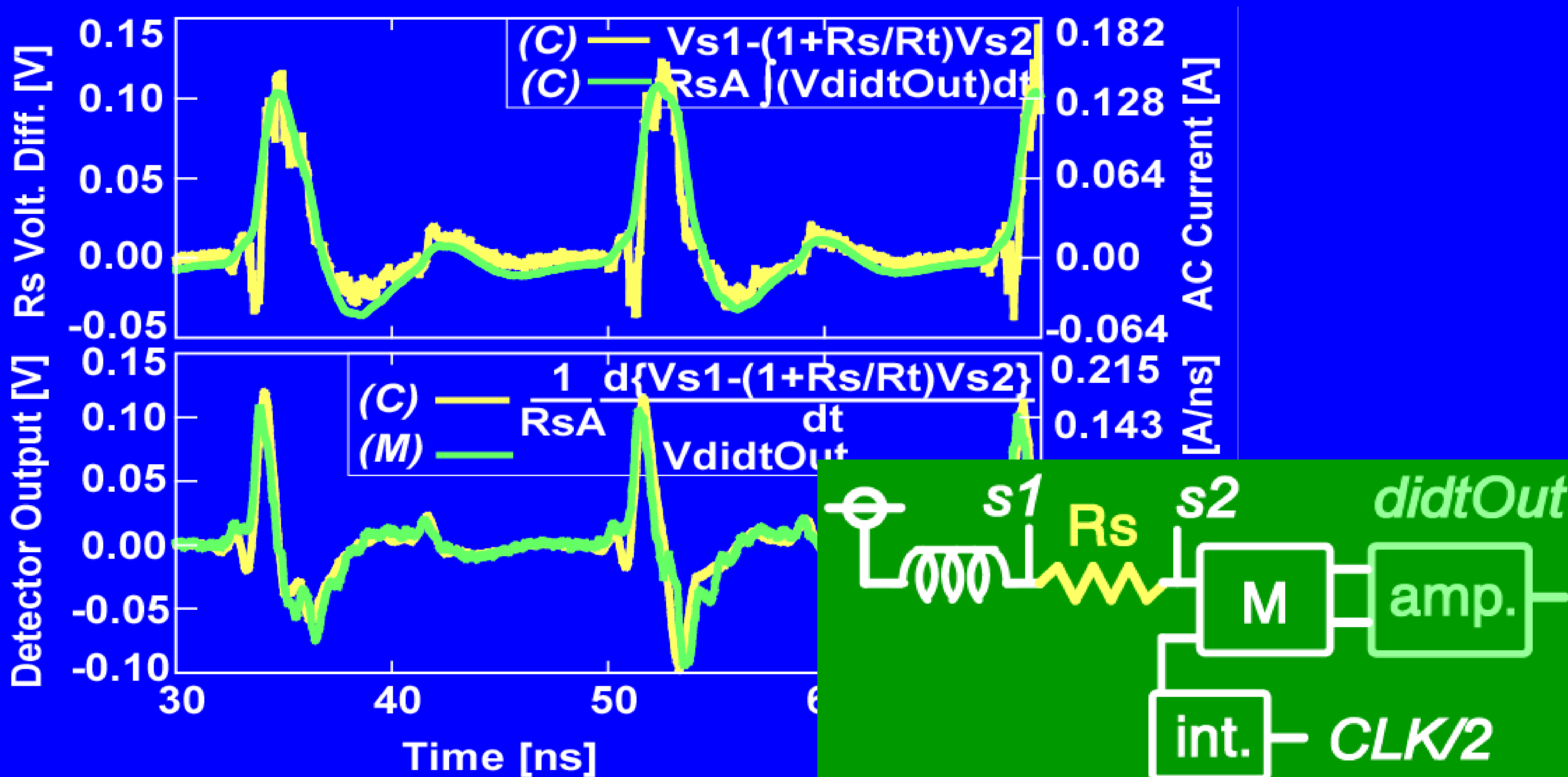


Activation, M dependence



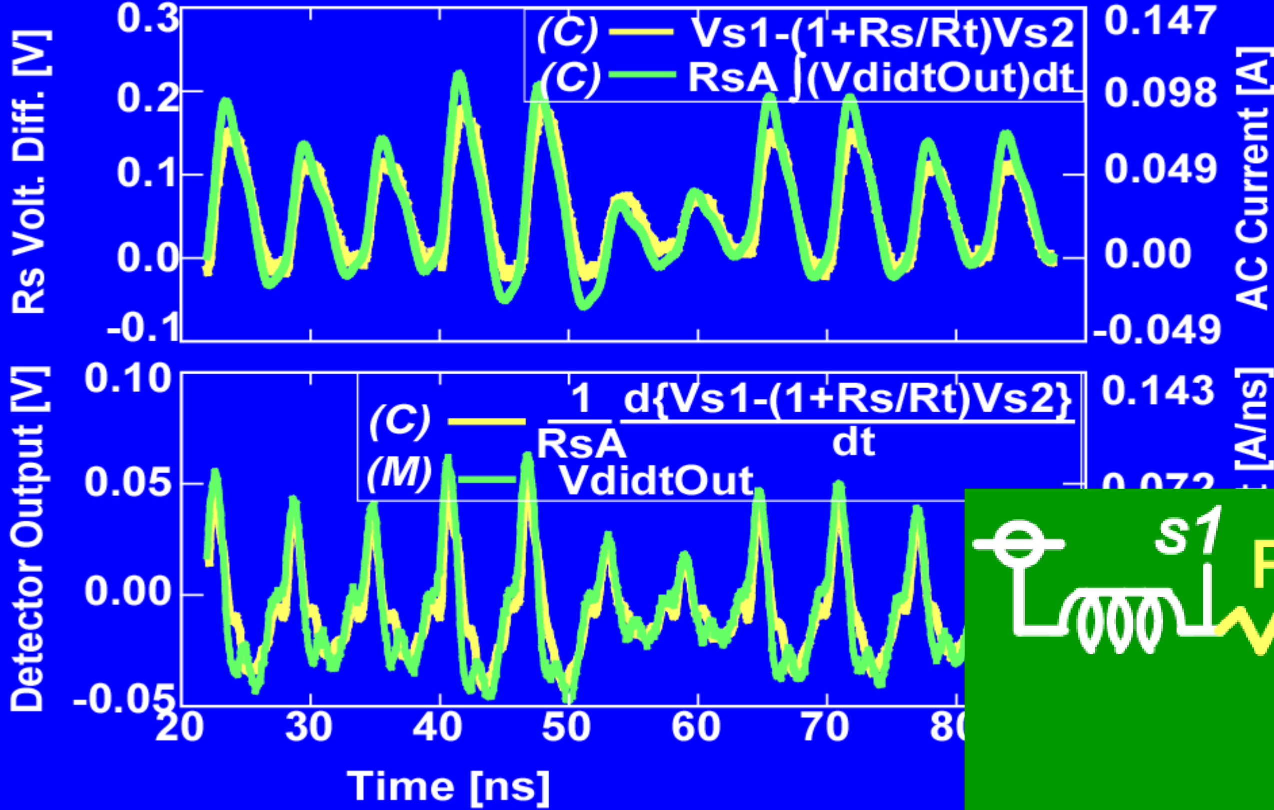
Error

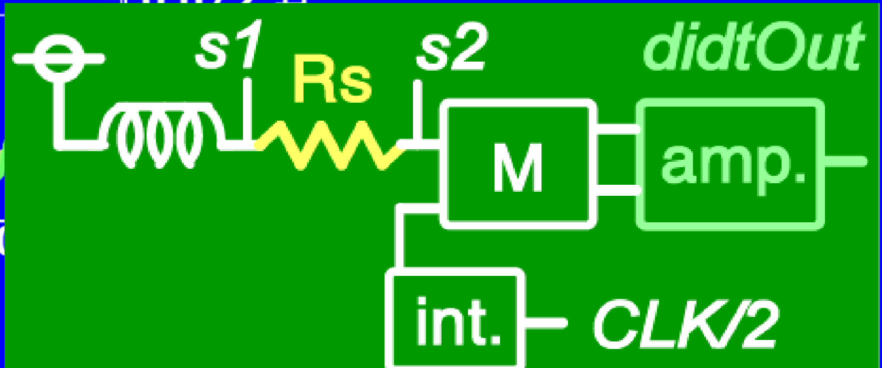
- δ=4.49mV, I=5.8mA
- δ=4.38mV, dI/dt=6.3mA/ns



