The "Ground" Myth

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IEEE

EMC SOCIETY

Outline

- Electromagnetics
- Skin Effect
- Inductance
- Ground
- Return Current Path

Electromagnetics
In the Beginning

- Electric and Magnetic effects not connected
- Electric and magnetic effects were due to ‘action from a distance’
- Faraday was the 1st to propose a relationship between electric lines of force and time-changing magnetic fields
  - Faraday was very good at experiments and ‘figuring out’ how things work

Maxwell

- Maxwell was impressed with Faraday's ideas
- Discovered the mathematical link between the "electro" and the "magnetic"
- Scotland's greatest contribution to the world (next to Scotch)

Maxwell's Equations – Differential Form

A difference in Magnetic Field across a small piece of space

A change in Electric Flux Density with respect to time

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

A difference in Electric Field across a small piece of space

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

A change in Magnetic Flux Density with respect to time

Maxwell's Equations are not Hard!

- Change in H-field across space ≈ Change in E-field (at that point) with time
- Change in E-field across space ≈ Change in H-field (at that point) with time
- (Roughly speaking, and ignoring constants)

Current Flow

- Most important concept of EMC
- Current flow through metal changes as frequency increases
- DC current
  - Uses entire conductor
  - Only resistance inhibits current
- High Frequency
  - Only small part of conductor (near surface) is used
  - *Resistance* is small part of current inhibitor
  - ***Inductance*** is major part of current inhibitor

Skin Depth

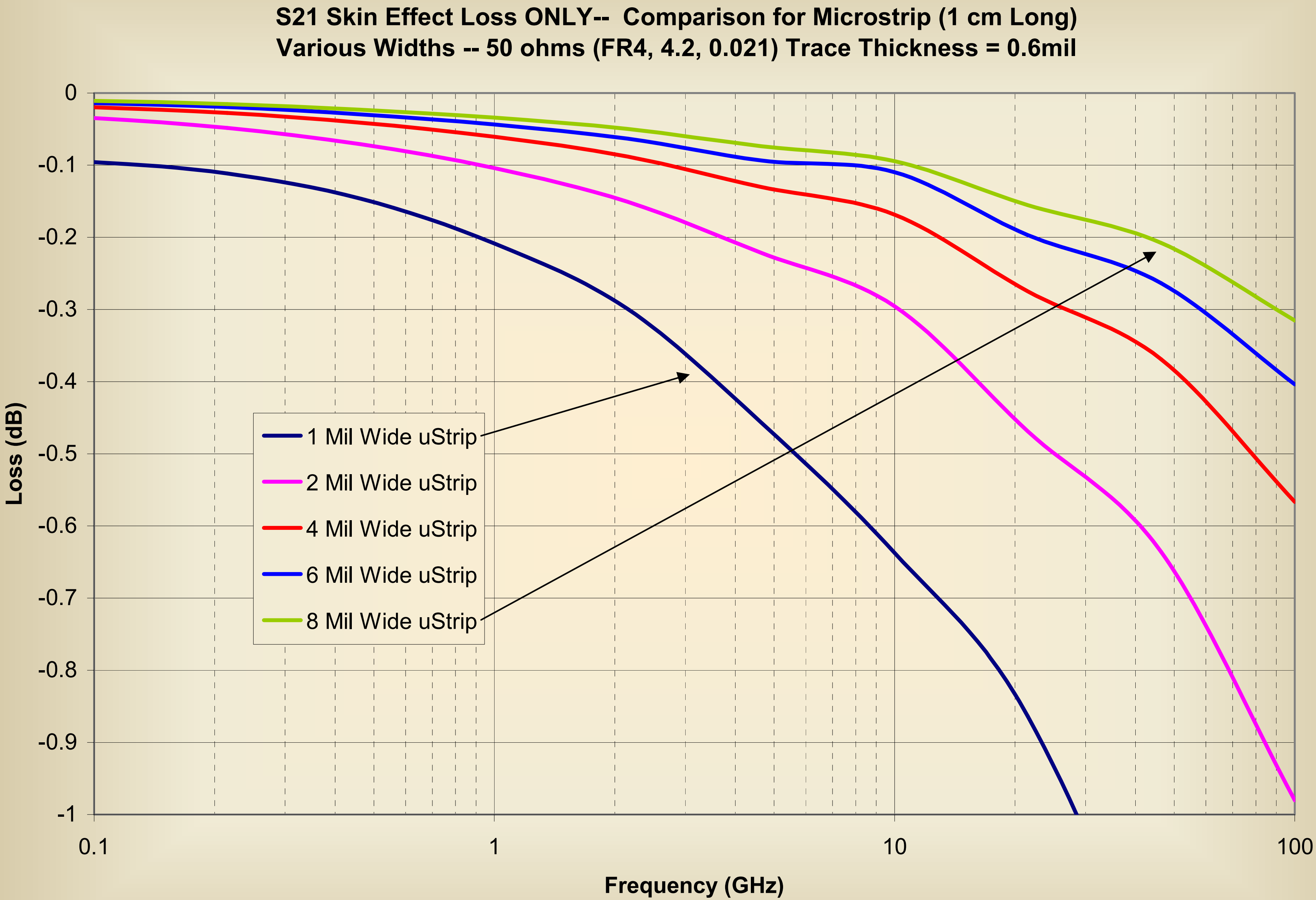
- High frequency current flows only near the metal surface at high frequencies

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

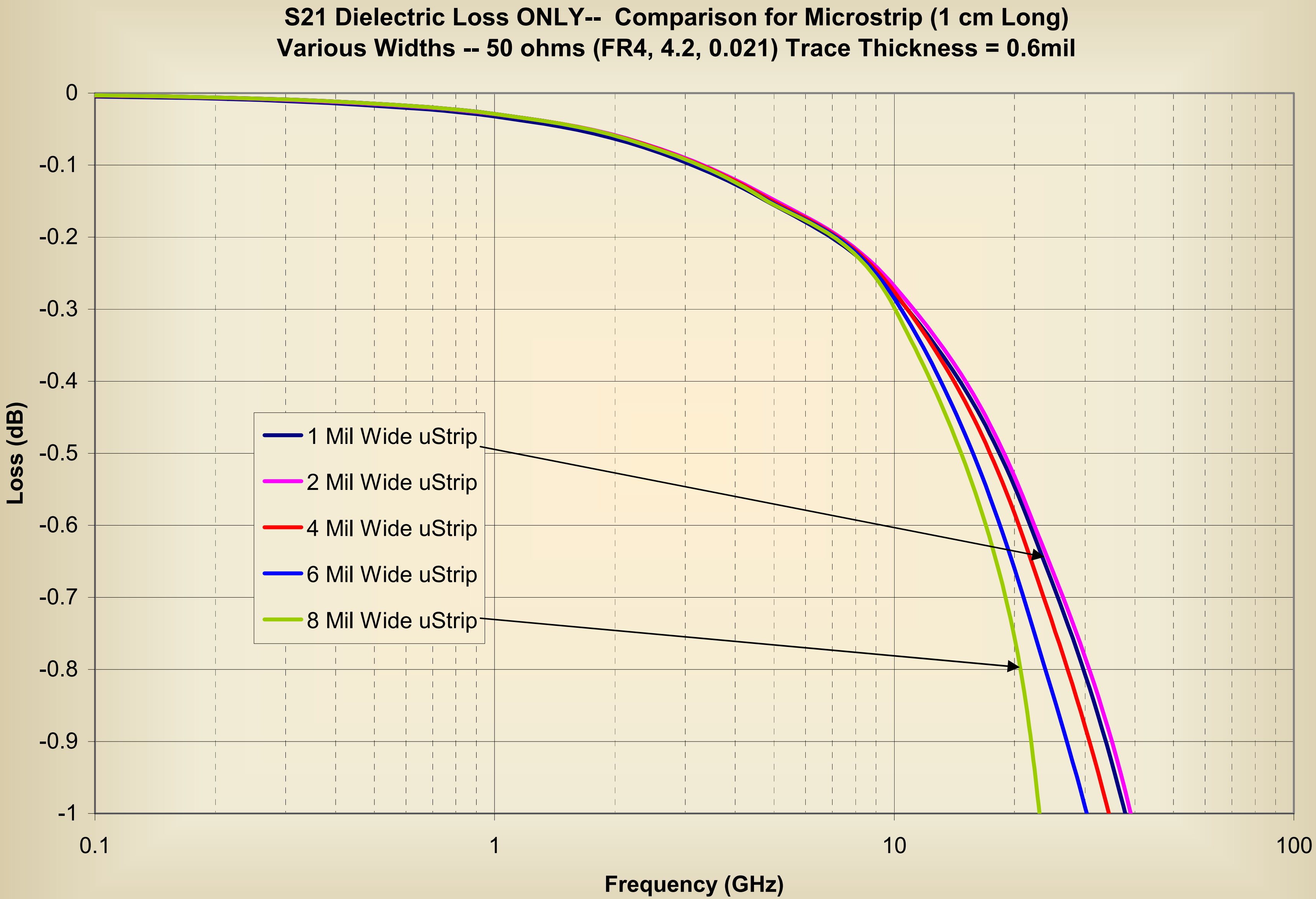
Frequency	Skin Depth	Skin Depth
60 Hz	260 mils	8.5 mm
1 KHz	82 mils	2.09 mm
10 KHz	26 mils	0.66 mm
100 KHz	8.2 mils	0.21 mm
1 MHz	2.6 mils	0.066 mm
10 MHz	0.82 mils	0.021 mm
100 MHz	0.26 mils	0.0066 mm
1 GHz	0.0823 mils	0.0021 mm

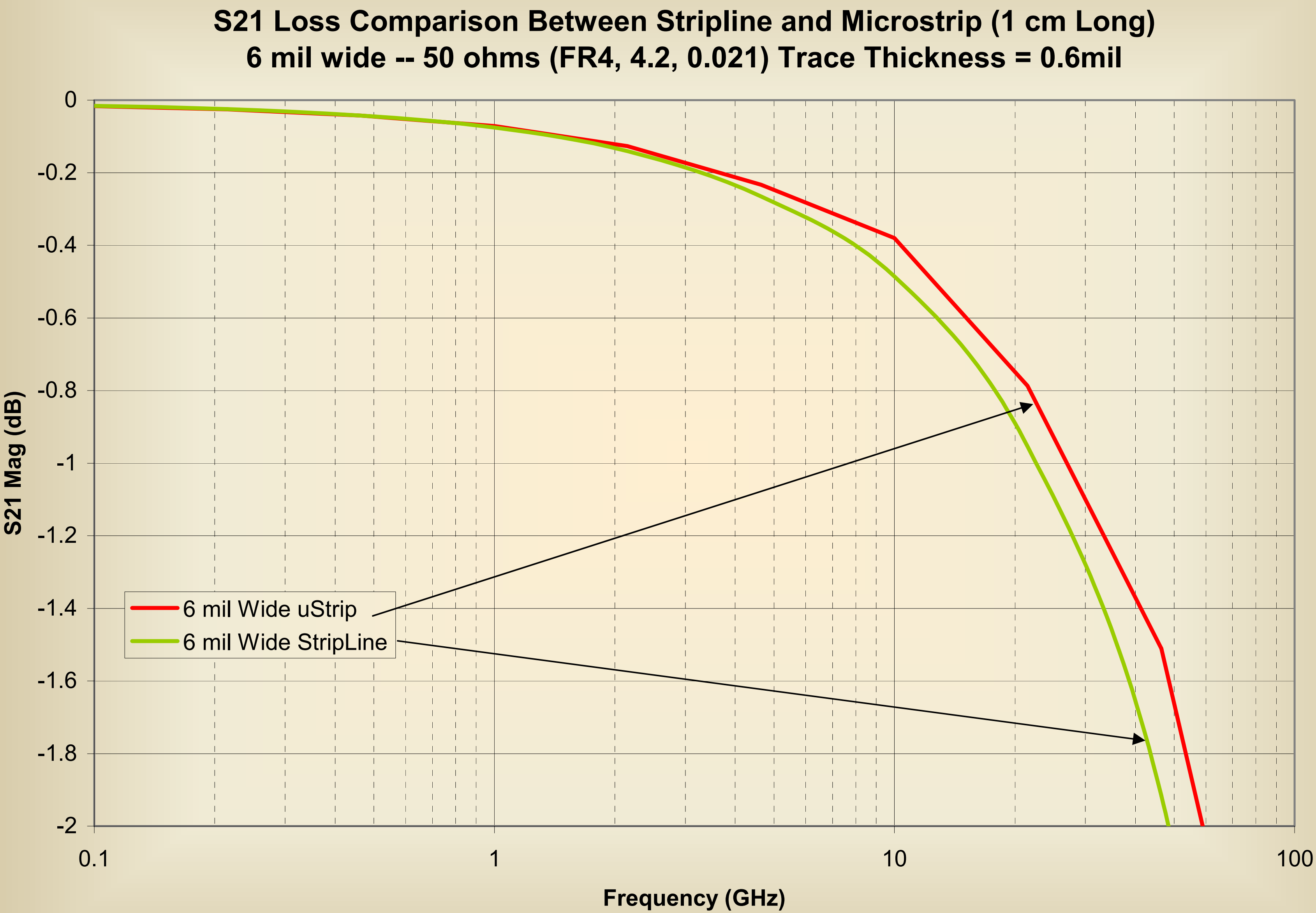
Current Migrates to Outer Portions of the Conductor at High Frequencies

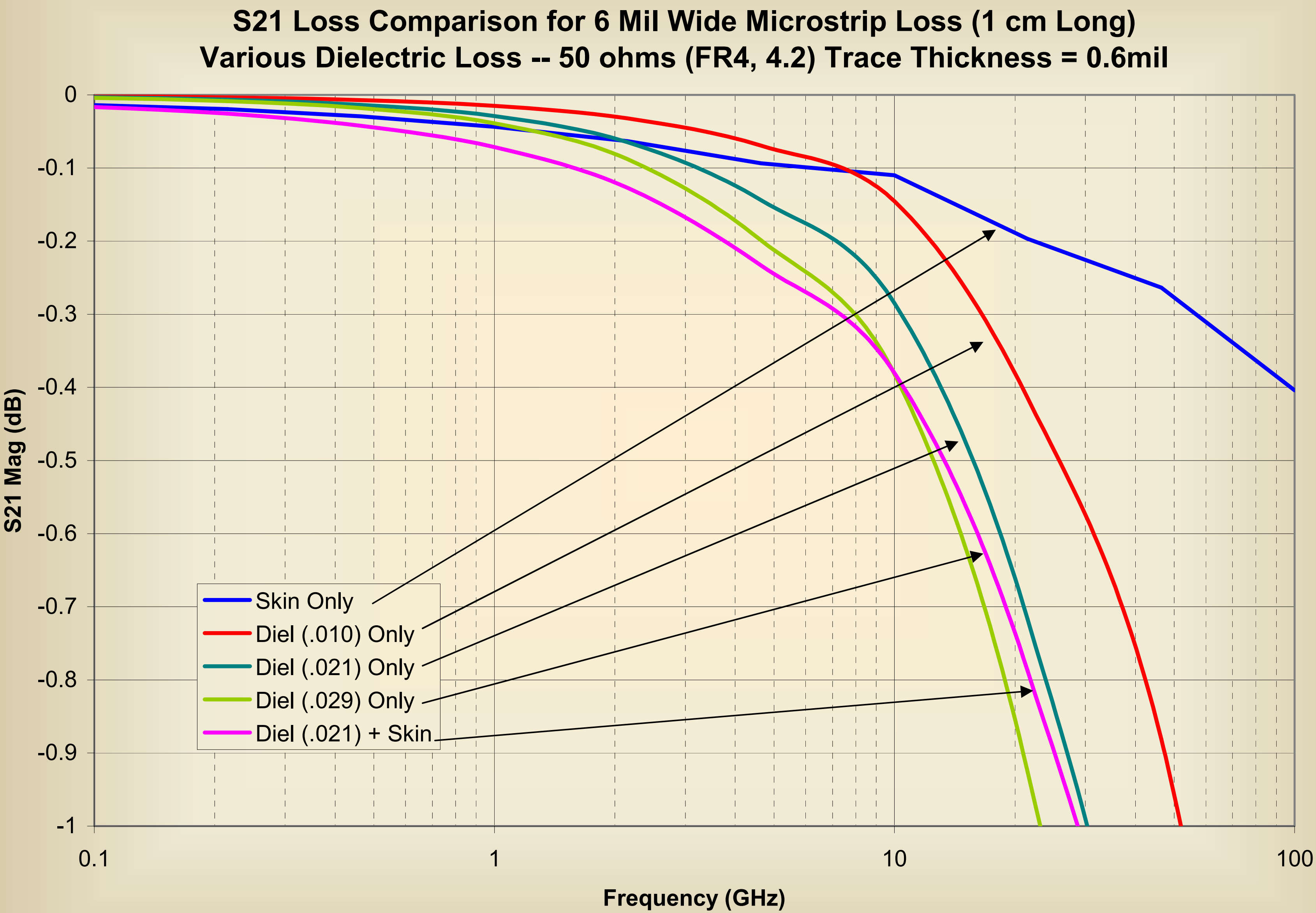
Resistance is determined by the area of the copper conductor actually used at each frequency!



S21 Skin Effect Loss ONLY-- Comparison for Microstrip (1 cm Long)
Various Widths -- 50 ohms (FR4, 4.2, 0.021) Trace Thickness = 0.6mil
Loss (dB)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0.1
1
10
100
Frequency (GHz)
1 Mil Wide uStrip
2 Mil Wide uStrip
4 Mil Wide uStrip
6 Mil Wide uStrip
8 Mil Wide uStrip


S21 Dielectric Loss ONLY-- Comparison for Microstrip (1 cm Long)
Various Widths -- 50 ohms (FR4, 4.2, 0.021) Trace Thickness = 0.6mil
Loss (dB)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0.1
1
10
100
Frequency (GHz)
1 Mil Wide uStrip
2 Mil Wide uStrip
4 Mil Wide uStrip
6 Mil Wide uStrip
8 Mil Wide uStrip


S21 Loss Comparison Between Stripline and Microstrip (1 cm Long)
6 mil wide -- 50 ohms (FR4, 4.2, 0.021) Trace Thickness = 0.6mil
S21 Mag (dB)
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0.1
1
10
100
Frequency (GHz)
6 mil Wide uStrip
6 mil Wide StripLine



S21 Loss Comparison for 6 Mil Wide Microstrip Loss (1 cm Long)
Various Dielectric Loss -- 50 ohms (FR4, 4.2) Trace Thickness = 0.6mil
S21 Mag (dB)
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0.1
1
10
100
Frequency (GHz)
Skin Only
Diel (.010) Only
Diel (.021) Only
Diel (.029) Only
Diel (.021) + Skin

At High Frequencies

- Resistive loss and dielectric loss are present
- Inductance will usually dominate

Inductance

- Current flow through metal => inductance!
- Fundamental element in EVERYTHING
- Loop area first order concern
- Inductive impedance increases with frequency and is MAJOR concern at high frequencies

$$X_L = 2\pi f L$$

Current Loop => Inductance

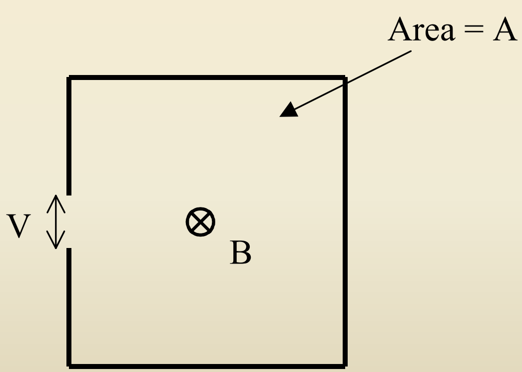
Courtesy of Elya Joffe

Inductance Definition

- Faraday's Law

$$\oint \overline{E} \cdot dl = -\iint \frac{\partial \overline{B}}{\partial t} \cdot d\overline{S}$$

- For a simple rectangular loop



$$V = -A\frac{\partial B}{\partial t}$$

The minus sign means that the induced voltage will work against the current that originally created the magnetic field!

Self Inductance

- Isolated circular loop

$$L \approx \mu_0 a \left(\ln \frac{8a}{r_0} - 2 \right)$$

- Isolated rectangular loop

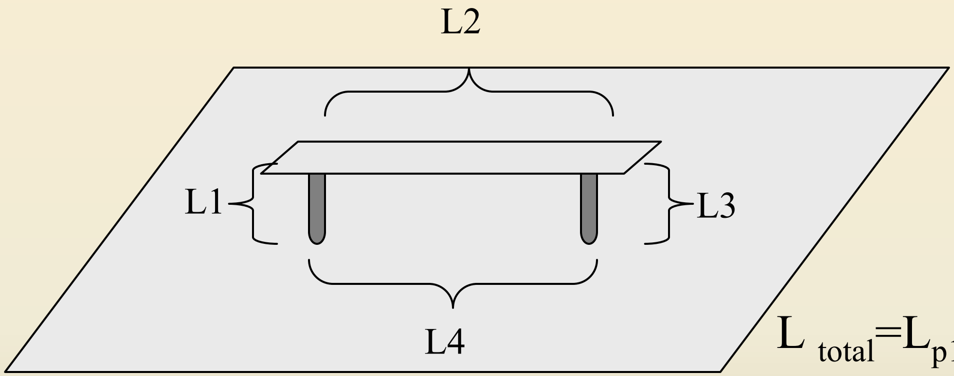
$$L = \frac{2\mu_0 a}{\pi} \left(\ln \frac{p + \sqrt{1 + p^2}}{1 + \sqrt{2}} + \frac{1}{p} - 1 + \sqrt{2} - \frac{1}{p} \sqrt{1 + p^2} \right)$$

Note that inductance is directly influenced by loop ***AREA*** and only less influenced by conductor size!

$$p = \frac{\text{length of side}}{\text{wire radius}}$$

Partial Inductance

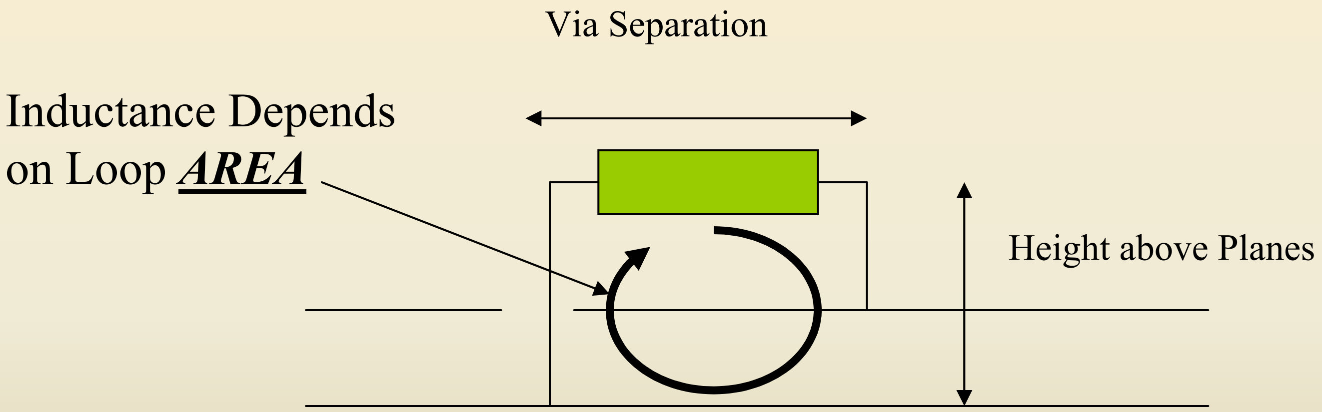
- Simply a way to break the overall loop into pieces in order to find total inductance



$$L_{total} = L_{p11} + L_{p22} + L_{p33} + L_{p44} - 2L_{p13} - 2L_{p24}$$

Decoupling Capacitor Mounting

- Keep as to planes as close to capacitor pads as possible



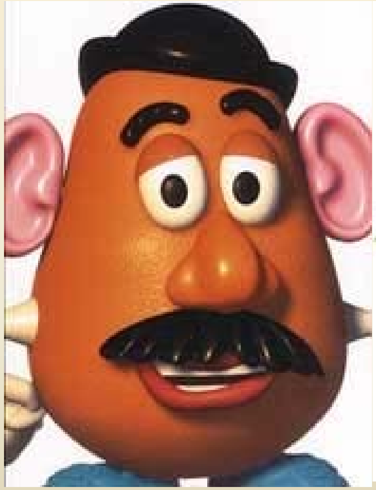
Important Points About Inductance

- Inductance is everywhere
- Loop area most important
- Inductance is everywhere

‘Ground’

- **Ground is a place where potatoes and carrots thrive!**
- ‘Earth’ or ‘reference’ is more descriptive
- Original use of “GROUND”
- Inductance is everywhere

$$X_L = 2\pi f L$$




What we Really Mean when we say ‘Ground’

- Signal Reference
- Power Reference
- Safety Earth
- Chassis Shield Reference

‘Ground’ is NOT a Current Sink!

- Current leaves a driver on a trace and must return (somehow) to its source
- This seems basic, but it is often forgotten, and is most often the cause of EMC problems

'Grounding' Needs Low Impedance at Highest Frequency

- Steel Reference Plate
  - 4 milliohms/sq @ 100KHz
  - 40 milliohms/sq @ 10 MHz
  - 400 milliohms/sq @ 1 GHz
- A typical via is about 2 nH
  - @ 100 MHz Z = 1.3 ohms
  - @ 500 MHz Z = 6.5 ohms
  - @ 1000 MHz Z = 13 ohms
  - @ 2000 MHz Z = 26 ohms

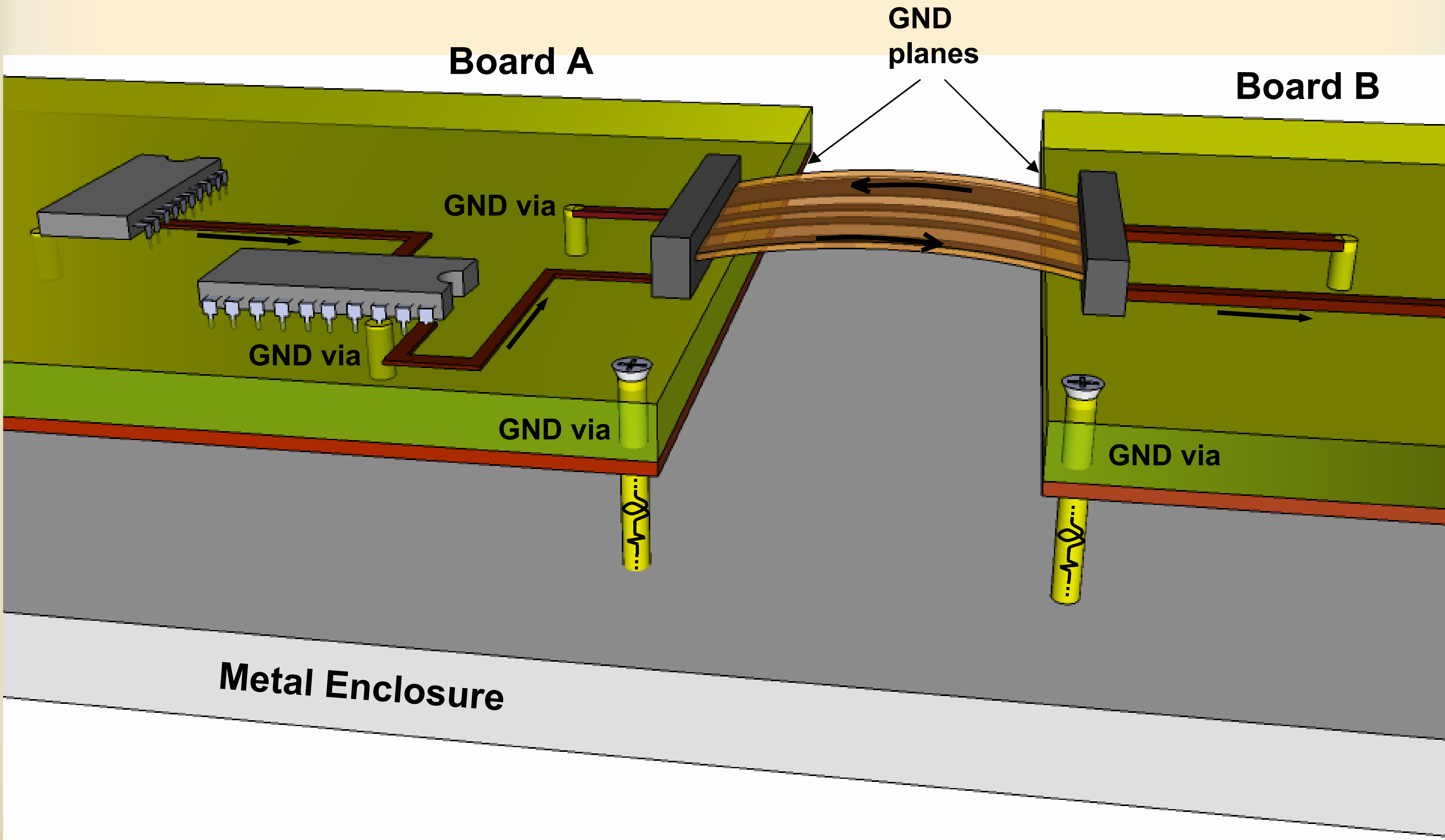
Single-point 'Ground'? Vs Multi-point 'Ground'?

