HOW TO PCB TRANSMISSION LINES

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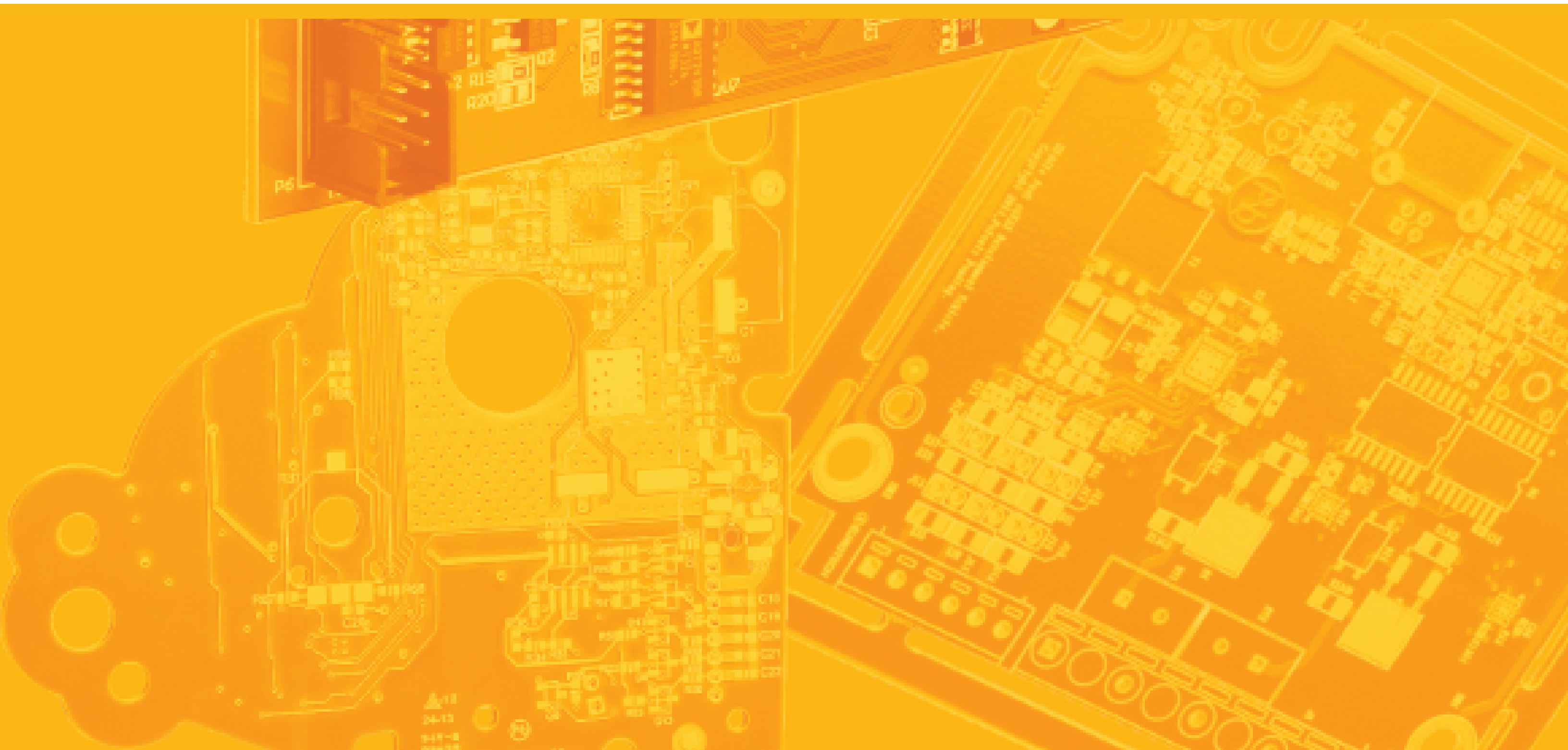

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1. What is a PCB transmission line?

A PCB transmission line is a type of interconnection used for moving signals from their transmitters to their receivers on a printed circuit board. A PCB transmission line is composed of two conductors: a signal trace and a return path, which is usually a ground plane. The volume between the two conductors is made up of the PCB dielectric material.

The alternating current that runs on a transmission line usually has a high enough frequency to manifest its wave propagation nature. The key aspect of the wave propagation of the electrical signals over a transmission line is that the line has an impedance at every point along its length and if the line geometry is the same along the length, the line impedance is uniform. We call such a line a controlled impedance line. Non-uniform impedance causes signal reflections and distortion. It means that at high frequencies, transmission lines need to have a controlled impedance to predict the behavior of the signals.

