Chapter 4

Coupled Microstrip Line

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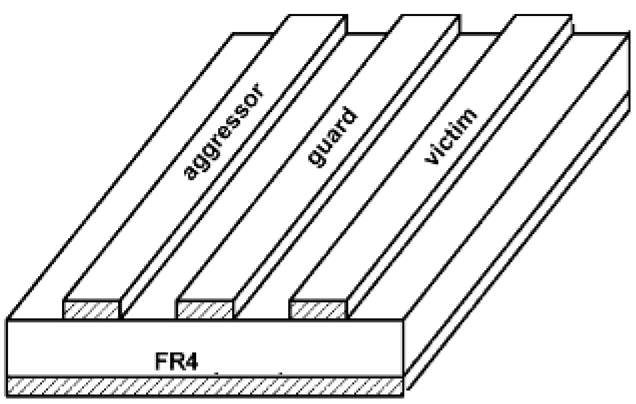
Outline

- Literature Examples
- Motivations
- Coupled Microstrip Line
- Coupled Microstrip Line Using Front-End Decoupling Capacitor
- Coupled Microstrip Line Using Distributed Decoupling Capacitors
- Conclusions

Literature Examples

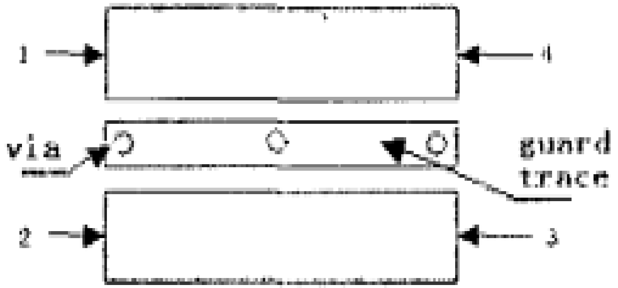
- Coupled Microstrip Line Using Guard Trace [1]
  - Advantages
    - Easy Implementation with the PCB process
  - Disadvantages
    - Slight reduction of the far-end crosstalk noise



[1] D. Brooks, *Signal Integrity Issues and Printed Circuit Board Design*. New York: Prentice Hall, pp. 233–234, 2003.

Literature Examples

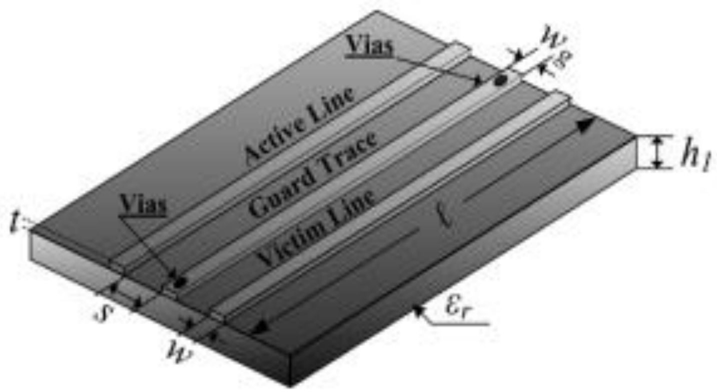
- Coupled Microstrip Line Using Grounded Guard Trace [2]
  - Advantages
    - Efficient reduction of the far-end crosstalk noise
  - Disadvantages
    - Layout areas are limited due to via placement



[2] L. Zhi, W. Qiang, and S. Changsheng, "Application of guard traces with vias in the rf pcb layout," in *Proc. IEEE 3rd International Symposium on Electromagnetic Compatibility*, pp. 771-774, May, 2002.

Literature Examples

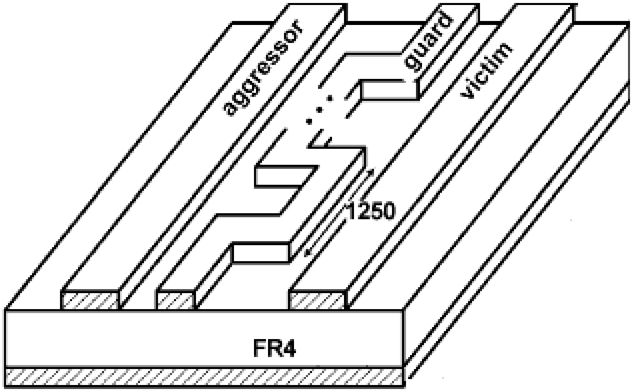
- Coupled Microstrip Line Using Grounded Guard Trace and Dielectric Overlay [3]
  - Advantages
    - Efficient reduction of far-end crosstalk noise with only two vias
  - Disadvantages
    - Additional cost of the dielectric overlay



[3] Y. S. Cheng, W. D. Guo, C. P. Hung, R. B. Wu, and D. D. Zutter, "Enhanced microstrip guard trace for ringing noise suppression using a dielectric superstrate, " *IEEE Trans. Adv. Packag*., vol. 33, no. 4, pp. 961–968, Nov. 2010.

Literature Examples

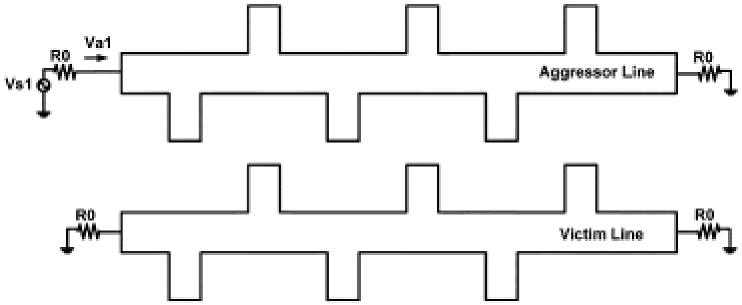
- Coupled Microstrip Line Using Serpentine Guard Trace [4]
  - Advantages
    - Efficient reduction of far-end crosstalk noise without using any vias and dielectric overlay
  - Disadvantages
    - Large area are needed for the serpentine guard trace



[4] K. Lee, H. B. Lee, H. K. Jung, J. Y. Sim, and H. J. Park, "A serpentine guard trace to reduce the far-end crosstalk voltage and the crosstalk induced timing jitter of parallel microstrip lines," *IEEE Trans. Adv. Packag.*, vol. 31, no. 4, pp. 809–817, Nov. 2008.

Literature Examples

- Coupled Microstrip Line Using Alternately Open-Circuited Stubs [5]
  - Advantages
    - Efficient reduction of the areas spent by the serpentine guard trace
  - Disadvantages
    - Large reflection



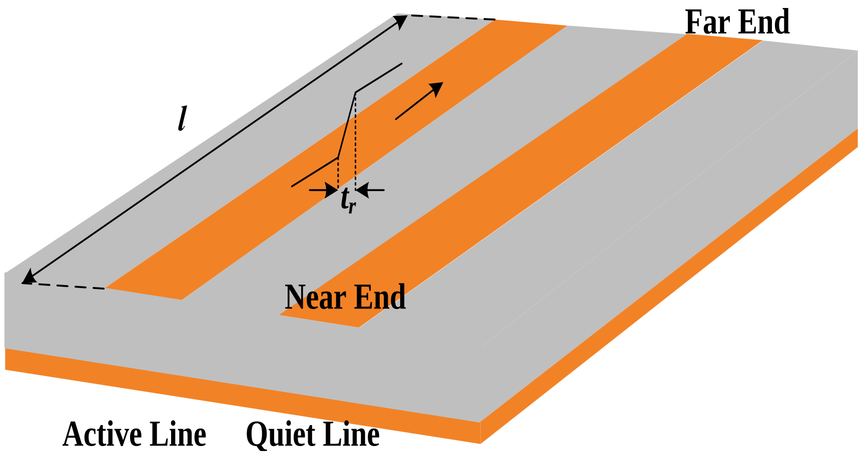
[5] S. K. Lee, K. Lee, H. J. Park, and J. Y. Sim, “FEXT-eliminated stub-alternated microstrip line formulti-gigabit/second parallel links,” *Electron. Lett.*, vol. 44, no. 4, pp.272–273, Feb. 2008.

Motivations

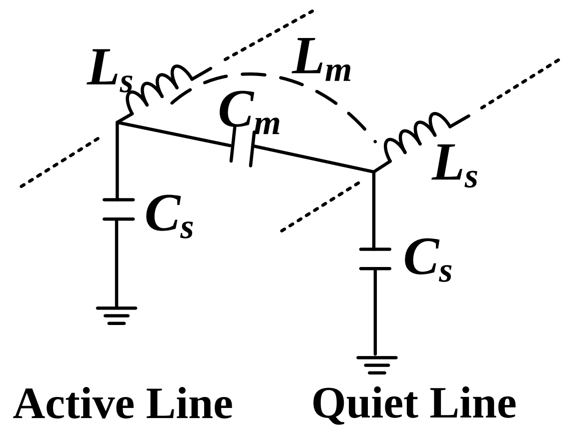
- To Save the Cost
  - Elimination of the Need of Dielectric Overlay
- To Increase the Routing Flexibility
  - Elimination of the Need of Vias
- To Save the Area
  - Elimination of the Need of Serpentine Guard Trace
- To Reduce the Reflection
  - Elimination of the Need of Alternately Open-Circuited Stubs

Coupled Microstrip Line

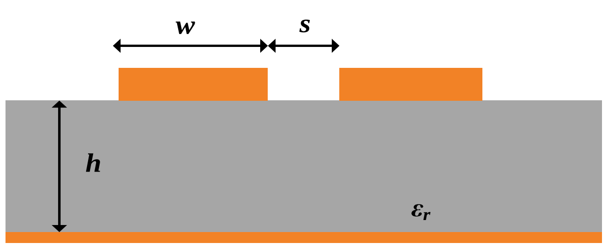
- Topology
  - FR4 Substrate with εr=4.4 and tanδ=0.02



