DesignCon® 2013

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SANTA CLARA CONVENTION CENTER

Dramatic Noise Reduction using Guard Traces with Optimized Shorting Vias

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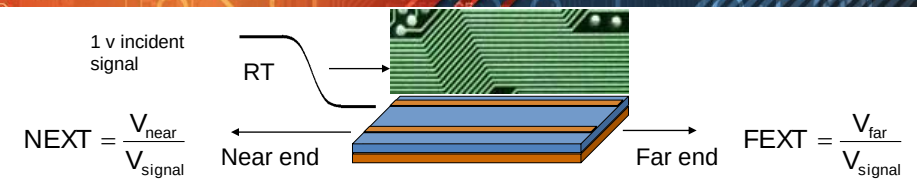
Be The Signal

13-WA_Bogatin_Simonovich_DramaticNoiseReductionUsingGuard

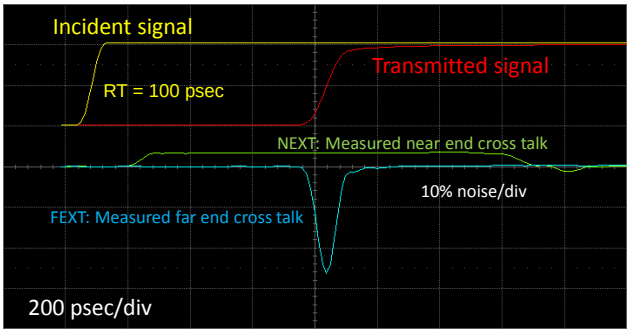
Overview

- Cross talk in uniform busses
- The nature of near and far end cross talk
- Impact of a guard trace on fringe fields
- Role of “contamination”
- How not to use guard traces
- Optimized shorting vias
- Second order, practical considerations

Measured Near and Far End XTK in Two Uniform Microstrips: 5 mil wide line and space, 4 inches long



Very different signatures
Very different magnitudes



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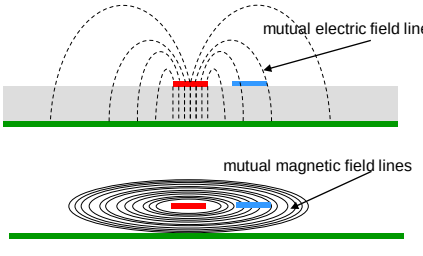
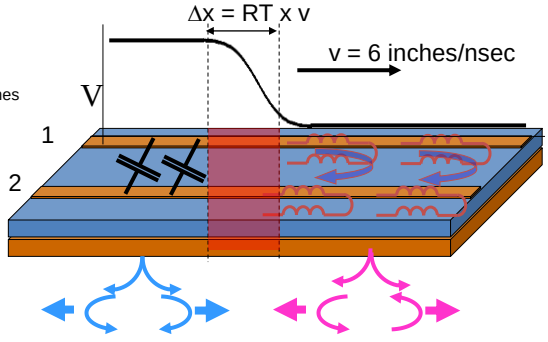
Fundamental Root Cause of Cross Talk

1) dV/dt, dI/dt thru Fringe Electric and Magnetic Fields
   - Changing mutual electric field
   - Changing mutual magnetic fields



2) Dynamic nature of signals and induced noise
   - Signals propagate
   - Noise propagates



@ Near end: $I_C + I_L$

@ Far end: $I_C - I_L$

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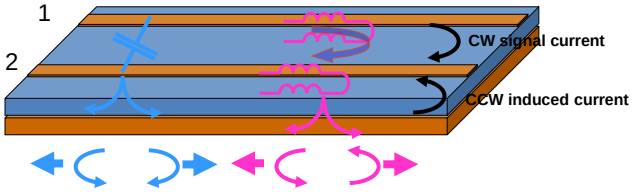
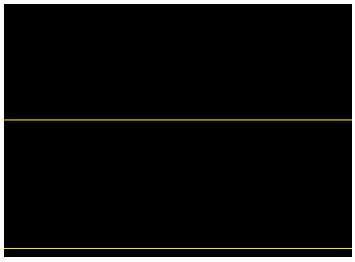
Different Signatures at Near End and Far End due to Propagation, CCW Induced L Noise Current



Near end noise "dribbling back"



$I_C + I_L$

Far end noise "snowballing"

