Overview and Comparison of Microwave PCB Transmission Line Circuits

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Overview and Comparison of Microwave PCB Transmission Line Circuits

Agenda

• Basic electromagnetics related to PCB technology
• Transmission line properties
• Transmission line circuits:
  – Microstrip
  – Coplanar
  – Stripline

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Basic electromagnetics related to PCB

Waves

Microwave engineering very frequently refer to “waves” and their properties.

Plane wave: wave propagation direction is perpendicular to the forces that create it.

Electric field is perpendicular to Magnetic field and also is perpendicular to wave direction.

Electric field = E
Magnetic field = H
Wave direction
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Basic electromagnetics related to PCB

Waves

Wavelength ($\lambda$) is the physical length from one point of a wave to the same point on the next wave

- Long wavelength = low frequency and the opposite is true
- Short wavelength = more waves in the same time frame so higher frequency

Amplitude is the height of the wave and often related to power

- High electric field = High magnetic field = High amplitude = High power
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Basic electromagnetics related to PCB

Waves

Transverse ElectroMagnetic (TEM) wave

- Electric field varies in z axis
- Magnetic field varies in x axis
- Wave propagation is in y axis

TEM wave propagation is most common in PCB technology, but there are other waves
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Basic electromagnetics related to PCB

Waves

Other wave propagation modes are:

- TE (transverse-Electric) or H wave; magnetic field travels along with wave
- TM (transverse-Magnetic) or E wave; electric field travels along with wave

TEM or quasi TEM waves are typically the intended wave for a transmission line

Some PCB design scenarios will have problems with “modes” or “moding”

Moding issues are when the intended TEM wave is interfered with another wave mode such as TE or TM modes; this is a spurious parasitic wave or unwanted
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Basic electromagnetics related to PCB

Properties

Relative permittivity ($\varepsilon_r$) or dielectric constant (Dk):
- The property of material which alters the electric field in the wave
- Very important property for microwave PCB design
- Materials used in PCB technology generally have Dk from 2 to 10
- The imaginary complex portion of Dk is Df (dissipation factor)
- Df is the amount of dielectric loss the material imparts on the wave

Relative permeability ($\mu_r$):
- The property of material which alters the magnetic field
- This property is rarely used in microwave PCB applications
- Most PCB materials have $\mu_r = 1$
- Some plated finishes used on PCB’s have ferromagnetic properties ($\mu_r >> 1$)
- Ferromagnetic issues typically cause more conductor loss
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Basic electromagnetics related to PCB

<table>
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Basic electromagnetics related to PCB

Properties

Conductivity ($\sigma$): Copper is typically the conductor for PCB’s
   - Most plating finishes in PCB technology have lower conductivity than copper
   - Lower conductivity causes more conductor loss
   - A copper surface which is rough will cause more conductor losses than smooth
   - Lower conductivity causes a deeper skin depth in the conductor

Skin depth is how deep the current density will be in the conductor

   - At DC (0 Hz) the current will use the entire conductor
   - At a higher frequency the current will use the “skin” of the conductor
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Basic electromagnetics related to PCB

Properties

A skin depth for a microwave circuit is typically very thin

- example 1: 1 GHz has a skin depth in copper of 0.082mils (82 micro-inches)
- example 2: 10 GHz has a skin depth of 0.026 mils (26 micro-inches)

Relationships:

- Increase in frequency, decrease in skin depth
- Increase in conductivity (less resistive), decrease in skin depth

Cross-sectional view of a rectangular conductor indicating current density (dark area) as it relates to skin depth

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Transmission line properties

- There are many kinds of transmission lines
  - Wires
  - Cables
  - Printed circuit boards (PCB)

Diagram:

- Generator: Generates Energy
- Transmission Line: Connects things together
- Load: Consumes Energy
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Transmission line properties

- Example of a transmission line with 3 dB insertion loss
- 3 dB is a loss of half of the power
- The load receives half of the power that the generator sent
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Transmission line properties

A “matched” system will have the same impedances
This allows excellent transfer of energy from source to load
There will be minimal losses due to the transmission line
The total loss called “insertion loss”
Insertion loss for a transmission line is a combination of:

Conductor loss, dielectric loss, radiation loss and leakage loss

Leakage loss is typically not an issue with PCB circuits
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Transmission line properties

