PCB West Sept. 16, 2015

Electromagnetic Fields and Signal Integrity

Doug Brooks, President

UltraCAD Design, Inc.

Outline

1. Five Basic Laws of Electronics
2. Laws of Electromagnetics
    1. Maxwell
3. Relationship Between SI issues and Electromagnetic Fields
    1. EMI
    2. Propagation Speed
    3. Crosstalk
    4. Trace Impedance

Objective

By envisioning the electromagnetic field, and how it changes as we change layout parameters,

we can envision how those layout parameter changes will impact signal integrity issues.

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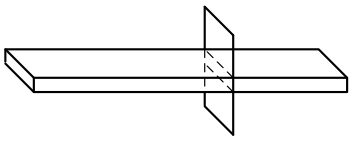
Definition

1 Amp = 6.25 x 10^{18} electrons (one Coulomb of charge) across a surface in one second.



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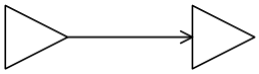
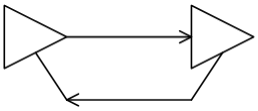
Five Basic Laws of Electronics

Current must flow in a closed loop
(Must have a complete circuit)



No signal can flow.



Signal flows.

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Five Basic Laws of Electronics

Current flows in a closed loop.

Corollary: Every signal must have a return

And you need to know where it is…..

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Five Basic Laws of Electronics

Current flows in a closed loop.

Corollary: Every signal must have a return

And you need to know where it is…..

Because most of our signal integrity problems are related to the lack of control over the return currents!

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Five Basic Laws of Electronics

Current flows in a closed loop.

Corollary: Every signal must have a return

And you need to know where it is…..

Bruce R. Archambeault, EMC (“Ground is where potatoes grow!”)
Howard Johnson, Mutual Inductance
Eric Bogatin, Coupling

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Five Basic Laws of Electronics

Current must flow in a closed loop
(Must have a complete circuit)
(Every signal must have a return)

Current is constant everywhere in the loop

Kirchhoff's First Law: **Current flowing into a node equals the current flowing out of the node**

Kirchhoff's Second Law: **Voltages around a loop sum to zero**

Ohm's Law: **V = I * Z**

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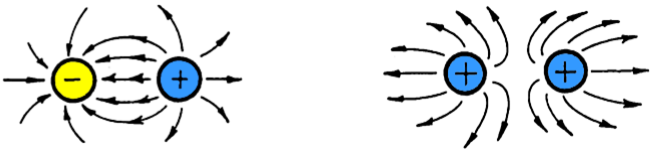
Laws of Electromagnetics

1. **Coulomb's Law (1785):** There are two kinds of charge, positive and negative. Like charges repel, unlike attract, with force proportional to the product of their charge and inversely proportional to the square of their distance.

Force lines are the "electric field," *(often referred to as the 'E' field).*



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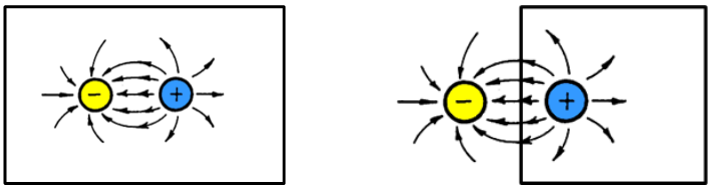
Laws of Electromagnetics

Gauss's Law of Electricity (1835, pub. 1867): The (net) electric flux (field) out of any closed surface is proportional to the total charge enclosed within the surface. *



* *http://hyperphysics.phy-astr.gsu.edu/hbase/electric/maxeq2.html*

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What is Flux?

In simple terms, flux is product of field times area……
IF field is uniform
IF field is perpendicular to surface

$$\Phi_E = \iint_S E \bullet ds = \iint_S E Cos(\Theta)\, ds$$

Flux **Vector** **Scalar (number)**

Double integral over surface area ds

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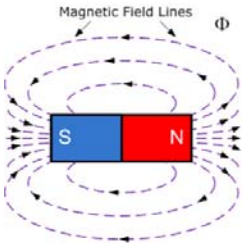
Laws of Electromagnetics

2. Gauss's Law: Every magnetic pole is a dipole with an equal and opposite pole. Magnetic force is a vector whose direction is a line along which the force acts. Magnetic force is inversely proportional to the square of the distance.

