ECE414/514
Electronics Packaging
Spring 2012 Lecture 7
Electrical E
Electromagnetism & Modeling

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Lecture topics

- SPICE review
- Worked transmission line example
- Electromagnetic waves on lines
- Electromagnetic modeling

Objectives

- Familiarize the student with SPICE
  - Note: Microsim (OrCad) PSPICE used below
  - LT-Spice available in the labs (Dept standard)
  - Use any equivalent program you choose
- Provide the skills to work simple examples
- Introduce basic concepts of TE, TM, and TEM waves on lines
- Present selected results of advanced electromagnetic modeling

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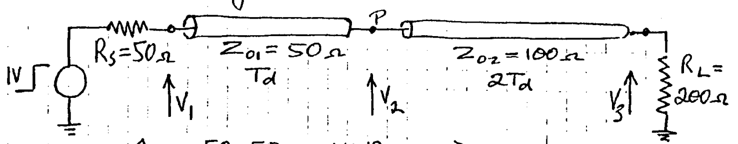
1. Getting started with SPICE

- Download any free limited capability version of SPICE
  - e.g. www.5spice.com or www.winportal.com or www.beigebag.com or www.orcad.com (for OrCAD PCB Designer Lite DVD or download), etc
  - Or download LT-Spice, www.linear.com/designtools/software/
  - or find LTSpice in the labs
- Install it according to instructions and normal procedures
  - See Hambley “Electrical Engineering” (Pearson/Prentice-Hall) for OrCAD tutorial (applies to others) or any of many SPICE tutorial books
- In your Program library, find “Schematics.”
  - Explore the window, e.g. the zoom, and position controls bottom and right, etc.

Example

- We will use the “bounce diagram” example from the reflections lecture (Electrical C)
- Step input to 50 ohm line Td delay, then into a 100 ohm line of 2Td delay, terminated in 200 ohms.
- We will use only the Edit, Draw, and Analysis menu boxes, and the V probe below.

(2) Two-segment line



$\Gamma_{VS} = \frac{50-50}{50+50} = 0$

wave →

$\Gamma_{VP} = \frac{100-50}{100+50} = 1/3$

$\Gamma_{VL} = \frac{200-100}{200+100} = \frac{1}{3}$

← wave

$\Gamma'_{VP} = \frac{50-100}{50+100} = -1/3$

- Draw circuit: Go to Draw, then to Place Part
  - There are different ways to get and place parts.
  - The easiest is to use the menu at the top right, but this contains parts you have used before, so starting off, you may need to go to Get New Part, OR Libraries (usually analog.slb here).
  - If we want a resistor, type R* in the box.
  - A range of components is selected. Click on R.
  - Use Place, or Place and Close, or Click on R in the top right menu box. All bring you to:---->
  - A symbol of the resistor is now attached to the cursor.
  - Drag it to the right place, and left click
  - It will be positioned, but another symbol is now being dragged, for positioning another.
  - We only want one R, so right click to close.

- Rotate
    - The resistor is horizontal; we want it vertical
    - We have to “select” the device
    - Draw a box around it with the left button
    - Color changes if successful
    - Go to Edit and select Rotate
    - Click away from device to de-select
    - Can drag device when “selected”
- Transmission lines, ground & source
    - Repeat for the lines (T), but now we want two
    - Repeat to place a ground (GND_EARTH)
    - You need THREE grounds for this circuit
    - At the load, at the source, AND where the “common” line connections meet
- Use Vpulse for the source

- Wiring
    - In Draw, select Wire
    - This gives you a pencil to draw connections
    - Move the pencil to close to one wire, and click
    - Move to next, and click again
    - Right click to turn the pencil off
- Attributes
    - Select the component you want to change from default values (sometimes tricky)
    - We specify component values with the Attributes button
    - Select the parameter to change
    - Type in the value
    - Save attribute
    - Do next

- Values
    - R=200
    - T1 (at source): Z0=50 TD=10n
    - T2 (to load): Z0=100 TD=20n
    - Vpulse: V1=0 V2=1 (or anything)
    - TD=0 TR=0.1n PW=500n
    - The times are to make the line delay much greater than the input step risetime, and to get the falling edge out of the times of interest
- Voltage probes
    - Use the mouse to click and drag the voltage probes from the menu bar to the points we want:
        - Source voltage
        - Mid-line voltage
        - Load resistor voltage
    - We want all wrt ground, so no need to insert ref points

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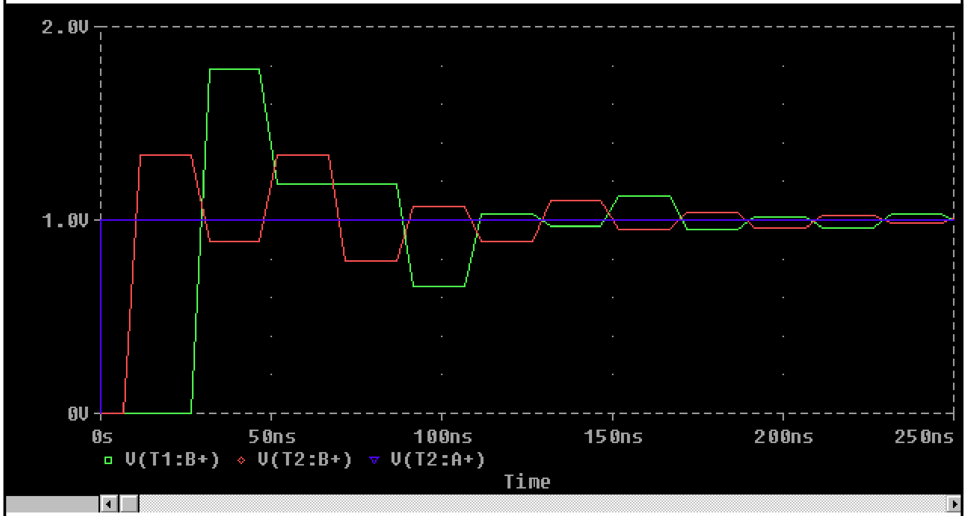
- Analysis
    - In the Analysis box:
        - Do Probe Set Up (Auto-run Probe)
        - In Set Up, set “Transient”
    - Hit Simulate (in Analysis box, or the icon to the left.)
    - Will show errors, or analysis run
    - Close box; Probe will come up
    - Probe may show no plots ---- no problem!
- Probe plots
    - Under Plot:
        - Choose the X-axis range user defined (say 250ns=0.2microsecs)
    - Under Trace:
        - Add trace
        - Select from the list (of all parameters stored from the transient analysis)
        - Convention is V(T1,A+) means input (A) “central” conductor of T1

