Electromagnetic Field Basics

The Good, the Bad, and the Ugly

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Abstract

PCB designers, and others who don't have a lot of background in EMC issues, usually don't have a good understanding of electromagnetic fields. So electromagnetic fields often get a bad rap. But in fact, they are neither good nor bad, *per se*. ANY (AC) signal traveling along a trace generates an electromagnetic field. It is the effect of this field that can be good or bad. This article looks at the basic concepts of EMI, EMC, crosstalk, inductance, ground bounce, and RF communications and shows how they are all interrelated. The article also shows why there only a relatively few PCB design rules we have available to us for controlling the signal integrity issues related to electromagnetic field radiation, but why those rules can be effective.

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Electromagnetic fields sometimes get a bad rap. Perhaps that is because they sound so much like "electromagnetic interference," which of course deserves its bad rap. Many of us have gone through electromagnetic compliance testing to make sure that the electromagnetic fields that radiate from our traces do not cause electromagnetic coupling into other systems causing electromagnetic interference in those systems. And if our systems pass electromagnetic compliance testing, we probably won't experience much electromagnetic susceptibility, either.

Confused yet? Don't feel alone. These terms get many of us designers (who usually don't have experience in EMC testing) all twisted up. This article will help you sort through all this. And along the way, we'll find out that electromagnetic fields have as many good consequences as they have bad ones. A radiated electromagnetic field is not the bad guy, it is the circumstances surrounding it that determines whether it is good or bad.

Electromagnetic Fields

Current, by definition, is the flow of charge. One amp is defined as one coulomb of charge passing by a point in one second.[1] As current flows down a wire, the charge density at any point along the wire changes as a function of the current at that point in time. This charge density creates a field that radiates as a vector directly away from the wire (see Figure 1).

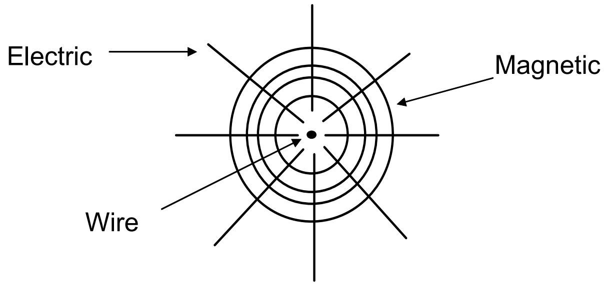


Figure 1 Electric and magnetic fields around a wire when there is current flowing.

When current flows, there is also a magnetic field that is generated around the wire. This is the fundamental concept behind an electromagnet. (Most of us boaters are aware that stray currents [from the ignition system, radio, etc.] can cause a magnetic field that in turn can cause our compass to shift—an obvious safety issue.) This magnetic field radiates away from the wire in a circular fashion.

The combination of these two fields is what we call an electromagnetic field. Any time we have a current we have an electromagnetic field. We cannot have a current flow without an electromagnetic field. And the three elements must track together. The magnetic field can't get out in front of or lag behind the electric field. The electrons can't get in front of or lag behind either field. All three must travel together. That is why signal propagation time is determined, not by how fast the electrons can travel in a wire, but by how fast the electromagnetic field can travel in the medium it travels through.[2]

Electromagnetic Coupling

Electromagnetic fields can result in currents that are coupled into other wires. But the electromagnetic field must be *changing* for this coupling to happen. *Changing* electromagnetic fields are caused by *changing* currents. Thus, DC currents cannot couple signals into other wires. Only AC currents can do that.

Electric coupling: Most of us learned long ago that like charges repel each other. Therefore, if a charge density exists at a point along a wire, it will tend to repel like charges away from that point in adjacent wires (see Figure 2). Those elements of charge that are repelled away are moving. By definition this is a current. So a changing electric field in one wire (as charge density changes) causes a changing current in another adjacent wire. This effect is often referred to as electric coupling, charge coupling, or capacitive coupling.

Figure 2 Changing charges in one wire repel (move) charges in an adjacent wire, resulting in a current there.

Magnetic coupling: If a current flowing along a wire causes a magnetic field around the wire, then a *changing* current in a wire causes a *changing* magnetic field around the wire. Michael Faraday (Faraday's Law) showed that a *changing* magnetic field causes an electric field that is perpendicular to the magnetic field. This electric field can cause a current to flow in an adjacent wire (see Figure 3). This is the fundamental principle behind a transformer; a changing current in the primary winding causes a changing magnetic field and thus a current to flow in the secondary winding. This effect is often referred to as magnetic coupling or inductive coupling.

