Radiation from Edge Effects in Printed Circuit Boards (PCBs)

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SCHOOL OF ENGINEERING
SFSU

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- ***Motivation***
- ***Problem definition***
- ***Problem setup***
- ***Physics of PCB propagation modes***
- ***Physics of PCB edge effects***

- ***Minimizing radiation from PCB edges***

Motivation

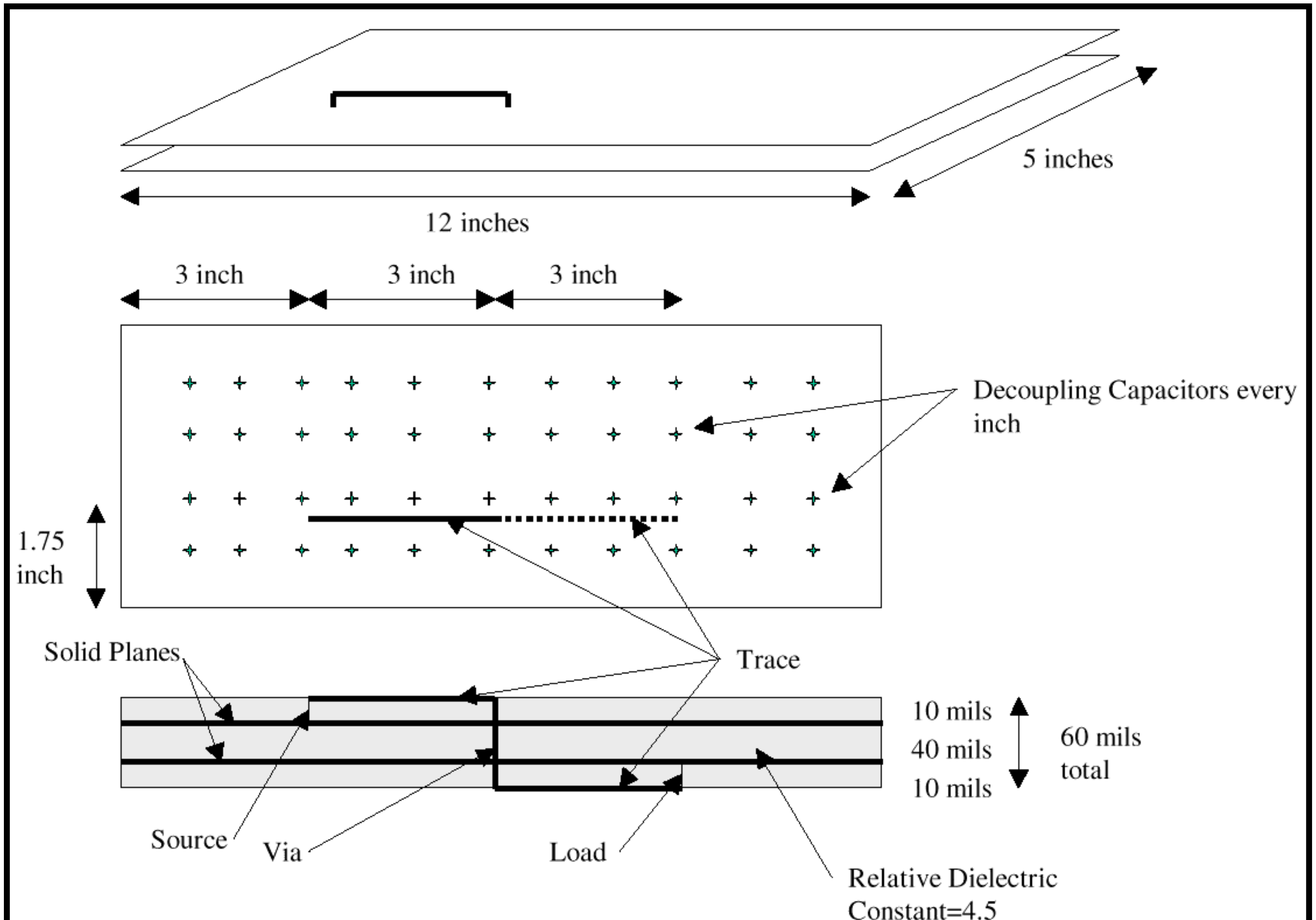
- ***As competitive forces drive product costs down, it becomes increasingly important to incorporate good EMC design practices into the product - especially ones that provide superior suppression at minimum cost.***

- ***Because PCB layout patterns (how traces and ground/power planes are stacked and routed) do not add to production costs, there is a tremendous interest in optimizing these structures to provide maximum EMC suppression.***

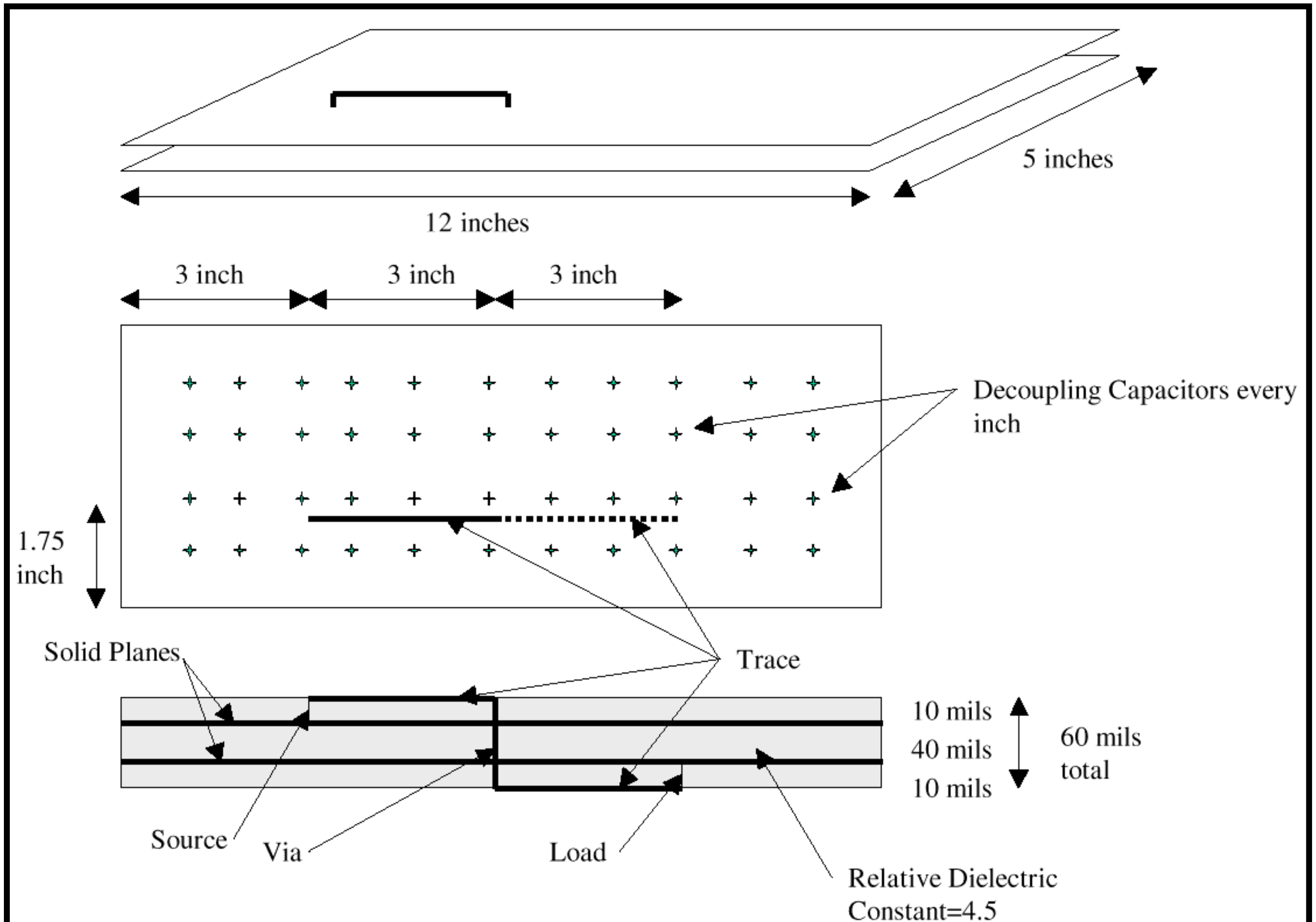
- ***The material presented tonight highlights some of the ongoing research in this area that the SFSU Center for Applied Electromagnetics is currently working on in conjunction with its Industry Partnership Program.***

- ***IEEE EMC Society Computational Electromagnetics TC-9 identified edge emissions as a significant EMC risk phenomenon, and included it as one of its four challenging EMC modeling problems.***

- ***Find the edge emissions from the following structure…..***



- ***Solution (from a modeling perspective)***
  - ***Find a big fast computer with enough memory to hold the entire model.***
  - ***Take a long coffee break….***
  - ***Results to be presented at the IEEE 2000 EMC Symposium***



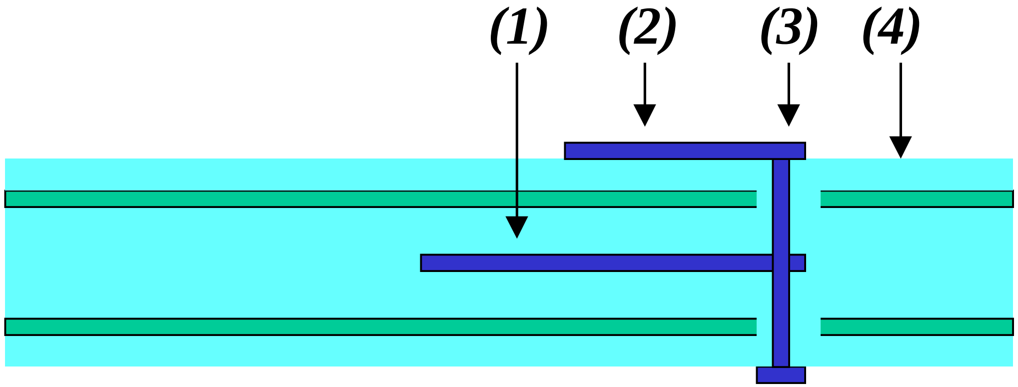
Motivation

- *Solution (from a modeling perspective*
  - *Find a big fast computer with enough memory to hold the entire model.*
  - *Take a long coffee break….*

- ***Modeling entire structure on a computer does not provide insight into what's going on.***
- ***If we "unbundle" the problem into its component pieces, look at the physics of each component, we can use the insight gained from this process to figure out what is going on.***
  - ***How bad is it?***
  - ***Does the 20H rule (pulling back power planes) work?***
  - ***Does fencing (grounding vias around periphery of PCB) work?***
  - ***Are these the only two techniques at our disposal?***

Problem Definition

- ***Traces [striplines (1), microstrips (2), and vias (3)] and dielectric (4) are used to route time-varying currents (digital signals, etc.) around on PCBs.***



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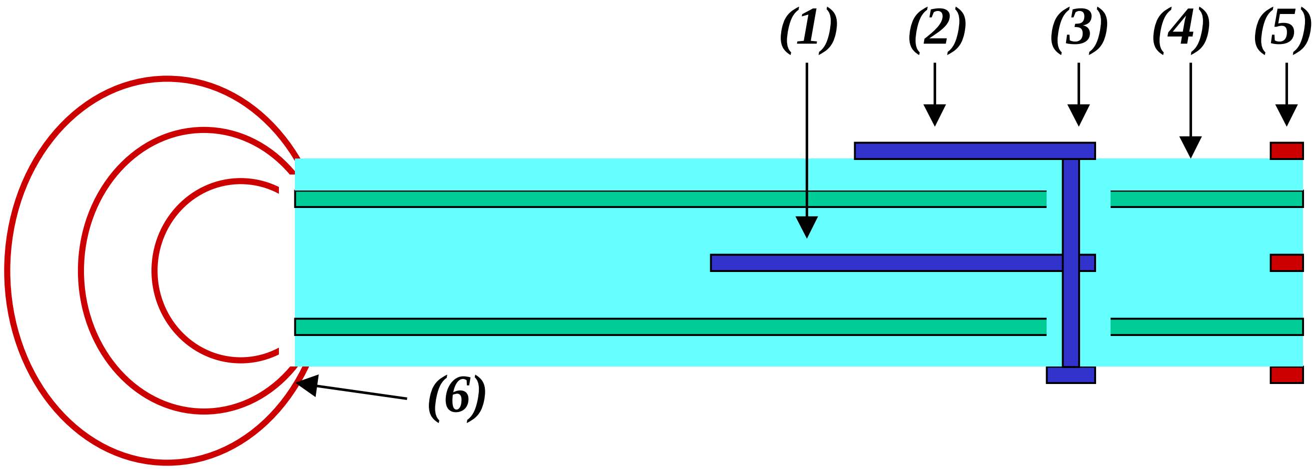
- ***Even if traces are not routed along the edge (5), radiation still occurs (6).***



