Electromagnetic Fields - Part 1

by Barry Olney | In-Circuit Design Pty Ltd | Australia

Our whole world (literally) revolves around electromagnetic fields. Much insight, into high-speed design, can be gained by understanding the behavior of transmission lines and the influence of their associated electromagnetic fields

Migrating birds, turtles, whales etc all use the Earth's magnetic field to navigate vast distances. Whales for instance, can negotiate a 9,000 mile stretch of open, ocean without varying from their course by more than 1 degree. However, one theory for their occasional mass beaching is due to the highly magnetic materials on the ocean floor which apparently mislead the whales pointing them in the wrong direction. Mass beaching of dolphins is far less common than that of whales. And among whales, deep-water species such as pilot whales and sperm whales are more likely to strand themselves on land than whale species such as orcas (killer whales) that live closer to surface. This phenomenon obviously does not affect birds insulated from the ocean floor by miles of water (and air) – and as for turtles – they are also surface dwellers and lay their eggs on the beach – so this may be an advantage for them.

The Earth's magnetic field is similar to that of a bar magnet tilted at 11 degrees in Figure 2. The problem with this model is that the Curie temperature of iron is about 770 C. At this temperature iron loses its ability to be magnetized. Heat energy scrambles the iron atoms so that they cannot line up and create a magnetic field. The Earth's core is much hotter than that and therefore not magnetic. So how did the Earth get its magnetic field?

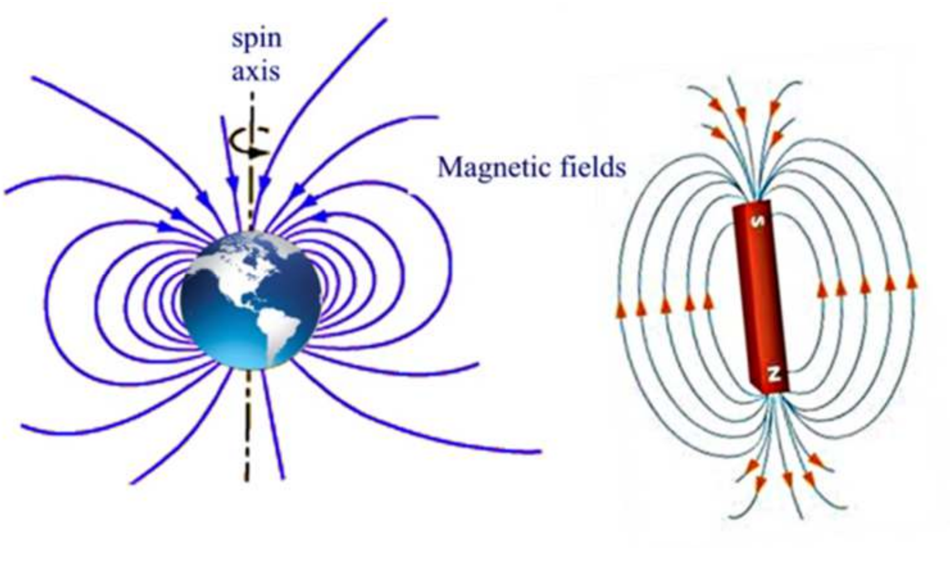

Figure 2. The Earth's magnetic field compared to a bar magnet's fields.

Magnetic fields surround electric currents, so it can be surmised that circulating electric currents in the Earth's molten metallic core are the origin of the magnetic field. The Earth's magnetic field is attributed to a dynamo effect of circulating electric current, but it is not constant in direction. It is interesting to note that rock specimens of different age, found in similar locations, have different directions of permanent magnetization. Evidence for 171 magnetic field reversals during the past 71 million years has been reported. However, predicting the next extinction level event is beyond the scope of this article.

In 1820, Hans Christian Oersted discovered that an electric current flowing through a wire caused a nearby compass to deflect. This indicated that the current in the wire was generating a magnetic field. He found that the magnetic field (or flux) existed in circular form around the wire and that the intensity of the field was directly proportional to the amount of current carried by the wire. He also found that the strength of the field was strongest next to the wire and diminished with distance from the conductor until it could no longer be detected.