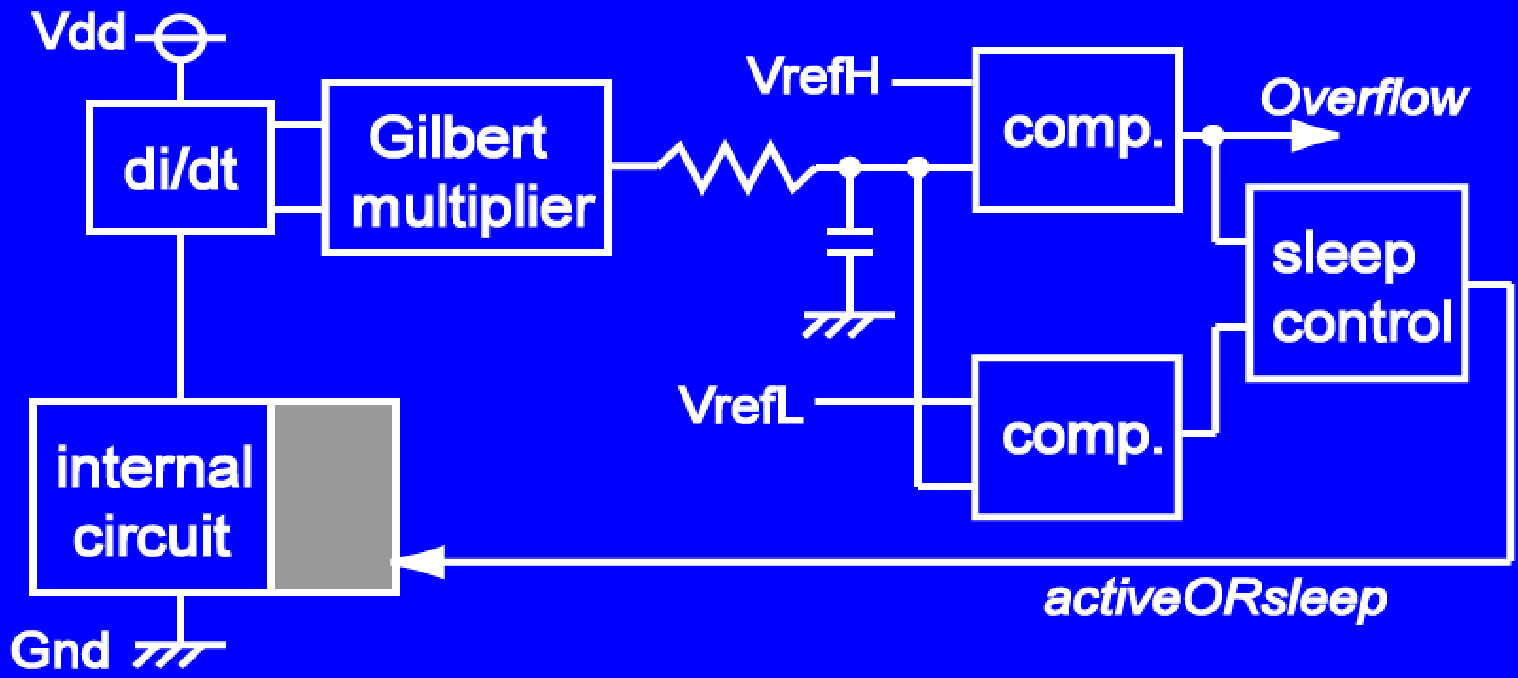
Error

- σ=9.10mV, I=4.46mA
- σ=6.30mV, dI/dt=9.01mA/ns

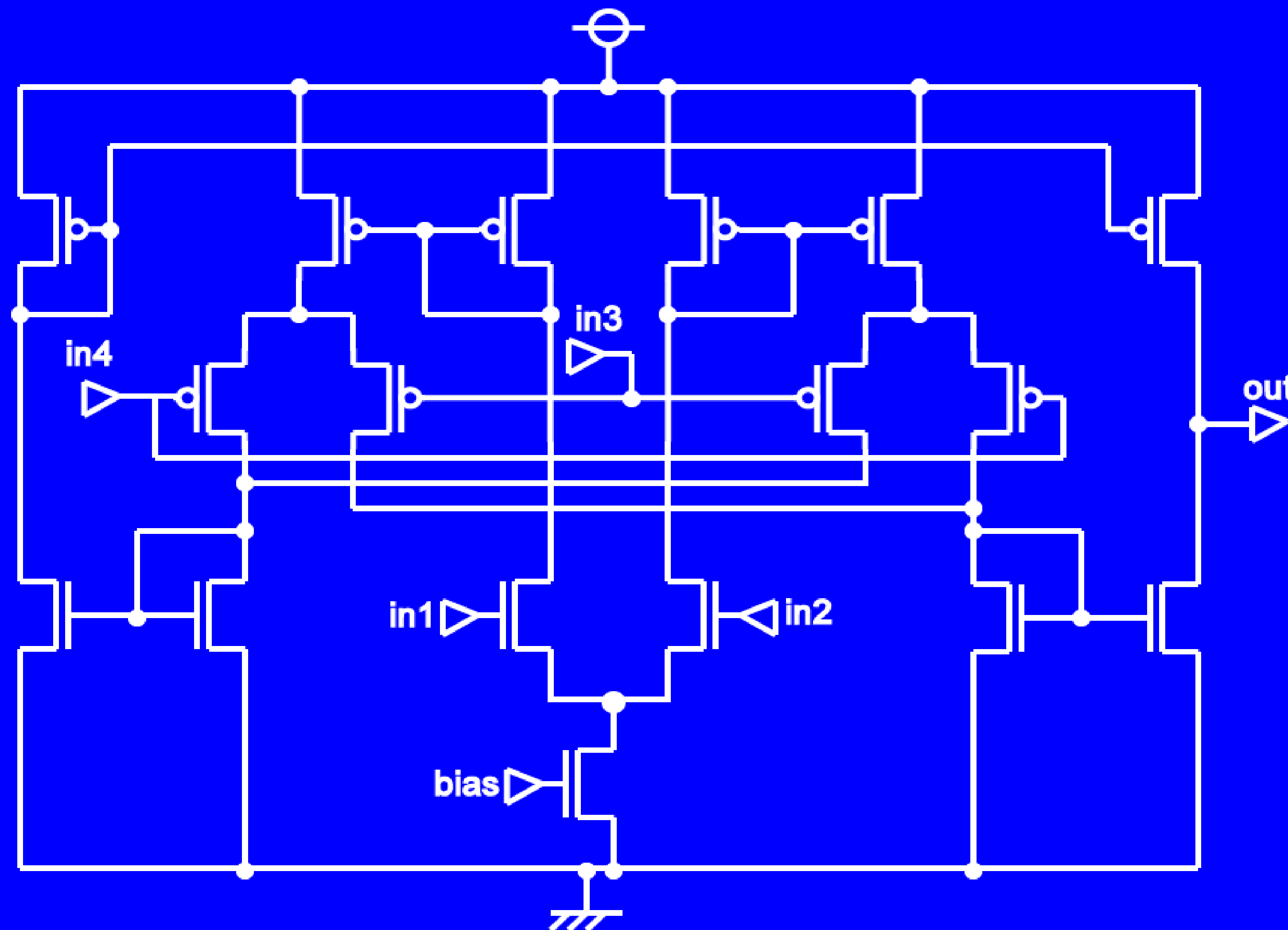




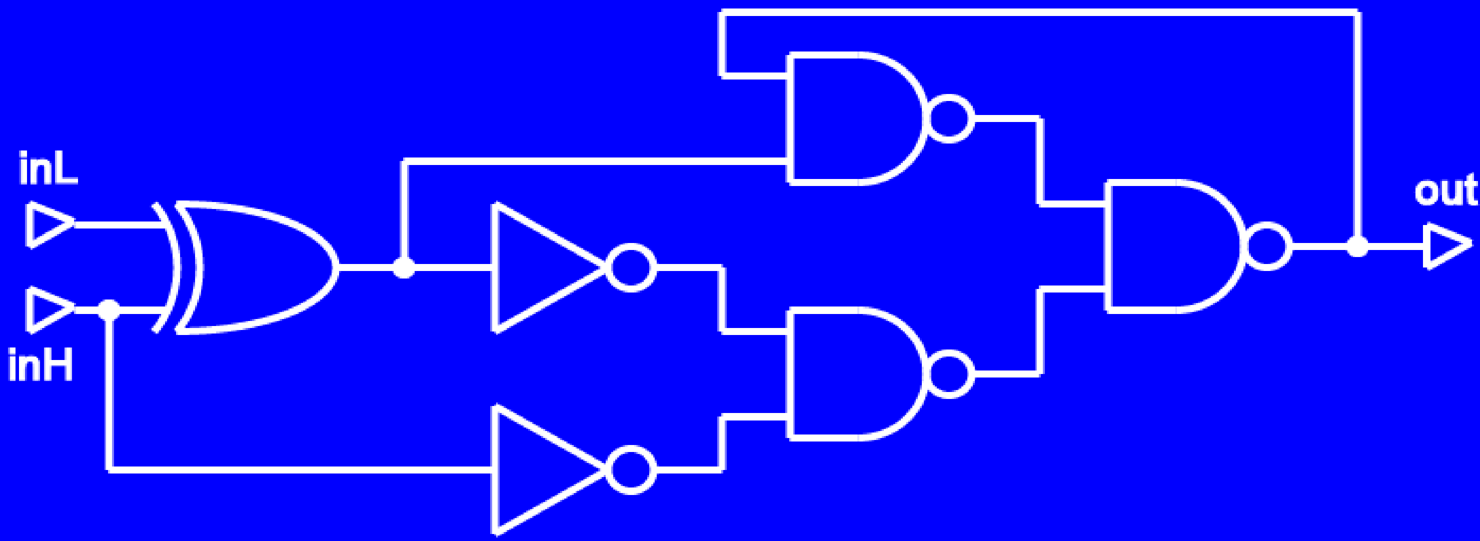
Feedback di/dt Control



Gilbert Multiplier

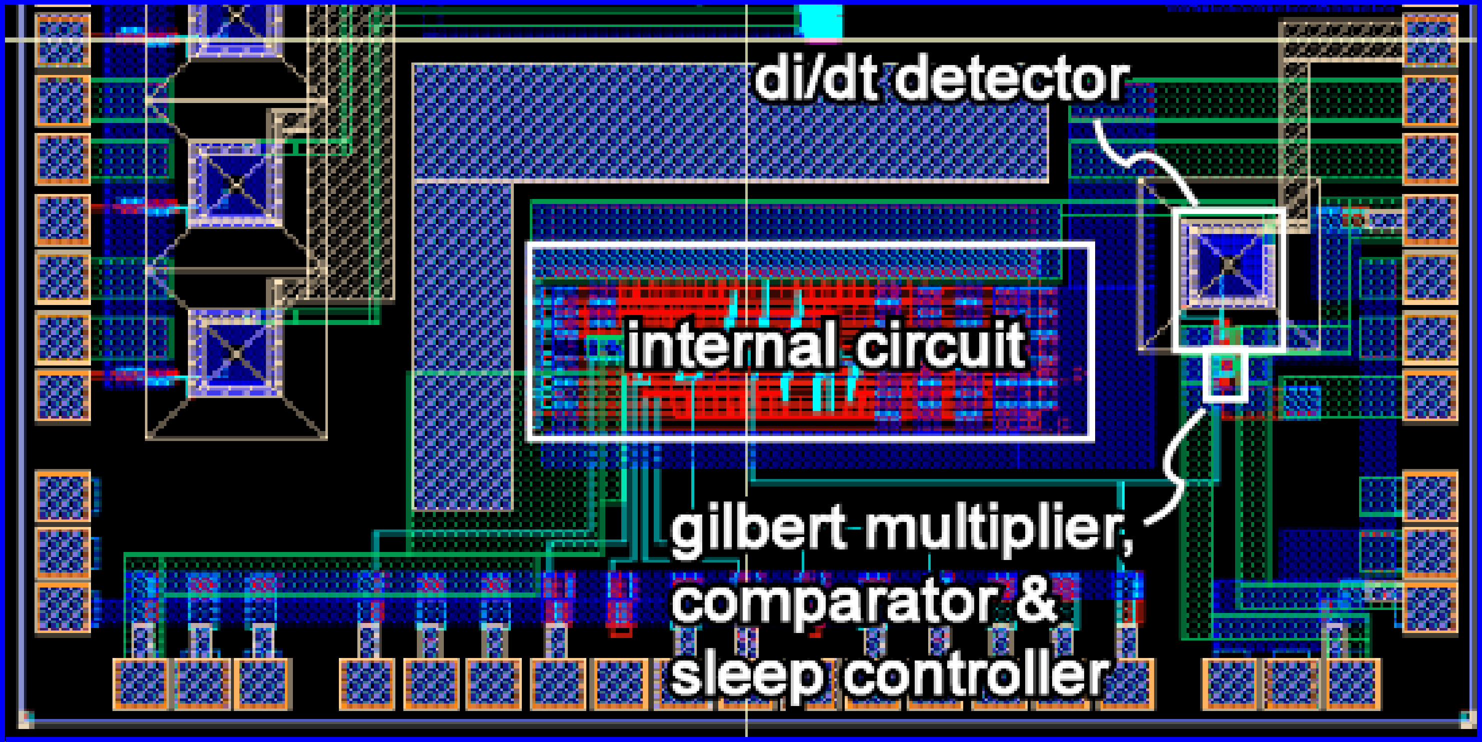