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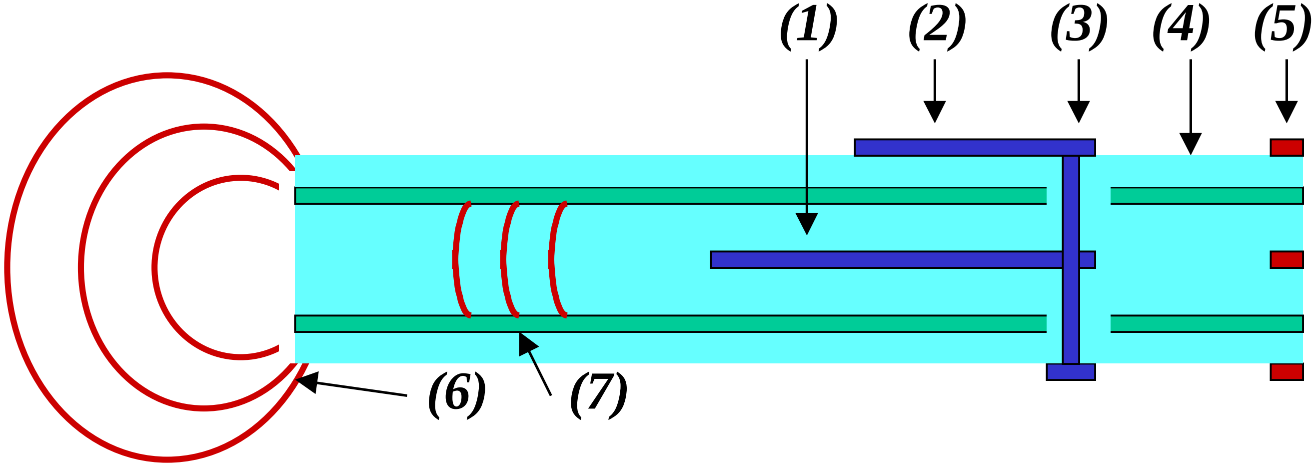
- ***We conclude currents in the traces create electromagnetic fields that propagate through the dielectric towards the edge (7).***



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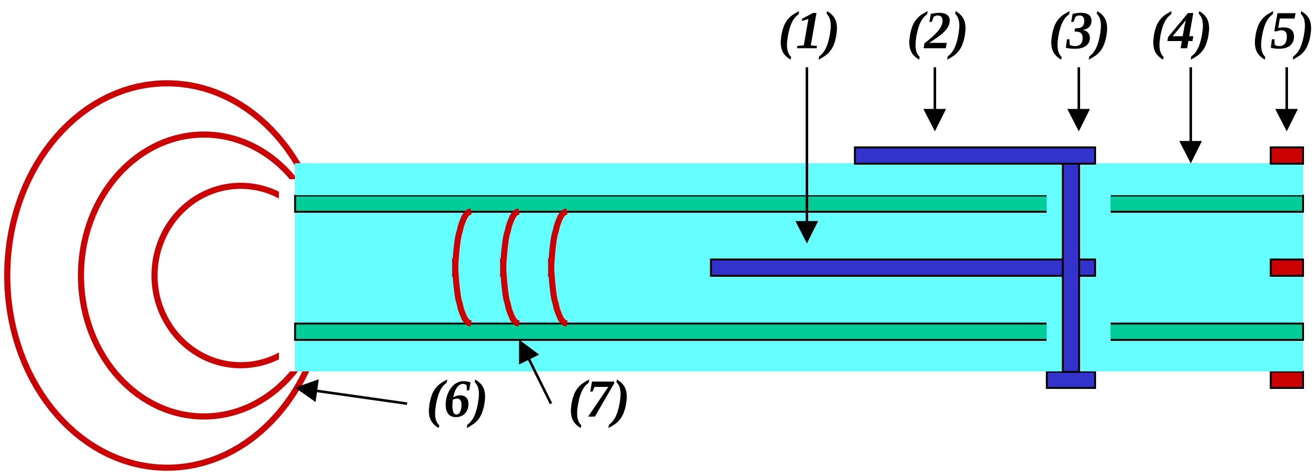
- *Traces [striplines (1), microstrips (2), and vias (3)] and dielectric (4) are used to route time-varying currents (digital signals, etc.) around on PCBs.*
- *Even if traces are not routed along the edge (5), radiation still occurs (6).*
- *We conclude currents in the traces create electromagnetic fields that propagate through the dielectric towards the edge (7).*
- ***If we understand how these fields are created, how they propagate to the edge, and how they radiate into the surrounding space once they get there, we can develop effective EMC guidelines to minimize radiation.***

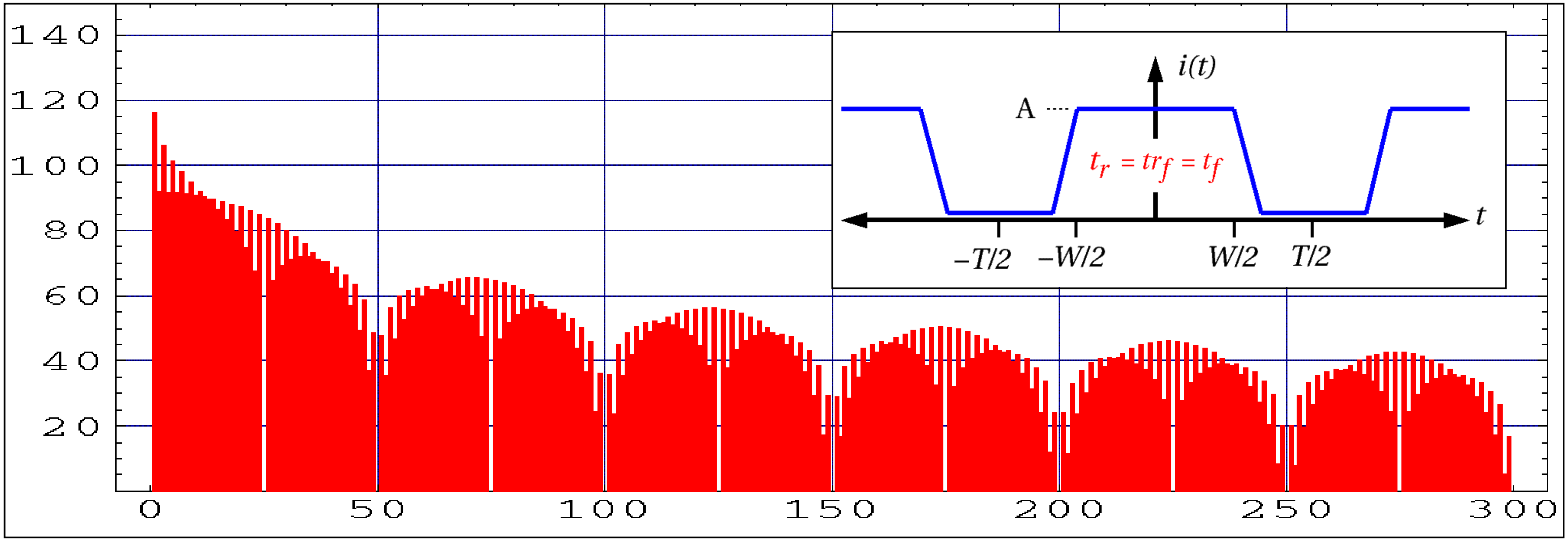


Problem Setup

- ***Stationary (Electrostatic) Fields***
  - *i = dq/dt = 0 = charge at rest*
  - *Only produce static E-fields*
  - *Example: Charged capacitor*
- ***Velocity (Magnetostatic) Fields***
  - *i = dq/dt = constant (DC current)*
  - *Only produce static H-fields*
  - *Example: Solenoid connected to a battery*
- ***Accelerating Fields***
  - $di/dt = d^2q/dt^2 \neq 0$
  - *Produce time-varying radiating electromagnetic fields [1], [2]***
  - *Example: Any time varying current waveform*

*** [1], [2] see references at end of presentation***

- ***Spectrum of digital signal currents produce radiating fields [3]***



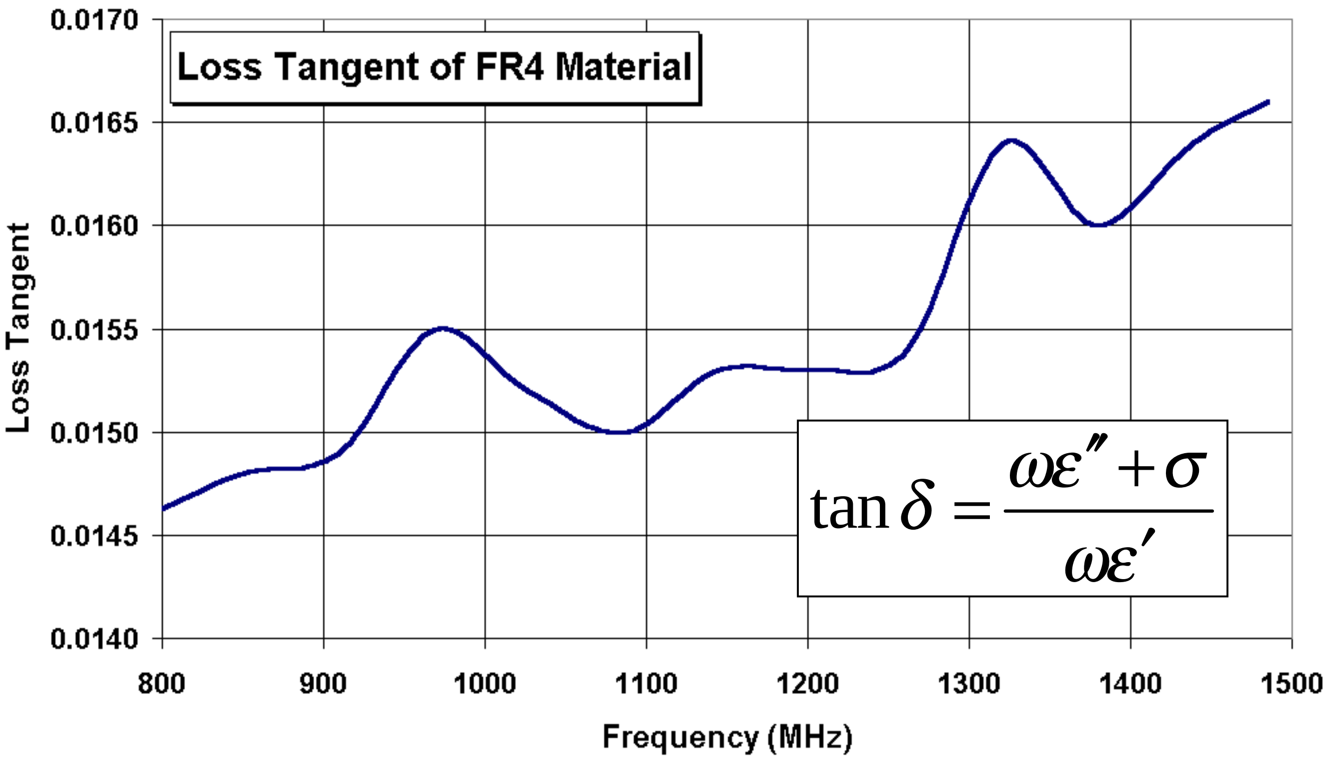
$$i(t) = \frac{dq}{dt} = a_0 + \sum_{n=1}^{\infty} a_n \cos\left(\frac{2n\pi}{T}t\right) + b_n \sin\left(\frac{2n\pi}{T}t\right) = a_0 + \sum_{n=1}^{\infty} a_n \cos\left(n\omega_0 t\right) + b_n \sin\left(n\omega_0 t\right)$$

$$\frac{di(t)}{dt} = \frac{dq^2}{dt^2} = \left[\sum_{n=1}^{\infty} n\omega_0 a_n \sin\left(n\omega_0 t\right) - n\omega_0 b_n \cos\left(n\omega_0 t\right)\right] \neq 0$$

Note: $n\omega_0 \Uparrow \quad \rightarrow \quad \frac{di(t)}{dt} \Uparrow$

Example: spectrum of 1 MHz 50% duty cycle 5 µsec rise/fall time trapezoidal waveform

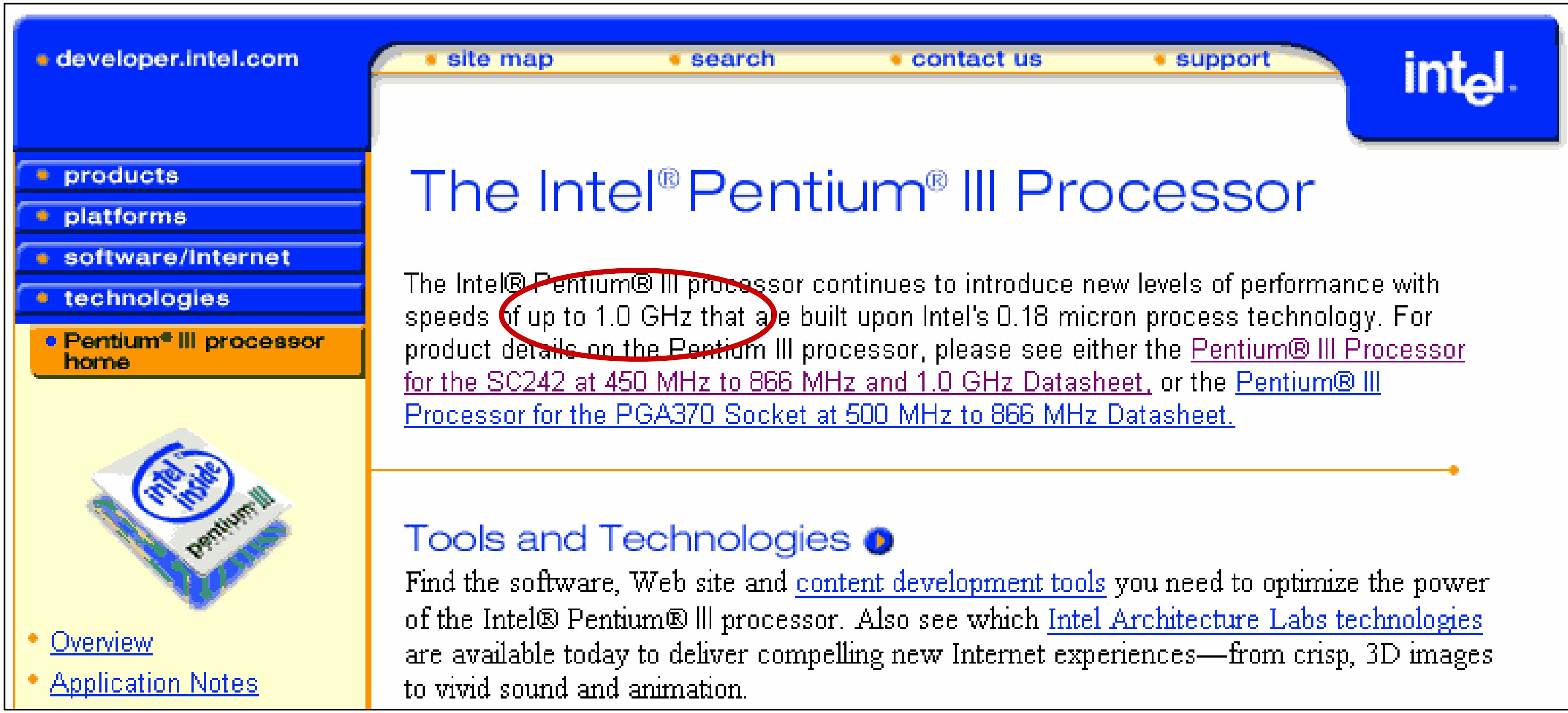
- ***Losses in typical PCB dielectric increase with frequency.***
  - ***Attenuation of higher frequency harmonics distorts clock waveforms.***
  - ***Limits useable range of typical (inexpensive) PCBs to ≈ 2 GHz.***
  - ***Attenuation acts like a natural "low pass filter".***
  - ***Non-linear behavior requires discrete frequency modeling techniques.***



$$\tan\delta = \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'}$$

$\omega\varepsilon''$ + σ = dielectric damping losses + conduction losses, $\omega\varepsilon'$ stored energy [4]