Tools

- Next slide shows output
- Copy to Clipboard if necessary, using Tools

Probe output

Copy to Clipboard if necessary, using Tools



Compare previous results

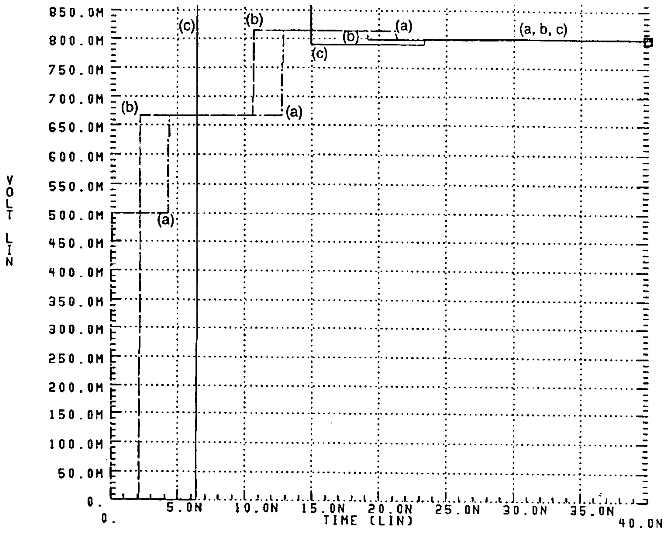


Figure 6.16 Voltage waveforms at (a) source, (b) junction of the two transmission line segments and (c) far end. See Fig. 6.15.

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2. Electromagnetic Waves

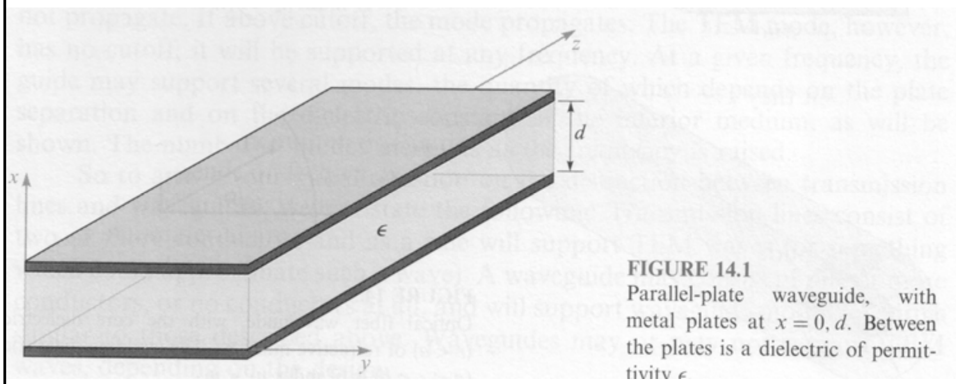
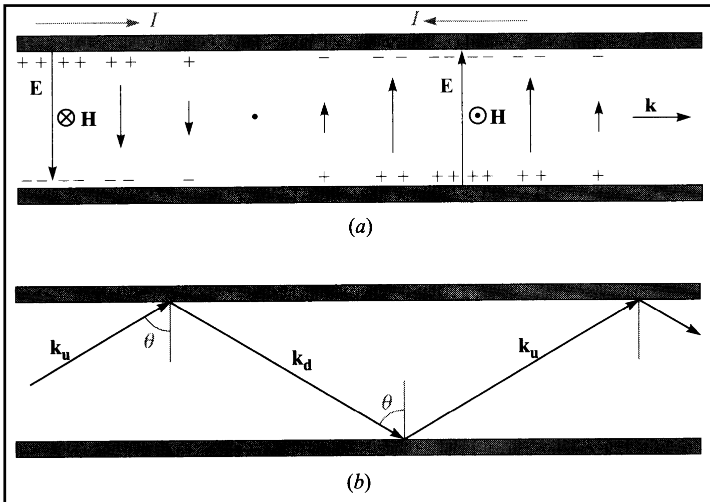


FIGURE 14.1
Parallel-plate waveguide, with metal plates at $x = 0, d$. Between the plates is a dielectric of permittivity ϵ.

Parallel Plate Waveguides



TEM wave

TE & TM waves

FIGURE 14.6
(*a*) Electric and magnetic fields of a TEM (transmission line) mode in a parallel-plate waveguide, forming a plane wave that propagates down the guide axis. (*b*) Plane waves that reflect from the conducting walls can produce a waveguide mode that is no longer TEM.

Parallel Plate Waveguides

As for free space wave propagation :

$$\nabla^2 E_s = -k^2 E_s \quad \text{where } k = n\omega/c = \frac{\omega}{(c/n)} = \frac{2\pi n}{\lambda} = \frac{2\pi}{(\lambda/n)}$$

Assume (TE) s-polarized waves
n = refractive index

For transverse electric waves : $E_x = 0$ $E_y \neq 0$ $E_z = 0$

$$\text{so} \quad \frac{\partial^2 E_{ys}}{\partial x^2} + \frac{\partial^2 E_{ys}}{\partial y^2} + \frac{\partial^2 E_{ys}}{\partial z^2} + k^2 E_{ys} = 0$$