$I_C - I_L$

5 Secret to understanding cross talk: dynamic nature of the signals!

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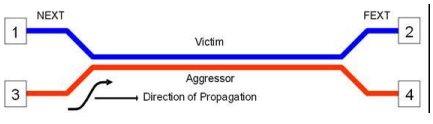
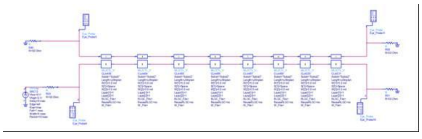
Simulation Methodology, Using Agilent's ADS

- From C and L matrix elements, and dynamic propagation of signals, NEXT and FEXT can be accurately predicted





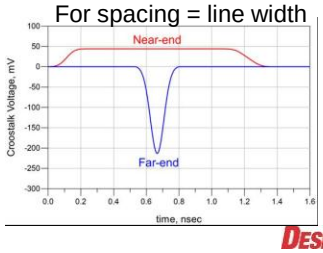
$$k_{ne} = \frac{1}{4}\left(\frac{C_{ij}}{C_{ii}} + \frac{L_{ij}}{L_{ii}}\right) \qquad k_{fe} = \frac{1}{2}\left(\frac{C_{ij}}{C_{ii}} - \frac{L_{ij}}{L_{ii}}\right)$$

$$V_{ne} = V_{signal} \times k_{ne}$$

$$V_{fe} = V_{signal} \times \left\{\frac{Len}{RT}\frac{1}{v} \times k_{fe}\right\} = V_{signal} \times \left\{\frac{Len}{RT}\frac{\sqrt{Dk_{eff}}}{c} \times k_{fe}\right\} = V_{signal} \times \left\{\frac{1.5}{0.1}\frac{\sqrt{2.7}}{11.8} \times k_{fe}\right\}$$

$$= V_{signal} \times 2.09 \times k_{fe}$$

For spacing = line width



Len = 1.5 inches
RT = 0.1 nsec
Zo = 50 Ohms
5 mil wide line
Dk = 4 (Dk_eff = 2.7 for MS)

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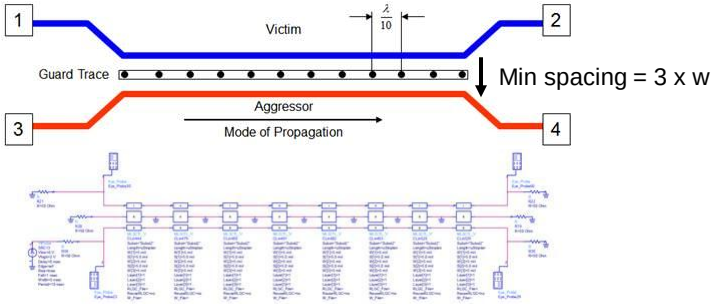
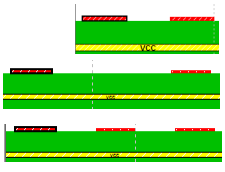
Adding a Guard Trace



- Just increasing spacing to victim line:
  - Reduced C, L matrix elements → reduced cross talk on the victim line
- Impact from the guard trace:
  - Increased spacing to victim AND presence of the guard trace → different C, L matrix elements → different directly coupled noise to victim line (not affected by termination of the guard trace)
  - "Pollution" from noise on the guard trace inducing additional "dynamic" noise on the victim line, adding with the directly coupled noise from the aggressor to the victim (strongly affected by termination of the guard trace)

Microstrip Matrix Elements



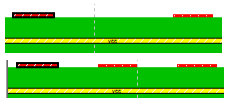
	Cii (pF/in)	Cij (pF/in)	Cij/Cii	Lii (nH/in)	Lij (nH/in)	Lij/Lii	kne	kfe
Tight coupling	2.77	0.116	0.0419	6.97	0.772	0.1108	0.0382	-0.0344
3x spacing, no guard	2.77	0.0177	0.0064	7.00	0.188	0.0269	0.0083	-0.0102
With guard	2.77	0.0136	0.0049	6.97	0.200	0.0287	0.0084	-0.0119

Note: in C matrix elements, all other conductors are gnded
In L matrix elements, all other conductors are open

- Observations on direct coupling, aggressor → victim:
  - Relative C, L matrix elements significantly reduced by increased spacing
  - Adding guard trace reduces relative C coupling slightly, increases relative inductive coupling slightly
  - Directly coupled near end, far end coupling coefficients, nearly the same, with and without guard trace