It is crucial to not ignore the transmission line effects in order to avoid signal reflections, crosstalk, electromagnetic noise and other issues which could severely impact the signal quality and cause errors.

1.1 Transmission line examples

There are usually two basic types of signal transmission line interconnects used in PCBs: microstrips and striplines. There is a third type – coplanar without a reference plane but it is not very common in use.

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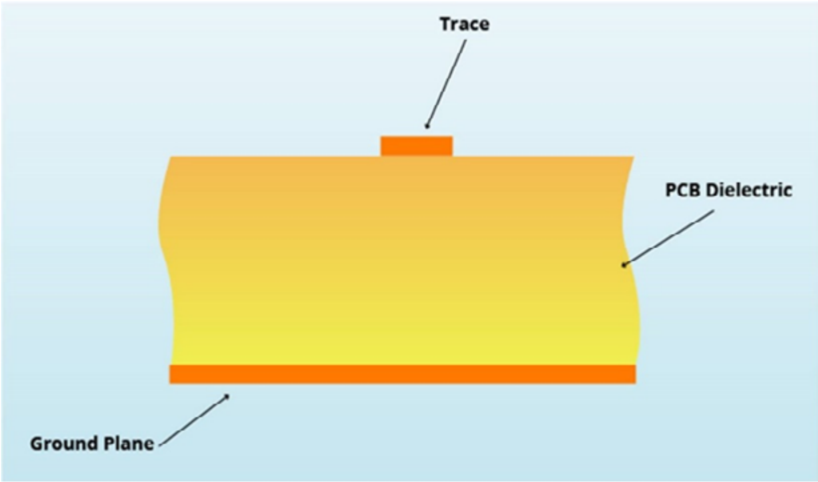
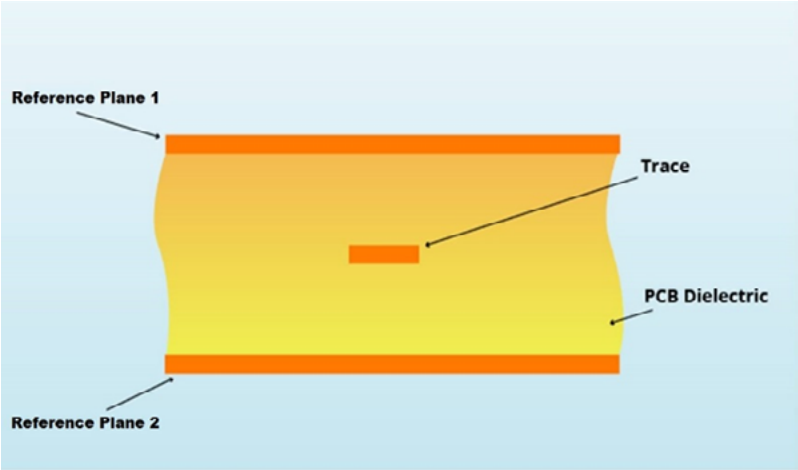
Notes

A microstrip transmission line is composed of a single uniform trace – for the signal – located on the outer layer of a PCB, and parallel to a conducting ground plane, which provides the return path for the signal. The trace and the ground plane are separated by a certain height of PCB dielectric. Below is an uncoated microstrip:



A stripline is composed of a uniform trace – for the signal – located on the inner layer of a PCB. The trace is separated on each side by a parallel PCB dielectric layer and then a conducting plane. So it has two return paths – reference plane 1 and reference plane 2.