If waveguide width (y direction) >> thickness (x direction) and assuming propagation in the z direction

$$\frac{\partial^2 E_{ys}}{\partial y^2} = 0$$ and z direction variation of form $\exp -j\beta_m z$

then

$$E_{ys} = E_0 f_m(x) \exp -j\beta_m z$$ for "mode number" m

Substitute $E_{ys} = E_0 f_m(x) \exp -j\beta_m z$

into $\frac{\partial^2 E_{ys}}{\partial x^2} + \frac{\partial^2 E_{ys}}{\partial z^2} + k^2 E_{ys} = 0$

gives $\frac{d^2 f_m(x)}{dx^2} + (k^2 - \beta_m^2) f_m(x) = 0 \Rightarrow \frac{d^2 f_m(x)}{dx^2} + K_m^2 f_m(x) = 0$

where $K_m^2 = k^2 - \beta_m^2$

with general solution $f_m(x) = \cos K_m x + \sin K_m x$

Boundary conditions: $E_y = 0$ at $x = 0, d$ (due to conducting planes)

$\therefore f_m(x) = \sin \frac{m\pi}{d} x$

& $E_{ys} = E_0 \sin\left(\frac{m\pi x}{d}\right) \exp -j\beta_m z$

Transverse Electric (TE) & Transverse Magnetic (TM) Waves

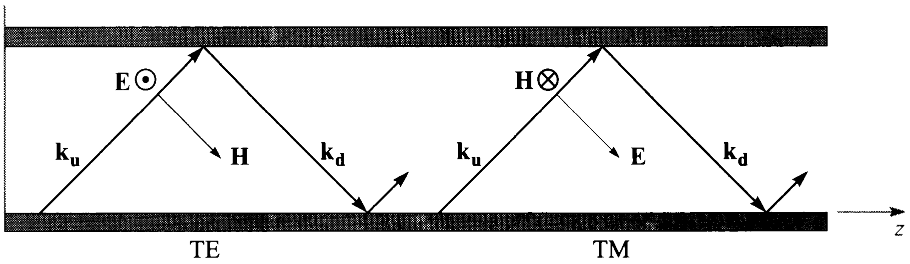
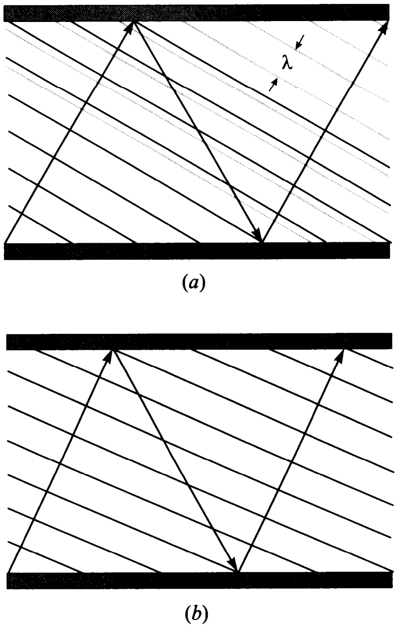


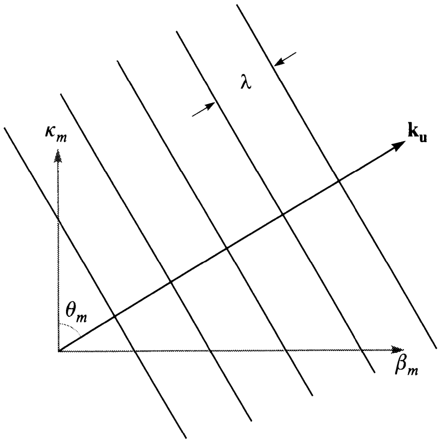
FIGURE 14.7
Plane wave representation of TE and TM modes in a parallel-plate guide.



Waves must be in-phase for propagation,

i.e. integral number of wavelengths between reflections

FIGURE 14.8
(*a*) Plane wave propagation in a parallel-plate guide in which the wave angle is such that the upward-propagating waves are not in phase. (*b*) The wave angle has been adjusted so that upward waves are in phase, resulting in a guided mode.



Relationships between propagation constants

FIGURE 14.9
The components of the upward wavevector are κ_m and β_m, the transverse and axial phase constants. To form the downward wavevector, $\mathbf{k_d}$, the direction of κ_m is reversed.

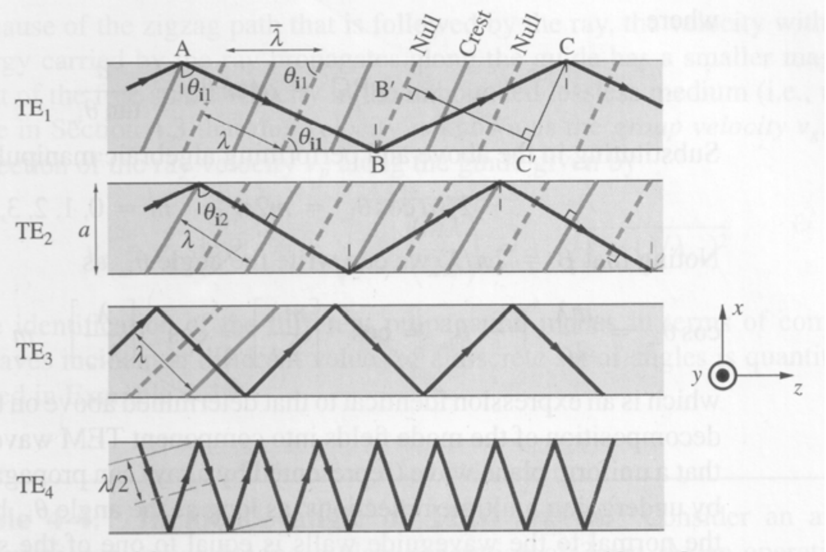


FIGURE 4.9. Representation of propagating waveguide modes as "rays" reflecting between the parallel plates. The dashed lines represent the phase fronts, and the solid lines represent the ray paths.