Sleep Controller

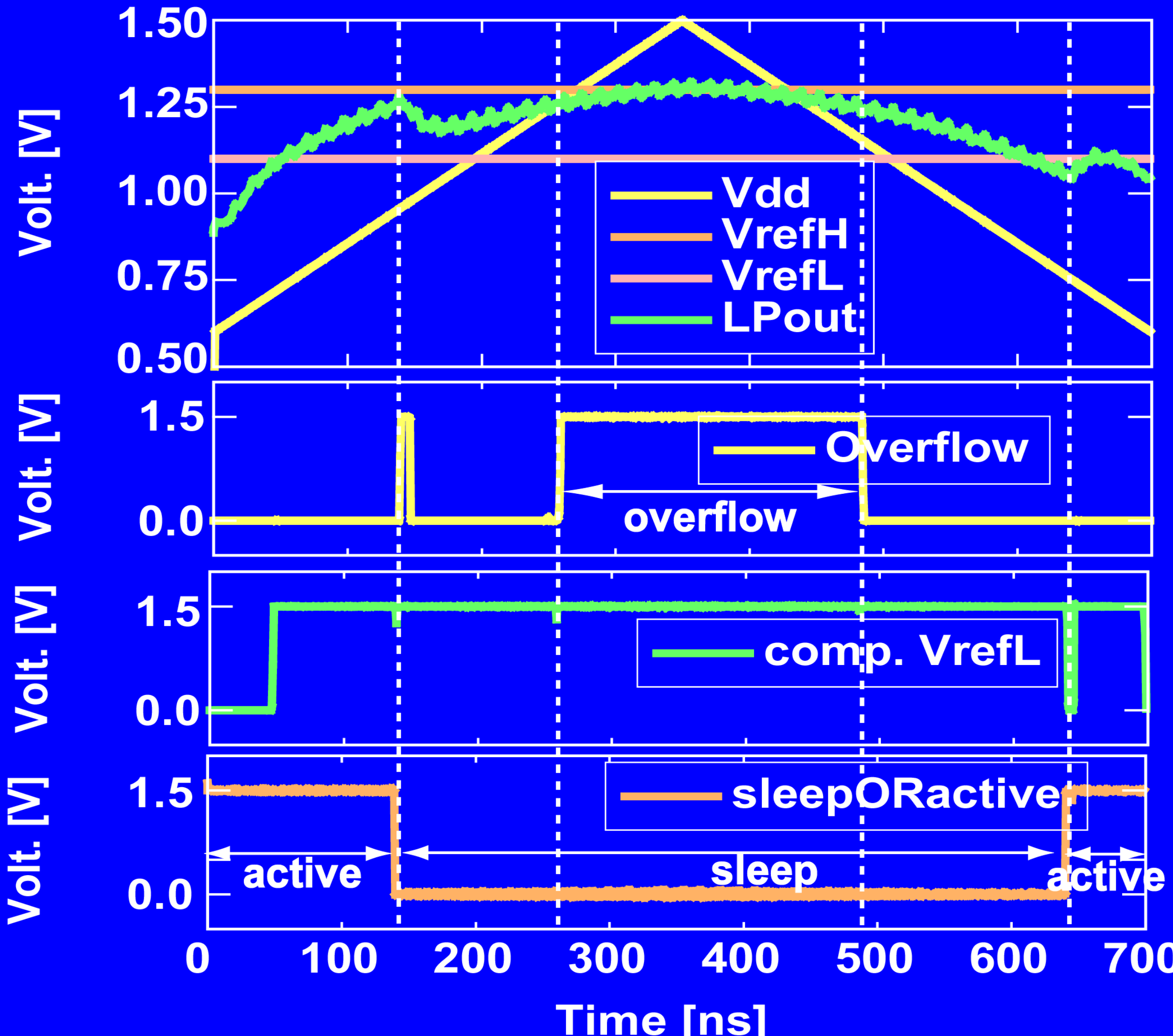


Chip Layout of di/dt Controller

- **0.15um SOI-CMOS technology**



Simulation Waveforms

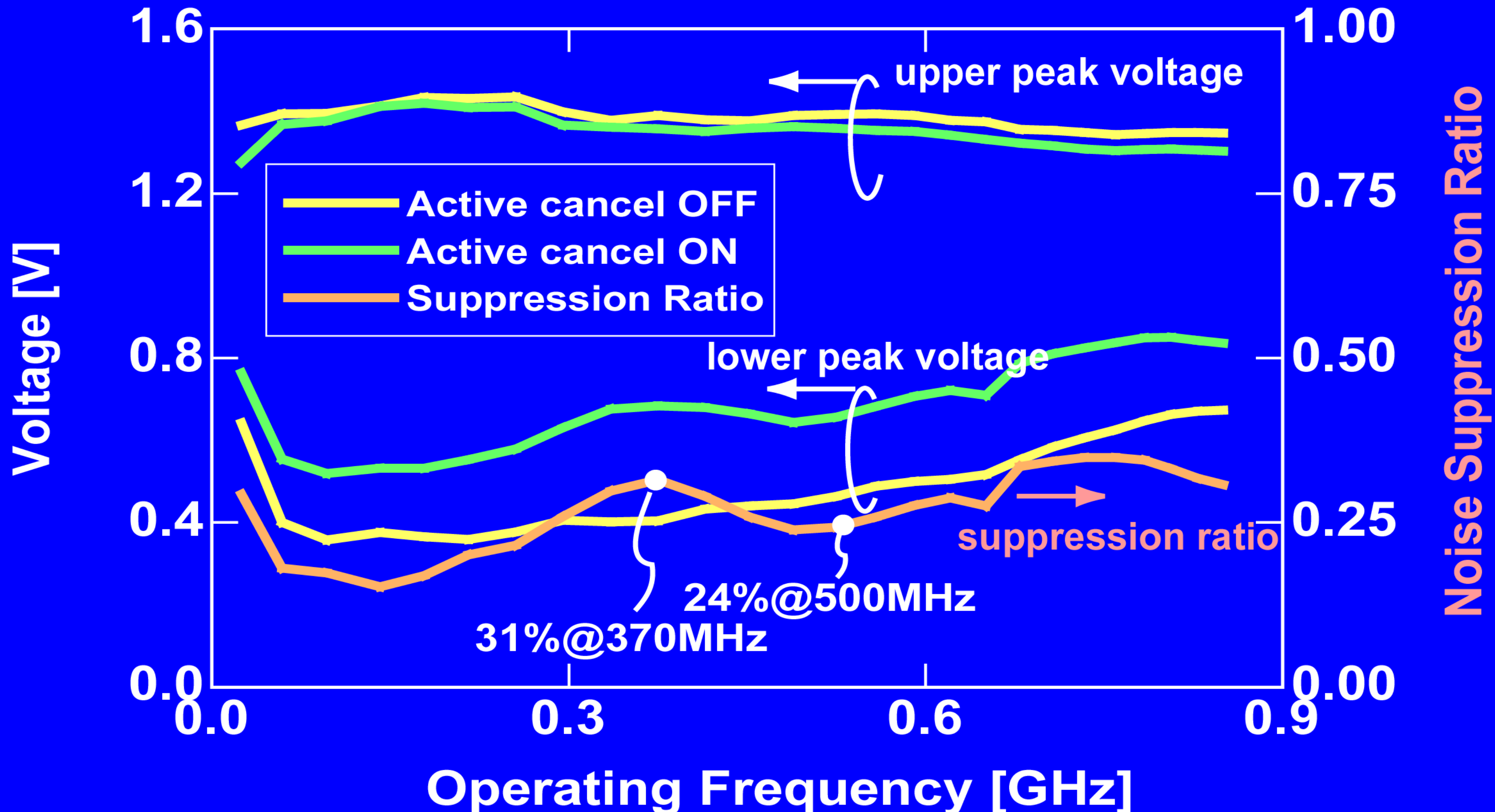


Short Summary

- On-chip di/dt detector is demonstrated
- It consists of a power supply line, underlying spiral inductor, an amplifier
- di/dt waveforms obtained from the di/dt detector and the resistor agree well
- Current waveform can be calculated by integrating the detector output by time
- The di/dt detector circuit detects the decoupling capacitor effects as well