- Which do I ***want***?
- Which do I ***get***?

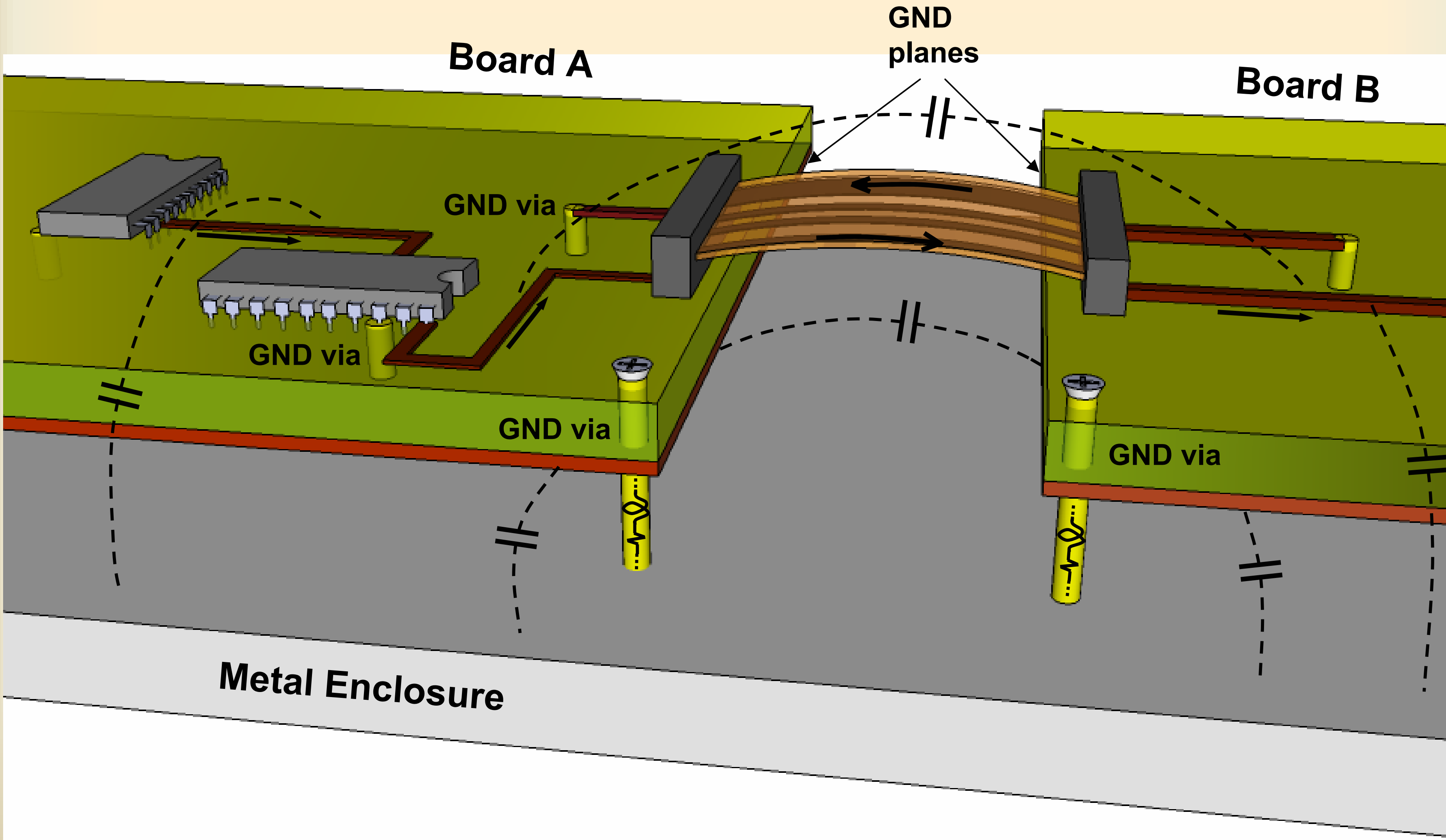
Single Point 'Ground' Myth

- At high frequencies, inductance makes this impossible!
- At high frequencies, parasitic capacitance makes this impossible!
- Depends on the amount of 'Ground' error your system can stand…...

Single-Point Ground Concept

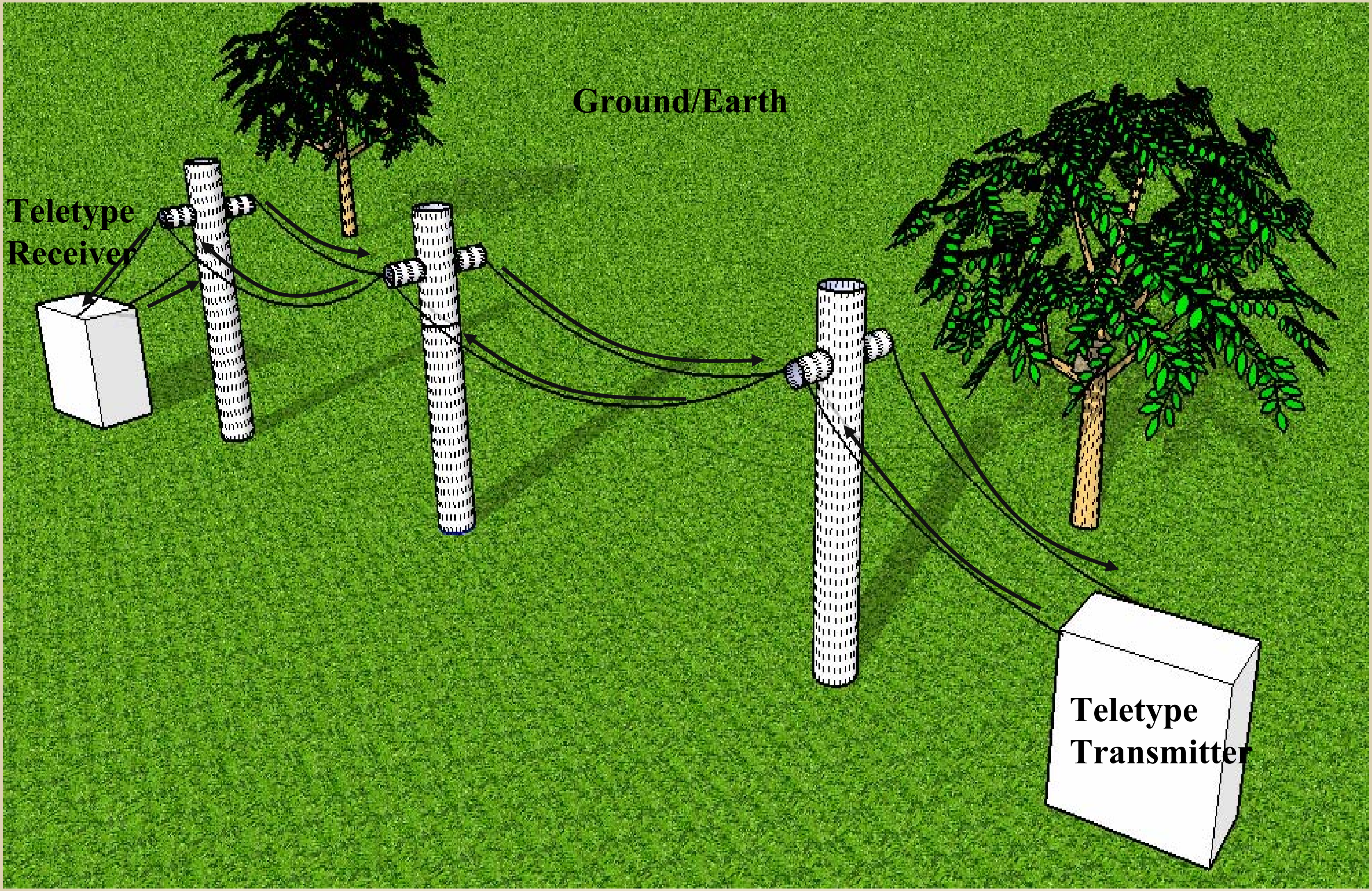


Reality Overcomes Single-Point Ground Intentions



Where did the Term "GROUND" Originate?

- Original Teletype connections
- Lightning Protection


Ground/Earth
Teletype
Receiver
Teletype
Transmitter

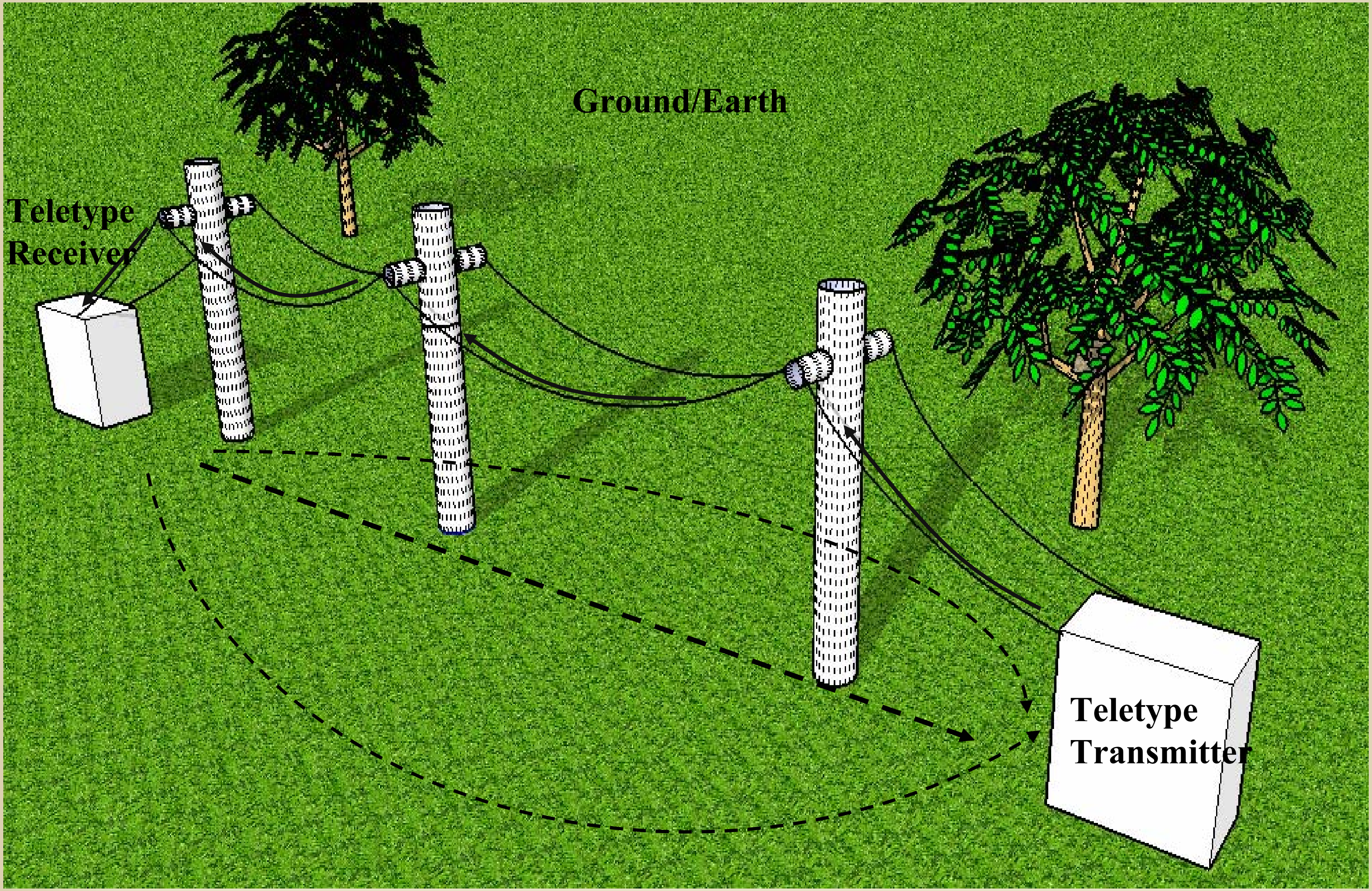
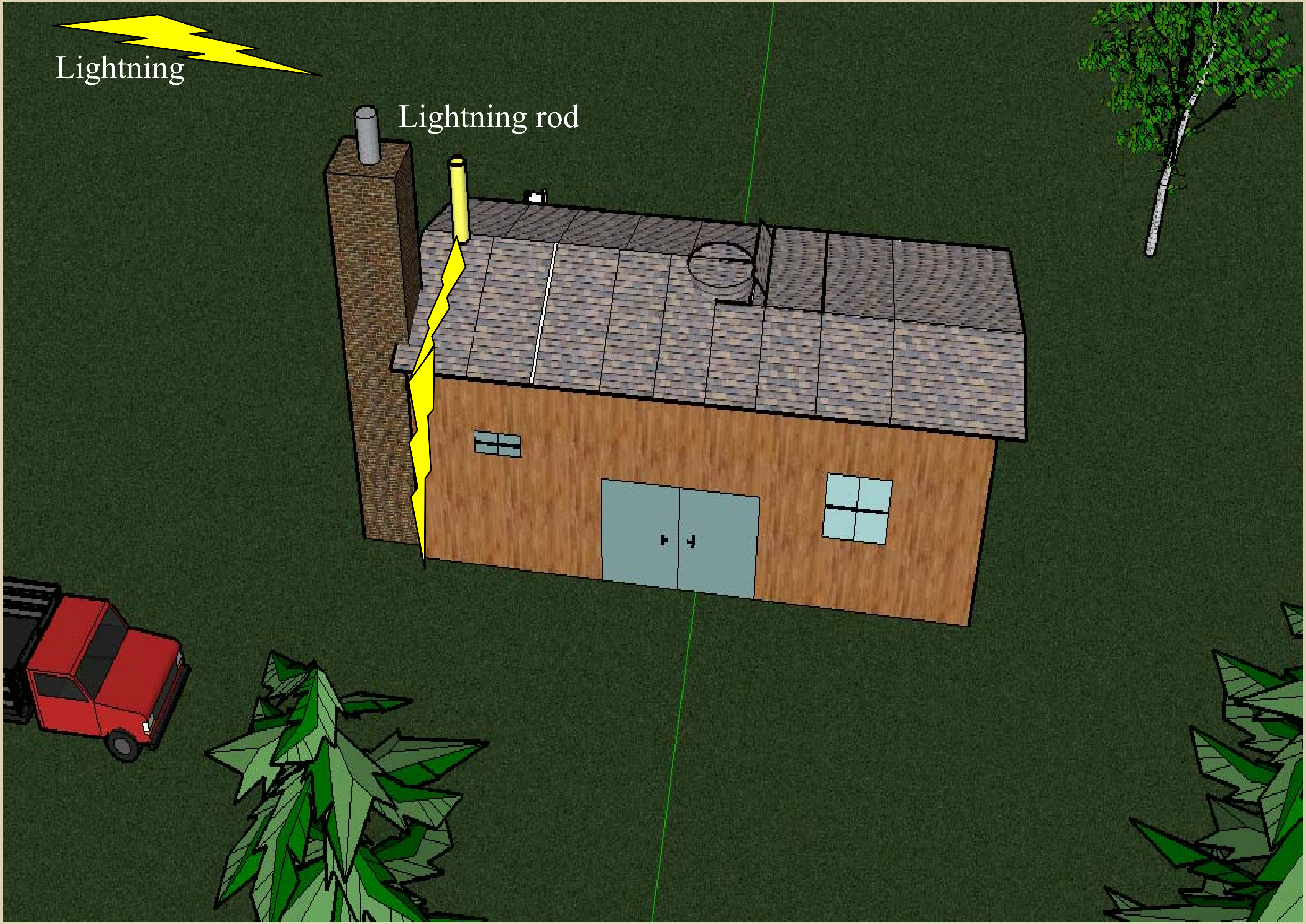

Ground/Earth
Teletype
Receiver
Teletype
Transmitter

FIG 7

Lightning striking house

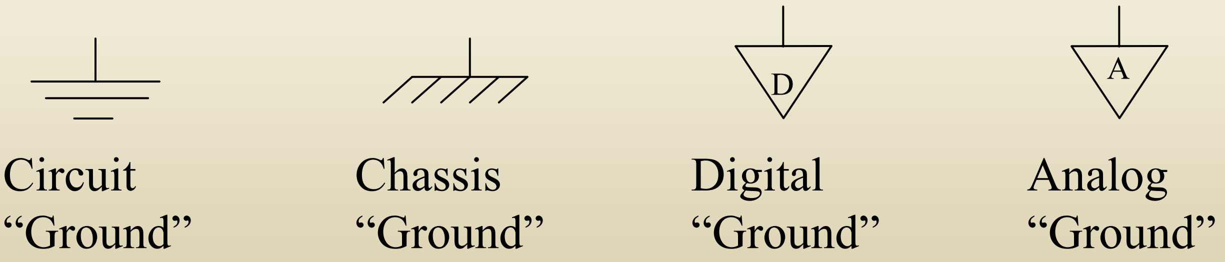
Lightning effect without rod

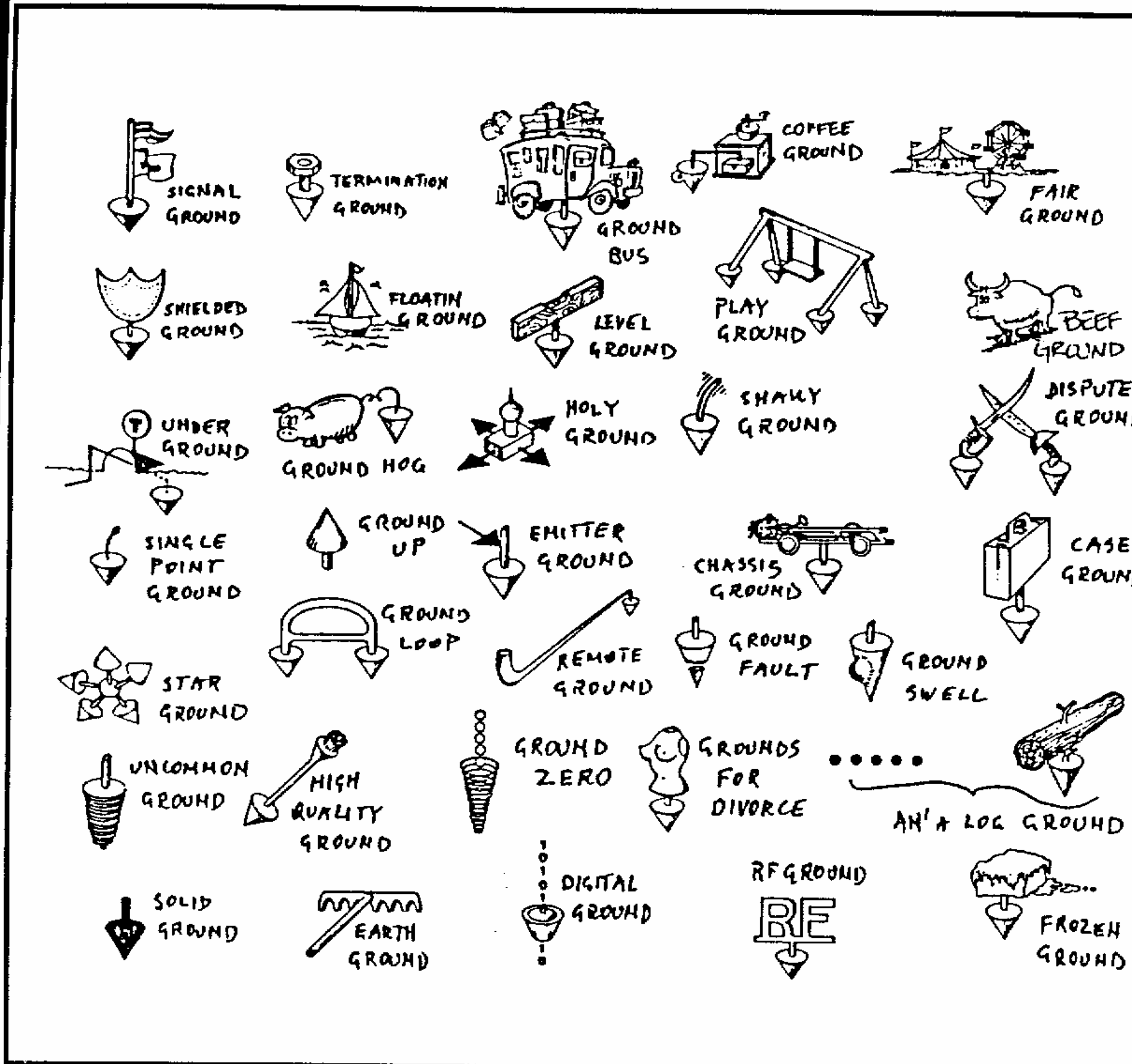
Lightning effect with rod



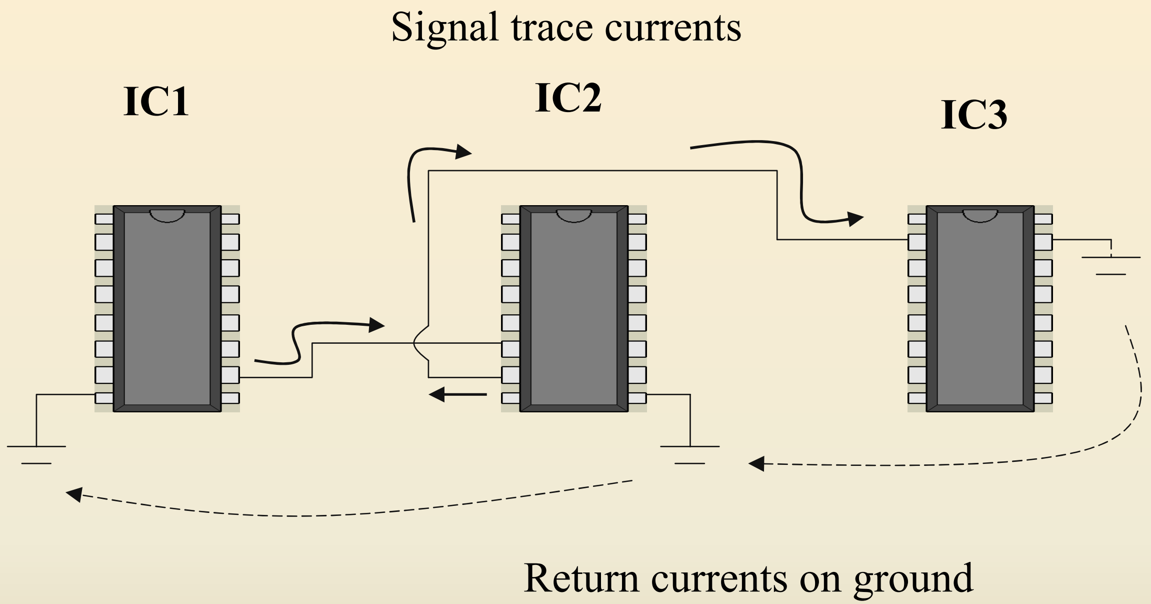
What we Really Mean when we say 'Ground'

- Signal Reference
- Power Reference
- Safety Earth
- Chassis Shield Reference

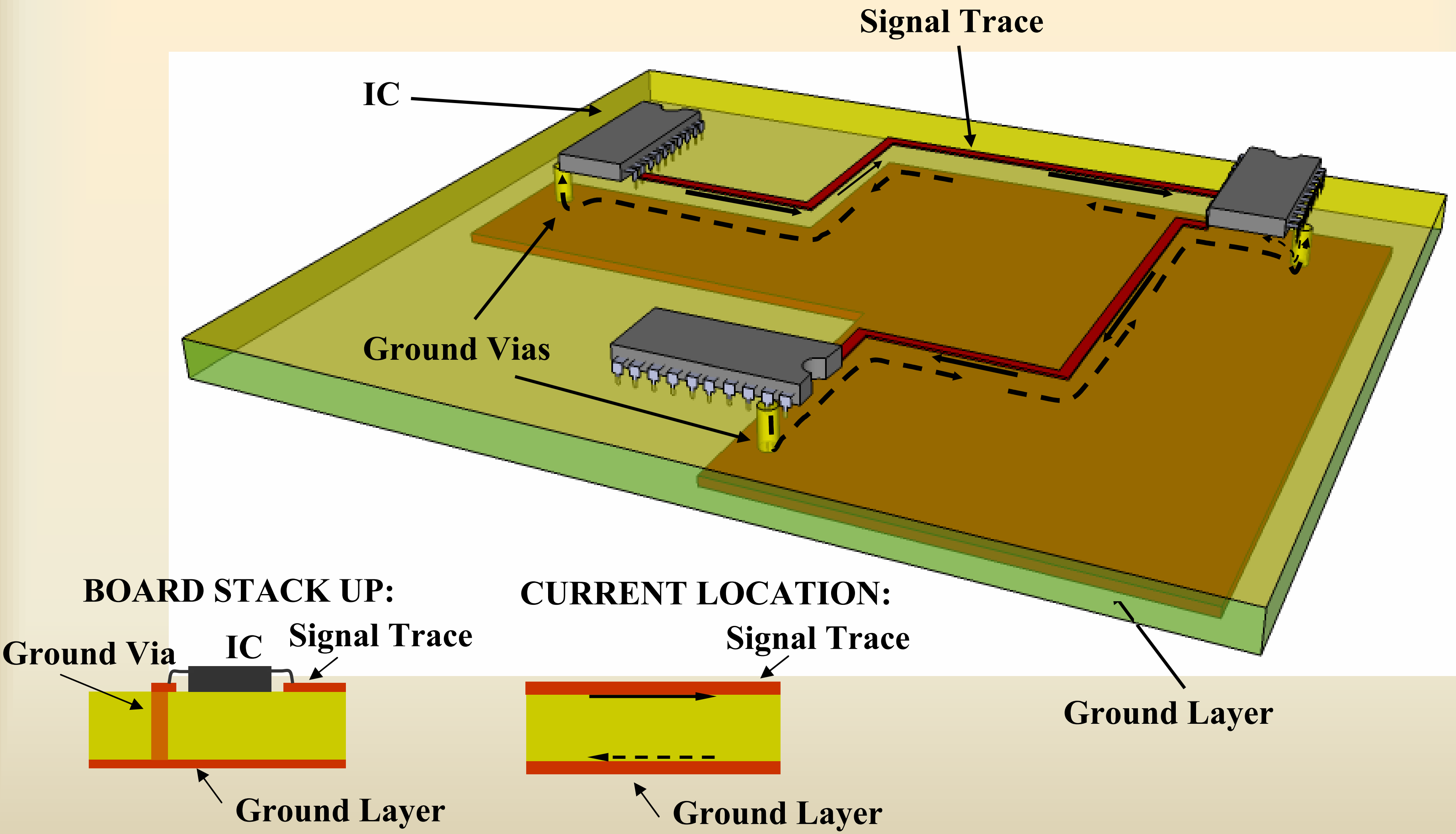



SIGNAL GROUND
TERMINATION GROUND
GROUND BUS
COFFEE GROUND
FAIR GROUND
SHIELDED GROUND
FLOATIN GROUND
LEVEL GROUND
PLAY GROUND
BEEF GROUND
UNDER GROUND
GROUND HOG
HOLY GROUND
SHAKY GROUND
DISPUTE GROUND
SINGLE POINT GROUND
GROUND UP
EMITTER GROUND
CHASSIS GROUND
CASE GROUND
GROUND LOOP
REMOTE GROUND
GROUND FAULT
GROUND SWELL
STAR GROUND
UNCOMMON GROUND
HIGH QUALITY GROUND
GROUND ZERO
GROUNDS FOR DIVORCE
AN' A LOG GROUND
SOLID GROUND
EARTH GROUND
DIGITAL GROUND
RF GROUND
RF
FROZEN GROUND