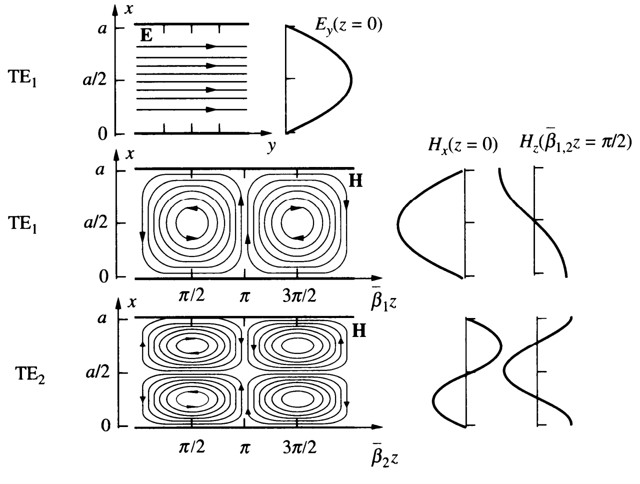


FIGURE 4.2. TE_1 and TE_2 modes. The electric and magnetic field distributions for the TE_1 and the magnetic field distribution for the TE_2 modes in a parallel-plate waveguide. Careful examination of the field structure for the TE_1 mode indicates that the magnetic field lines encircle the electric field lines (i.e., displacement current) in accordance with [4.1*a*] and the right-hand rule. The same is true for the TE_2 mode, although the electric field distribution for this mode is not shown.

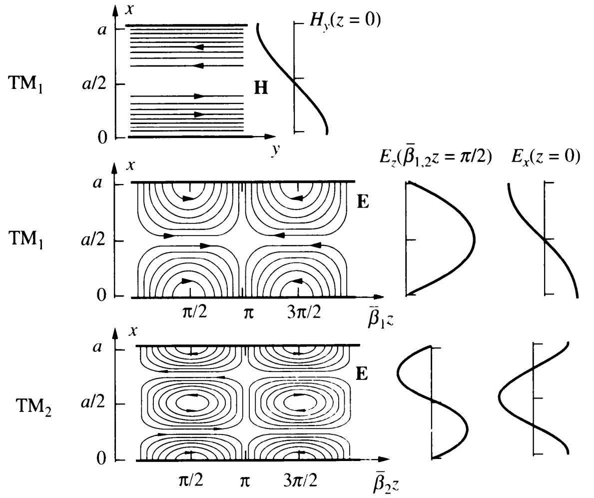


FIGURE 4.3. TM$_1$ and TM$_2$ modes. The electric and magnetic field distributions for the TM$_1$ and TM$_2$ modes in a parallel-plate waveguide. Note that for TM$_1$ the electric field lines encircle the magnetic field lines (Faraday's law) in accordance with [4.1*c*]. The same is true for TM$_2$, although the magnetic field distribution for TM$_2$ is not shown.

TEM Wave
(Coaxial cable supports TEM transmission)

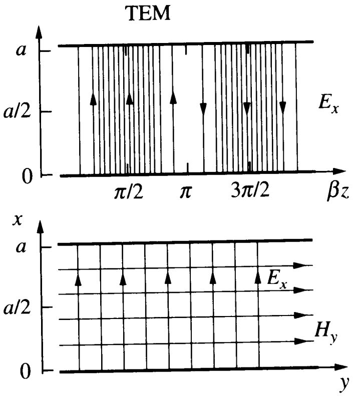


FIGURE 4.4. TEM mode. Electric and magnetic fields between parallel planes for the TEM (TM$_0$) mode. Only electric field lines are shown in the top panel; the magnetic field lines are out of (or into) the page.

2 TEMs → TE_m

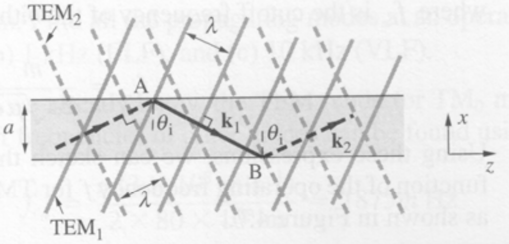


FIGURE 4.8. Two TEM waves forming a TE_m wave in a parallel-plate waveguide. Waveguide modes represented as a superposition of two TEM waves. TEM_1 propagates in the direction $\hat{\mathbf{k}}_1 = \mathbf{k}_1/|\mathbf{k}_1|$ with surfaces of constant phase (i.e., phase fronts) indicated by solid lines. TEM_2 propagates in the direction $\hat{\mathbf{k}}_2 = \mathbf{k}_2/|\mathbf{k}_2|$, with phase fronts shown in dashed lines. The same type of decomposition, and thus the same picture shown here, is also valid for the TM_m modes.

TE and TM Cut-off Frequency

TE (or TM–"p-polarization") cut-off frequency for mode m

$$\omega_{c_m} = \frac{m\pi c}{nd} \quad \text{i.e. when } d = \frac{m}{n}\cdot\frac{\lambda_{cm}}{2}$$

Total phase shift $x=0$ to $x=d$ to $x=0$ $\Rightarrow 2K_m d = 2m\pi$ for propagation (since reflective phase shifts at the conductor surfaces $= 2\pi$ (TE) or $= 0$ (TM))

i.e. $K_m = m\pi/d$ for propagation

$$= k\cos\theta_m \quad \text{i.e. } \theta_m = \cos^{-1}\frac{m\pi}{kd} = \cos^{-1}\frac{m\pi c}{\omega nd} = \cos^{-1}\frac{m\lambda}{2nd}$$

Propagation constant $\beta_m = \sqrt{k^2 - K_m^2} = k\sqrt{1-\left(\frac{m\pi}{kd}\right)^2}$

$$= k\sqrt{1-\left(\frac{m\pi c}{\omega nd}\right)^2}$$

Cut off when $\beta_m = 0$ i.e. when $\omega_{cm} = \frac{m\pi c}{nd}$

so write $\beta_m = \frac{n\omega}{c}\sqrt{1-\left(\frac{\omega_{cm}}{\omega}\right)^2}$ → real (propagation) for $\omega > \omega_{cm}$

$= \frac{2\pi n}{\lambda}\sqrt{1-\left(\frac{\lambda}{\lambda_{cm}}\right)^2}$ → imaginary for $\omega < \omega_{cm}$ (evanescent wave)