Problem Setup



- ***1-2 GHz sine waves good "compromise" modeling source.***
  - ***Fundamental harmonic of next generation CPUs.***
  - ***Still in useable range of typical PCB dielectrics.***
  - ***Can use existing FEM/FDTD programs that require constant ε', ε", σ.***

Problem Setup

- ***To find fields we need to solve Maxwell's two curl equations.***
- ***From current density, J, we can find E and H.***
- ***From E and H we can determine propagation modes.***
- ***From E x H (Poynting vector) we can find power properties.***
  - ***Power density of wave at different positions in PCB structures.***
  - ***Direction power is flowing (what happens inside and around a PCB).***

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \qquad \nabla \times \mathbf{H} = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t}$$

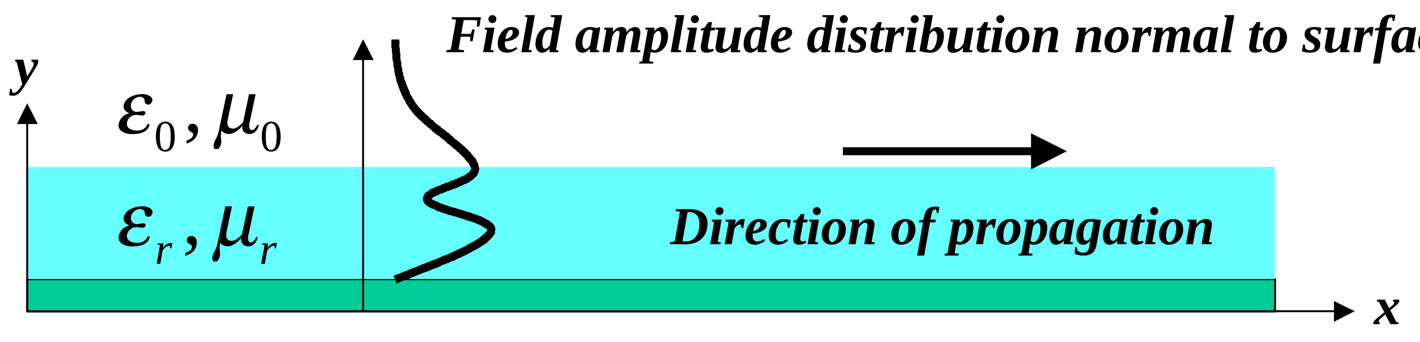
$$\mathbf{E} = \hat{\mathbf{x}} E_x + \hat{\mathbf{y}} E_y + \hat{\mathbf{z}} E_z \quad (\text{V/m}) \qquad \mathbf{H} = \hat{\mathbf{x}} H_x + \hat{\mathbf{y}} H_y + \hat{\mathbf{z}} H_z \quad (\text{A/m})$$

$$\mathbf{P} = \mathbf{E} \times \mathbf{H} \quad (\text{V/m})(\text{A/m}) \quad \Rightarrow \quad (\text{W/m}^2)$$

Physics of PCB Structures

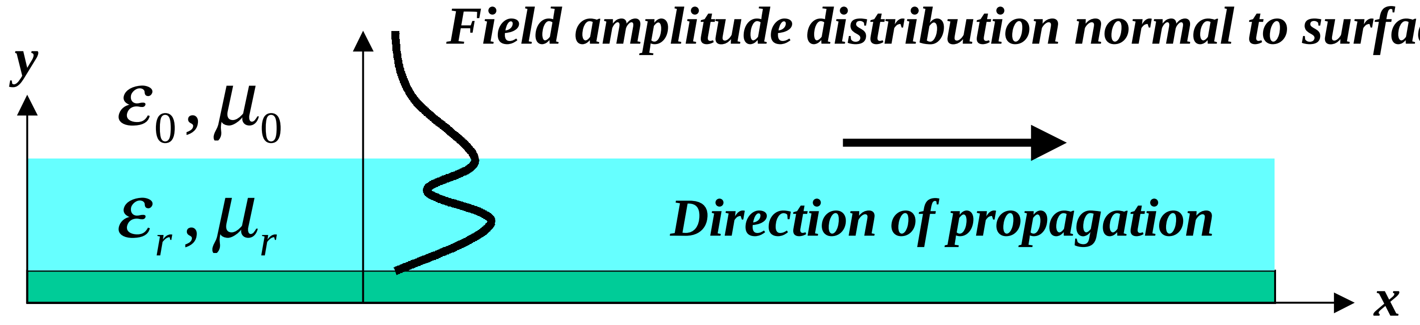
- ***Number of propagating modes in and around a PCB structure.***
  - ***Surface waves propagate along the top and bottom surfaces of a PCB.***
  - ***TEM waves propagate along traces and between power/ground planes.***
  - ***Ground/power planes - in conjunction with the impedance discontinuities along the PCB edges - create resonant cavities that support TE/TM modes.***
- ***We need to understand how the structures of a PCB can create and support these waves and modes before we can develop and evaluate cost effective EMC solutions.***

Physics of PCB Structures (Surface Waves)



- *Surface waves propagate along reactive Z planes. [9], [10]*
  - *Originally predicted by Tesla. Formally developed by Uller (1903) and Zenneck (1907).*
  - *If surface appears capacitive can support TE_n (n=1, 3, 5,…) modes.*
  - *If surface appears inductive can support TM_n (n=0, 2, 4,…) modes.*
    - *Dielectric over a ground plane (e.g. a PCB) can be made to look like an inductive surface.*

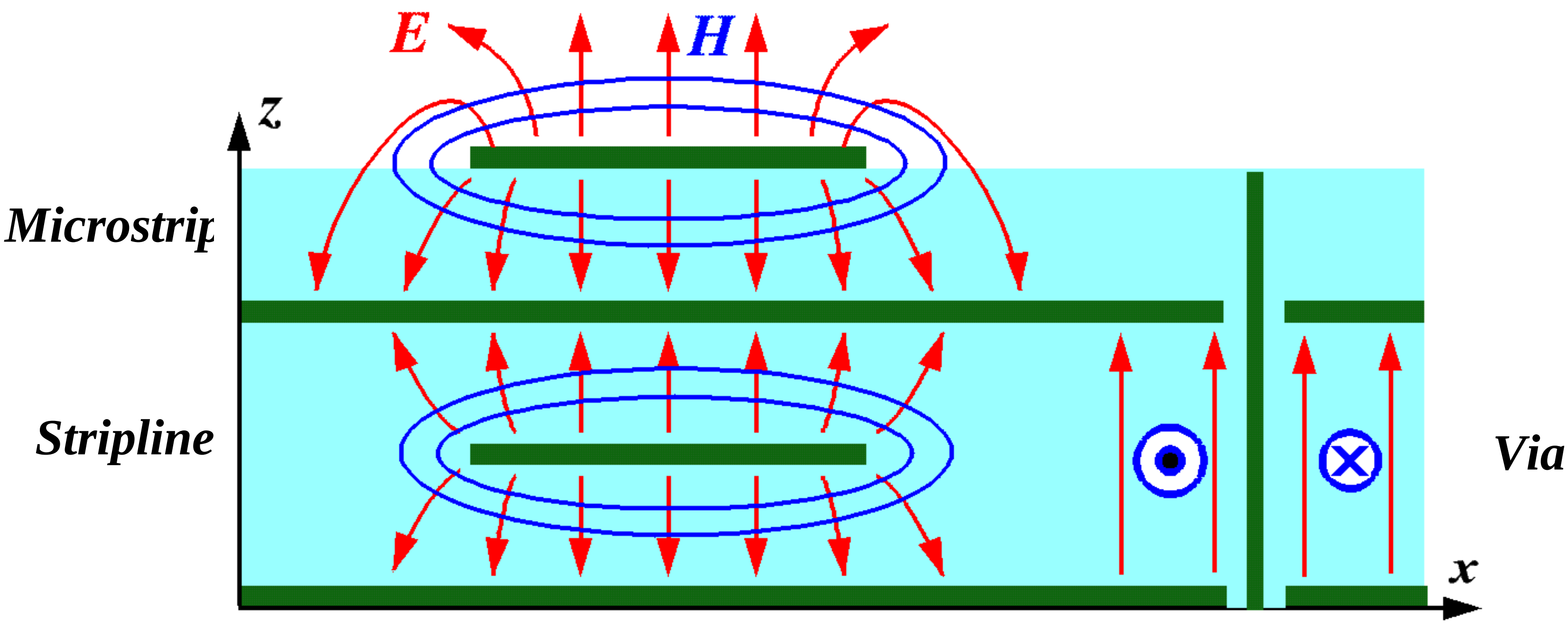
Physics of PCB Structures (Surface Waves)



- ***Field decays exponentially in y direction.***
  - ***For thin coatings and long wavelengths (> mm wavelengths), field decays slowly (extends far above the PCB). [11]***
  - ***Radiation from PCB edges can launch surface waves across PCB surfaces.***

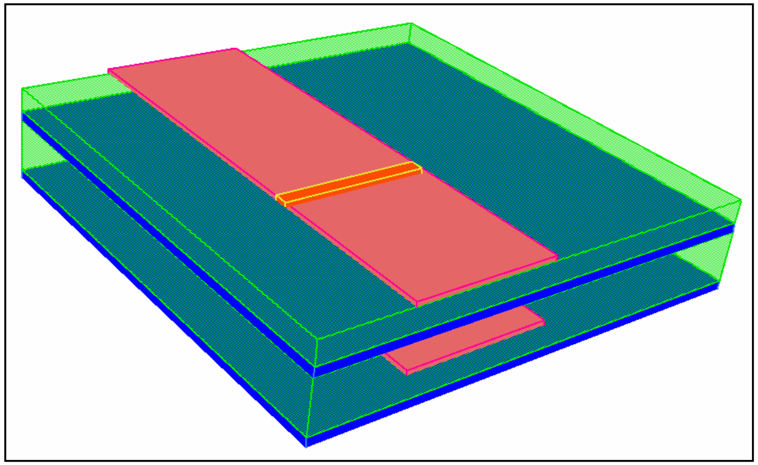
Physics of PCB Structures (TEM Modes)

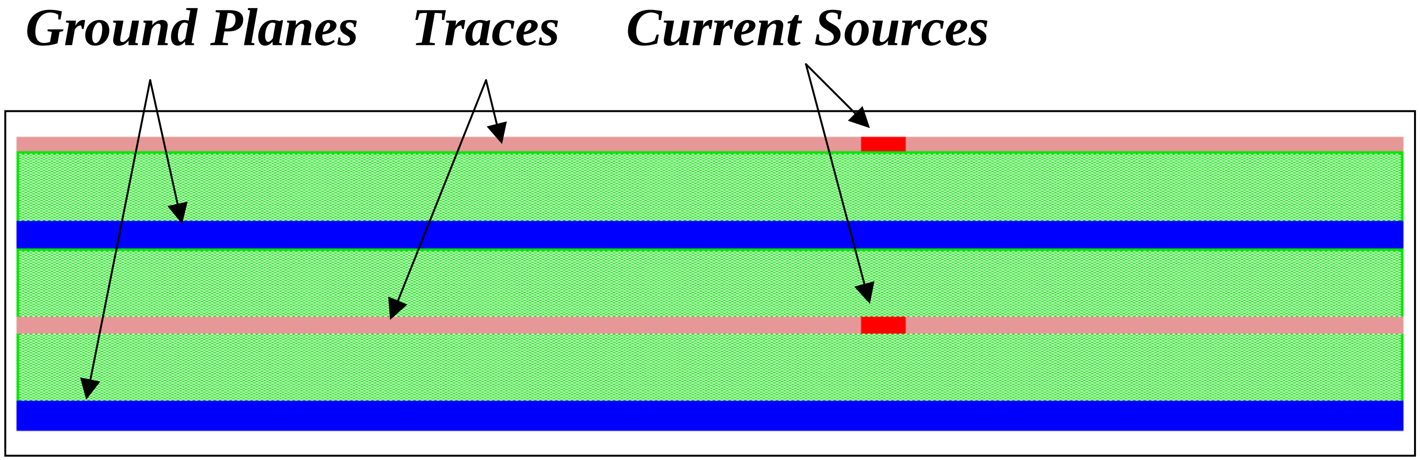
- ***Three kinds of PCB structures generate TEM mode waves.***
  - ***Microstrips: outer (visible) trace routed over a plane.***
  - ***Striplines: inner trace routed between two planes.***
  - ***Vias.***



Physics of PCB (TEM Modes)

