Chapter 6

Differential Serpentine Delay Line

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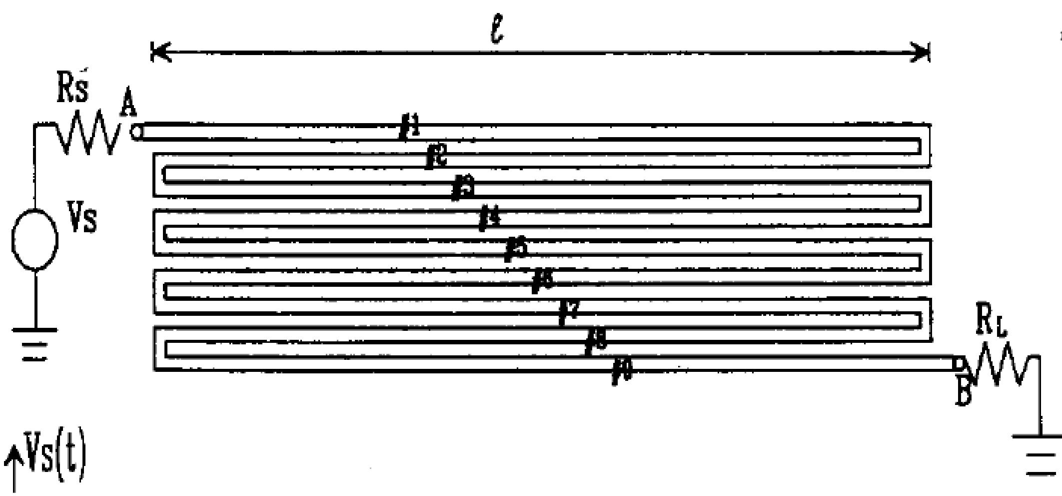
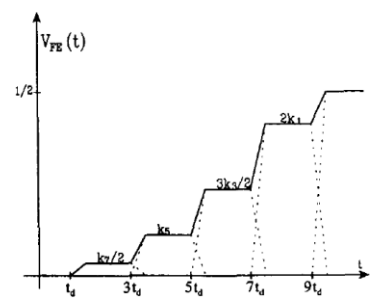
Outline

- Literature Examples
- Motivations
- Differential Serpentine Delay Line
- Differential Serpentine Delay Line Using Timing-Offset Differential Signal
- Differential Serpentine Delay Line with Strongly-Coupled Turns
- Differential Serpentine Delay Line with Strongly-Coupled Turns Using Timing-Offset Differential Signal
- Scaled Down Verifications
- Conclusions

Literature Examples

- Serpentine Delay Line [1]
  - Advantages
    - Easy Implementation with the PCB process
  - Disadvantages
    - Laddering wave at the receiving signal, deteriorating the SI and reducing the time delay

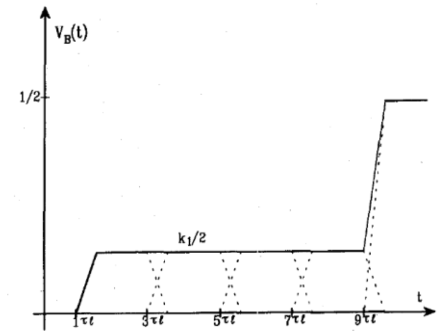


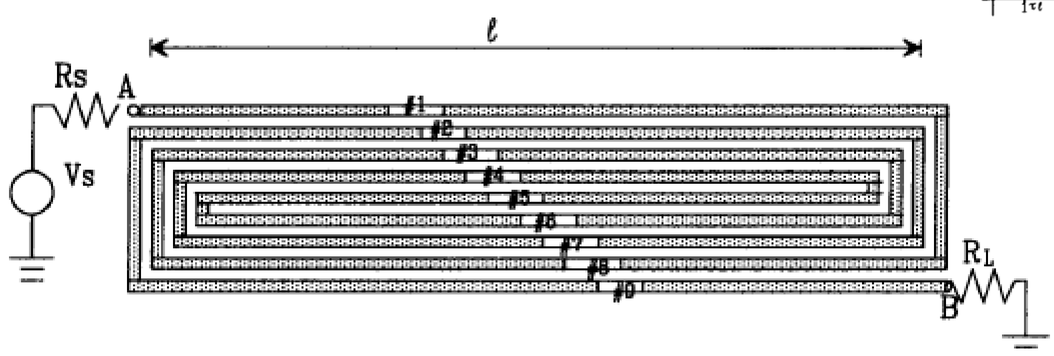


[1] R. B. Wu and F. L. Chao, "Laddering wave in serpentine delay line," *IEEE Trans*. Compon., Packag., Manuf. Technol., B, vol. 18, no. 4, pp. 644-650, Nov. 1995.

Literature Examples

- Spiral Delay Line [2]
  - Advantages
    - Noise uniformly distributes on the receiving signal, maintaining the SI and time delay
  - Disadvantages
    - Noise accumulates at the sending end

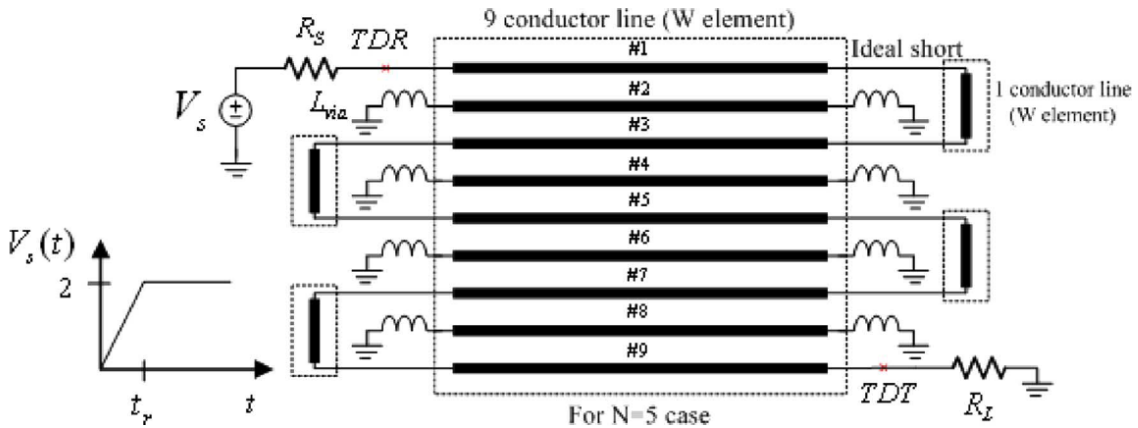




[2] R. B. Wu and F. L. Chao, "Flat spiral delay line design with minimum crosstalk penalty," *IEEE Trans*. Compon., Packag., Manuf. Technol., B, vol. 19, no. 2, pp. 397-402, May 1996.

Literature Examples

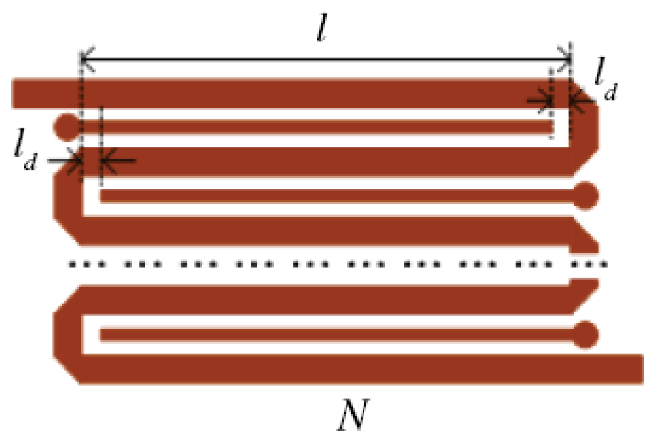
- Serpentine Delay Line with Guard Trace [3]
  - Advantages
    - Efficient suppression of the noise at the receiving end
  - Disadvantages
    - Guard trace will occupy additional areas



[3] G. H. Shiue, C. Y. Chao, and R. B. Wu, "Guard trace design for improvement on transient waveforms and eye diagrams of serpentine delay lines," *IEEE Transactions on Advanced Packaging*, vol. 33, pp. 1051-1060, Nov. 2010.

Literature Examples

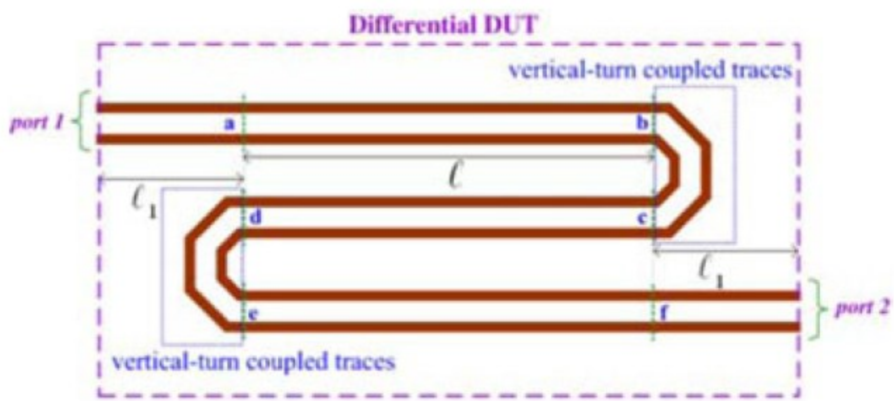
- Serpentine Delay Line with Guard Trace [4]
  - Advantages
    - More efficient suppression of the noise at the receiving end with only one via
  - Disadvantages
    - Noise at the sending end could not be efficient eliminated



[4] G. H. Shiue, J. H. Shiu, P. W. Chiu, and C. M. Hsu, "Improvements of time-domain transmission waveform and eye diagram of serpentine delay line using open-stub type guard traces in embedded microstrip line," *IEEE Trans*. Component., Package., Manuf. Technol., vol. 1, no. 11, pp. 1706-1717, Nov. 2011.

Literature Examples

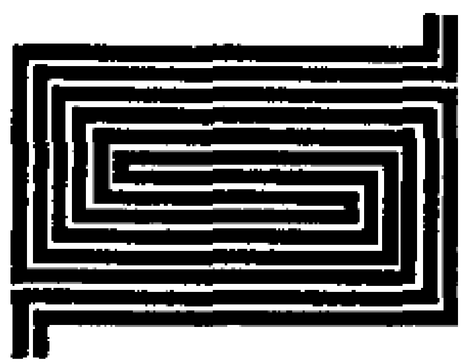
- Differential Serpentine Delay Line [5]
  - Advantages
    - Efficient suppression of the common-mode noise at the receiving end
  - Disadvantages
    - With even turns, the common-mode noise at the receiving end could not be efficiently eliminated



[5] G. H. Shiue, J. H. Shiu, Y. C. Tsai, and C. M. Hsu, "Analysis of common-mode noise for weakly coupled differential serpentine delay microstrip line in high-speed digital circuits," *IEEE Transactions on Electromagnetic Compatibility*., vol., pp.00-00, 2011.

Literature Examples

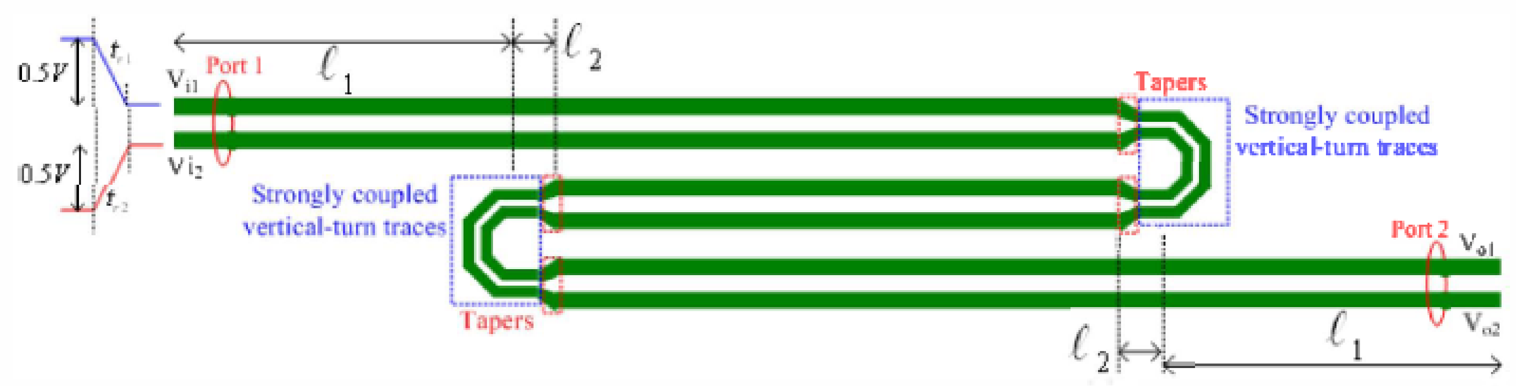
- Differential Spiral Delay Line [6]
  - Advantages
    - Efficient suppression of the common-mode noise at the receiving end
  - Disadvantages
    - Differential-mode noise at the sending end will be increased



[6] W. D. Guo, G. H. Shiue, C. M. Lin, and R. B. Wu , "Comparisons between serpentine and flat spiral delay lines on transient reflection/transmission waveforms and eye diagrams," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no.4, pp. 1379-1387, Apr. 2006.

Literature Examples

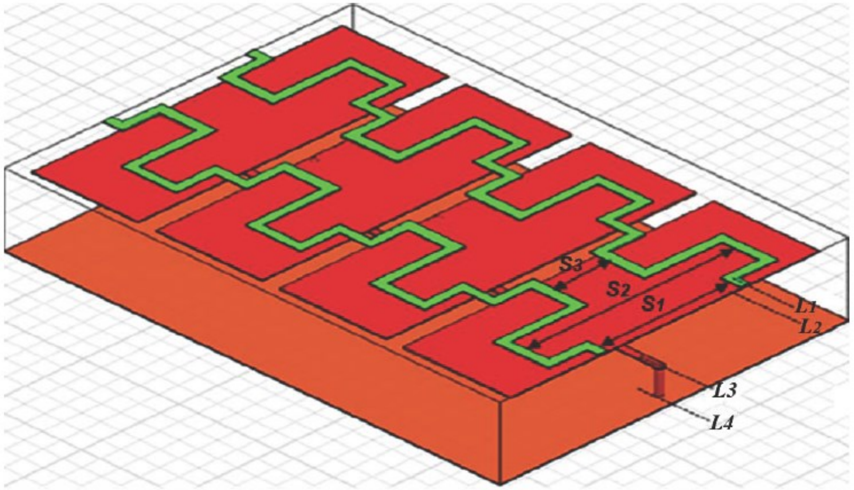
- Differential Serpentine Delay Line with Strongly-Coupled Turns [7]
  - Advantages
    - More efficient suppression of the common-mode noise at the receiving end
  - Disadvantages
    - More differential-mode noise at the sending end will be increased



[7] G. H. Shiue, Y. C. Tsai, C. M. Hsu, and J. H. Shiu, "Common-mode noise reduction schemes for differential serpentine delay microstrip line in high-speed digital circuits," *IEEE 20th Topical Meeting on Electrical Performance of Electronic Packaging*, pp. 211-214, Oct. 2011.

Literature Examples

- Differential Delay Line with Common-Mode Noise Filter [8]
  - Advantages
    - Broadband response of common-mode noise suppression at the receiving end and compact size
  - Disadvantages
    - Ground bounce from vias, causing power integrity problems



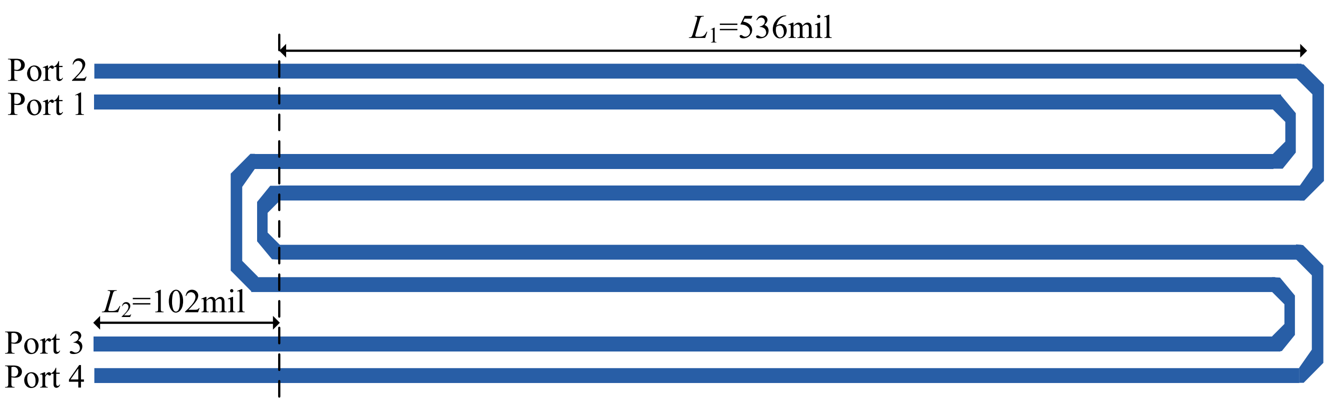
[8] C.-H. Tsai and T.-L. Wu, "A broadband and miniaturized common-mode filter for gigahertz differential signals based on negative-permittivity metamaterials," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no.1, pp. 195-202, Jan. 2010.