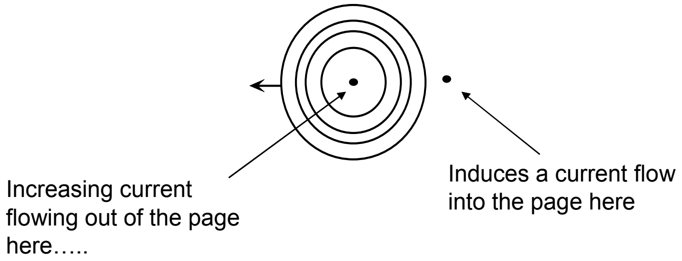


Figure 3 A changing current causes a changing magnetic field that in turn causes a changing current in an adjacent wire.

Consequences

There is nothing inherently good or bad about electromagnetic coupling. Whether the consequences of this coupling are beneficial or not depends entirely on the circumstances. There are many positive effects. Electromagnetic coupling is the primary principle behind a transformer. The magnetic aspect of electromagnetic coupling provides the principle behind a motor or a relay. Faraday's Law is the fundamental principle behind an electrical generator. Transmitters and receivers (radio, television, CB radio, automotive wireless door locks, etc) work by electromagnetic radiation coupling into a receiving antenna on a specific frequency.

But electromagnetic coupling is also at the heart of almost all the negative signal integrity issues that board designers face. Therefore, it is important to understand how and where electromagnetic coupling manifests itself in our circuits. For example, electromagnetic coupling results in a coupled current in another wire or trace. This is a bad thing if we are coupling at an undesired frequency into adjacent traces on our boards. We call it crosstalk. Many of us think it is a really bad thing if we are coupling a signal into an antenna at the FCC compliance testing range. We commonly call the effect of this type of coupling "Electromagnetic Interference" or *EMI*. But in the specific case of *differential* signals the coupling into an adjacent trace is beneficial.[3] That is why we route differential signals close to each other, to maximize this coupling effect.

Most of us are aware that when a signal trace is routed over a plane, the return signal "wants" to be on the plane directly under the trace. Although this is an example of a single-ended trace, in a sense it is a differential pair (involving differential coupling) because the return signal (equal to and opposite from the driven signal) automatically travels as close as possible to the signal itself. The reason is that this path is the lowest impedance path. The core phenomenon here is the electromagnetic coupling between the trace and the plane.[4]

A concept that is difficult for many people to understand is that if a signal on one wire can electromagnetically couple into another wire, then it can also electromagnetically couple *into itself*. This creates an induced (coupled) signal on the wire that opposes the driving signal that creates it in the first place. It may take a brief period of time for the driving signal to overcome this coupled signal. We describe this effect as *inductance*. The core cause of inductance in a wire or trace is the magnetic field created by the driving signal that induces a current in the *same* wire or trace in the opposite direction.

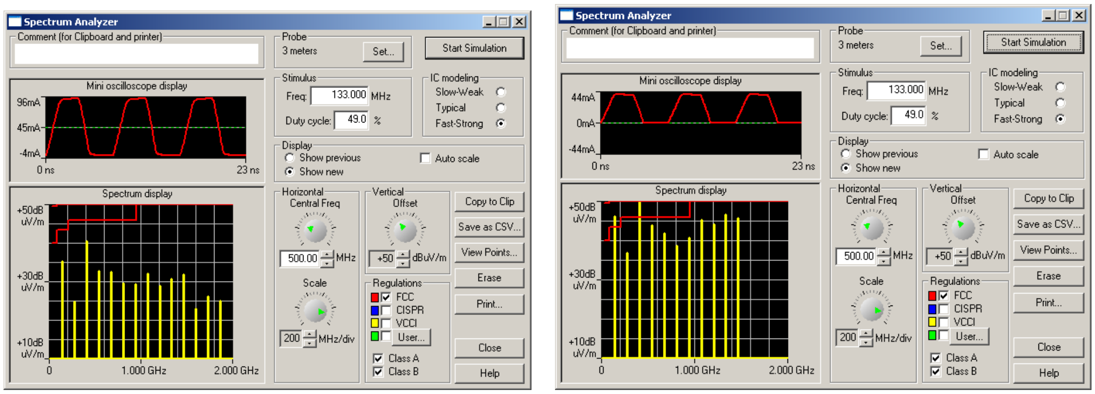
All wires and traces have some inductance, so this is not necessarily a bad thing. But the *effect* of inductance (a noise voltage) is typically a function of rise time (di/dt), how fast the signal changes in a given increment of time. This is the cause behind ground bounce on our circuit boards when we use fast rise-time devices, a problem we try to correct with bypass capacitors.