Traces in a multilayer PCB act in much the same way. A current loop produces a field similar to that of the Earth – although much smaller of course. Electromagnetic fields are produced when a logic driver delivers a high speed, fast rise time pulse into a trace. The electromagnetic wave propagates down the length of the trace radiating into the surrounding dielectric material and coupling energy to nearby trace segments. These electromagnetic fields are not restricted to the multilayer substrate and if proper care is not taken may emit radiation causing electromagnetic interference.

A stripline configuration (traces embedded between planes) contains this radiation very well but microstrip (outer layer traces) tend to emit high levels of radiation. This can be seen in Figure 3. Notice how the fields do not cross the plane layers. So each microstrip and each stripline configuration is totally isolated from the layers above or below. That is why high-speed, critical signals should always be routed between two planes in a stripline configuration. I discussed this in detail in a past column Beyond Design: Embedded Signal Routing where I said: "Routing high-speed signals embedded between the planes reduces the radiated emissions by as much as 10 dB. Adding a series terminator may help reduce this even further, but this should be determined by simulation and there has to be a trade-off with other factors as in any design".

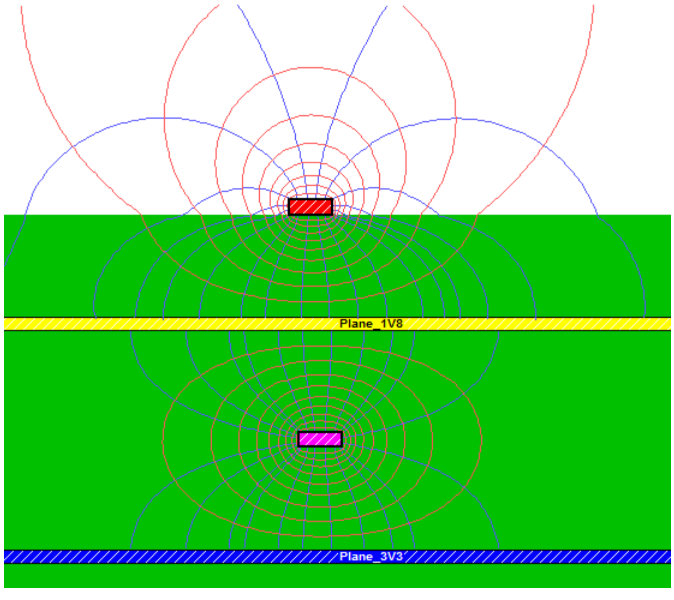

Figure 3. Electromagnetic fields of traces on a multilayer PCB displayed in HyperLynx

In Figure 3, electric field lines are plotted in blue. These can be thought of as the "lines of force." Note that they begin and end on conductor surfaces (where physical charges reside). They refract (i.e., change direction) at boundaries between different dielectrics. Electric fields, which capacitively couple current into a nearby trace, are somewhat absorbed by the plane but still tend to radiate noise outward.

Magnetic fields are plotted in red. These existed in circular form around the trace along which the electric potential (i.e., voltage) is a constant. They form closed contours around one or more conductors, and refract at dissimilar dielectric boundaries and couple voltage inductively into a nearby trace. The inductance of the trace depends on the geometry of the circuit and the magnetic properties of the media containing the field.