Motivations

- To Increase the Routing Flexibility
  - Elimination of the Need of Vias
- To Save the Area
  - Elimination of the Need of Guard Traces
- To Efficiently Reduce the Common-Mode Noise at the Receiving End
  - No Matter Even or Odd Turns Are Used
- To Efficiently Reduce the Differential-Mode Noise at the Sending End
  - Elimination of the Strongly-Coupled Turns

Differential Serpentine Delay Line

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

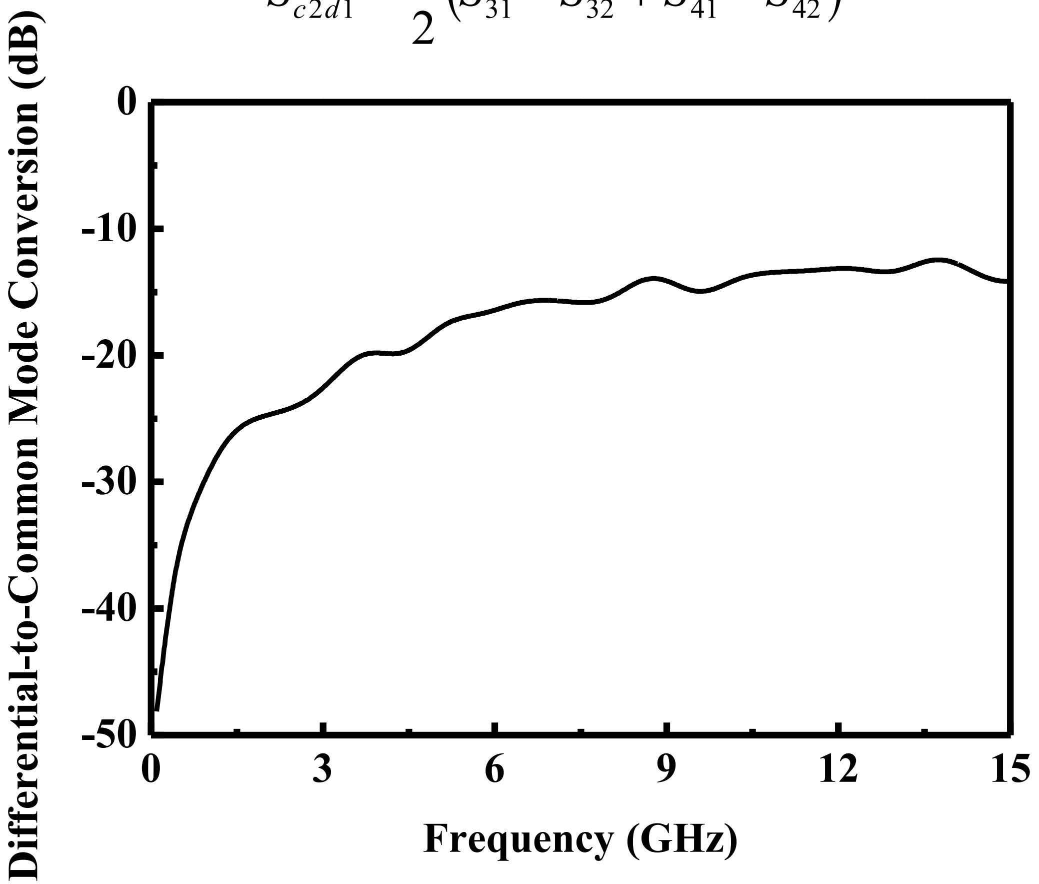


W	***S***	***H***	***D***
7.5 mil	9.5 mil	5.5 mil	24.75 mil

Differential Serpentine Delay Line

- Mixed Mode *S*-parameters
  - Differential- to Common-Mode Conversion

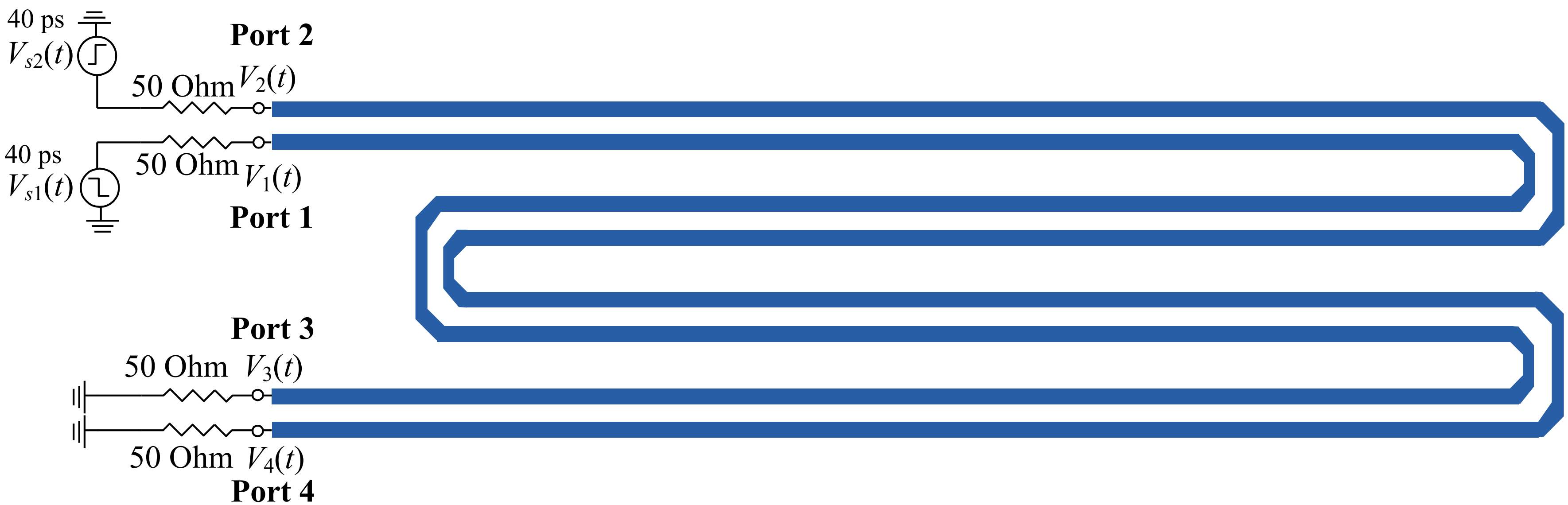
$$S_{c2d1} = \frac{1}{2}\left(S_{31} - S_{32} + S_{41} - S_{42}\right)$$



Differential Serpentine Delay Line

- Time-Domain Simulation Setup
  - Input Source
    - Differential signal with amplitude ±0.5 V and rise time 40 ps

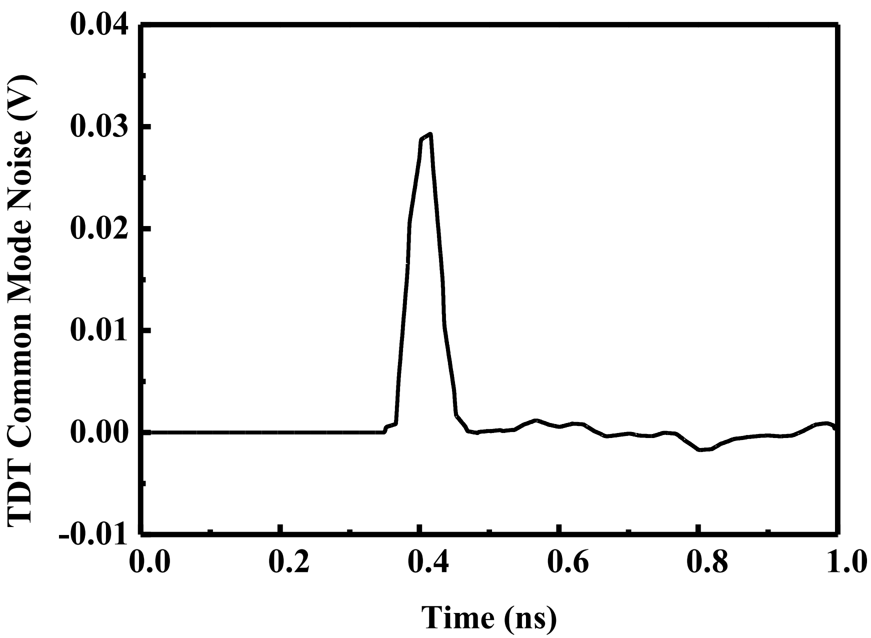
$$V_{TDR\_differential} = \left(V_2(t) - \frac{V_{s2}(t)}{2} \right) - \left(V_1(t) - \frac{V_{s1}(t)}{2} \right)$$

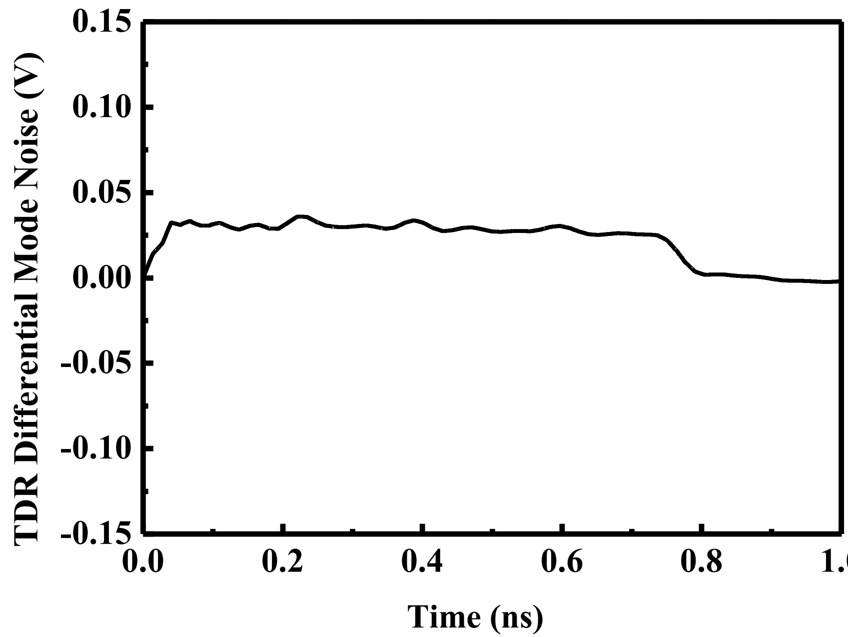


$$V_{TDT\_common} = \frac{V_3(t) + V_4(t)}{2}$$

Differential Serpentine Delay Line

- Time-Domain Simulation Results
  - TDT Common-Mode and TDR Differential-Mode Noises





TDT common-mode noise (V)	0.0289
TDR Differential-mode noise (V)	0.0356

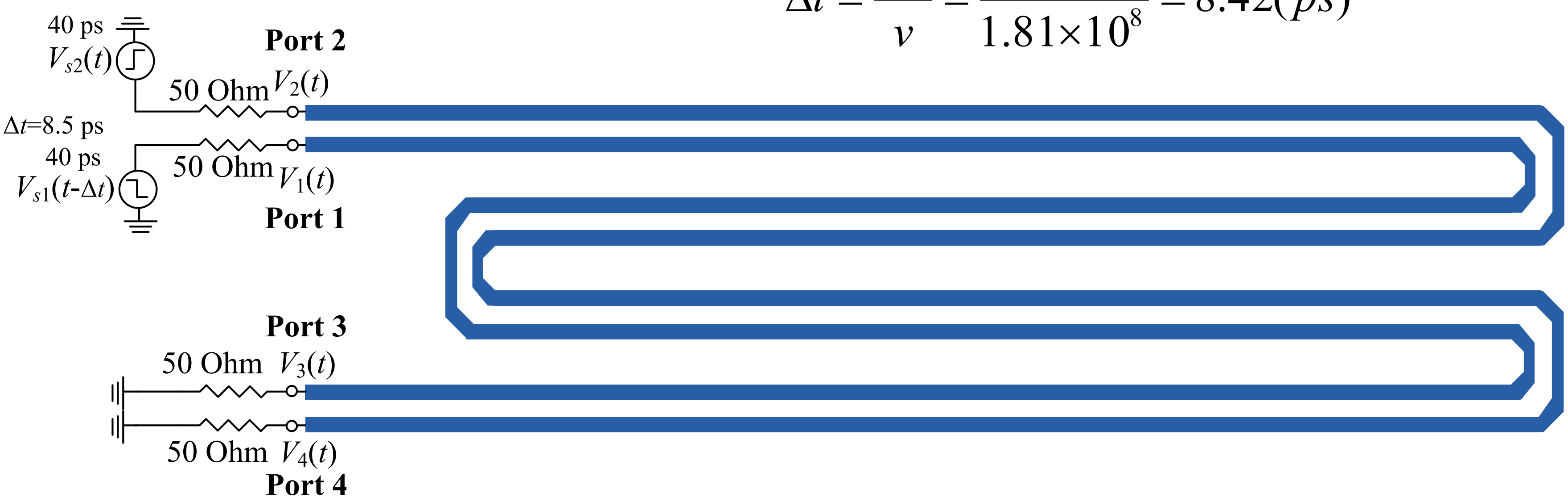
Differential Serpentine Delay Line Using Timing-Offset Differential Signal

- Time-Domain Simulation Setup
  - Input Source
    - Differential signal with amplitude ±0.5 V and rise time 40 ps

Required Offset time

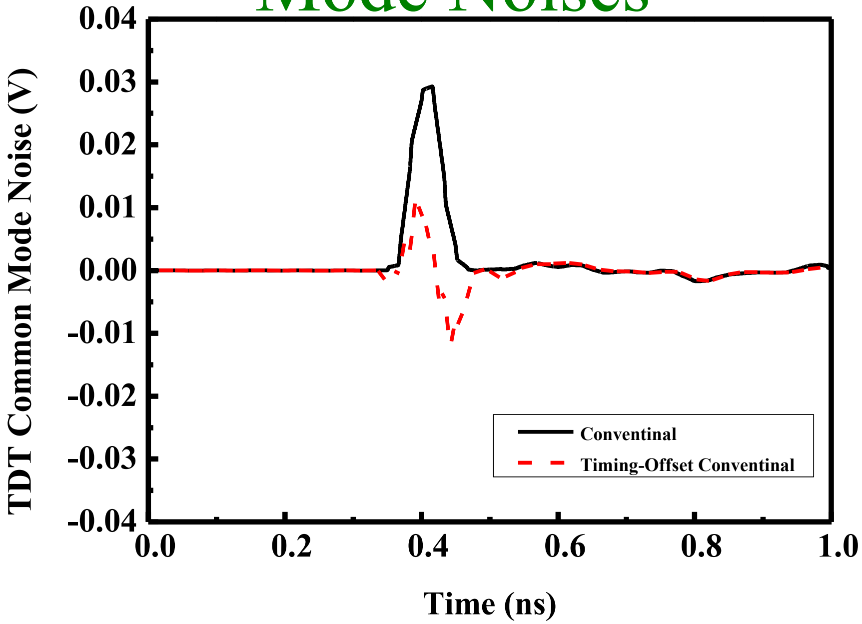
$$v = \left(v_{odd} + v_{even}\right) \times 0.5 = 1.81 \times 10^{8} (m/s)$$

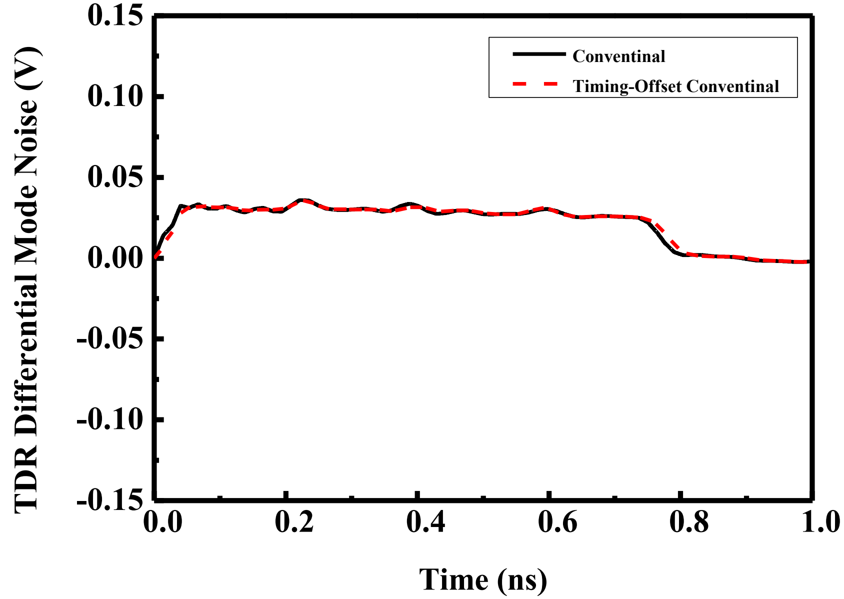
$$\Delta t = \frac{\Delta L}{v} = \frac{60mil}{1.81 \times 10^{8}} = 8.42(ps)$$