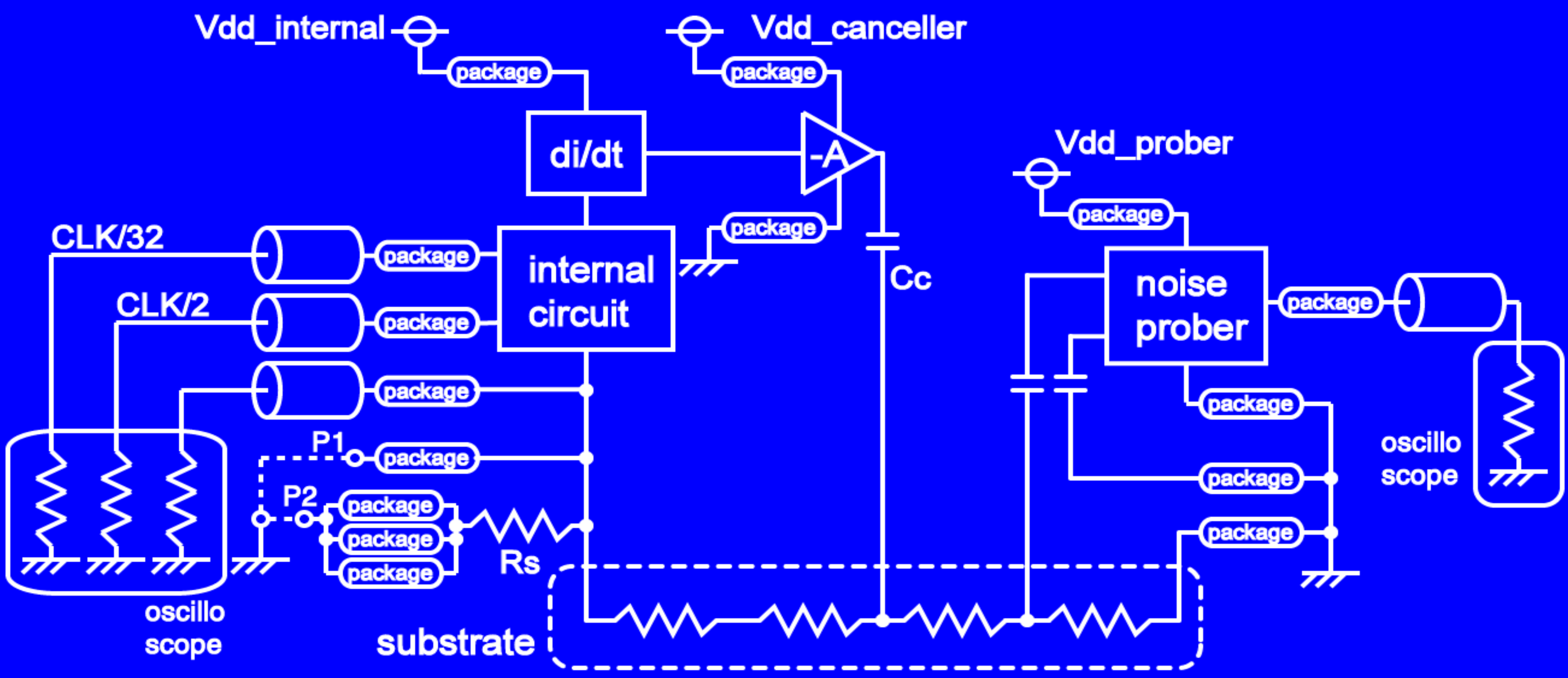
Active Noise Cancelling

Frequency Dependence (random)



