Theoretical Study of Stubs for Power Line Noise Reduction

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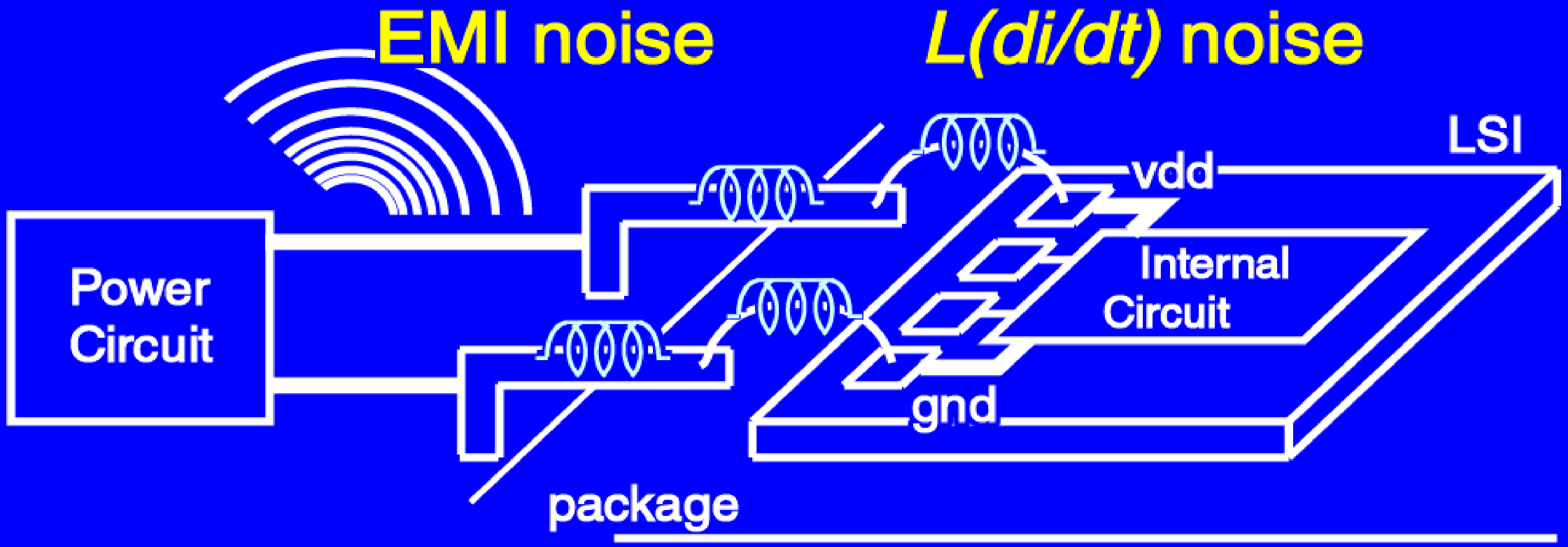
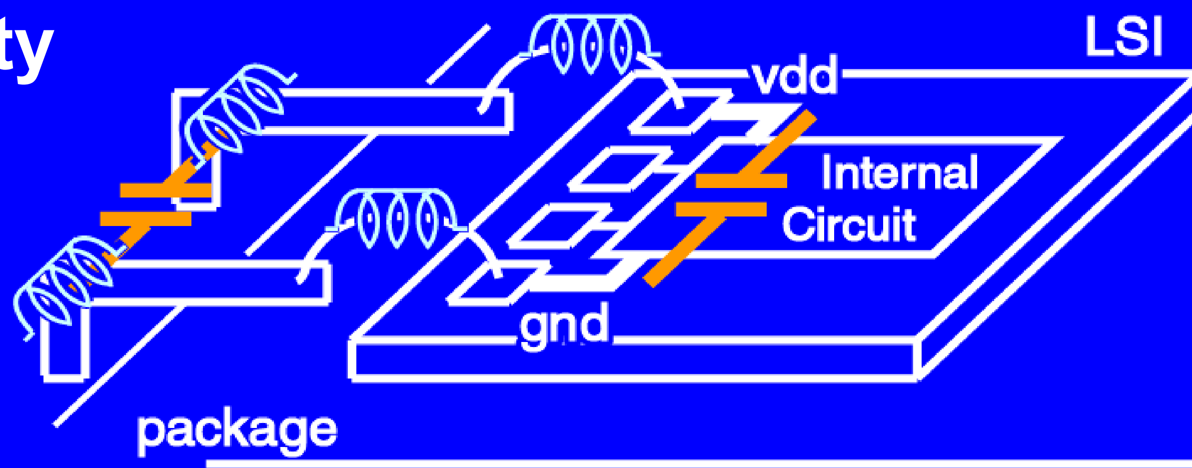
Background

- di/dt is becoming critical issue
  - L(di/dt) noise of low voltage LSIs
  - EMI noise of high-speed operation LSIs
- Need to suppress the di/dt



Conventional di/dt Reduction

- De-coupling capacitor
  - Area penalty
  - Parasitic inductance



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

Contents

- Stub theorem and design
- Simulation results
  - Simulation waveforms
  - Frequency components
- Analytical model using Equivalent termination approximation
- Future prediction of stub effects
- Conclusion

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)

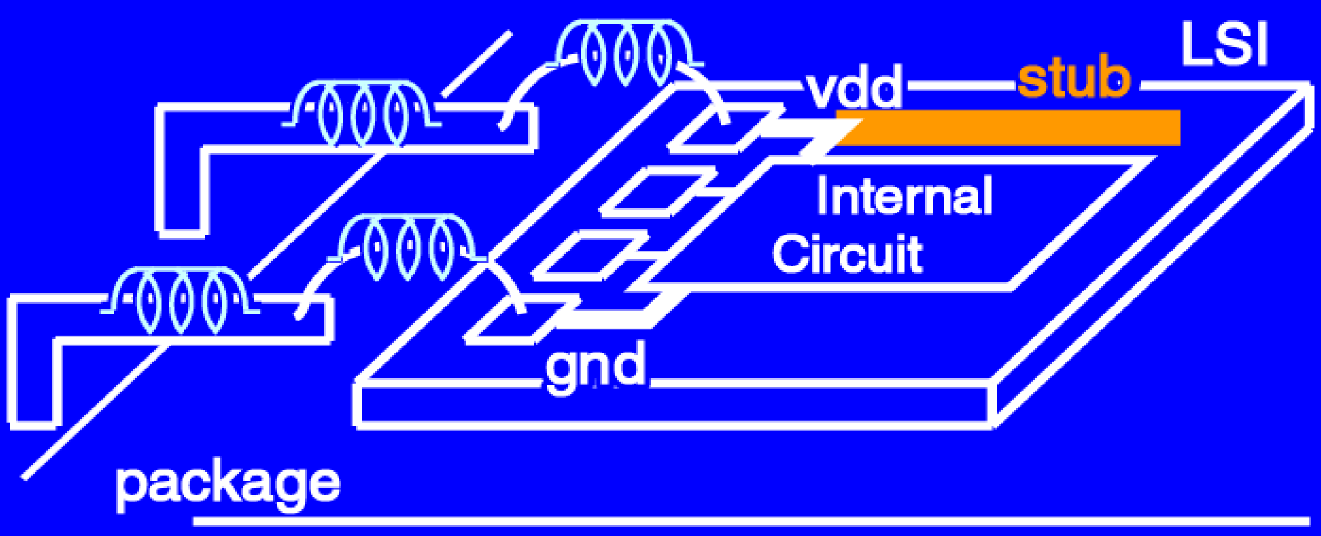
$$Zstub = Z0\frac{\cos\beta l}{j\sin\beta l}$$