Differential Serpentine Delay Line Using Timing-Offset Differential Signal

- Time-Domain Simulation Results
  - TDT Common-Mode and TDR Differential-Mode Noises



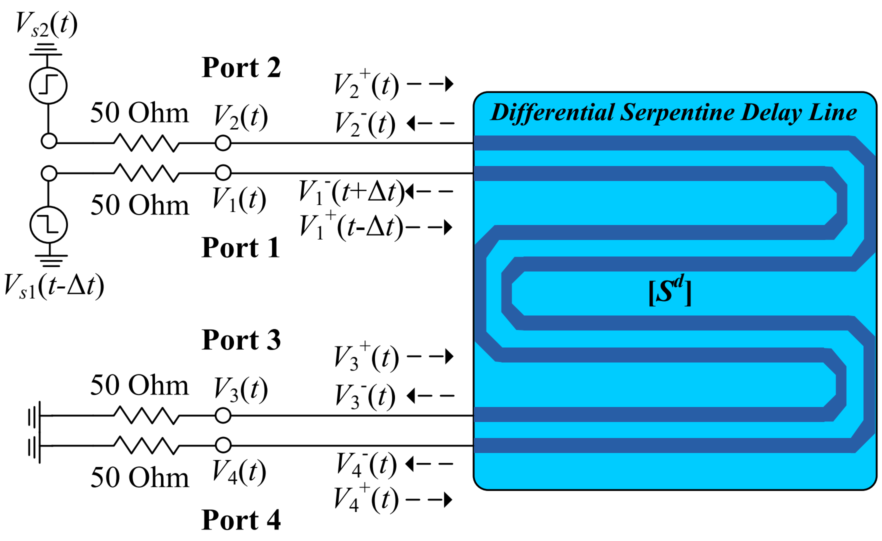


TDT common-mode noise (V)	Conventional	0.0289
	Timing-Offset Conventional	0.0117
TDR differential-mode noise (V)	Conventional	0.0356
	Timing-Offset Conventional	0.0357

Differential Serpentine Delay Line Using Timing-Offset Differential Signal

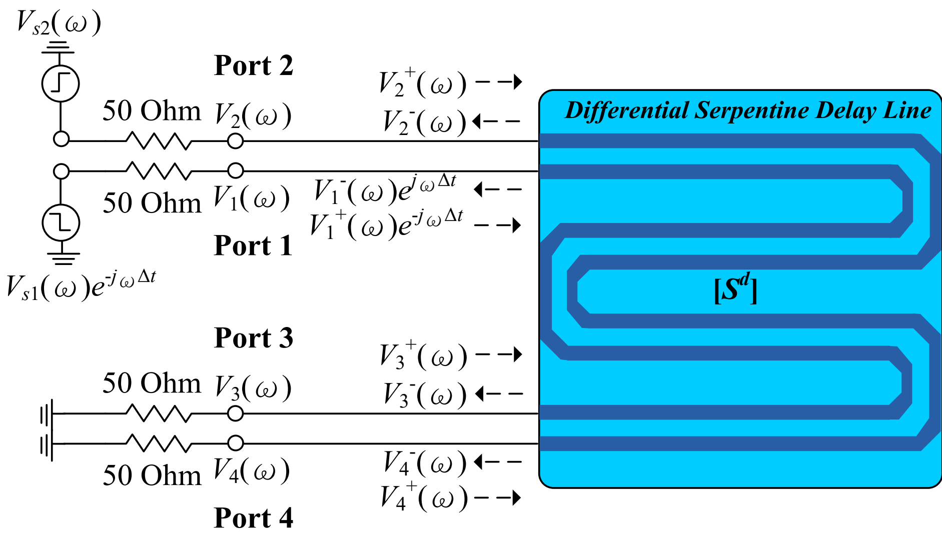
- Equivalent Mixed Mode *S*-parameters
  - Time- and Frequency-Domain Circuits

A



Time-Domain Simulation Circuit

B



Frequency-Domain Simulation Circuit

Differential Serpentine Delay Line Using Timing-Offset Differential Signal

- Equivalent Mixed Mode *S*-parameters
  - From the Frequency-Domain Circuit

$$\begin{bmatrix} V_1^-(\omega)e^{j\omega\Delta t} \\ V_2^-(\omega) \\ V_3^-(\omega) \\ V_4^-(\omega) \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} V_1^+(\omega)e^{-j\omega\Delta t} \\ V_2^+(\omega) \\ V_3^+(\omega) \\ V_4^+(\omega) \end{bmatrix}$$

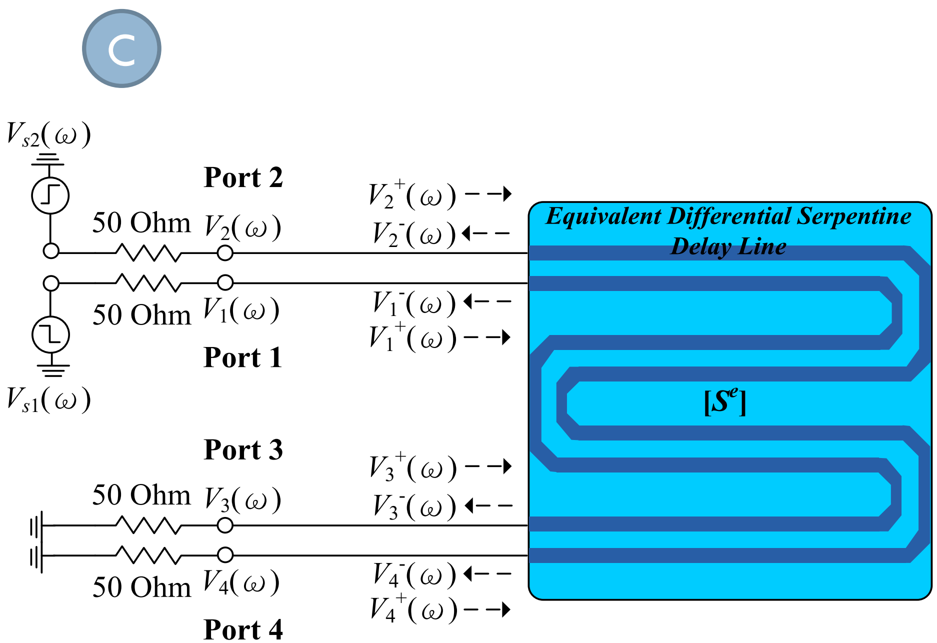
$$\left[S^d\right] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

$$\begin{bmatrix} V_1^-(\omega) \\ V_2^-(\omega) \\ V_3^-(\omega) \\ V_4^-(\omega) \end{bmatrix} = \begin{bmatrix} S_{11}e^{-j2\omega\Delta t} & S_{12}e^{-j\omega\Delta t} & S_{13}e^{-j\omega\Delta t} & S_{14}e^{-j\omega\Delta t} \\ S_{21}e^{-j\omega\Delta t} & S_{22} & S_{23} & S_{24} \\ S_{31}e^{-j\omega\Delta t} & S_{32} & S_{33} & S_{34} \\ S_{41}e^{-j\omega\Delta t} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} V_1^+(\omega) \\ V_2^+(\omega) \\ V_3^+(\omega) \\ V_4^+(\omega) \end{bmatrix}$$

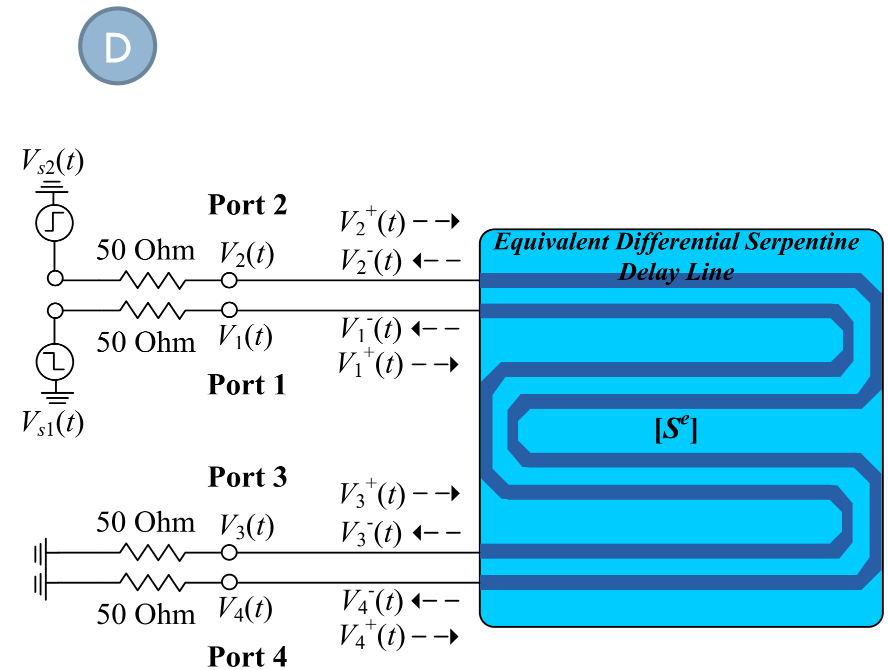
$$\left[S^e\right] = \begin{bmatrix} S_{11}^e & S_{12}^e & S_{13}^e & S_{14}^e \\ S_{21}^e & S_{22}^e & S_{23}^e & S_{24}^e \\ S_{31}^e & S_{32}^e & S_{33}^e & S_{34}^e \\ S_{41}^e & S_{42}^e & S_{43}^e & S_{44}^e \end{bmatrix} = \begin{bmatrix} S_{11}e^{-j2\omega\Delta t} & S_{12}e^{-j\omega\Delta t} & S_{13}e^{-j\omega\Delta t} & S_{14}e^{-j\omega\Delta t} \\ S_{21}e^{-j\omega\Delta t} & S_{22} & S_{23} & S_{24} \\ S_{31}e^{-j\omega\Delta t} & S_{32} & S_{33} & S_{34} \\ S_{41}e^{-j\omega\Delta t} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

Differential Serpentine Delay Line Using Timing-Offset Differential Signal

- Equivalent Mixed Mode S-parameters
  - Equivalent Time- and Frequency-Domain Circuits



Frequency-Domain Simulation Circuit



Time-Domain Simulation Circuit

Differential Serpentine Delay Line Using Timing-Offset Differential Signal

- Equivalent Mixed Mode *S*-parameters
  - Equivalent Differential-to-Common Mode Conversion

$$S^{e}_{c2d1} = \frac{1}{2}\left(S^{e}_{31} - S^{e}_{32} + S^{e}_{41} - S^{e}_{42}\right)$$

  - Equivalent Differential-to-Common Mode Reflection

$$S^{e}_{c1d1} = \frac{1}{2}\left(S^{e}_{11} - S^{e}_{12} + S^{e}_{21} - S^{e}_{22}\right)$$

  - Equivalent Differential-to-Differential Mode Reflection

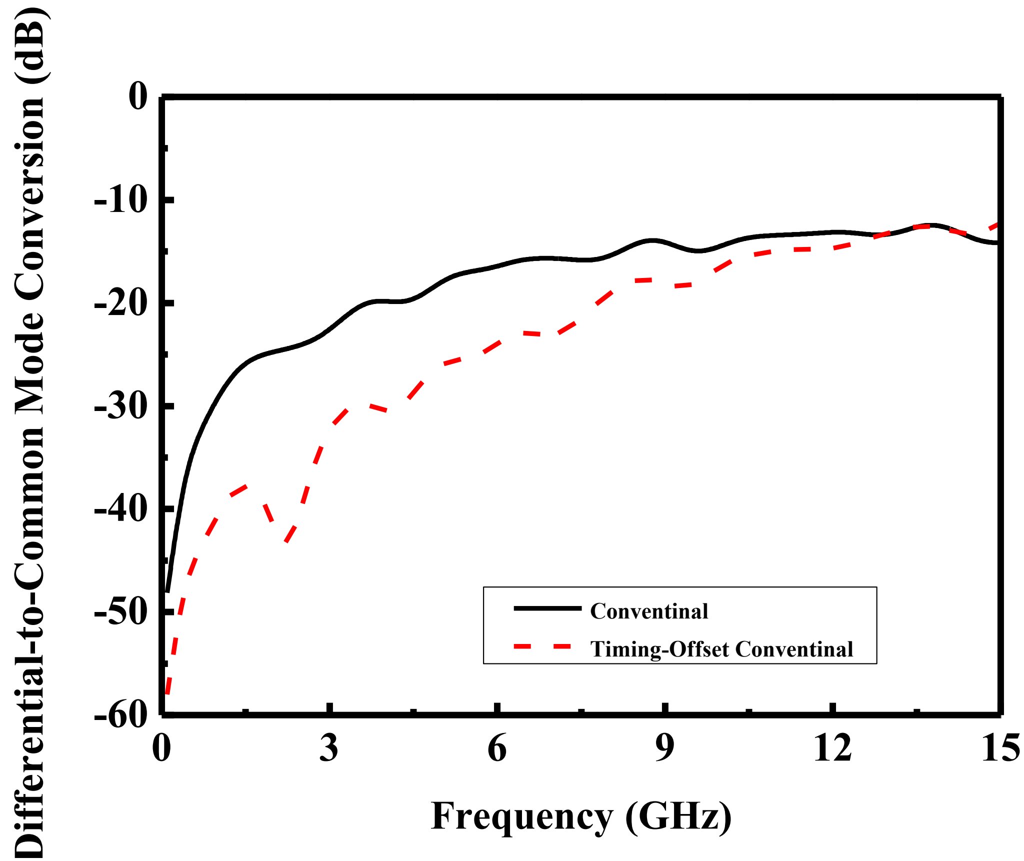
$$S^{e}_{d1d1} = \frac{1}{2}\left(S^{e}_{11} - S^{e}_{12} - S^{e}_{21} + S^{e}_{22}\right)$$

  - Equivalent Differential-to-Differential Mode Transmission

$$S^{e}_{d2d1} = \frac{1}{2}\left(S^{e}_{31} - S^{e}_{32} - S^{e}_{41} + S^{e}_{42}\right)$$

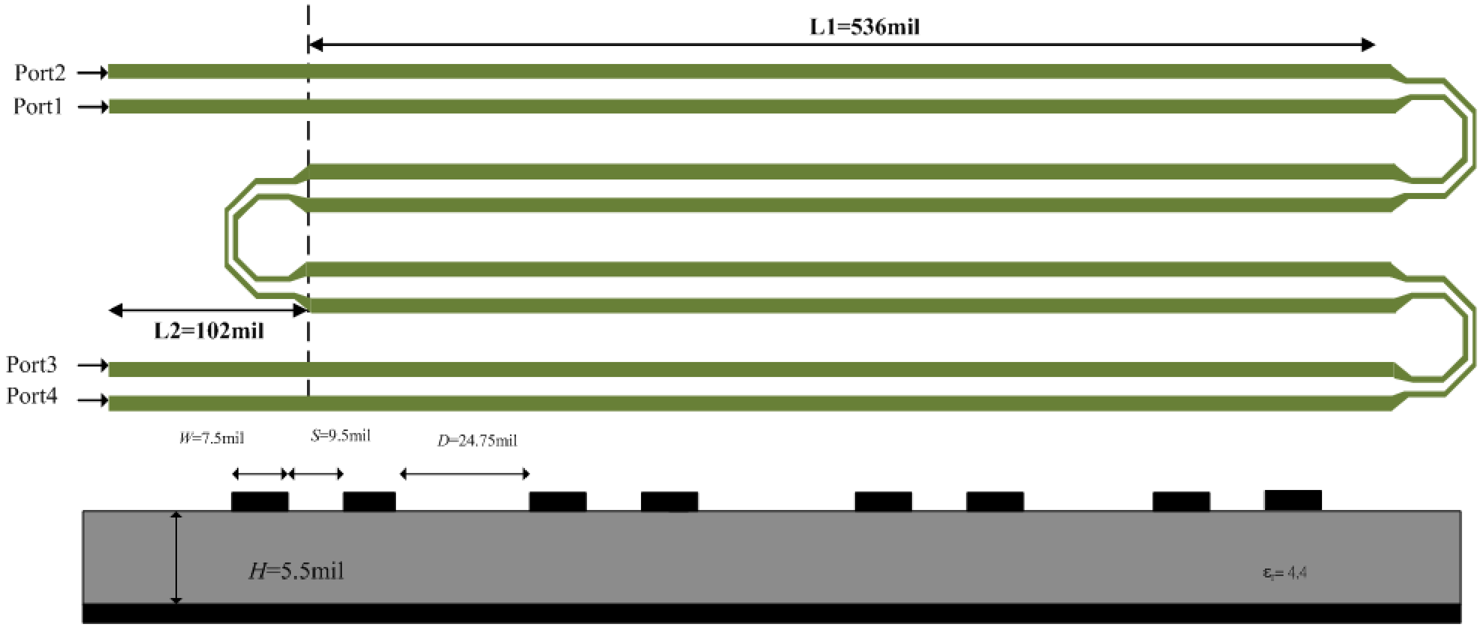
Differential Serpentine Delay Line Using Timing-Offset Differential Signal