3-D view



Equivalent circuit



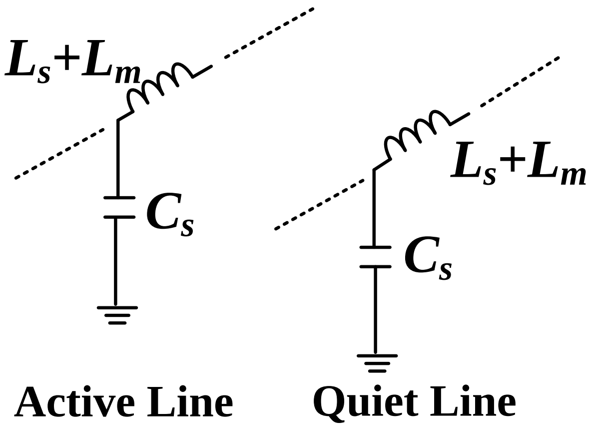
Cross-sectional view

w (mm)	s (mm)	h (mm)	l (mm)
1.42	0.7	0.8	40

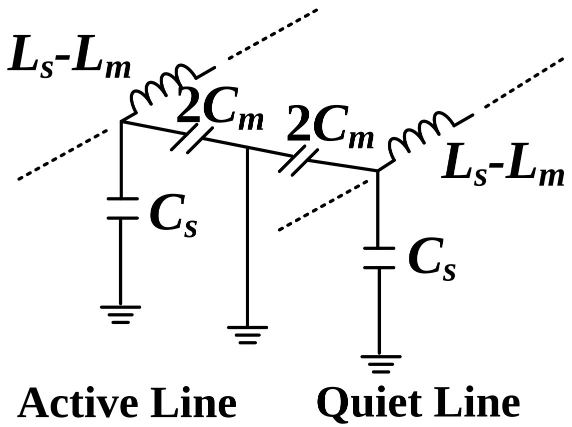
Dimensions

Coupled Microstrip Line

- Even- and Odd-Mode Equivalent Circuits



Even-mode equivalent circuit



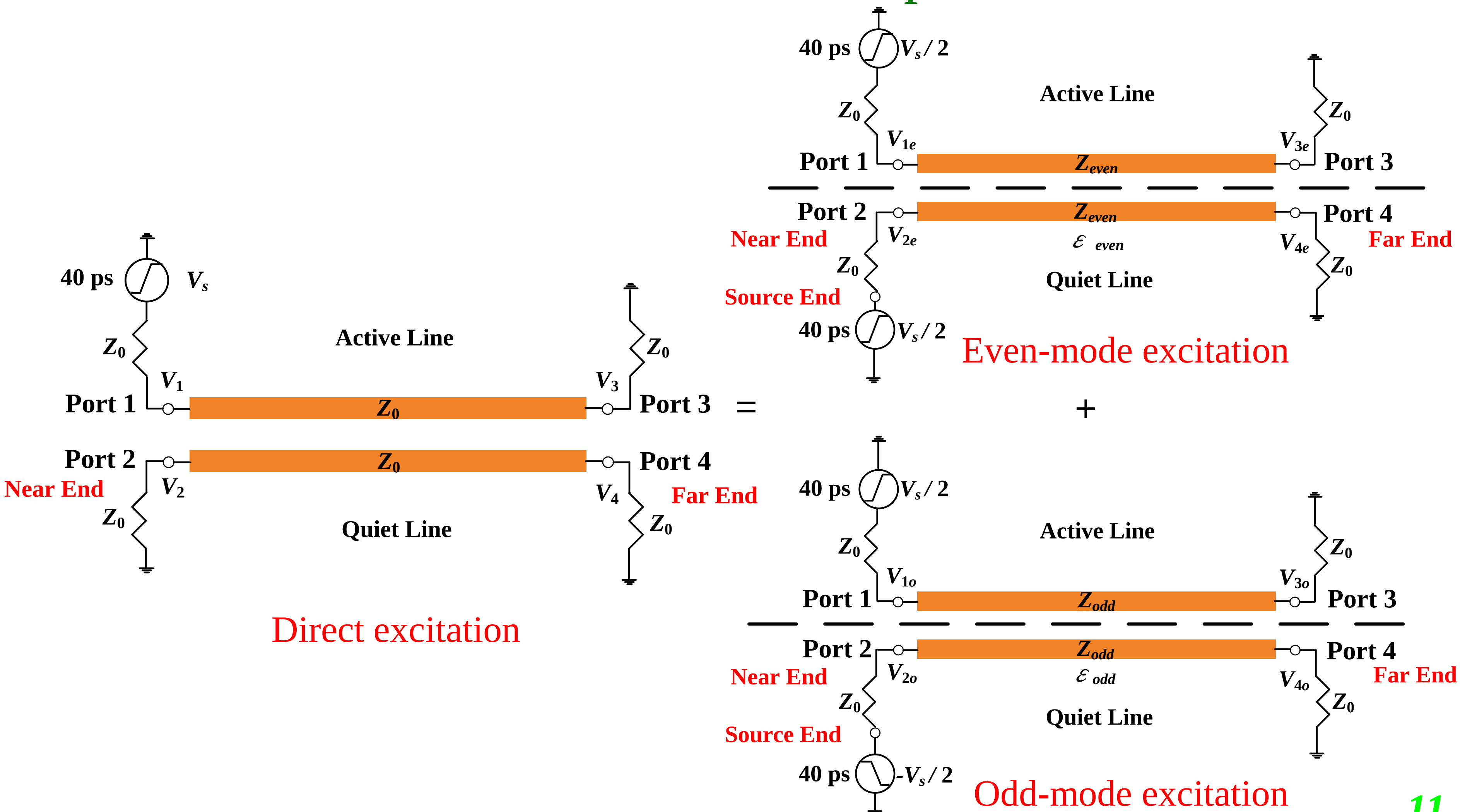
Odd-mode equivalent circuit

$$TD_{even} = l\sqrt{(L_s + L_m)(C_s)}$$

$$TD_{odd} = l\sqrt{(L_s - L_m)(C_s + 2C_m)}$$

Coupled Microstrip Line

- FEXT and NEXT
  - Even-and Odd-mode Decomposition

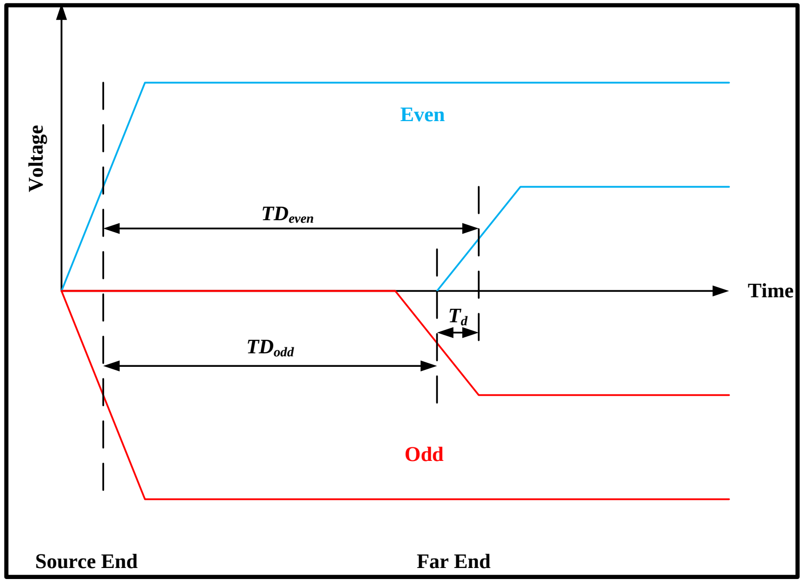


Coupled Microstrip Line

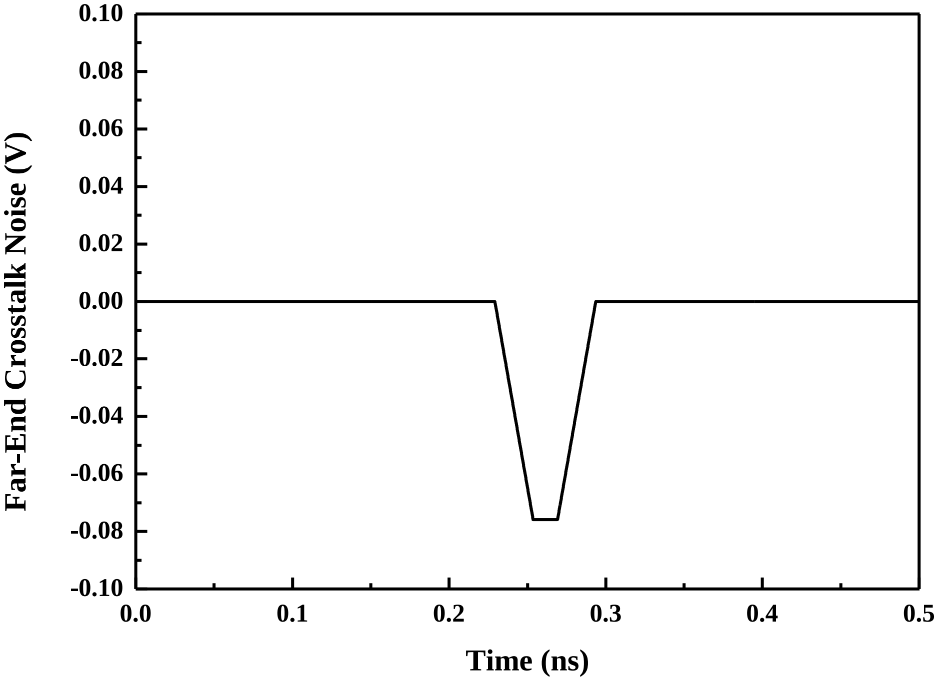
- FEXT and NEXT
  - Ideal Coupled Line

TD_{even} (ps)	TD_{odd} (ps)	T_d (ps)
253.614	229.202	24.412

Far-end crosstalk noise (volt)	0.076



FEXT: $V_{4e}(t)$ and $V_{4o}(t)$

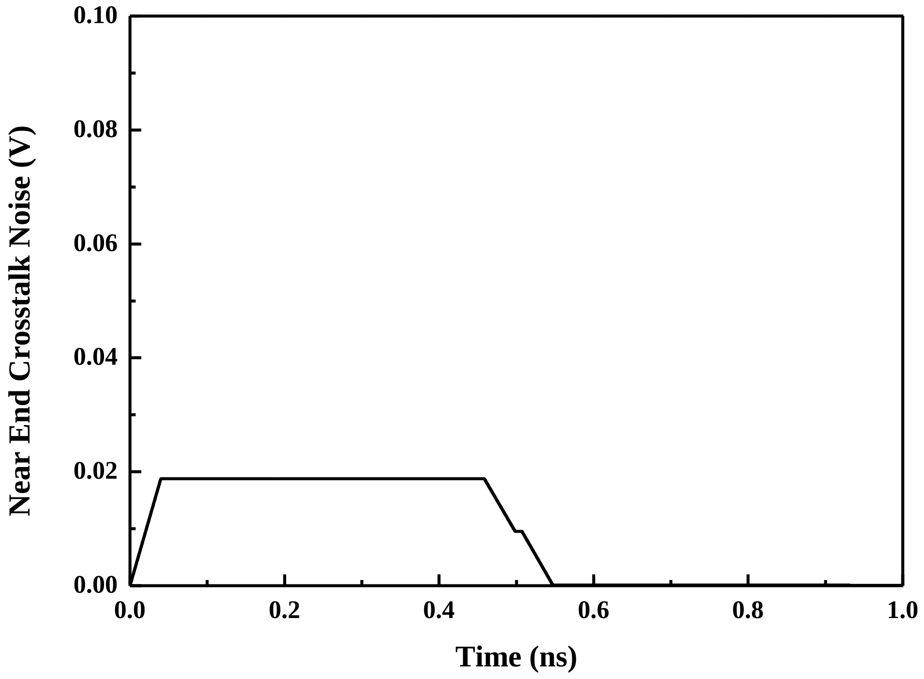


FEXT: $V_4(t)$

Coupled Microstrip Line

- FEXT and NEXT
  - Ideal Coupled Line

Near-end crosstalk noise (volt)	0.019



NEXT: $V_2(t)$

Coupled Microstrip Line

- FEXT and NEXT
  - Estimation Equations
    - Peak of NEXT occurs at $t=t_r$

$$\boxed{V_2(t_r) = V_{2e}(t_r) + V_{2o}(t_r)}$$

$$V_{2e}(t_r) = \frac{V_s}{2}\left(\frac{Z_{even}}{Z_{even} + Z_0}\right)$$

$$V_{2o}(t_r) = -\frac{V_s}{2}\left(\frac{Z_{odd}}{Z_{odd} + Z_0}\right)$$

- Peak of FEXT occurs at $t=TD_{even}$

$$V_4(t) = V_{4o}(t) + V_{4e}(t)$$

$$\boxed{|V_4(TD_{even})| = V_{max}\min\left(\frac{T_d}{t_r}, 1\right)}$$

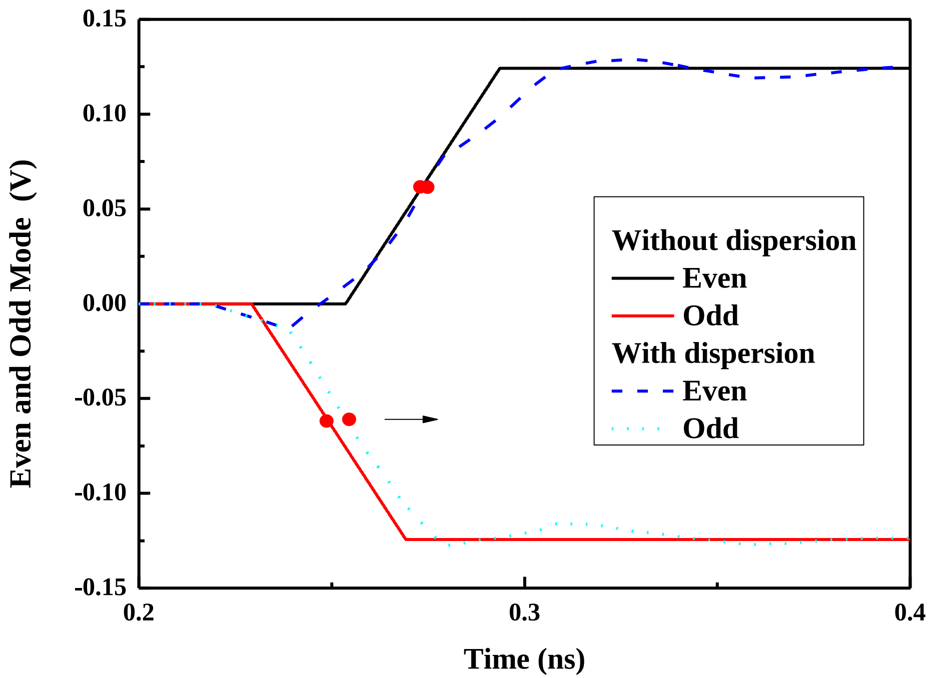
$$V_{max} = \frac{Z_0}{Z_{even} + 2Z_0 + Z_{odd}} V_s$$

Coupled Microstrip Line

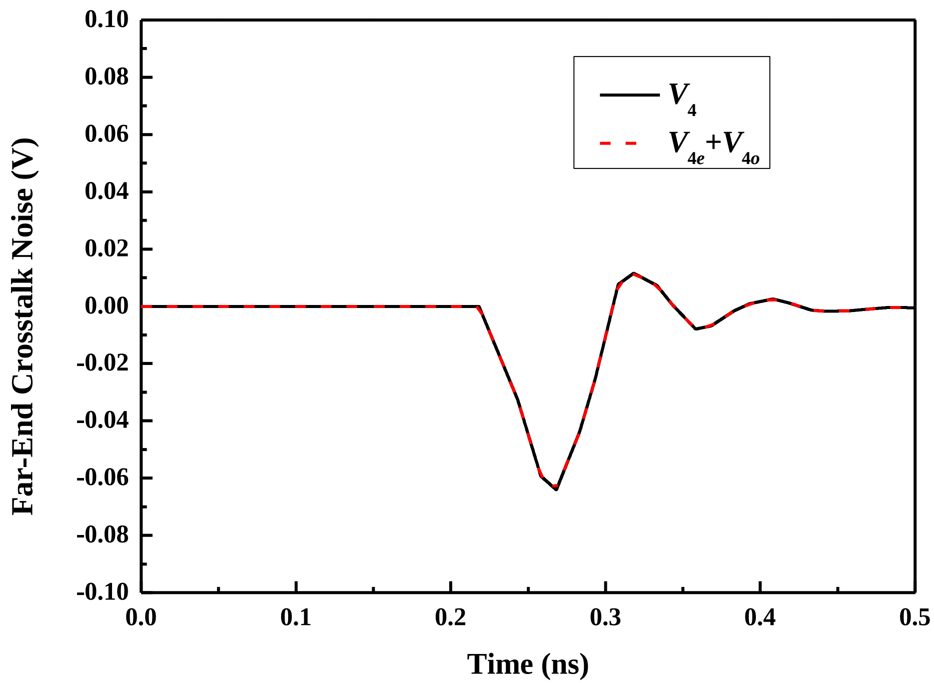
- FEXT and NEXT
  - Lossless Coupled Microstrip Line