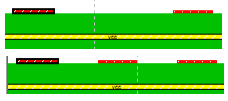
Net Backward Propagating and Forward Propagating Noise on Microstrip Victim Line

For the special case: Len = 1.5 inch, RT = 0.1 nsec



WORST CASE Backward propagating noise:

No guard, direct aggressor to victim (Vne):	0.83%
With guard, direct aggressor to victim (Vne):	0.84%
Re-infected from guard (V23-ne):	0.14%
Re-infected from guard, effective (V23-ne-eff):	-0.06%

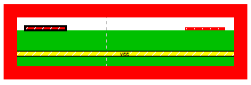


WORST CASE Forward propagating noise:

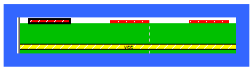
No guard, direct aggressor to victim (Vfe):	-2.1%
With guard, direct aggressor to victim (Vfe):	-2.5%
Re-infected from guard (V23-fe):	+0.5%
Re-infected from guard, effective (V23-fe-eff):	+0.84%

- Observations
  - Without guard trace NEXT ~ -42 dB. FEXT ~ 0.14% x Len[inches]/RT[nsec]. If this is "good enough", don't add a guard trace.
  - Directly coupled noise on victim line dominates noise
  - Re-infected noise on victim line from noise on guard trace can add or subtract depending on reflections (far end noise will scale with Len/RT)

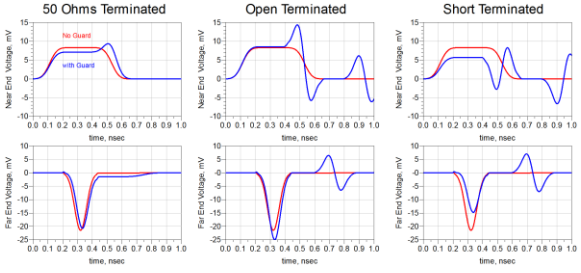
Microstrip: Impact on Victim Line with and without Guard trace



Near End

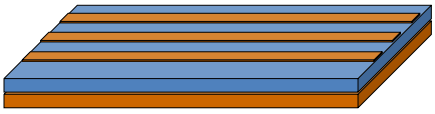


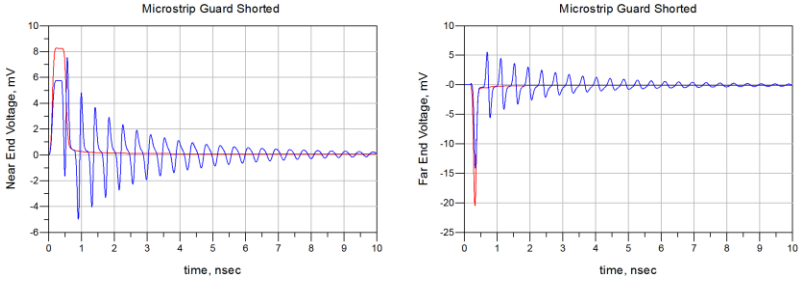
Far End



- Near end, far noise signature polluted with far end noise contamination from guard trace
- Far end noise can grow with longer Len, shorter RT
- Net noise on victim line can be >> with guard trace than without, independent of terminations

Multiple Reflections on Guard Trace Re-infect Victim Line for a Long Time





Enhanced noise on victim line at resonance frequency of guard trace: $f_{res} = \frac{11.8\ \text{GHz}}{\sqrt{Dk}\ 2 \times \text{Len[inches]}} = \frac{3\ \text{GHz}}{\text{Len[inches]}}$ (in FR4)

Stripline Matrix Elements

	Cii (pF/in)	Cij (pF/in)	Cij/Cii	Lii (nH/in)	Lij (nH/in)	Lij/Lii	kne	kfe
Tight coupling	3.213	0.333	0.1036	8.119	0.841	0.1036	0.0518	0.0000
3x spacing, no guard	3.162	0.020	0.0063	8.162	0.053	0.0064	0.0032	-0.0001
With guard	3.213	0.002	0.0006	8.118	0.091	0.0112	0.0029	-0.0053

$$V_{fe} = V_{signal} \times \left\{ \frac{\text{Len}}{\text{RT}} \frac{1}{v} \times k_{fe} \right\} = V_{signal} \times \left\{ \frac{\text{Len}}{\text{RT}} \frac{\sqrt{Dk_{eff}}}{c} \times k_{fe} \right\} = V_{signal} \times \left\{ \frac{1.5}{0.1} \frac{\sqrt{2.7}}{11.8} \times k_{fe} \right\}$$