- ***Fields in microstrips and striplines follow currents in trace.***
  - ***Relatively little energy propagates away from the trace.***
  - ***Some examples of*** **|E** x **H|** ***in a section of microstrip and stripline.***

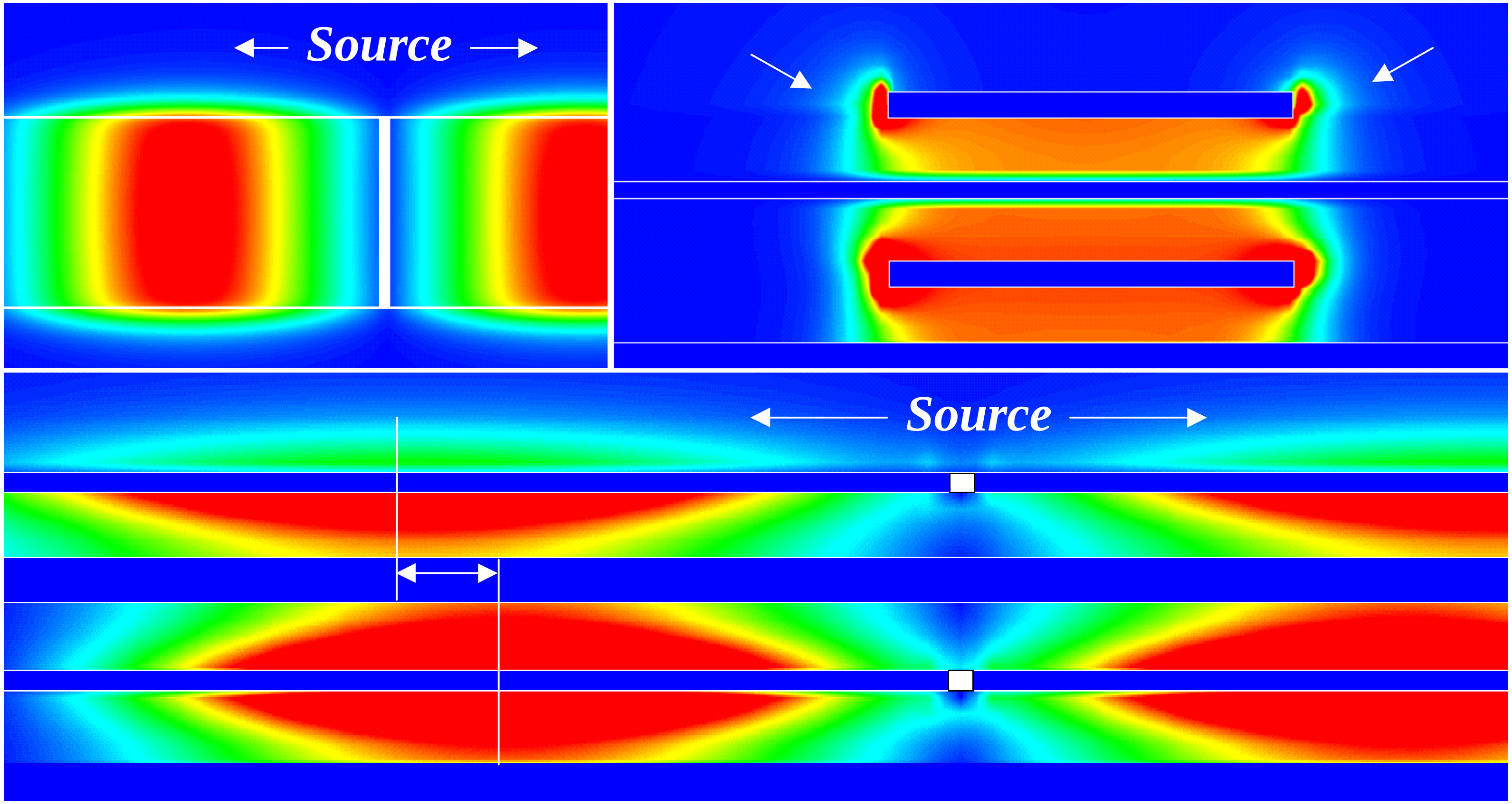




Physics of PCB (TEM Modes)

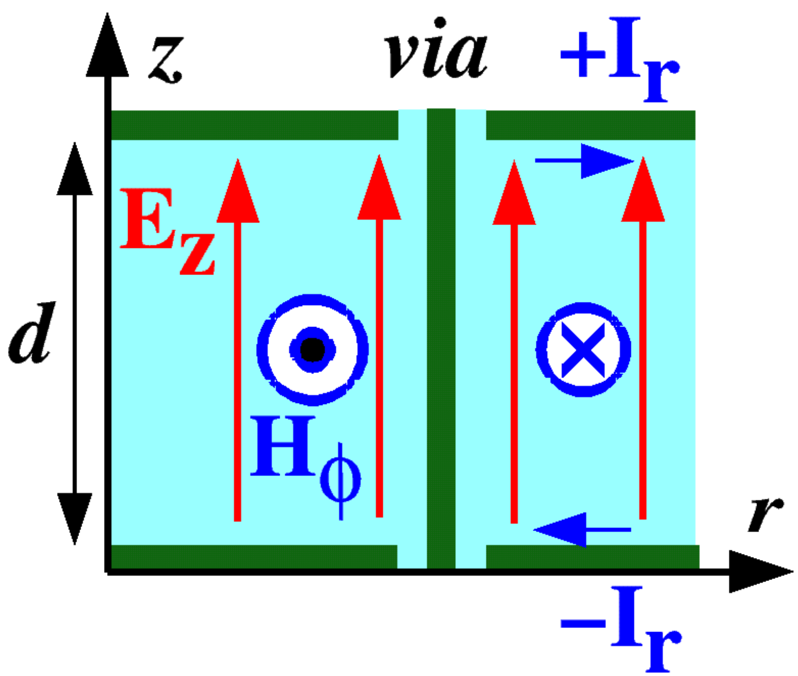
- ***Fields in microstrips and striplines follow currents in trace.***
  - *Relatively little energy propagates away from the trace.*
  - *Some examples of |**E** x **H**| in a section of microstrip and stripline.*

Top View (microstrip) *Cross Section View*



Side View

- ***Currents on vias launch radial TEM waves into the dielectric planes. [7]***
  - ***E-field normal to ground planes (E_z).***
  - ***H-field circumferentially (H_ϕ).***
  - ***Wave impedance changes with radial distance from via.***



$$V_d = E_z d$$

$$I_r = 2\pi r H_\phi$$

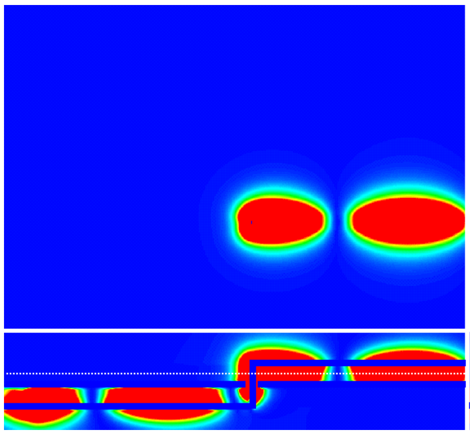
$$Z_{total} = \frac{V_d}{I_r} = \frac{E_z d}{2\pi r H_\phi}$$

$$= \frac{d}{2\pi r}\left(\frac{E_z}{H_\phi}\right)$$

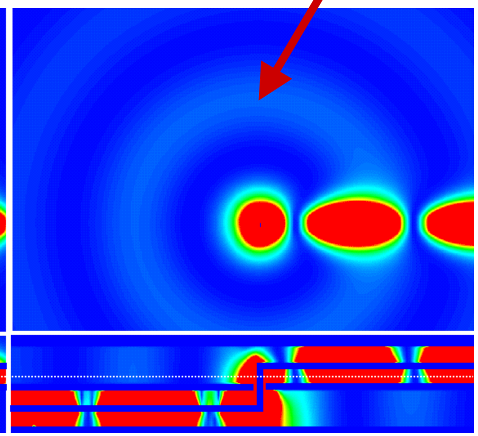
Physics of PCB (TEM Modes)

- ***Some examples of via induced power density fields.***

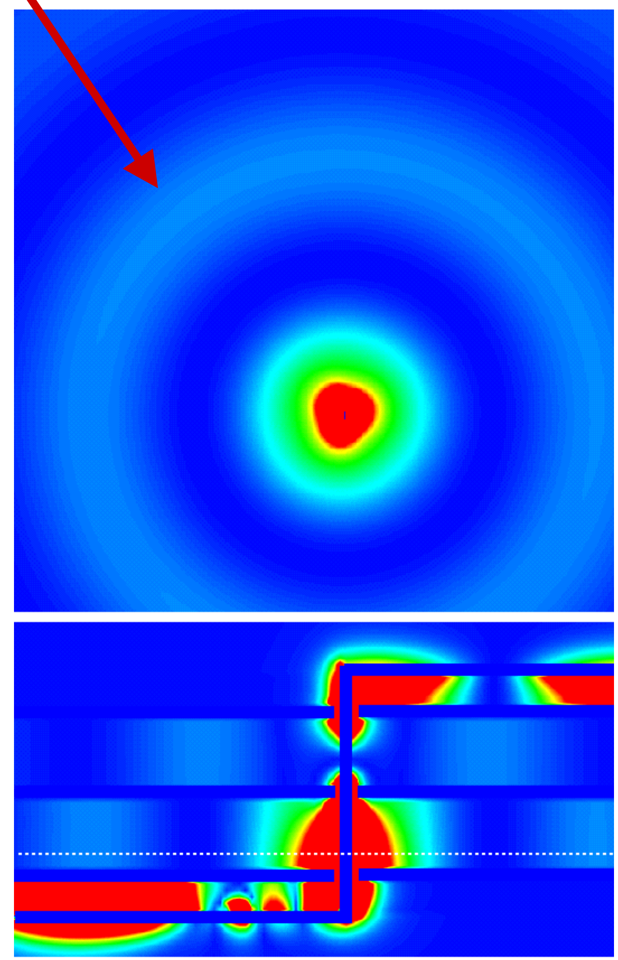
Radial waves from via propagating towards edge.



Microstrip to Microstrip



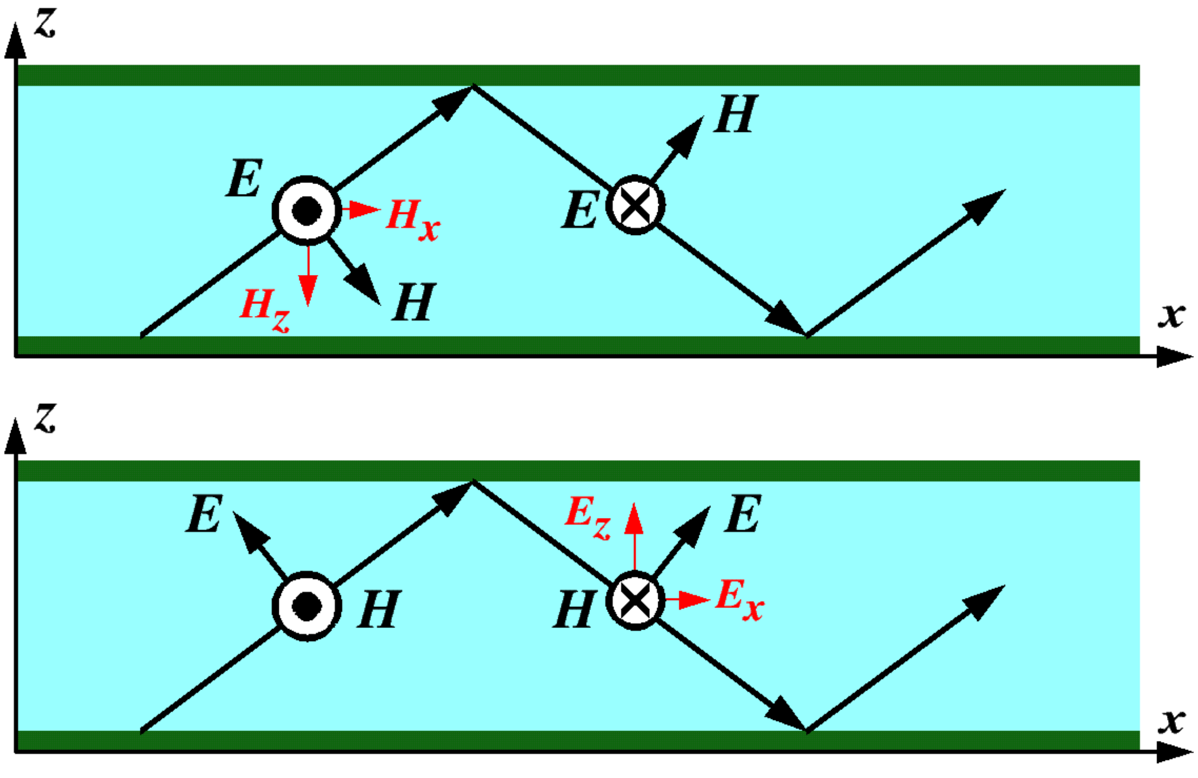
Stripline to Stripline



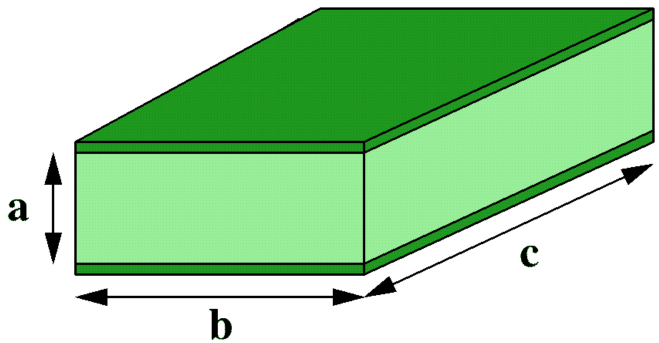
Microstrip to microstrip routed through planes (Worst Offender)