A “mis-matched” system will have losses due to reflections

There are actually two reflection points for this example:

1. Reflection occurs at the generator going from 50 ohms to 30 ohms
2. Reflection occurs at the load going from 30 ohms to 50 ohms

The insertion loss for this transmission line is 3 dB
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Transmission line properties

S – Parameters
(scattering parameters)

![Signal Flow Diagram]

S parameters are an easy way to analyze loss

S21 is insertion loss
S21 is the energy at port 2 that came from port 1

S11 is return loss or loss due to reflections at port 1
S11 is the energy received at port 1 that came from port 1
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Transmission line properties

S - Parameters

Insertion loss ($S_{21}$)

This is loss vs. frequency for a 6” long transmission line

Marker 3 shows about 6.8 dB loss at 29.5 GHz

A circuit that has the exact same performance however is 3” long, would ideally have half the loss
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Transmission line properties

S - Parameters

Return loss ($S_{11}$) is reflection at port 1; yellow curve

Marker 1 shows return loss of -17.9 dB at 38.7 GHz for port 1.

Return loss ($S_{22}$) is reflection at port 2; magenta curve.

Overall the magenta curve ($S_{22}$) is higher for return loss which means that it is worse than $S_{11}$.

Rule of thumb: Return loss should be better than -15 dB (more negative) for having minimal effect on the insertion data.
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Transmission line properties

Signal launch

- Signal launch is extremely critical to get the energy from one interconnect (coaxial cable) to another interconnect (transmission line PCB)
- Example using a microstrip transmission line
  - Microstrip is a 2 copper layer PCB having a signal layer and ground layer
- The transition from coax to microstrip is plagued with mismatch issues
- The main issue is the cable has a different wave propagation mode than the transmission line
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Transmission line properties

Signal launch

- Coaxial cable uses a TE wave propagation mode
- Microstrip uses a quasi-TEM wave propagation
- In the connector area (signal launch area) the wave has to change propagation modes
- The change causes stray electrical reactance's to disturb the propagation on the transmission line, making return loss higher and insertion loss worse

Electric field in microstrip

Electric field in coaxial
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Specific Transmission line circuits

- Microstrip
- Coplanar
- Stripline
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**Microstrip Transmission line circuits**

Most common transmission line used in the microwave PCB industry

It is simple, cheap to construct, good reliability and easy for assembly

Wave propagation: Quasi - TEM mode (dominate wave propagation mode)

Due to the wave using air and substrate there is an “effective Dk”

The effective Dk is the Dk which the wave experiences (air+substrate)

Since the wave will move different in the air than the substrate:

  the wave is not a pure TEM wave, but a quasi-TEM wave

  there will be some dispersion (wave property changes with frequency)
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Microstrip Transmission line circuits

Losses:

Dielectric loss:
mostly due to dissipation factor of the substrate
soldermask will typically increase dielectric loss

Conductor loss is due to several issues:
skin effect (frequency dependent), surface roughness\(^1\), plated finish
surface roughness will also affect the wave propagation constant\(^1\)
The surface roughness will cause a longer path for the wave propagation and that affects losses and the “apparent Dk” of the circuit
Losses (cont.) and fields

Radiation loss:
- energy radiated and lost from the circuit
- frequency dependent (higher frequency has more radiation loss)
- substrate thickness dependent (thinner has less radiation loss)
- Dk dependent (higher Dk has less radiation loss)
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Microstrip Transmission line circuits

Insertion loss curves with different losses shown at different thicknesses.

Measured data was from circuits made using RO4350B™ laminate with ½ oz ED copper.
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Coplanar Transmission line circuits

There are several types of coplanar circuits

Mostly used at microwave frequencies is the conductor back coplanar waveguide (CBCPW) also called ground coplanar waveguide (GCPWG)

CBCPW circuits need PTH (plated through hole) via’s to connect the ground planes on the top layer (coplanar layer) to the bottom ground plane

Via hole placement is critical for obtaining the desired impedance and loss performance
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Coplanar Transmission line circuits