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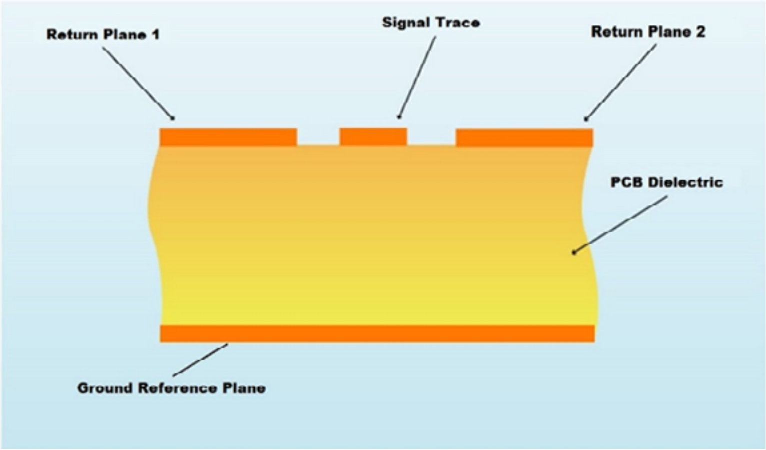
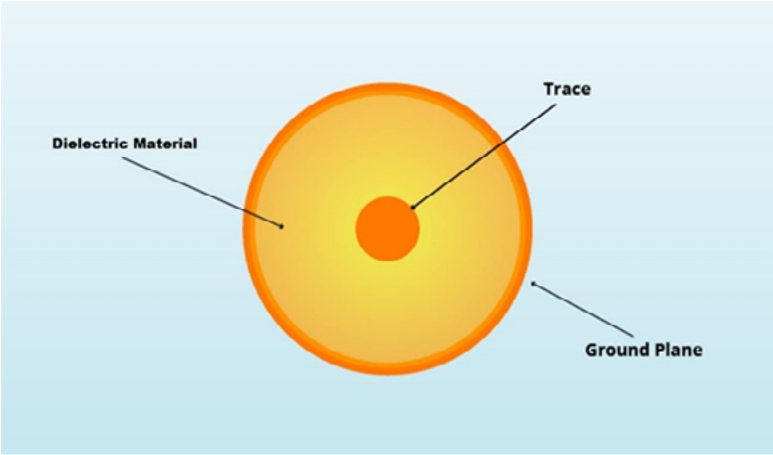
In addition to conventional microstrips and striplines described above, a coplanar waveguide structure has the signal trace and the return path conductor on the same layer of the PCB. The signal trace is at the center and is surrounded by the two adjacent outer ground planes; it is called "coplanar" because these three flat structures are on the same plane. The PCB dielectric is located underneath. Both microstrips and striplines may have a coplanar structure. Below is a coplane microstrip waveguide with a ground plane:



1.2 Example of a coaxial cable

A coaxial line has a circular shape and is not a PCB transmission line. This circular cable is composed of a central wire conductor for the signal and an outer circular conductor for the return path. The space between the two conductors is filled by a dielectric material. The outer conductor wire completely surrounds the signal wire. Coaxial lines are mostly used as cables for high-frequency applications, such as television, etc. A coaxial cable must have a uniform geometry of conductors and the properties of the dielectric material must be uniform along the entire geometry.



It is essential to keep in mind that a PCB transmission line is composed of not only the signal trace but also the return path, which is usually an adjoining ground plane or a coplanar conductor, or a combination of both.

Notes

1.3 When is an interconnection to be treated as a transmission line?

The set of electrical conductors (as stated above, at least two conductors are required: one for the signal and the other one for the return path, which is usually a ground plane) used for connecting a signal between its source and its destination is called a transmission line (and not just an interconnection) if it is not possible to ignore the time it takes for the signal to travel from the source to the destination, as compared to the time period of one-fourth of the wavelength of the higher frequency component in the signal.

Two very important properties of a transmission line are its characteristic impedance and its propagation delay per unit length; and if the impedance is not controlled along its entire length, or the line is not terminated by the right value of impedance, signal reflections, crosstalk, electromagnetic noise, etc. will occur, and degradation in signal quality may be severe enough to create errors in information being transmitted and received.

When the signal frequencies (in case of analog signals) or the data transfer rates (in case of digital signals) are low (less than 50 MHz or 20 Mbps), the time it will take for a signal to travel from its source to its destination on a PCB would be very small (< 10%) compared to the time period of one-fourth of a wavelength or the fastest rise/fall time of a digital pulse signal. In this case, it is possible to approximate the interconnect by assuming that the signal at the destination follows the signal at its source at the same time. In such a low-speed scenario, the PCB signal can be analyzed by conventional network analysis techniques and we can ignore any signal propagation time or transmission line reflections, etc.

Notes

However, when dealing with signals at higher frequencies or higher data transfer rates, the signal propagation time on PCB conductors between the source and the destination cannot be ignored in comparison to the time period of one-fourth of a wavelength or the fastest pulse rise/fall time. Therefore, it is not possible to analyze the behavior of such high-speed signals on PCB interconnects using ordinary network analysis techniques. The interconnects need to be considered as transmission lines and analyzed accordingly.