Physics of PCB Structures (TE/TM Modes)

- ***Conductive planes and impedance discontinuities along edges can support TE and TM modes.***
- ***Examples of TE (top) and TM (bottom) mode plane waves propagating (bouncing back and forth) between two (infinite) conductive planes. [8]***



Physics of PCB Structures (TE/TM Resonant Modes)



- ***In finite sized PCBs, ground planes and edges support TE_{mnp} and TM_{mnp} resonant modes at frequencies, f_c.***
  - ***m, n, p = modes (0, 1, 2, 3, …)***

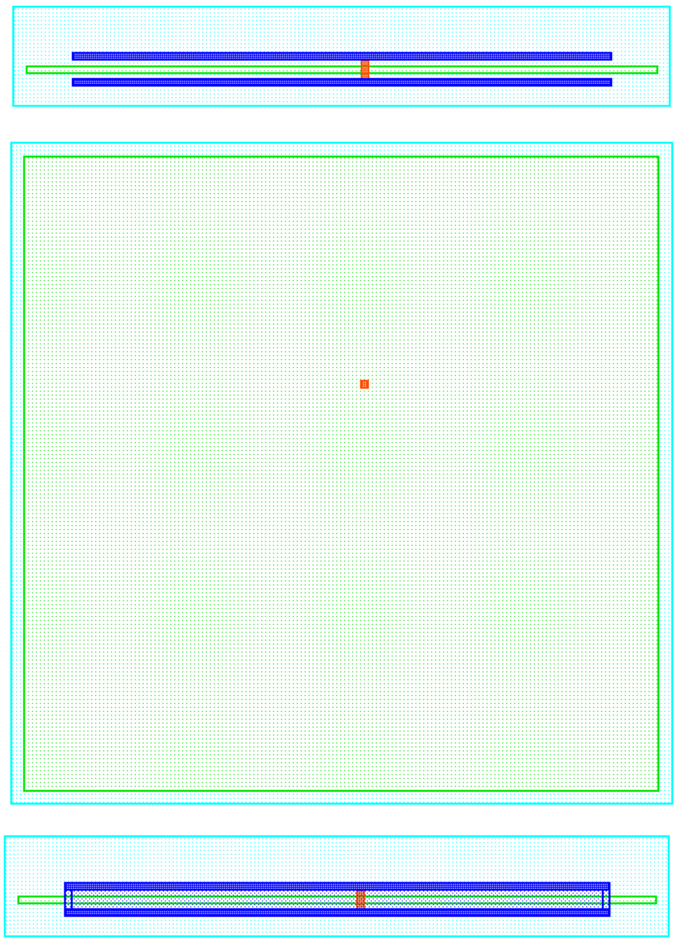
$$f_c(m,n,p)=\frac{1}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m}{a}\right)^2+\left(\frac{n}{b}\right)^2+\left(\frac{p}{c}\right)^2}$$

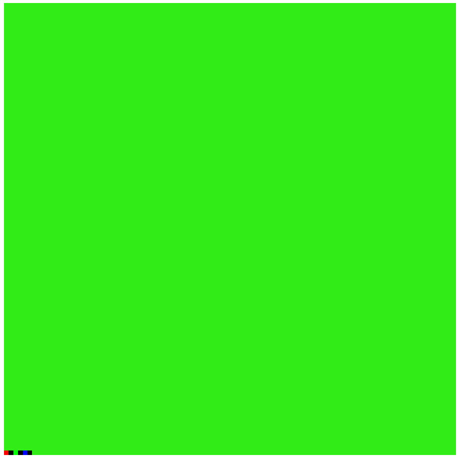
- ***For a 12” x 12” PCB constructed with FR4 dielectric (ε_r = 4.5).***

$$f_c(0,1,1)=\frac{1}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{0}{0.010''}\right)^2+\left(\frac{1}{12''}\right)^2+\left(\frac{1}{12}\right)^2}=217\text{ MHz}$$

Physics of PCB Structures (TE/TM Resonant Modes)

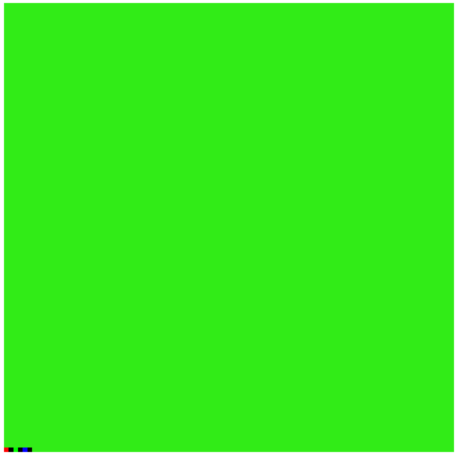
- ***Example of a double sided printed circuit board excited by a via.***





Edges left open (animation)

To start animation place mouse over animation region and click left mouse key once.



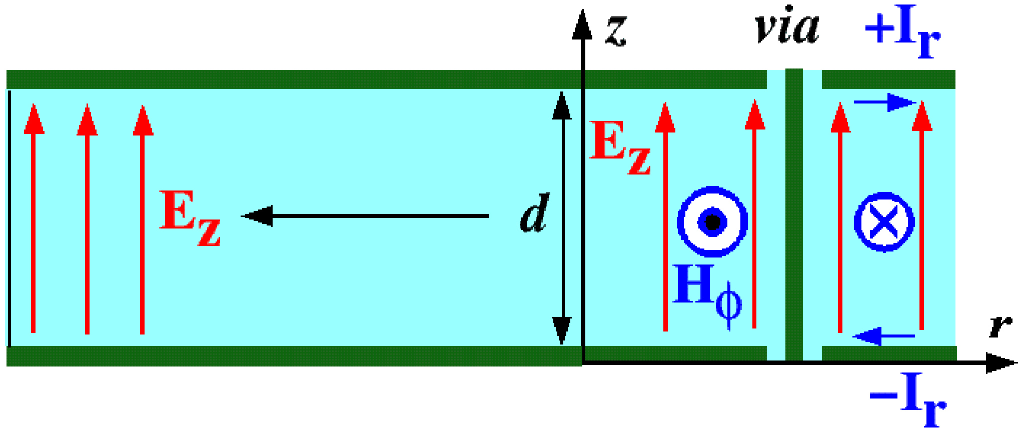
Edges shorted (via fencing) (animation)

- ***Edge treatments impact radiation and resonance amplitudes.***

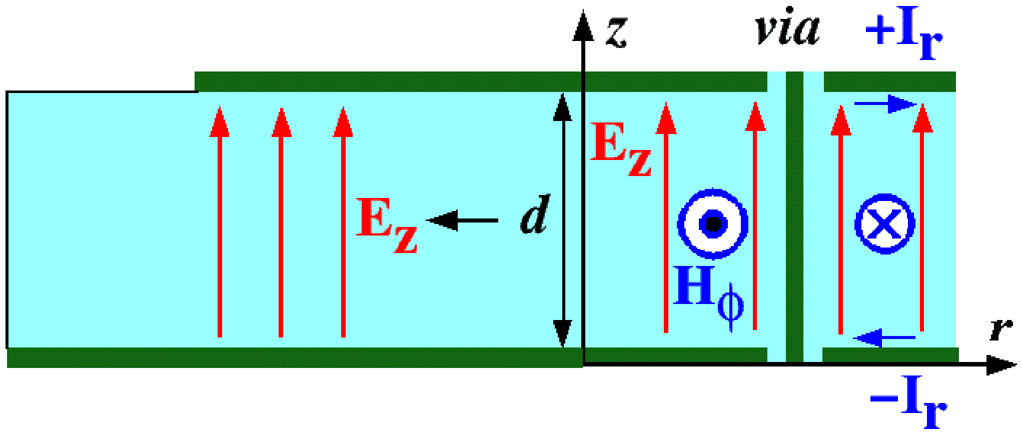
Physics of PCB Structures (Edge Effects)

- *Open edges behave like equivalent magnetic current sources. [12]*

Looks like a cross-section of a "Slot Antenna"



Looks like a cross-section of a "Patch Antenna".



- *Edge treatments impact radiation and resonance amplitudes.*

Physics of PCBs (Summary)

- ***Currents on vias (e.g. structures normal to power and ground planes) are the dominant exitation mechanism.***

- ***Propagation towards edges of radial electromagnetic waves are the dominant propagation mode.***

- ***If the edges are left open can have significant radiation (same physical mechanism used in slot and path antennas).***

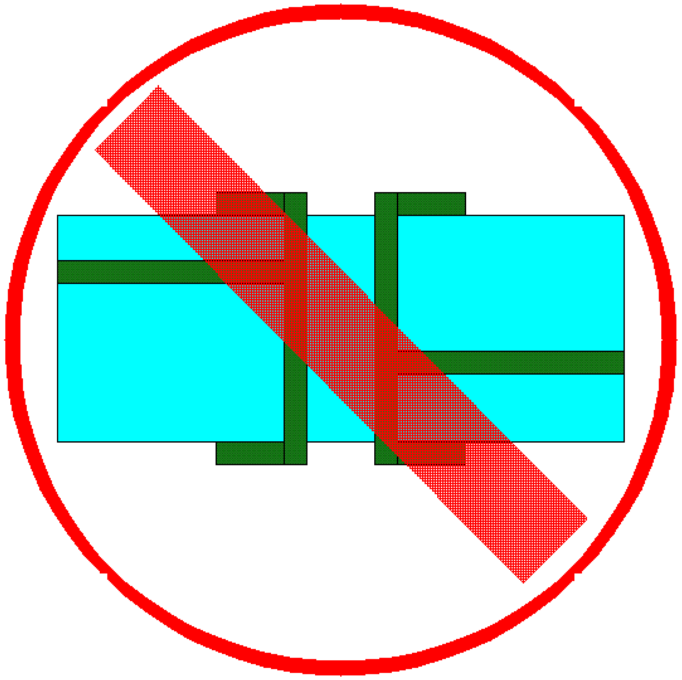
- ***If edges are shorted (via fences) PCB behaves like a resonant cavity.***

Radiation from Edge Effects in Printed Circuit Boards (PCBs)

- ***Motivation***
- ***Problem definition***
- ***Problem setup***
- ***Physics of PCB propagation modes***
- ***Physics of PCB edge effects***

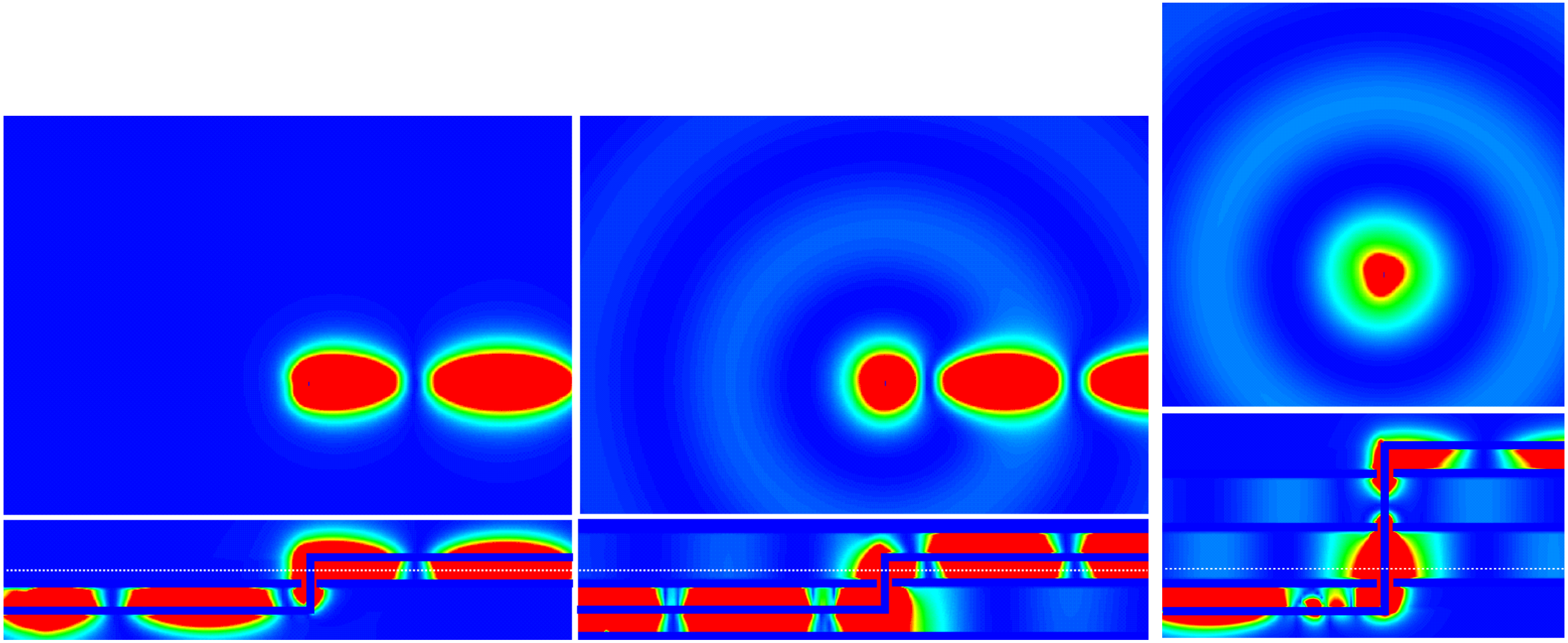
- ***Minimizing radiation from PCB edges***

- ***EMC Rule #1: Always work on the source first.***
  - ***Don’t launch radial TEM modes.***
  - ***Eliminate vias.***
  - ***If eliminate all vias, then do not have a problem.***
  - ***Only use single sided boards without plated through holes and surface mount components!!***