- Equivalent Mixed Mode *S*-parameters
  - Equivalent Differential-to-Common Mode Conversion



Differential Serpentine Delay Line with Strongly-Coupled Turns

- Topology [9]
  - FR4 substrate with ε_r=4.4 and tanδ=0.02



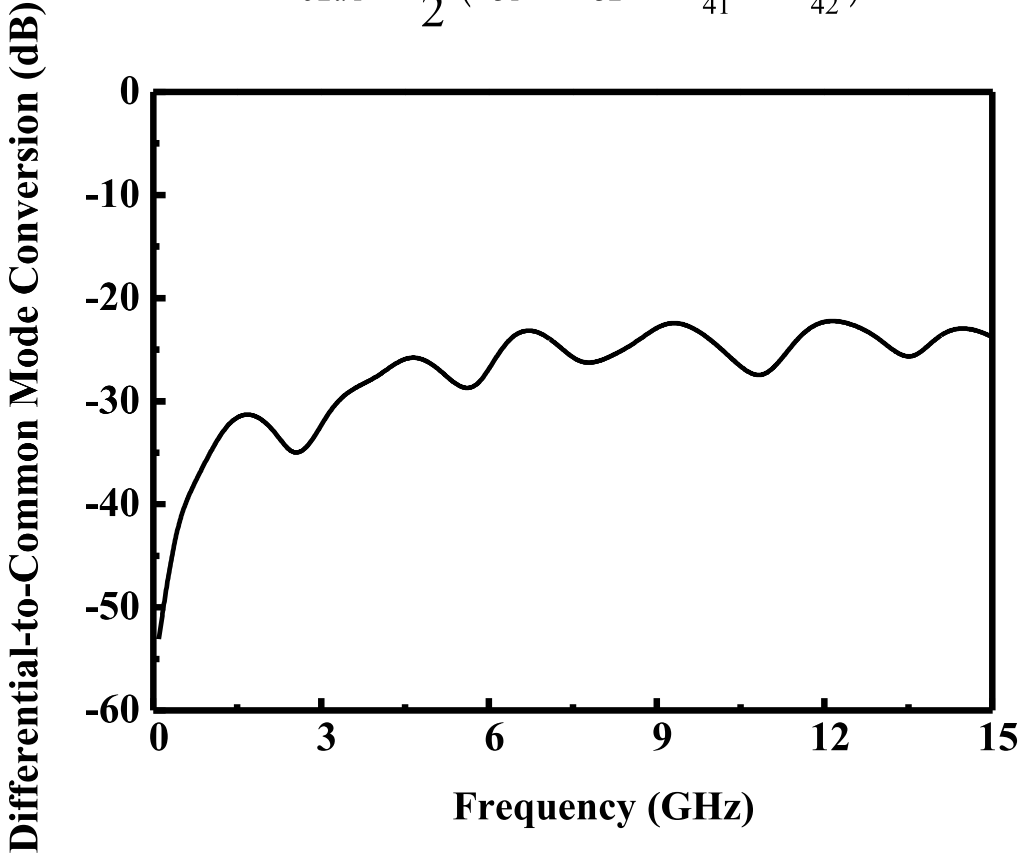
W	*S*	*H*	*D*
7.5 mil	9.5 mil	5.5 mil	24.75 mil

[9] G. H. Shiue, Y. C. Tsai, C. M. Hsu, and J. H. Shiu, "Common-mode noise reduction schemes for differential serpentine delay microstrip line in high-speed digital circuits," *IEEE 20th20 th Topical Meeting on Electrical Performance of Electronic Packaging*, pp. 211-214, Oct. 2011.

Differential Serpentine Delay Line with Strongly-Coupled Turns

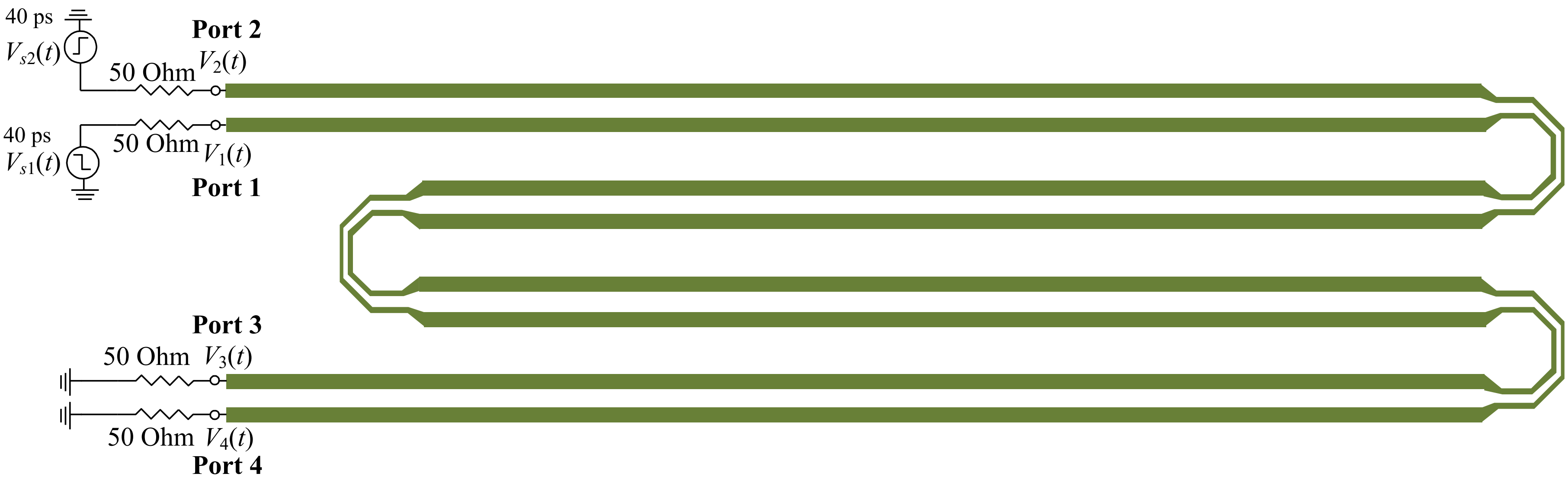
- Mixed Mode *S*-parameters
  - Differential- to Common-Mode Conversion

$$S_{c2d1} = \frac{1}{2}\left(S_{31} - S_{32} + S_{41} - S_{42}\right)$$



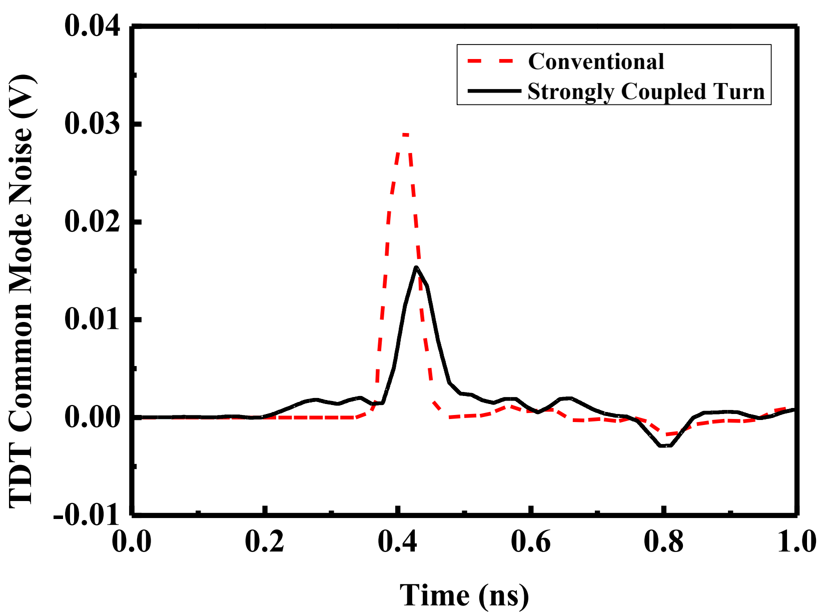
Differential Serpentine Delay Line with Strongly-Coupled Turns

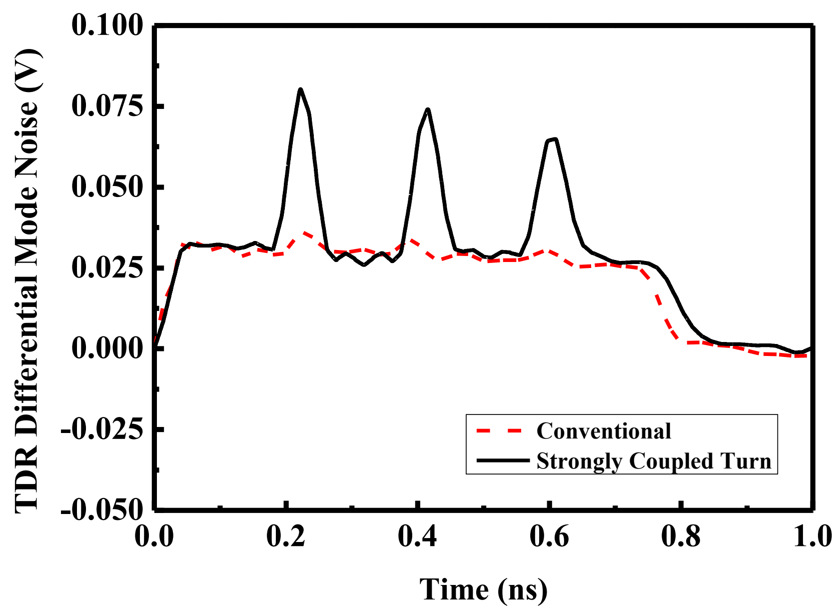
- Time-Domain Simulation Setup
  - Input Source
    - Differential signal with amplitude ±0.5 V and rise time 40 ps



Differential Serpentine Delay Line with Strongly-Coupled Turns

- Time-Domain Simulation Results
  - TDT Common-Mode and TDR Differential-Mode Noises





TDT common-mode noise (V)	0.0154
TDR Differential-mode noise (V)	0.0769

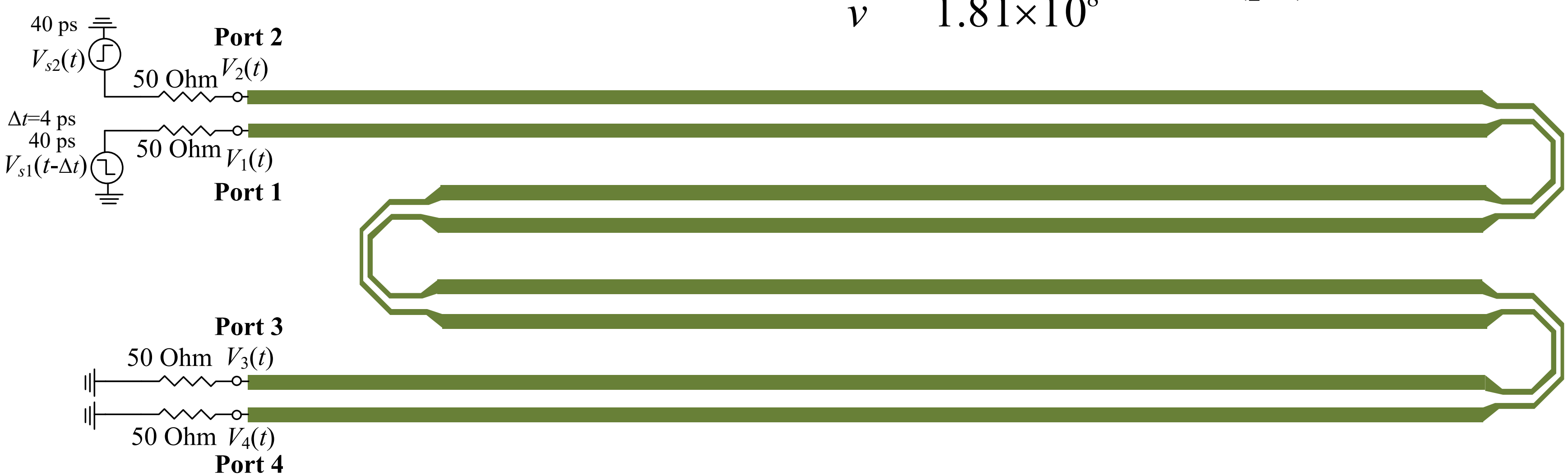
Differential Serpentine Delay Line with Strongly-Coupled Turns Using Timing-Offset Differential Signal

- Time-Domain Simulation Setup
  - Input Source
    - Differential signal with amplitude ±0.5 V and rise time 40 ps

Required Offset time

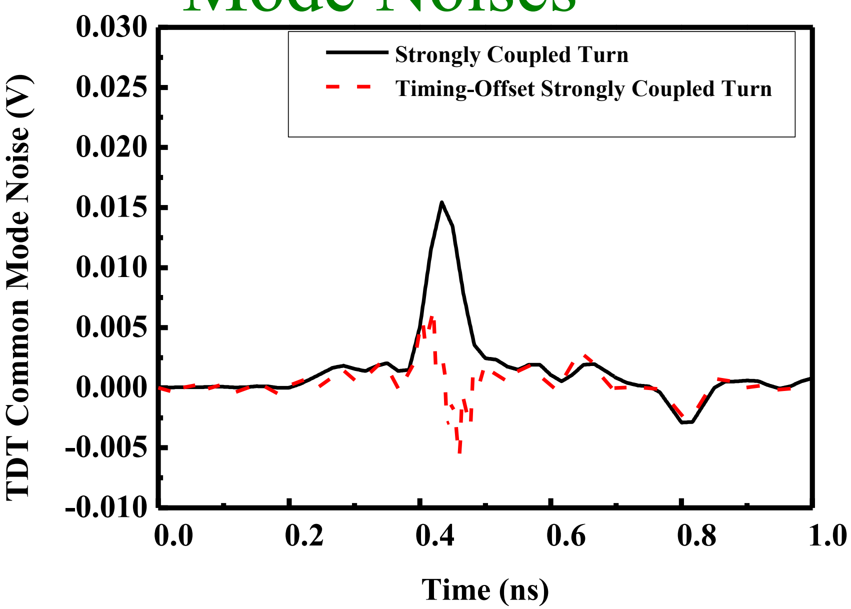
$$v = \left(v_{odd} + v_{even}\right) \times 0.5 = 1.81 \times 10^{8} (m/s)$$

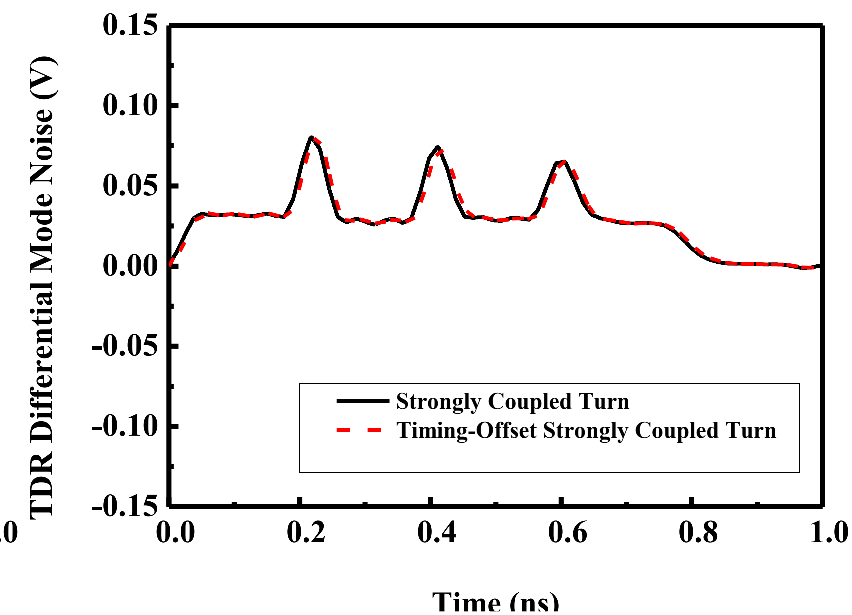
$$\Delta t = \frac{\Delta L}{v} = \frac{26mil}{1.81 \times 10^{8}} = 3.64(ps)$$



Differential Serpentine Delay Line with Strongly-Coupled Turns Using Timing-Offset Differential Signal

- Time-Domain Simulation Results
  - TDT Common-Mode and TDR Differential-Mode Noises