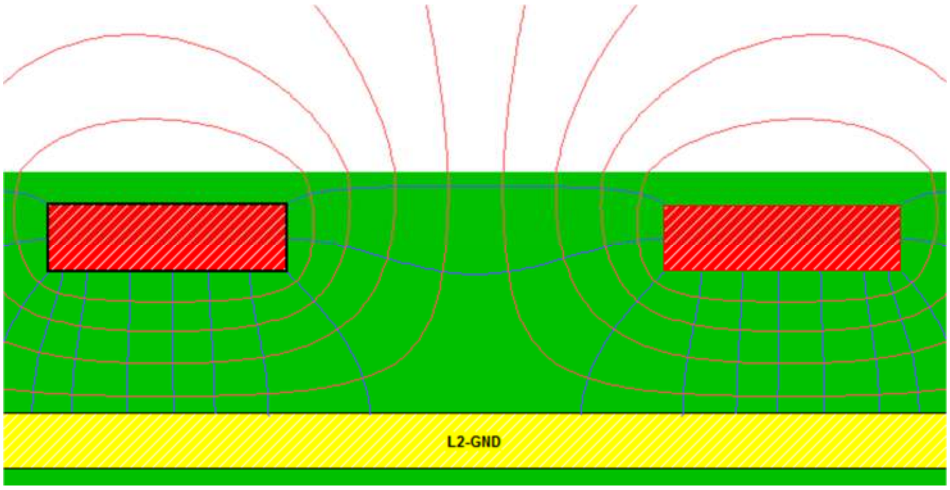

Figure 4. Microstrip Differential Pair coupling

The differential pair in Figure 4 illustrates the electromagnetic field coupling between the two trace segments. Magnetic fields tend to radiate into air which is actually just another dielectric with a dielectric constant of one.

Crosstalk is caused by capacitive and inductive coupling:

- Capacitive coupling causes signal voltages to couple current into nearby nets. This is also referred to as forward or far end crosstalk (FEXT).
- Inductive coupling causes signal currents to couple voltage into nearby nets. This is also referred to as backward or near end crosstalk (NEXT).

Points to remember:

- Our whole world literally revolves around electromagnetic fields. Migrating birds, turtles, whales etc all use the Earth’s magnetic field to navigate vast distances.
- The Earth's magnetic field is attributed to a dynamo effect of circulating electric current in the core.
- Electromagnetic fields are produced when a logic driver delivers a high speed, fast rise time pulse into a trace. The electromagnetic wave propagates down the length of the trace radiating in to the surrounding dielectric material and coupling energy to nearby trace segments.
- In a multilayer board, each microstrip and each stripline configuration, is totally isolated from the layers above or below.
- Electric fields, which capacitively couple current into a nearby trace, are somewhat absorbed by the plane but still tend to radiate noise outward.
- Magnetic fields refract at dissimilar dielectric boundaries and couple voltage inductively into a nearby trace.

Part 2 of “**Beyond Design: Electromagnetic Fields**” continues next month. In Part 2, we will look at how electromagnetic fields influence transmission lines and how they can be applied to a BEM field solver.

References:

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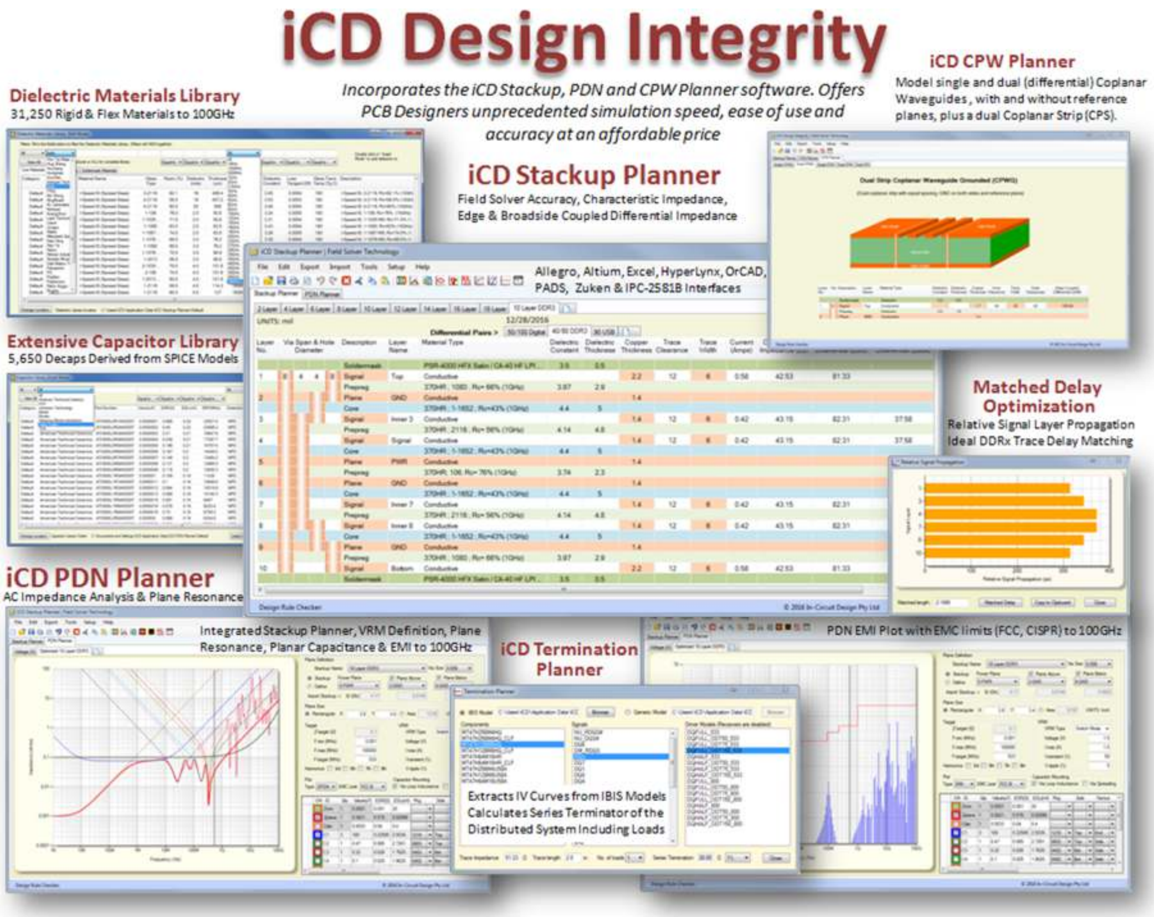
EMC and the PCB – Mark Montrose
National Geographic Jan-Feb 2013
The ICD Stackup and PDN Planner can be downloaded from www.icd.com.au