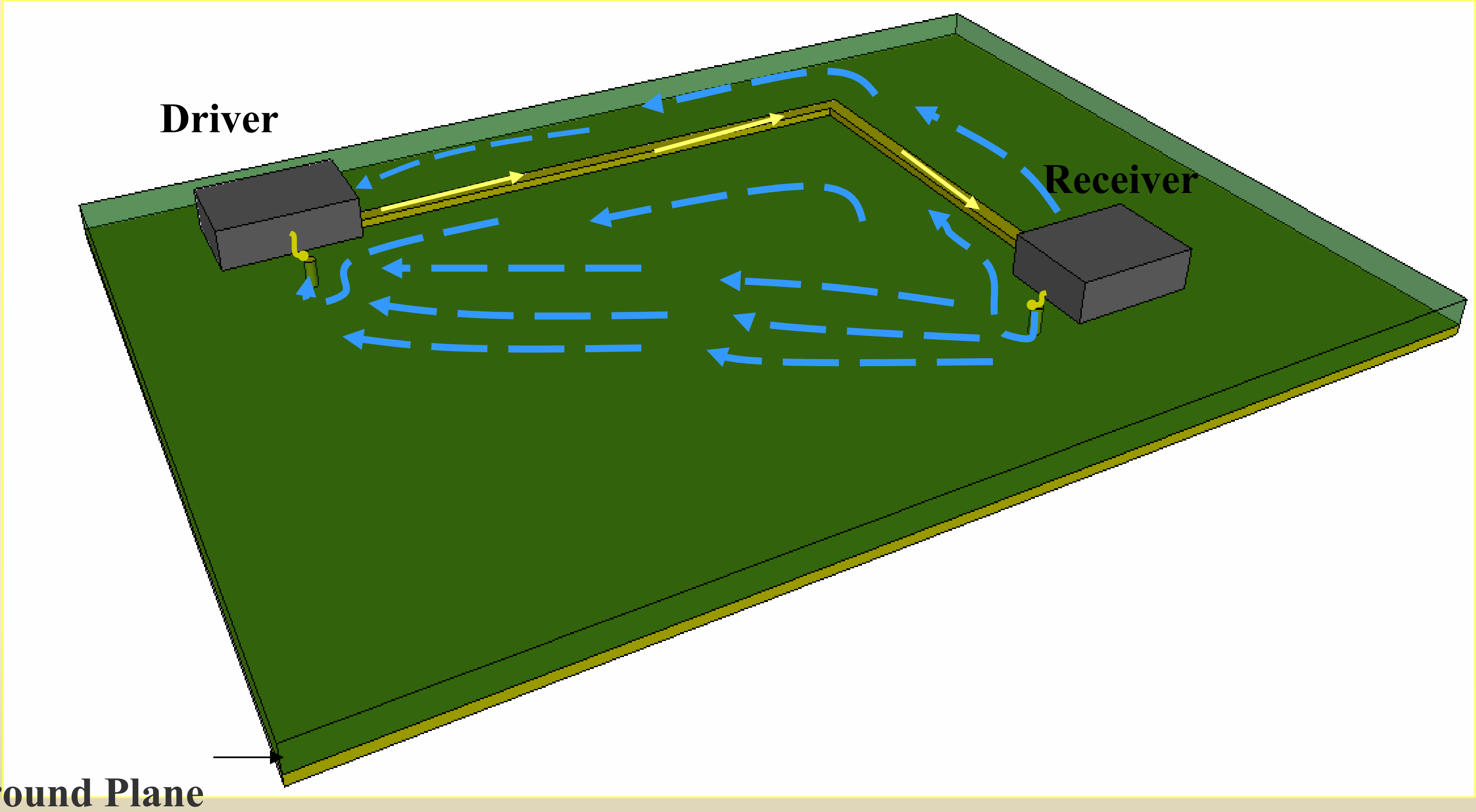
Schematic with Return Current Shown



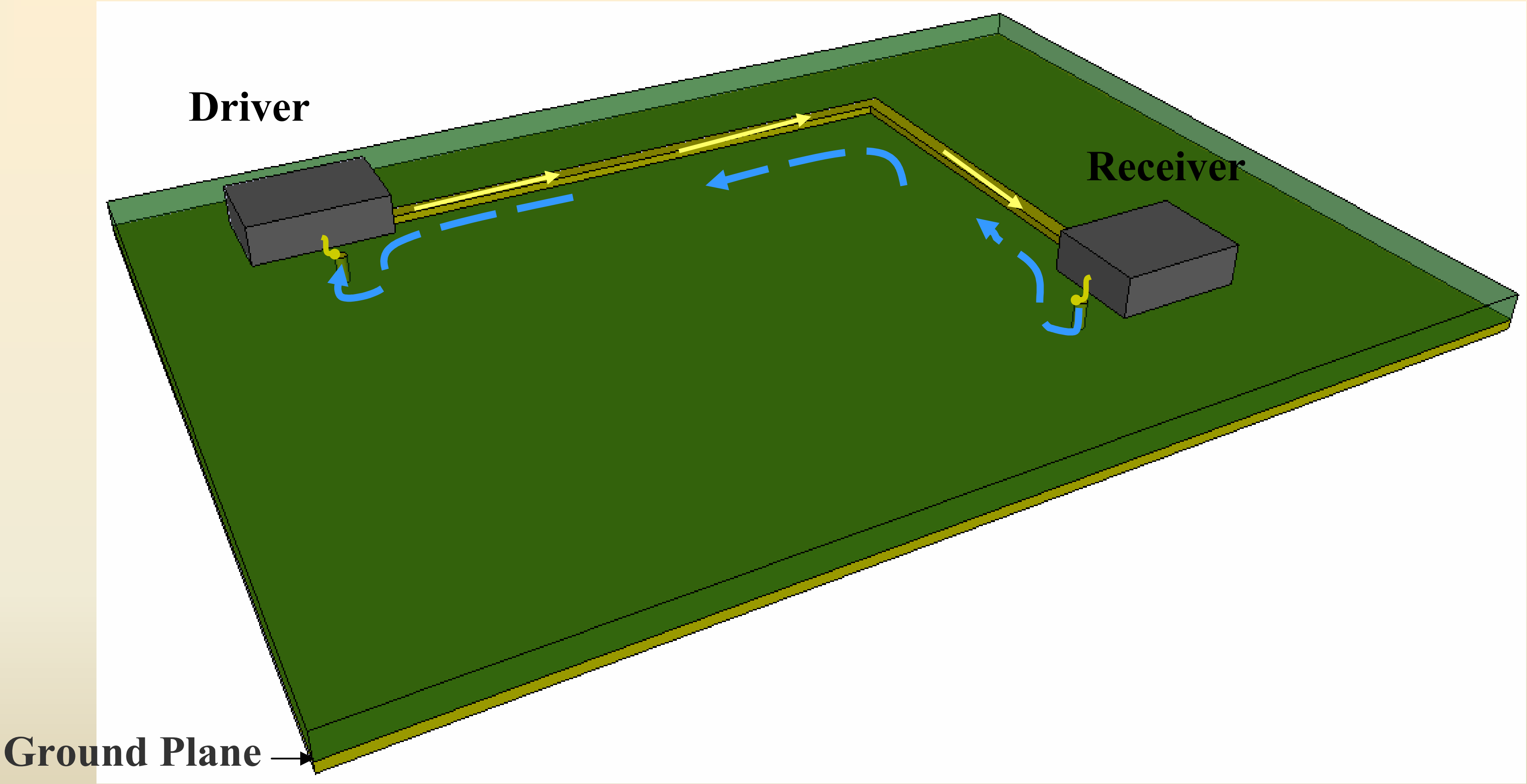
Actual Current Return is 3-Dimensional



Low Frequency Return Currents Take Path of Least ***Resistance***

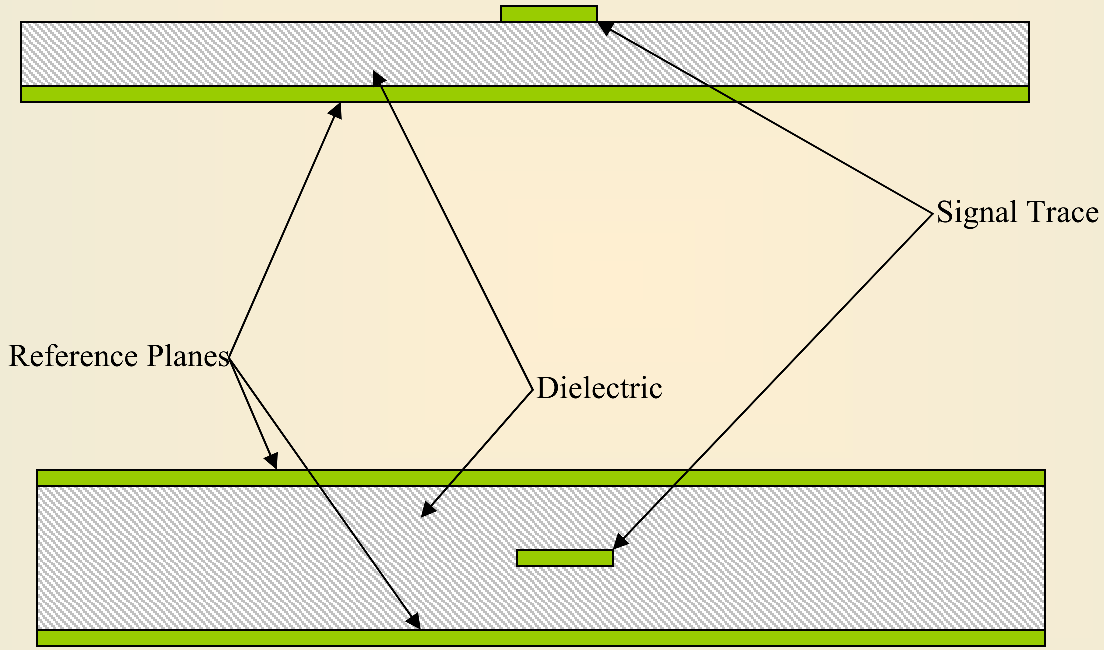


High Frequency Return Currents Take Path of Least ***Inductance***



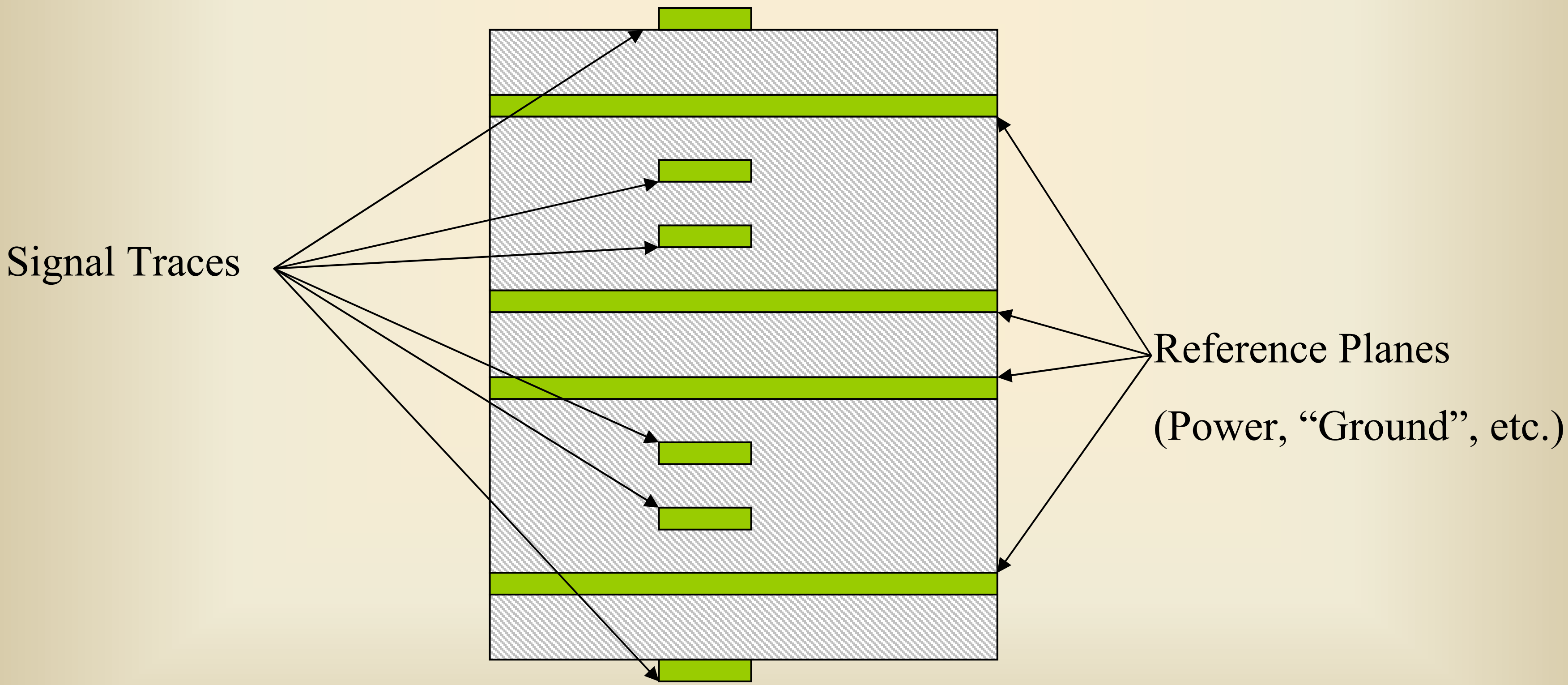
Traces/nets over a Reference Plane

Microstrip Transmission Line

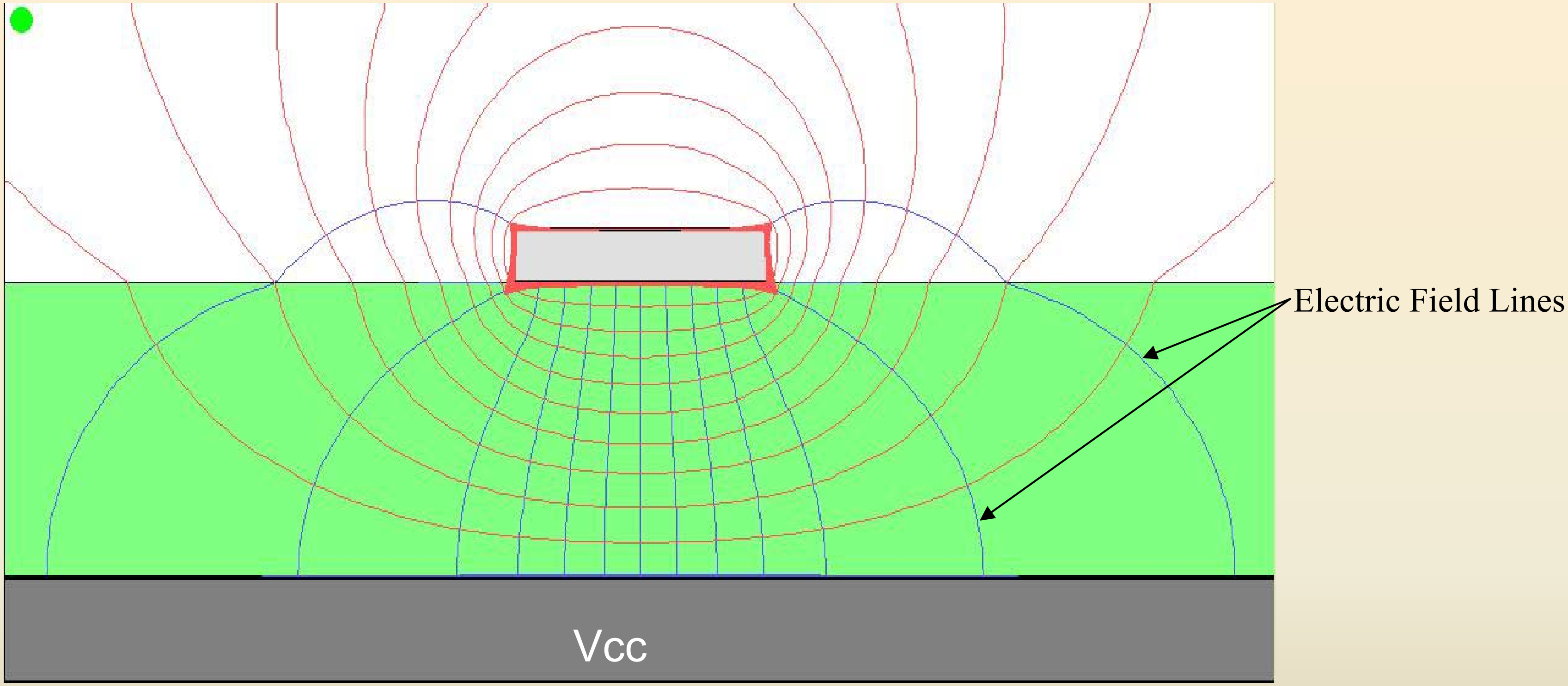


Stripline Transmission Line

Traces/nets and Reference Planes in Many Layer Board Stackup



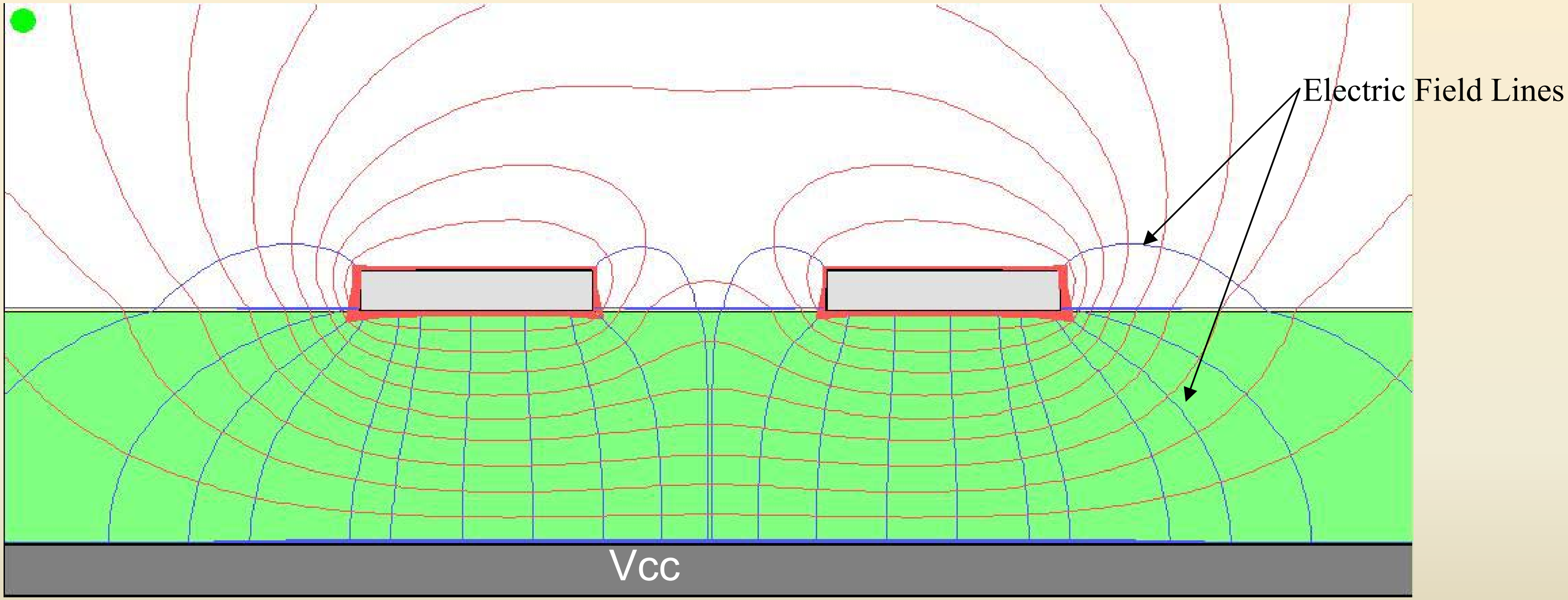
Microstrip Electric/Magnetic Field Lines
(8mil wide trace, 8 mils above plane, 65 ohm)



Microstrip Electric/Magnetic Field Lines

Common Mode

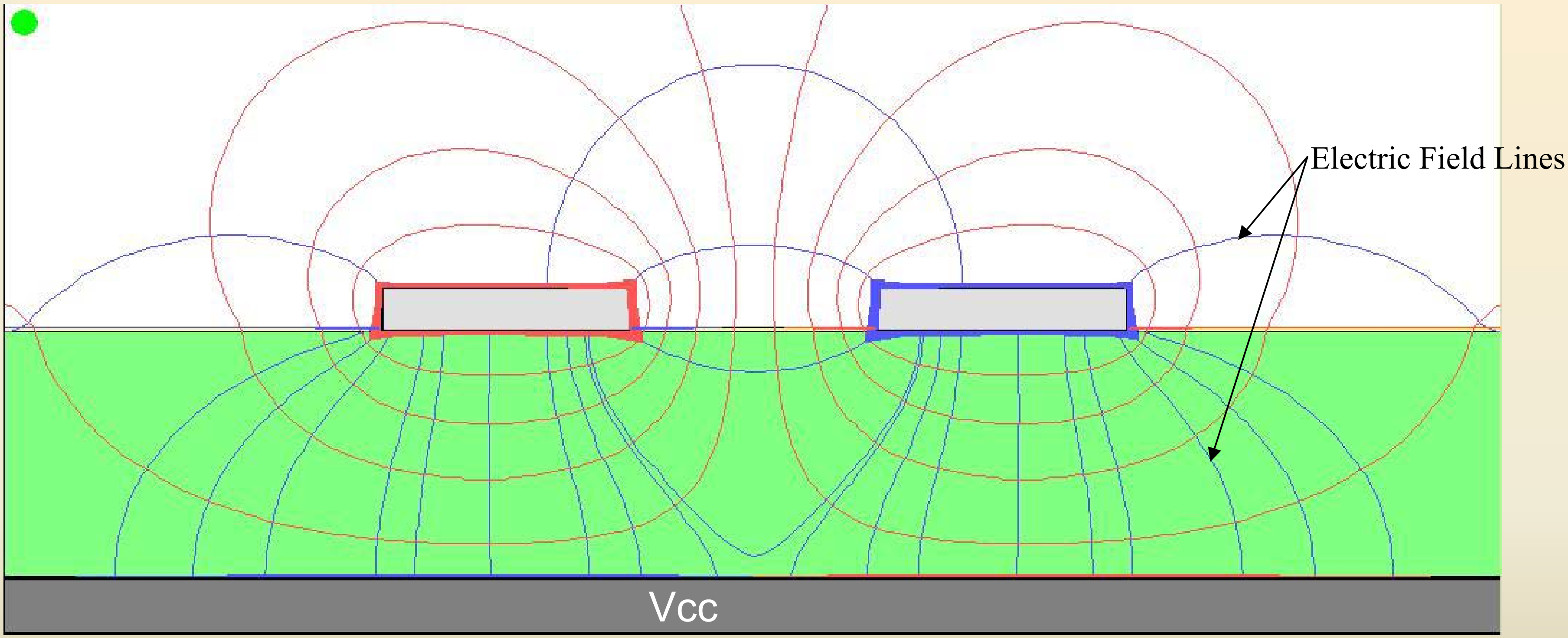
8 mil wide trace, 8 mils above plane, 65/115 ohm)



Microstrip Electric/Magnetic Field Lines

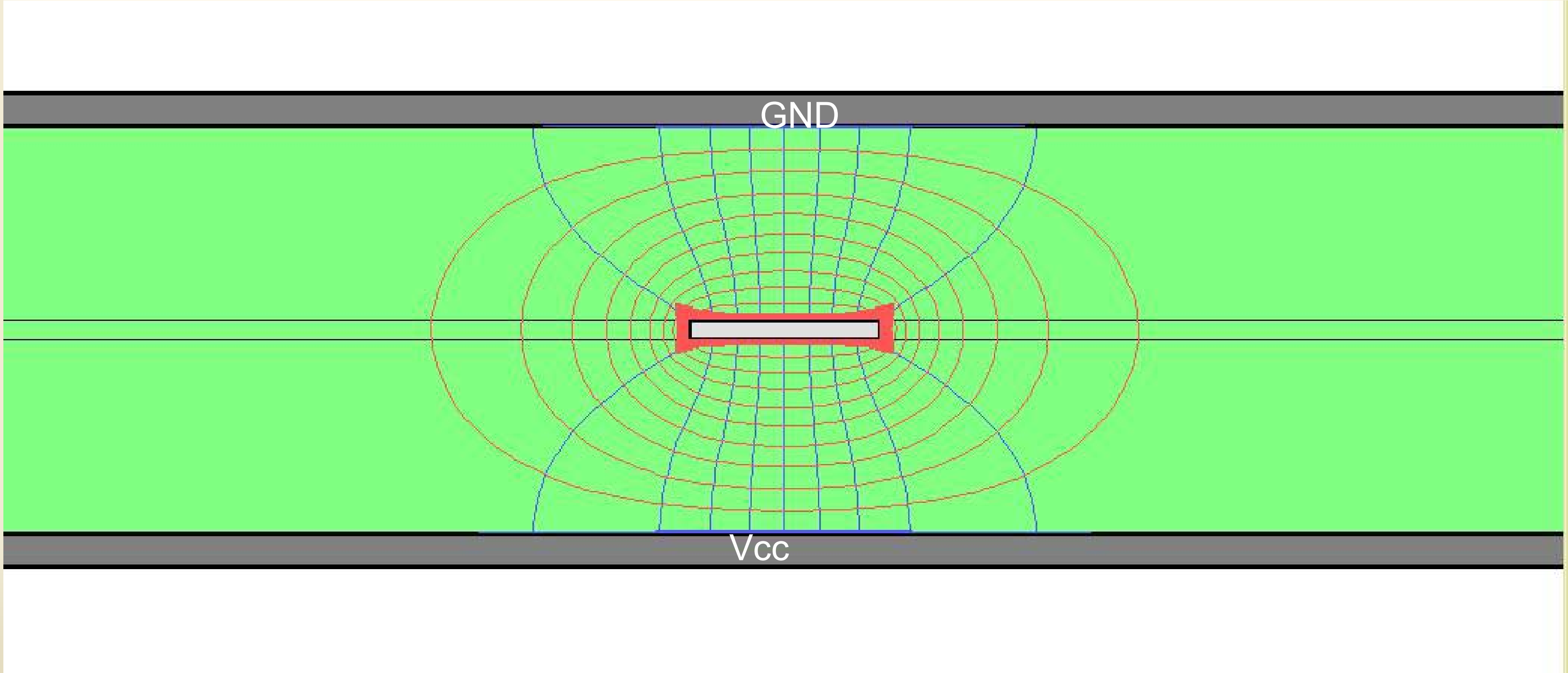
Differential Mode

8 mil wide trace, 8 mils above plane, 65/115 ohm)

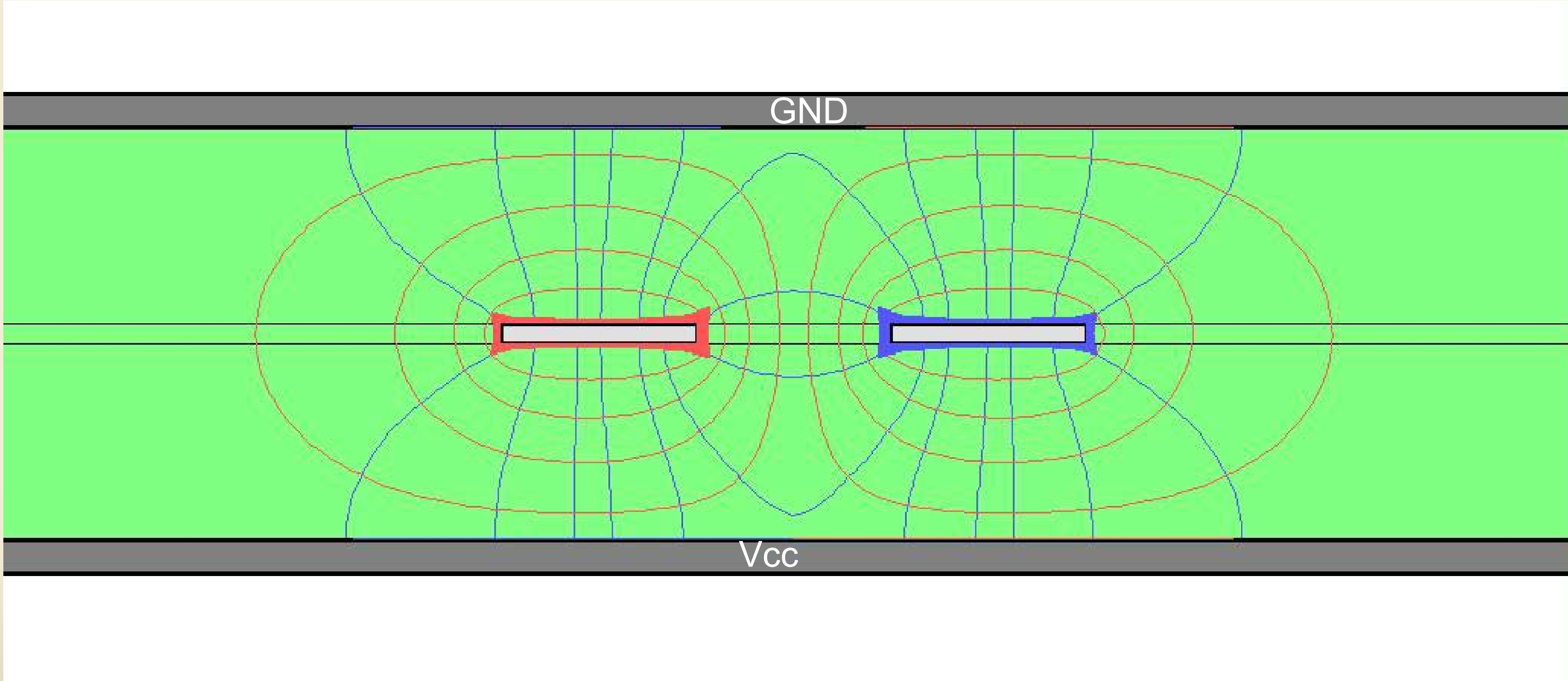


Electric/Magnetic Field Lines

Symmetrical Stripline

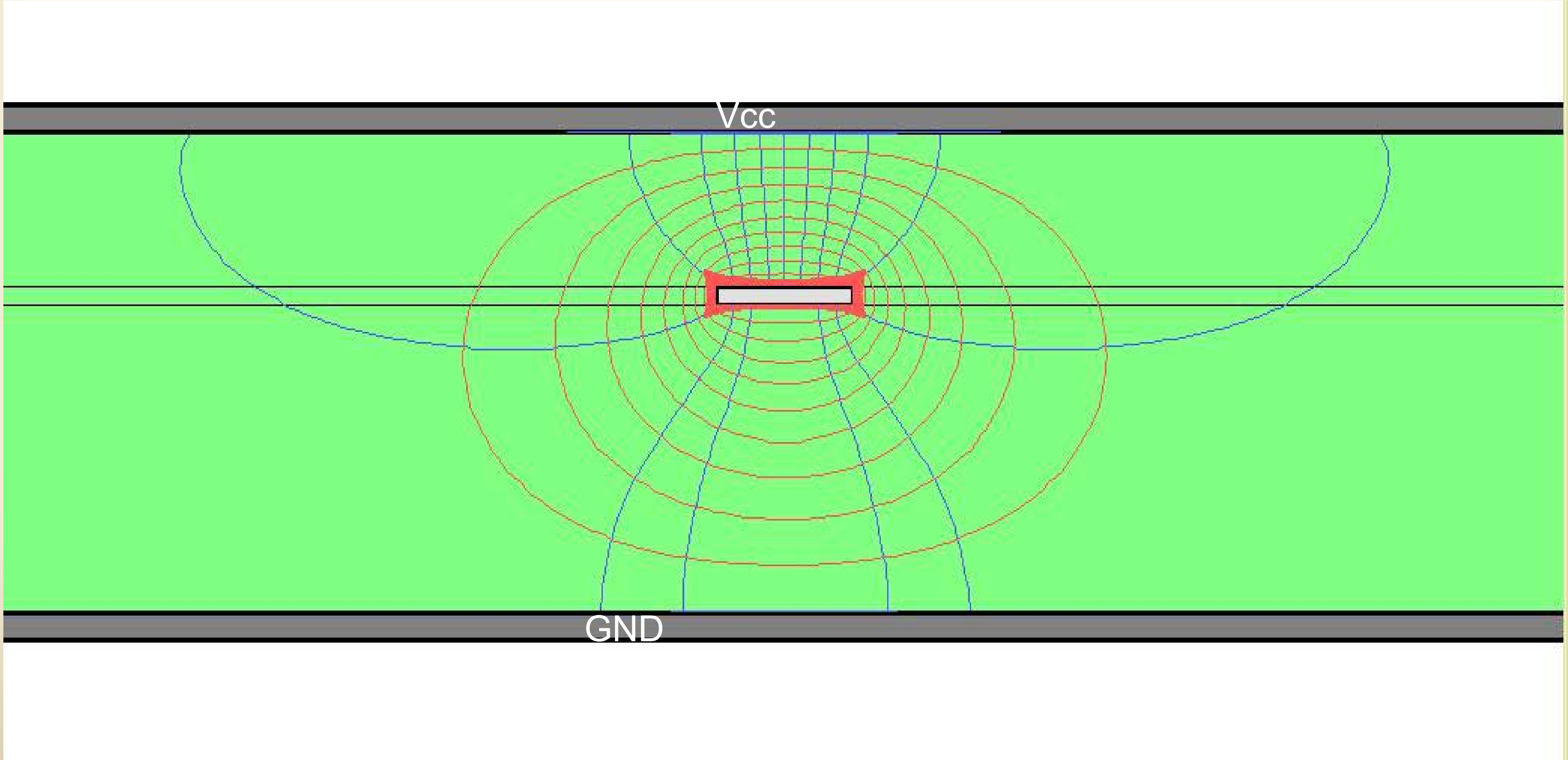


Electric/Magnetic Field Lines
Symmetrical Stripline (Differential)