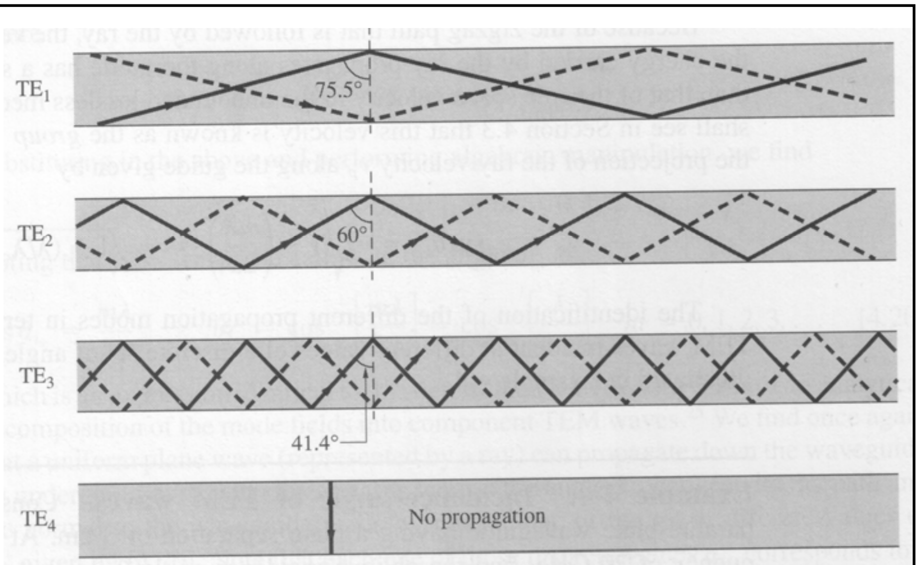


FIGURE 4.10. Incidence angle of component TEM waves. Different TE$_m$ modes represented by ray paths propagating inside the parallel-plate waveguide at different angles of incidence θ_{i_m}.

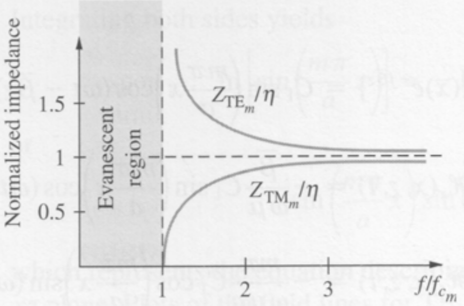


FIGURE 4.12. TE$_m$ and TM$_m$ wave impedances. The frequency dependence of normalized wave impedances (normalized to η) for TE$_m$ and TM$_m$ modes. Note that $\eta = \sqrt{\mu/\epsilon}$ and $f_{c_m} = m/(2a\sqrt{\mu\epsilon})$.

Microstrip transmission line

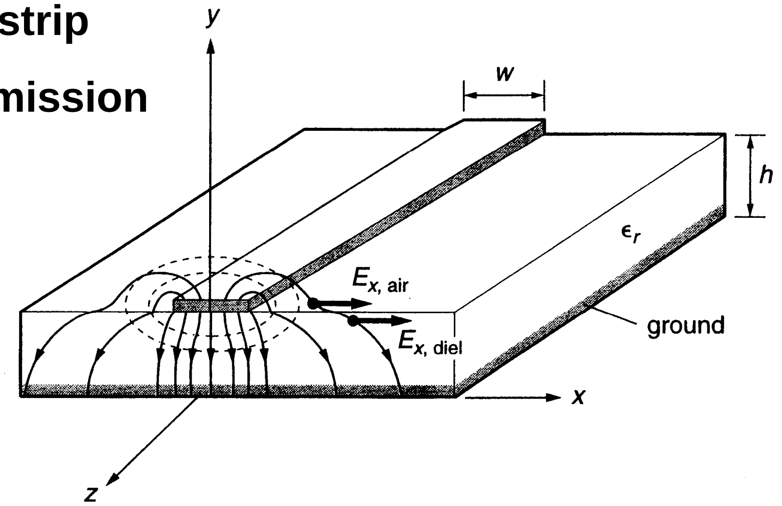


Figure 23.8 Sketch of a microstrip line. The electric field lines are sketched in solid line, and the magnetic field lines in dashed line.

Microstrip

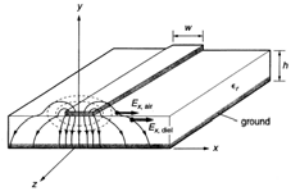


Figure 23.8 Sketch of a microstrip line. The electric field lines are sketched in solid line, and the magnetic field lines in dashed line.

At the boundary $E_{x\text{ diel}} = E_{x\text{ air}}$ and H will be continuous (since no discontinuity in μ), so use

$$\vec{E} = -\mu \frac{\partial}{\partial t}(\nabla \times \vec{H}) \Rightarrow \epsilon_r \frac{\partial H_{z\text{air}}}{\partial y} - \frac{\partial H_{z\text{diel}}}{\partial y} = (\epsilon_r - 1)\frac{\partial H_y}{\partial z}$$

RHS $\neq 0$ ($\epsilon_r > 1$ & $H_y \neq 0$)

$\therefore$ LHS $\neq 0$ & $\therefore H_z \neq 0$ & Similarly show $E_z \neq 0$

$\therefore$ Propagating wave has non-zero H_z & E_z

i.e. must contain TE and TM modes. $\Rightarrow$ "quasi-TEM"

3. Electromagnetic Modeling

(Fang)

FE/FDTD simulations

Pulse transmission

Right-angled bend

Crosstalk (orthogonal lines)