TD_{even} (ps)	TD_{odd} (ps)	T_d (ps)
254.414	234.002	20.412

Far-end crosstalk noise (volt)	0.0641



FEXT: $V_{4e}(t)$ and $V_{4o}(t)$

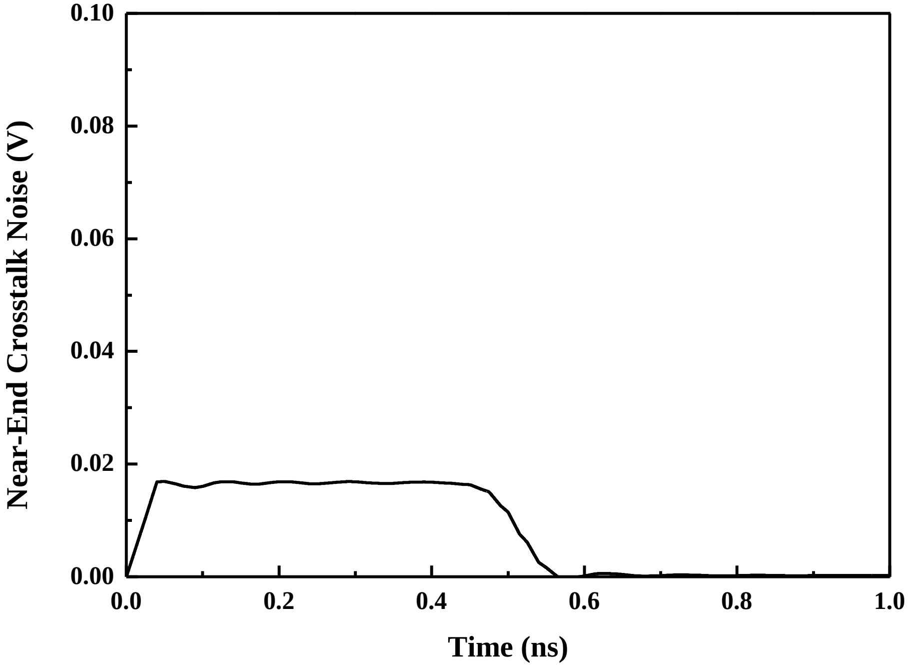


FEXT: $V_4(t)$

Coupled Microstrip Line

- FEXT and NEXT
  - Lossless Coupled Microstrip Line

Near-end crosstalk noise (volt)	0.0169



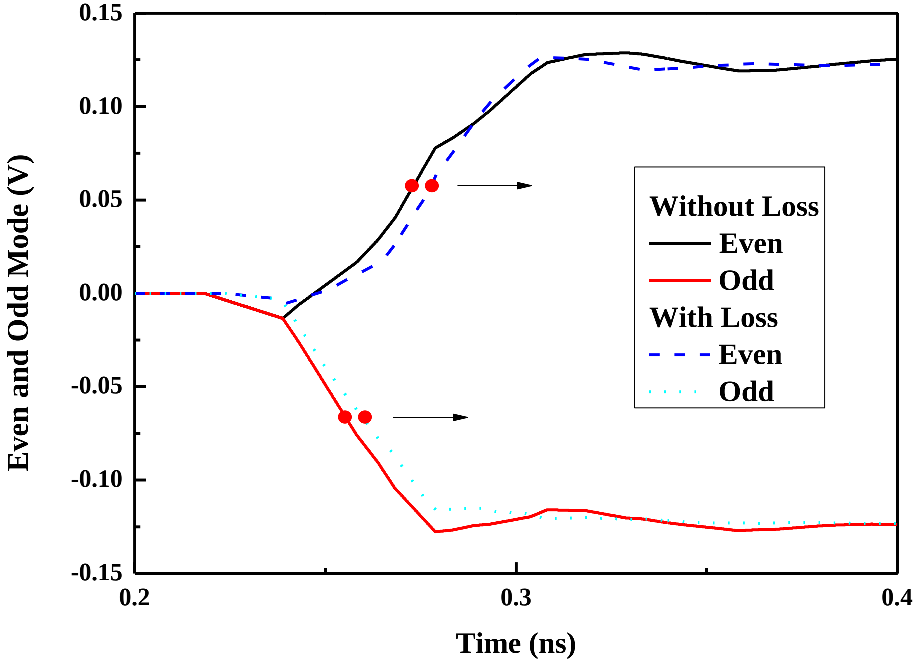
NEXT: $V_2(t)$

Coupled Microstrip Line

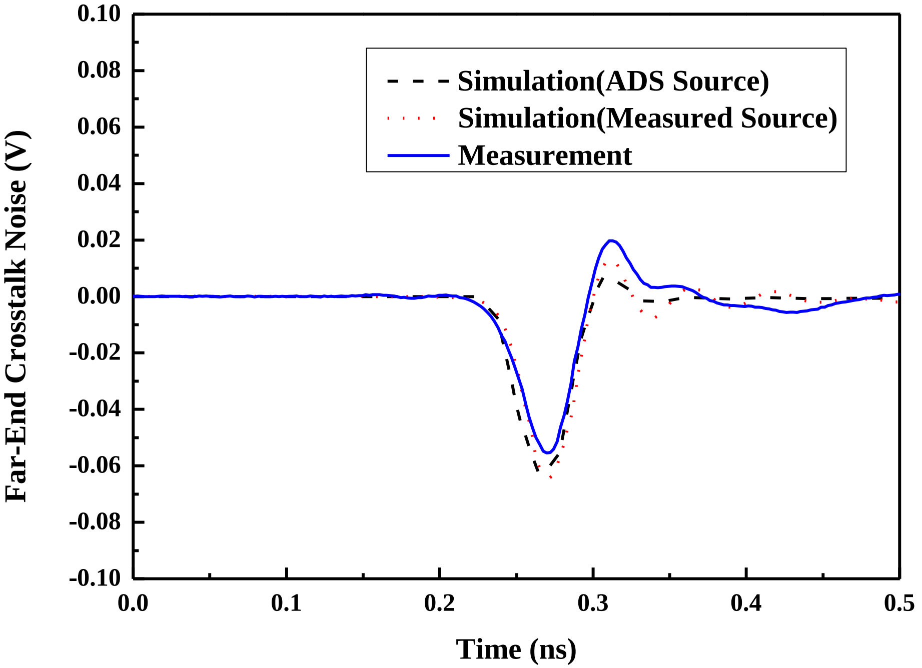
- FEXT and NEXT
  - Lossy Coupled Microstrip Line

TD_{even} (ps)	TD_{odd} (ps)	T_d (ps)
258.814	238.202	20.612

Far-end crosstalk noise (volt)	Simulation	0.063
	Measurement	0.055



FEXT: $V_{4e}(t)$ and $V_{4o}(t)$

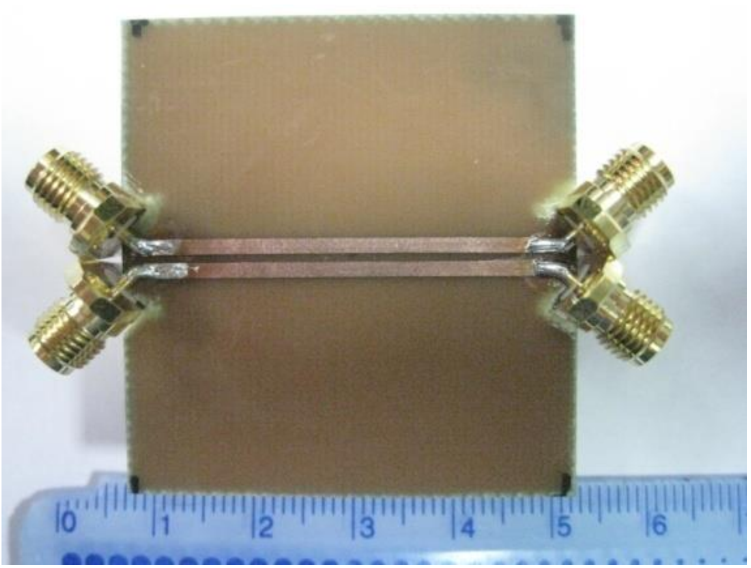


FEXT: $V_4(t)$

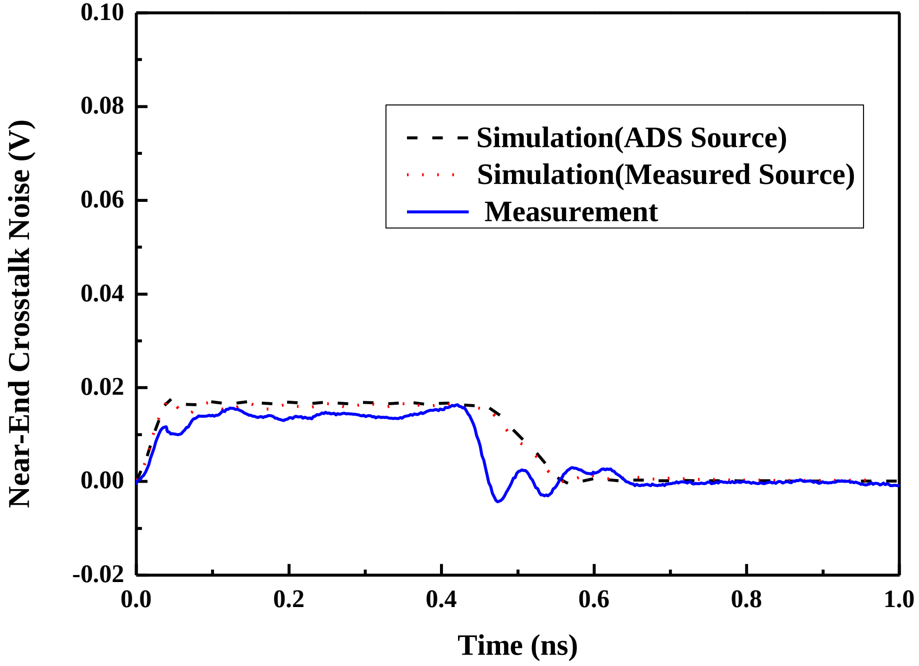
Coupled Microstrip Line

- FEXT and NEXT
  - Lossy Coupled Microstrip Line

Near-end crosstalk noise (volt)	Simulation	0.0180
	Measurement	0.0163



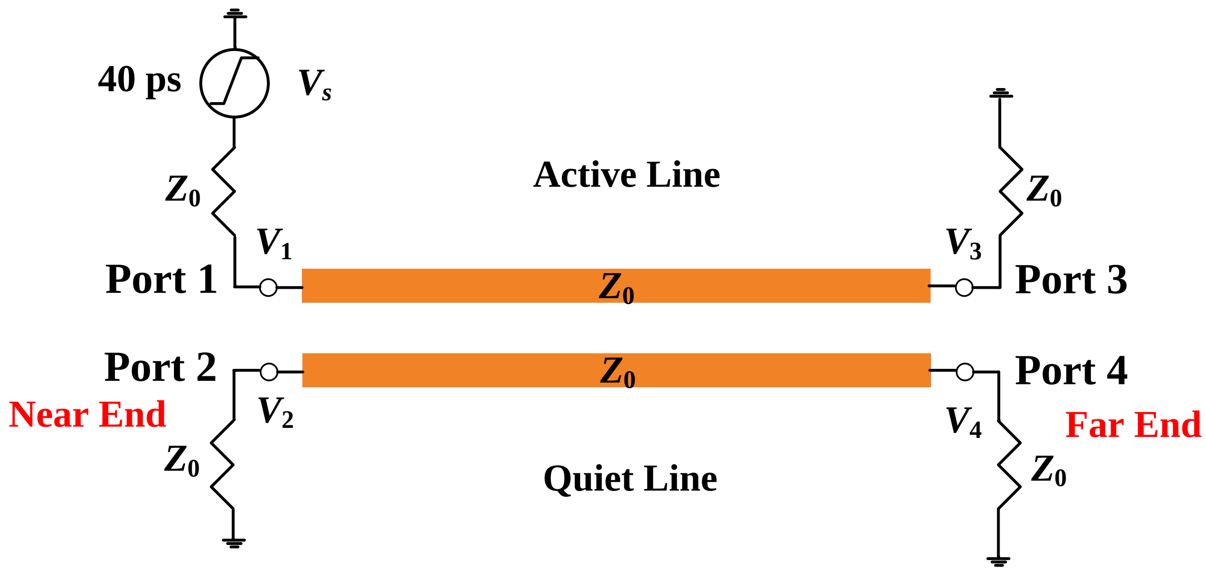
Real circuit



NEXT: $V_2(t)$

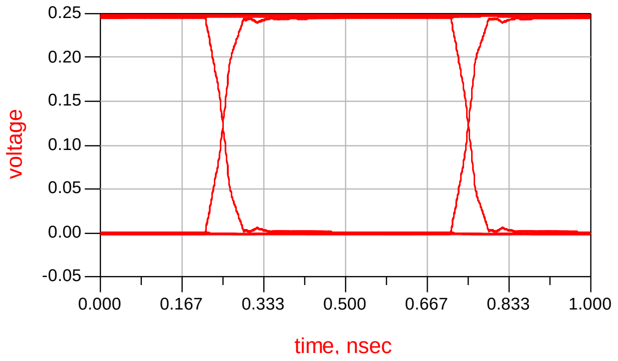
Coupled Microstrip Line

- Eye Diagram
  - Simulation Setup
    - Source V_S: pseudo random bit sequence (PRBS)
    - Observation V_3