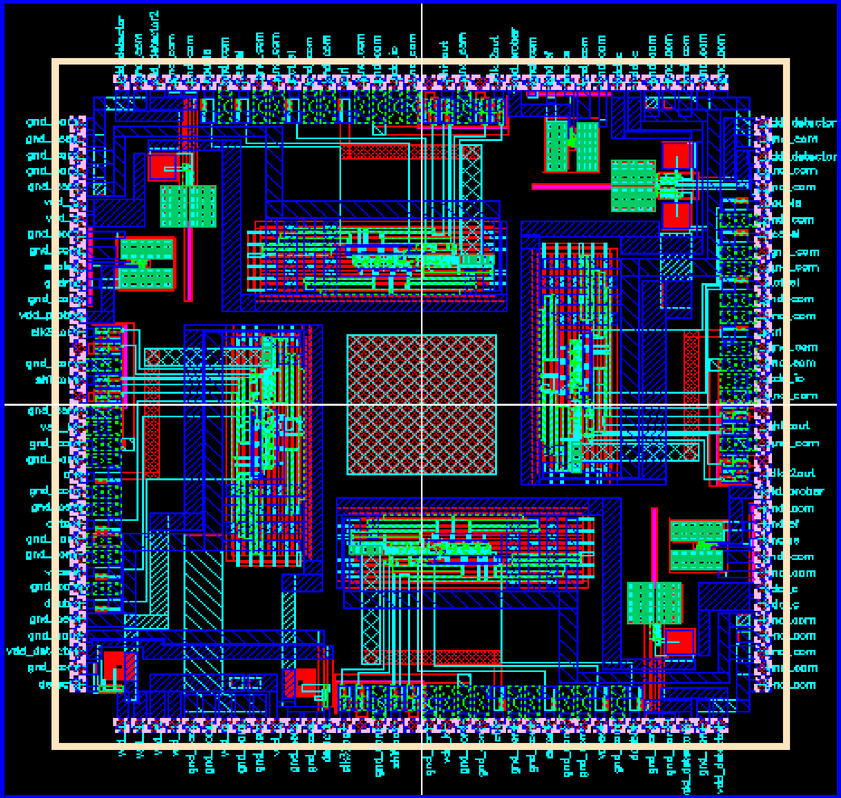
Overall Circuit

- Change the Gnd line impedance by the chip mount

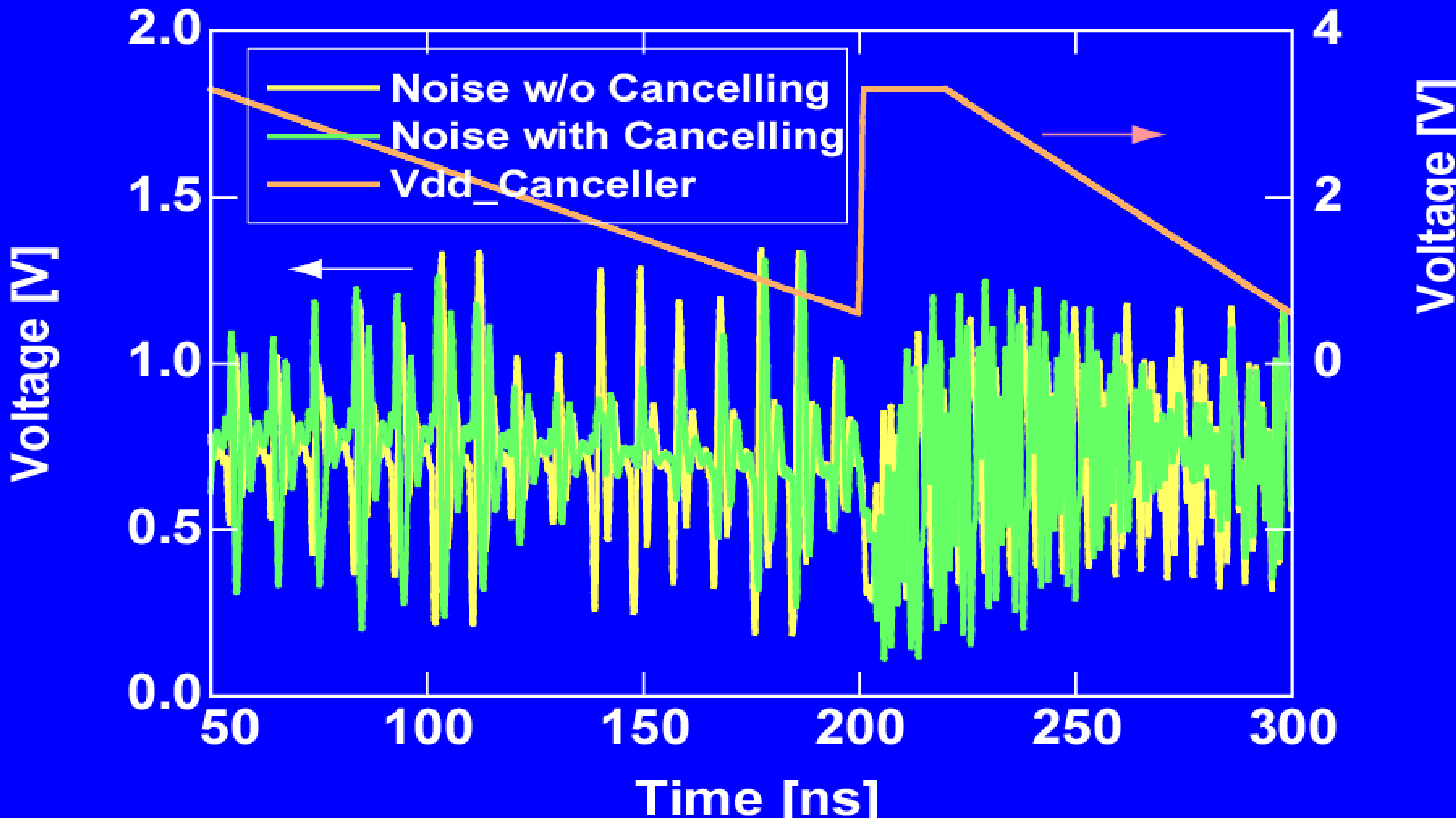