Via effects

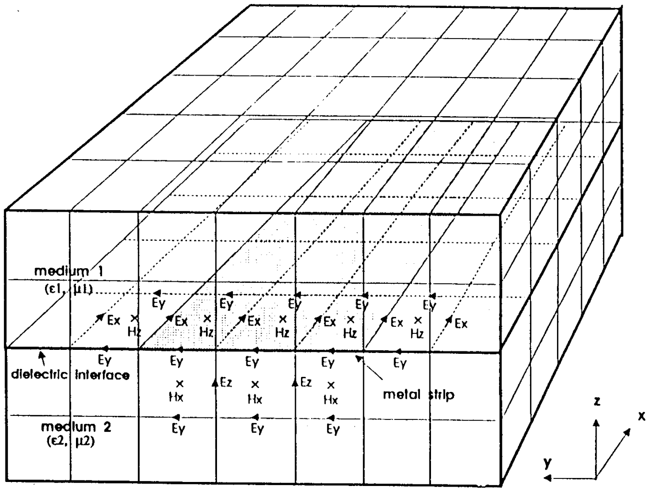
Experimental verification

Capacitor placement

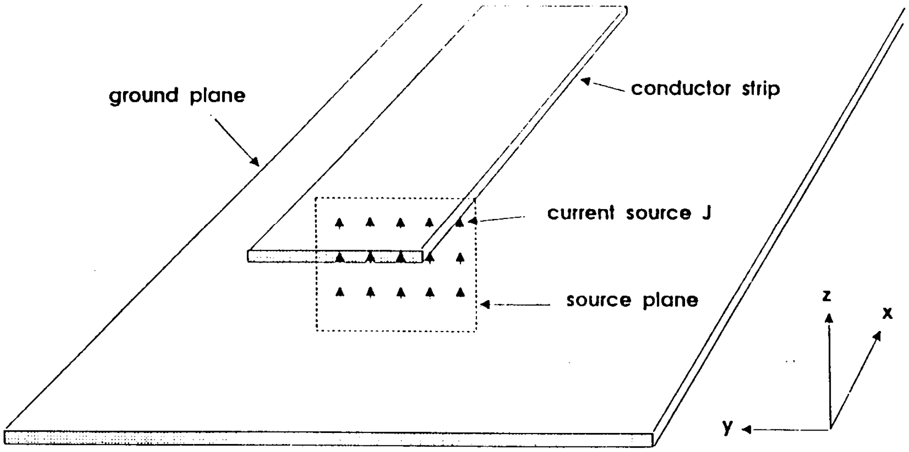
Simulation demo

Note free demo software from www.sonnetsoftware.com

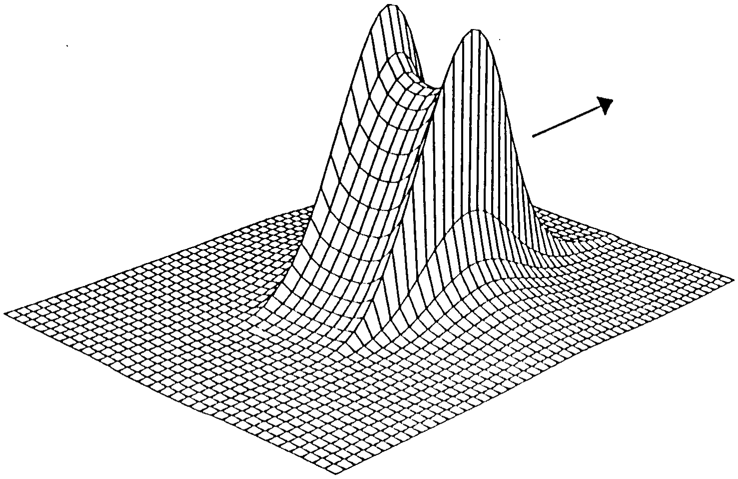
Finite element mesh



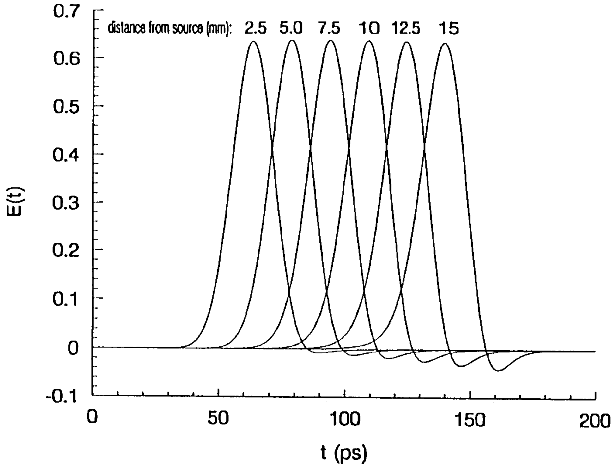
a. Current pulse excitation of line



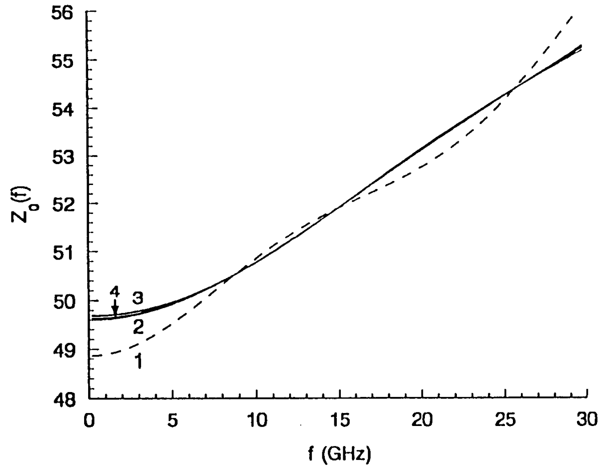
Electric field distribution on line



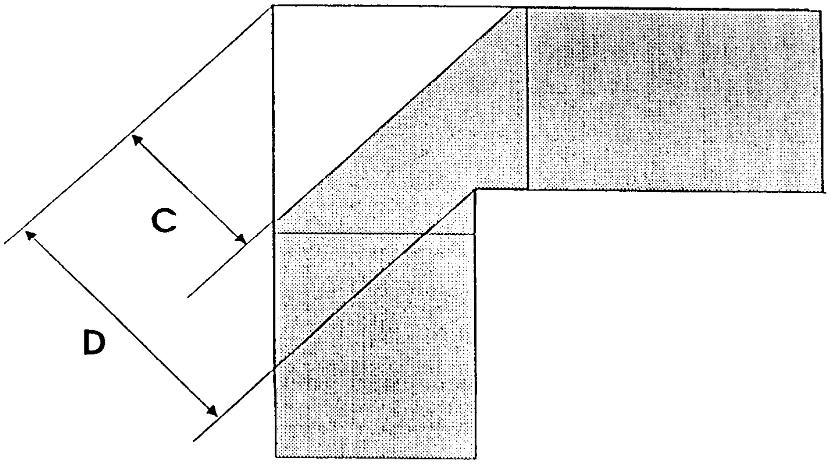
E_Z waveforms at different distances from the source at time t.