Force lines are the "magnetic field," *(often referred to as the 'H' field).*



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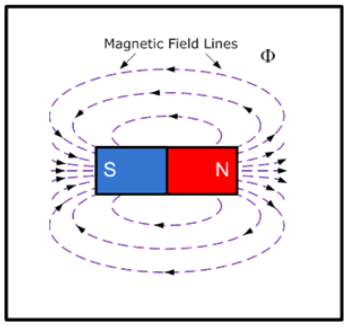
Laws of Electromagnetics

Gauss's Law of Magnetism: *The net magnetic flux (field) out of any closed surface is zero.* *



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* ***http://hyperphysics.phy-astr.gsu.edu/hbase/electric/maxeq2.html***

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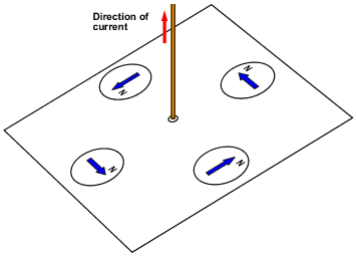
Laws of Electromagnetics

3. **Ampere's Law (1825):** An electric current is accompanied by a magnetic field whose direction is at right angles to the current flow. (Therefore, a *changing* current is accompanied by a *changing* magnetic field.) *(This field is often referred to as the 'B' field.)*

   This is the principle behind an electromagnet.

   (Can verify with a wire, battery, and a compass.)



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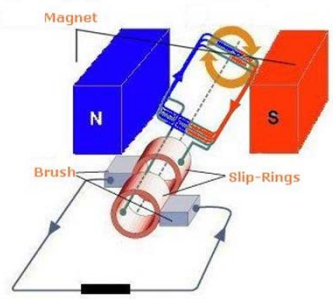
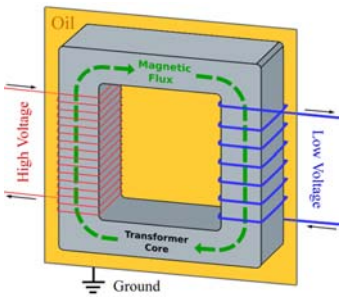
Laws of Electromagnetics

4. **Faraday's Law of Magnetic Induction (1831):** A changing magnetic field is accompanied by a changing electric field at right angles to the change of the magnetic field.

   This is the principle behind a motor, transformer or generator.





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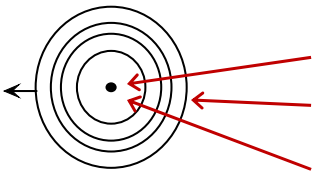
Laws of Electromagnetics

3. **Ampere's Law (1825):** An electric current is accompanied by a magnetic field whose direction is at right angles to the current flow. (Therefore, a *changing* current causes a *changing* magnetic field.)

4. **Faraday's Law of Magnetic Induction (1831):** A changing magnetic field is accompanied by a changing electric field at right angles to the change of the magnetic field.



Nature of Induction:

An increasing current into page here:

Causes a changing magnetic field here

Induces a current in opposite direction here:

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Laws of Electromagnetics

3. **Ampere's Law (1825):** An electric current is accompanied by a magnetic field whose direction is at right angles to the current flow. (Therefore, a *changing* current causes a *changing* magnetic field.)

4. **Faraday's Law of Magnetic Induction (1831):** A changing magnetic field is accompanied by a changing electric field at right angles to the change of the magnetic field.

Note: If we have one of these……..
the other is automatically created……
forever……..