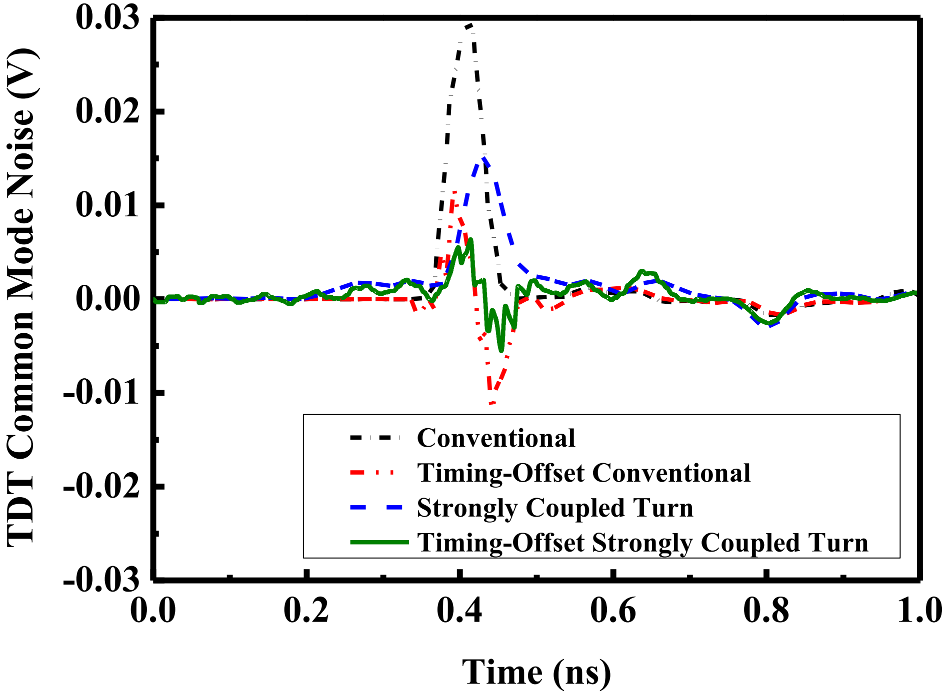


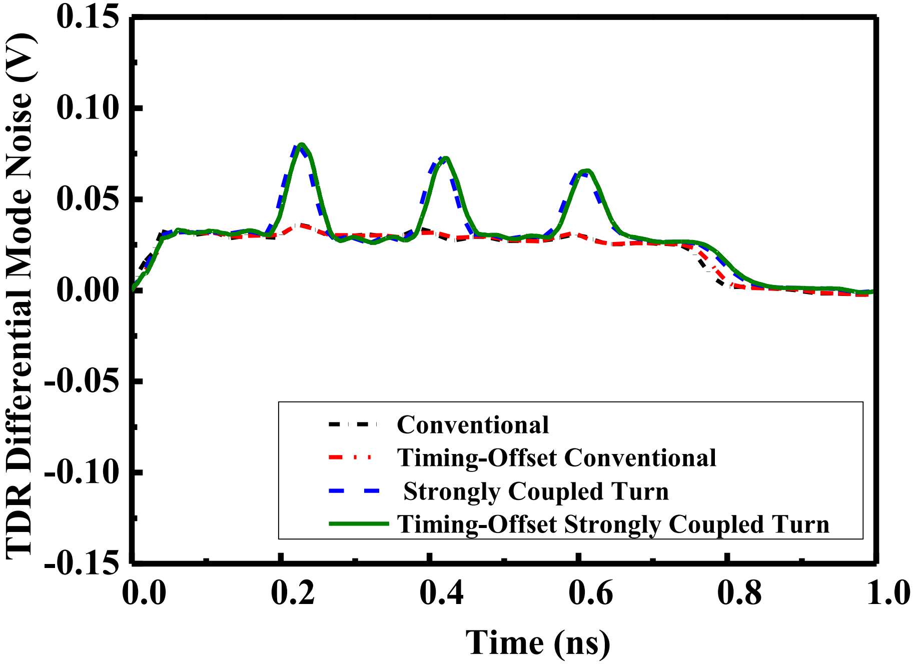


TDT common-mode noise (V)	Strongly Coupled Turn	0.0154
	Timing-Offset Strongly Coupled Turns	0.0065
TDR differential-mode noise (V)	Strongly Coupled Turn	0.0769
	Timing-Offset Strongly Coupled Turns	0.0801

Differential Serpentine Delay Line with Strongly-Coupled Turns Using Timing-Offset Differential Signal

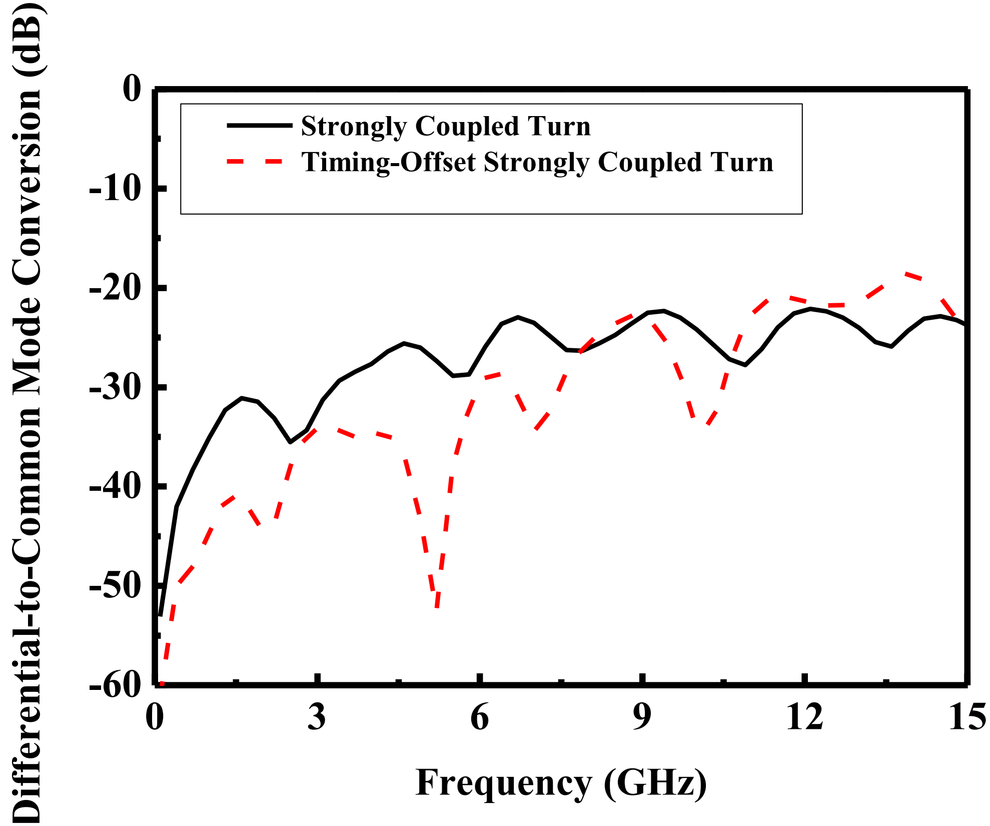
- Time-Domain Simulation Results
  - TDT Common-Mode and TDR Differential-Mode Noises
    - Comparison between the four structures





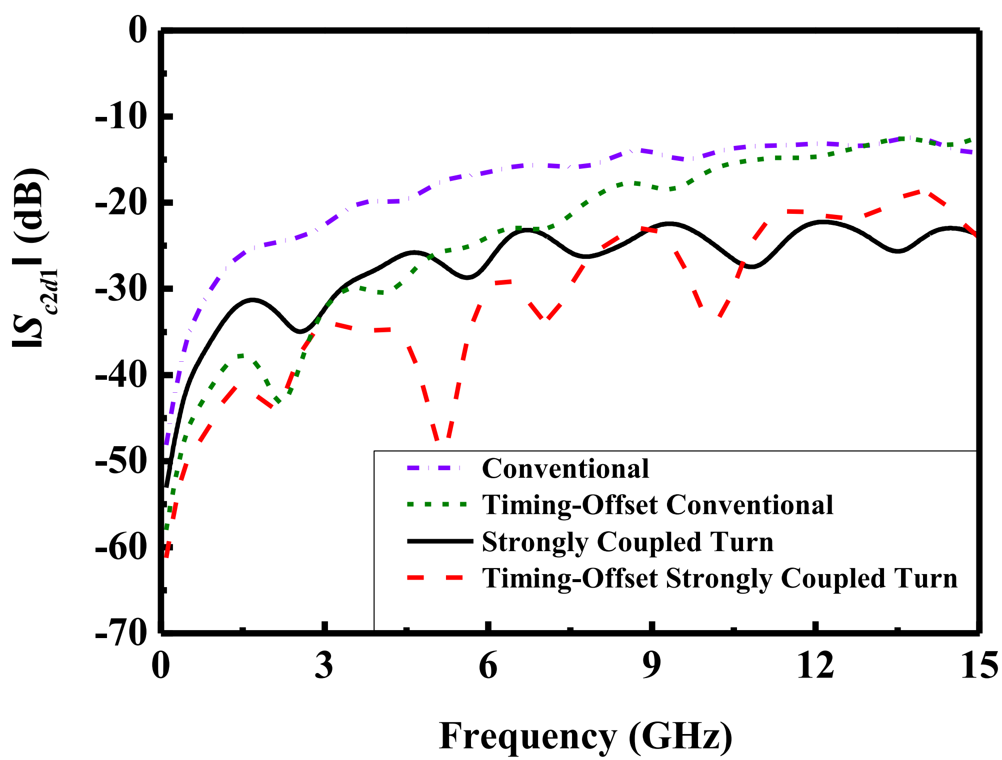
Differential Serpentine Delay Line with Strongly-Coupled Turns Using Timing-Offset Differential Signal

- Equivalent Mixed Mode *S*-parameters
  - Equivalent Differential-to-Common Mode Conversion



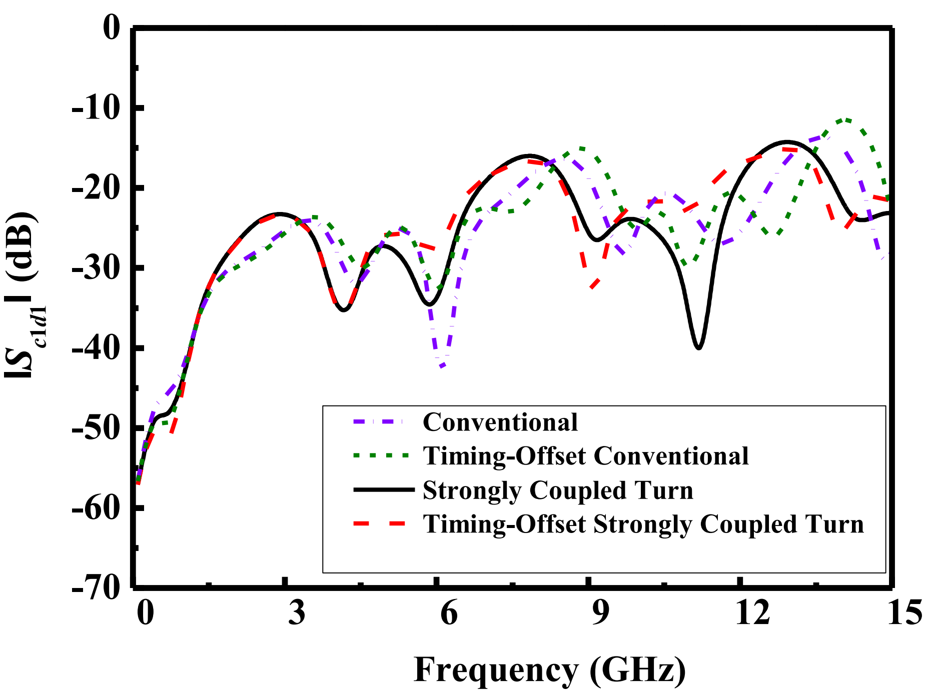
Differential Serpentine Delay Line with Strongly-Coupled Turns Using Timing-Offset Differential Signal

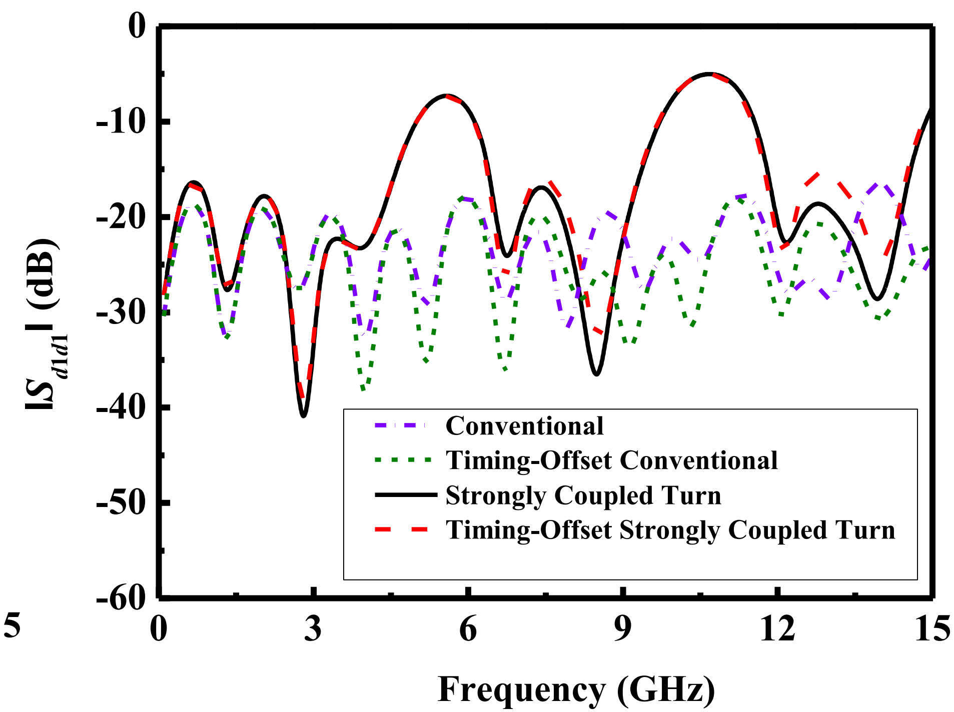
- Equivalent Mixed Mode *S*-parameters
  - Comparison between the Four Structures
    - Differential- to common-mode conversion



Differential Serpentine Delay Line with Strongly-Coupled Turns Using Timing-Offset Differential Signal

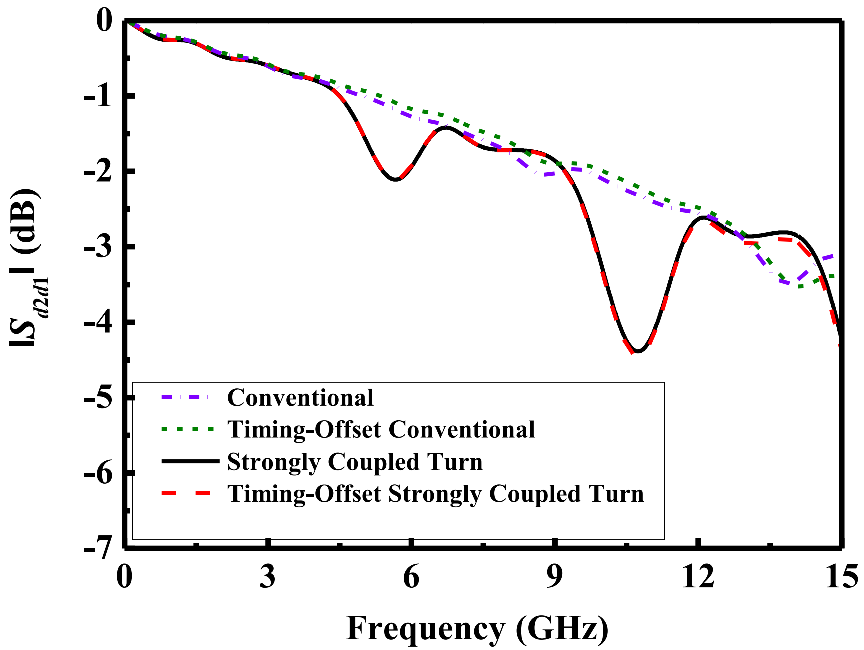
- Equivalent Mixed Mode *S*-parameters
  - Comparison between the Four Structures
    - Differential- to common-mode reflection
    - Differential- to differential-mode reflection