Bio -

Barry Olney is Managing Director of In-Circuit Design Pty Ltd (ICD), Australia. The company developed the ICD Stackup Planner and ICD PDN Planner software, is a PCB Design Service Bureau and specializes in board level simulation.



Electromagnetic Fields - Part 2

by Barry Olney | In-Circuit Design Pty Ltd | Australia

In last month's column, "**Beyond Design: Electromagnetic Fields – Part 1**", we looked at how magnetic fields revolve around the Earth and how these fields are also present in a multilayer board. In Part 2, we will look at how electromagnetic fields influence transmission lines and how they can be applied in a BEM field solver.

Maxwell's Equations describe the relationship between electric and magnetic fields. These equations describe the field strength and current density within a closed-loop environment. They require extensive knowledge of higher order Calculus – so I will not bore you (or me) with further details. However, much insight, into high-speed design, can be gained by understanding the behavior of transmission lines and their associated electromagnetic fields.

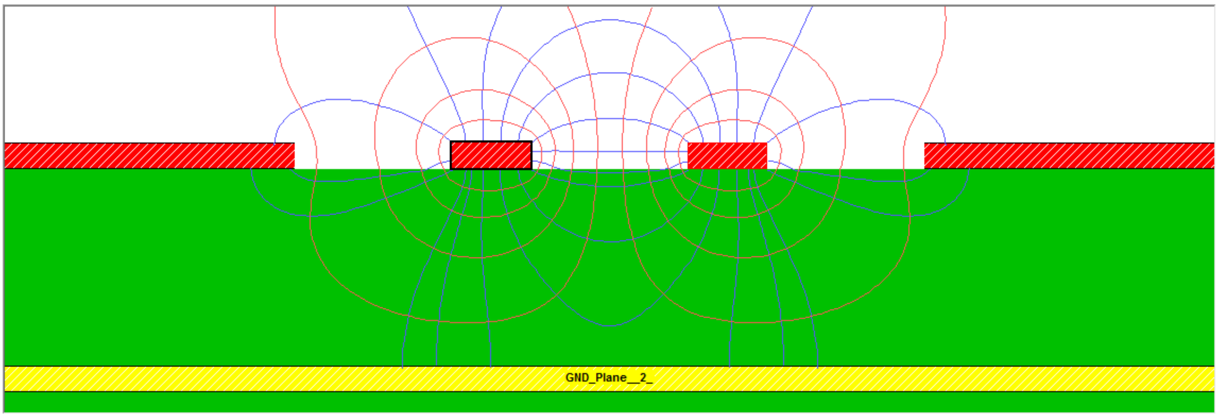


Figure 5. Differential pair as a coplanar wave guide

In Figure 5, copper is poured around the differential pair. This configuration is commonly used in RF design and is called coplanar wave guides. As mentioned in my previous column Ground Pours: To Pour or Not to Pour?, this is not a particularly good strategy for high-speed, digital design as it tends to alter (lower) the impedance of traces that run adjacent to a ground pour area. The traces of the differential pair are still coupled to each other and the ground plane, but are also coupled to the copper pour. This will reduce the impedance by ~25% and provide little additional shielding as the ground plane below is already used as a reference plane.