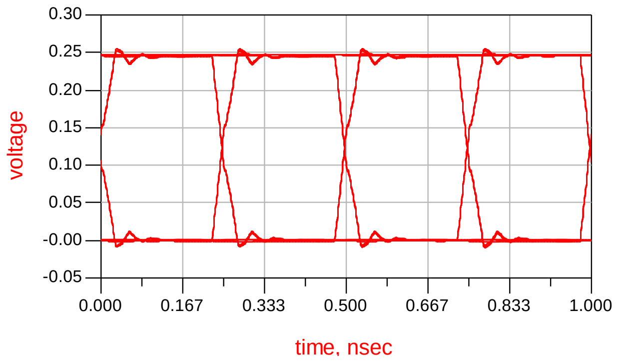


Coupled Microstrip Line

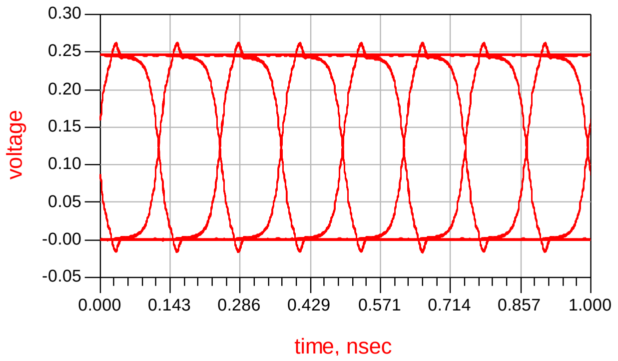
- Eye Diagram
  - Using Various Bit Rate and Rise Time (BR/10)



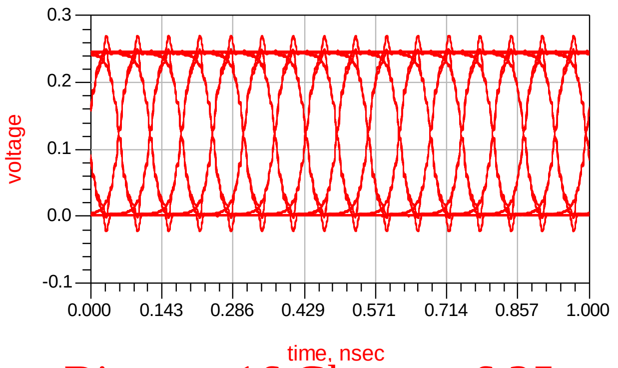
Bit rate=2 Gbps, t_r=50 ps



Bit rate=4 Gbps, t_r=25 ps



Bit rate=8 Gbps, t_r=12.5 ps



Bit rate=16 Gbps, t_r=6.25 ps

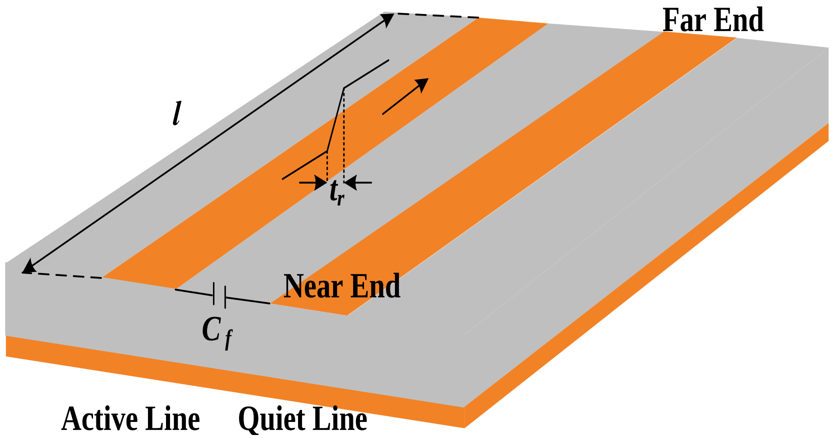
Coupled Microstrip Line

- Eye Diagram
  - Eye Height, Width, and Jitter

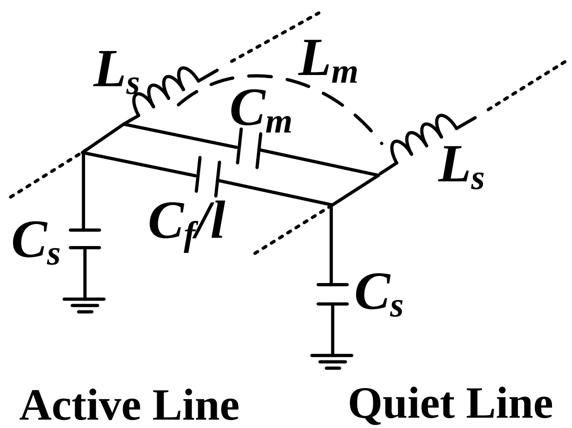
	Eye High (%)	Eye Width (%)	Jitter (%)
BR = 2 Gbps, t_r = 50 ps	97.2	99.6	4.44
BR = 4 Gbps, t_r = 25 ps	95.2	99.6	4.44
BR = 8 Gbps, t_r = 12.5 ps	94	99.76	4.432
BR = 16 Gbps, t_r = 6.25 ps	79.6	99.2	13.36

Coupled Microstrip Line Using Front-End Decoupling Capacitor

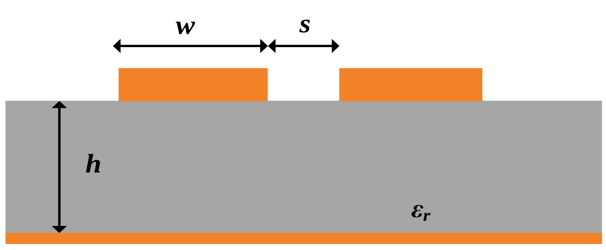
- Topology
  - FR4 Substrate with ε_r=4.4 and tanδ=0.02



3-D view



Equivalent circuit



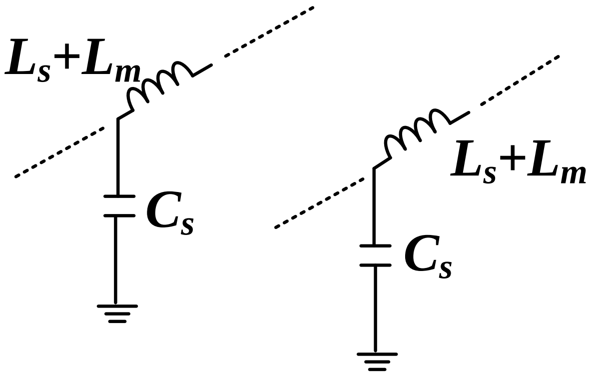
Cross-sectional view

w (mm)	s (mm)	h (mm)	l (mm)
1.42	0.7	0.8	40

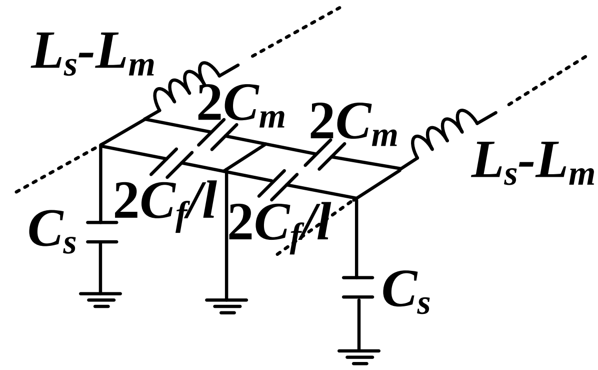
Dimensions

Coupled Microstrip Line Using Front-End Decoupling Capacitor

- Even- and Odd-Mode Equivalent Circuits



Even-mode equivalent circuit



Odd-mode equivalent circuit

$$TD_{even} = l\sqrt{(L_s + L_m)(C_s)}$$

$$TD^{c}{}_{odd} = l\sqrt{(C_s + 2C_m + \boxed{\frac{2C_f}{l}})(L_s - L_m)}$$

Coupled Microstrip Line Using Front-End Decoupling Capacitor

- Design Concept
  - Make TD_{even} and TD_{odd} Equal through Adding the Front-End Decoupling Capacitor C_f

$$T_d = TD_{even} - TD_{odd} = TD^c_{odd} - TD_{odd}$$

$$T_d = l\sqrt{L_s - L_m}\left(\sqrt{C_s + 2C_m + \frac{2C_f}{l}} - \sqrt{C_s + 2C_m}\right)$$

TD_{even} : even-mode time delay with or without the front-end decoupling capacitor

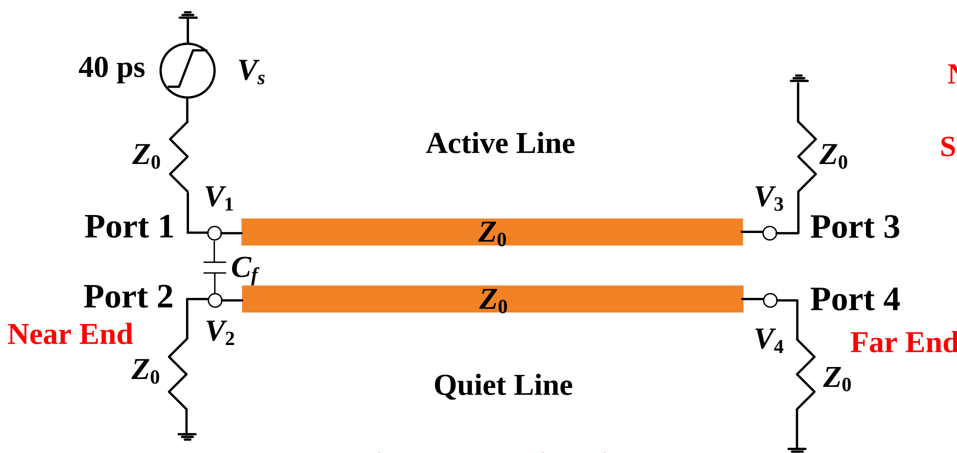
TD_{odd} : odd-mode time delay without the front-end decoupling capacitor

TD^c_{odd} : odd-mode time delay with the front-end decoupling capacitor

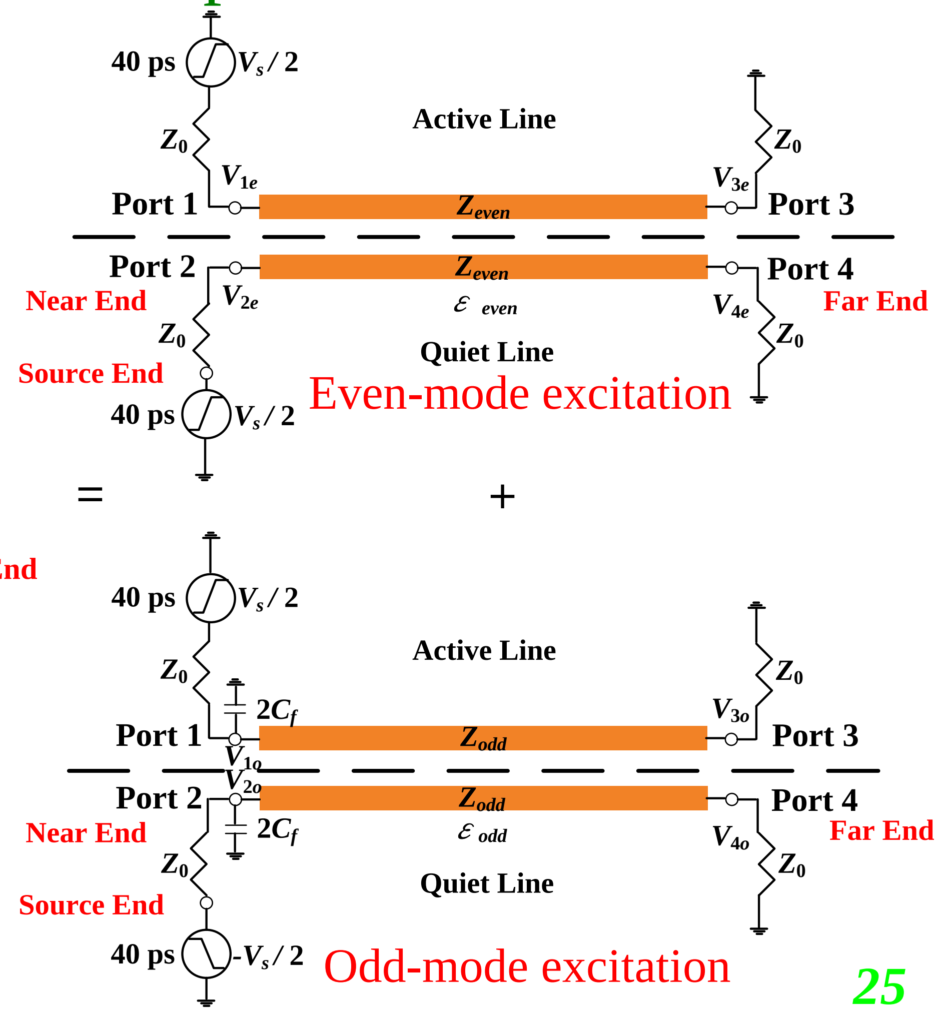
T_d : time difference between the odd-mode and even-mode time delays