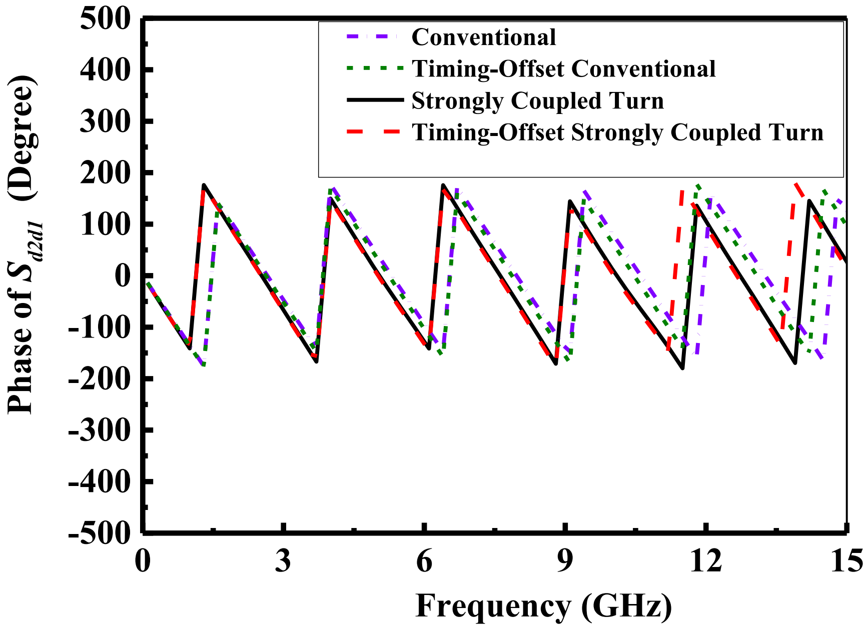




Differential Serpentine Delay Line with Strongly-Coupled Turns Using Timing-Offset Differential Signal

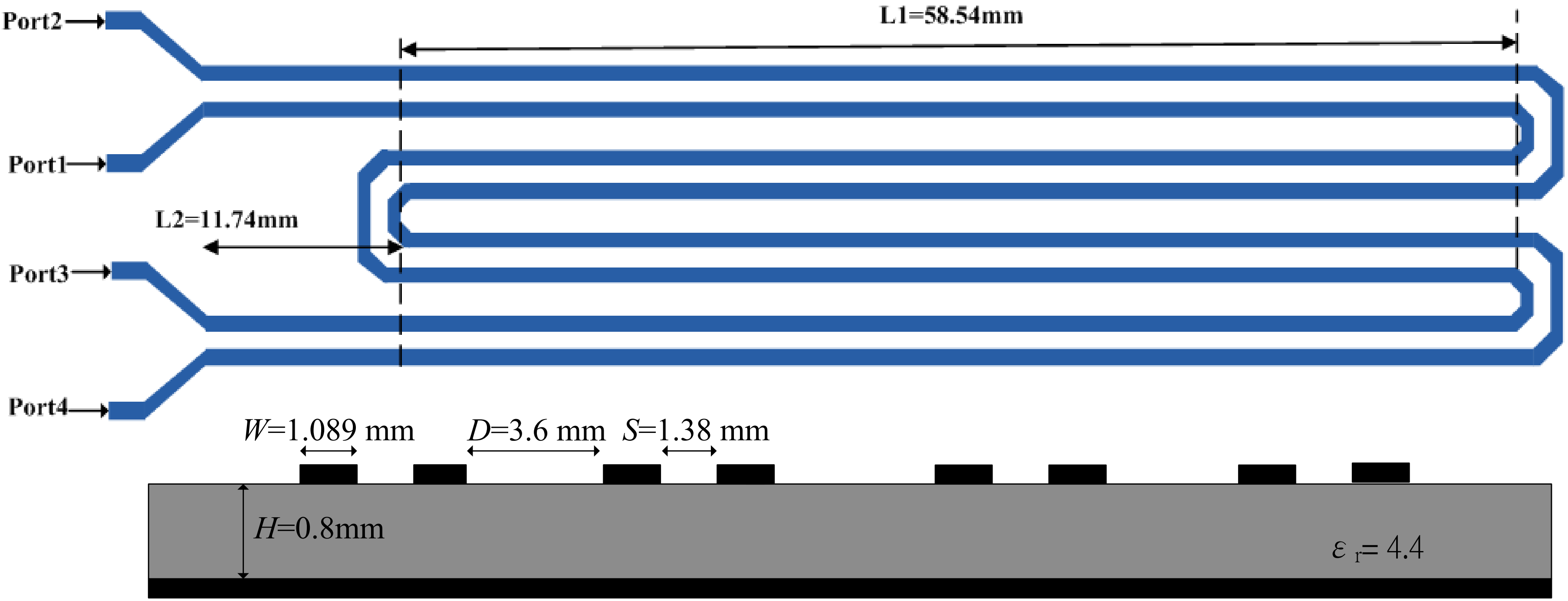
- Equivalent Mixed Mode *S*-parameters
  - Comparison between the Four Structures
    - Differential- to differential-mode transmission





Scaled Down Verifications

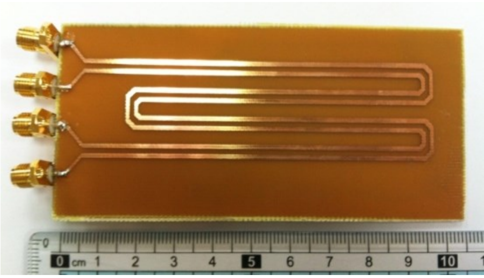
- Differential Serpentine Delay Line
  - 5.72 Times Scaled Down Topology
    - FR4 substrate with ε_r=4.4 and tanδ=0.02

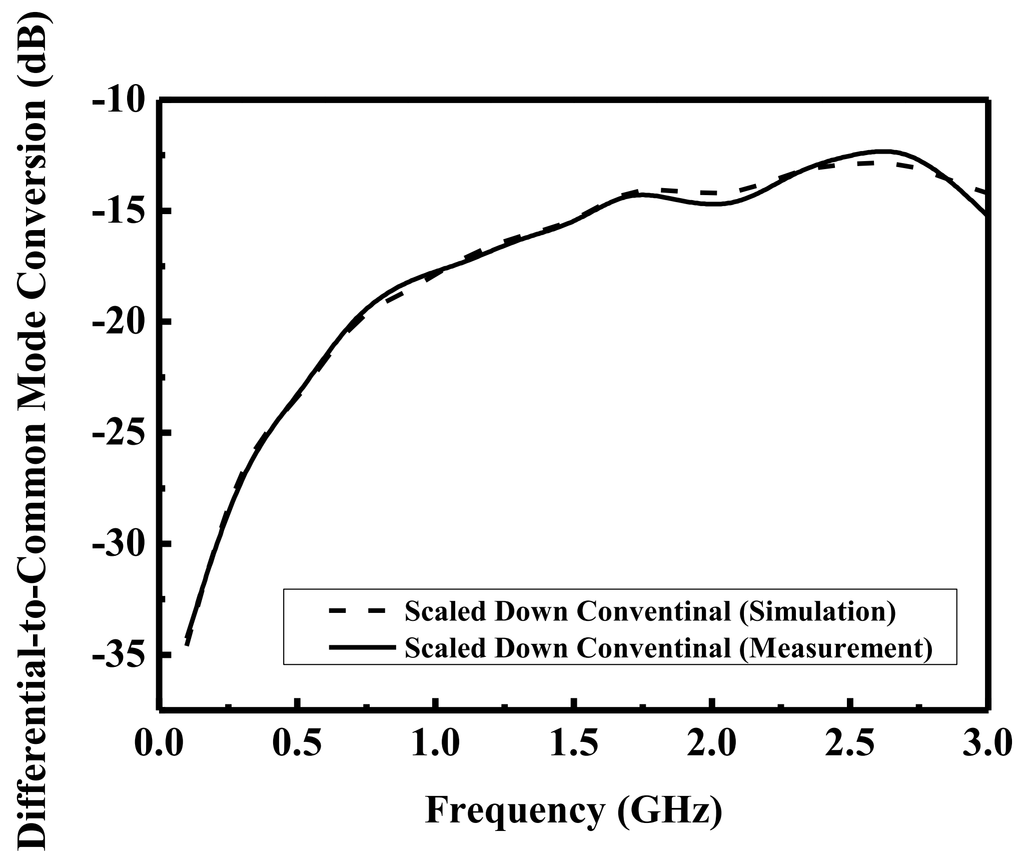


W	*S*	*H*	*D*
1.089 mm	1.38 mm	0.8 mm	3.6 mm

Scaled Down Verifications

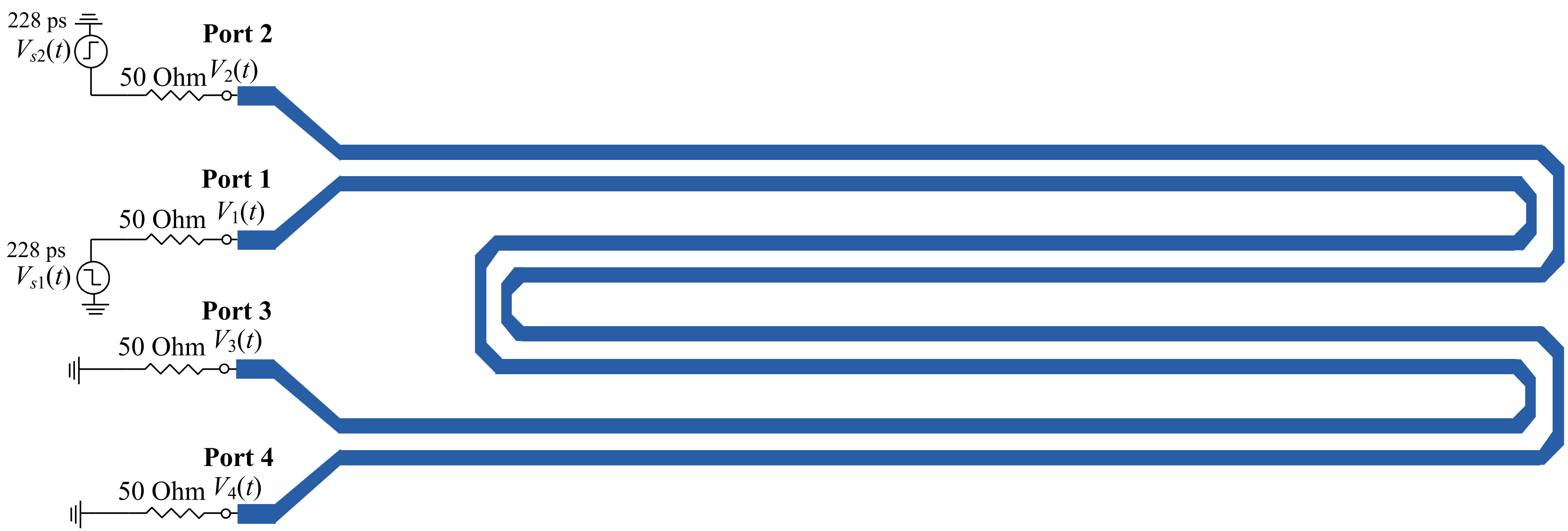
- Differential Serpentine Delay Line
  - Mixed Mode S-parameters
    - Differential- to Common-Mode Conversion





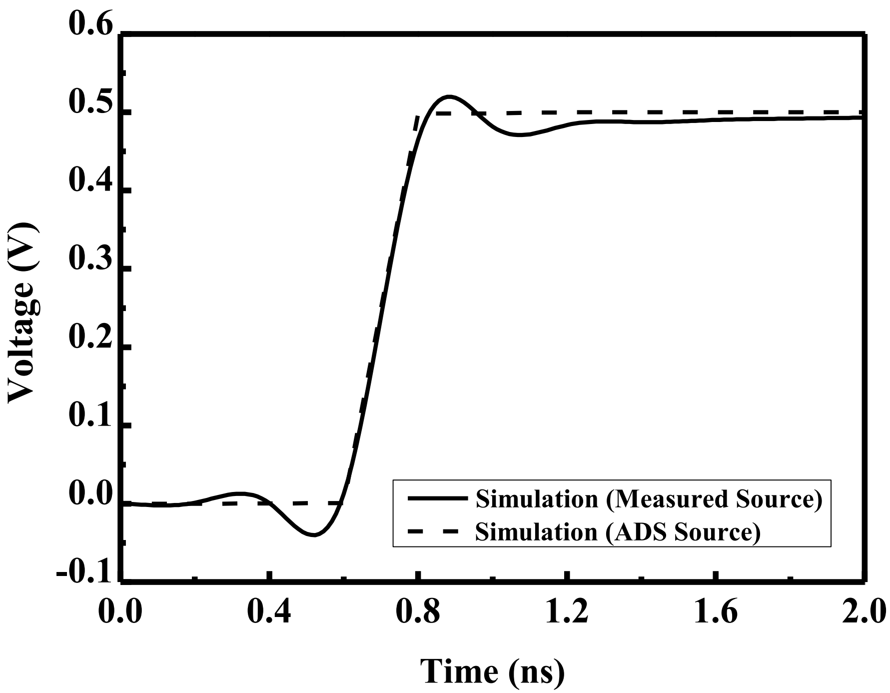
Scaled Down Verifications

- Differential Serpentine Delay Line
  - Time-Domain Simulation Setup
    - Input source: differential signal with amplitude ±0.5 V and rise time 228 ps

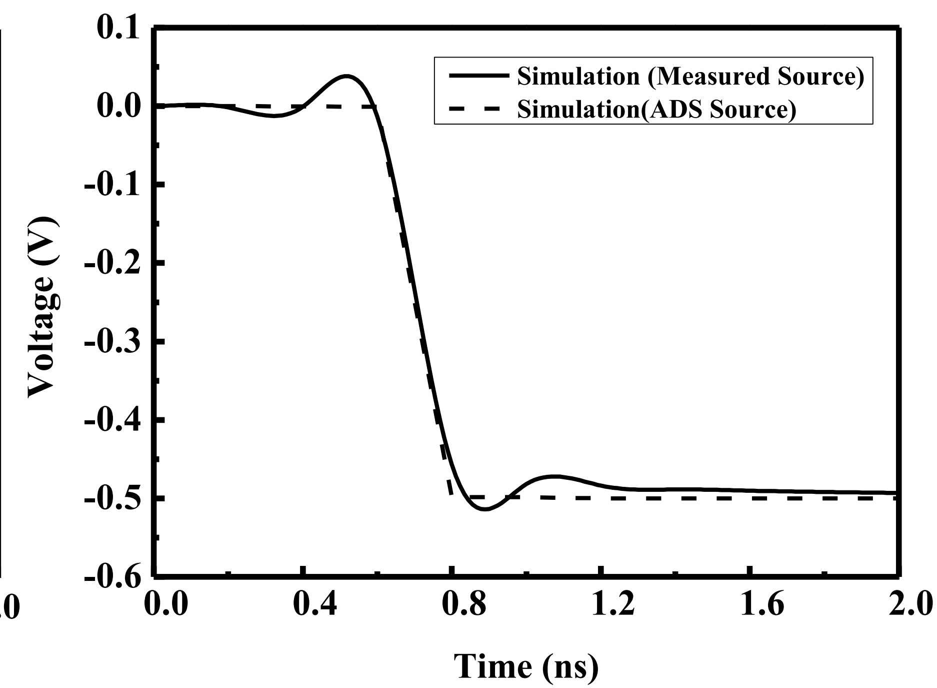


Scaled Down Verifications

- Differential Serpentine Delay Line
  - Time-Domain Simulation Setup
    - Measured and ADS sources used in simulation



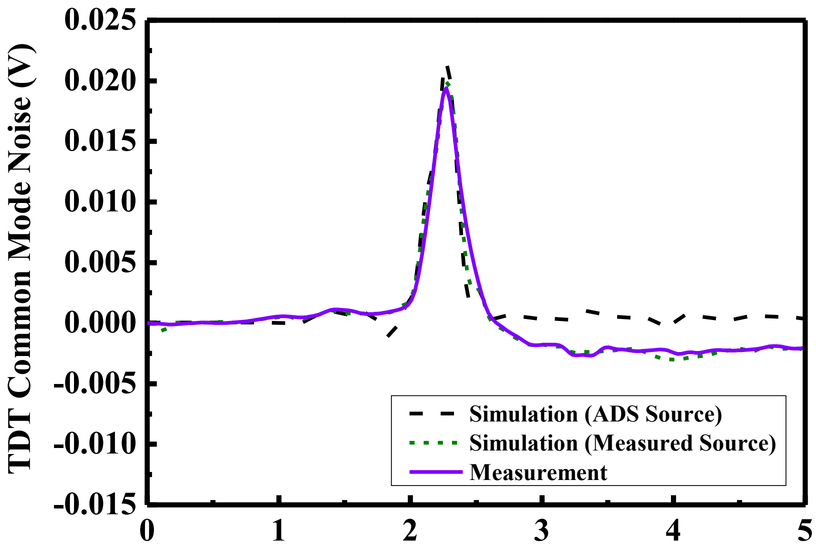
Channel 1

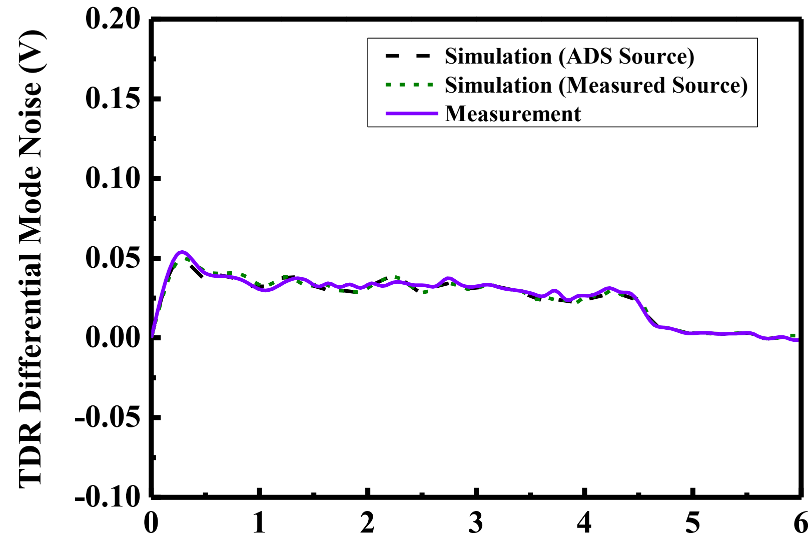


Channel 2

Scaled Down Verifications

- Differential Serpentine Delay Line
  - Time-Domain Results
    - TDT Common-Mode and TDR Differential-Mode Noises