First Rule ofThumb

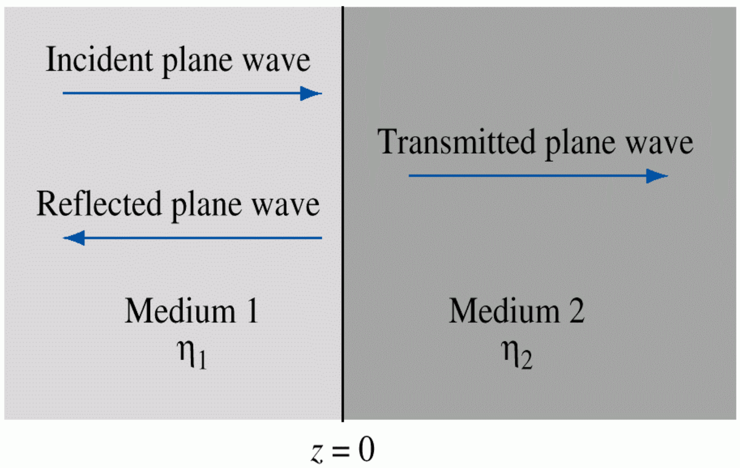
- ***More practical to eliminate unnecessary vias.***
  - ***Use layout/EMC expert system algorithms that minimize # of vias.***
  - ***Use blind vias.***
  - ***Route between "adjacent" layers whenever possible (e.g. don't pass through two planes).***
  - ***Keep high speed signals on one layer (don't move from layer to layer).***



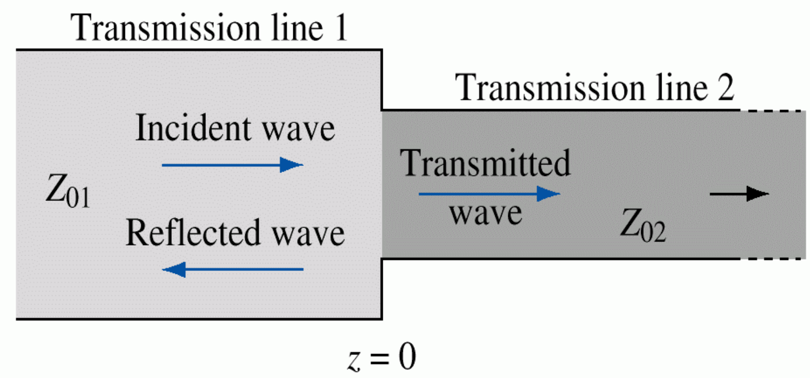
Second Rule of Thumb

- ***EMC Rule #2: If you can't fight them, join them.***
  - ***Fight fire with fire.***
  - ***Add more vias.***
  - ***Add lots and lots of vias!!***

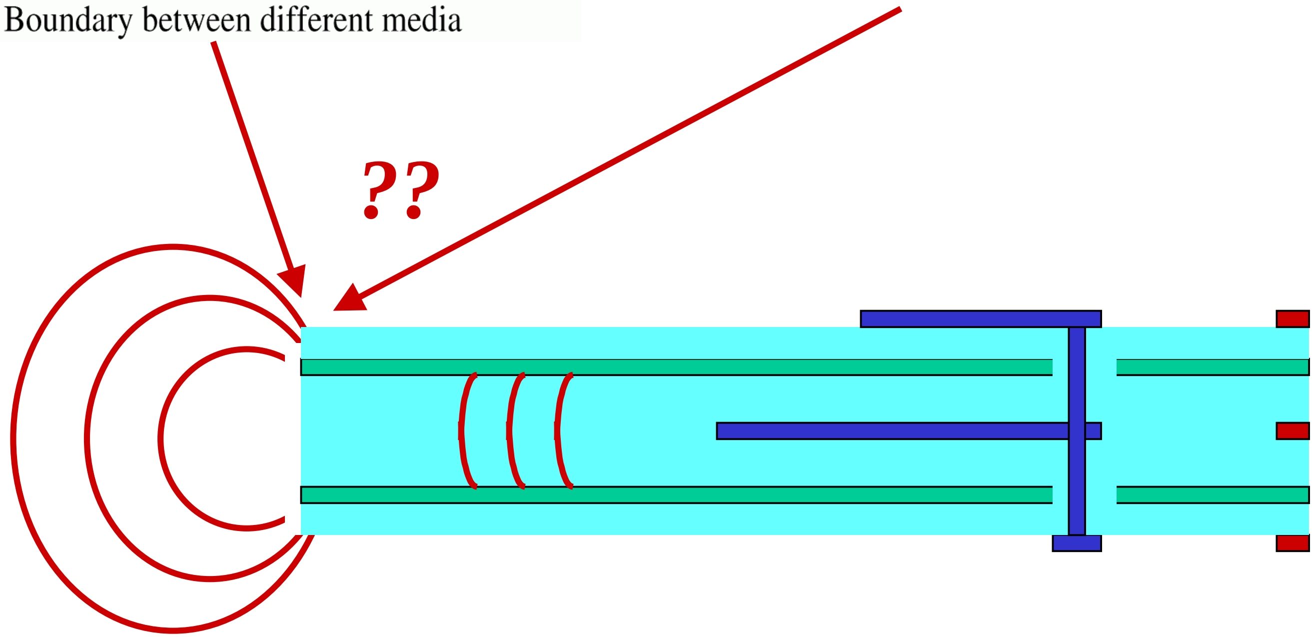
Transmission Line Terminations



(b) Boundary between different media

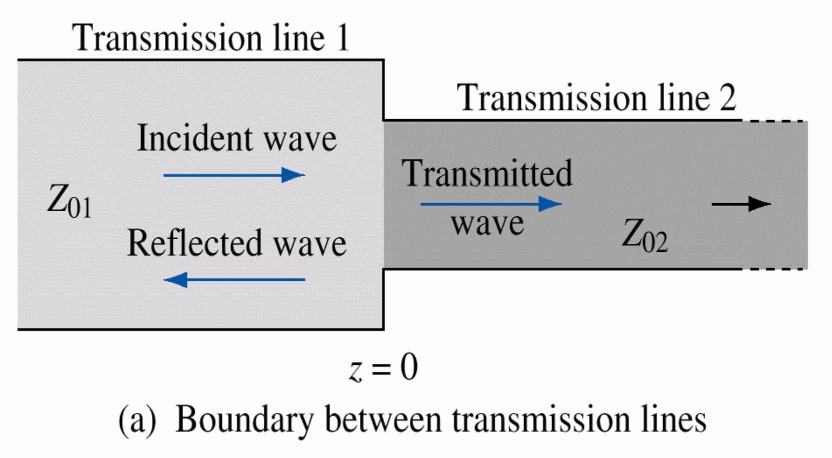


(a) Boundary between transmission lines

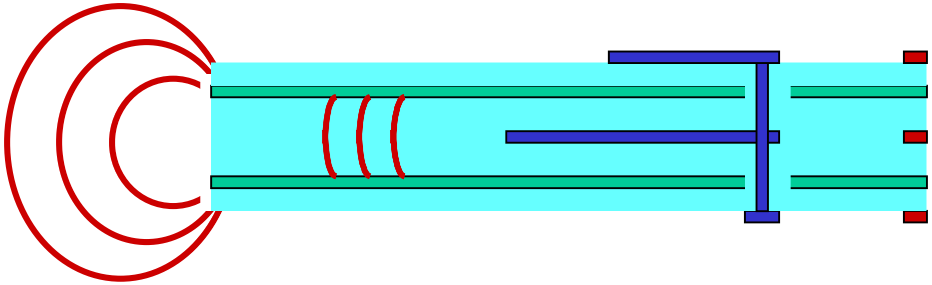


Figures from [12]

Transmission Line Terminations



(a) Boundary between transmission lines

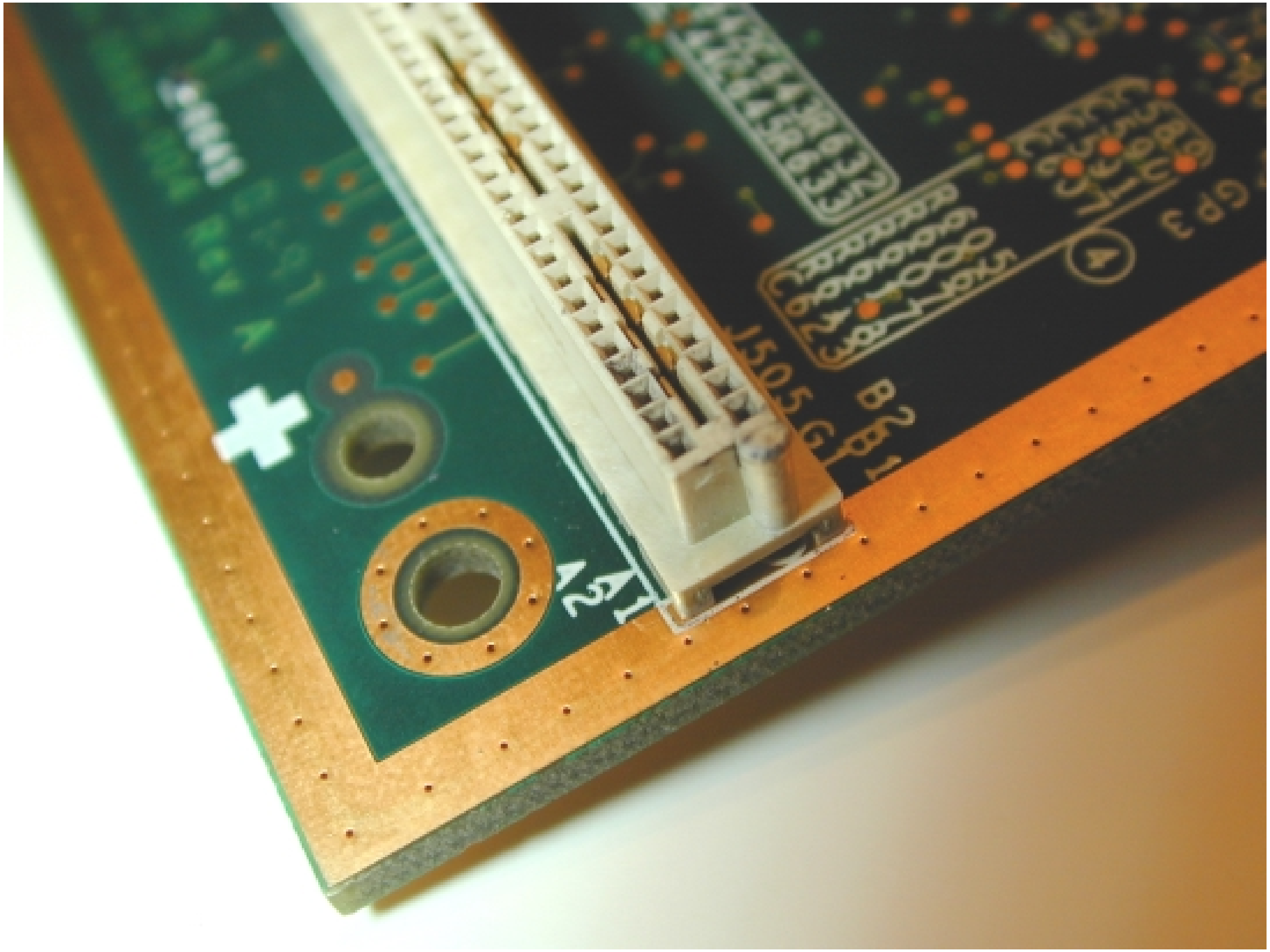


$$\Gamma_{\text{plane wave}} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \qquad \Gamma_{\text{transmission line}} = \frac{Z_{02} - Z_{01}}{Z_{02} + Z_{01}}$$

- ***Goal is to minimize transmission.***
- ***One way to do this is to maximize reflections.***
- ***Increase the impedance mismatch.*** $|\Gamma_{max}| = 1$.
- ***A maximum mismatch occurs with shorts and opens.***
- ***Can't get any more "open" than what we already have. *****
- ***Shorts looks like the only "other" feasible option.***

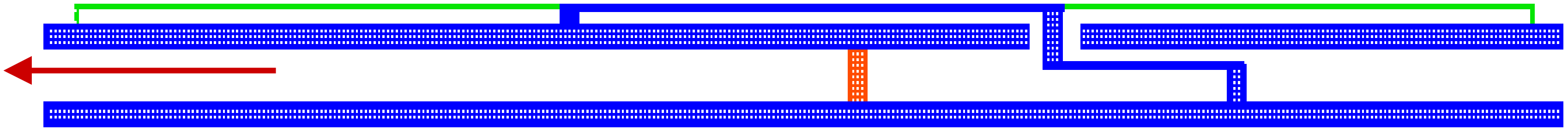
***** Not totally true.***

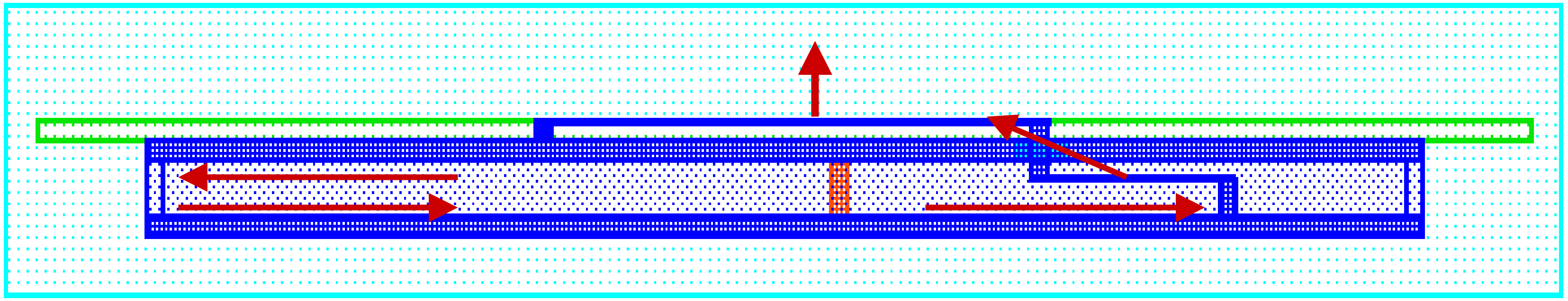
Transmission Line Terminations



What Bounces Back Finds Another Way Out

- ***Principle of Reciprocity***
  - ***Structures that radiate efficiently are also efficient receptors.***