Coupled Microstrip Line Using Front-End Decoupling Capacitor

- FEXT and NEXT
  - Even-and Odd-mode Decomposition



Direct excitation



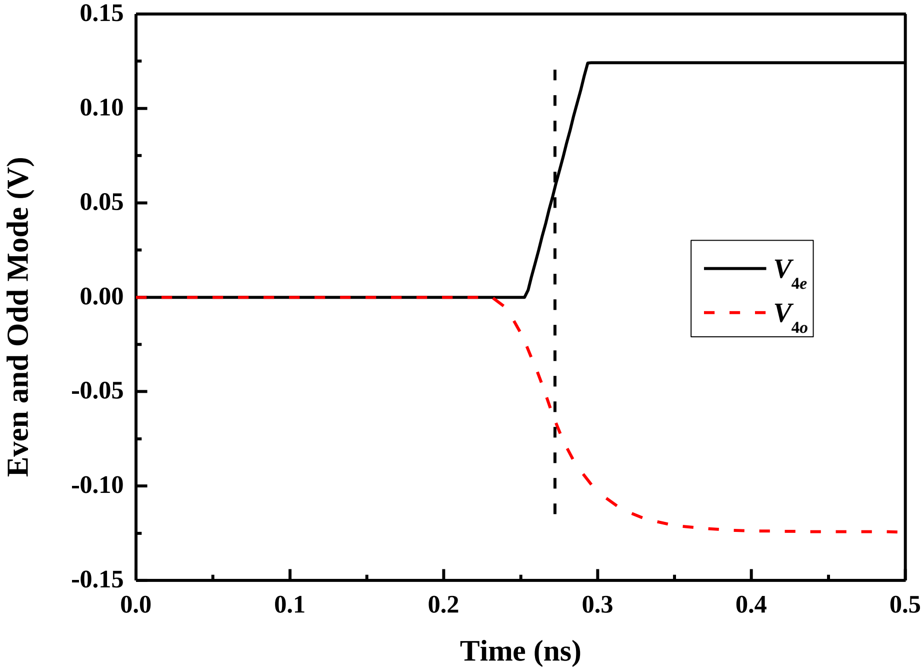
T_d (ps)	C_f (pF)
24.412	0.6

Coupled Microstrip Line Using Front-End Decoupling Capacitor

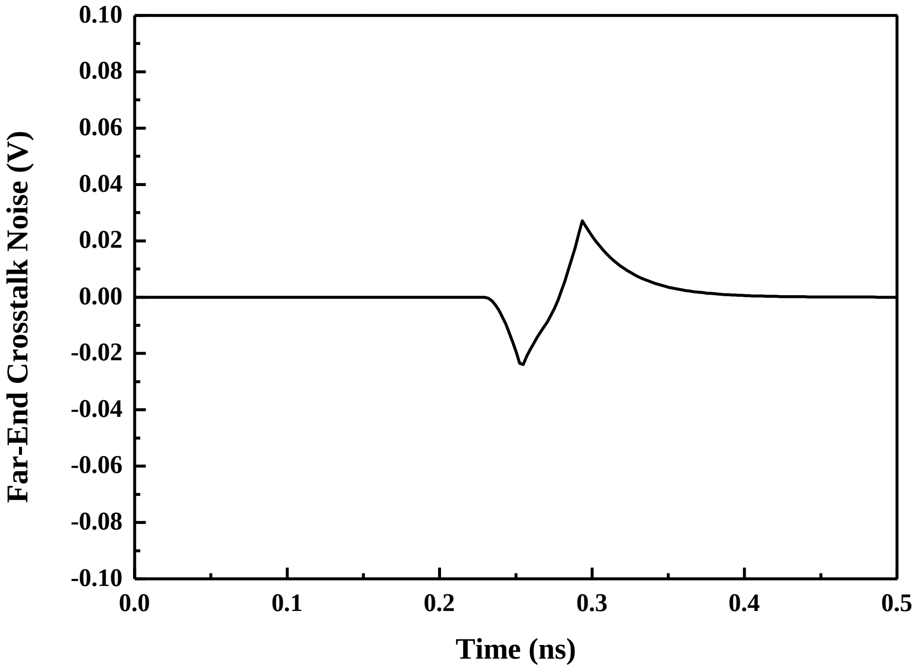
- FEXT and NEXT
  - Ideal Coupled Line

TD_{even} (ps)	TD^{c}_{odd} (ps)	T_d (ps)
253.614	253.614	0

Far-end crosstalk noise (volt)	0.027



FEXT: $V_{4e}(t)$ and $V_{4o}(t)$

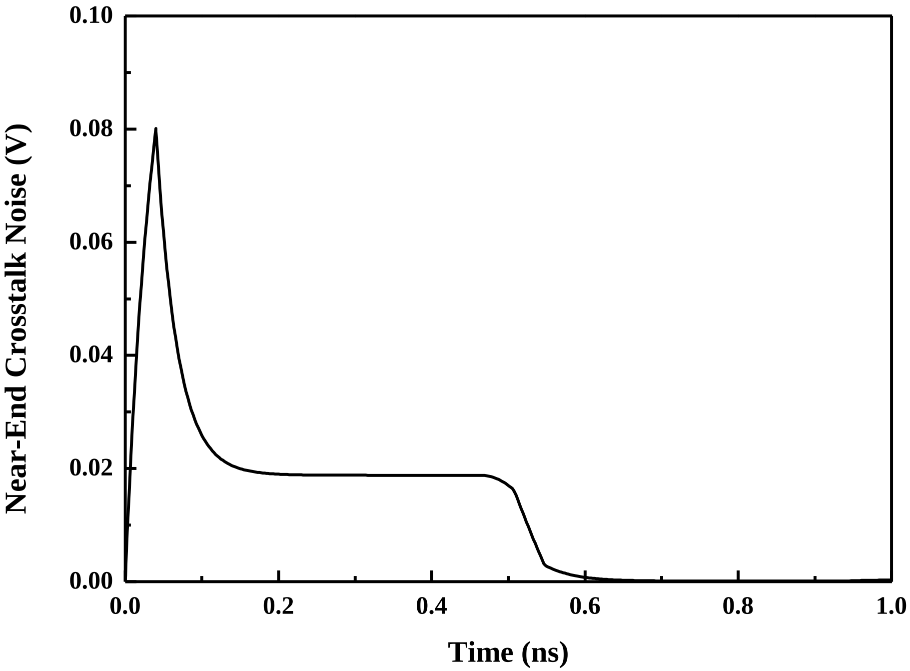


FEXT: $V_4(t)$

Coupled Microstrip Line Using Front-End Decoupling Capacitor

- FEXT and NEXT
  - Ideal Coupled Line

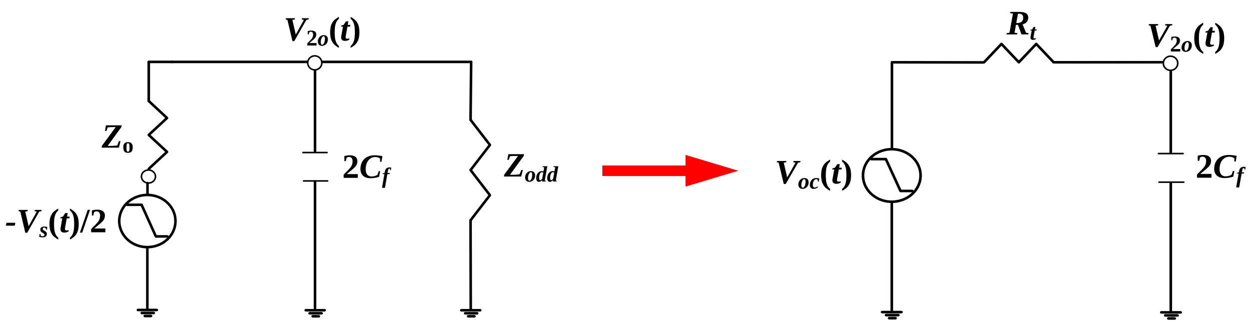
Near-end crosstalk noise (volt)	0.080



NEXT: $V_2(t)$

Coupled Microstrip Line Using Front-End Decoupling Capacitor

- FEXT and NEXT
  - Estimation Equations
    - Peak of NEXT of the odd-mode excitation



$$V_s(t) = \frac{V_s}{t_r}[tu(t)\text{-}(t\text{-}t_r)u(t\text{-}t_r)]$$

$$V_{oc}(t) = V_{oc}[tu(t)\text{-}(t\text{-}t_r)u(t\text{-}t_r)]$$

$$V_{oc} = -\frac{V_s}{2t_r}\left(\frac{Z_{odd}}{Z_0 + Z_{odd}}\right) \qquad R_t = \frac{Z_0 Z_{odd}}{Z_0 + Z_{odd}}$$

$$\boxed{V_{2o}(t) = V_{oc}\tau[(e^{-t/\tau} - 1)u(t)\text{-}(e^{-(t-t_r)/\tau} - 1)u(t\text{-}t_r)] + V_{oc}(t)}$$

Coupled Microstrip Line Using Front-End Decoupling Capacitor

- FEXT and NEXT
  - Estimation Equations
    - Peak of NEXT occurs at $t=t_r$

$$V_2(t_r) = V_{2e}(t_r) + V_{2o}(t_r)$$

$$V_{2e}(t_r) = \frac{V_s}{2}\left(\frac{Z_{even}}{Z_{even} + Z_0}\right)$$

$$V_{2o}(t_r) = V_{oc}\tau(e^{-t_r/\tau} - 1) + V_{oc}t_r$$

$$\boxed{V_2(t_r) = \frac{V_s}{2}\left(\frac{Z_{even}}{Z_{even} + Z_0}\right) + V_{oc}\tau(e^{-t_r/\tau} - 1) + V_{oc}t_r} \qquad \tau = 2R_t C_f$$

    - Peak of FEXT occurs at $t=TD_{odd}+T_d+t_r$

$$V_4(t) = V_{4o}(t) + V_{4e}(t)$$

$$V_{4o}(t) = \left(\frac{2Z_0}{Z_0 + Z_{odd}}\right)V_{2o}(t - TD_{odd})$$

$$\boxed{V_4(TD_{odd} + T_d + t_r) = \left(\frac{2Z_0}{Z_0 + Z_{odd}}\right)[V_{oc}\tau(e^{-(t_r+T_d)/\tau} - e^{-T_d/\tau}) + V_{oc}t_r] + V_{max}}$$

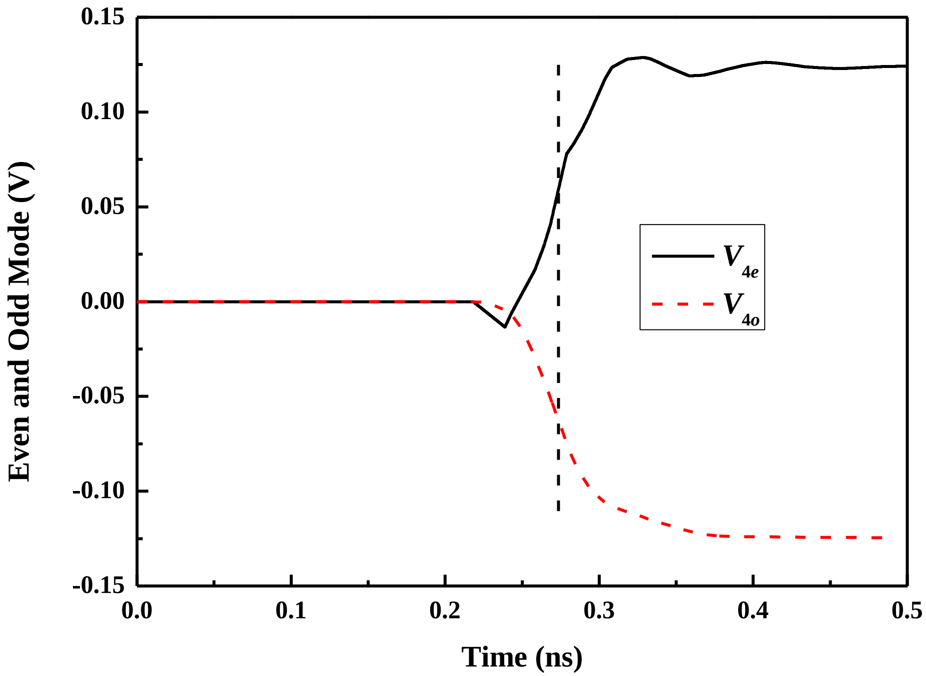
Coupled Microstrip Line Using Front-End Decoupling Capacitor