(Near field vs. far field)

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Laws of Electromagnetics

1. **Gauss's Law of Electricity (1835, pub. 1867):** The (net) electric (field) out of any closed surface is proportional to the total charge enclosed within the surface.
2. **Gauss's Law of Magnetism:** The net magnetic (field) out of any closed surface is zero.
3. **Ampere's Law (1825):** An electric current is accompanied by a magnetic field whose direction is at right angles to the current flow. (Therefore, a *changing* current causes a *changing* magnetic field.)
4. **Faraday's Law of Magnetic Induction (1831):** A changing magnetic field is accompanied by a changing electric field at right angles to the change of the magnetic field.

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James Clerk Maxwell

Maxwell's contribution was not the basic laws. His contribution was the development if a system of four mathematical equations that described the laws as a closed system. They were published in:
Treatise on Electricity and Magnetism, 1873

http://venus.ece.ndsu.nodak.edu/~baiocchi/maxwell.htm

Brooks, "*Maxwell's Equations Without the Calculus*," Amazon Kindle Edition

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Excellent Book

Faraday, Maxwell, and the Electromagnetic Field

By: Nancy Forbes and Basil Mahon

Available through Amazon

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Maxwell's Equations

Integral Form

I	$\varepsilon_o \oint \kappa \mathbf{E} \cdot d\mathbf{S} = q$	Gauss's Law for Electricity. The surface integral of electric field over any closed surface is proportional to the enclosed charge. The k factor is the dielectric constant, equal to 1 in free space.
II	$\oint \mathbf{B} \cdot d\mathbf{S} = 0$	Gauss's Law for Magnetism. The integral of magnetic flux density over any closed surface is zero. This is the mathematical expression of the fact that no magnetic monopoles have ever been discovered.
III	$\oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt}$	Faraday's Law of Induction. The line integral of electric field over any closed path is proportional to the rate of change of magnetic flux in the enclosed region.
IV	$\oint \frac{1}{\kappa_m} \mathbf{B} \cdot d\mathbf{l} = \mu_o \left(\varepsilon_o \frac{d\Phi_E}{dt} + i \right)$	Ampere's Law (as extended by Maxwell). The line integral of magnetic flux density over any closed path is proportional to the rate of change of electric field and electric current in the enclosed region. The k_m factor is the relative permeability, equal to 1 in free space.

http://www.netdenizen.com/emagnet/thebasics/maxwelletc.htm

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Maxwell's Equations

Differential Form

Gauss's law of electricity $\nabla \cdot \mathbf{D} = \rho$

Gauss's law of magnetism $\nabla \cdot \mathbf{B} = 0$

Faraday's Law $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$

Ampere's law $\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$

$\nabla \bullet$ = Del operator = Divergence
∇x = Del operator = Curl

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Objective

By envisioning the electromagnetic field, and how it changes as we change layout parameters,

we can envision how those layout parameter changes will impact signal integrity issues.

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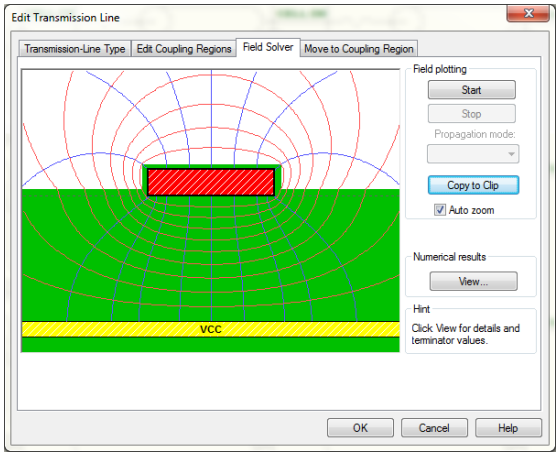
What Do The Fields Look Like?



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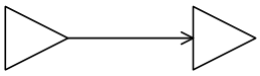
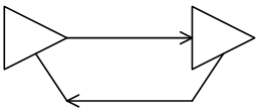
EMI

Recall: Current flows in a loop.

Corollary: Every Signal Has a Return!



No signal can flow.



Signal flows.