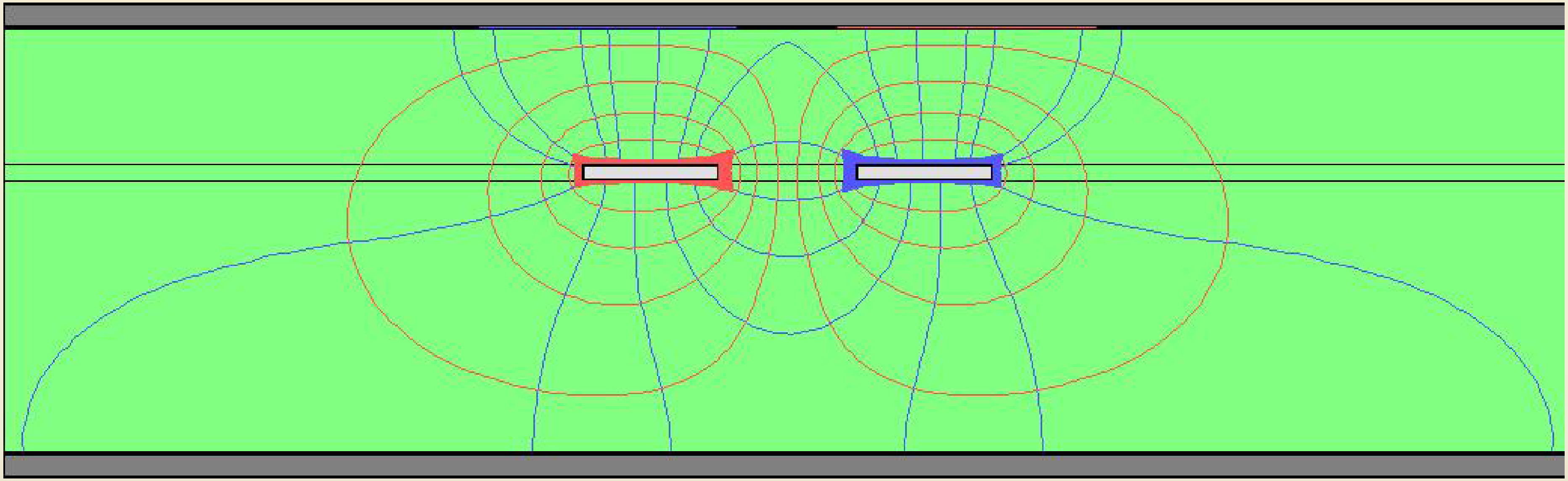
Electric/Magnetic Field Lines

Asymmetrical Stripline



Electric/Magnetic Field Lines

Asymmetrical Stripline (Differential)



What About Pseudo-Differential Nets?

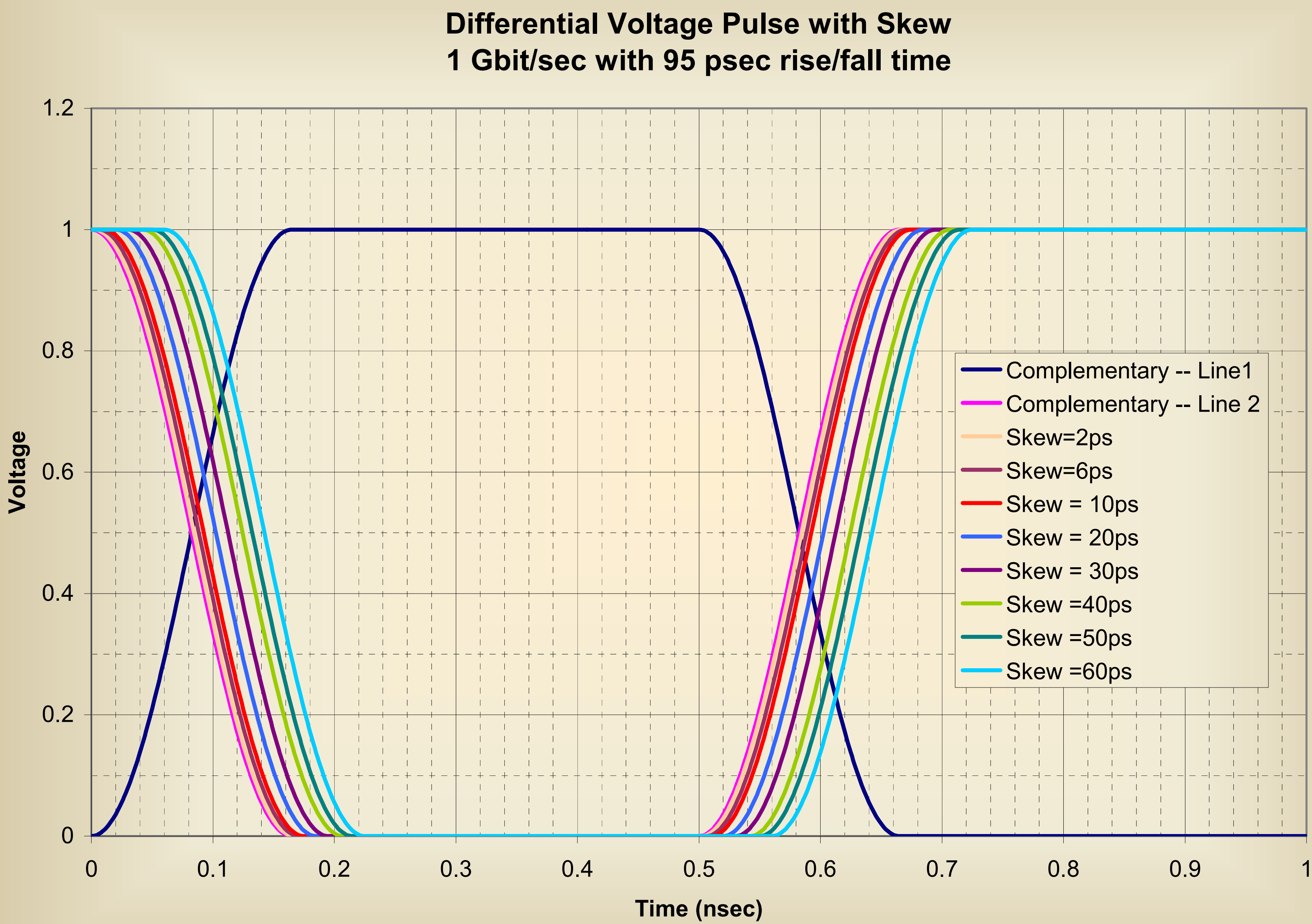
- So-called differential traces are NOT truly differential
  - Two complementary single-ended drivers
    - Relative to ‘ground’
  - Receiver is differential
    - Senses difference between two nets (independent of ‘ground’)
    - Provides good immunity to common mode noise
    - Good for signal quality/integrity

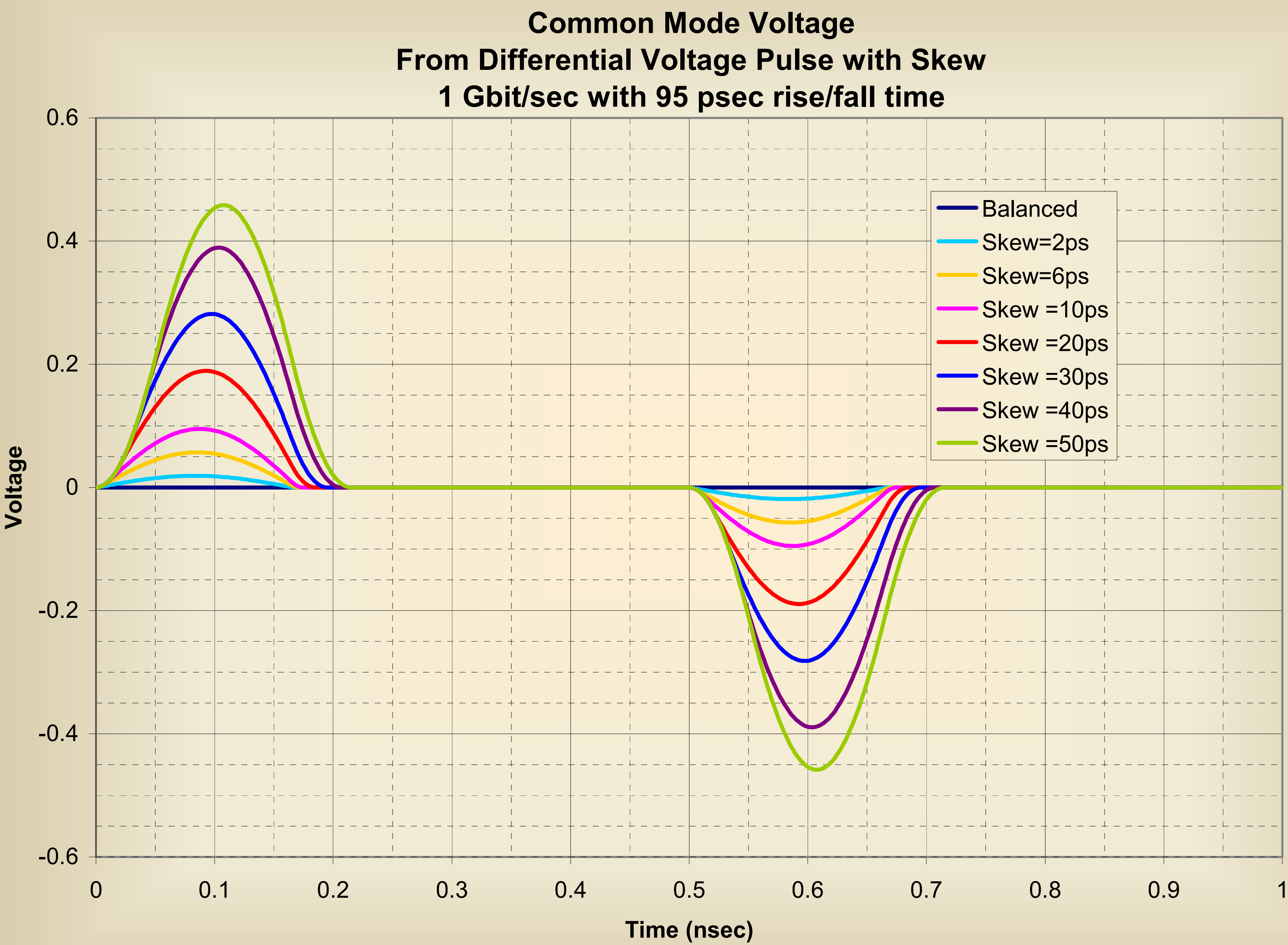
Pseudo-Differential Nets Current in Nearby Plane

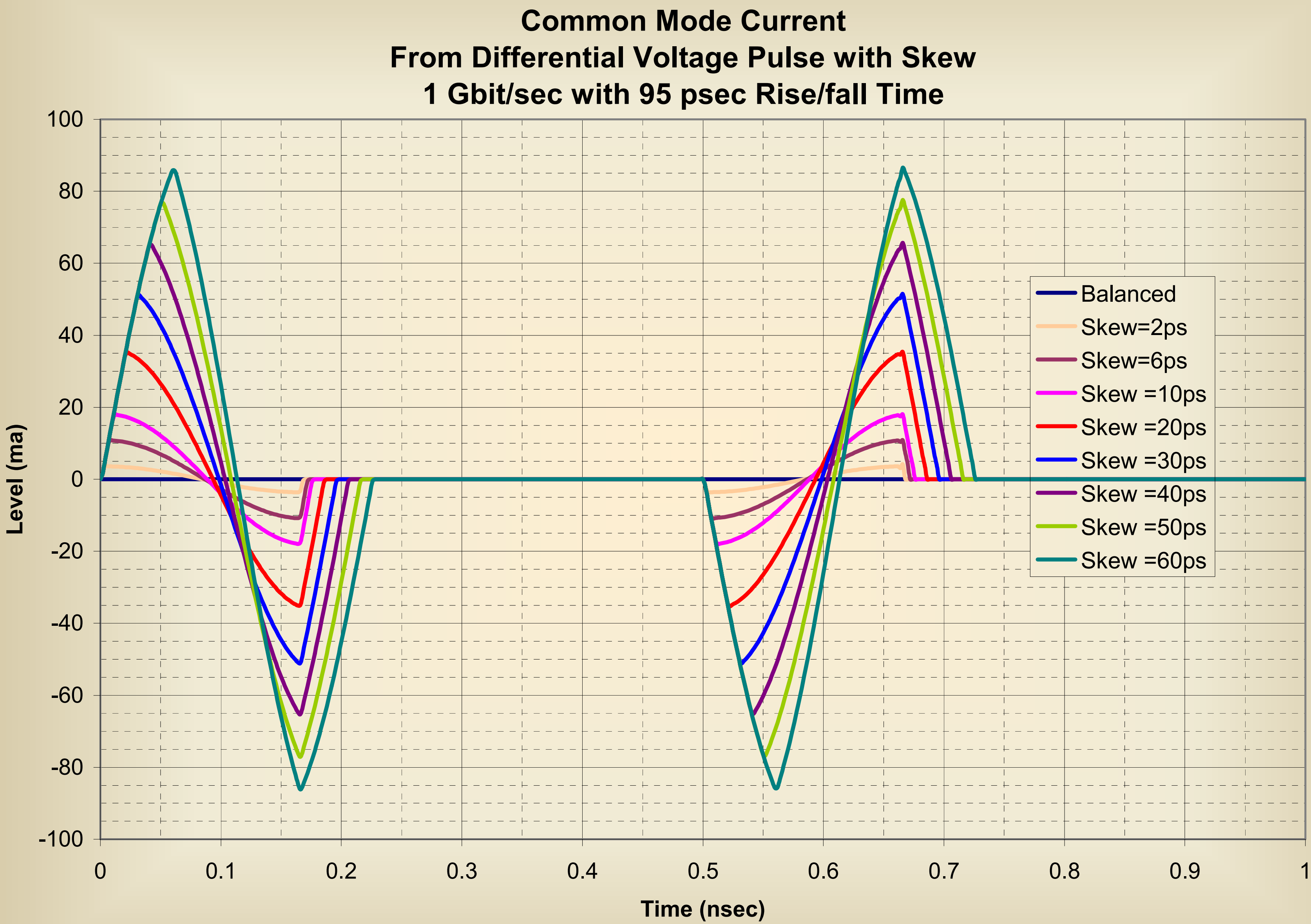
- Balanced/Differential currents have matching current in nearby plane
  – No issue for discontinuities
- Any unbalanced (common mode) currents have return currents in nearby plane that must return to source!
  – All normal concerns for single-ended nets apply!

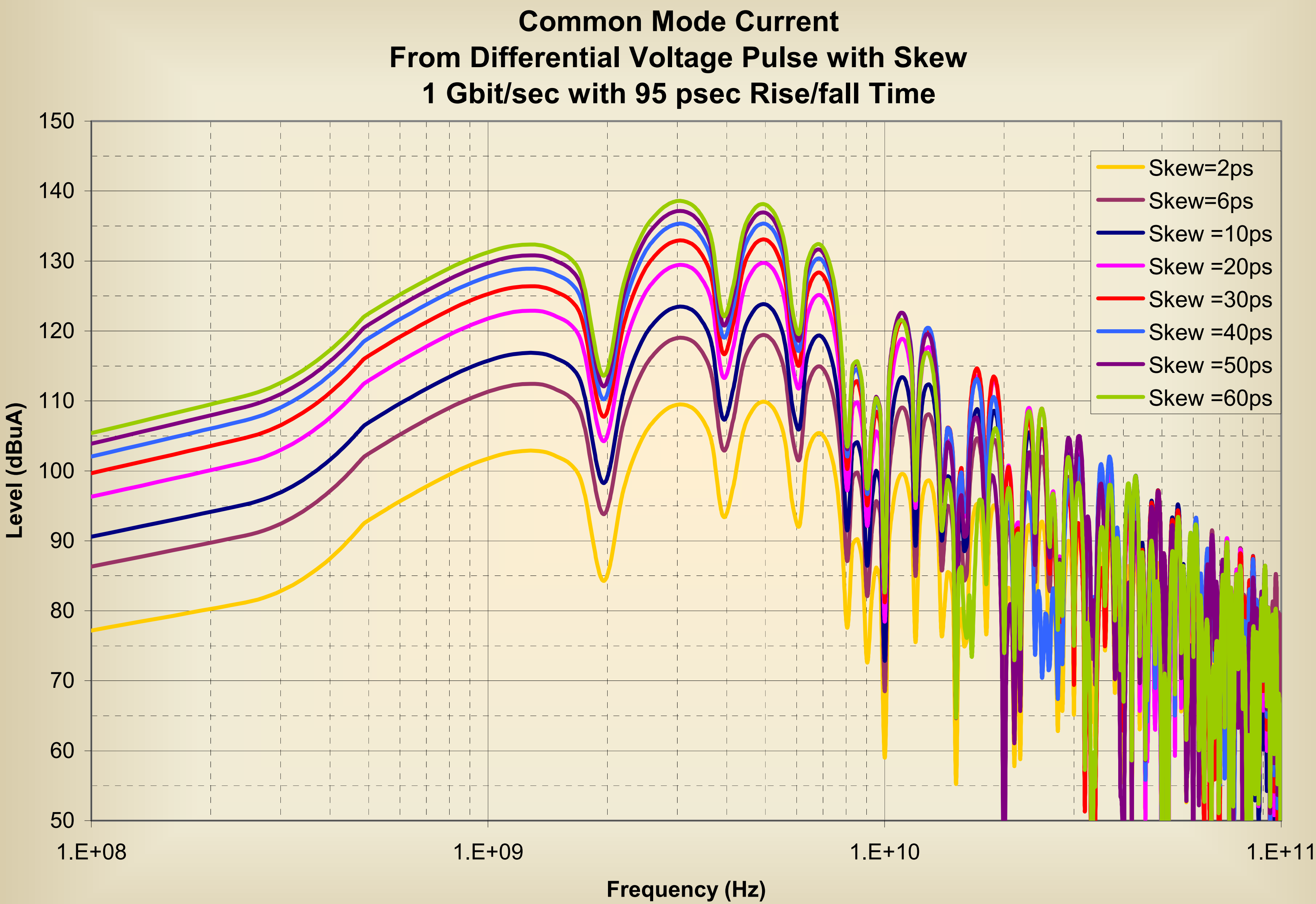
Pseudo-Differential Nets

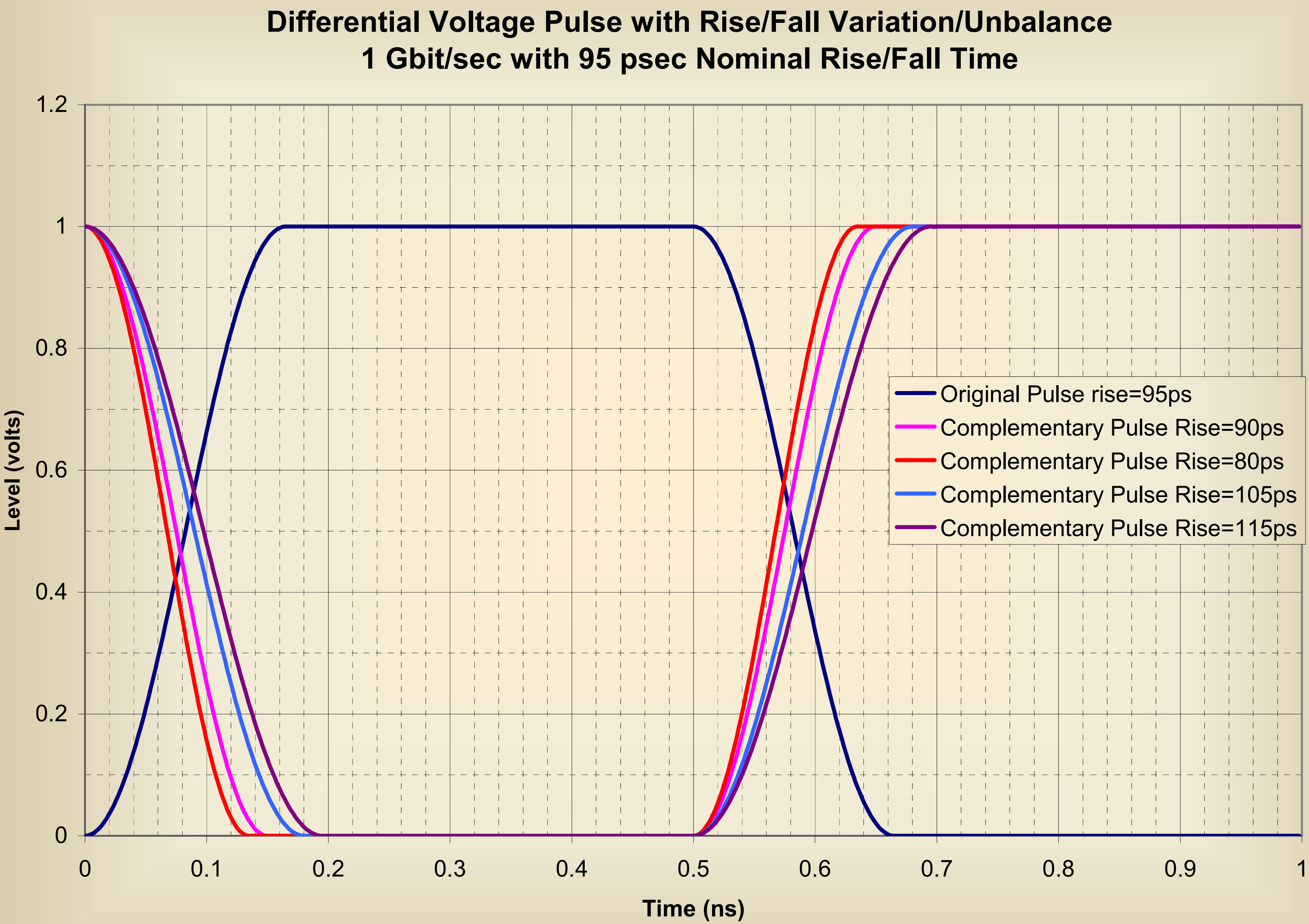
- Not really ‘differential’, since more closely coupled to nearby plane than each other
- Slew and rise/fall variation cause common mode currents!