- FEXT and NEXT
  - Lossless Coupled Microstrip Line

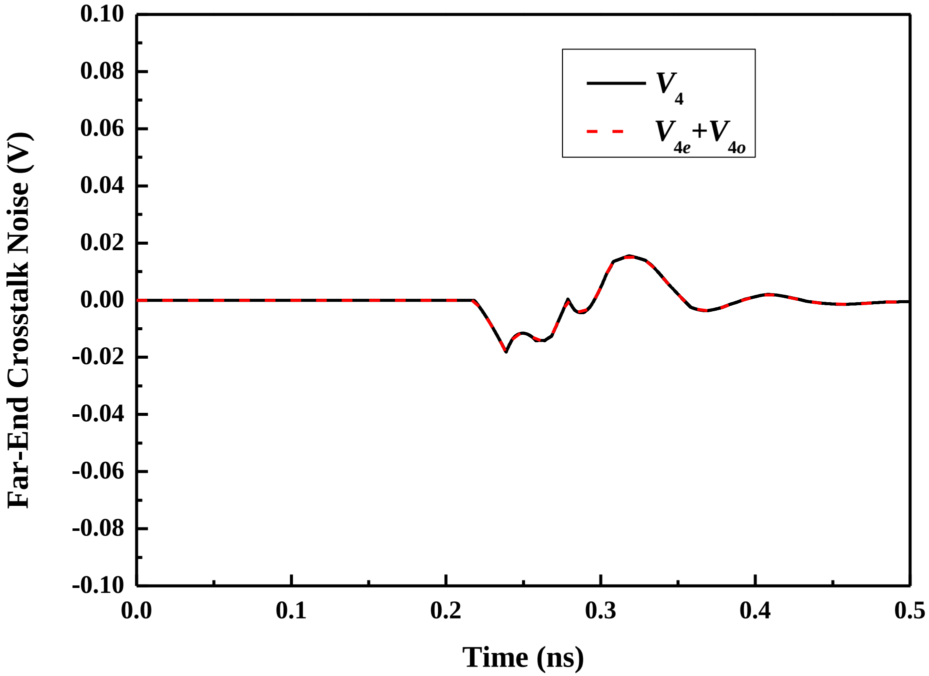
T_d (ps)	C_f (pF)
20.412	0.5

TD_{even} (ps)	TD^c_{odd} (ps)	T_d (ps)
254.414	254.414	0

Far-end crosstalk noise (volt)	0.018



FEXT: $V_{4e}(t)$ and $V_{4o}(t)$

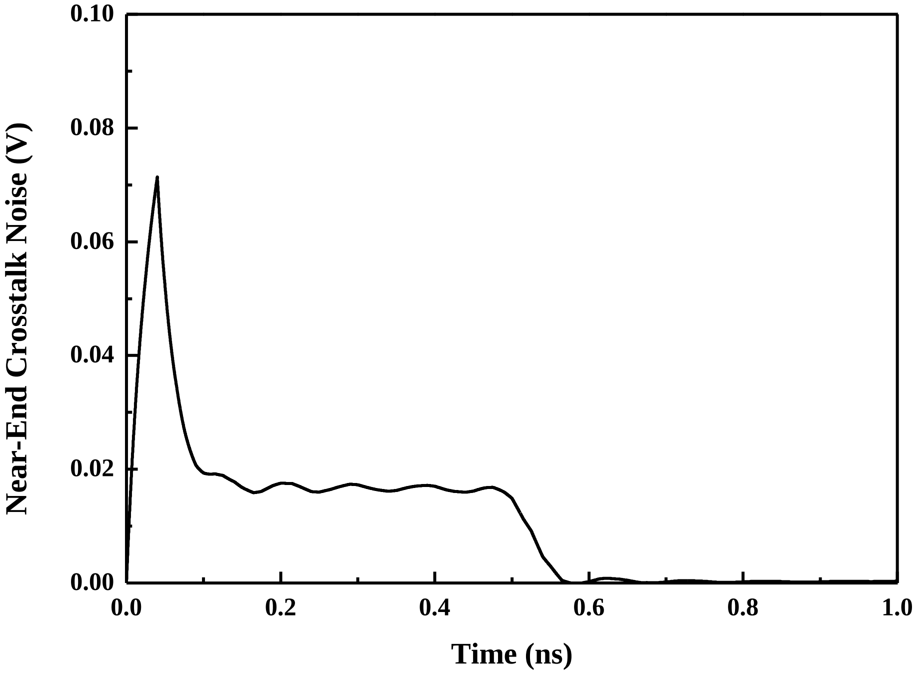


FEXT: $V_4(t)$

Coupled Microstrip Line Using Front-End Decoupling Capacitor

- FEXT and NEXT
  – Lossless Coupled Microstrip Line

Near-end crosstalk noise (volt)	0.071



NEXT: $V_2(t)$

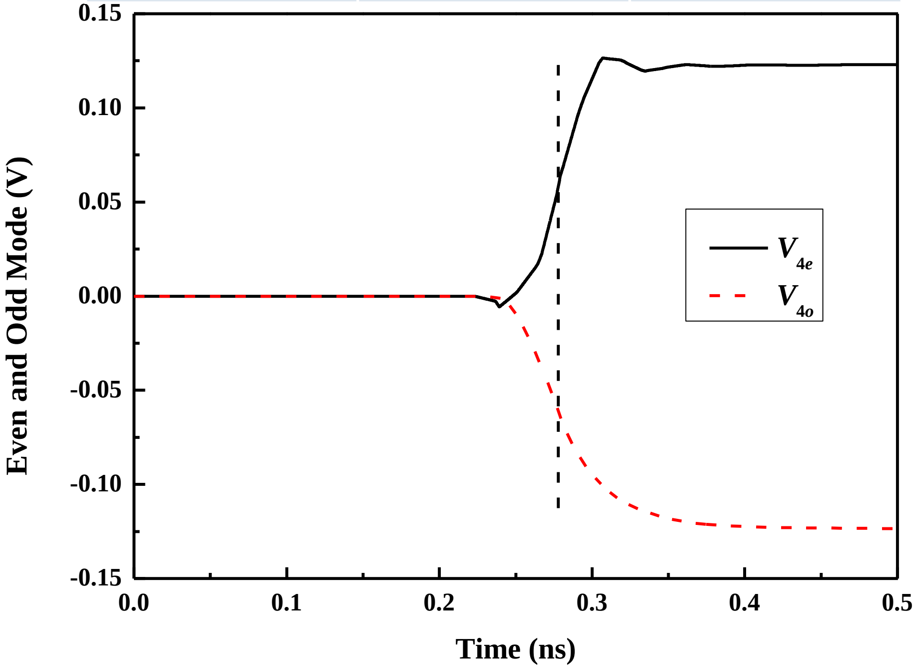
Coupled Microstrip Line Using Front-End Decoupling Capacitor

- FEXT and NEXT
  - Lossy Coupled Microstrip Line

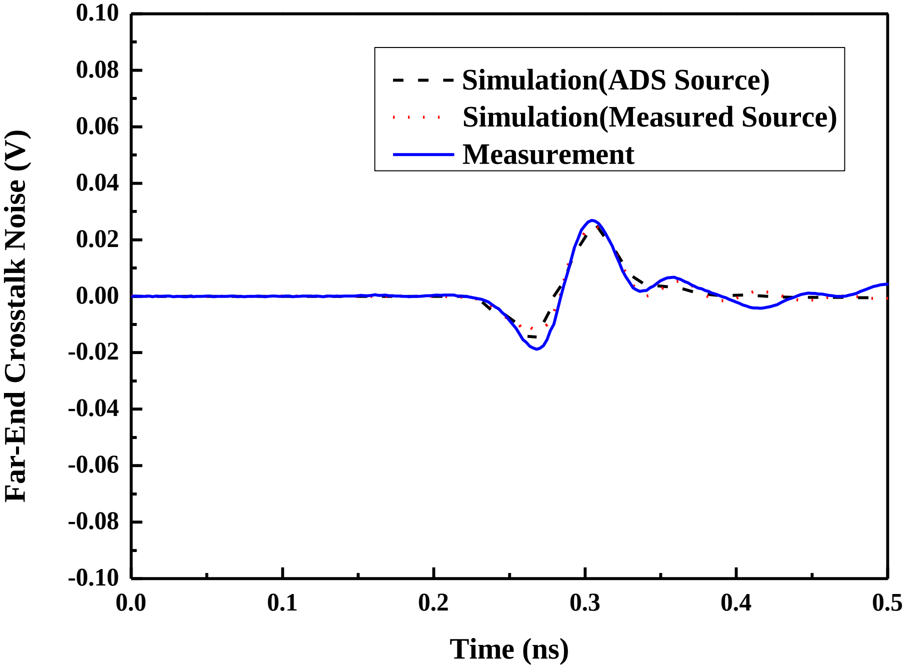
T_d (ps)	C_f (pF)
20.612	0.5

TD_{even} (ps)	TD^c_{odd} (ps)	T_d (ps)
258.814	258.814	0

Far-end crosstalk noise (volt)	Simulation	0.0257
	Measurement	0.0268



FEXT: $V_{4e}(t)$ and $V_{4o}(t)$

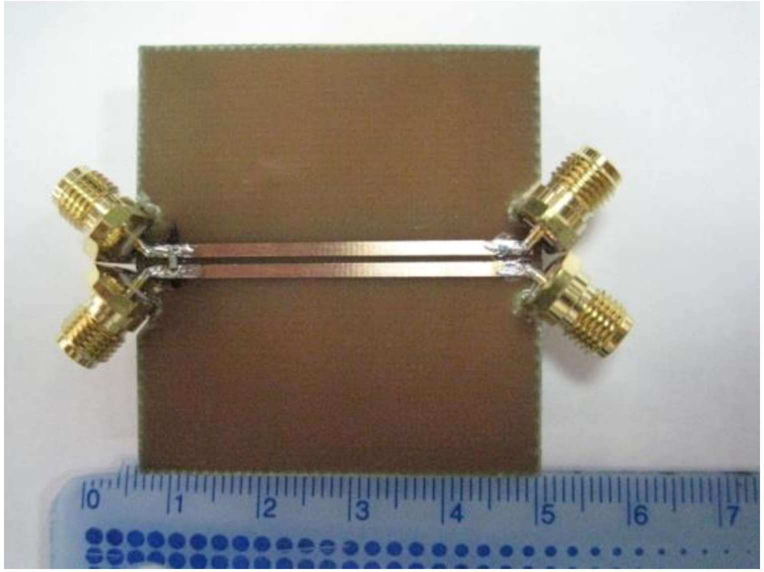


FEXT: $V_4(t)$

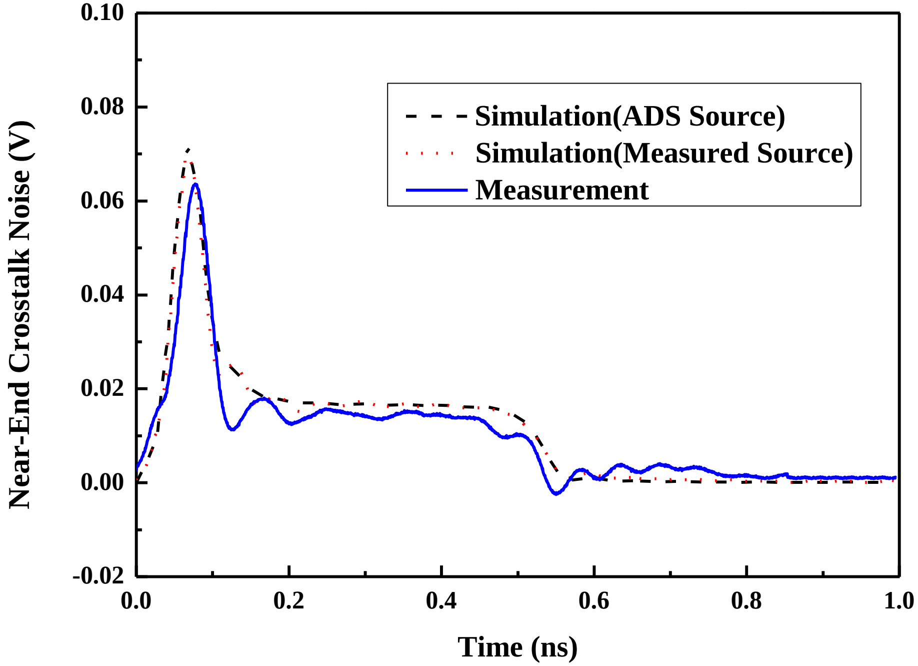
Coupled Microstrip Line Using Front-End Decoupling Capacitor

- FEXT and NEXT
  - Lossy Coupled Microstrip Line

Near-end crosstalk noise (volt)	Simulation	0.0710
	Measurement	0.0636



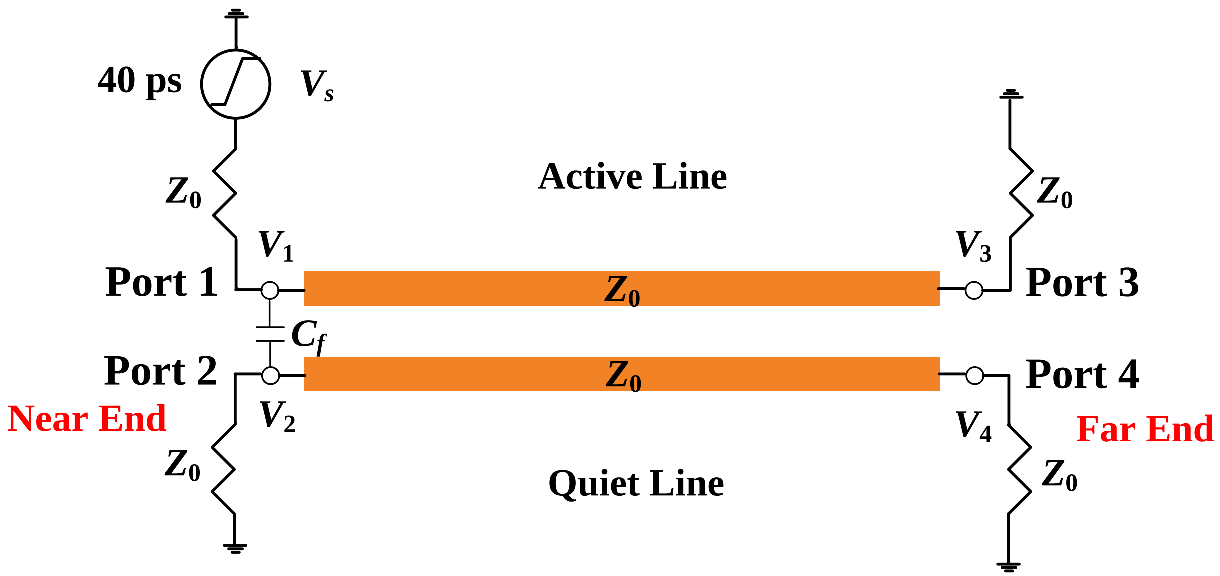
Real circuit



NEXT: $V_2(t)$

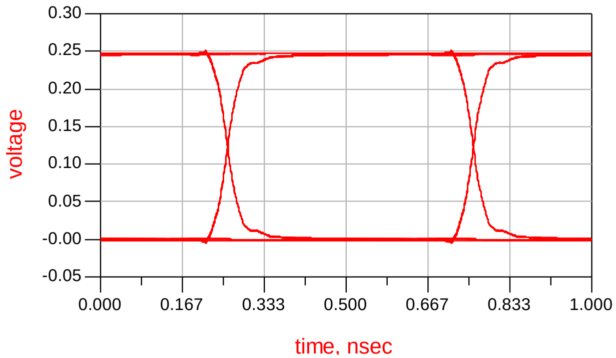
Coupled Microstrip Line Using Front-End Decoupling Capacitor