(Around the loop)

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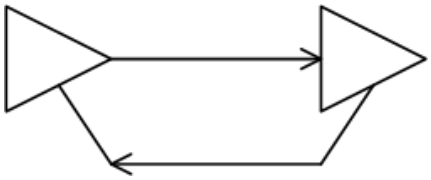
Loop Area

Loop Area is the physical area within the current loop.



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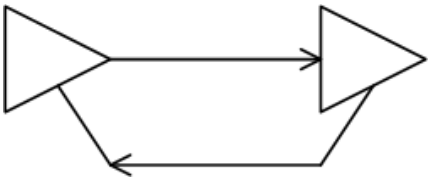
Loop Area

Loop Area is the physical area within the current loop.



Radiated electromagnetic energy is directly related to loop area.

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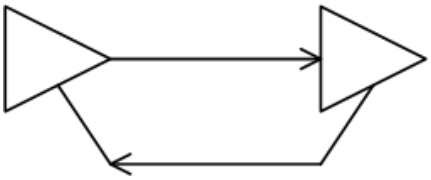
Loop Area

Loop Area is the physical area within the current loop.



Radiated electromagnetic energy is directly related to loop area.

(loop area, mutual inductance, reference plane impedance)

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Minimize EMI

Leads to: Fundamental Rule for Minimizing Radiation…

Minimize the loop area!

Route every trace as close as practical directly over a continuous, related, underlying plane.

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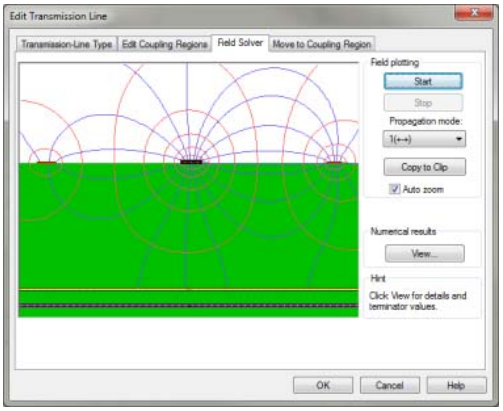
EMI Field



8 mil trace, 50 mil height,
50 mil separation

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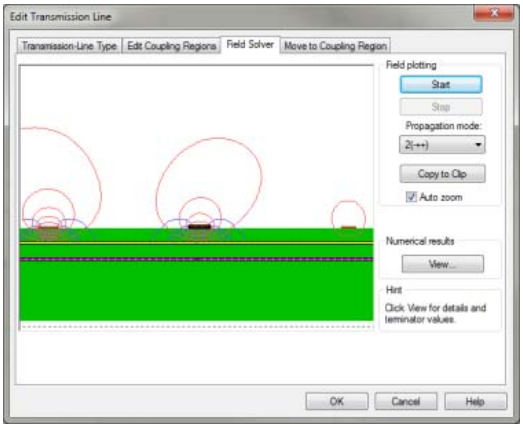
EMI Field



8 mil trace, 5 mil height,
50 mil separation
(related to inverse square law!)

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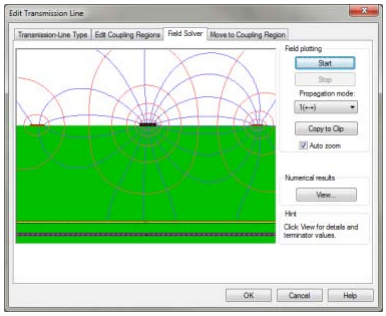
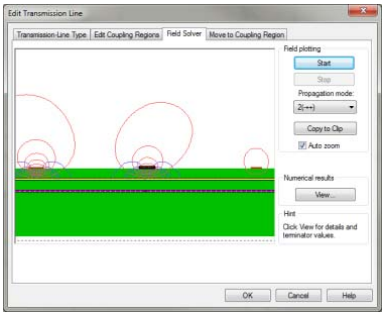
EMI Field