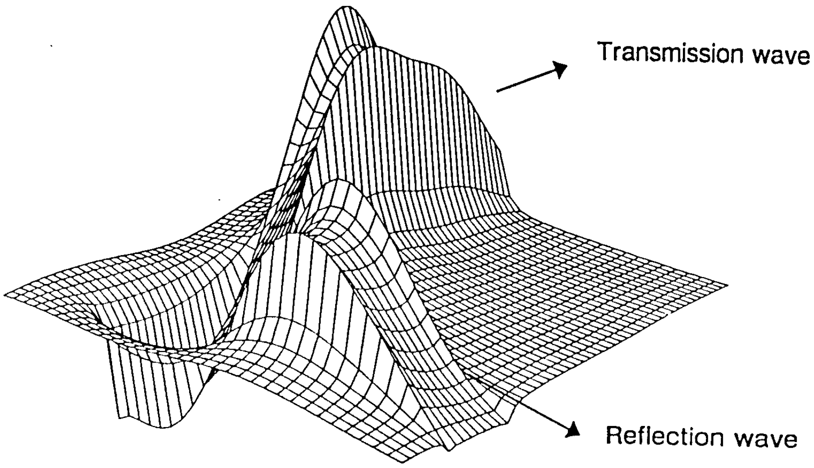
$Z_0(f)$ for different absorbing boundary conditions



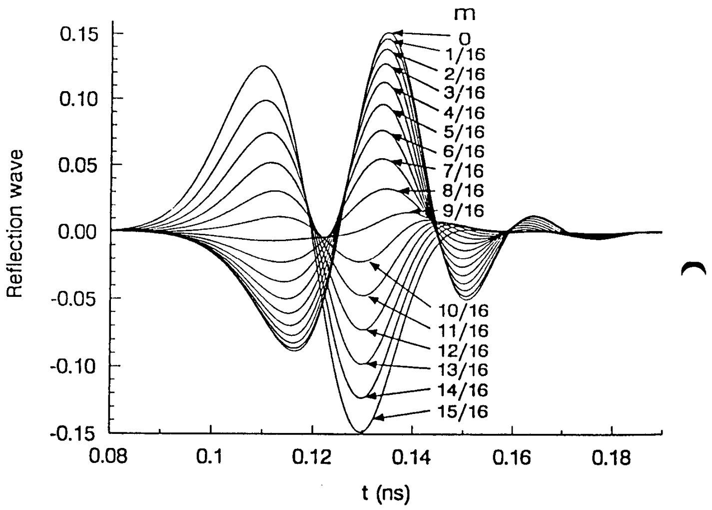
b. Chamfered right angle bend



Pulse after reflection from corner



Reflected Gaussian pulse waveforms for varied chamfer factor *m*



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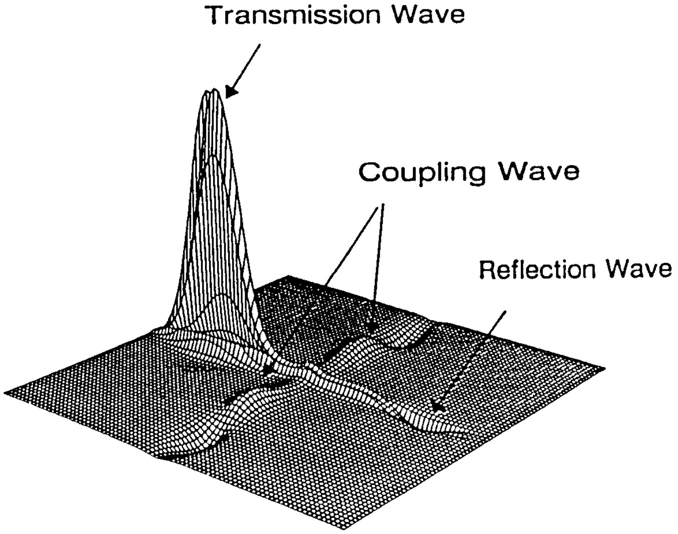
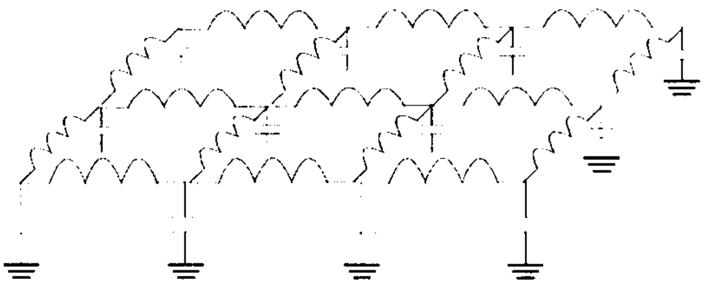
c. Orthogonal line crosstalk



d. Signal/power ground coupling

Capacitor-inductor mesh model



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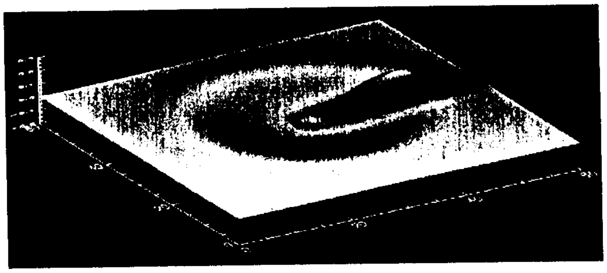
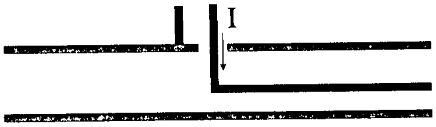
e. Simulation of multilayer packages (vias)

- EM fields decomposed into two parts:
  - Transmission line mode fields
    - Propagate along metal traces
    - Does not contribute to ground bounce
    - 3D fields
  - Parallel plate mode fields
    - Propagate between metal planes
    - Contributes to voltage power/ground bounce
    - 2D fields
- Simulations fast; then do interactions