2. Signal speed and propagation delay in a transmission line

At high frequencies, transmission lines need to have a controlled impedance to predict the behavior of the signals and avoid signal reflections, crosstalk, electromagnetic noise, etc. which could damage the signal quality and cause errors.

This is the reason why you need to know at which speed signals propagate on transmission lines and the time they take to do so. We will give you a few equations to calculate the signal speed and the propagation delay for both striplines and microstrips.

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2.1. Signal speed

Let's first discuss the speeds at which signals propagate on a PCB interconnect.

Electromagnetic signals travel in vacuum or air at the same speed as of light, which is:

$$Vc = 3\ \times 10^{8}\ M/\sec = 186{,}000\ \text{miles/second} = 11.8\ \ inch/nanosecond\ \text{(in/ns)}$$

A signal travels on a PCB transmission line at a slower speed, affected by the dielectric constant (Er) of the PCB material – the relations for calculating the signal speed on a PCB are given below:

Notes

Signal speed on striplines: $$V_{p\ (inner)} \approx \frac{Vc}{\sqrt{Er}} \approx \frac{11.8\ in/ns}{\sqrt{Er}} \qquad \text{(1a)}$$

Signal speed on microstrips: $$V_{p\ (outer)} \approx \frac{Vc}{\sqrt{Er_{eff}}} \approx \frac{11.8\ in/ns}{\sqrt{Er_{eff}}} \qquad \text{(1b)}$$

Where:

Vc is the velocity of light in vacuum or air
Er is the dielectric constant of the PCB material
Er_{eff} is the effective dielectric constant for microstrips; its value lies between 1 and Er, and is approximately given by:

$$Er_{eff} \approx (0.64\ Er + 0.36) \qquad \text{(1c)}$$

Thus, the speeds of signals on a PCB is less than that in air. If Er ≈ 4 (like for FR4 material types), then the speed of signals on a stripline is half that in air, i.e. it is about 6 in/ns.

Henceforth, we can use V_p to denote the speed of signals on a PCB.

Notes

2.2 Propagation delay (t_{pd})

The propagation delay is the time taken by a signal to propagate over a unit length of the transmission line:

$$t_{pd} = \frac{1}{V} \qquad (2a)$$

Where:

V is the signal speed in the transmission line

In vacuum or air, it equals 85 picoseconds/inch (ps/in).

On PCB transmission lines, the propagation delay is given by:

$$t_{pd} \approx 85\sqrt{Er}\ ps/in \text{ in striplines} \qquad (2b)$$

$$t_{pd} \approx 85\sqrt{Er_{eff}}\ ps/in \text{ in microstrips} \qquad (2c)$$

The signal speeds and propagation delays for a few PCB materials are given in the table below:

Material	Er	Er_{eff}	V	V stripline	t_{pd} microstrip	t_{pd} stripline
Vacuum or air	1	1	11.8 in/ns	11.8 in/ns	85 ps/in	
Isola 370HR	4.0	2.92	6.90 in/ns	5.9 in/ns	145 ps/in	170 ps/in
Isola I-SPEED	3.64	2.69	7.20 in/ns	6.18 in/ns	139 ps/in	162 ps/in
Isola I-META	3.45	2.57	7.36 in/ns	6.35 in/ns	136 ps/in	158 ps/in
Isola Astra MT77 or Tachyon 100G or Rogers 3003	3.0	2.28	7.8 in/ns	6.8 in/ns	128 ps/in	147 ps/in
Rogers 4000 series	3.55 – 3.66	2.63 – 2.7	~7.20 in/ns	~6.20 in/ns	~139 ps/in	~161 ps/in

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3. Critical Length, Controlled Impedance and Rise/Fall Time in Transmission Lines

Notes

When is the length of an interconnection to be considered as a controlled impedance transmission line? For high-speed or high-frequency signals, we need to consider transmission line effects. We can use a few thumb rules:

In case of high-frequency analog signals, let the maximum frequency content in the signal = f_m *Hz.*

Time period of 1 wavelength: $t_\lambda = \frac{1}{f_m}$ (3a)

Wavelength: $\lambda_m = \frac{V}{f_m} = \frac{t_\lambda}{t_{pd}} = \frac{1}{t_{pd}\, f_m}$ (3b)

3.1 Critical length l_c

For analog signals, the critical length l_c is defined as one-fourth of the wavelength of the highest signal frequency contained in the signal.