8 mil trace, 50 mil height, 50 mil separation



8 mil trace, 5 mil height, 50 mil separation

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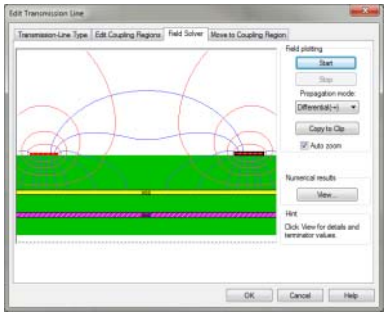
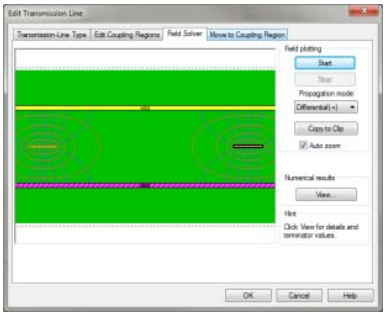
EMI Field

Microstrip Versus Stripline



Microstrip
8 mil traces, 50 mil separation, 10 mil above plane



Stripline
8 mil traces, 50 mil separation, 20 mil between planes

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Propagation Speed

Electronic signals propagate at the speed of light!

Speed of light = c = 186,282 miles per second!

$$\frac{186,282 Miles}{\sec} x \frac{5,280\, ft}{Mile} x \frac{12 in}{ft}$$ **= 11.8 in/ns**

Or, approximately, one foot per nanosecond (in air)!

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Propagation Speed

Signals slow down in any other environment.

$$c = 11.8 / \sqrt{\varepsilon_r}$$ **in/ns**

In FR4 $\varepsilon_r \approx 4$ **so..** $c = 11.8 / \sqrt{4} \approx 6$ **in/ns**

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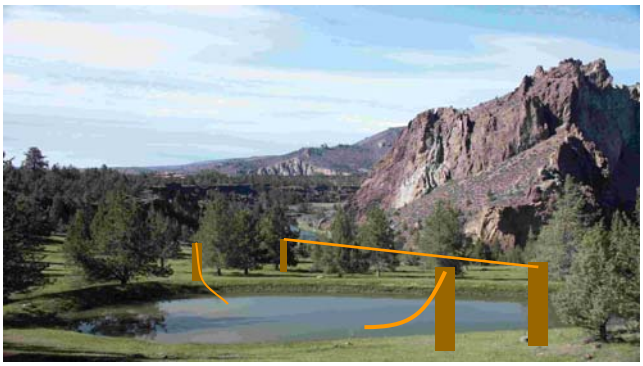
Propagation Speed



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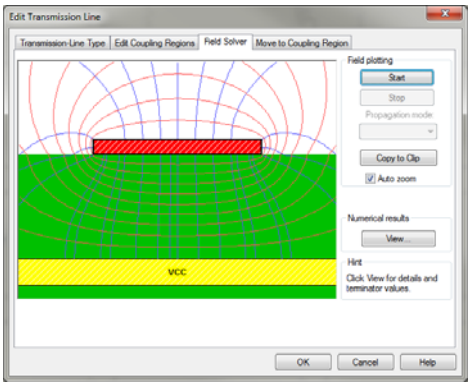
Propagation Speed



8 mil trace, 5 mil height

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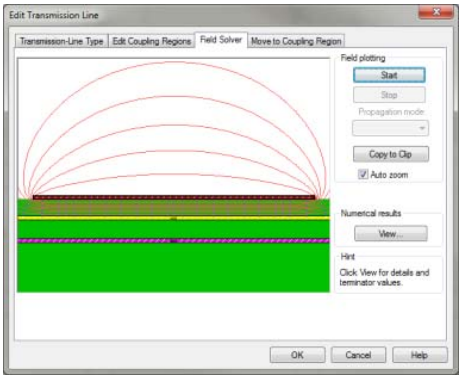
Propagation Speed