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

$$Zstub = 0$$

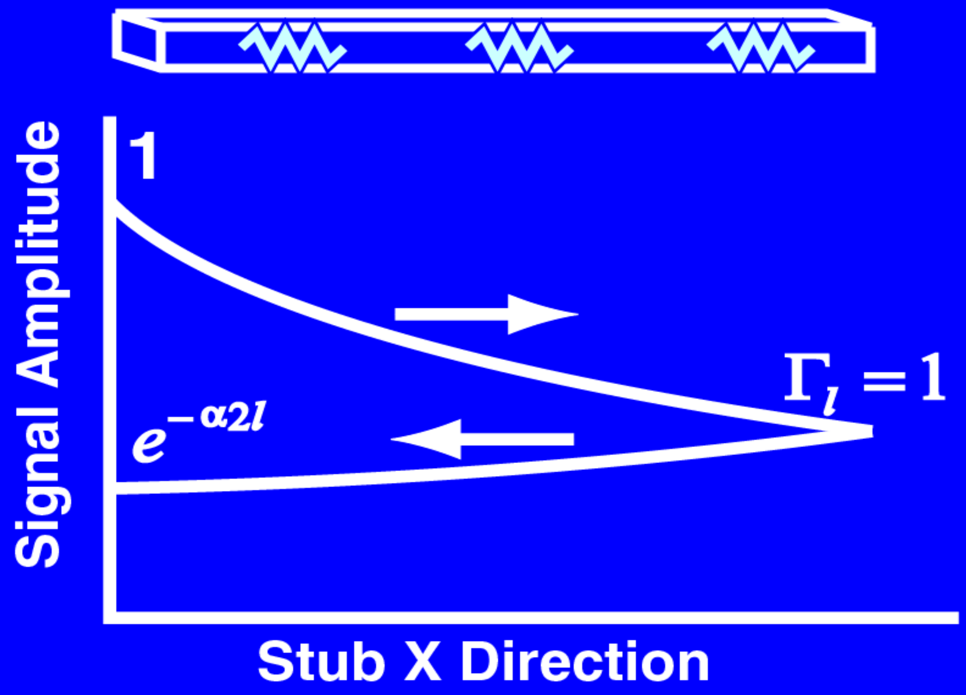
Power Line Noise Reduction

- Zstub = 0 → Equivalent to C=infty
- Attach the stub to the power line will reduce the power supply noise



Stub Resistance

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

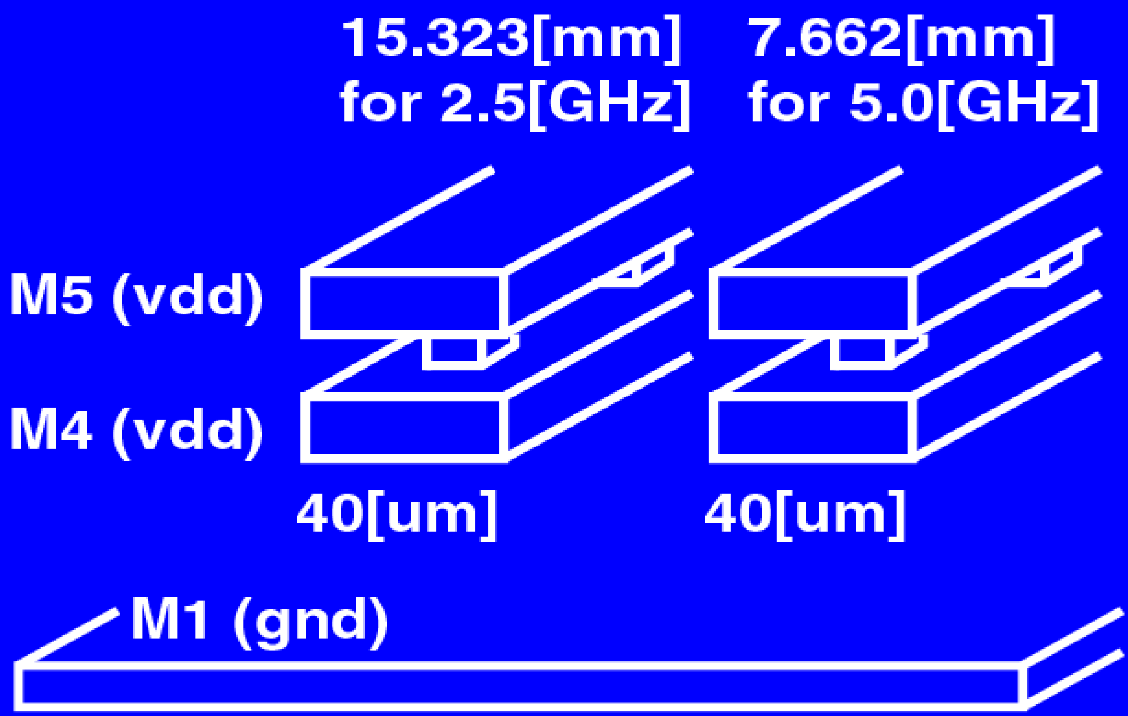


Stub Design

- **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 de-coupling capacitor***

Stub Structure

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



Parameters of our Stub

- R= 500Ω/m, L=102nH/m, C=407pF/m, G=0

  |Z0|=16.22Ω, arg(Z)=-8.6deg, α=-15.6/m

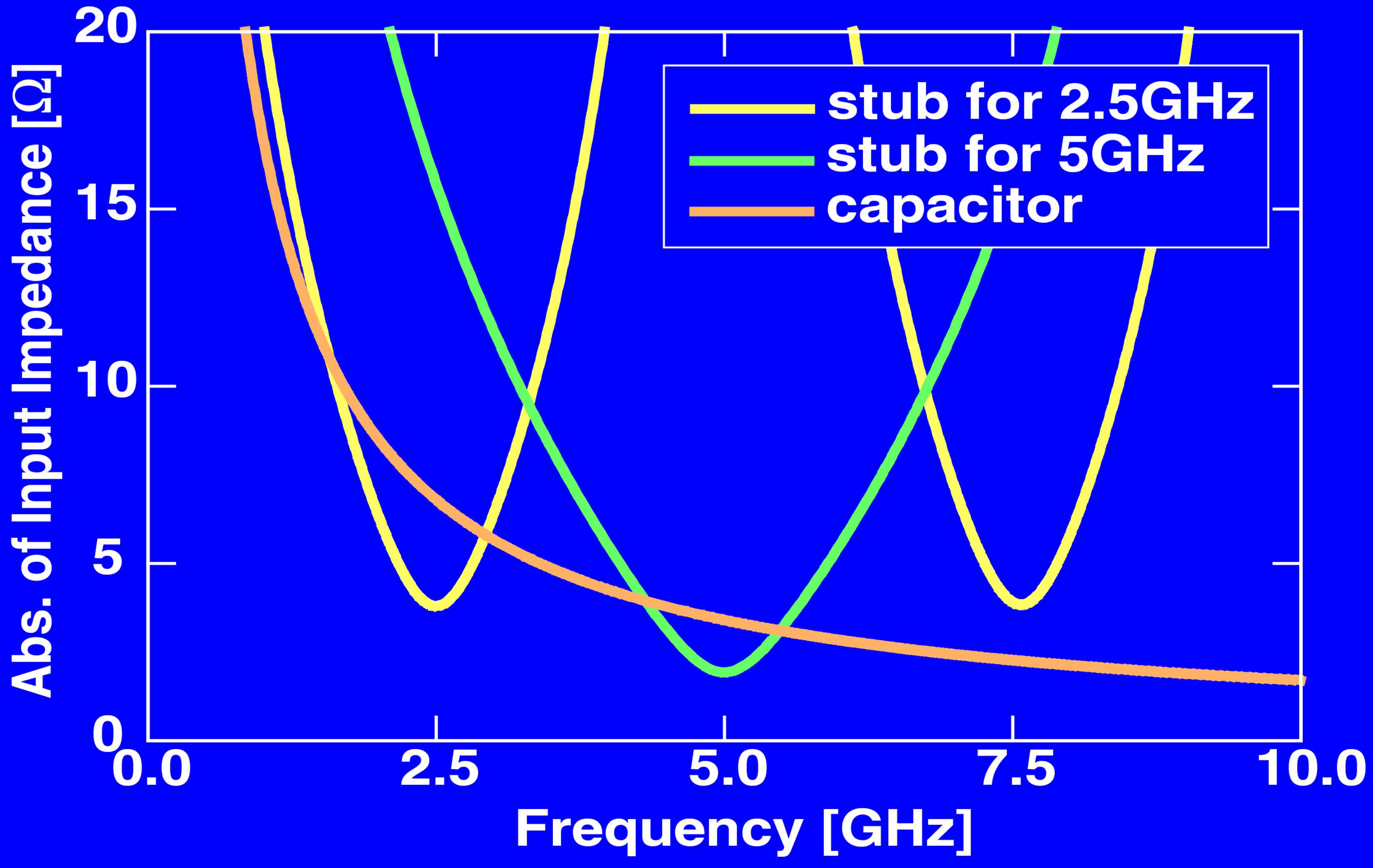
- For 2.5GHz stub:

  L=15.323mm, η=0.62, |Zstub|=3.8Ω,
- For 5.0GHz stub:

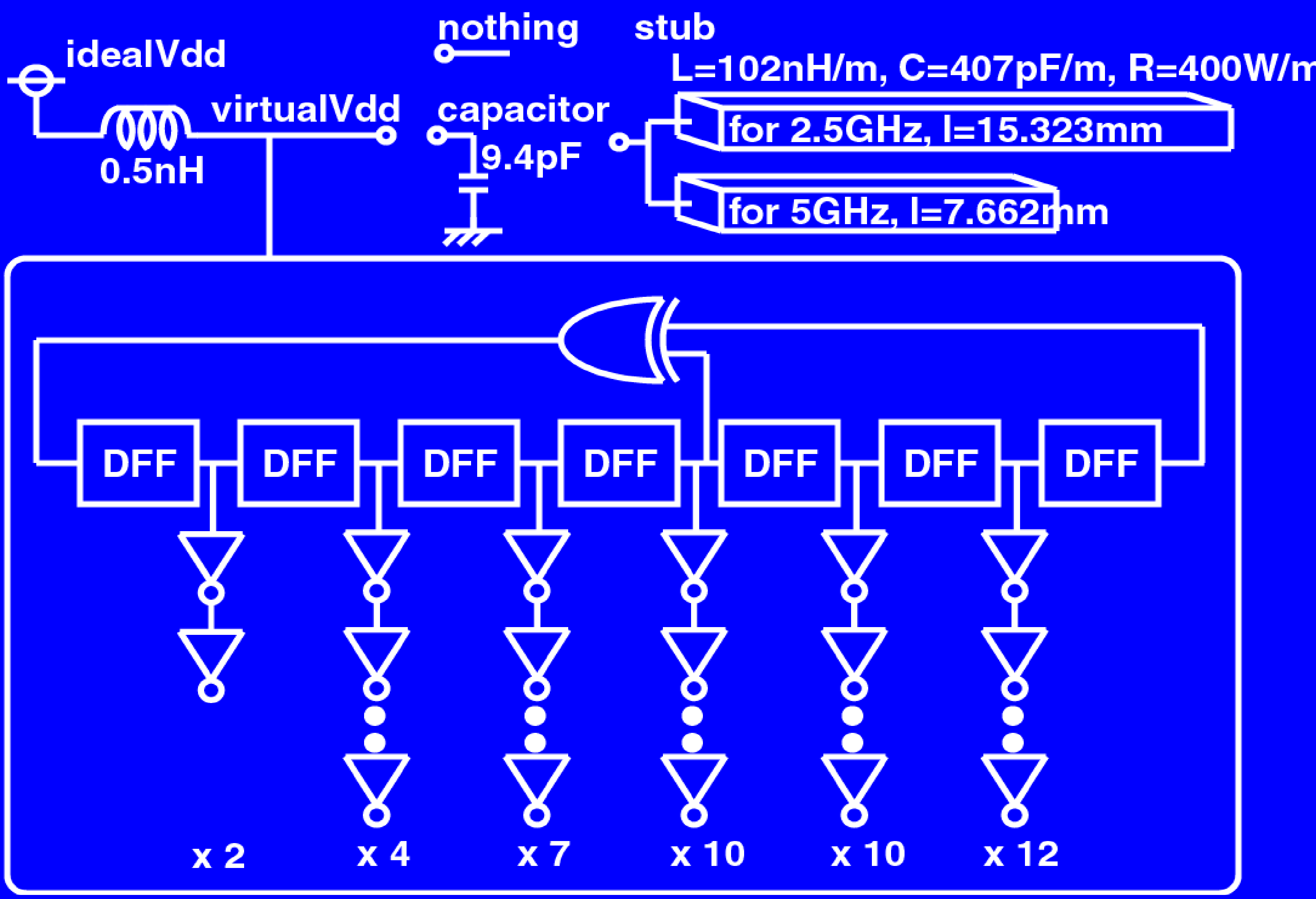
  L=7.662 mm, η=0.78, |Zstub|=1.9Ω,
- Cp = 407pF/m x (15.323+7.662mm)

  = 9.4pF (|Zp|=1/ωC=6.8Ω@2.5GHz)