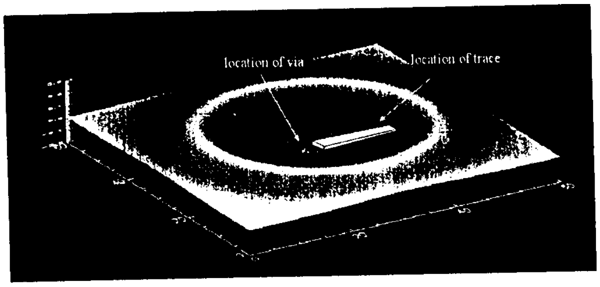
Electric fields between metal planes



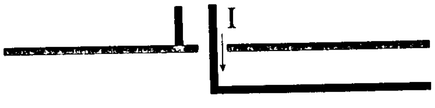
- A strip line mode field and a parallel plate mode field can be identified



Voltage distribution across metal planes



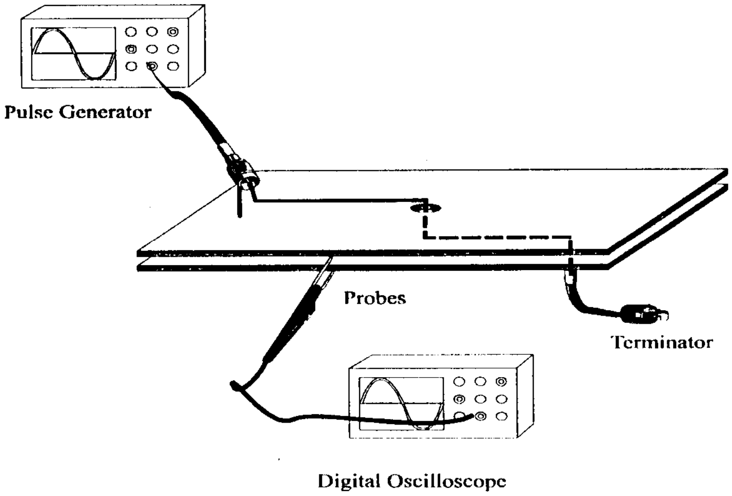
- Parallel plate mode field propagates away from the via in the radial direction (not along the signal trace)



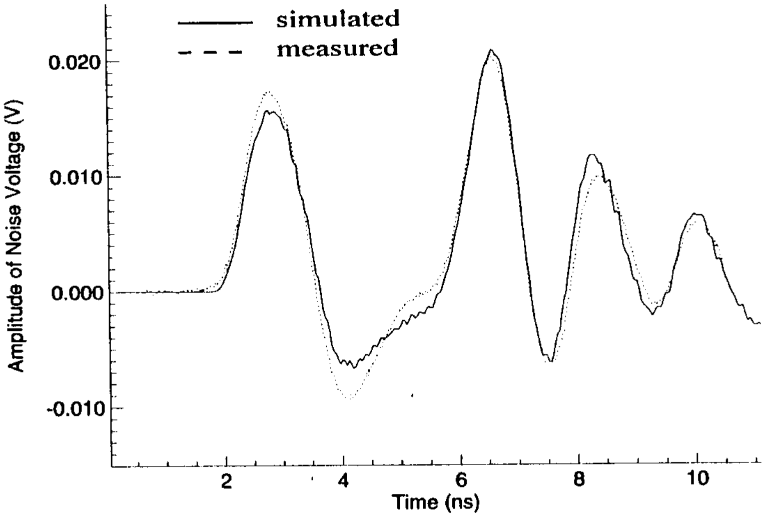
Performance comparison: CPU times

Mesh density	ASTAP IBM3090 mainframe	Separation technique IBM R/6000-350	CPU time ratio
30 H30	1min55.29s	0.18sec	640
42 H42	5min42.73s	0.35sec	980
60 H60	19min30.88s	0.74sec	1582

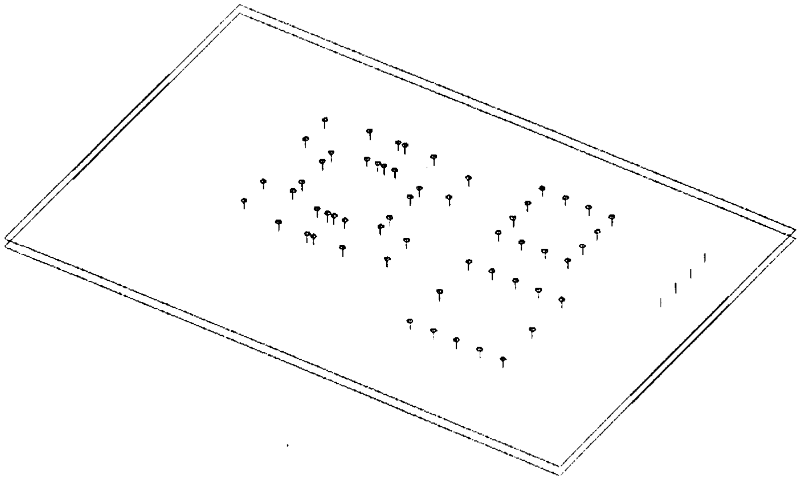
f. Experimental verification: set-up



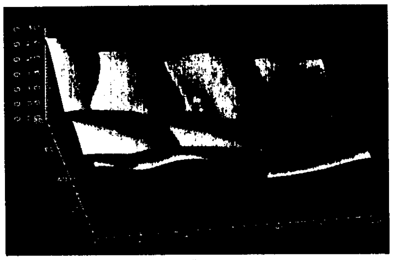
Experimental verification: results



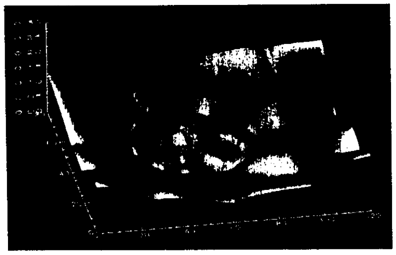
g. Delta-I & decoupling capacitor placement simulation



Voltage waveforms across board



← no decaps



10 decaps placed

23 decaps placed

Evaluation of decoupling capacitor data