80 mil trace, 5 mil height

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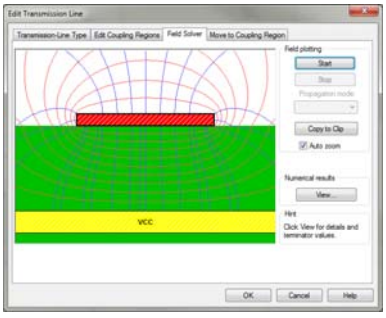
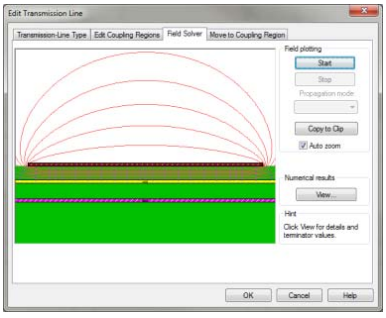
Propagation Speed

Impact of Width, Microstrip



8 mil trace, 5 mil height



80 mil trace, 5 mil height

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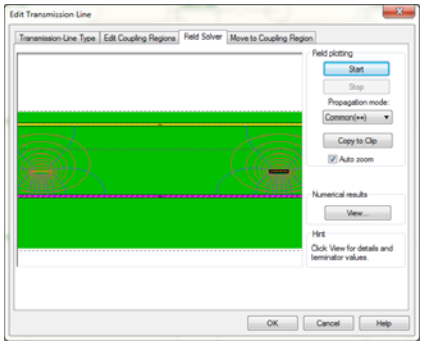
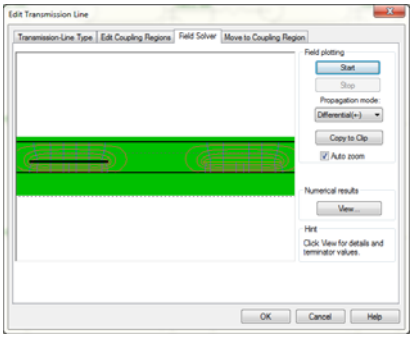
Propagation Speed

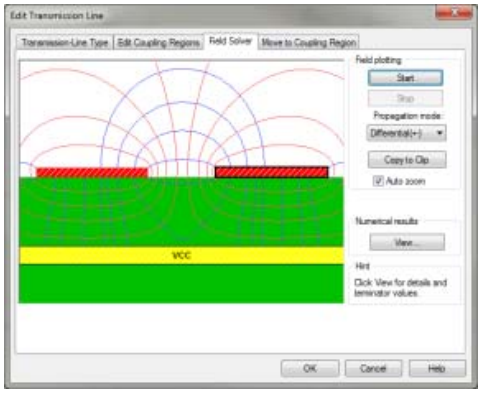
Impact of Width, Stripline





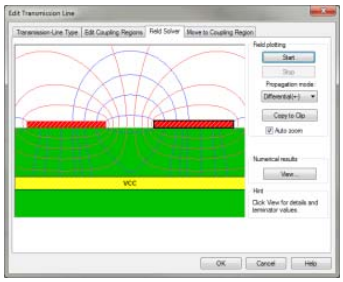
8 mil wide traces **80 mil wide traces**

Crosstalk



8 mil traces, 5 mil height, 5 mil separation

Crosstalk



Design Rules for Crosstalk:

- **Route traces close to the underlying plane…**
- **Separate the traces…**

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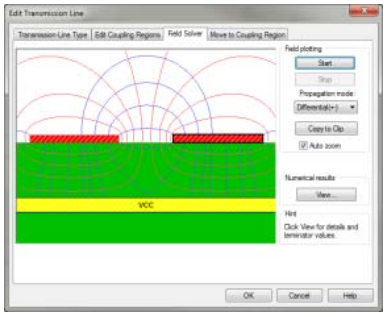
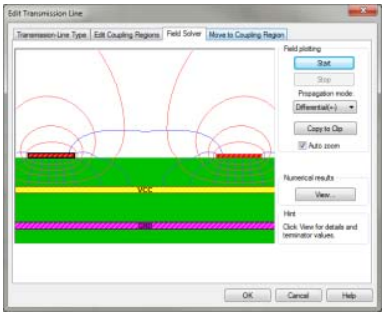
Crosstalk