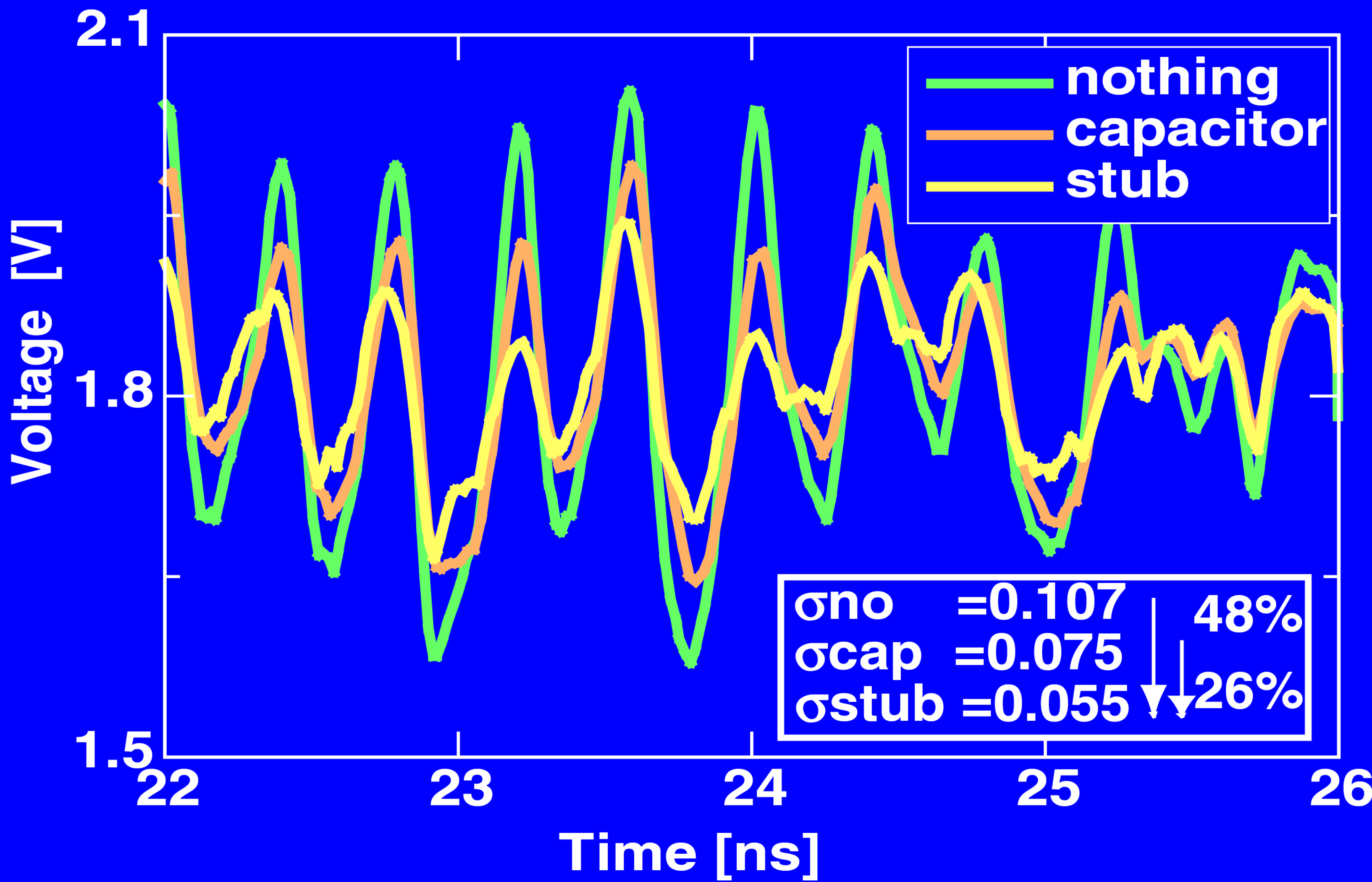
Stub Input Impedance vs. Freq



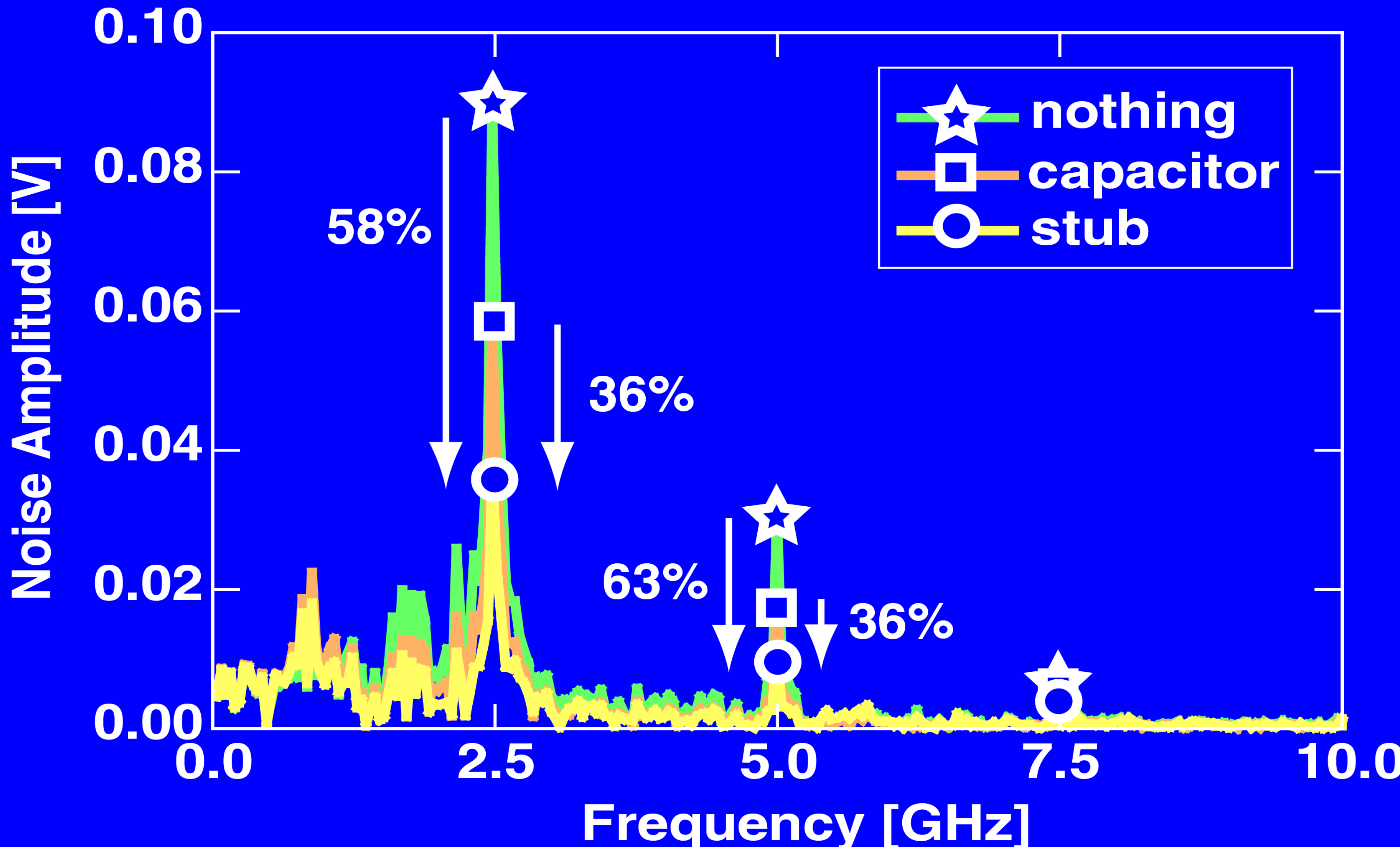
Test Circuit



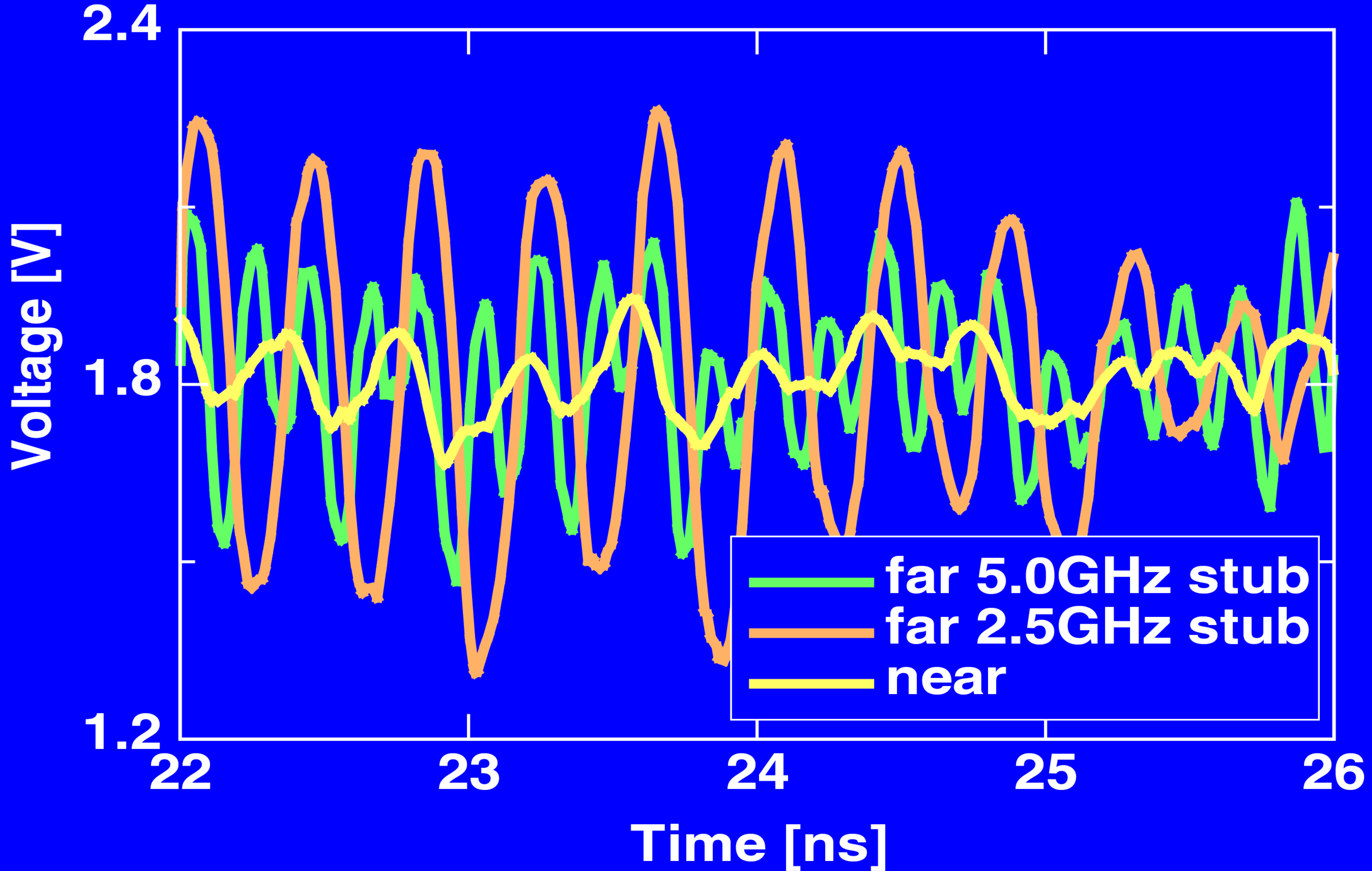
Power Line Noise Waveform