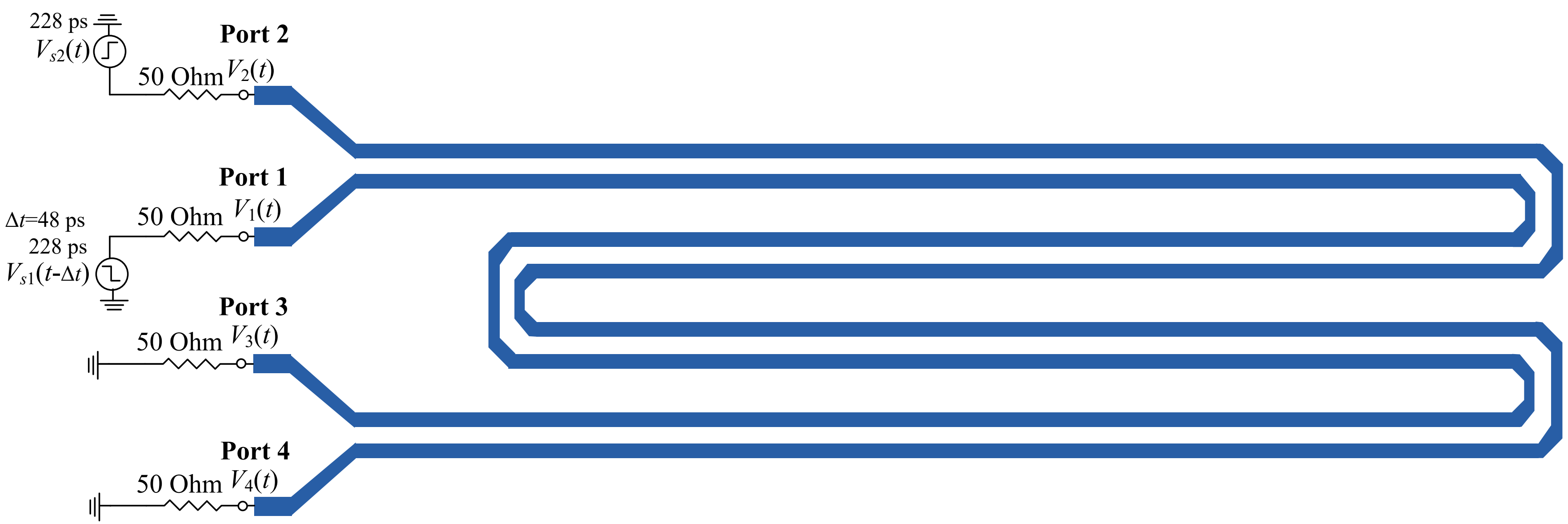




TDT common-mode noise(V)	Simulation (ADS source)	0.0215
	Measurement	0.0194
TDR differential-mode noise (V)	Simulation (ADS source)	0.0497
	Measurement	0.0532

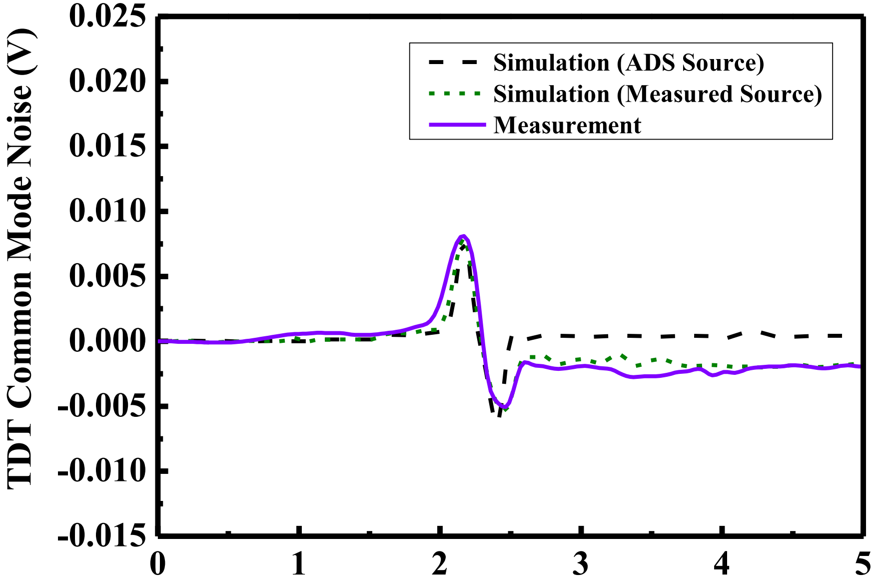
Scaled Down Verifications

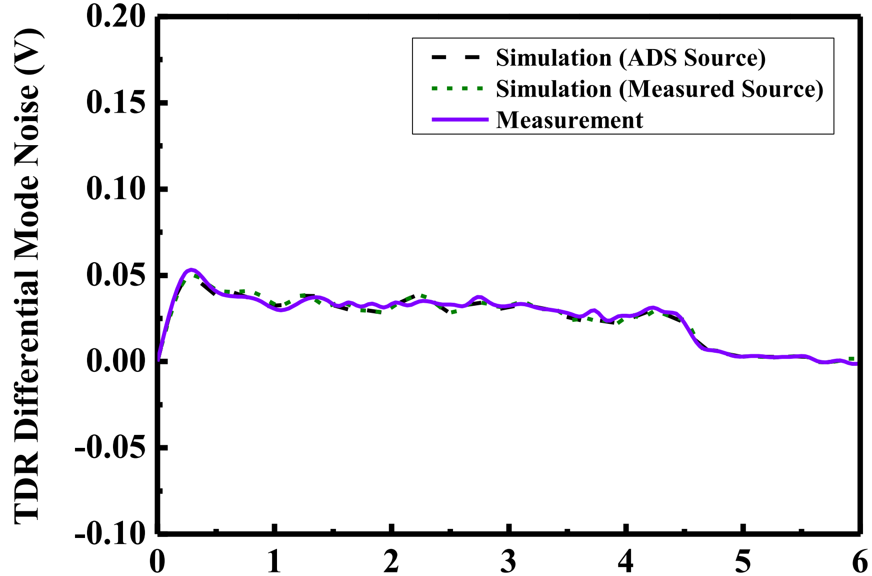
- Differential Serpentine Delay Line
  - Time-Domain Simulation Setup
    - Input source: differential signal with amplitude ±0.5 V, rise time 228 ps, and offset time 48 ps.



Scaled Down Verifications

- Differential Serpentine Delay Line
  - Time-Domain Results
    - TDT Common-Mode and TDR Differential-Mode Noises

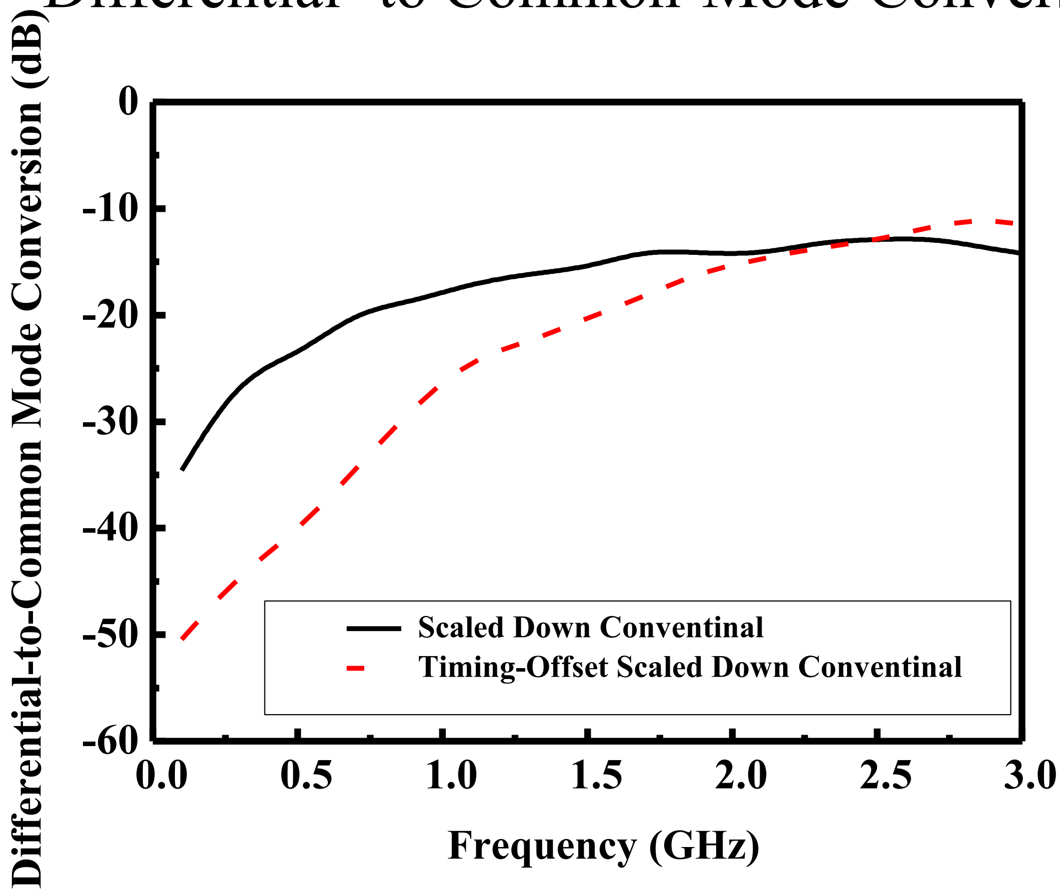




TDT common-mode noise(V)	Simulation (ADS source)	0.0078
	Measurement	0.0081
TDR differential-mode noise (V)	Simulation (ADS source)	0.0497
	Measurement	0.0533

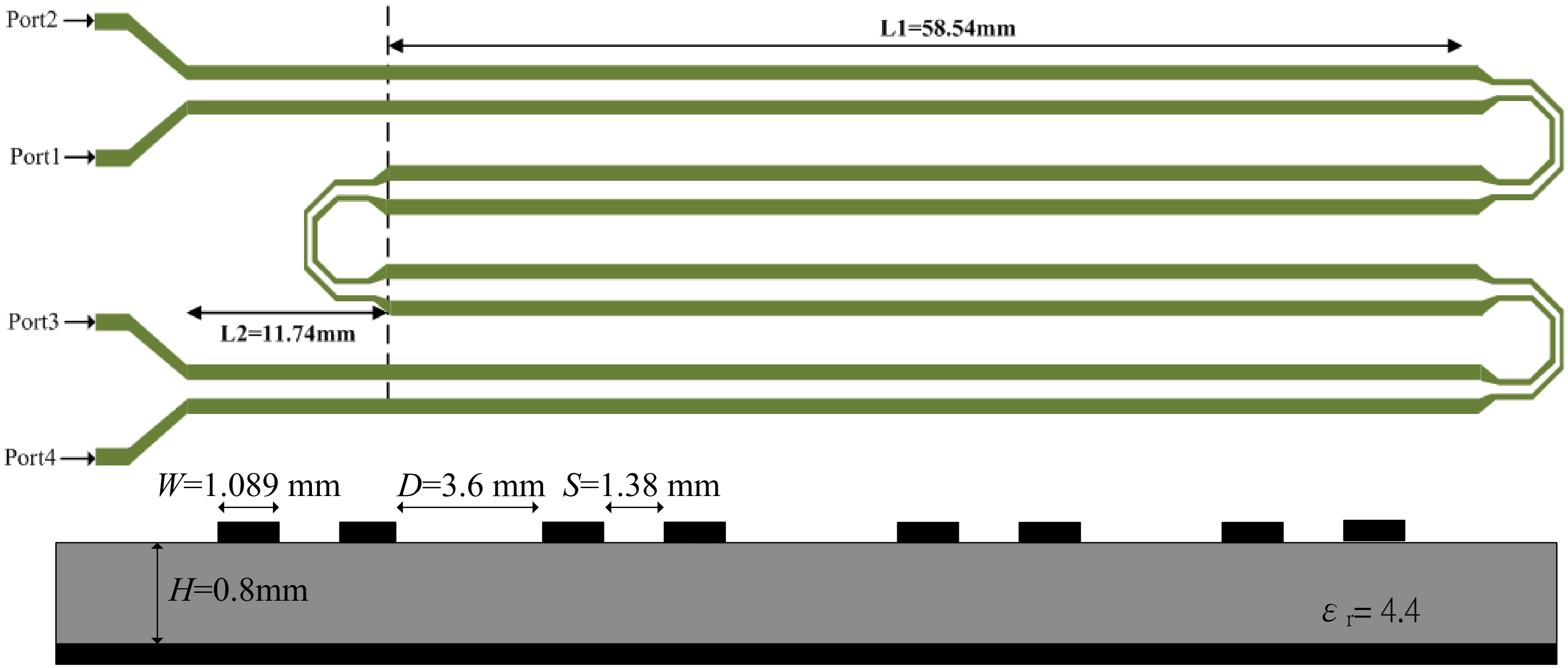
Scaled Down Verifications

- Differential Serpentine Delay Line
  - Mixed Mode S-parameters
    - Differential- to Common-Mode Conversion



Scaled Down Verifications

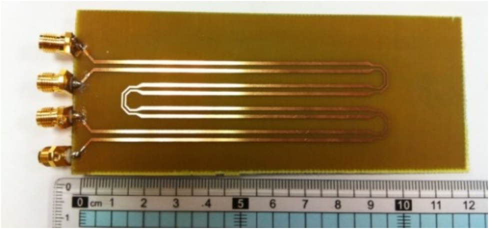
- Differential Serpentine Delay Line with Strongly-Coupled Turns
  - 5.72 Times Scaled Down Topology