- Eye Diagram
  - Simulation Setup
    - Source V_S: pseudo random bit sequence (PRBS)
    - Observation V_3

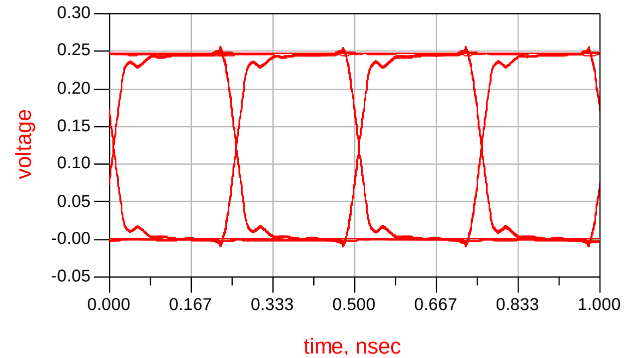


Coupled Microstrip Line Using Front-End Decoupling Capacitor

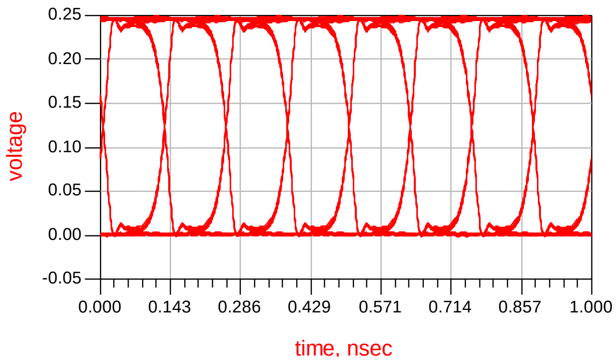
- Eye Diagram
  - Using Various Bit Rate and Rise Time (BR/10)



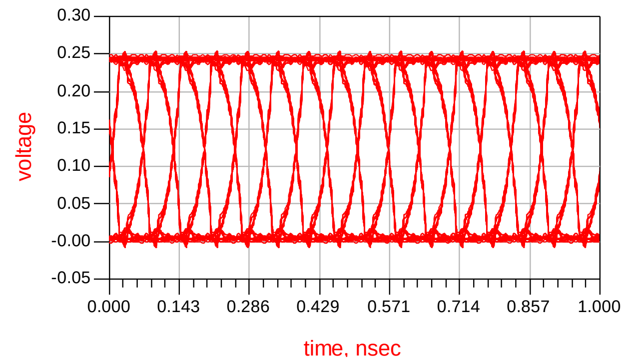
Bit rate=2 Gbps, t_r=50 ps



Bit rate=4 Gbps, t_r=25 ps



Bit rate=8 Gbps, t_r=12.5 ps



Bit rate=16 Gbps, t_r=6.25 ps

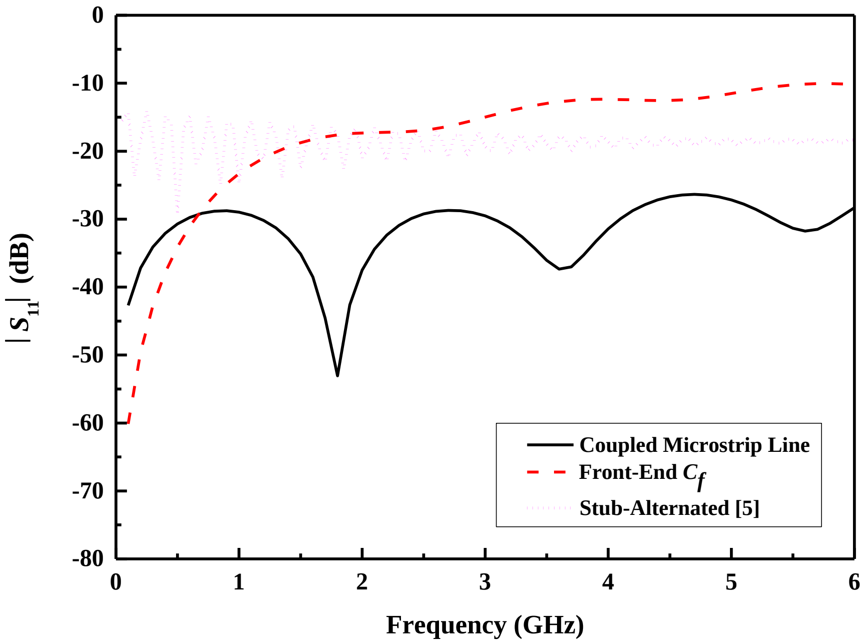
Coupled Microstrip Line Using Front-End Decoupling Capacitor

- Eye Diagram
  - Eye Height, Width, and Jitter

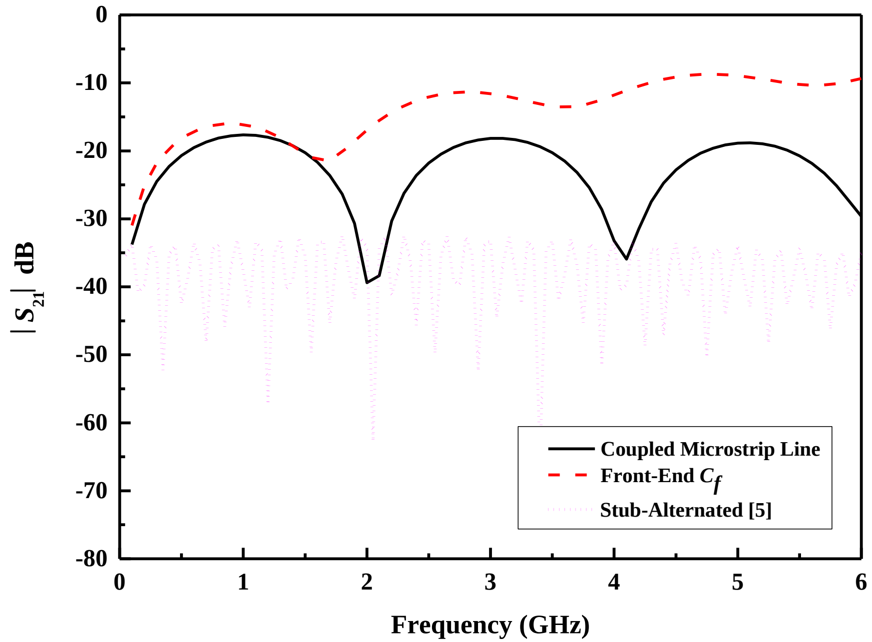
	Eye High (%)	Eye Width (%)	Jitter (%)
BR = 2 Gbps, t_r = 50 ps	97.2	99.6	4.44
BR = 4 Gbps, t_r = 25 ps	88.8	99.6	4.44
BR = 8 Gbps, t_r = 12.5 ps	86	99.2	8.88
BR = 16 Gbps, t_r = 6.25 ps	64.4	97.44	31.2