$= V_{signal} \times 2.09 \times k_{fe}$

For the special case of Len = 1.5 inches, RT = 0.1 nsec

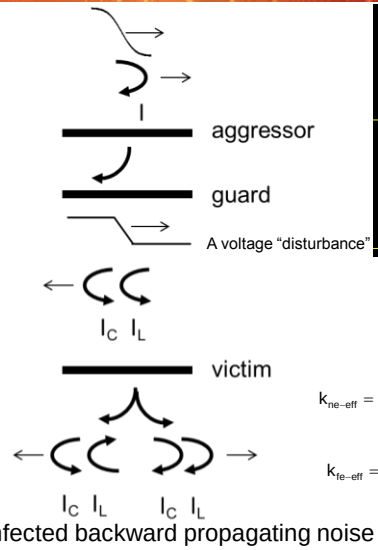
In stripline, with a guard:

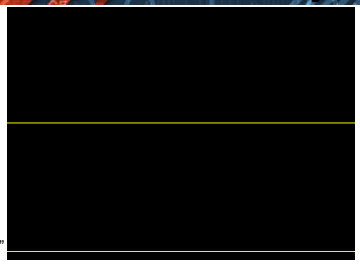
$V_{fe} = V_{signal} \times 2.09 \times k_{fe} = V_{signal} \times 2.09 \times (-0.0053)$

$= -V_{signal} \times 1.1\%$

- Observations:
  - C matrix elements dramatically reduced with guard trace
  - L matrix elements INCREASED with guard trace
  - Near end coupling slightly less with guard trace
  - *There may be far end cross talk in stripline with a guard trace*

A Counter-intuitive Feature of Contaminated Noise in Stripline





$$k_{ne-eff} = \frac{1}{4}\left(\frac{C_{ij}}{C_{ii}} - \frac{L_{ij}}{L_{ii}}\right) = \frac{1}{4}(4.2\% - 11\%) = -1.7\%$$

$$k_{fe-eff} = \frac{1}{2}\left(\frac{C_{ij}}{C_{ii}} + \frac{L_{ij}}{L_{ii}}\right) = \frac{1}{2}(4.2\% + 11\%) = +7.6\%$$

Infected backward propagating noise currents on victim line subtract!

Infected forward propagating noise currents on victim line, add!

Net Backward Propagating and Forward Propagating Noise on Stripline Victim Line

Worst Case backward propagating noise:

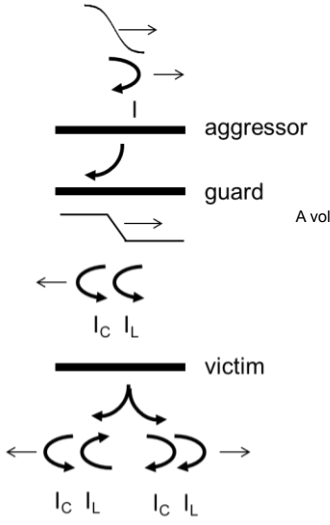
No guard, direct aggressor to victim (Vne):	0.32%
With guard, direct aggressor to victim (Vne):	0.29%
Re-infected from guard (V23-ne):	0.27%
Re-infected from guard, effective (V23-fe):	0%

Worst Case forward propagating noise:

No guard, direct aggressor to victim (Vfe):	0%
With guard, direct aggressor to victim (Vfe):	-1.1%
Re-infected from guard (V23-ne-eff):	0%
Re-infected from guard, effective (V23-fe-eff):	+1.1%

- Observations:
  - Without guard trace, far end cross talk = 0, near end cross talk is < -50 dB. If this is "good enough", don't even think about a guard trace.
  - Under some cases with guard trace, near end noise on victim line can be dramatically reduced even lower
  - Under some cases, far end cross talk on victim line can be dramatically reduced even lower

Why NO Far End Cross Talk on Stripline with Guard Trace



A voltage "disturbance"

[redacted]

1→3 directly coupled far end noise expected with a guard trace:

$$V_{fe} = V_{signal} \times 2.09 \times k_{fe} = V_{signal} \times 2.09 \times (-0.0053)$$
$$= -V_{signal} \times 1.1\%$$

$$k_{fe-eff} = \frac{1}{2}\left(\frac{C_{ij}}{C_{ii}} + \frac{L_{ij}}{L_{ii}}\right) = \frac{1}{2}(10.4\% + 10.4\%) = +10.4\%$$