Critical length: $l_c = \frac{\lambda_m}{4} = \frac{1}{4\, t_{pd}\, f_m}$ (4a)

In case of digital signals, the fastest rise/fall time of a signal pulse is the most important parameters as it defines the transition time from one logic level to another logic level – basically, the transition time of the data bit. For digital signals, the critical length l_c is defined as the line length over which the signal propagation time is half of the fastest rise/fall time of the signal pulses.

Notes

If t_r = fastest rise/fall time of the digital signal, the time of the propagation of the signal over the length l_c is $t_{pd}.l_c = \frac{t_r}{2}$ (by definition of l_c).

Critical length: $$l_c = \frac{t_r}{2t_{pd}} = \frac{t_r V}{2} \qquad (4b)$$

This definition implies that the signal should be able to travel from the source over a length l_c of the line and then return over the same length l_c of the line back to the source point in a total time equal to the rise/fall time t_r.

Equations 4a and 4b above are related if we consider the highest frequency content in a digital signal rise/fall time.

The highest frequency content in a digital signal of rise/fall time t_r is given by (as per Fourier Analysis):

$$f_m = \frac{0.5}{t_r} \qquad (5a)$$

Therefore, the wavelength of 1 cycle of f_m: $$\lambda_m = \frac{1}{f_m\, t_{pd}} = \frac{t_r}{0.5 t_{pd}} \qquad (5b)$$

Thus, the critical length: $$l_c = \frac{t_r}{2t_{pd}} = \frac{10.5\lambda_m}{2} = \frac{\lambda_m}{4} = \frac{1}{4t_{pd}\, f_m} \qquad (5c)$$

Which is the same as Equation 4a above.

3.2 Shortline

If the line length $l < \frac{l_c}{1.5} \equiv \frac{\lambda_m}{6}$, there is a shortline and it is not necessary to consider its transmission line effects, nor to design it as a controlled impedance line.

But if the line length $> \frac{l}{1.5} = \frac{\lambda_m}{6}$, it then becomes necessary to consider the transmission line effects and to design such lines as controlled impedance lines.

Example:

If the fastest signal rise/fall time is: t_r=$1ns$, then, assuming the FR4 material with a dielectric constant Er = 4, $V_p = \frac{1}{t_{pd}}$ $\approx 6in/ns$, and the critical length $l_c = \frac{t_r V_p}{2}$ =$3in.$ Therefore, signal traces longer than $\frac{3}{1.5}$ =2 *inches* need to be designed as controlled impedance lines. Note here that t_r of $1ns$ corresponds to a maximal signal frequency: $f_m = \frac{0.5}{t_r}$ =500 *MHz.*

Notes

3.3 Estimate the rise/fall time from data transfer rate (DTR) or clock frequency

The data transfer rate (DTR) is measured in bits per second (bps or bits/sec or b/s) and the clock frequency (F_{clock}) in Hz.
DTR is usually ≥ $2F_{clock}$. Henceforth, it will be safe to use the following rule:

$$DTR = 2F_{clock} \qquad \text{(6a)}$$

If we don't know the signal rise/fall time, we can use the following rule:

Signal rise/fall time: $t_r = 7\%\ of\ period\ of\ F_{clock} = 14\%\ of\ one\ bit\ width$

ie. $t_r = \frac{0.07}{F_{clock}} = \frac{0.14}{DTR}$ (6b)

Critical length: $l_c = \frac{t_r V}{2} = \frac{0.035V}{F_{clock}} = \frac{0.07V}{DTR}$ (6c)

Or $l_c = \frac{t_r}{2tpd} = \frac{0.035}{tpd\ F_{clock}} = \frac{0.07}{tpd\ F_{clock}}$ (6d)

Notes

Example:

For F_{clock}=1GHz or DTR=2$Gbps$, and for a PCB material with Er = 4, we get:

$$t_r = \frac{0.07}{1GHz} = 0.07\ ns = 70\ ps$$

And $$l_c = 0.07\ ns \times \frac{0.07\ ns \times 6\ in/ns}{2} = 0.21\ inch$$

3.4 3 dB bandwidth

For a signal with rise/fall time t_r, the 3 dB bandwidth is given by the following rule:

$$BW_{3dB} = \frac{0.35}{t_r} \qquad (7a)$$

Therefore, for a clock of frequency F_{clock}, we get:

$$BW_{3dB} = \frac{0.35}{0.07}\ F_{clock} = 5\ F_{clock} \qquad (7b)$$

Or $$BW_{3dB} = \frac{0.35}{0.14}\ DTR = 2.5\ DTR \qquad (7c)$$

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4. Analyzing a transmission line

Notes

Basically, high-speed or high-frequency signals generate electromagnetic fields around them during their travel along a transmission line, and their behavior is best analyzed using Maxwell's electromagnetic equations and the theory of electromagnetic wave propagation. In this method, we have to deal with electric and magnetic fields instead of usual voltages and currents. The voltage between the signal line and its return path will generate an electric field and a current in the conductors, which in turn will create a magnetic field around them. Thus, voltage, current, and electric and magnetic fields all travel as waves along the transmission line.