Controlling the Signal Integrity Issues

Electromagnetic field creation and radiation is the core problem behind many of the signal integrity issues on our circuit boards. It is the cause of EMI. It is the cause of crosstalk. It is the fundamental principle behind the inductance that causes ground bounce and is one of the primary contributors to power system noise. Most of the SI design rules we have for PCBs are designed to deal with electromagnetic coupling and/or its components and effects. And the number of design rules we use to control things is surprisingly small.

Use of power and ground planes: One way to reduce inductance is to increase the trace width. Wider wires and traces have lower current densities for the same current levels and therefore, lower self-coupling. Planes are about the ultimate in trace width. As a result, planes typically provide the lowest inductance path for our power supplies. This is one technique that helps control ground bounce and power system instability.

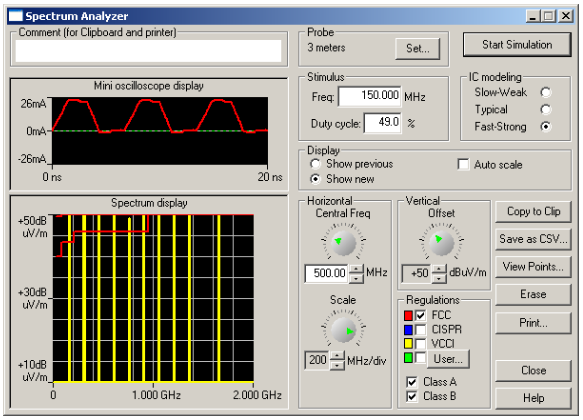
Routing traces close to planes: Routing traces very close to the underlying plane helps to confine the electromagnetic field in the narrow area between the signal and its return (on the plane). It also minimizes the loop area between the signal and its return. Consequently, it minimizes the portion of the electromagnetic field that can radiate out to other areas. This is a primary control for EMI and for crosstalk. (See Figures 4a and 4b)



Probe: 3 meters
Stimulus: Freq: 133.000 MHz; Duty cycle: 49.0 %
IC modeling: Slow-Weak ○ Typical ○ Fast-Strong ●
Display: ○ Show previous ● Show new ☐ Auto scale
Horizontal: Central Freq 500.00 MHz; Scale 200 MHz/div
Vertical: Offset +50 dBuV/m
Regulations: ☑ FCC ☐ CISPR ☐ VCCI ☐ User...
☑ Class A ☑ Class B

(a) (b)

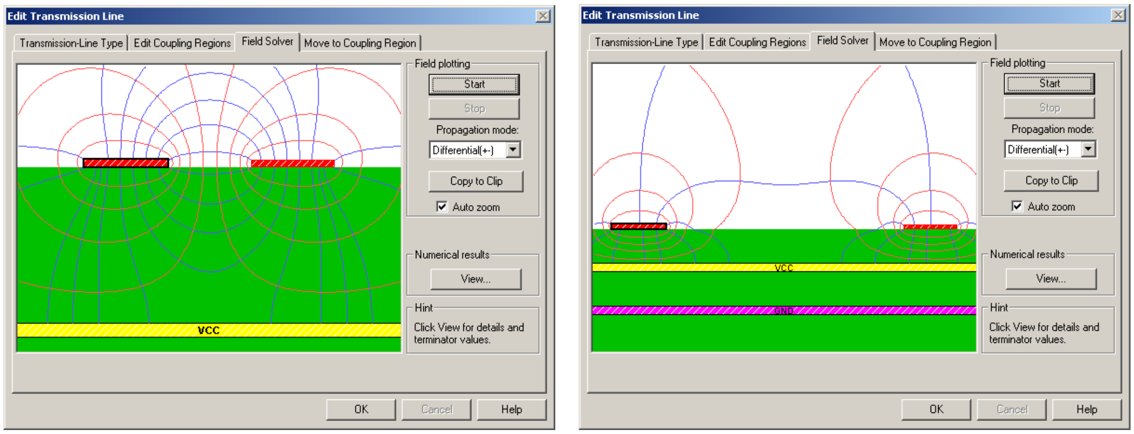
Figure 4a: HyperLynx spectrum analyzer results for two properly terminated traces, both 10 mils wide and 3" long. Trace (a) is 5 mils from the underlying plane, trace (b) is 40 mils from the underlying plane. This analysis suggests that case (b) would fail FCC compliance testing, while case (a) would not.