Re-infected far end noise on victim from guard trace:

$$V_{23-fe-eff} = (V_{signal} \times k_{ne}) \times 2.09 \times k_{fe-eff} = V_{signal} \times 0.052 \times 2.09 \times (0.104)$$
$$= V_{signal} \times 1.1\%$$

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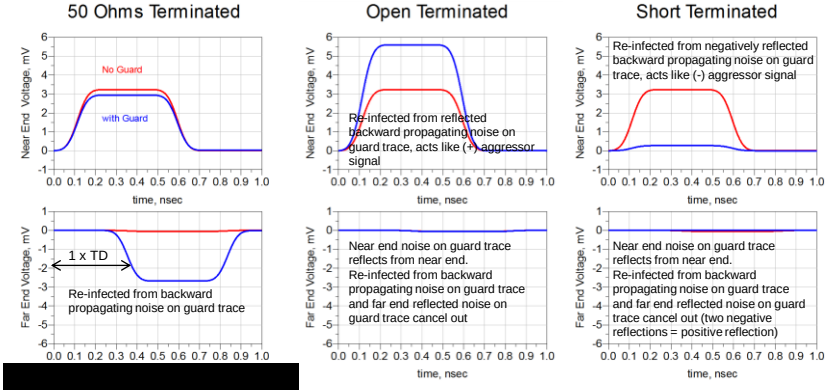
Stripline: Impact on Victim Line with and without Guard trace



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Dramatic reduction of near end noise, far end noise in stripline with guard trace shorted on the two ends.

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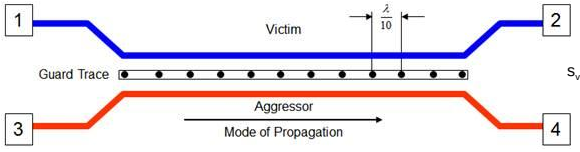
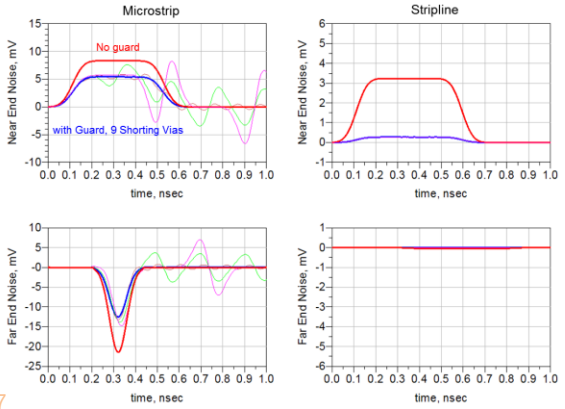
Do You Need Multiple Shorting Vias?



Spacing = 1/10th λ

$$s_{vias} = \frac{1}{10} \times \frac{v}{BW} = \frac{1}{10} \times \frac{\left(\frac{11.8}{\sqrt{Dk_{eff}}}\right)}{\left(\frac{0.338}{RT}\right)} = \frac{3.5}{\sqrt{Dk_{eff}}} \times RT$$

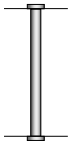


- For RT = 0.1 sec, s_{vias} = 0.18 mils and Len = 1.5 inches, 1/10th wave spacing requires 9 vias
- Increasing number of shorting vias: 2, 3, 5, 9
- In microstrip, using min number of vias, cross talk reduced by ~ 40%
- In stripline, any number of shorting vias reduces near end cross talk from -50 dB to -74 dB.

Practical Design Considerations

- Via inductance
- Via impact on line to line spacing
- Length of guard trace vs coupled length

Via Inductance



≈ **10nH/inch (Typ.)**

- Assume a shorting via of 10 mils and risetime of 0.1nsec What is the impedance?