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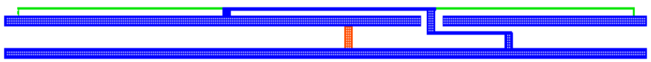
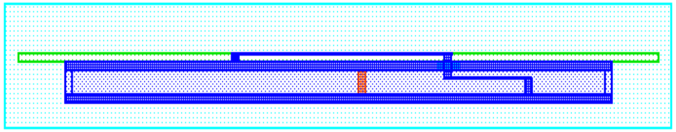
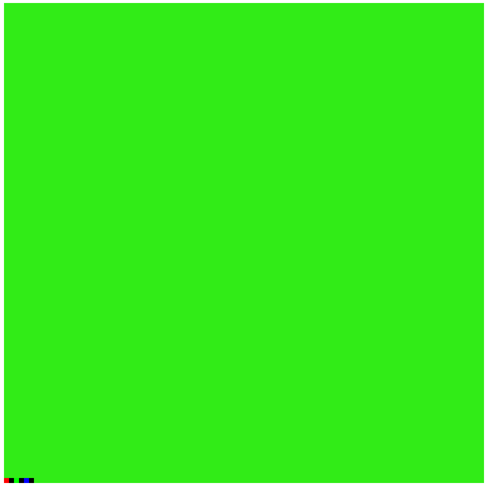


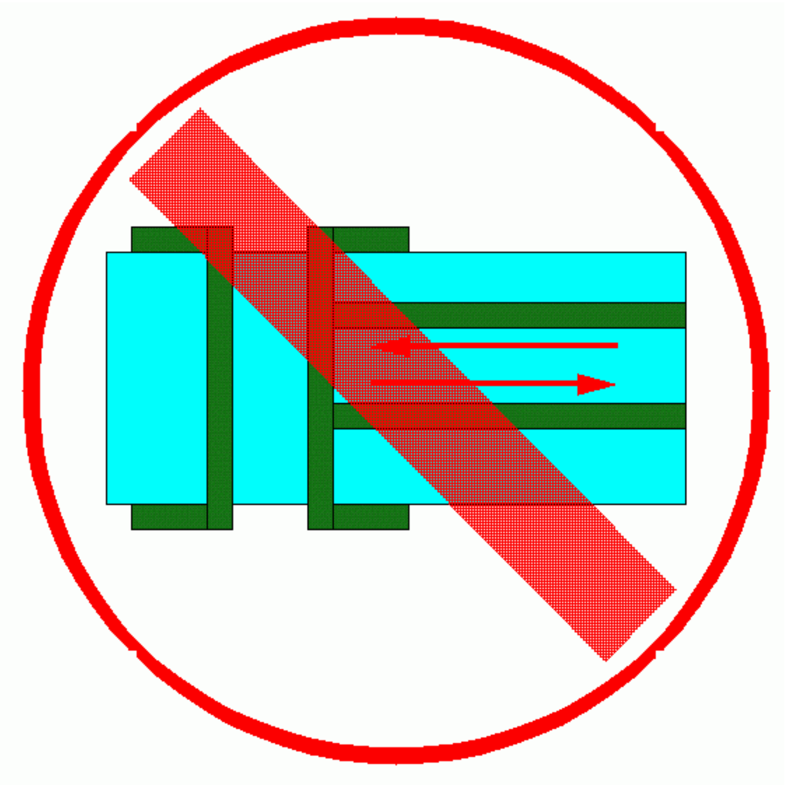


Animation



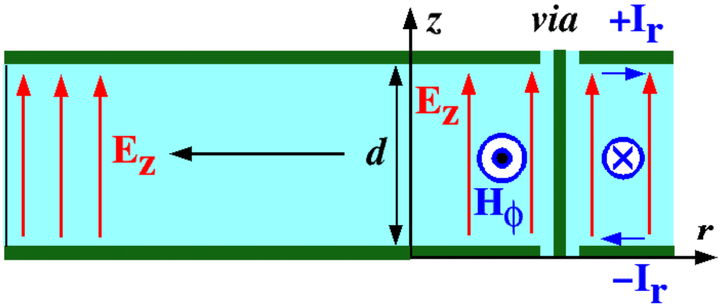
Animation

- ***EMC Rule #3: Eliminate (minimize) Resonances.***
  - ***Don't short out the edges (no fences).***

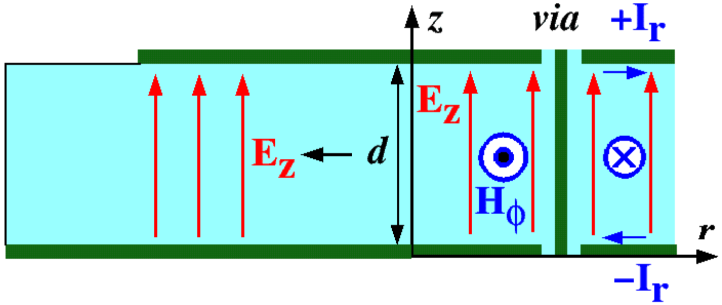


- ***EMC Rule #3: Eliminate (minimize) Resonances.***
  - *Structure the edge so it provides a smooth transition for electromagnetic waves to transition into the outside world.*
  - *Minimize reflections back into the PCB.*

If a "Slot Antenna" structure does not provide a smooth enough transition….



… make it look more like a "Patch Antenna" structure.



IEEE Std 145-1993: Antenna: That part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves.

Third Rule of Thumb

- ***EMC Rule #3: Eliminate (minimize) Resonances.***
  - ***The 20H rule provides a smooth transition.***
  - ***Move back one of the planes by a distance 20 times the separation height between the planes.***
  - ***For 0.010" separation, use 0.2".***
    For double sided PCB (0.060"), use 1.2".

    Should not route traces over "pullback region".

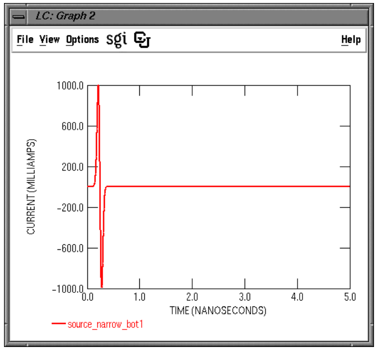
      For a 6" x 6" double sided board reduces useable area by:
      6 x 6 = 36 in^{2}.
      (6-1.2-1.2) x (6-1.2-1.2)= 3.6 x 3.6 = 13 in^{2}.
      36/13=2.8 times

Sigh!!

- ***Does it work?***

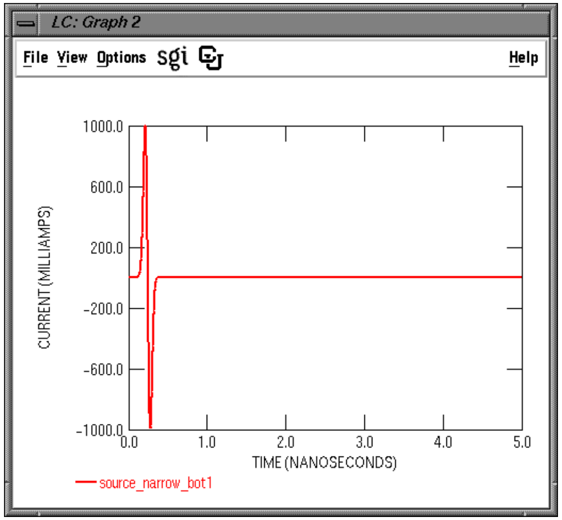
	No 20H	***With 20H***
Side View		
TopView		
Side View		
TopView		
	Animations	***Animations***

1 GHz Sinusoidal

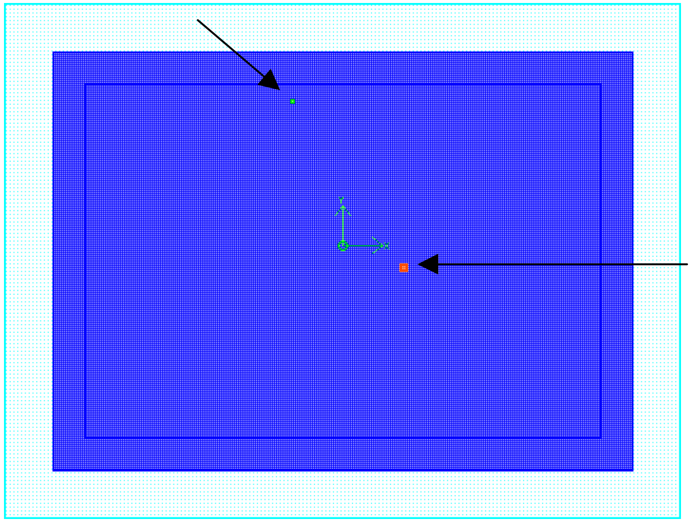


Gaussian Derivative

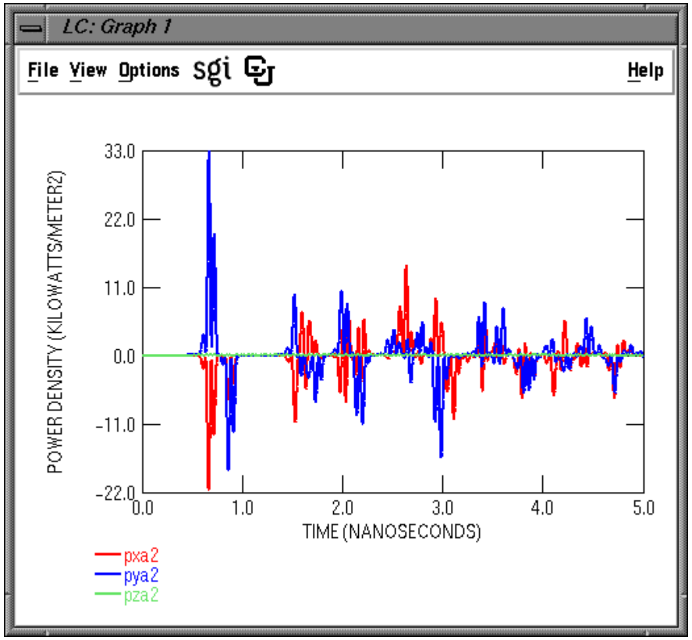
- ***Does it work?***



Probes

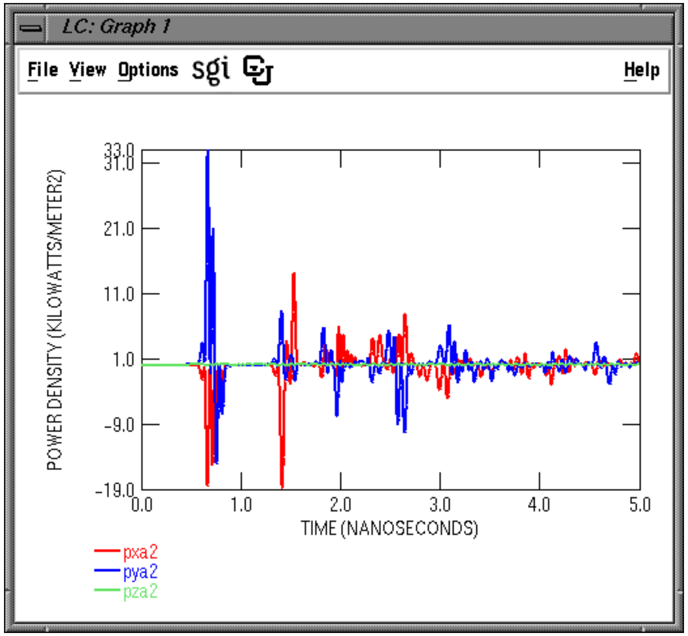


Source



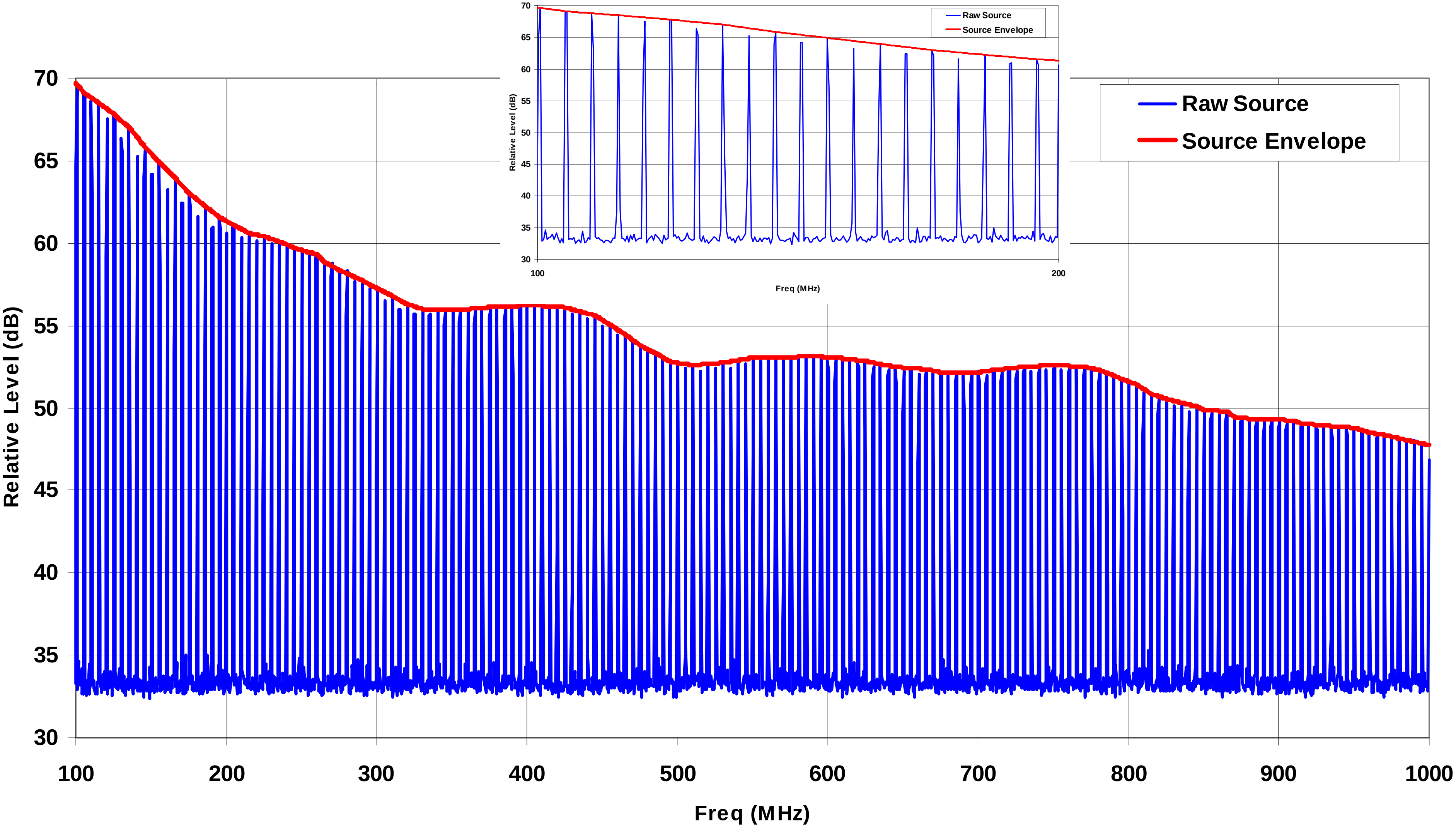
No 20H

With 20H



See some resonance damping….