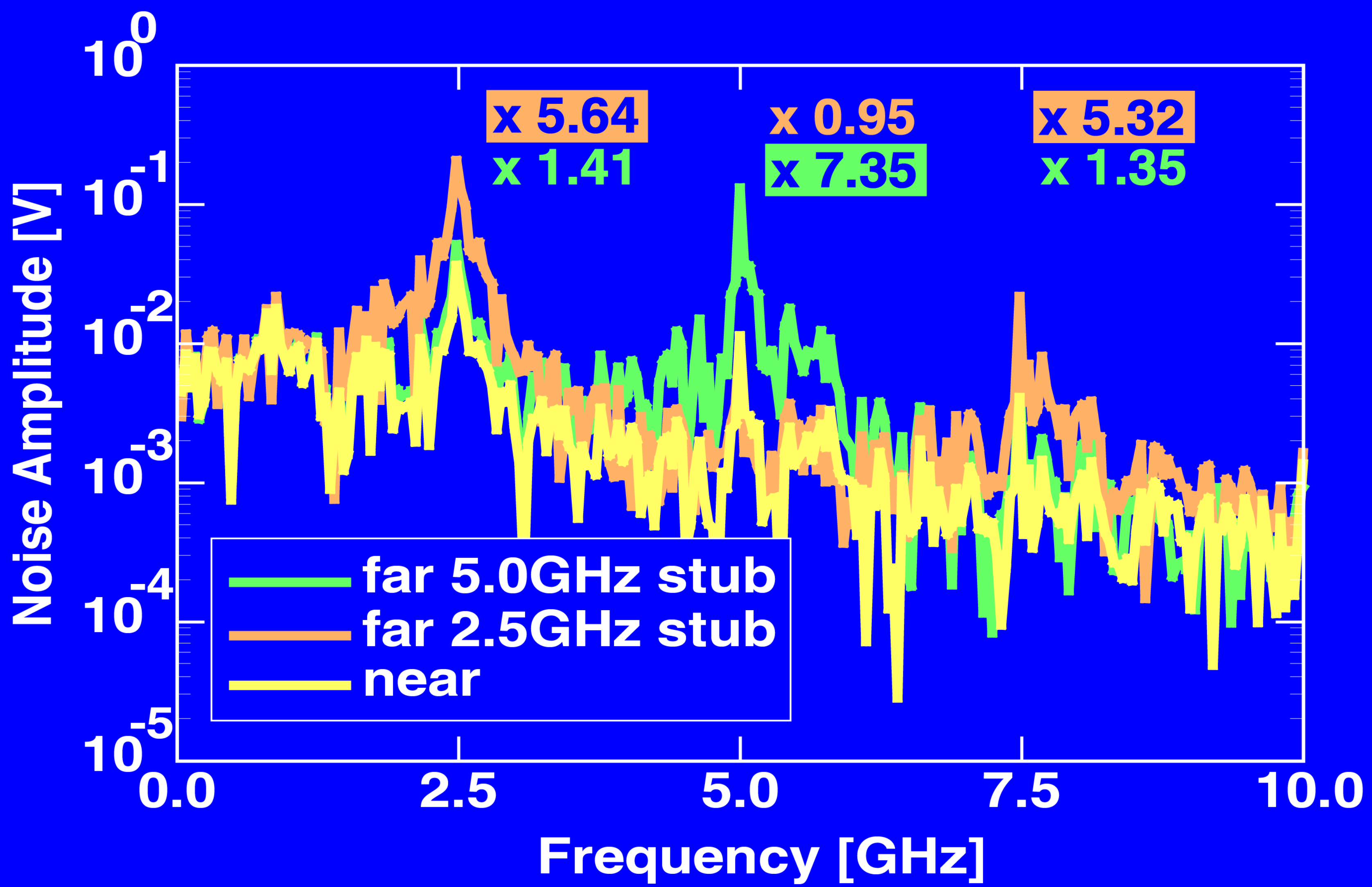
Power Line Noise Spectrum



Waveforms of Far End Terminal



Spectrum of Far End Terminal

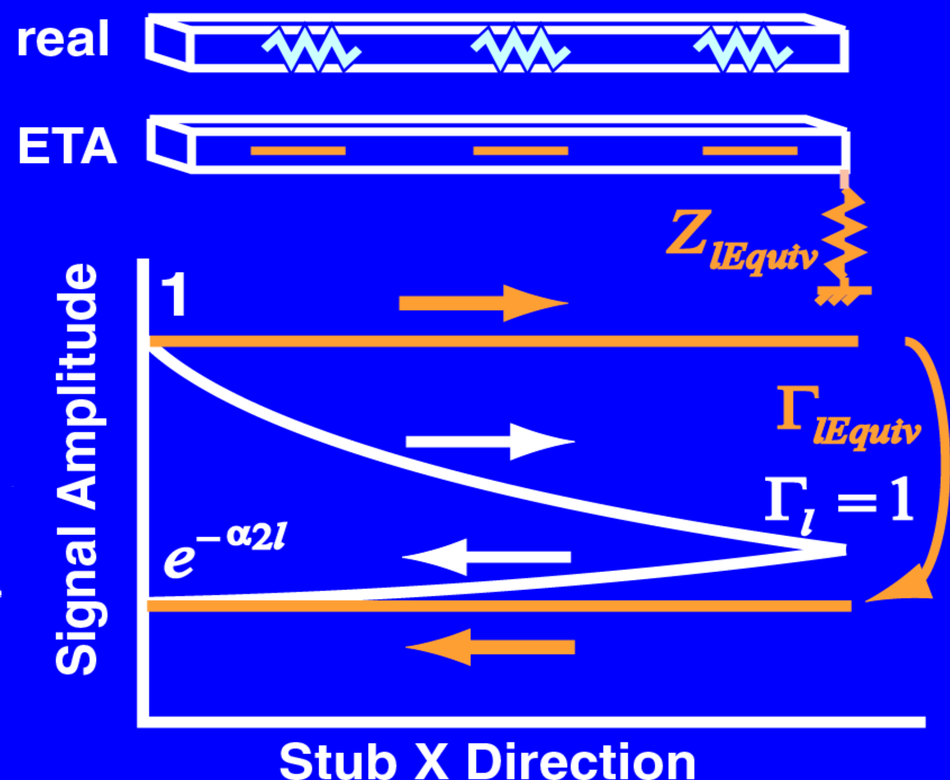


Equivalent Termination Approx.