Coupled Microstrip Line Using Front-End Decoupling Capacitor

- *S*-Parameters
  - Reflection and Near-End Coupling Coefficients



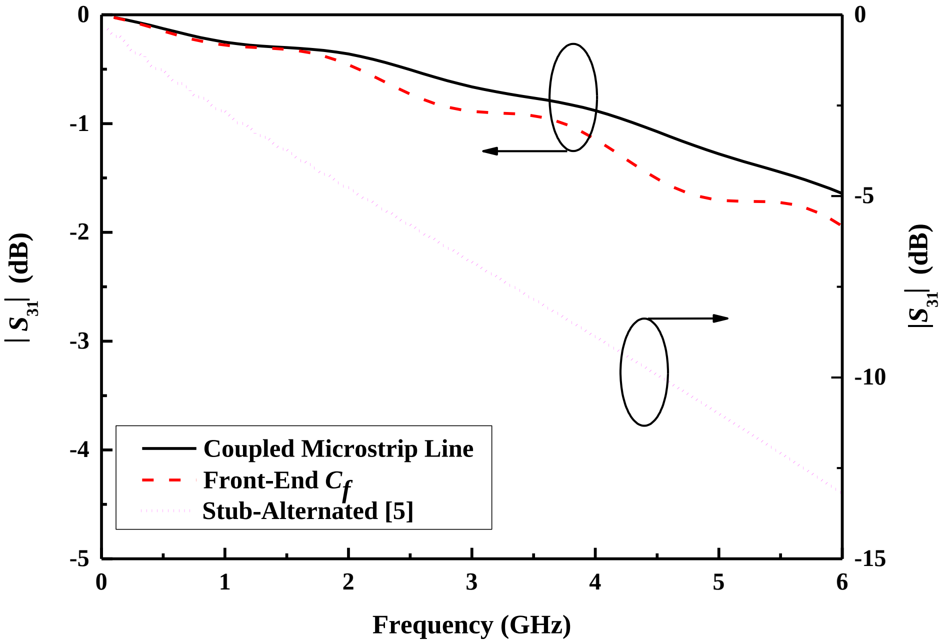
Reflection coefficient



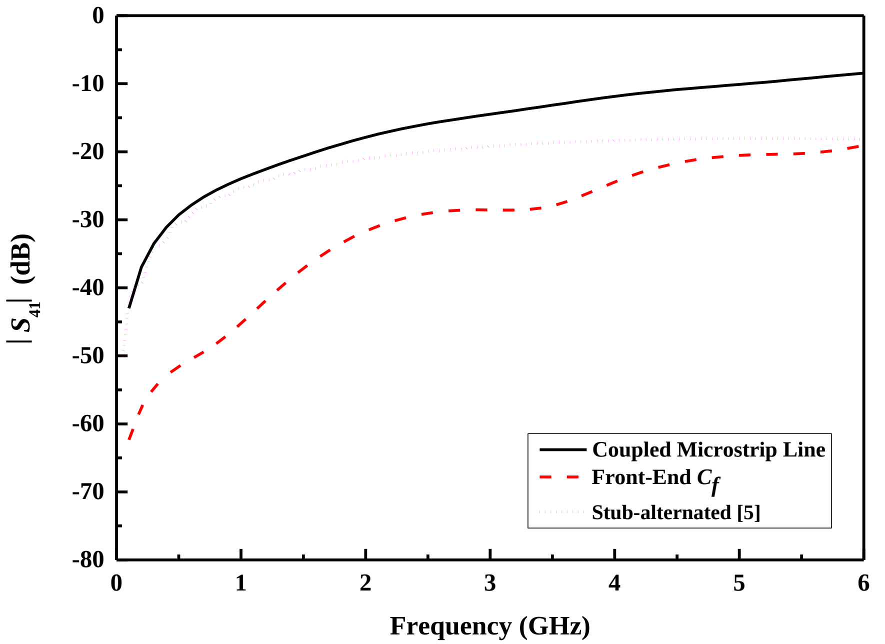
Near-end coupling coefficient

Coupled Microstrip Line Using Front-End Decoupling Capacitor

- *S*-Parameters
  - Transmission and Far-End Coupling Coefficients



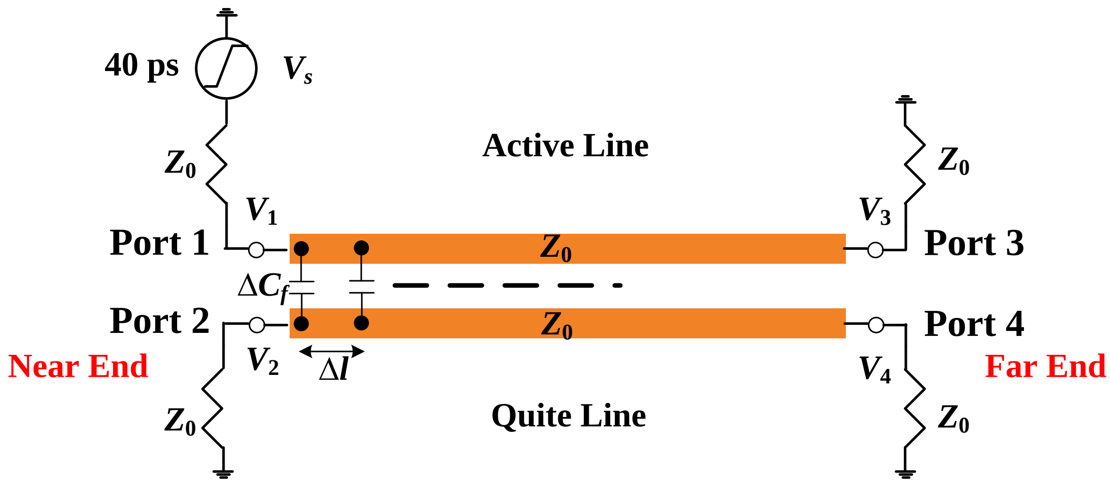
Transmission coefficient



Far-end coupling coefficient

Coupled Microstrip Line Using Distributed Decoupling Capacitors

- FEXT and NEXT
  - Lossy Coupled Microstrip Line $C_f = 0.5\,\mathrm{pF}$



$$\lambda = \frac{3\times 10^8}{f_{3dB}} \frac{1}{\sqrt{\varepsilon_{eff}}}$$

$$f_{3\mathrm{dB}} = \frac{0.35}{t_r}$$

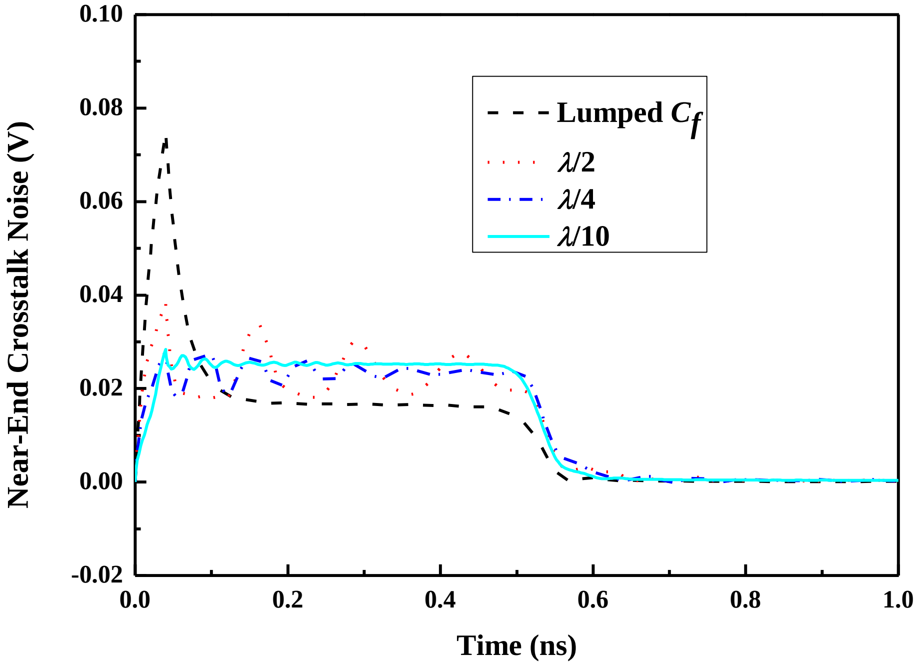
Δl (mm)	Number of distributed decoupling capacitor	Value of distributed decoupling capacitor (pF)
9.2 (λ/2)	4	0.1250
4.6 (λ/4)	8	0.0625
1.9 (λ/10)	20	0.0250

Coupled Microstrip Line Using Distributed Decoupling Capacitors

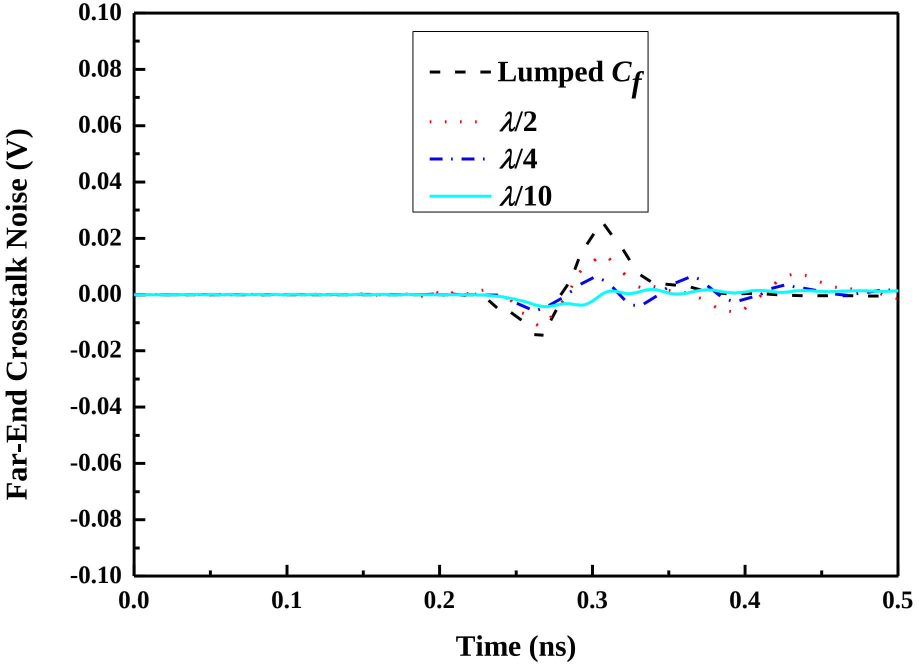
- FEXT and NEXT
  - Lossy Coupled Microstrip Line

Near-end crosstalk noise (volt)	Lumped C_f	0.071
	$\lambda/10$	0.028

Far-end crosstalk noise (volt)	Lumped C_f	0.0257
	$\lambda/10$	0



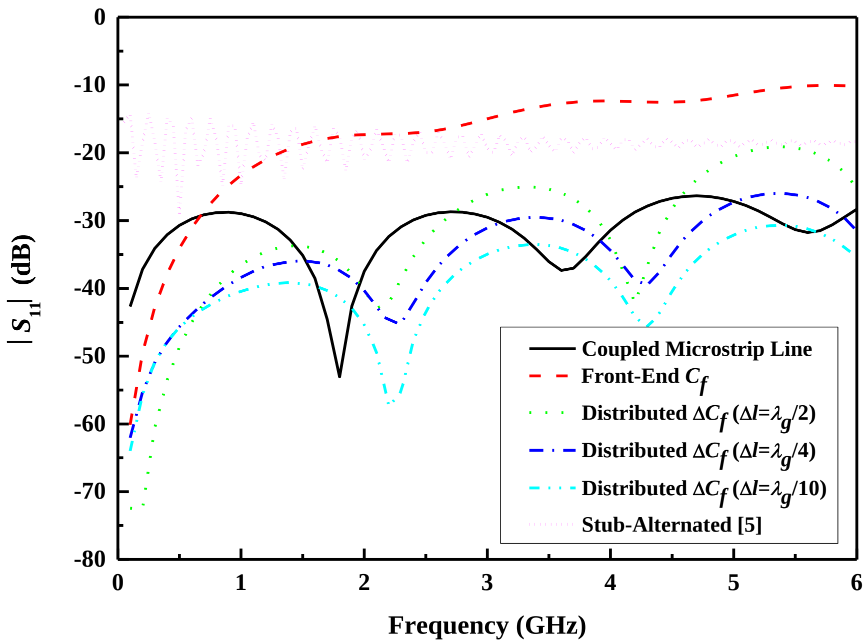
FEXT: $V_2(t)$



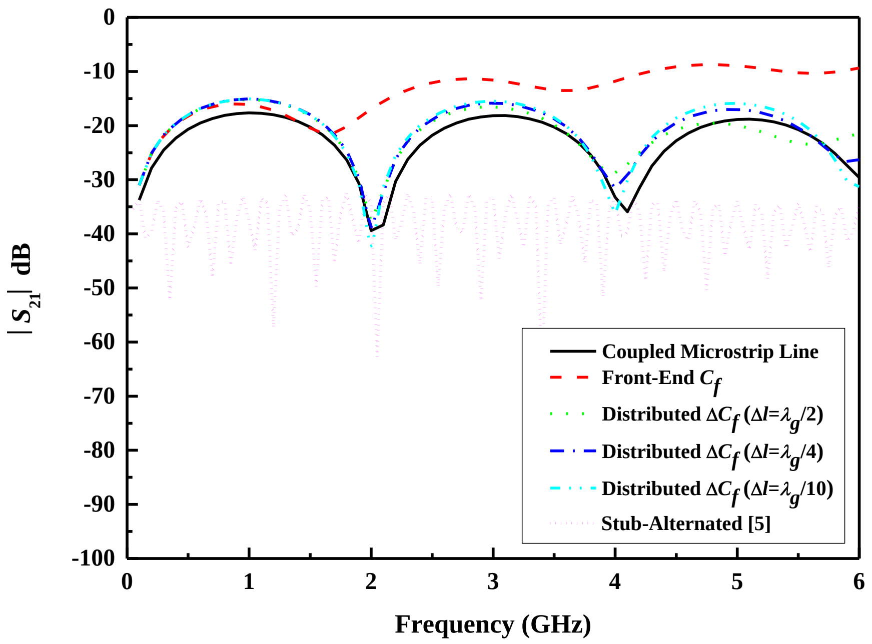
NEXT: $V_4(t)$

Coupled Microstrip Line Using Distributed Decoupling Capacitors

- *S*-Parameters
  - Reflection and Near-End Coupling Coefficients



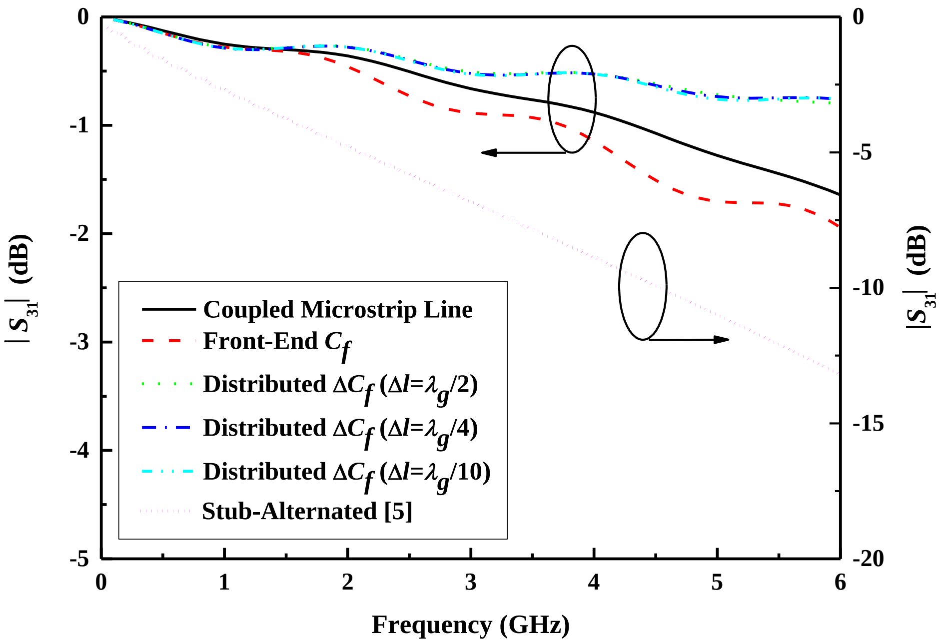
Reflection coefficient



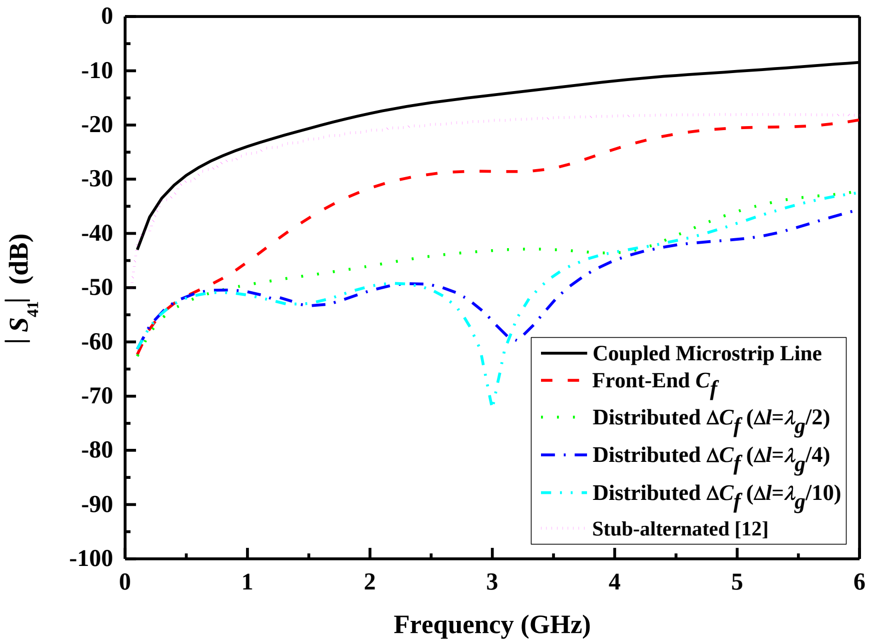
Near-end coupling coefficient

Coupled Microstrip Line Using Distributed Decoupling Capacitors

- *S*-Parameters
  - Transmission and Far-End Coupling Coefficients



Transmission coefficient



Far-end coupling coefficient

Conclusions

- FEXT and NEXT

	FEXT (volt)		NEXT (volt)	
	Measurement	Simulation	Measurement	Simulation
Conventional	0.0550	0.0630	0.0163	0.0180
Front-end capacitor	0.0268	0.0257	0.0636	0.0710
Distributed capacitors	X	0	X	0.0280

- Eye Diagram
  - Performance Degraded Due to Adoption of Decoupling Capacitor
- *S*-Parameters
  - Performance Restored While Using Distributed Capacitors