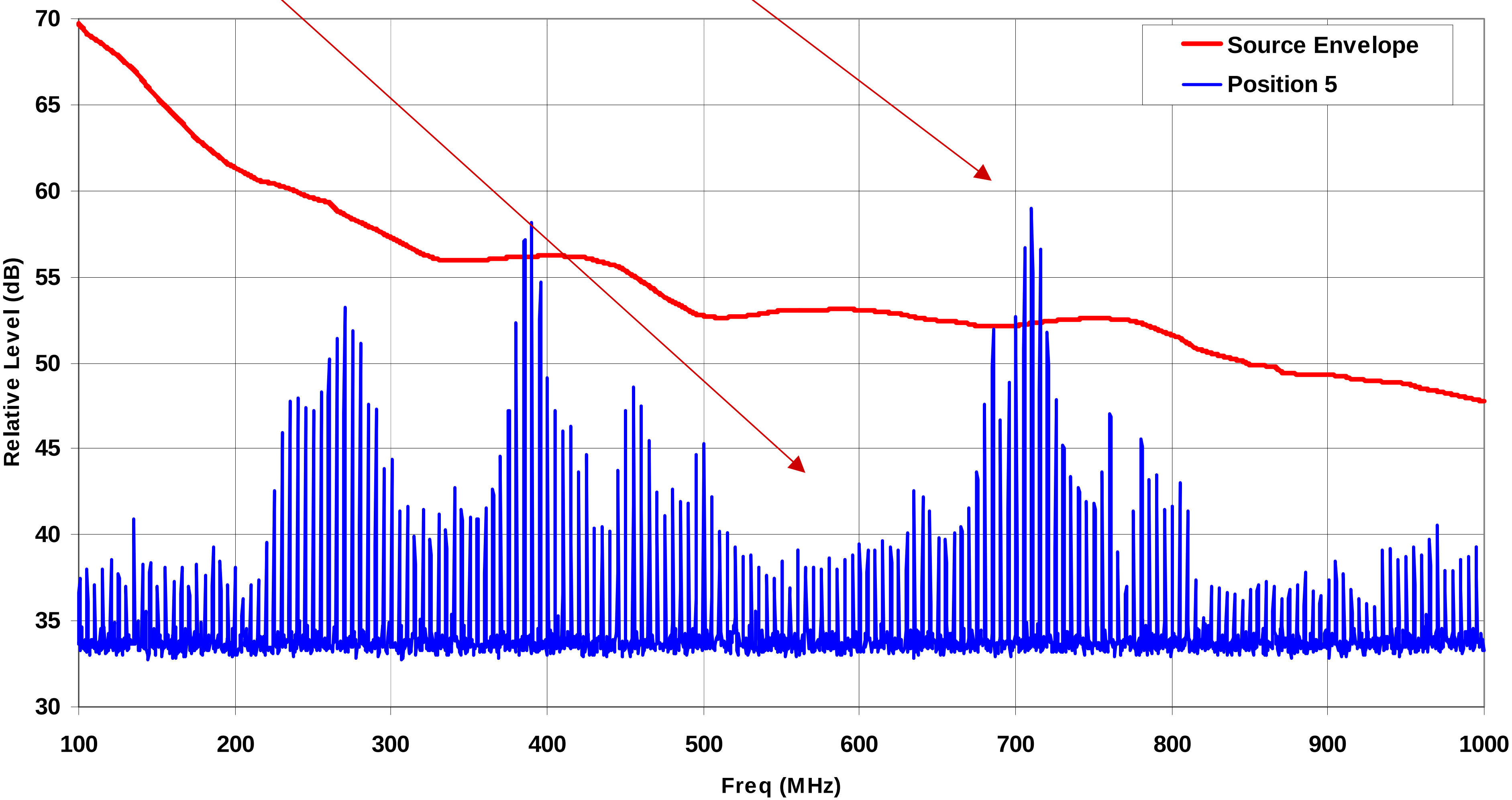
- ***Q: Where does the energy go?***
  - ***No apparent dummy loads to convert it into harmless heat.***



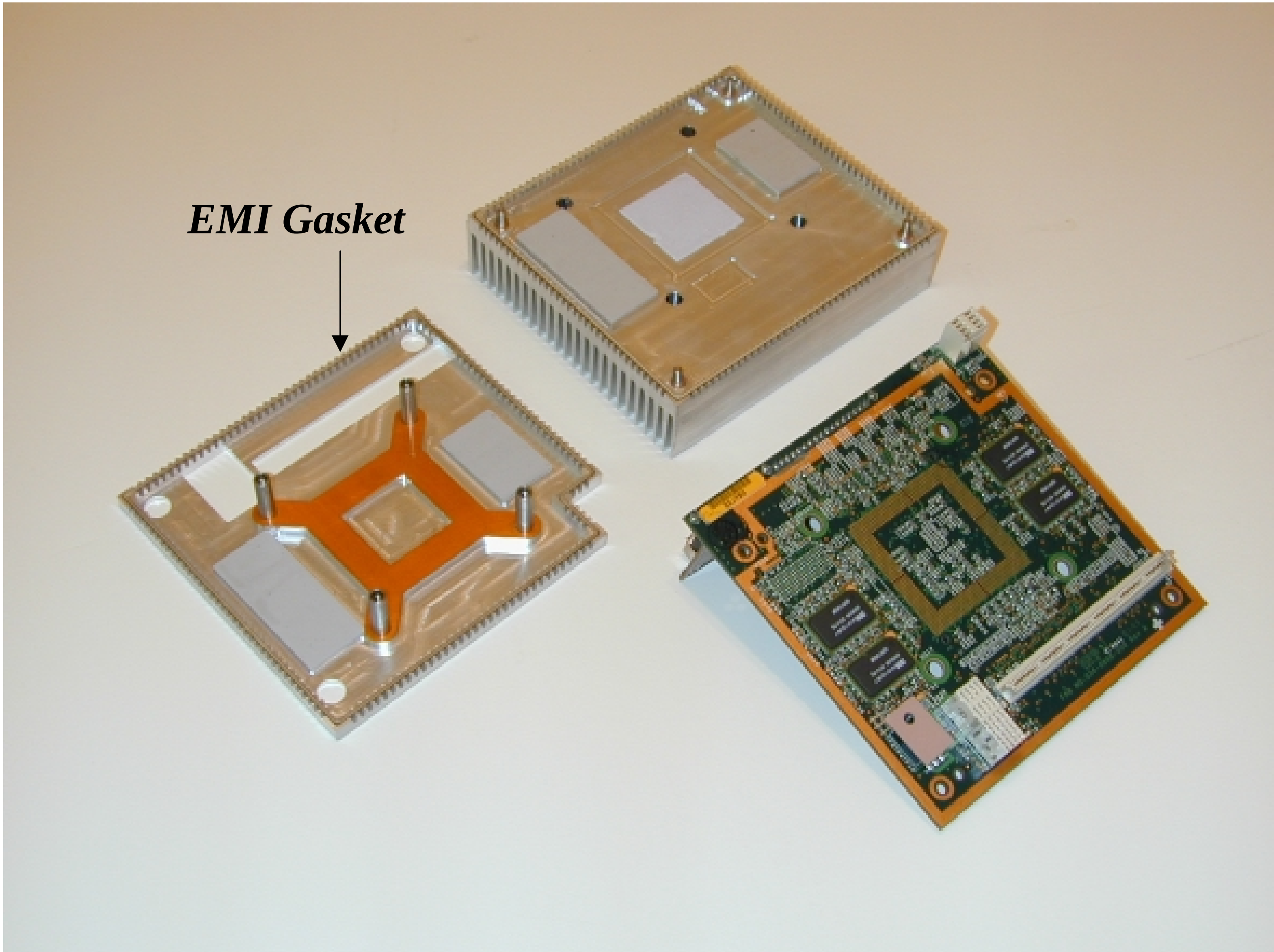
- *A: Goes and excites the enclosure cavity!*

If spectrum of energy is here – good shape!

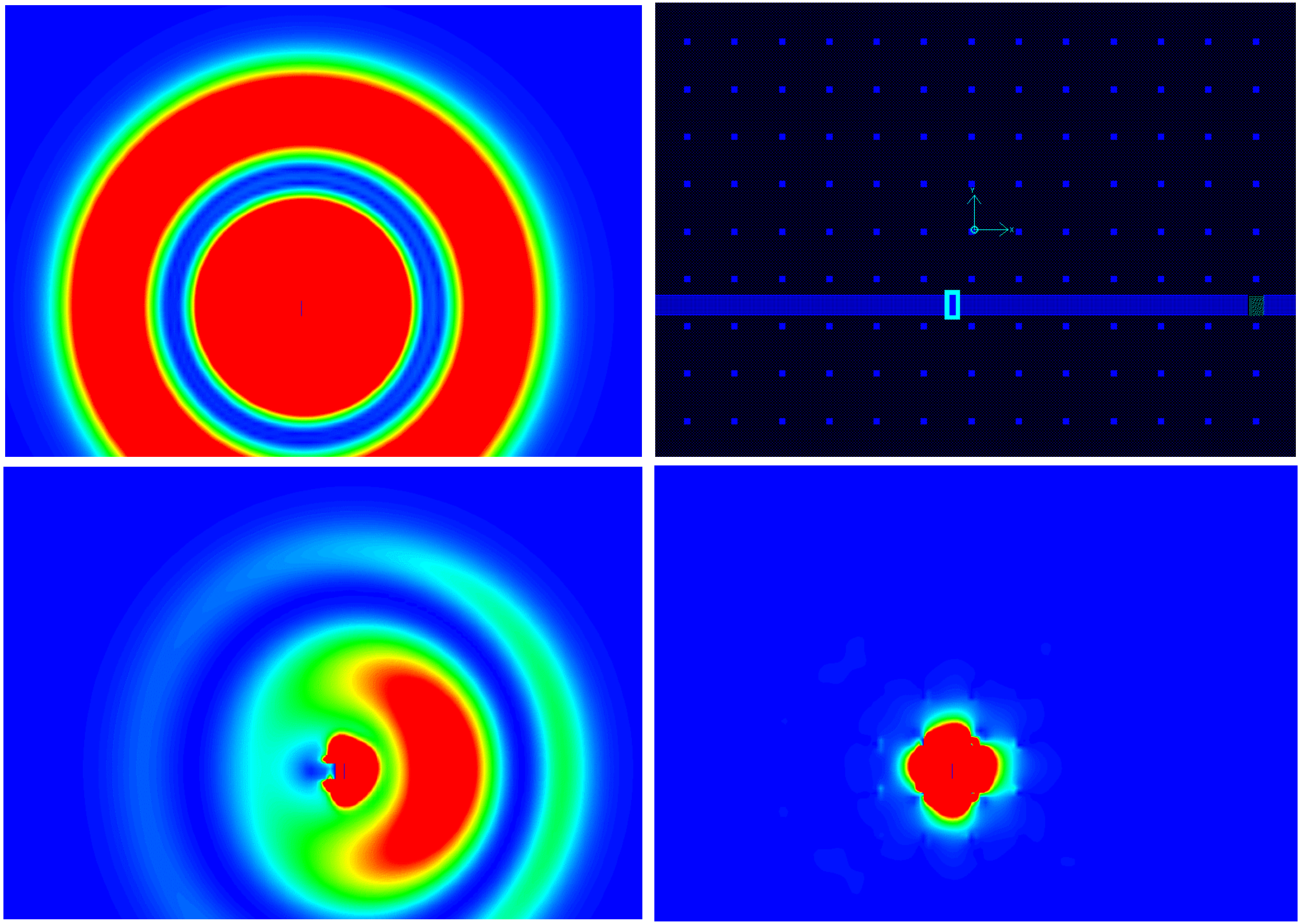
If spectrum of energy is there – may have problems!



Closing Comments (Fences + Vias)



Closing Comments (Adjacent gnd/sig Vias)



Lots of vias seem to hold their own against Fences and 20H

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