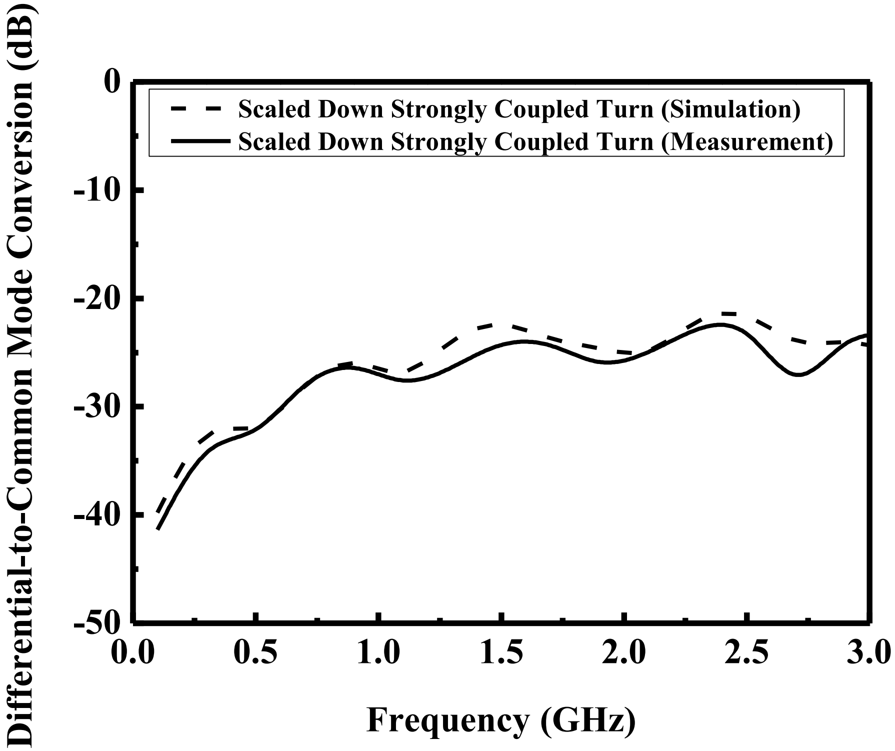
W	S	H	D
1.089 mm	1.38 mm	0.8 mm	3.6 mm

Scaled Down Verifications

- Differential Serpentine Delay Line with Strongly-Coupled Turns

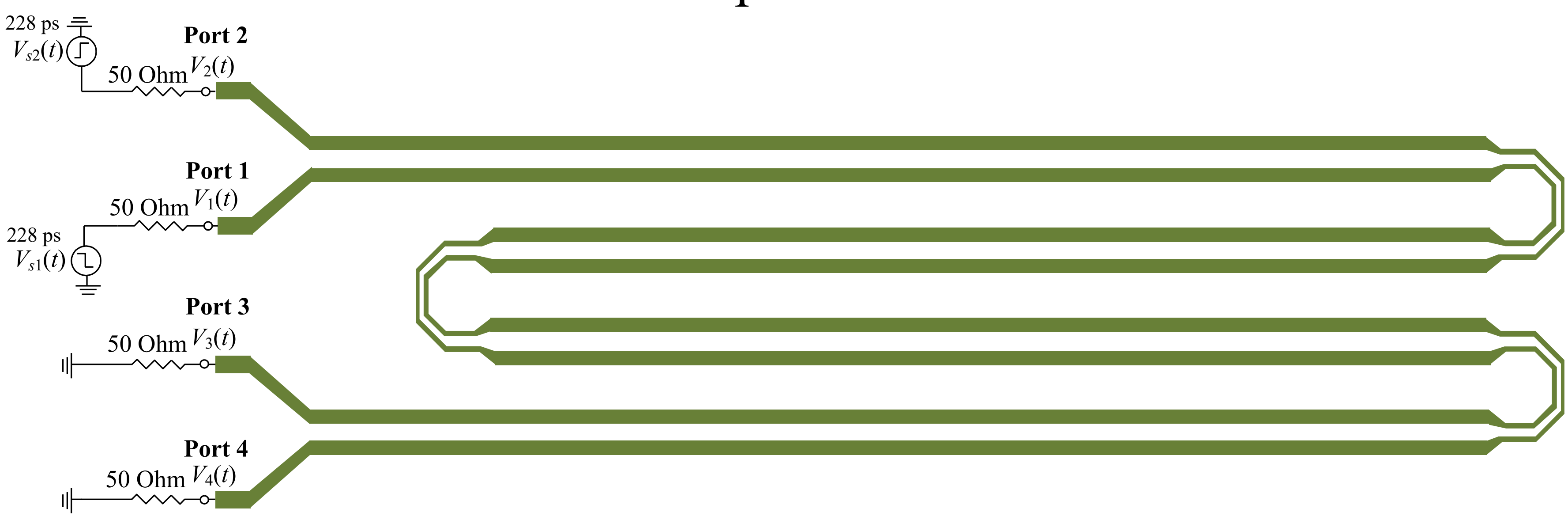


  - Mixed Mode S-parameters
    - Differential- to Common-Mode Conversion



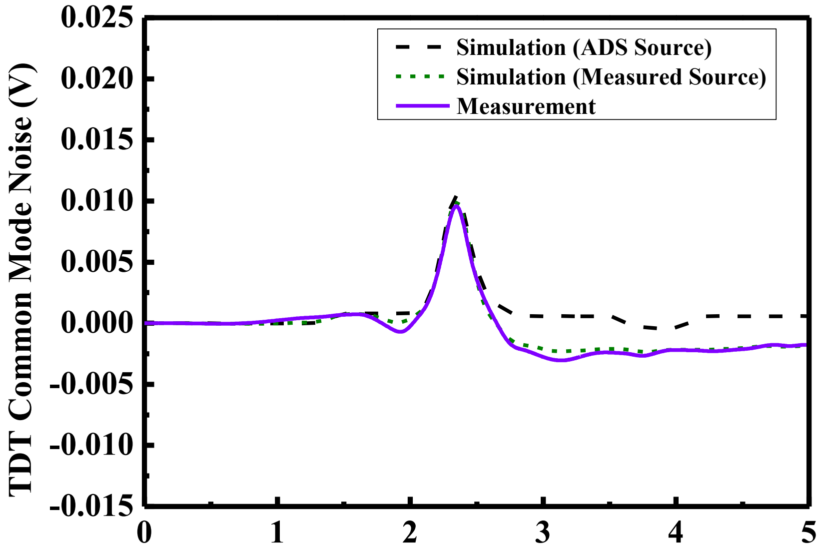
Scaled Down Verifications

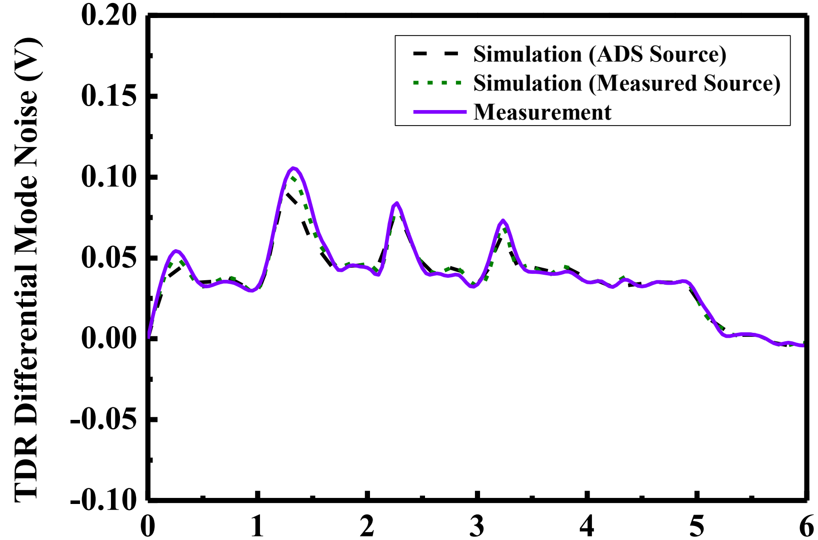
- Differential Serpentine Delay Line with Strongly-Coupled Turns
  - Time-Domain Simulation Setup
    - Input source: differential signal with amplitude ±0.5 V and rise time 228 ps



Scaled Down Verifications

- Differential Serpentine Delay Line with Strongly-Coupled Turns
  - Time-Domain Results
    - TDT Common-Mode and TDR Differential-Mode Noises

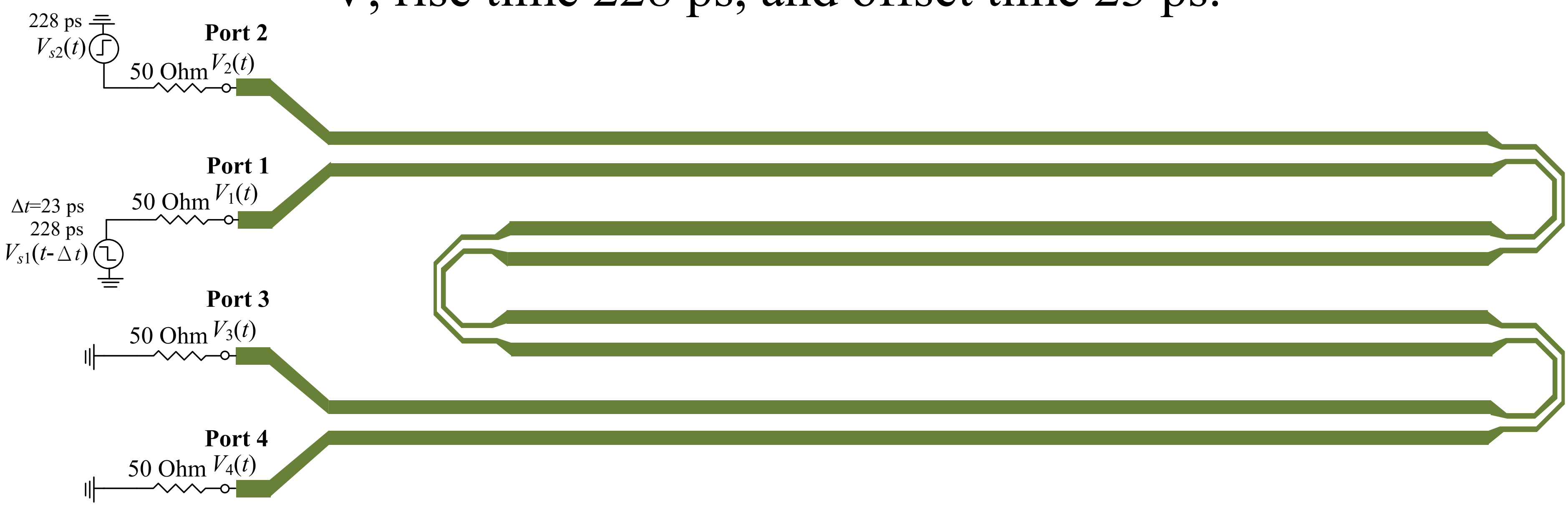




TDT common-mode noise(V)	Simulation (ADS source)	0.0105
	Measurement	0.0098
TDR differential-mode noise (V)	Simulation (ADS source)	0.0892
	Measurement	0.0978

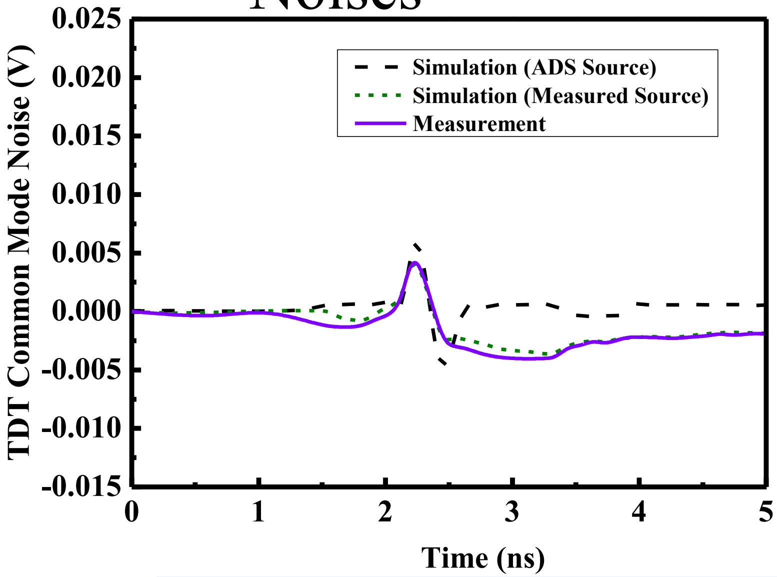
Scaled Down Verifications

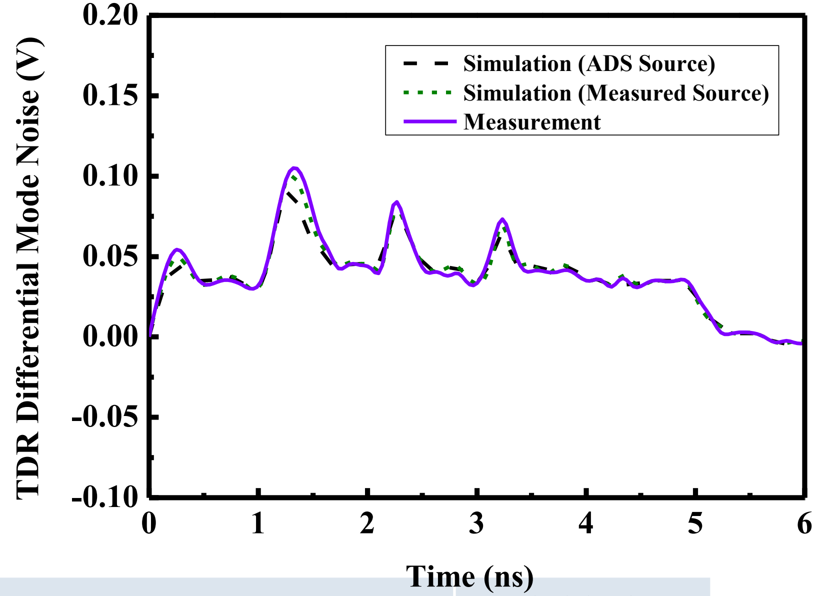
- Differential Serpentine Delay Line with Strongly-Coupled Turns
  - Time-Domain Simulation Setup
    - Input source: differential signal with amplitude ±0.5 V, rise time 228 ps, and offset time 23 ps.



Scaled Down Verifications

- Differential Serpentine Delay Line with Strongly-Coupled Turns
  - Time-Domain Results
    - TDT Common-Mode and TDR Differential-Mode Noises

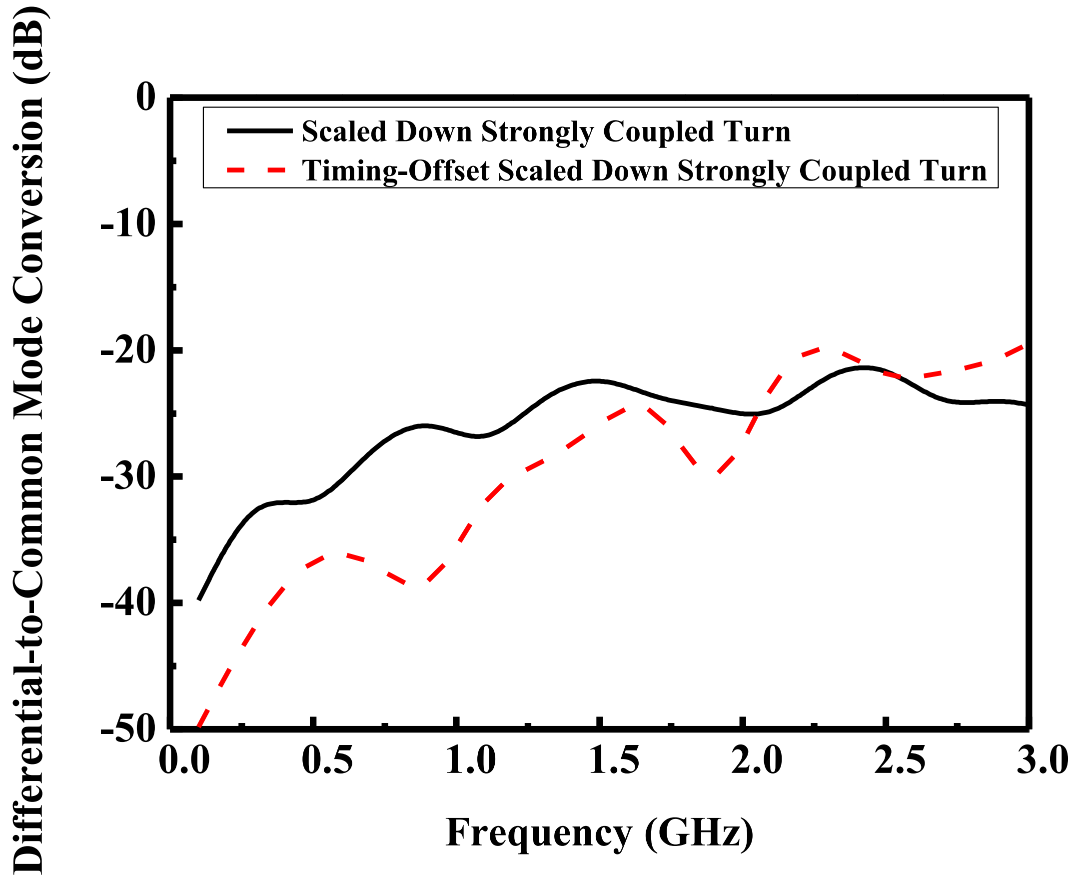




TDT common-mode noise(V)	Simulation (ADS source)	0.0059
	Measurement	0.0046
TDR differential-mode noise (V)	Simulation (ADS source)	0.0892
	Measurement	0.0978

Scaled Down Verifications

- Differential Serpentine Delay Line with Strongly-Coupled Turns
  - Mixed Mode S-parameters
    - Differential- to Common-Mode Conversion



Conclusions

- Various Differential Serpentine Delay Lines
  - TDT Common-Mode and TDR Differential-Mode Noises

	Conventional	Timing-offset differential signal	Strongly-coupled turns	Strongly-coupled turns with timing-offset differential signal
TDT common-mode noise (V)	0.0289	0.0117	0.0154	0.0065
TDR differential-mode noise (V)	0.0356	0.0357	0.0769	0.0801

Conclusions

- Various Scaled Down Differential Serpentine Delay Lines
  - TDT Common-Mode and TDR Differential-Mode Noises

		Conventional	Timing-offset differential signal	Strongly-coupled turns	Strongly-coupled turns with timing-offset differential signal
TDT common-mode noise (V)	Simulation (ADS source)	0.0215	0.0078	0.0105	0.0059
	Simulation (Measured source)	0.0199	0.0079	0.0103	0.0048
	Measurement	**0.0194**	**0.0081**	**0.0098**	**0.0046**
TDR differential-mode noise (V)	Simulation (ADS source)	0.0497	0.0497	0.0892	0.0892
	Simulation (Measured source)	0.0487	0.0487	0.0966	0.0966
	Measurement	**0.0532**	**0.0533**	**0.0978**	**0.0978**