CBCPW circuits have an effective Dk like microstrip
Dispersion is much less for CBCPW than microstrip
Radiation losses are significantly better than microstrip
Less dispersion and radiation loss: capable of higher frequency ranges
Dominate wave mode propagation is quasi-TEM
Moding issues are greatly reduced compared to microstrip
Signal launch issues are significantly better for CBCPW than microstrip
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Coplanar Transmission line circuits

Losses and fields:

Dielectric loss:
- Mostly due to dissipation factor of the substrate
- Soldermask will have more effect on dielectric loss than on microstrip

Conductor loss:
- Same issues as microstrip
- Overall there are more conductor loss for CBCPW than microstrip
- Conductor losses due to finish plating are worse for CBCPW

Radiation loss:
- When designed properly these can be extremely small or negligible
The insertion loss slope transitions, indicates where radiation loss becomes significant

Excerpt from an excellent paper from Southwest Microwave Inc. study[2]
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Coplanar Transmission line circuits

Effect of via placement on 1” long CBCPW Insertion loss (blue) return loss (red, VSWR)

Via pitch should be 1/8 wavelength of highest operating frequency

Excerpts from Southwest Microwave Inc. study[2]
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Stripline Transmission line circuits

Probably the second most common transmission line used in the PCB industry

More complex to fabricate, moderate in cost, moderate reliability and more difficult for assembly as compared to microstrip or CBCPW

Has the capability for extremely wideband (wide frequency range) applications

If all substrate material has the same Dk:

will have a true TEM wave mode propagation
extremely little or no dispersion

When designed correctly, there will be no radiation loss
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Stripline Transmission line circuits

Losses and fields:

Dielectric loss:
   Mostly due to dissipation factor of the substrate

Conductor loss:
   Skin effects, copper surface roughness
   Conductor losses due to copper surface roughness is much more difficult to model for stripline due to 4 planar copper-substrate interfaces which often have very different roughness

Generally a 50ohm stripline can have higher loss than microstrip and some CBCPW, mostly due to conductor loss, however there are exceptions.
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Stripline Transmission line circuits

Via placement is critical for stripline

Via pitch should be a distance less than ¼ the wavelength or smaller, of the highest operating frequency (same as CBCPW)

Via distance (3X) from the signal shown above is much less critical than pitch

Signal launch is very problematic for stripline
  The signal launch via has increased inductance
  The launch via can have a stub which acts like an antenna
  The design around the launch via has stepped impedance changes as the via goes down through different material layers
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Stripline Transmission line circuits

Multilayer PCB Example of signal launch issues

Effects of the electric signal path from the connector to the signal plane of the circuit:

Connector is TE mode

Transition from connector to circuit has an air-substrate Dk difference

Dk difference causes some reflection

The signal PTH via by itself has increased inductance

Layer 2 copper has a tight space between the ground and signal pad of the via. This tight space increases capacitance which offsets the via inductance

From layer 2 to layer 3 the electric fields expand and capacitance has less effect, inductance of the via dominates in this area

The transition from the signal via to the signal layer causes significant reflections and additional capacitance. This is a transition from TE to TEM mode. The signal pad is enlarged and the ground pads are spaced away to allow more inductance in this area to offset the added capacitance due to the mode transition.
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Stripline Transmission line circuits

Multilayer PCB Example of signal launch issues

This example will have significantly different electrical performance if the geometry remains the same but the Dk of the material changes.

A change in Dk will change all of the capacitance-inductance transitions.

This example will have significantly different electrical performance if the material Dk remains the same but the thickness of each layer changes.

The thickness change will alter the capacitance-inductance transitions.

In some cases, a thickness change of 1mil on the substrate layers, will be significant.

Cross-sectional view in signal launch area

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Stripline Transmission line circuits

Screen-shots of stripline circuits being tested for insertion loss and return loss.

Same exact circuit construction, materials and connectors are used.

Only difference is the gap around the signal launch pad to the ground pad.

Gap=17mils

Gap=13mils
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Stripline Transmission line circuits

Screen-shots of stripline circuits being tested for insertion loss and return loss

Same construction in the body of the circuit, same materials, but different connectors with signal launch

End launch connector using CBCPW launch - Stripline

Vertical connector launch to conventional stripline

Stripline  CBCPW Launch (2x)

Fair comparison warning: Insertion loss is not at the same scale for both charts
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References:


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