Equivalent Circuit

$$Z_{via} = \sqrt{R_{via}^{\ 2} + XL_{via}^{\ 2}}$$

If $R_{via} << XL_{via}$

$$Z_{via} \approx 2\pi fL \approx 2\pi \frac{0.35}{0.1\text{nsec}}(0.1\text{nH})$$

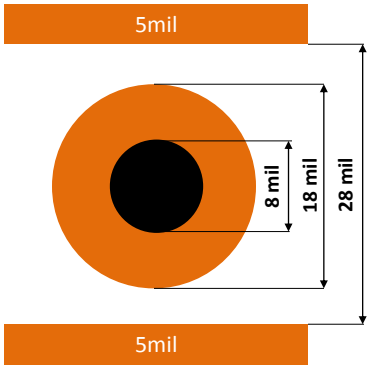
$$\approx 2\Omega$$

Via Impact on Line-Line Spacing

Technology Limitations

- Smallest practical through-hole drill is 8mils
- Minimum pad = 10 mil over drill
- Minimum pad-trace separation = 5 mils

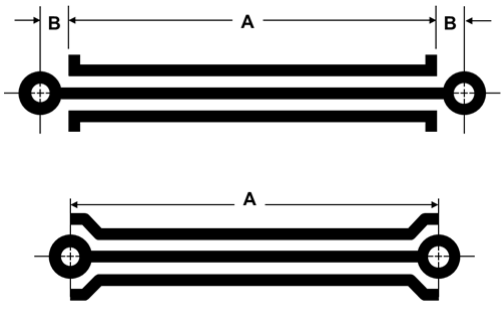
Minimum Trace-trace Spacing



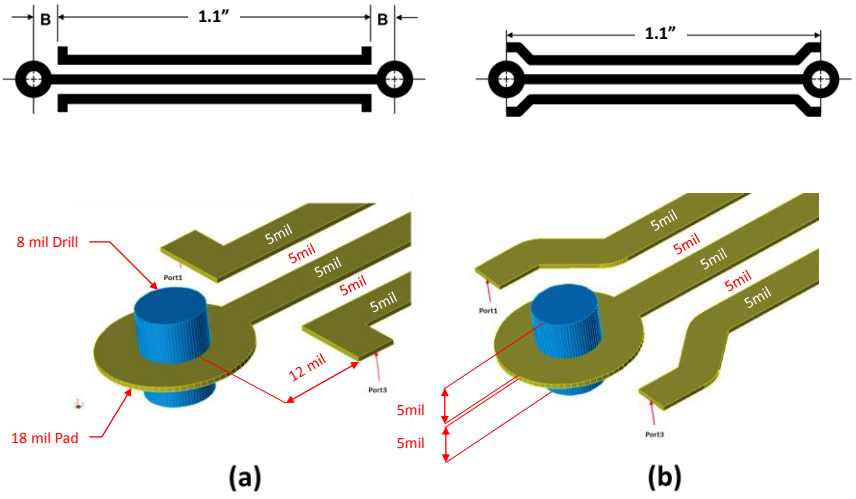
Over 5 X Line-width just to fit in shorting vias!

Shorted Guard Trace in Stripline

- Dramatic noise reduction in stripline => guard shorted at each end only
- 2 practical implementations