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

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

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



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

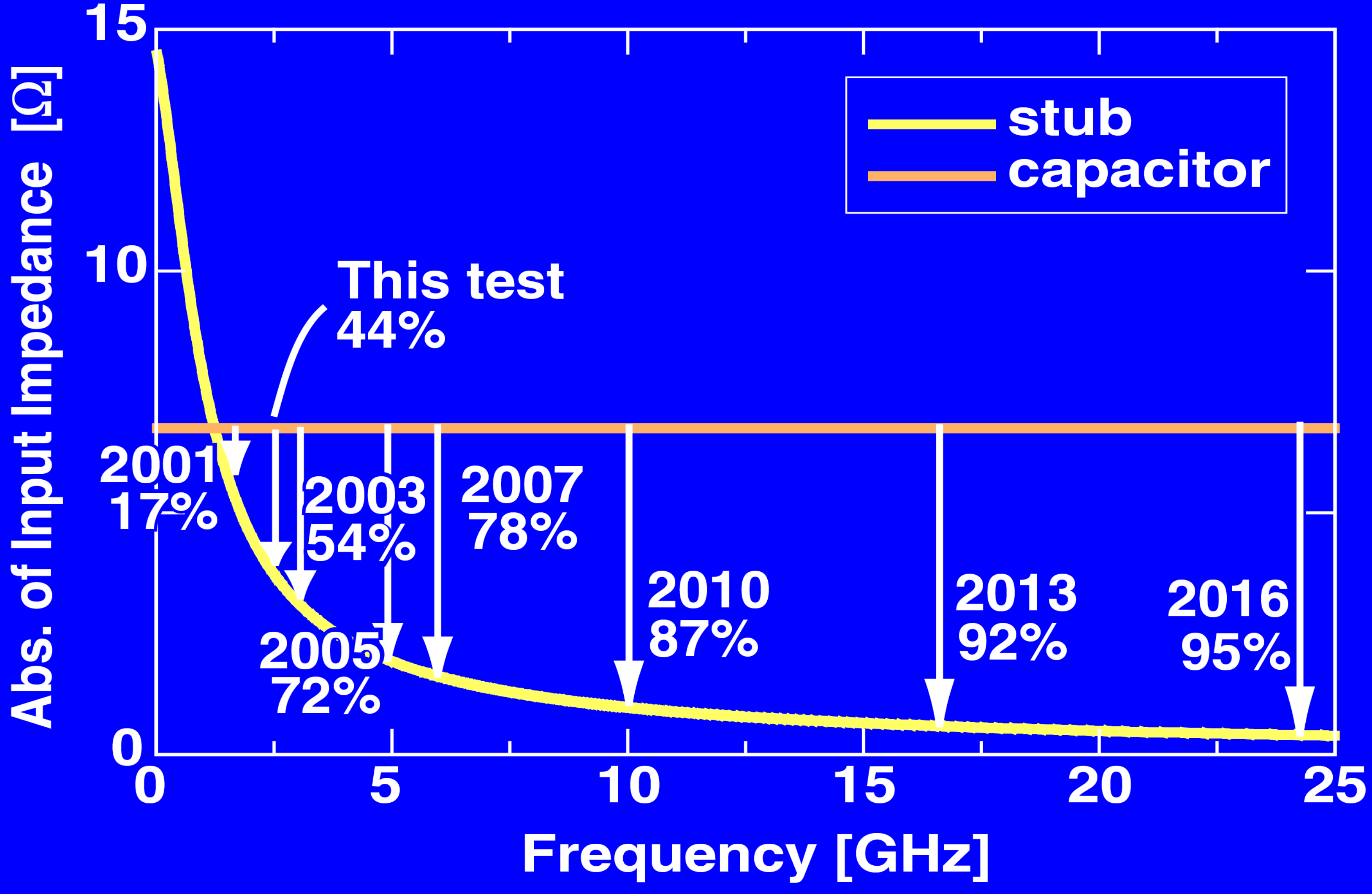
$$\frac{Vfar}{Vnear} = -j\frac{1+\eta}{1-\eta}$$

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

$$Z_{stub} = \begin{array}{c} \sqrt{\dfrac{R + j\omega L}{G + j\omega C}} \quad \text{(initial)} \\ \Big\downarrow \quad \tau = \dfrac{1}{-2f \log|\eta \Gamma_s|} \\ \dfrac{\cos\beta l}{j \sin\beta l} \approx \sqrt{\dfrac{L}{C}\dfrac{1-\eta}{1+\eta}} \quad \text{(steady)} \end{array}$$

Stubs in High Frequency Case



Conclusion

- The stub reduces 48% and 26% of the di/dt noise compared with nothing and de-coupling capacitor case, in our 1.8V 2.5GHz test circuit
- Analytical model of lossy transmission line stubs for power line noise reduction was investigated
- The stub can suppress the noise more efficiently in higher speed LSIs.

Q&A

ETA: Simulation Technique

- RLC ladder
  – Divide the stub into multiple sections
  x Un-realistic LC oscillation
  x More simulation time
- W element
  – If you have a recent version of HSPICE
- ETA with ideal transmission line
  – Require an ideal transmission line element
  o 13% faster simulation time
  x Error if the stub resistance become big

Parameters of our Stub (2)

- R=500W/m, L=102nH/m, C=407pF/m, G=0
- |Z0|=16.22Ω, arg(Z)=-8.6deg, α=-15.6/m
- For 2.5GHz stub: |Zstub|=3.8Ω

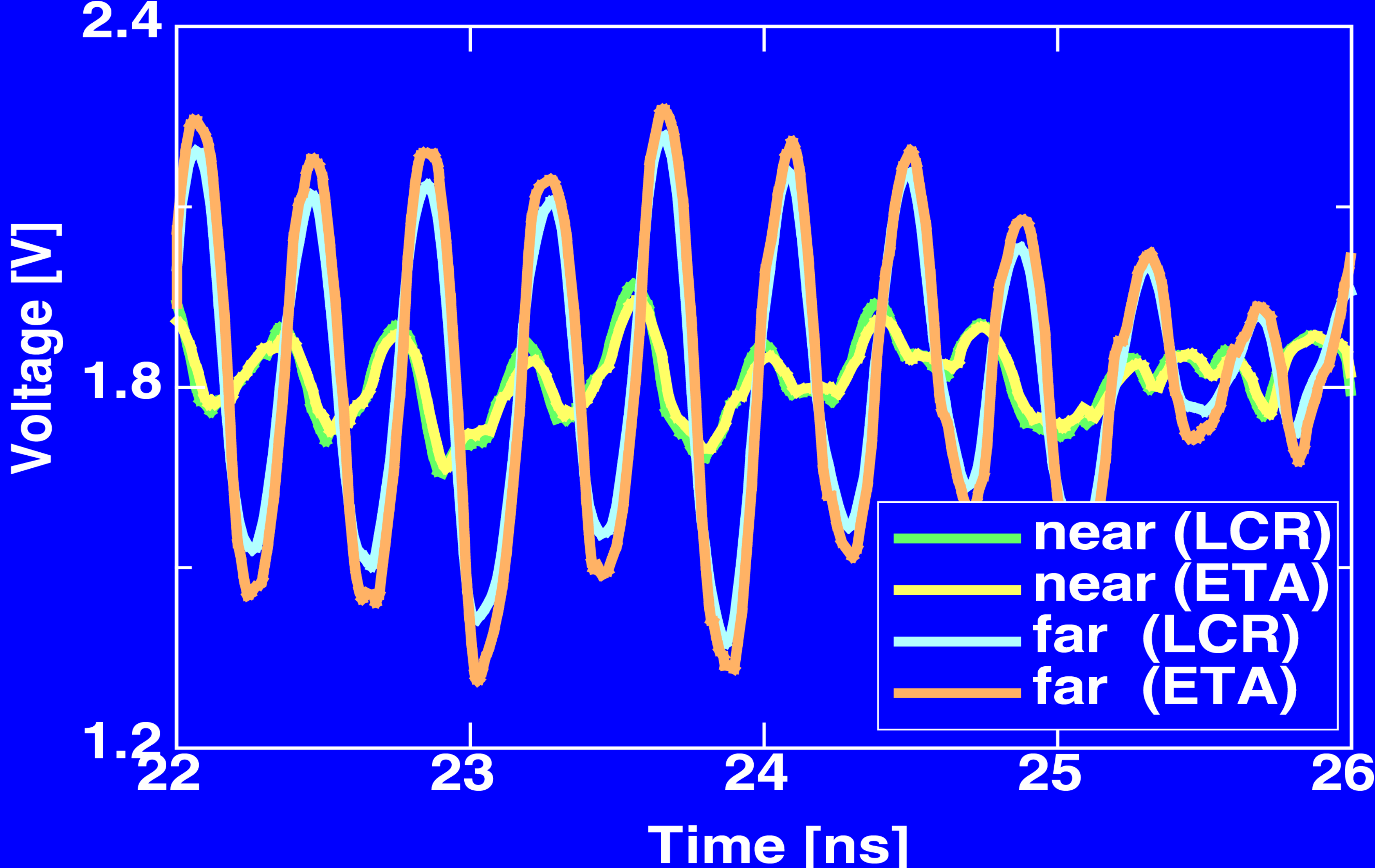
  L=15.323mm, η=0.62, Z_{lEquiv} = 67.6Ω