Figure 6 shows how the fields interact for two common stripline configurations: Edge coupled differential (top) and offset, broadside coupled differential (bottom). In the top example, the traces are closely coupled to each other and also to the ground plane above. Since they are located much closer to that plane, the fields follow the path of least inductance rather than coupling to the plane further below (although it does have some influence).

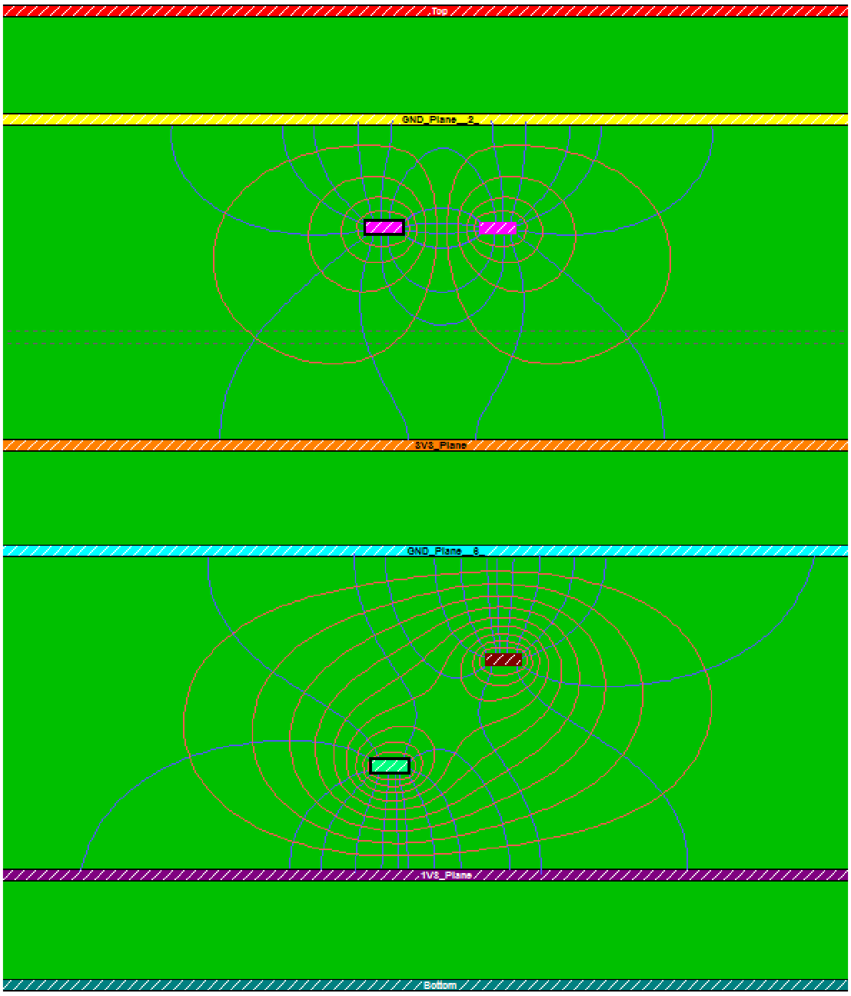


Figure 6. Edge coupled differential (top) and broadside coupled differential (bottom)

In this case, the ground plane above will be used for the current return path of the signal. It is crucial to understand which plane will be used for the return current path. In general, for offset striplines, whichever plane is closest to the trace has the most influence on impedance. Smack in the middle – both planes are equally important. But, this would not be a good layout approach as both would also equally act as the return path. Therefore, a deliberate offset is advised to eliminate this possibility and to be absolutely sure that the correct plane will be used for the return path.