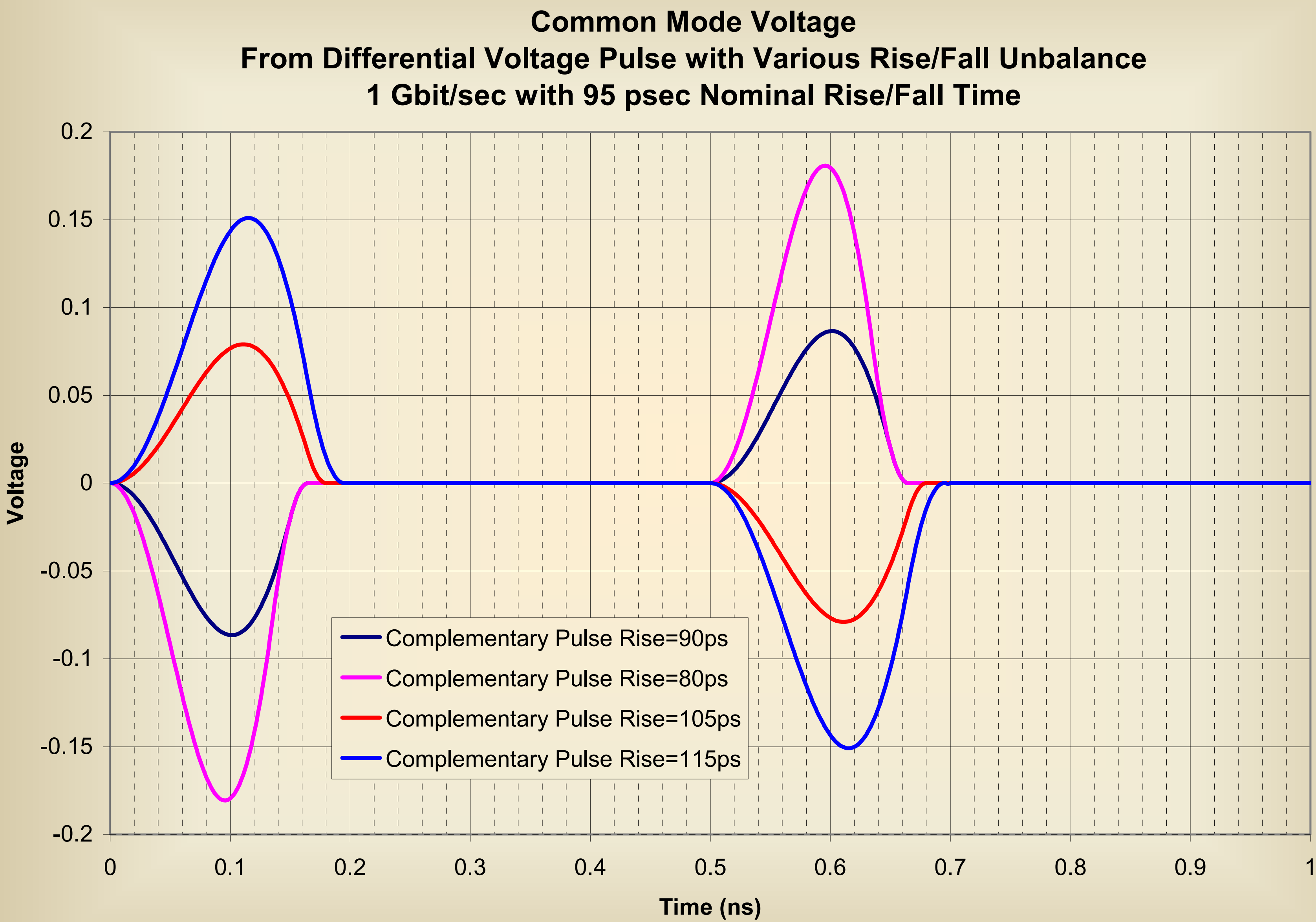

Differential Voltage Pulse with Skew
1 Gbit/sec with 95 psec rise/fall time
1.2
1
0.8
0.6
0.4
0.2
0
Voltage
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (nsec)
Complementary -- Line1
Complementary -- Line 2
Skew=2ps
Skew=6ps
Skew = 10ps
Skew = 20ps
Skew = 30ps
Skew =40ps
Skew =50ps
Skew =60ps

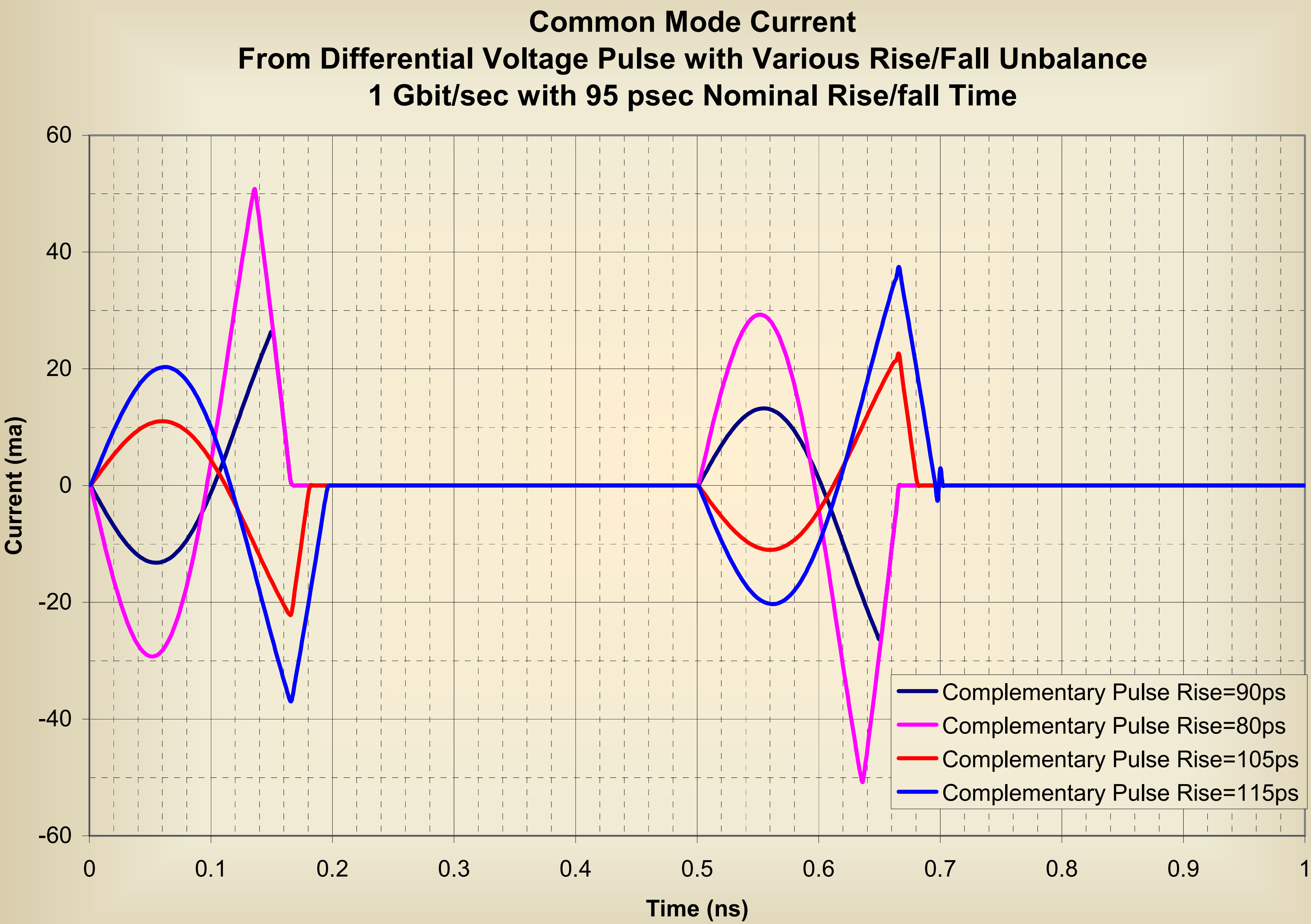

Common Mode Voltage
From Differential Voltage Pulse with Skew
1 Gbit/sec with 95 psec rise/fall time
Voltage
Time (nsec)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Balanced
Skew=2ps
Skew=6ps
Skew =10ps
Skew =20ps
Skew =30ps
Skew =40ps
Skew =50ps


Common Mode Current
From Differential Voltage Pulse with Skew
1 Gbit/sec with 95 psec Rise/fall Time
100
80
60
40
20
0
-20
-40
-60
-80
-100
Level (ma)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (nsec)
Balanced
Skew=2ps
Skew=6ps
Skew =10ps
Skew =20ps
Skew =30ps
Skew =40ps
Skew =50ps
Skew =60ps

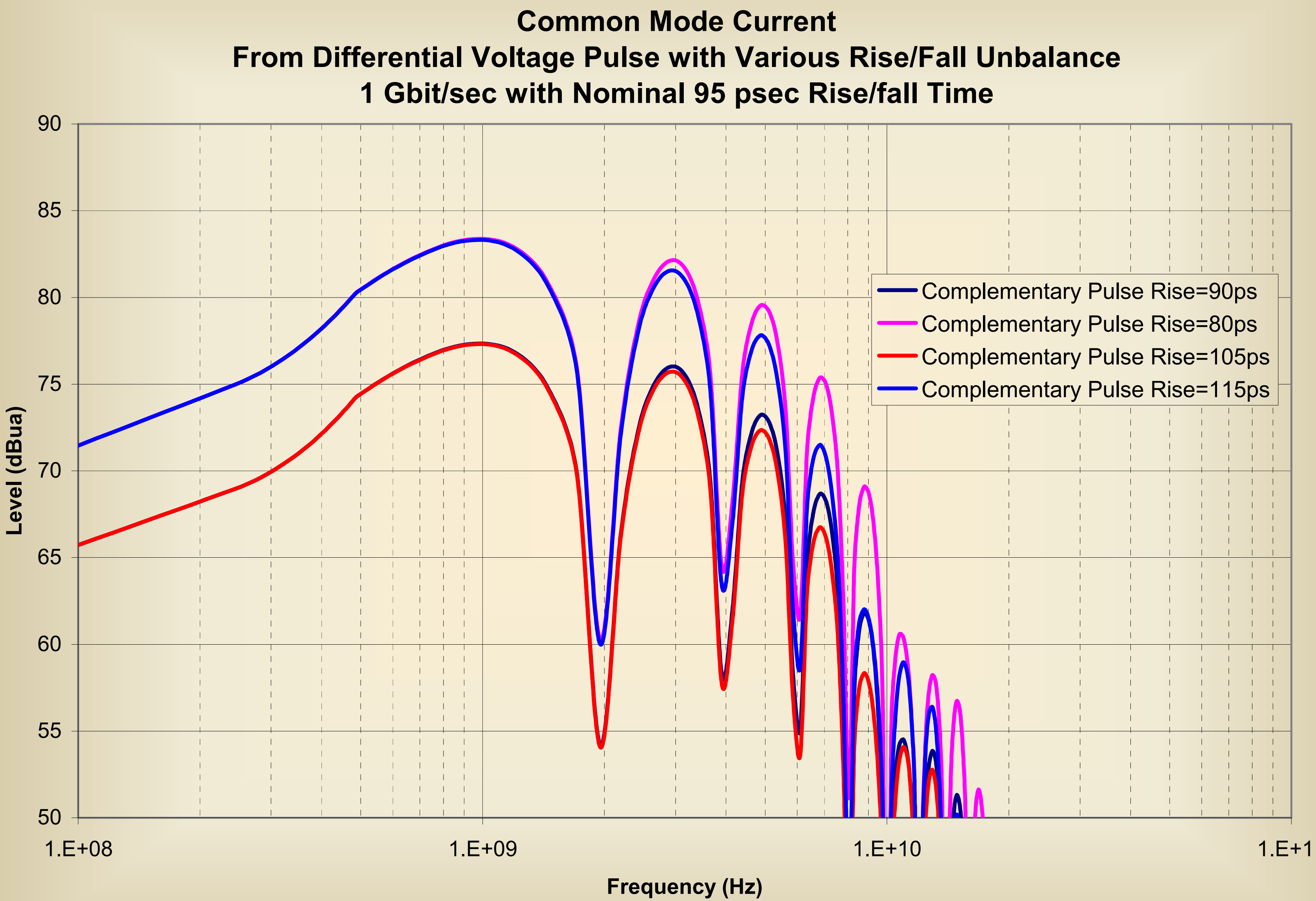

Common Mode Current
From Differential Voltage Pulse with Skew
1 Gbit/sec with 95 psec Rise/fall Time
150
140
130
120
110
100
90
80
70
60
50
Level (dBuA)
1.E+08
1.E+09
1.E+10
1.E+11
Frequency (Hz)
Skew=2ps
Skew=6ps
Skew =10ps
Skew =20ps
Skew =30ps
Skew =40ps
Skew =50ps
Skew =60ps


Differential Voltage Pulse with Rise/Fall Variation/Unbalance
1 Gbit/sec with 95 psec Nominal Rise/Fall Time
Level (volts)
Time (ns)
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Original Pulse rise=95ps
Complementary Pulse Rise=90ps
Complementary Pulse Rise=80ps
Complementary Pulse Rise=105ps
Complementary Pulse Rise=115ps


Common Mode Voltage
From Differential Voltage Pulse with Various Rise/Fall Unbalance
1 Gbit/sec with 95 psec Nominal Rise/Fall Time
Voltage
Time (ns)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Complementary Pulse Rise=90ps
Complementary Pulse Rise=80ps
Complementary Pulse Rise=105ps
Complementary Pulse Rise=115ps



Common Mode Current
From Differential Voltage Pulse with Various Rise/Fall Unbalance
1 Gbit/sec with 95 psec Nominal Rise/fall Time
Current (ma)
60
40
20
0
-20
-40
-60
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time (ns)
Complementary Pulse Rise=90ps
Complementary Pulse Rise=80ps
Complementary Pulse Rise=105ps
Complementary Pulse Rise=115ps

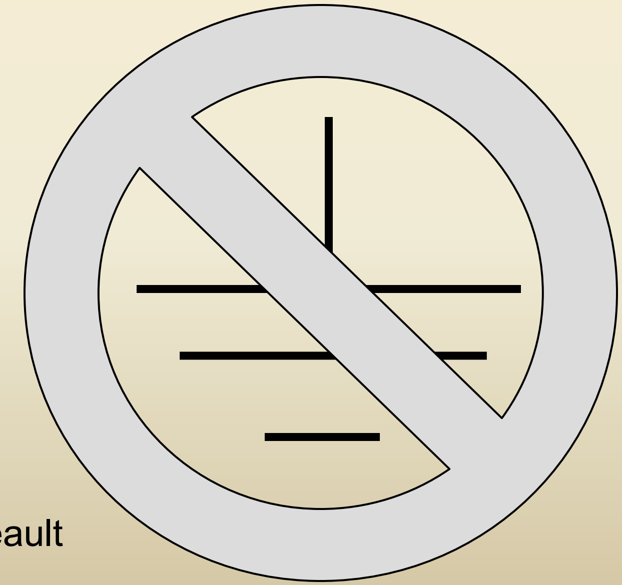

Common Mode Current
From Differential Voltage Pulse with Various Rise/Fall Unbalance
1 Gbit/sec with Nominal 95 psec Rise/fall Time
Level (dBua)
90
85
80
75
70
65
60
55
50
1.E+08
1.E+09
1.E+10
1.E+11
Frequency (Hz)
Complementary Pulse Rise=90ps
Complementary Pulse Rise=80ps
Complementary Pulse Rise=105ps
Complementary Pulse Rise=115ps

Pseudo-Differential Net Summary

- Small amounts of skew can cause significant common mode current
- Small amount of rise/fall time deviation can cause significant amount of common mode current
- Discontinuities (vias, crossing split planes, etc) and convert significant amount of differential current into common mode current

Return Current vs.. "Ground"

- For high frequency signals, "Ground" is a concept that does not exist
- The important question is "where does the ***return current*** flow?"



Referencing Nets
(Where does the Return Current Flow??)

- Microstrip/Stripline across split in reference plane
- Microstrip/Stripline through via (change reference planes)
- Mother/Daughter card

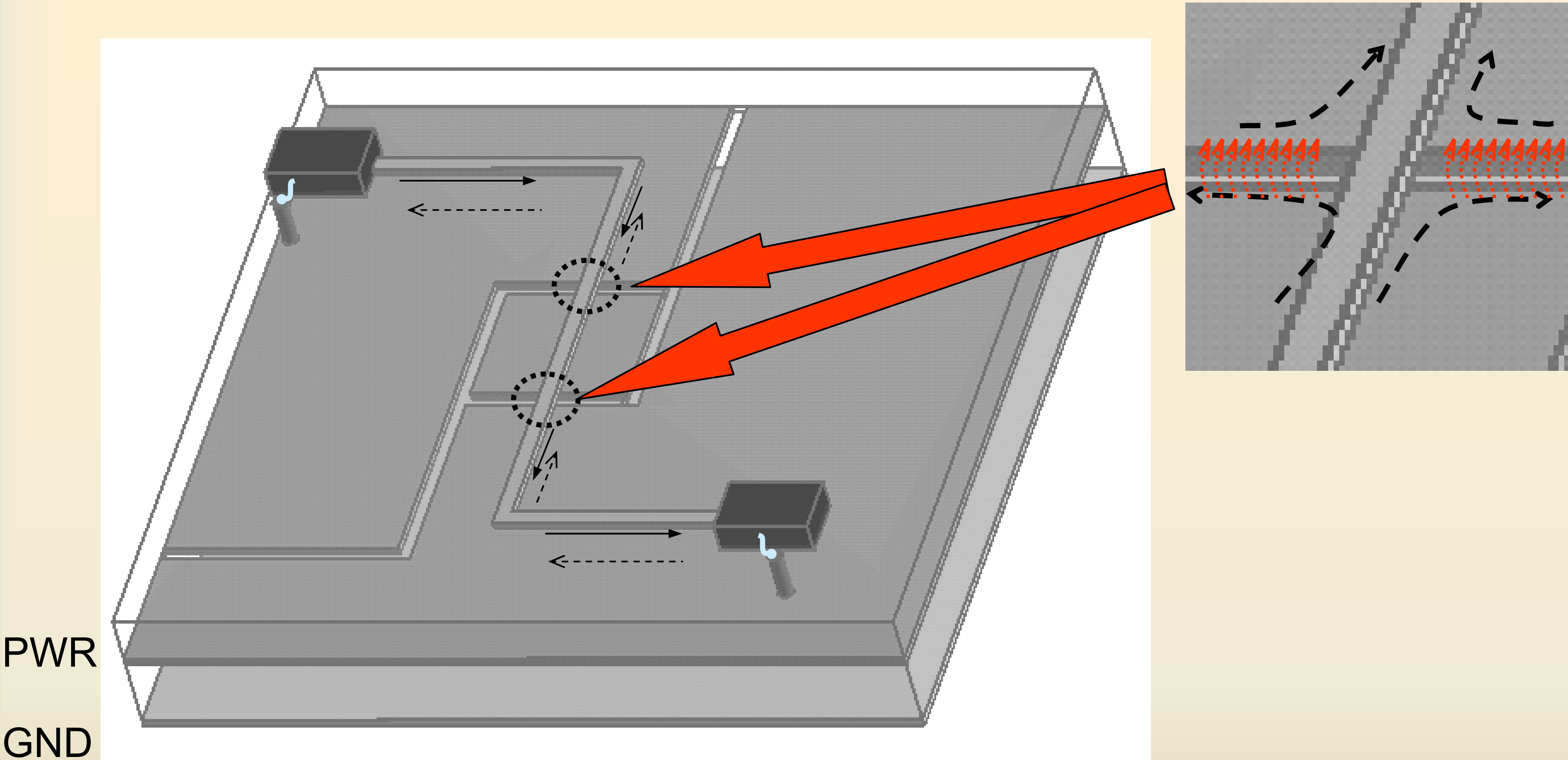
Microstrip/Stripline Across Split in Reference Plane

- Don't Cross Splits with Critical Signals!!!
  - Bad practice
  - Stitching capacitor required across split to allow return current flow
    - must be close to crossing
    - must have low inductance
    - limited frequency effect --- due to inductance
  - Major source of Common Mode current!

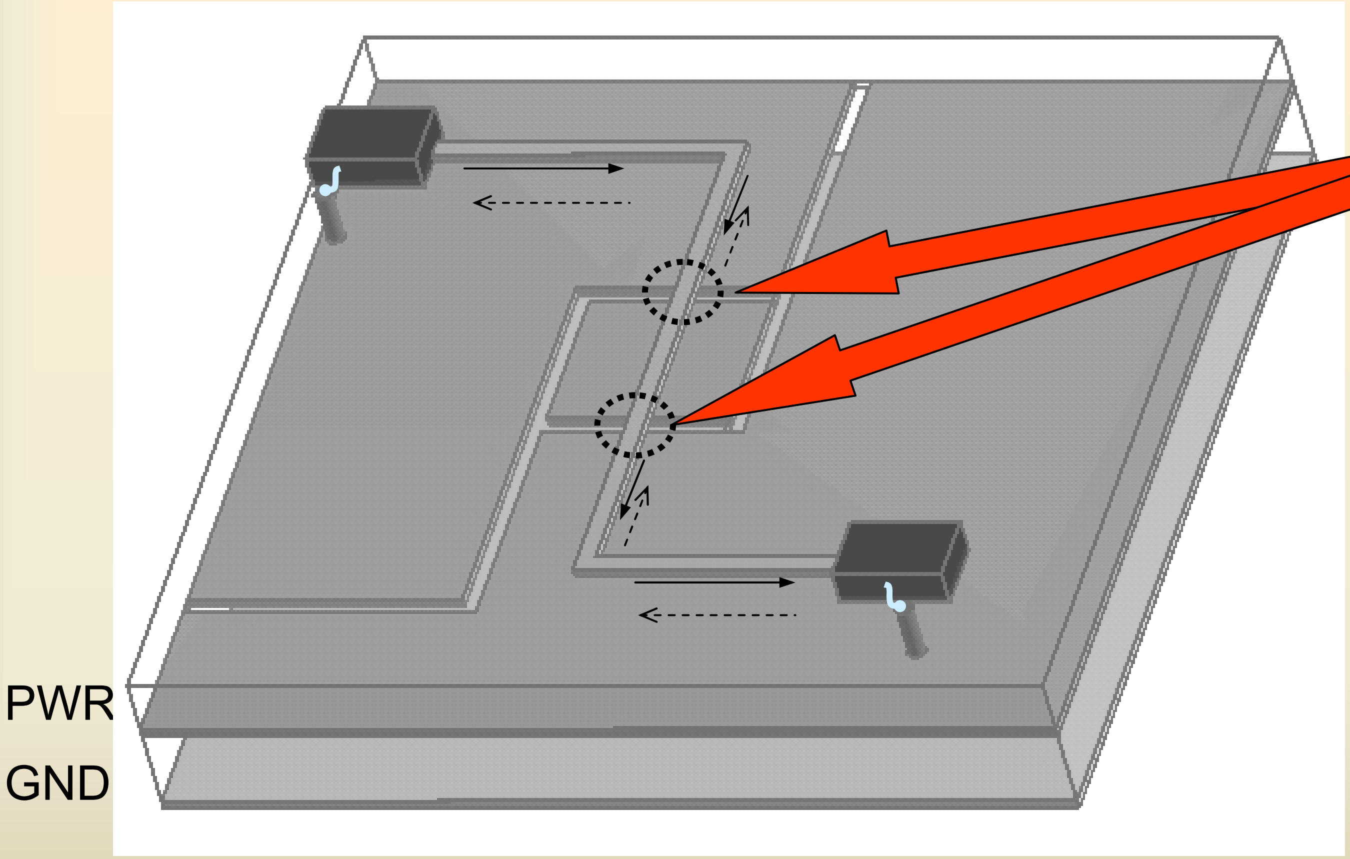
Splits in Reference Plane

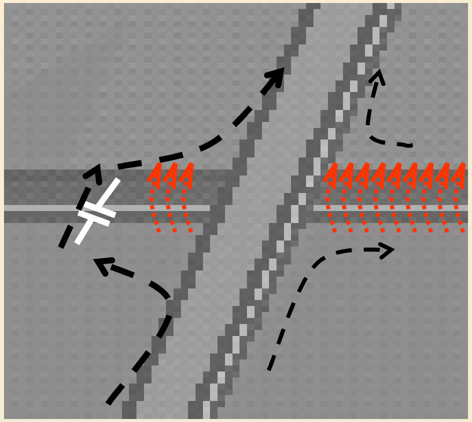
- Power planes often have splits
- Return current path interrupted
- Consider spectrum of clock signal
- Consider stitching capacitor impedance
- High frequency harmonics not returned directly

Split Reference Plane Example



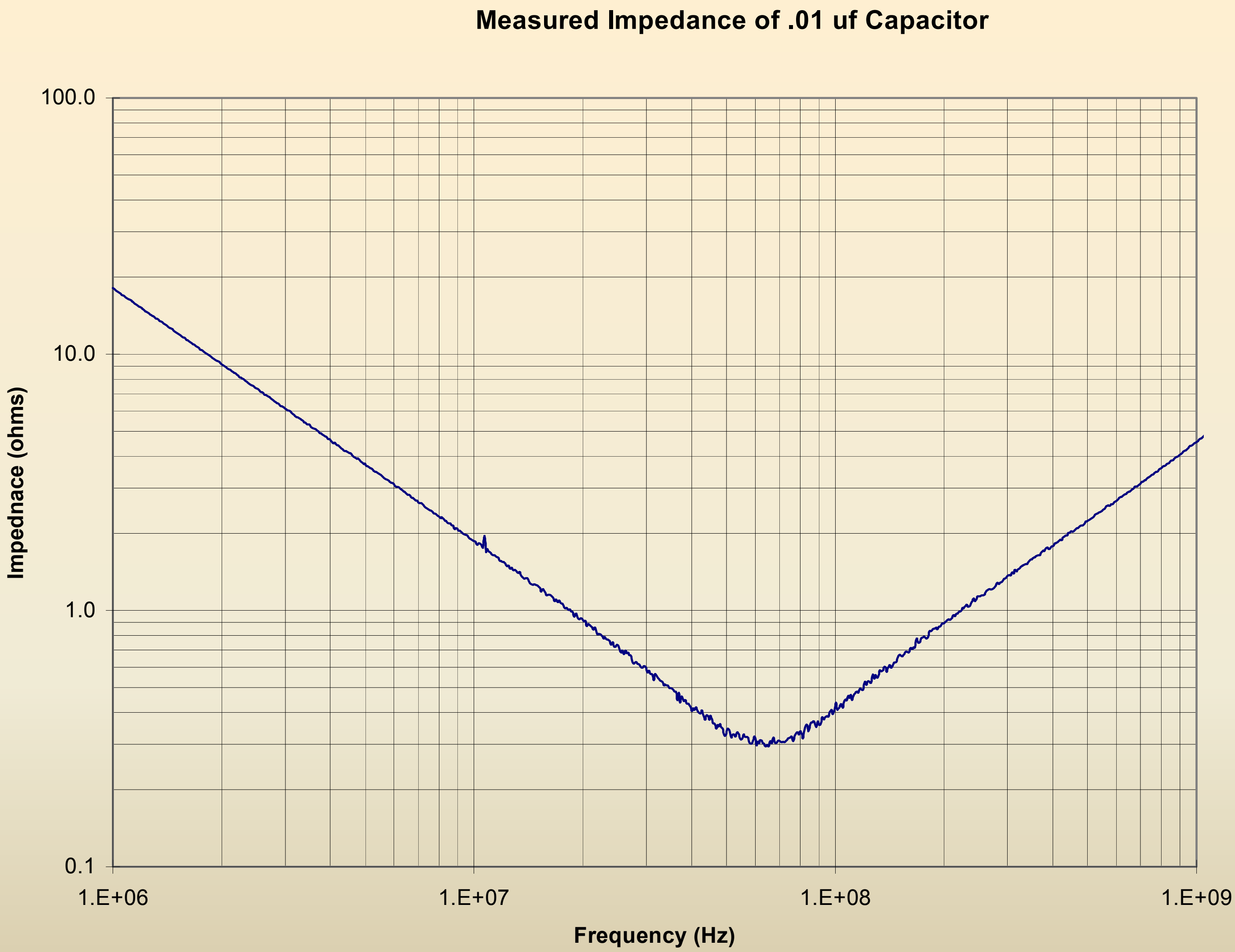
Split Reference Plane Example
With Stitching Capacitors



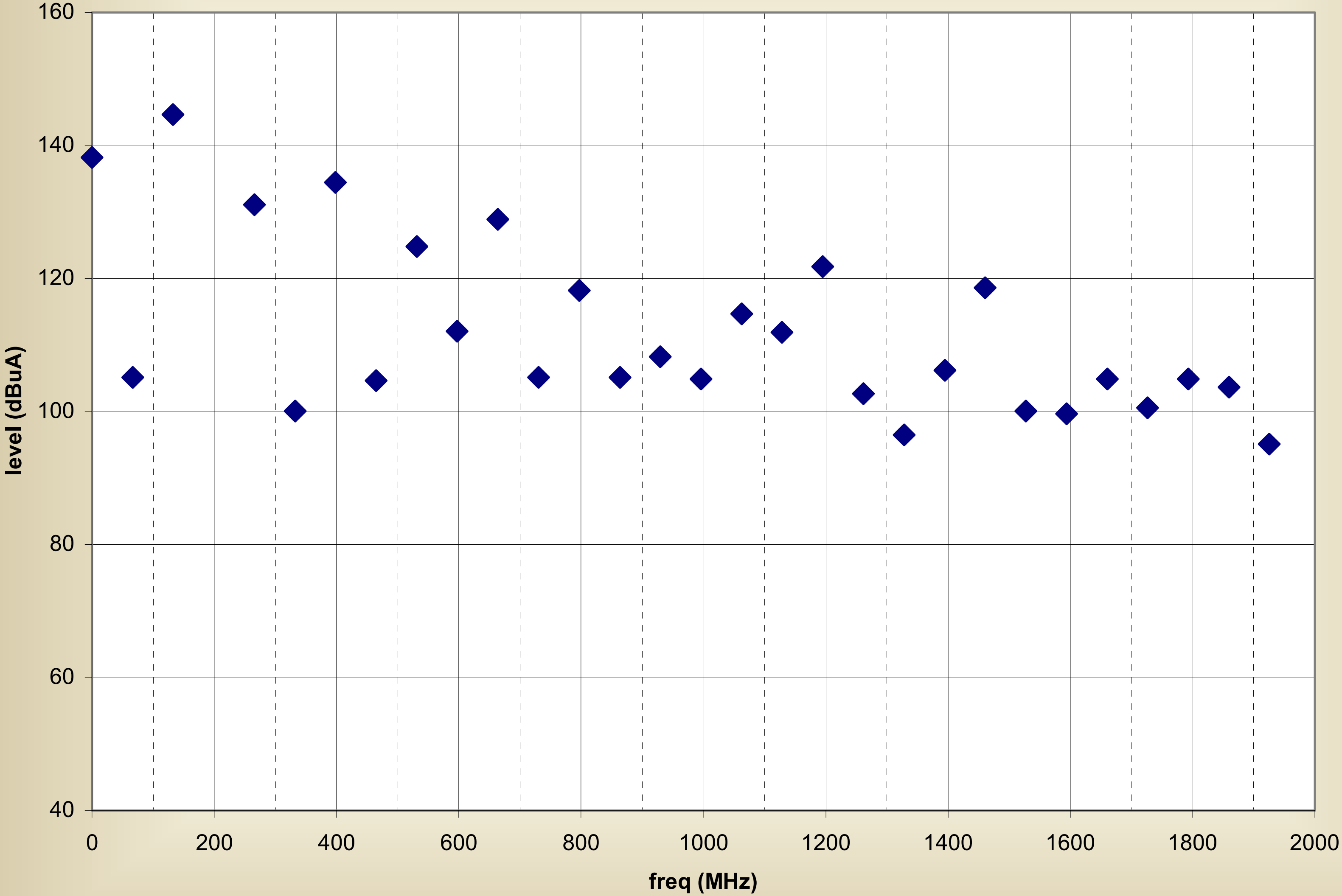


Stitching Capacitors Allow Return current to Cross Splits ???