Chip Layout

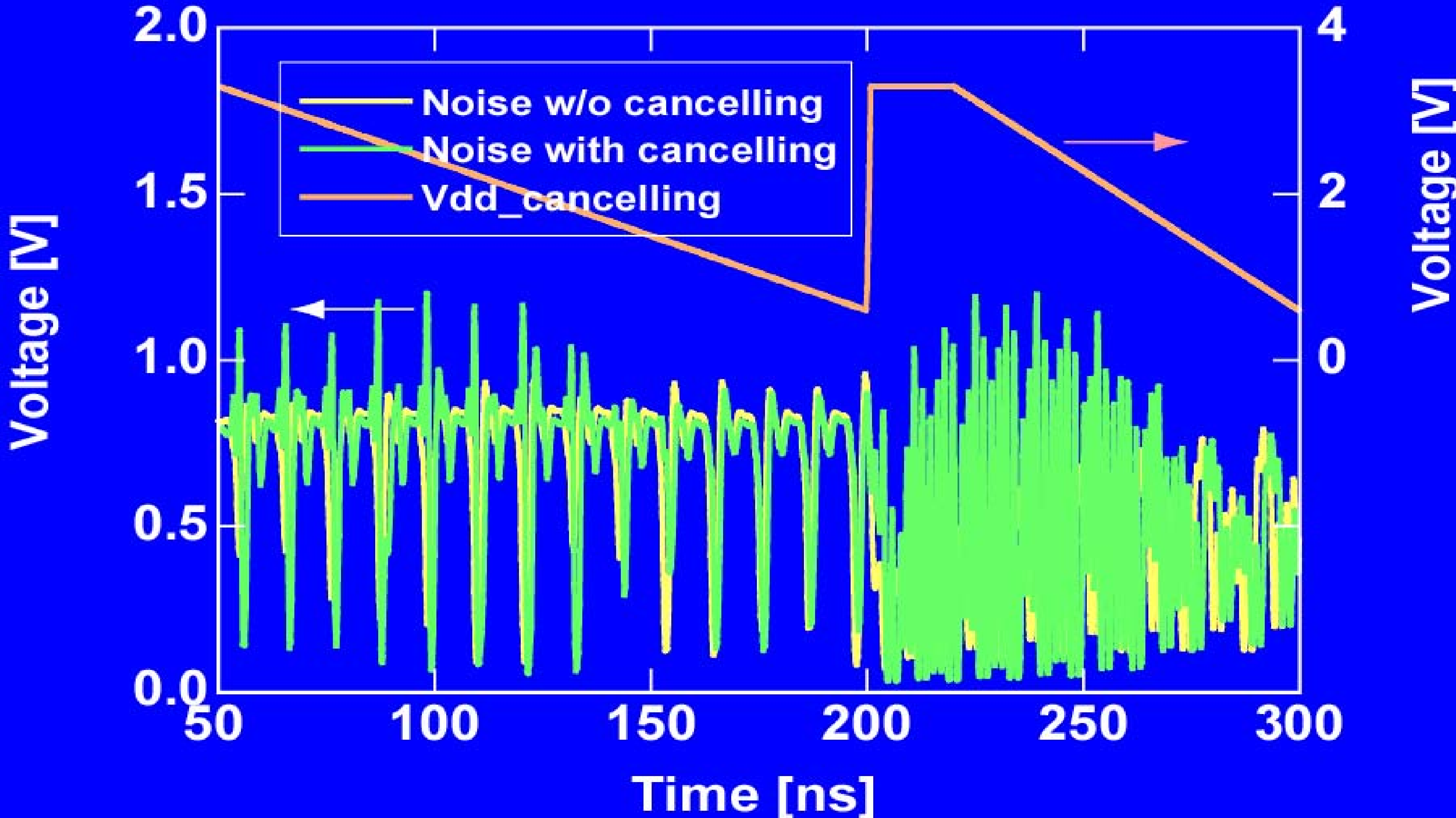
- 0.35um 3ML 2P CMOS (4.9mm x 4.9mm)
- Chip delivery date will be 10/8