  Vfar/Vnear=-4.26j, τ =557ps
- For 5.0GHz stub: |Zstub|=1.9Ω

  L=7.662 mm, η=0.78, Z_{lEquiv} = 131.0Ω

  Vfar/Vnear=-8.27j, τ =603ps
- Cp = 9.4pF (|Zp|=1/ωC=6.8Ω)

Waveforms using LCR/ETA



ETA: Voltage at Near/Far End

- The voltage ratio of the near and far end terminal is expressed as:

$$\frac{V_{far}}{V_{near}} = -j\frac{1+\eta}{1-\eta}$$

  if ETA is used

- The ratio is 4.26, 8.27 for 2.5GHz, 5GHz stubs in our test case
  – The difference comes from non-nf_0 components

ETA: Time Constant

- At the initial state, stub input impedance is the same as the system impedance

$$Z_{stub} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \text{ (initial)} \longrightarrow \frac{\cos\beta l}{j \sin\beta l} \text{ (steady)}$$

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

- τ =557ps/603ps for 2.5GHz/5GHz stubs in our test case

Frequency Components

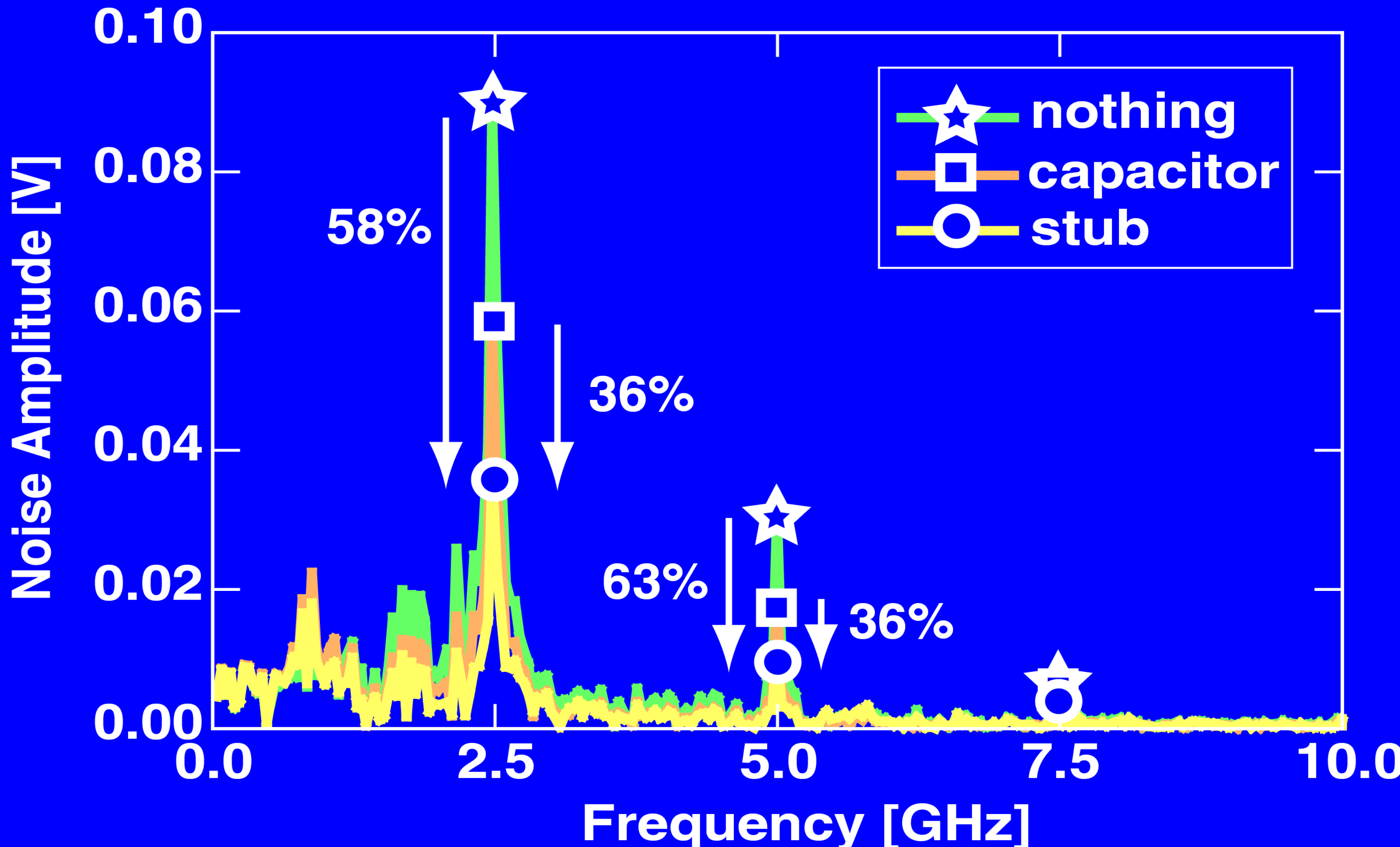
- Repeat the same signal at every clock

  → only *nf_0* component
- Random switching

  → non-*nf_0* component

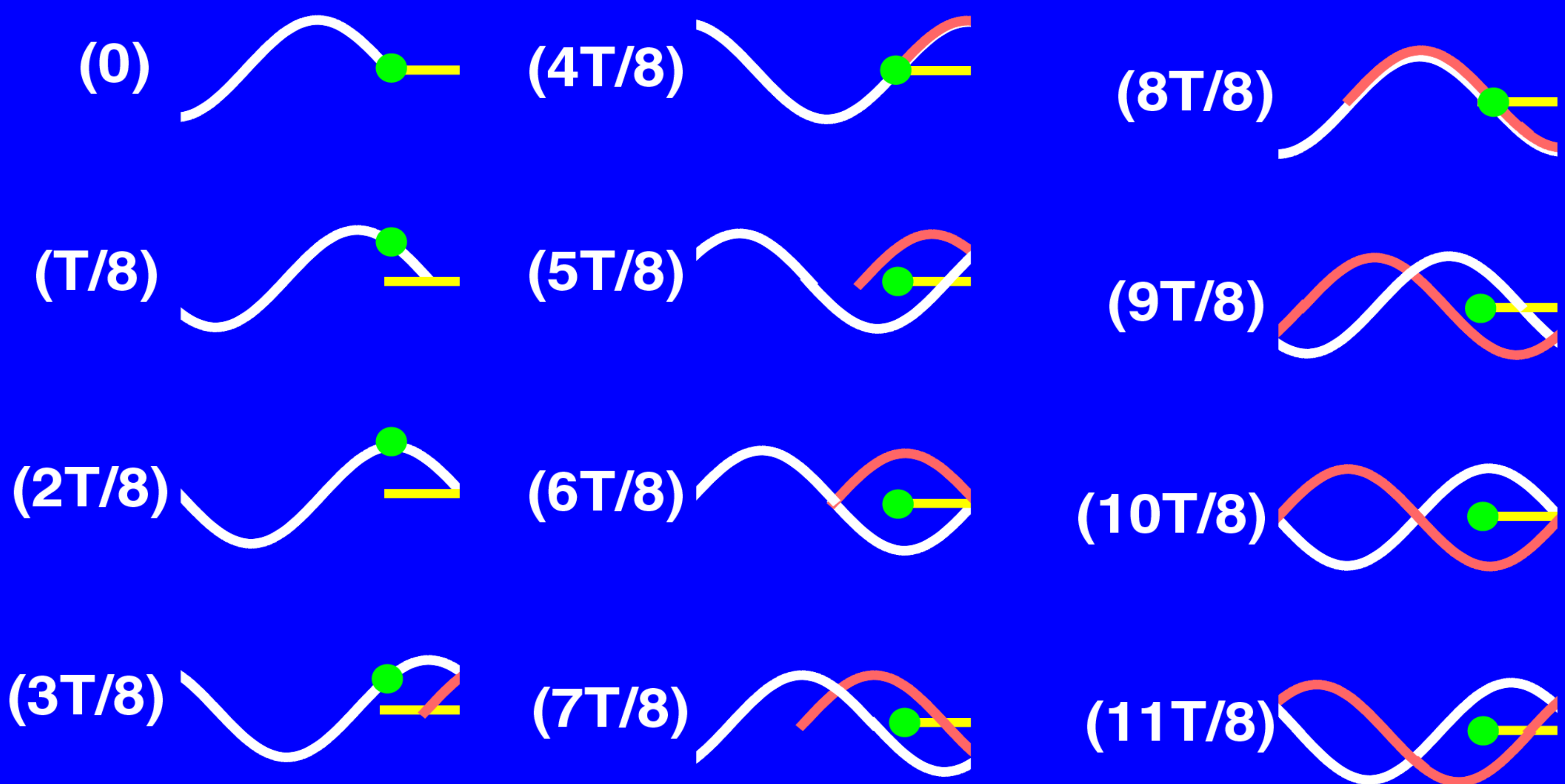
  but still, *nf_0* is the dominant

Power Line Noise Spectrum



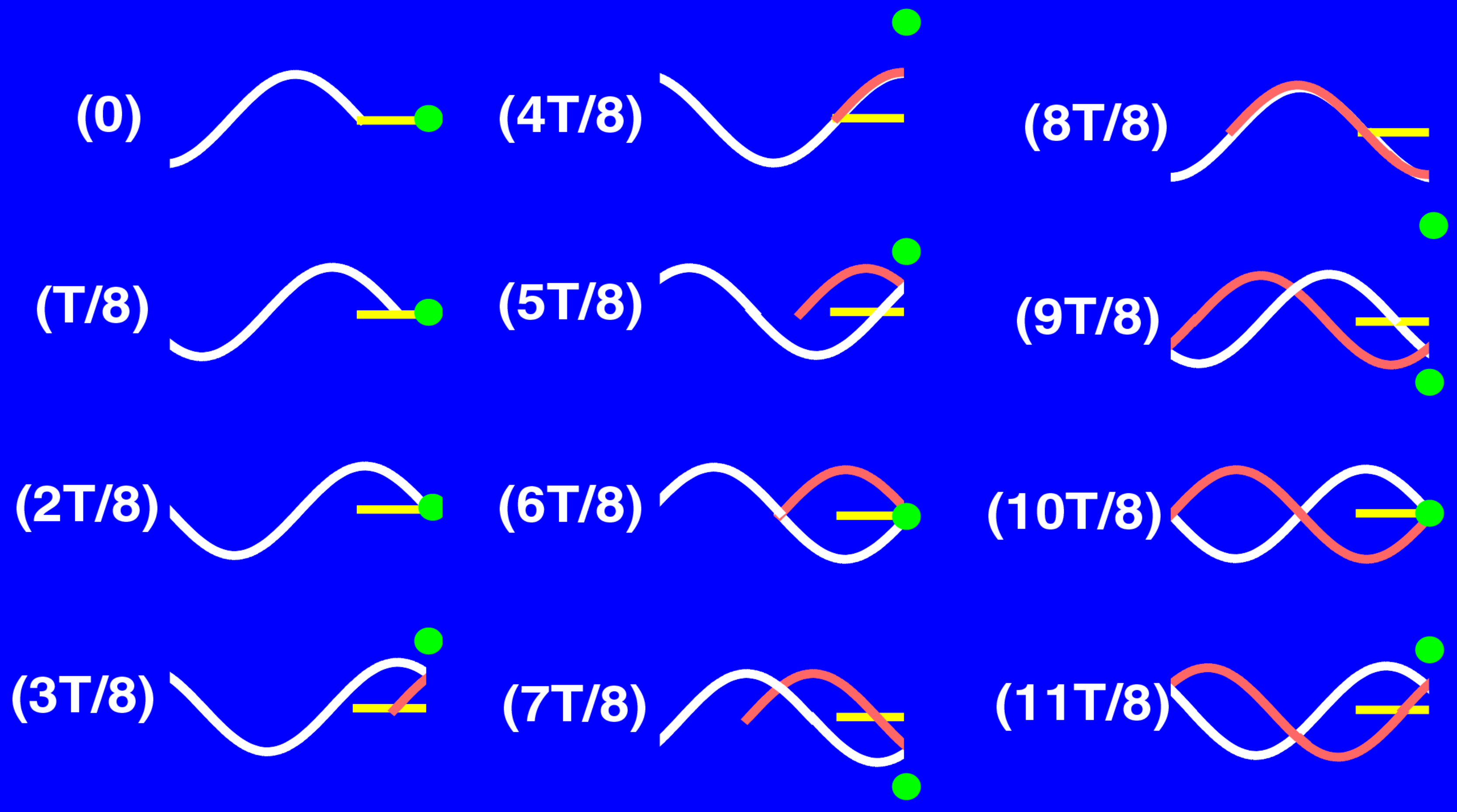
Waveform in the Ideal Stub

- The voltage of forward- and backward-going wave is canceled at the near end



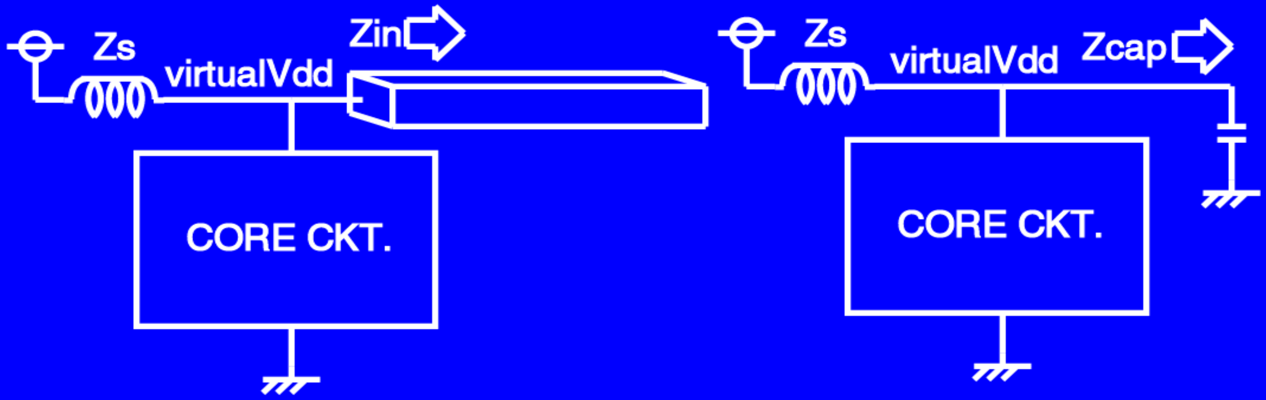
Voltage Swing at Far End

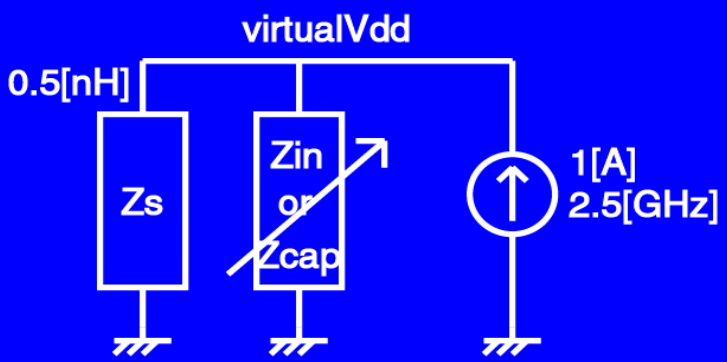
- The voltage swing at far end is bigger



Stub Optimization Step

- Sweep the stub width, calculate Zin and Zcap, probe the virtualVdd node





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)

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

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