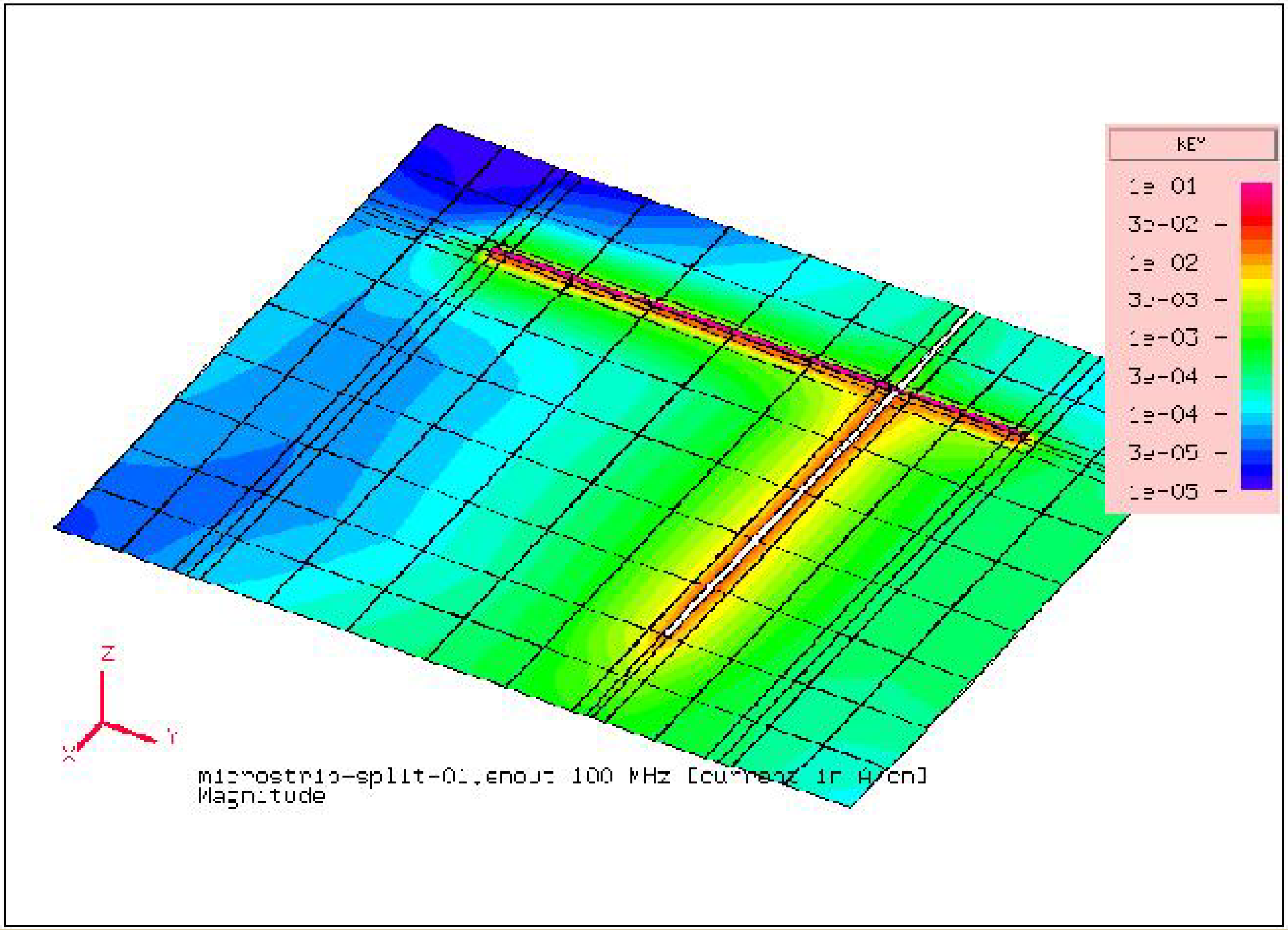
Capacitor Impedance



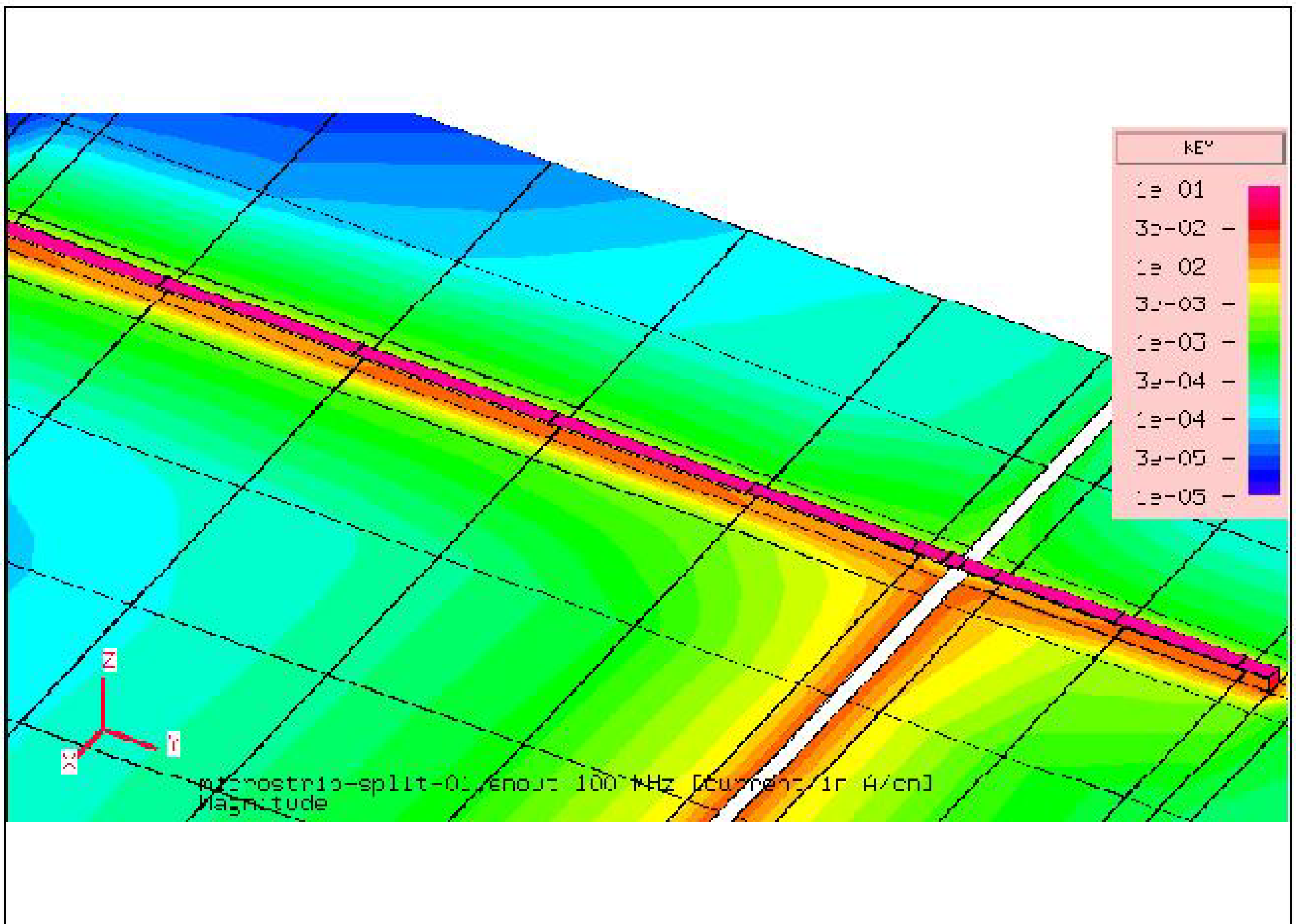
Frequency Domain Amplitude of Intentional Current Harmonic Amplitude
From Clock Net



MoM Microstrip Model Current Distribution Example



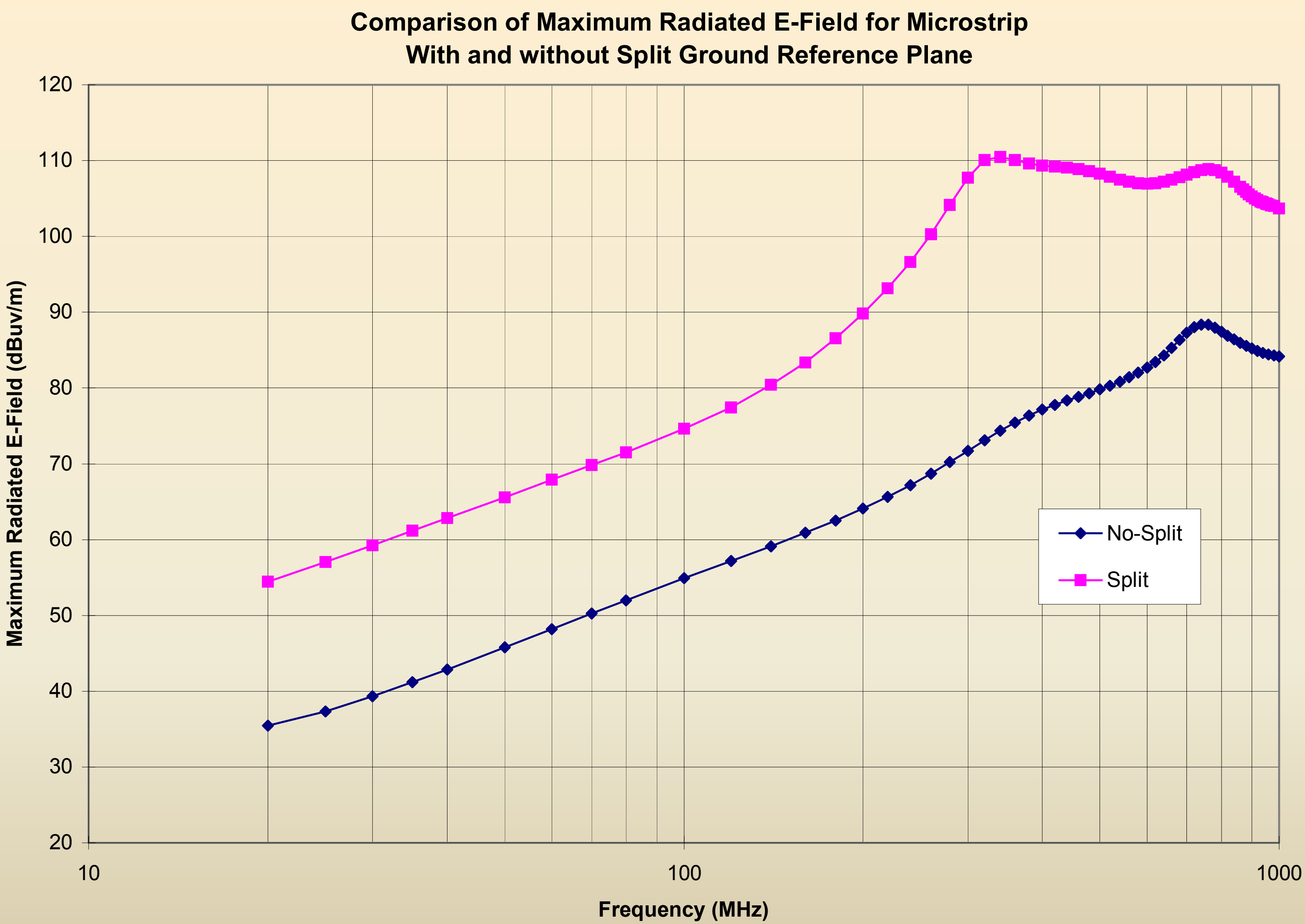
MoM Microstrip Model Current Distribution Example



Emissions From Board

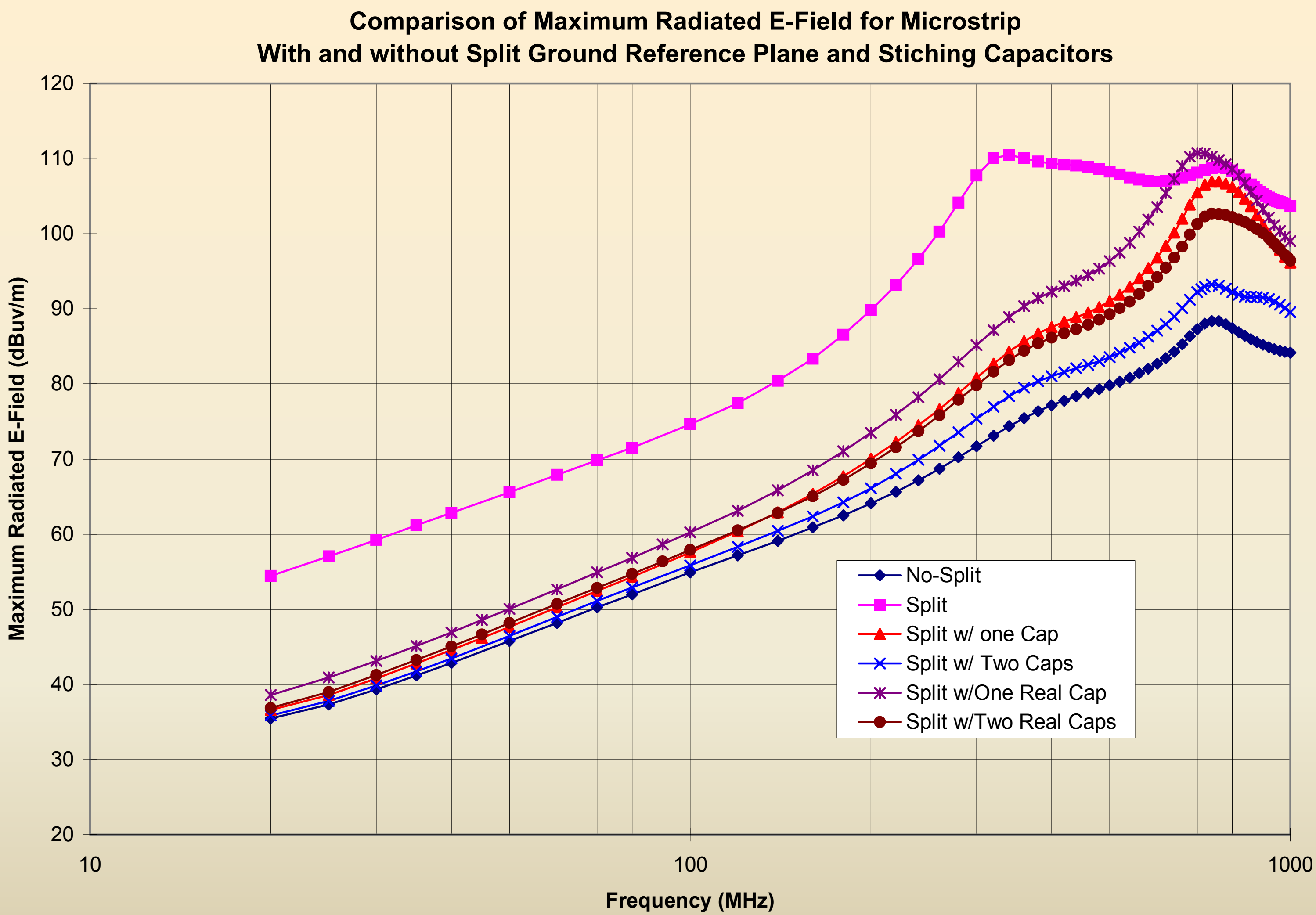
- Far field emissions not important unless it is an unshielded product
- Near field emissions above board **<u>ARE</u>** important
- Example of emissions from board with critical net crossing split reference plane

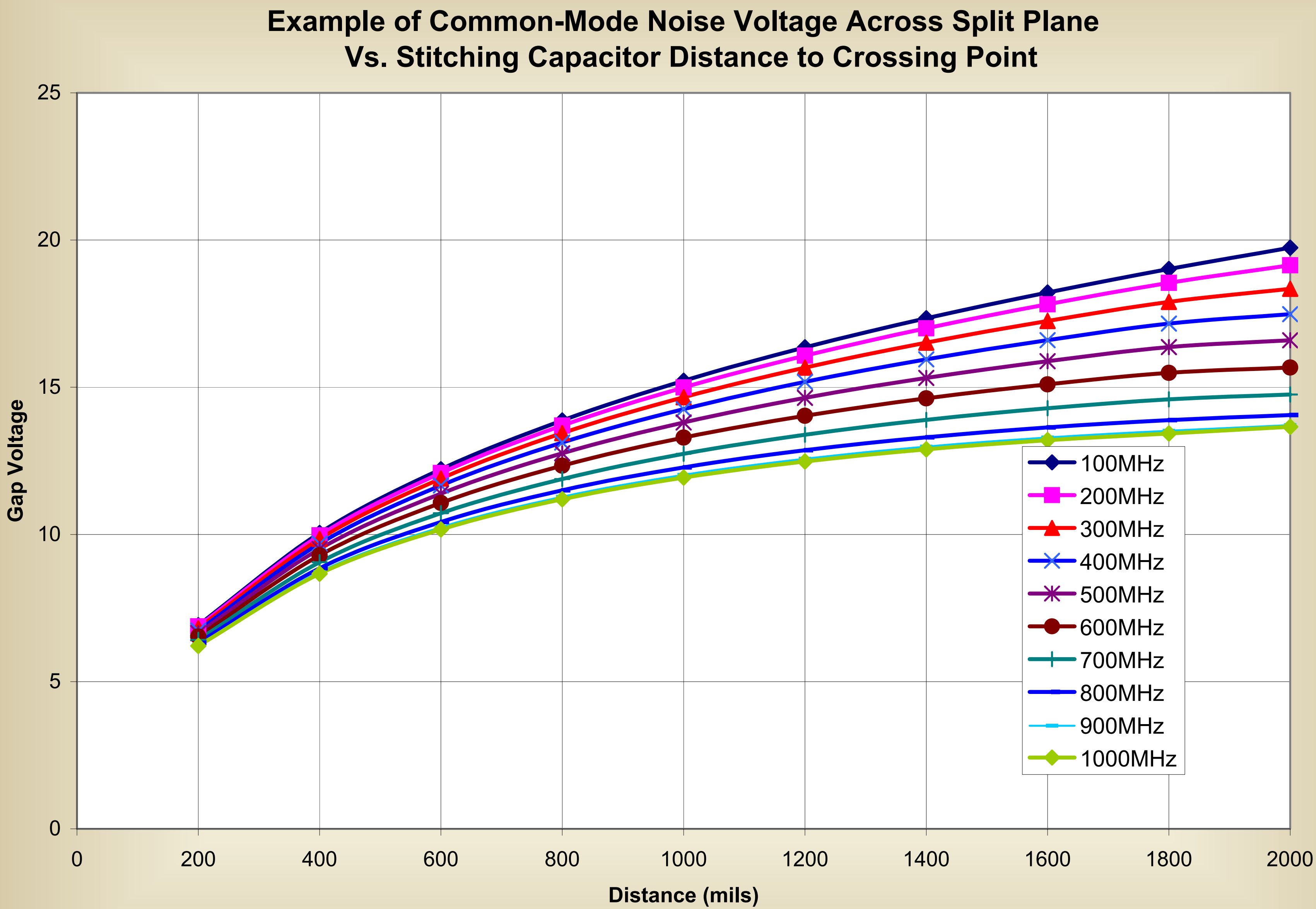
Near Field Radiation from Microstrip on Board with Split in Reference Plane



With “Perfectly Connected” Stitching Capacitors Across Split

Stitching Caps with Via Inductance



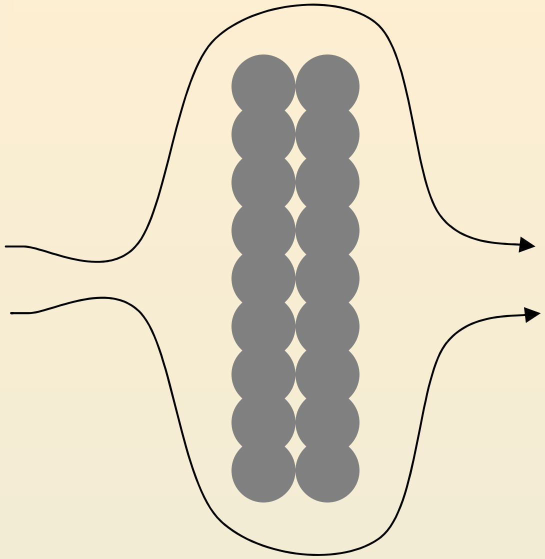


Example of Common-Mode Noise Voltage Across Split Plane
Vs. Stitching Capacitor Distance to Crossing Point
Gap Voltage
Distance (mils)
0
5
10
15
20
25
0
200
400
600
800
1000
1200
1400
1600
1800
2000
100MHz
200MHz
300MHz
400MHz
500MHz
600MHz
700MHz
800MHz
900MHz
1000MHz

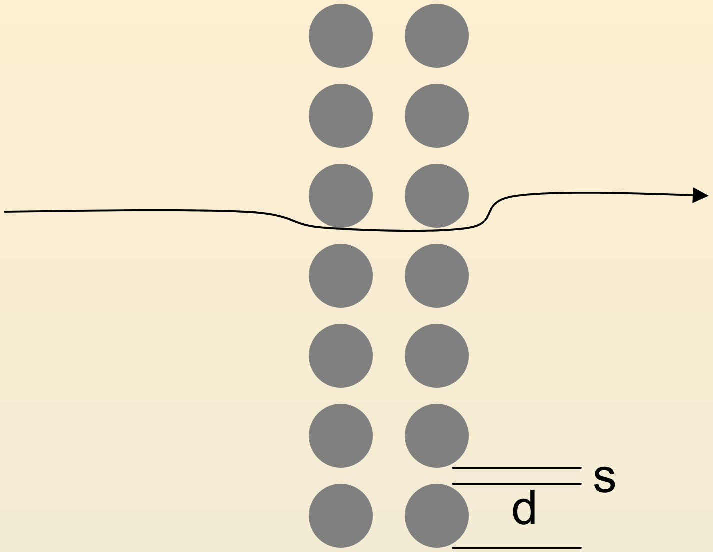
Are Stitching Capacitors Effective ???

- YES, at low frequencies
- No, at high frequencies
- Need to limit the high frequency current spectrum
- Need to avoid split crossings with ALL critical signals

Pin Field Via Keepouts??



Return Current must go around entire keep out area --- just as bad as a slot

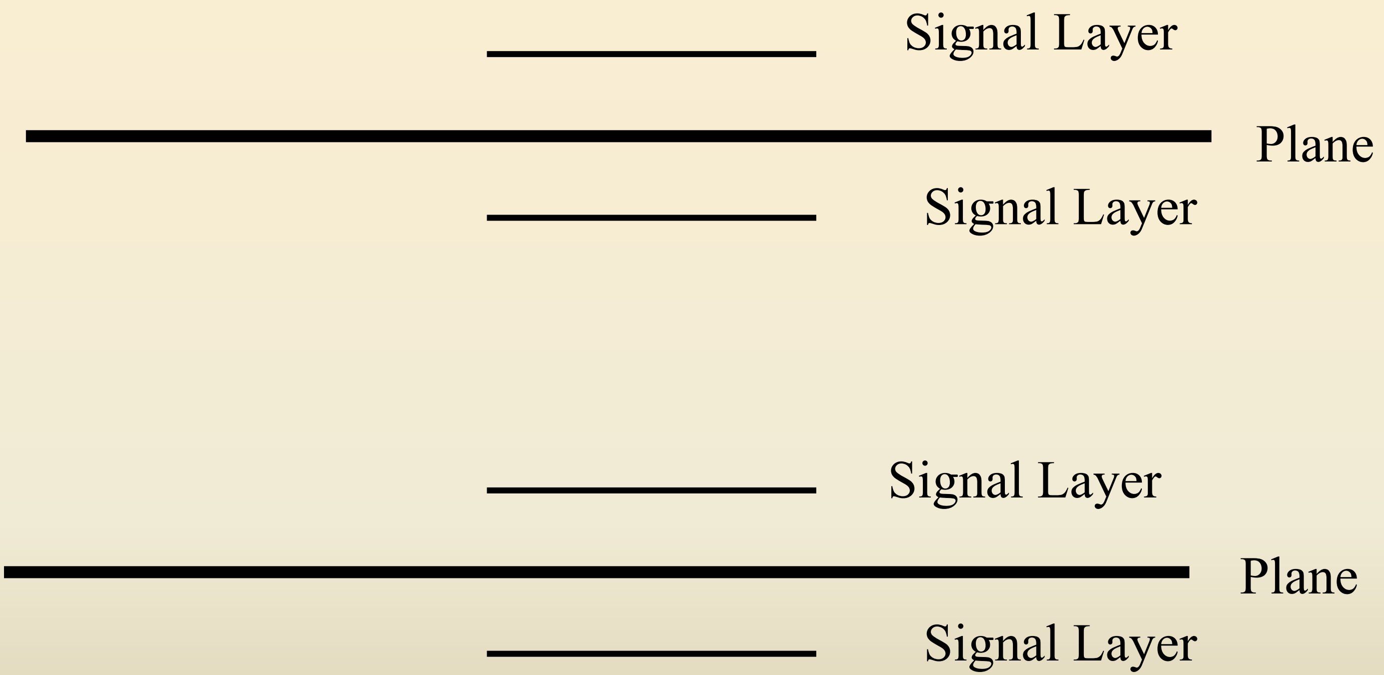


Return current path deviation minimal

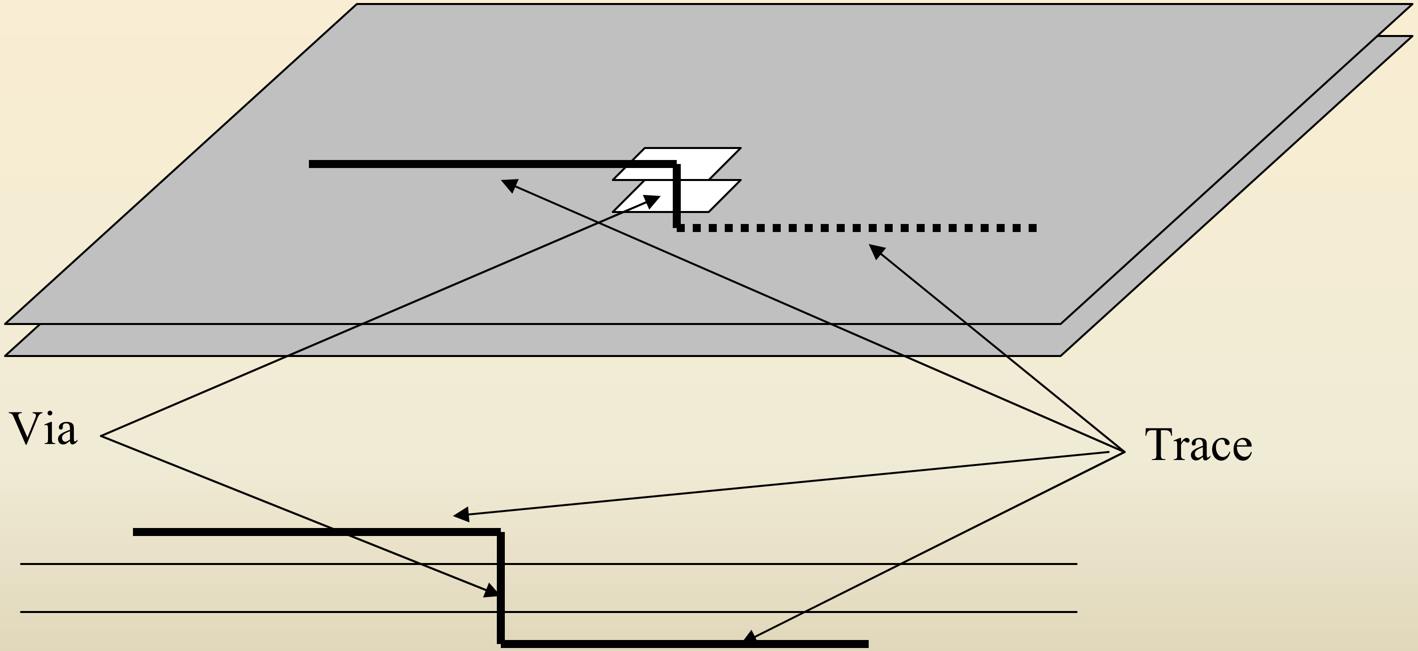
Recommend s/d > 1/3

Changing Reference Planes

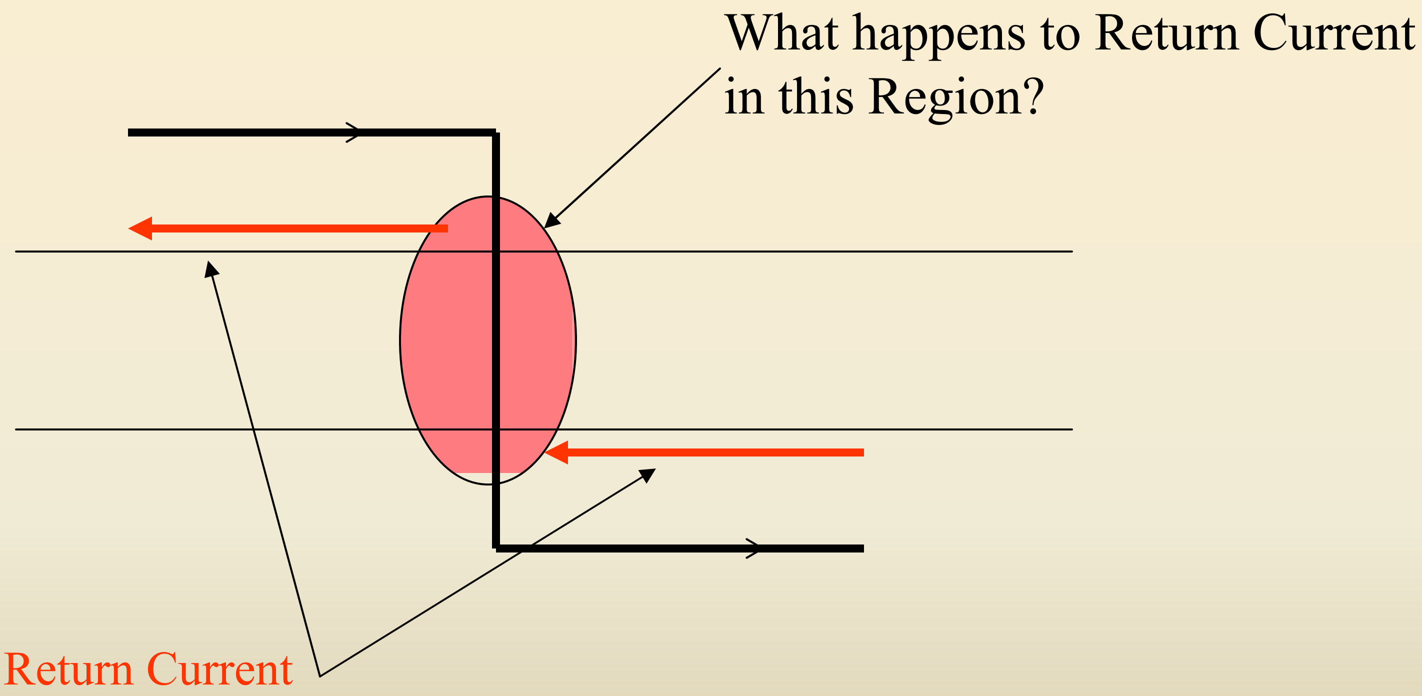
Six-Layer PCB Stackup Example



Microstrip/Stripline through via (change reference planes)