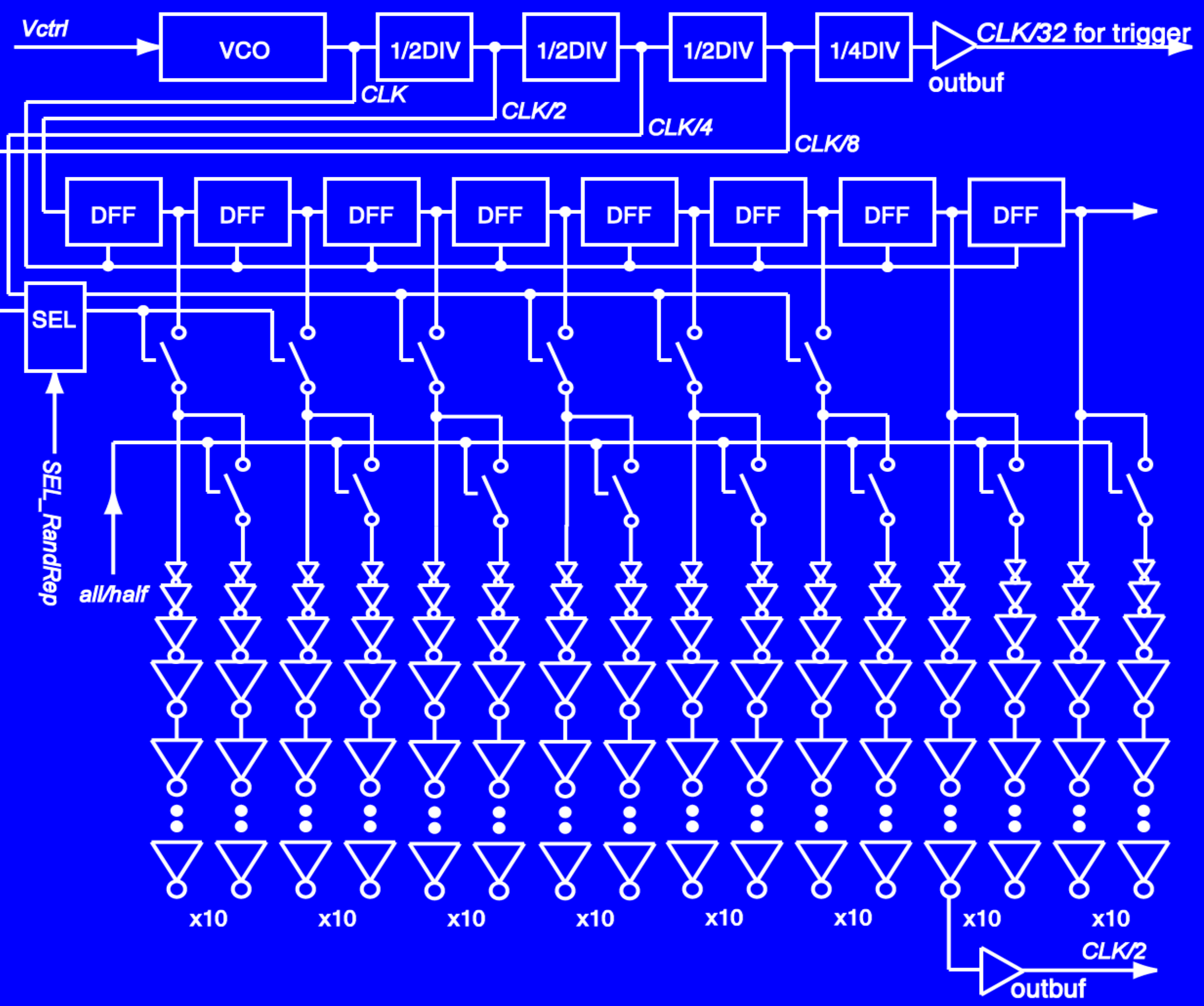
Waveforms (Inductive)



Waveforms (Resistive)



Internal Circuit as Noise Source



Future Works

Conclusion (1/2)

- Chapter 2
  - Stubs and decoupling capacitors are compared for power supply noise reduction
  - Boundary frequency is clarified
  - Circuit simulations confirmed the noise reduction
  - Stubs will have more advantage over capacitors for LSIs with higher operating frequency
- Chapter 3
  - The on-chip stub does not show the power supply reduction effects because of bents, resistance
  - The off-chip stubs show clear noise reduction
  - Stub frequency dependence is observed
  - Straight on-chip stub integration will be possible in the near future

Conclusion (2/2)

- Chapter 4
  - On-chip di/dt detector is demonstrated
  - di/dt waveforms obtained from the di/dt detector and the resistor agree well
  - Current waveform can be calculated by integrating the detector output by time
- Chapter 5
  - Feedforward active noise cancelling is proposed
  - di/dt is used for anti-phase signal generation, and injected into substrate
  - No-body-contact amplifier is used for the probing
  - Simulation results show the substrate noise cancelling effects for a test circuit