Probe: 3 meters
Stimulus: Freq: 150.000 MHz; Duty cycle: 49.0 %
IC modeling: Slow-Weak ○ Typical ○ Fast-Strong ●
Display: ○ Show previous ● Show new ☐ Auto scale
Horizontal: Central Freq 500.00 MHz; Scale 200 MHz/div
Vertical: Offset +50 dBuV/m
Regulations: ☑ FCC ☐ CISPR ☐ VCCI ☐ User...
☑ Class A ☑ Class B

Figure 4b: This extreme case simulates the spectrum analyzer results of a trace with no reference plane. This design would fail compliance testing miserably.[5]

Separation of traces as far apart as practical: Since electromagnetic coupling is inversely related to the square of the distance, routing traces far apart helps reduce coupling between traces. This is a control for crosstalk. (See Figure 5)



Propagation mode: Differential(+-)

Hint: Click View for details and terminator values.

(a) (b)

Figure 5: This field view from HyperLynx shows electric and magnetic field lines between two traces. Here are two extremes: (a) traces very close together and far away from the underlying plane, (b) traces far apart and close to the underlying plane. The difference in coupling is obvious.

Use of parallel plane pairs: Bypass capacitors sometimes exhibit enough inherent inductance at higher-frequency harmonics that we cannot achieve the power system stability we need. The capacitance formed by plane pairs, with their inherently lower inductance, help stabilize power systems at these higher-frequency harmonics. The primary benefit here is lower inductance. Conceptually we can think of that resulting from the very wide surface area of the plane. This is a control for power system stability.

Summary

Changing electromagnetic fields occur any time we have a changing current traveling along a trace. If we are not careful with our system designs, these changing fields can couple unwanted signals into other circuits, a problem we call crosstalk (if the other circuits are nearby) or EMI (if the other circuits are further away). Circuits that cause EMI problems also tend to be susceptible to radiation, a condition we refer to as electromagnetic susceptibility. We go through electromagnetic compliance (EMC) testing at FCC testing ranges to ensure that our systems will not generate strong-enough electromagnetic fields to cause EMI problems.

Footnotes

1. One coulomb is defined as 6.25 x 10^18 electrons. So current is actually the flow of negatively charged electrons (which would flow from – (minus) to + (plus)). But Benjamin Franklin said that electricity flows from + (plus) to – (minus), perhaps the only mistake he ever made. We have accepted his idea ever since. Conceptually, it makes no difference how you view current flow as long as you are consistent (unless you are a semiconductor physicist, a person who really does care about electrons and the “holes” they leave behind.)

2. See Douglas Brooks, “Propagation Times and Critical Length, How They Interrelate”, available at www.mentor.com/pcb/tech_papers.cfm .

3. See Douglas Brooks, “Differential Trace Design Rules; Truth vs. Fiction”, available at www.mentor.com/pcb/tech_papers.cfm .

4. For an in-depth discussion of the relationship between magnetic coupling and inductance, see Brooks, Douglas, Signal Integrity Issues and Printed Circuit Board Design, Prentice Hall, 2003, Appendix B, “Why Inductors Induct.”

5. Actually, the HyperLynx Spectrum Analyzer tool cannot simulate a problem without an assumed plane. This figure was modeled with a plane far away. This result would not be significantly different if we could assume a plane infinitely far away, i.e. no plane.

About the Author

Douglas Brooks has a B.S and an M.S in Electrical Engineering from Stanford University and a PhD from the University of Washington. During his career has held positions in engineering, marketing, and general management with such companies as Hughes Aircraft, Texas Instruments and ELDEC.

Brooks has owned his own manufacturing company and he formed UltraCAD Design Inc. in 1992. UltraCAD is a service bureau in Bellevue, WA, that specializes in large, complex, high density, high speed designs, primarily in the video and data processing industries. Brooks has written numerous articles through the years, including articles and a column for Printed Circuit Design magazine, and has been a frequent seminar leader at PCB Design Conferences. His primary objective in his speaking and writing has been to make complex issues easily understandable to those without a technical background. You can visit his web page at http://www.ultracad.com and e-mail him at doug@ultracad.com.