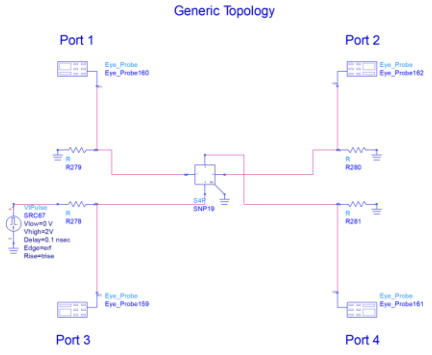


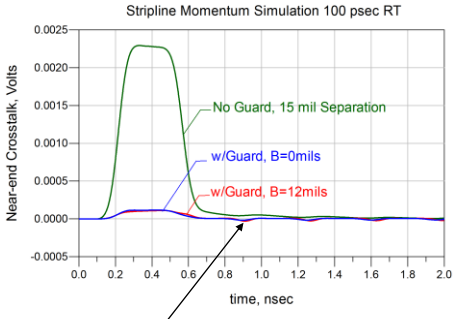
ADS Momentum Stripline Models



The reference planes are not shown for clarity

Simulated Results RT=100 psec

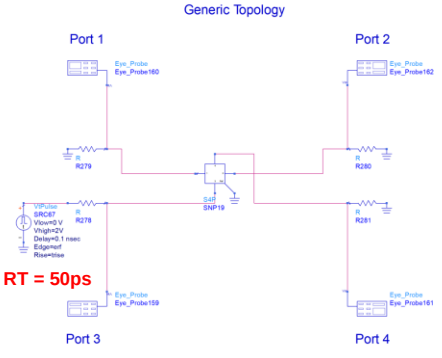


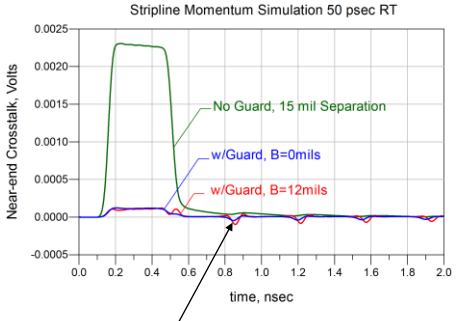


- Ripple due to additional inductive via length to reference plane
- Effectively no difference in noise signature for either topology

What About Silicon Technology Advancement?

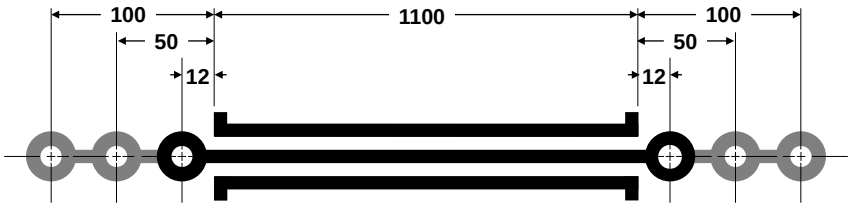
- Impact of via inductance depends on rise time and length of via

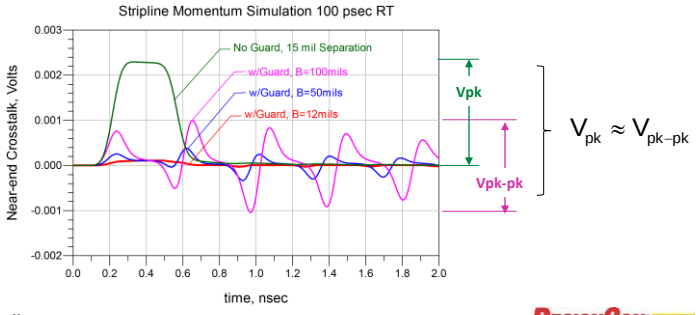




- Increased noise ripple when the rise time is reduced to 50 psec
- Increased noise magnitude when guard trace is extended

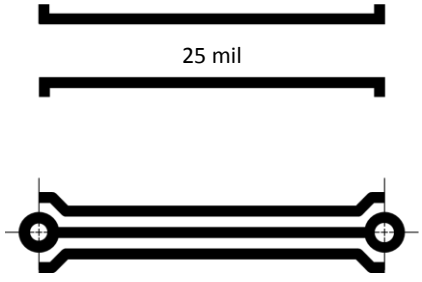
Guard Trace vs Coupled Lengths

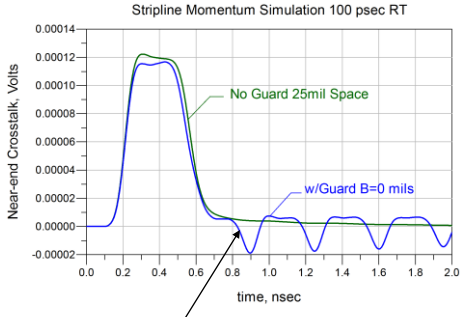




25 **Note: Dimensions are in mils**

No Guard w/25 mil Space





Increased spacing to 5 x line width nets same NEXT but without additional reinfected noise

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Summary and Conclusions

- In most digital applications, a guard trace is not needed to reduce cross talk below the -40 dB level. Just increased spacing does this.
- If less than -40 dB is need, do not use microstrip.
- In microstrip, a guard trace, with ANY termination, can often do more harm than benefit. Avoid guard traces in microstrip.
- Best case, optimized shorting vias on microstrip guard results in no more than 40% reduction in near, far end cross talk- small gain and high risk.
- In stripline, a guard trace should be shorted to the return path just at the ends
  - Only consider guard trace if – 50 dB isolation is not enough.
  - Use the same return plane voltages top and bottom
  - Place the shorting via as close to the coupled region as possible
  - Not necessary to use multiple shorting vias along the length of the guard trace- forces larger spacing than necessary
- Anything else may result in worse noise with a guard trace than without

The End

Thank You!

Lamsim Enterprises inc.