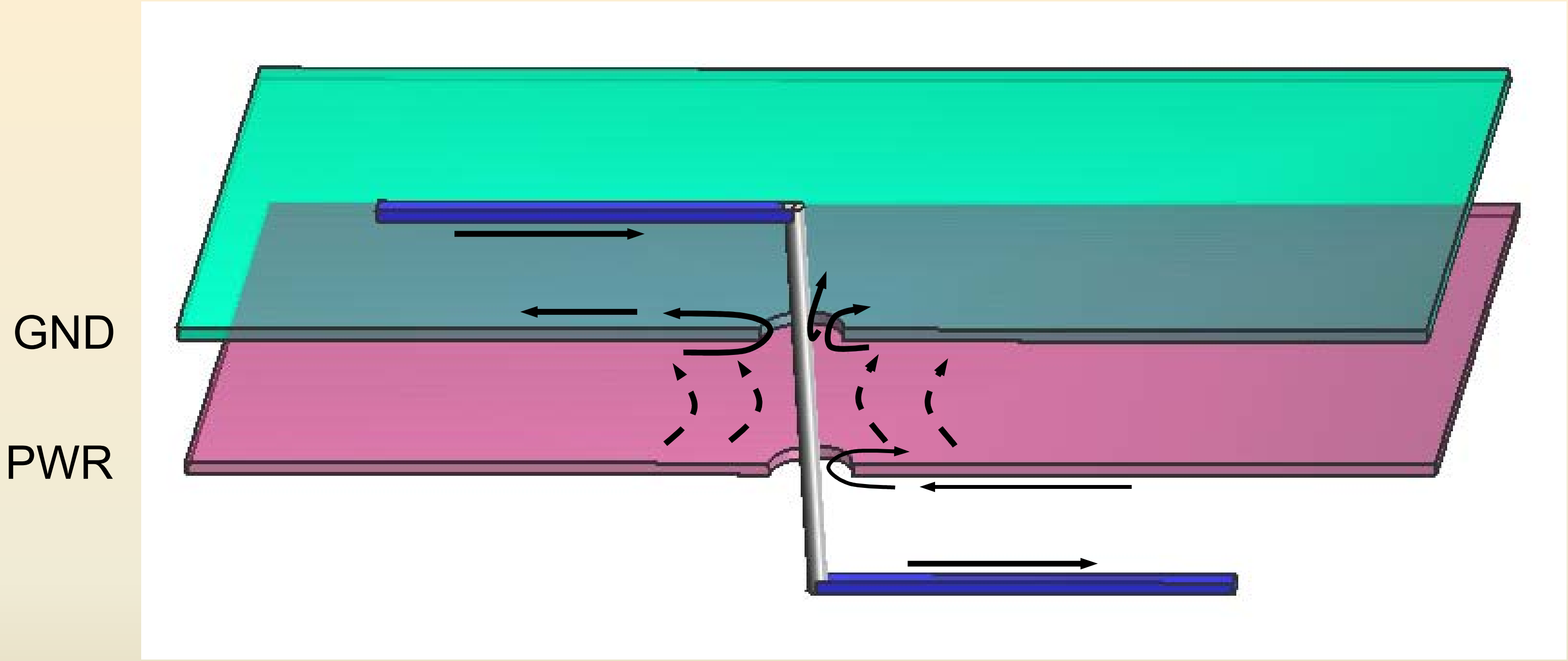
How can the Return Current Flow When Signal Line Goes Through Via??



How can the Return Current Flow When Signal Line Goes Through Via??

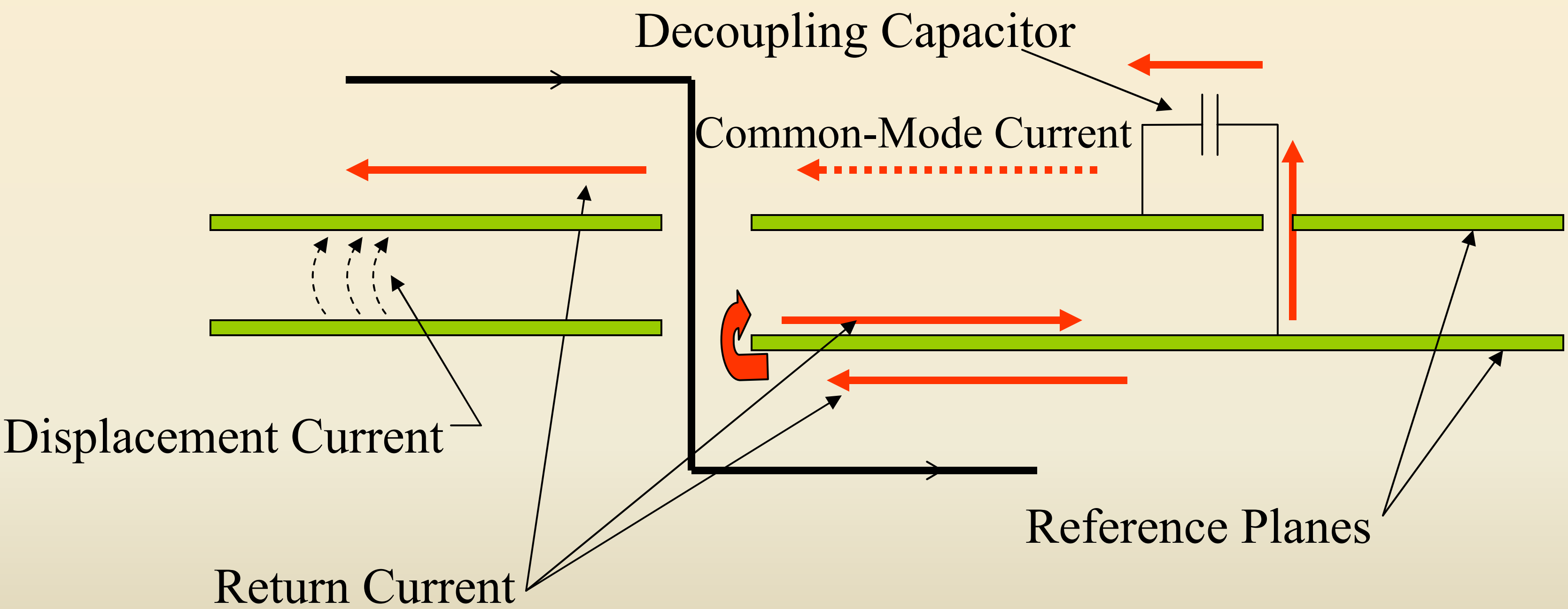
- Current can NOT go from one side of the plane to the other through the plane
  - skin depth
- Current must go around plane at via hole, through decoupling capacitor, around second plane at the second via hole!
- Use displacement current between planes

Return Current without Intentional Path

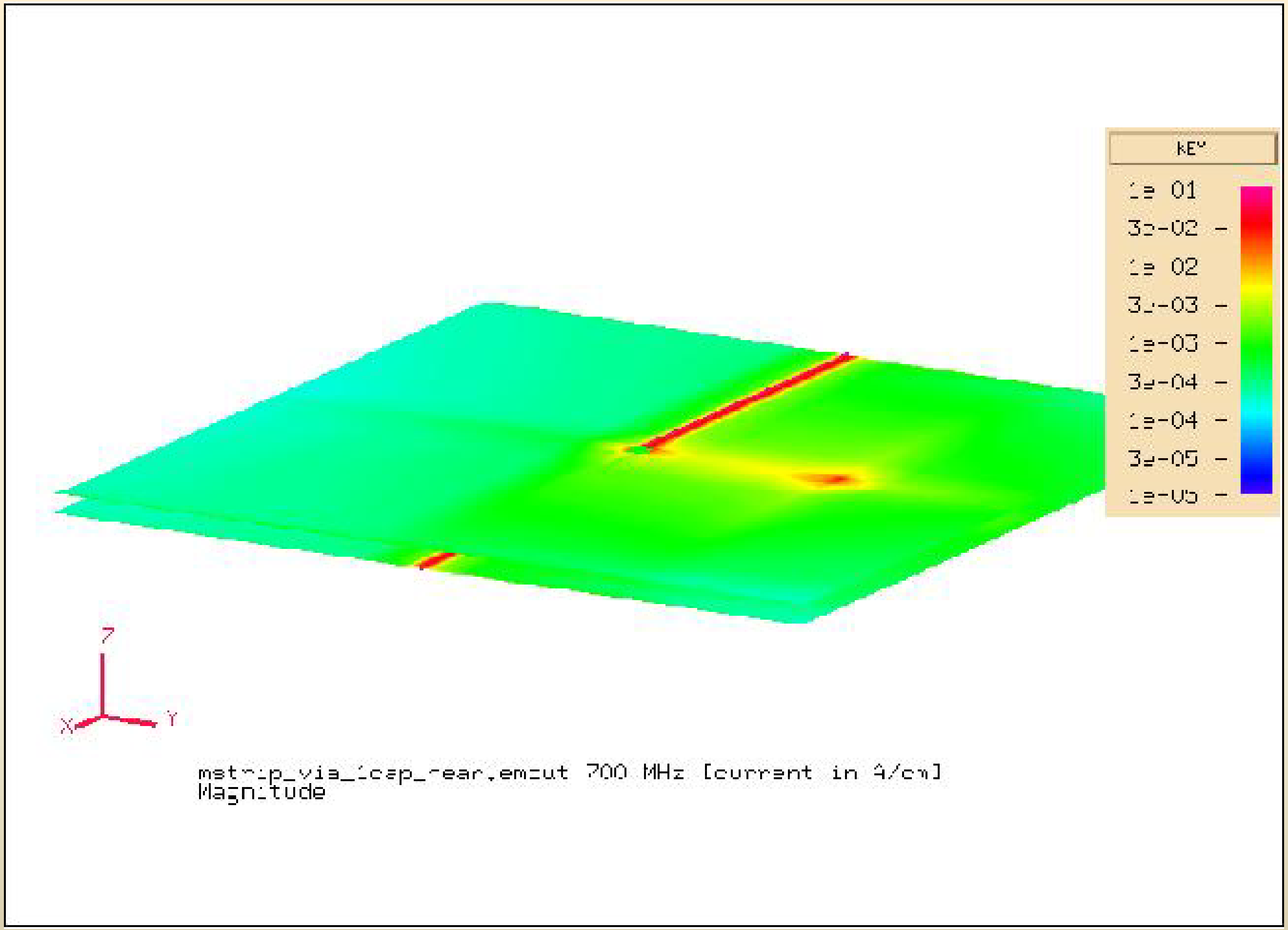


Return Current Across Reference Plane Change

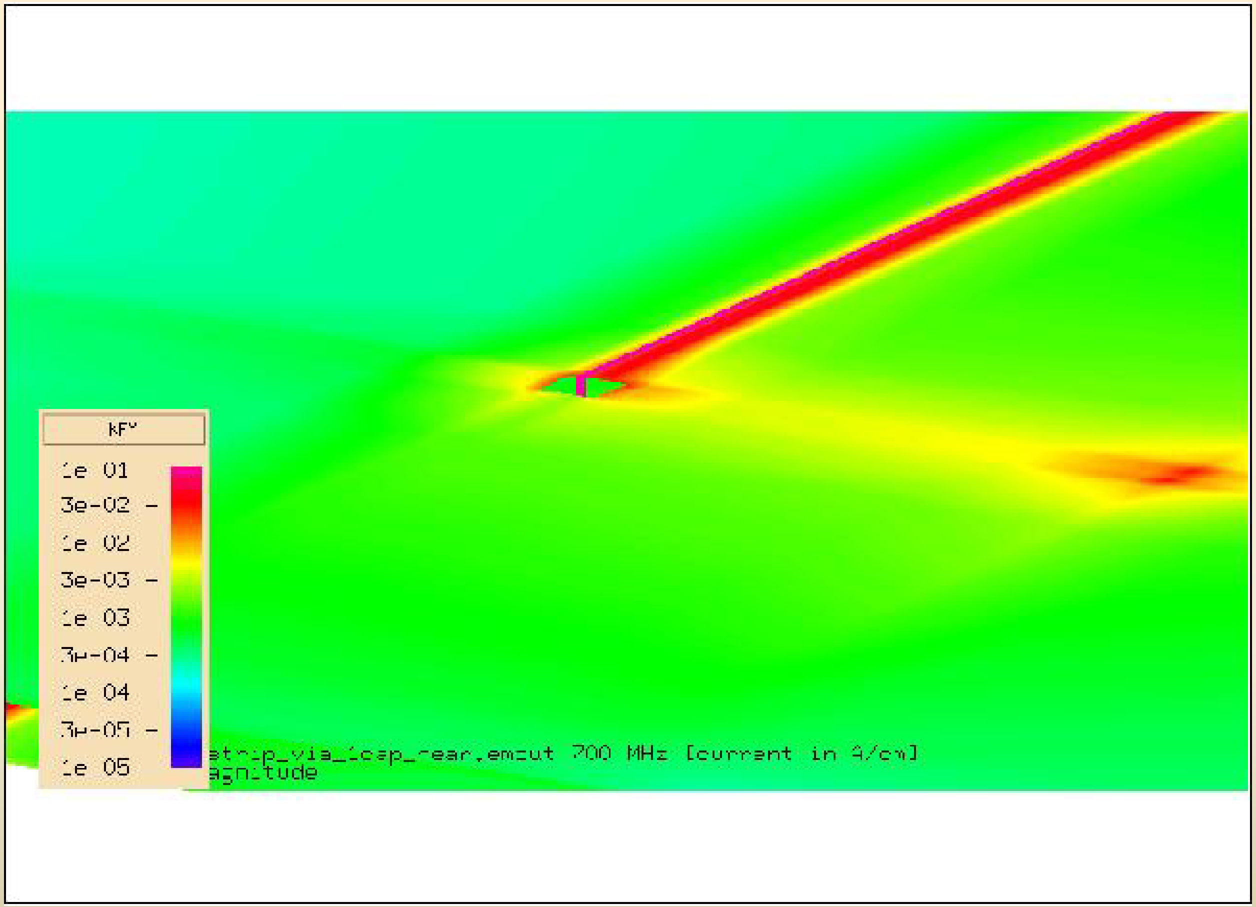
With Decoupling Capacitor (on Top)



RF Current @ 700 MHz with One Capacitor 0.5” from Via



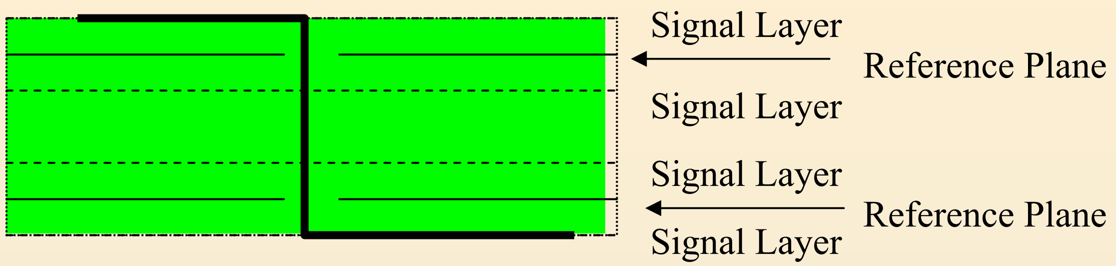
RF Current @ 700 MHz with One Capacitor 0.5” from Via
(expanded view)



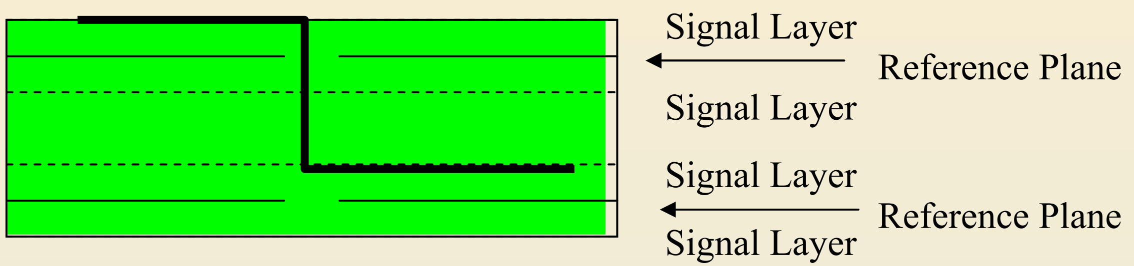
Possible Routing Options

Six-Layer Board

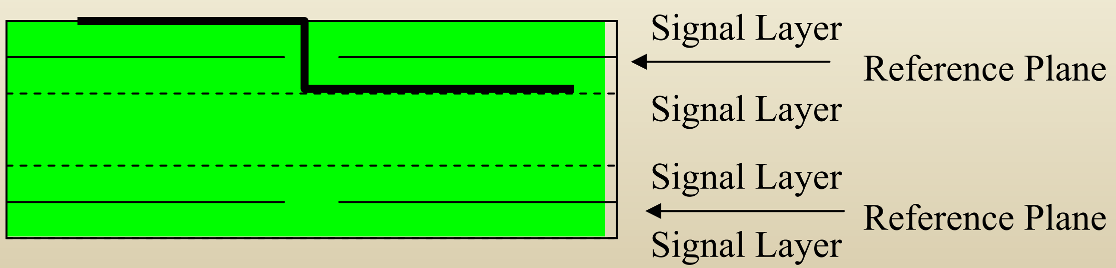
Bad



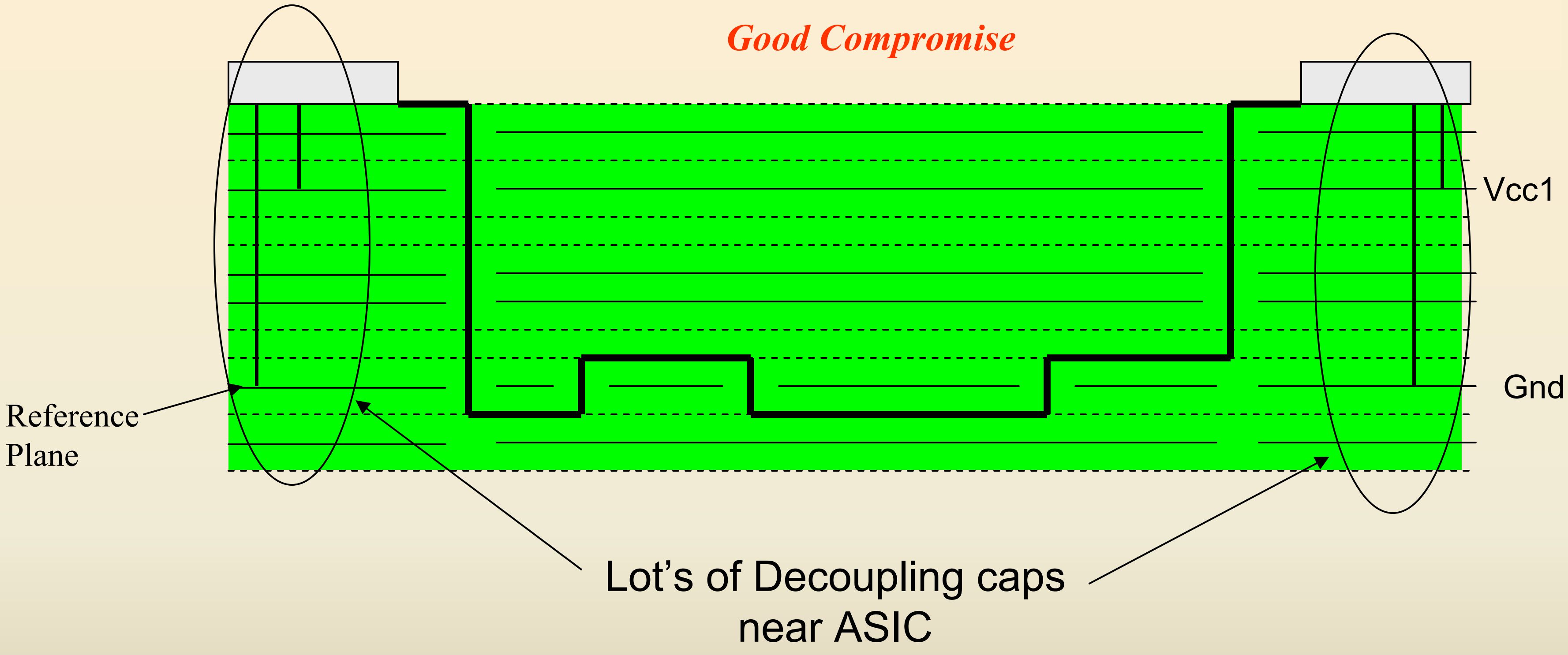
Bad



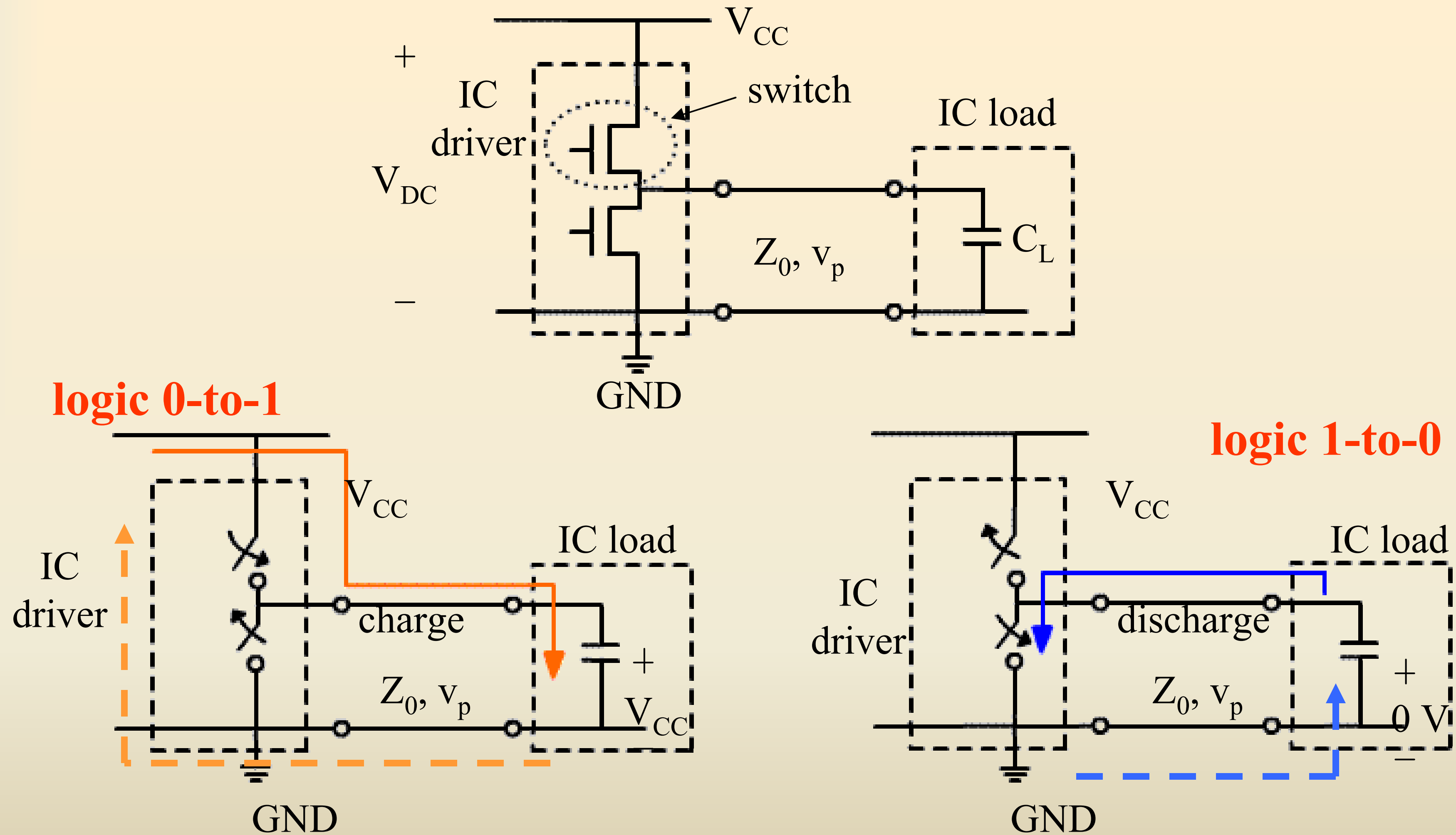
Good



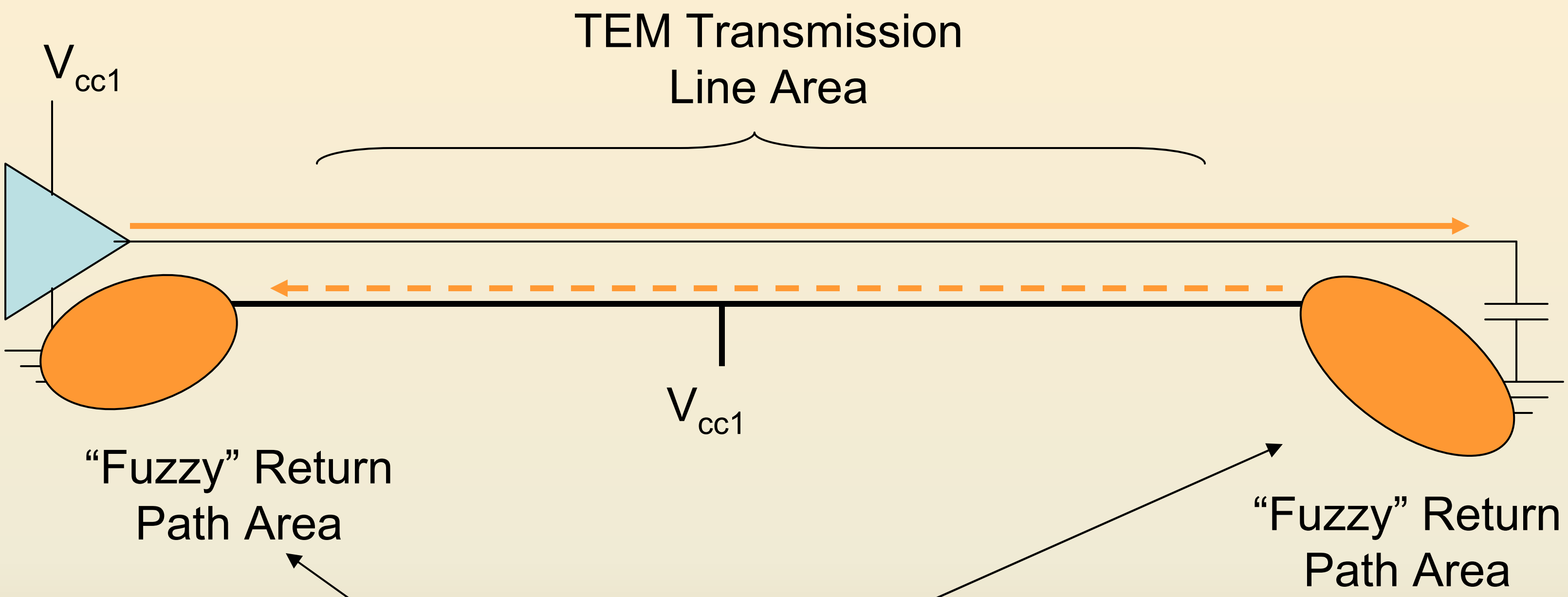
Compromise Routing Option for Many Layer Boards



Typical Driver/Receiver Currents



Suppose The Trace is Routed Next to Power (not Gnd)

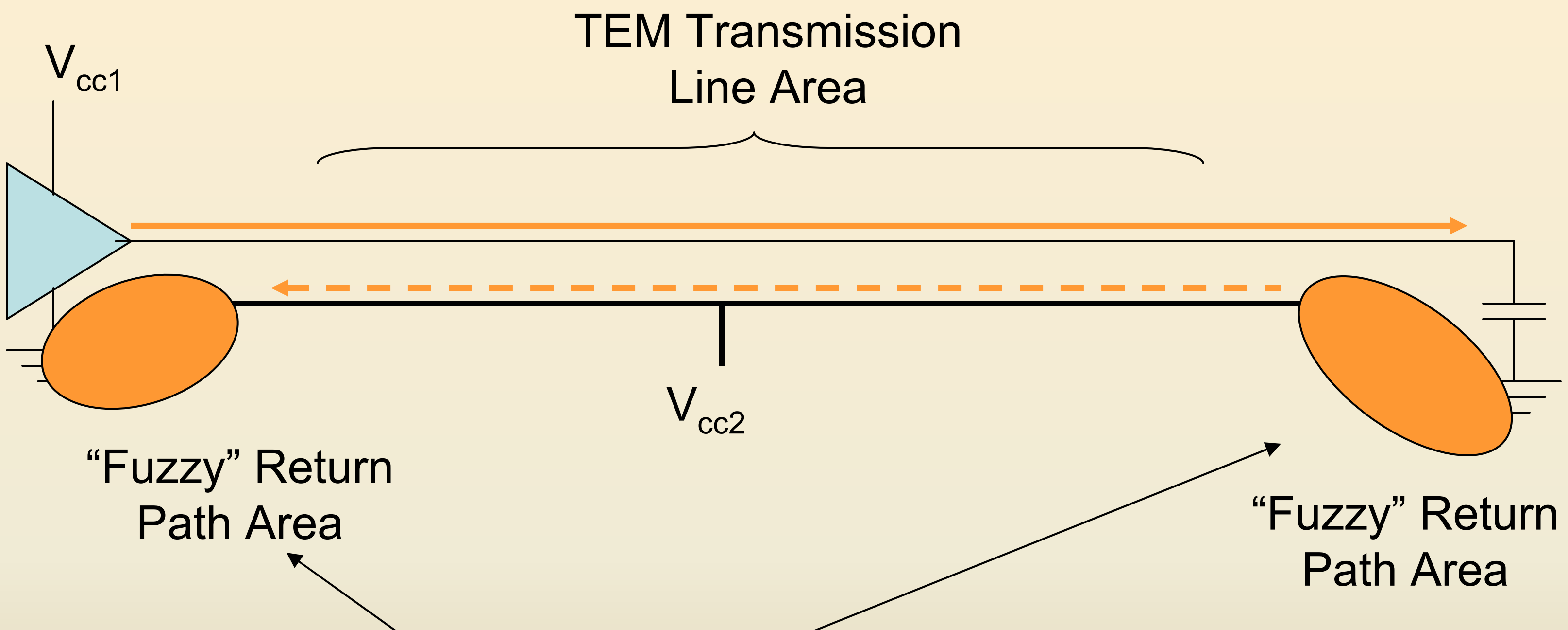


Return Path Options:

-- Decoupling Capacitors

-- Distributed Displacement Current

Suppose The Trace is Routed Next to a *DIFFERENT* Power (not Gnd)



Return Path Options:

-- Decoupling Capacitors ??? *May not be any nearby*!!