In the bottom example, each trace is coupled to the nearest plane and loosely (offset) broadside coupled to each other. This coupling should be avoided in multilayer boards as it causes crosstalk. It is best to route these two signal layers orthogonally or better still – only have one signal layer between planes to totally eliminate this issue.

The impedance of broadside coupled traces is affected by the mechanical registration of layers, of the substrate, during the fabrication process. IPC recommend layer-to-layer registration between any two adjacent layers to be within 2 mils. So as you can imagine, the likelihood of two traces aligning perfectly is improbable. For instance, for a 4 mil trace it could well be that there is only an overlap of 2 mil. One possible application where broadside coupling may have an advantage, over edge coupled traces, is when routing an interleaved bus on a backplane - routing a number of differential pairs through a succession of connector pin fields where only a single trace fits between pins.

A Boundary Element Method (BEM) Field Solver, such as that integrated in the ICD Stackup Planner, harnesses the field charges surrounding the traces to calculate an impedance matrix. The boundaries (both dielectric/metal and dielectric/dielectric) are split into many elements and each element is assumed to have a uniform charge density. Hence, small elements are needed where the charge density changes rapidly and larger elements where the charge density is more uniform. Defining the elements is as much an art as a science and this all impacts on the speed of simulation. Green's Theorem Method and the matrix inversion yields a solution of an integral equation.

To increase simulation speed, ICD has developed unique, proprietary algorithms to automatically adjust the solution space relative to the defined variables.

Figure 7. The electromagnetic fields as seen by the field solver in the ICD Stackup Planner.

In Figure 7, I have roughly drawn in the fields that would be seen by the field solver software integrated into the ICD Stackup Planner. A 16 element impedance matrix is required to extract all the values of the stripline configuration (layer 3 & 4) where there are two signal layers between the planes.

Z11	Z12	Z13	Z14
Z21	Z22	Z23	Z24
Z31	Z32	Z33	Z34
Z41	Z42	Z43	Z44

Zdbs = Z11 – 2*Z13 + Z33
Zdiff = Z11 -2*Z12 + Z22
Zdiff = Z33 -2*Z34 + Z44
Zdbs = Z22 – 2*Z24 + Z44

where Zdiff is edge coupled and Zdbs is broadside coupled differential impedance

The impedance matrix gives the impedance of the system of coupled nets in the coupling region. The values in the diagonal matrix positions (example Z12 and Z21) can be thought of as giving the impedances to ground of the corresponding nets, accounting for the presence of the other nearby, coupled traces. When an IC drives into one of the lines, however, it "sees" not only the diagonal impedance for that line, but also some of the off-diagonal terms in the matrix.

For traces that are only weakly coupled, the diagonal impedance terms are dominant, and the diagonal values are close to what they would be if the lines were completely isolated from each other. As the coupling becomes stronger, the diagonal terms deviate more from their standalone values, and the off-diagonal terms increase.

If the configuration is microstrip or embedded microstrip (rather than stripline), and the electromagnetic fields they generate lie in a mixture of dielectrics (e.g., FR-4 and air), then multiple propagation velocities exist per line.

Much insight, into high-speed design, can be gained by understanding the behaviour of transmission lines and the influence of their associated electromagnetic fields. Controlled impedance design can be simplified and the path of the return current can be visualized by understanding the field coupling.

Points to remember:

- Maxwell's Equations describe the relationship between electric and magnetic fields. Green's Theorem method and the matrix inversion yields a solution of an integral equation.
- Return current paths follow the path of least inductance rather than coupling to a plane further away.
- For offset striplines, which ever plane is closest to the trace, has the most influence on impedance. A deliberate offset is advised to eliminate this possibility and to be absolutely sure which plane will be used for the return path.
- The impedance of broadside coupled traces is affected by the mechanical registration of layers, of the substrate, during the fabrication process and should be avoided.
- A Boundary Element Method (BEM) Field Solver, such as that integrated in the ICD Stackup Planner, harnesses the field charges surrounding the traces to calculate an impedance matrix.
- The impedance matrix gives the impedance of the system of coupled nets in the coupling region.

References:

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The ICD Stackup and PDN Planner can be downloaded from www.icd.com.au
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