Impact of Separation



8 mil traces, 5 mil height, 5 mil separation



8 mil traces, 5 mil height, 25 mil separation

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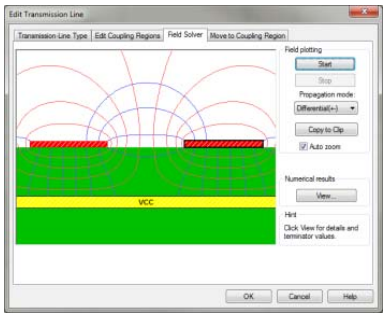
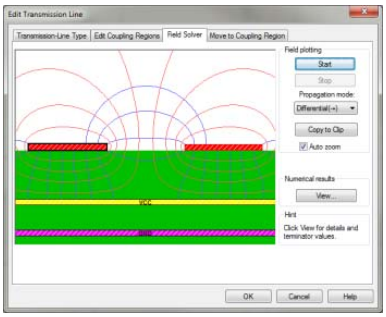
Trace Impedance

Impact of Scaling



8 mil trace, 8 mil separation,
5 mil above plane, 0.5 oz thickness



16 mil trace, 16 mil separation,
10 mil above plane, 1.0 oz thickness

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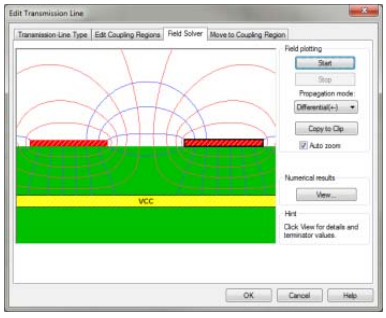
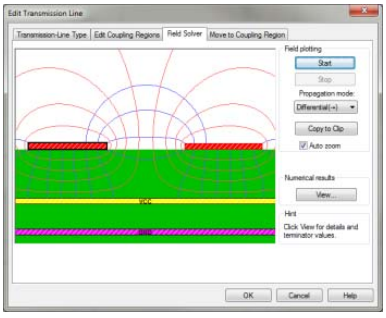
Trace Impedance

Impact of Scaling



8 mil trace, 8 mil separation,
5 mil above plane, 0.5 oz thickness

Z_0 = 53.7 Ohms



16 mil trace, 16 mil separation,
10 mil above plane, 1.0 oz thickness

Z_0 = 53.7 Ohms

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Summary

By envisioning the electromagnetic field, and how it changes as we change layout parameters……

we can envision how those layout parameter changes will impact signal integrity issues.

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Thanks for Attending!

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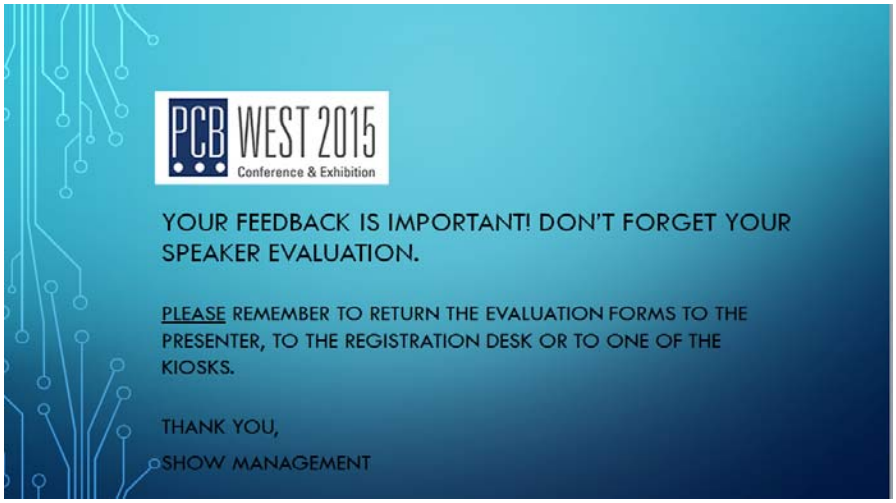

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