-- Distributed Displacement Current – *Increased current spread*!!!

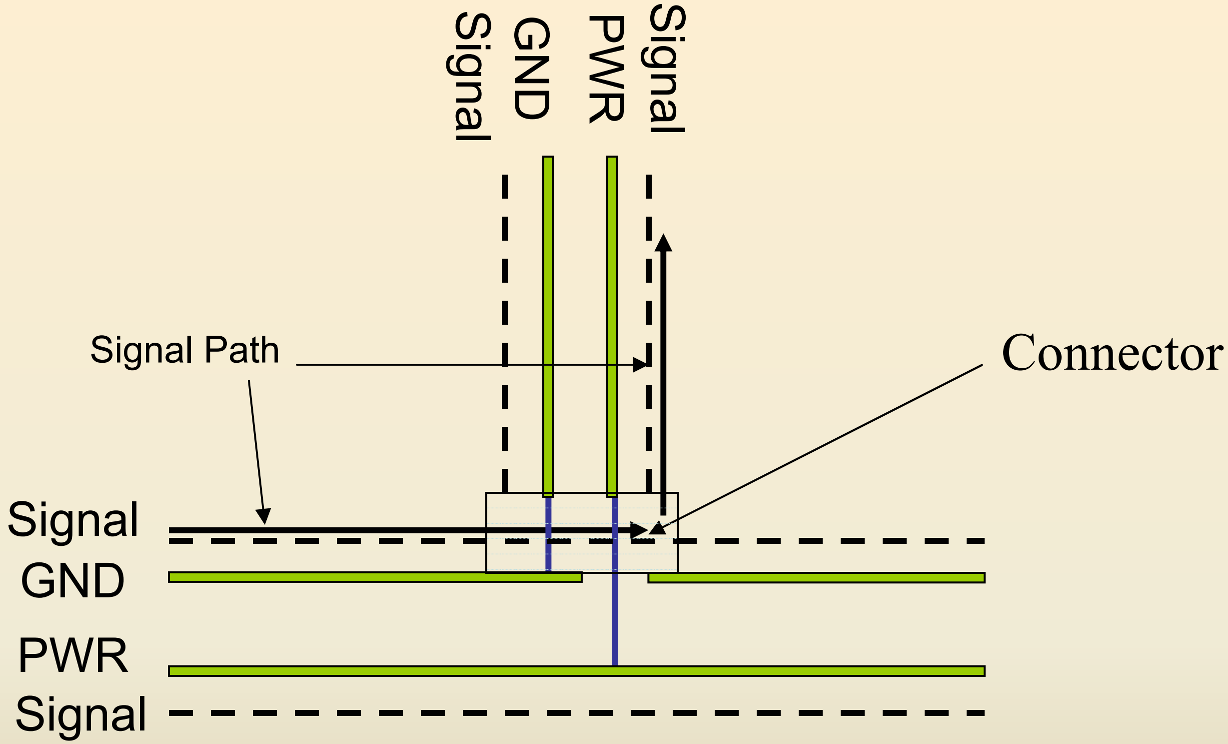
Via Summary

- ✓ Route critical signals on either side of ONE reference plane
- ✓ Drop critical signal net to selected layer close to driver/receiver
  - ✓ Many decoupling capacitors to help return currents
- ✓ Do NOT change reference planes on critical nets unless ABSOLUTELY NECESSARY!!
- ✓ Make sure at least 2 decoupling capacitors within 0.2” of via with critical signals

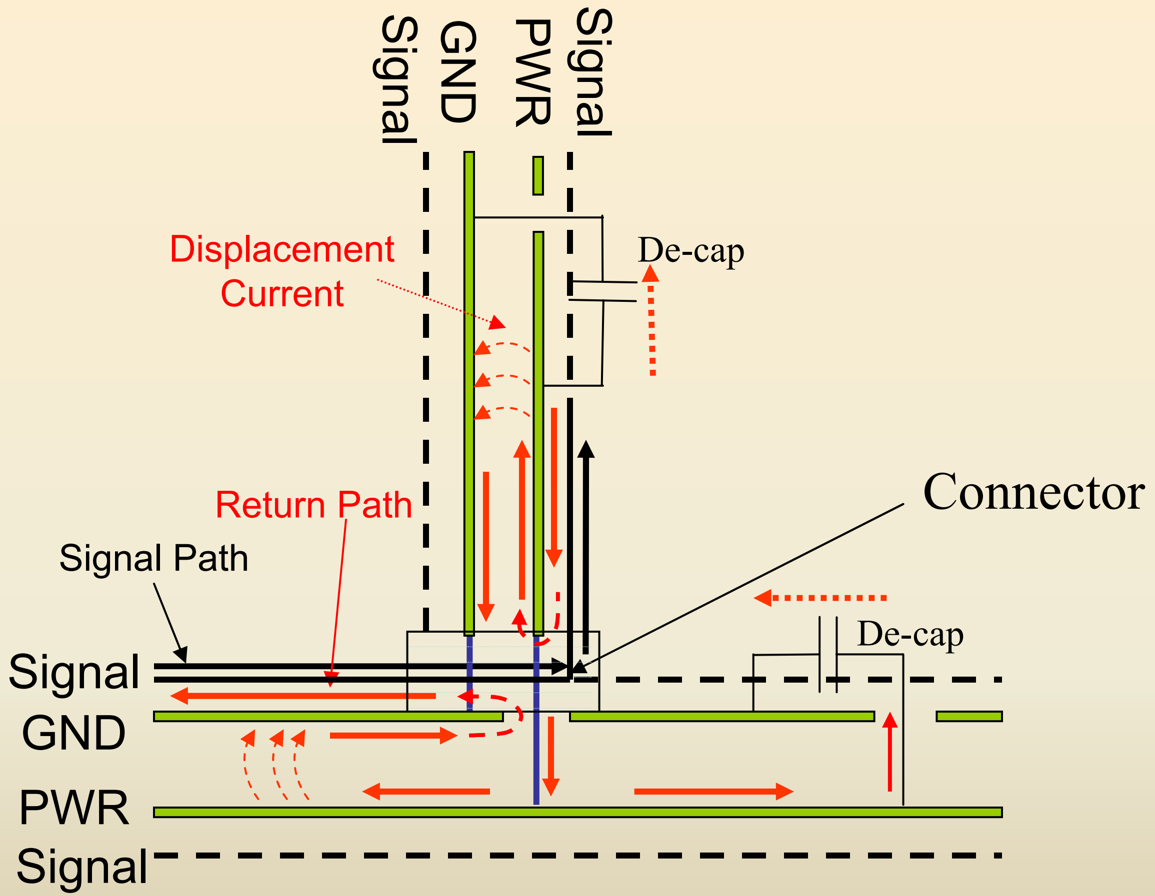
Mother/Daughter Board Connector Crossing

- Critical Signals must be referenced to same plane on both sides of the connector

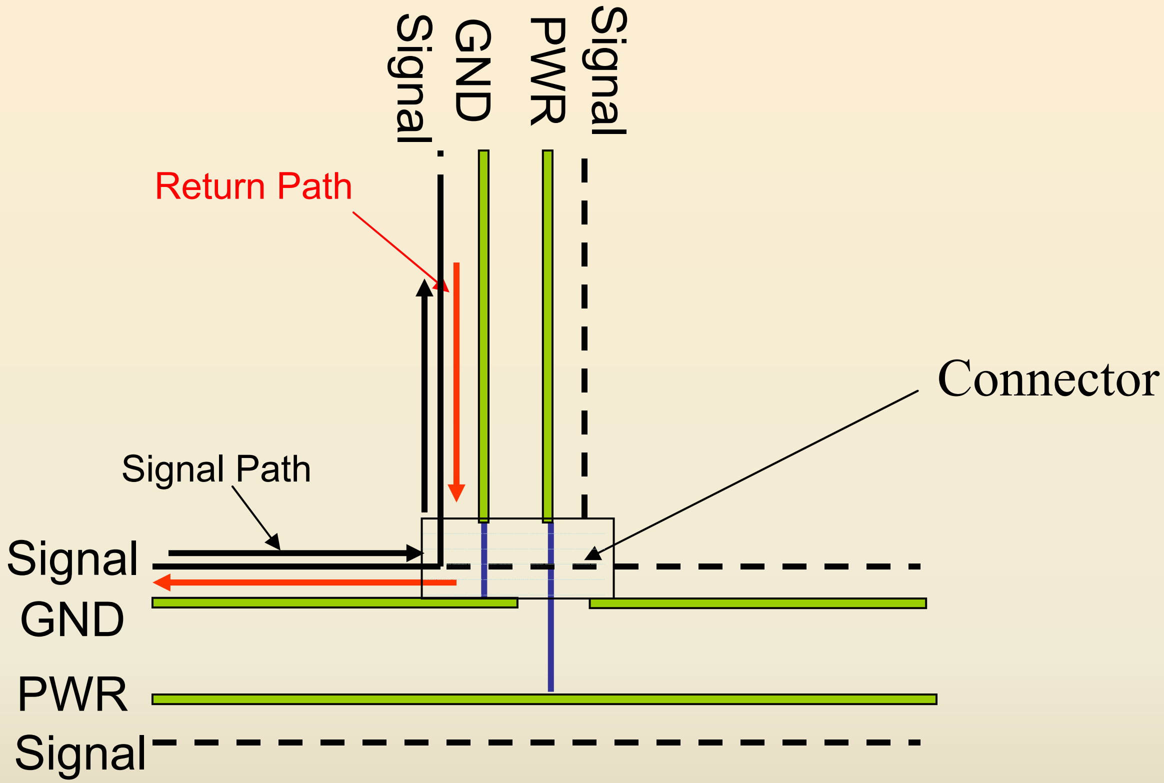
Mother/Daughter Board Connector Crossing



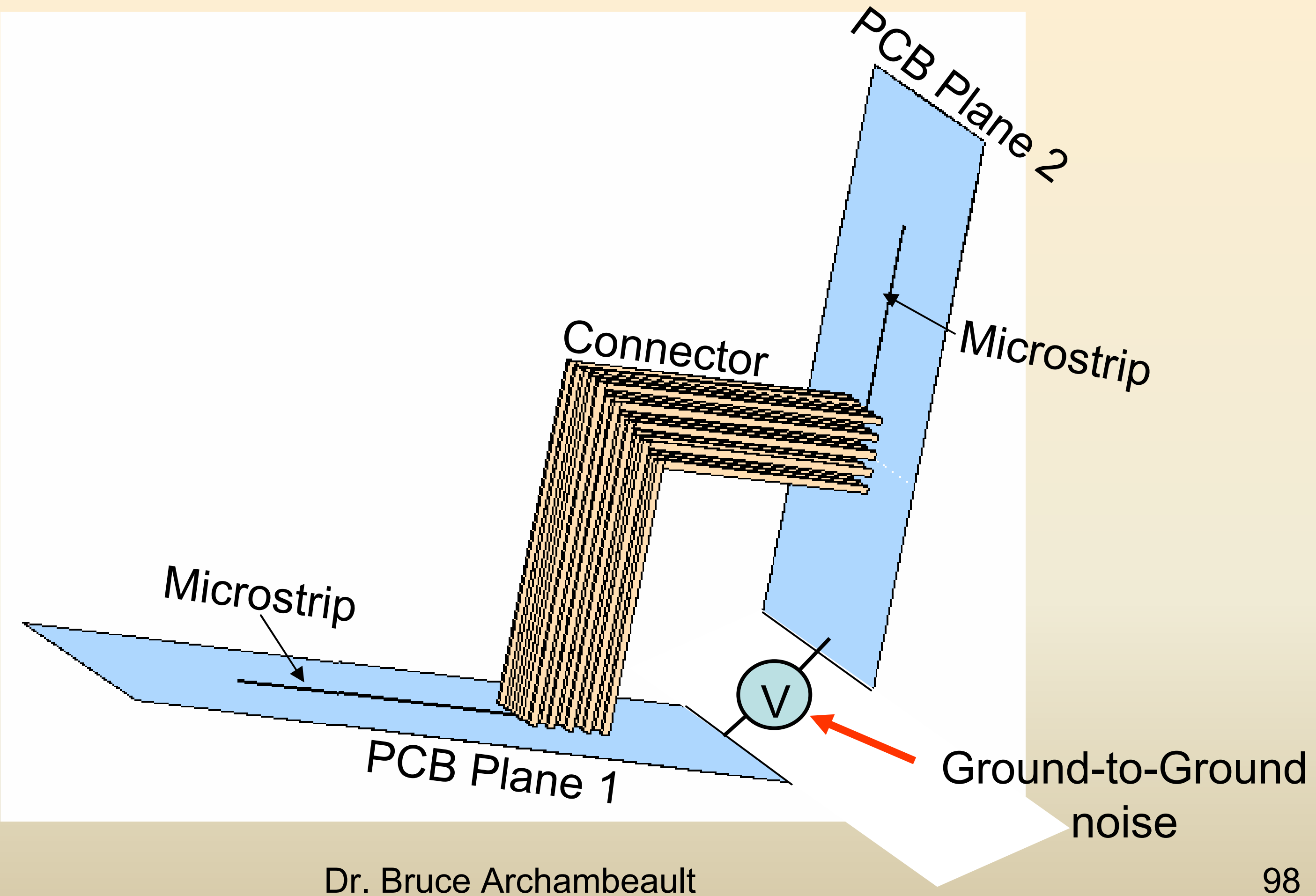
Return Current from Improper Referencing Across Connector



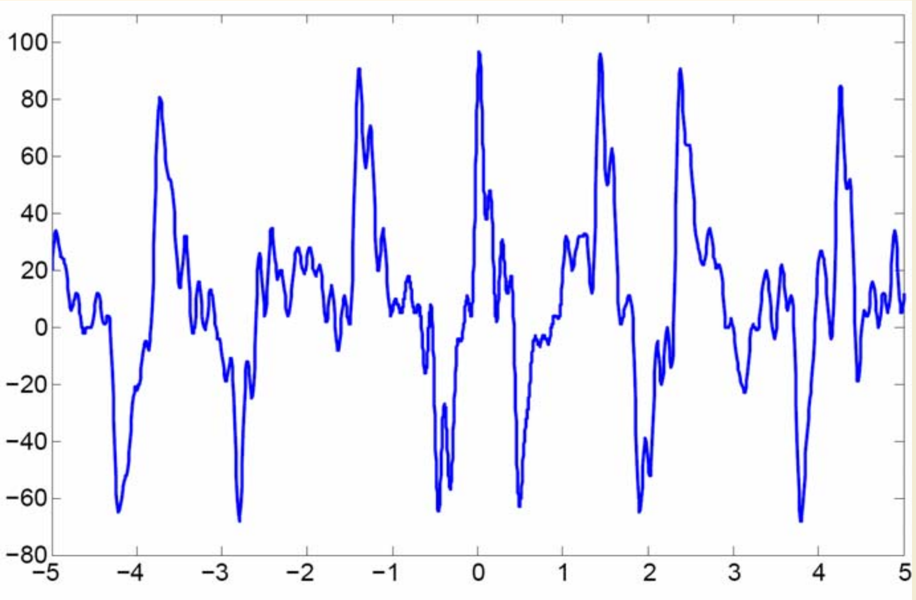
Return Current from Proper Referencing Across Connector



Board-to-Board Differential Pair Issues



Example Measured Differential Individual Signal-to-GND

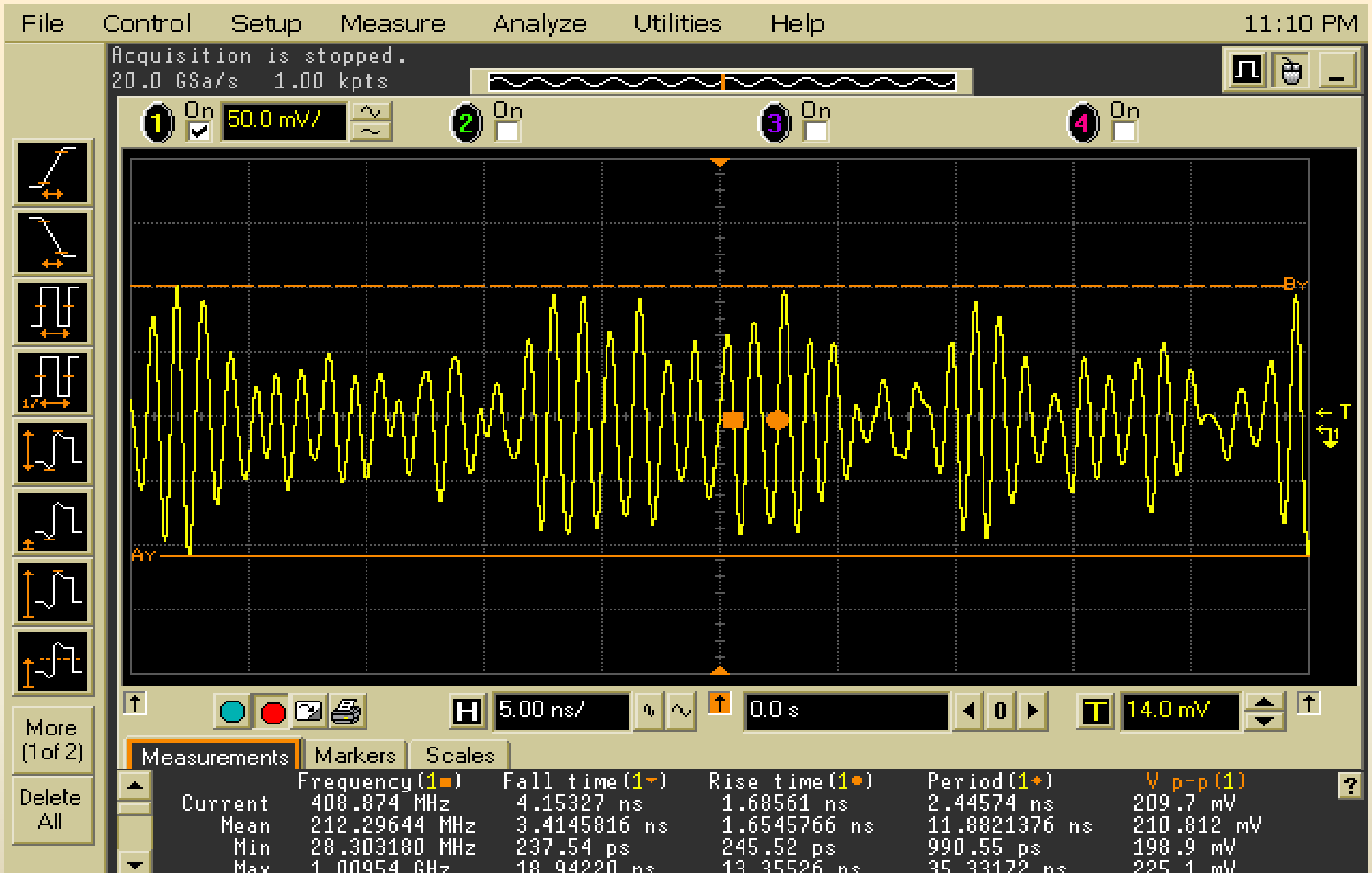


500 mV P-P (each)

Individual Differential Signals ADDED

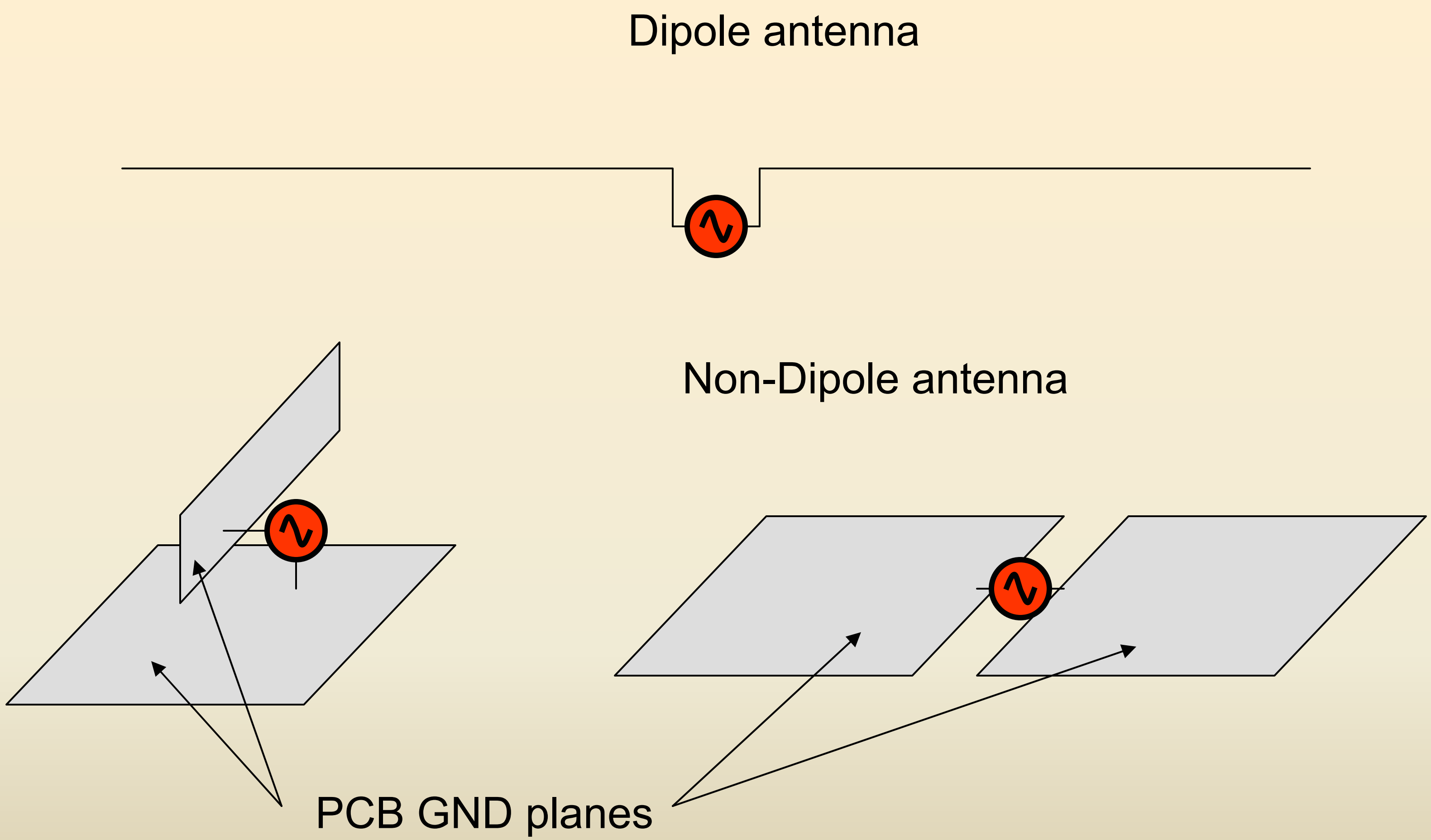
Common Mode Noise 170 mV P-P

Measured GND-to-GND Voltage

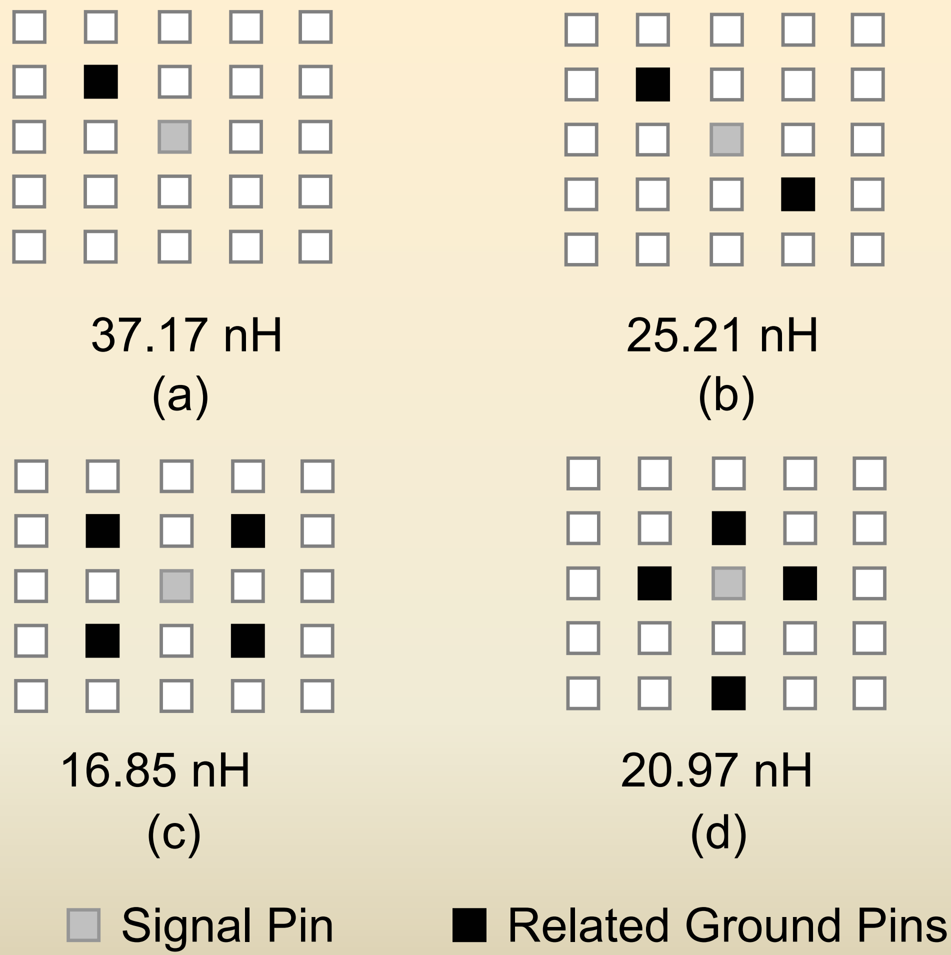


205 mV P-P

Antenna Structures



Pin Assignment Controls Inductance for CM signals



How Many "Ground" Pins Across Connector ???

- Nothing ***MAGICAL*** about "ground"
- Return current flow!
- Choose the number of power and "ground" pins based on the number of signal lines referenced to power or "ground" planes
- Insure signals are referenced against same planes on either side of connector

Ground Myth Summary

- **THERE IS NO SUCH THING AS *"GROUND"***
- Define which *reference* type is needed
- Plan the return current path
  - Avoid split reference planes & changing reference planes
- Differential signals have significant common mode, and must follow normal EMC rules

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