There exists a close analogy between the electromagnetic waves propagation and the propagation of voltages and currents along a transmission line. As it is easier to think in terms of familiar voltages and currents rather than electric and magnetic fields, we should use the voltage/current analysis of the transmission line in the following treatment.

A transmission line is a large number of infinitesimal length segments, and each segment can be analyzed by network theory concepts at a particular point in space and time, ignoring the travel time in the infinitesimal segment as its length is extremely small.

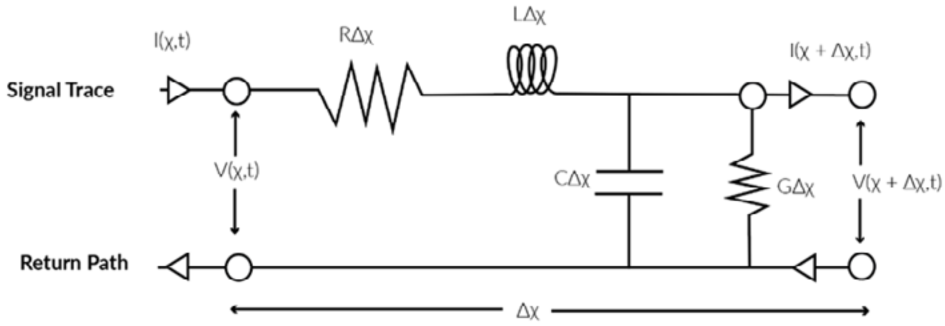
In this analysis technique, we will be dealing with quantities like voltages and currents, and line parameters like resistance, inductance, capacitance, and conductance. We will model an infinitesimal segment of a PCB transmission line in terms of the following parameters of the transmission line:

R = the resistance of the transmission line per unit length (or p.u.l.)
(R in Ohms p.u.l.)
L = the inductance of the transmission line p.u.l. (L in Henrys p.u.l.)
C = the capacitance of the transmission line p.u.l. (C in Farads p.u.l.)
G = the conductance of the transmission line p.u.l. (G in Mhos p.u.l.)

Notes

We can denote the length of the infinitesimal transmission line by Δx.

Then, we can picture this transmission line segment as follows:



<u>Where:</u>

V(x,t) = signal voltage at location x at time t
I(x,t) = signal current at location x at time t

Let's do the analysis of this circuit in the frequency domain. Here, we assume that the signals vary with time sinusoidally with an angular frequency ω, so that the time varying part of *V(x,t)* and *I(x,t)* can be shown by the factor $e^{\wedge j\omega t}$ and we now have:

$$V(x,t) = V(x)\,e^{j\omega t} \qquad (8a)$$

And $$I(x,t) = I(x)e^{j\omega t} \qquad (8b)$$

Using Kirchhoff's laws on the above segment, we obtain the following relations:

$$\frac{dV(x)}{dx} = -(R + j\omega L)\,I(x) \qquad (9a)$$

And $$\frac{dI(x)}{dx} = -(G + j\omega C)\,V(x) \qquad (9b)$$

And from these, by differentiation, we get:

$$V(x) = V(0)e^{-ax} \qquad (11a)$$

And from Equation 9, $$I(x) = \frac{aV(o)e^{-ax}}{(R+j\omega L)} = \sqrt{\frac{G+j\omega C}{R+j\omega L}}\,V(x) \qquad (11b)$$

Where: $$a = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta \qquad (11c)$$

a has units of p.u.l.

If we multiply Equation 11a by $e^{j\omega t}$ to reincorporate the time variations of the sinusoidal voltages and currents, we will see that now the equations represent voltage and current signal waves traveling in the positive x direction over the transmission line:

$$V(x) = V(0)e^{-\alpha}e^{j(\omega t - \beta x)} \qquad (11d)$$

4.1 The characteristic impedance of a uniform transmission line

Notes

From the above Equations 11, we will obtain a relationship between $V(x)$ and $I(x)$ as follows:

$$Z(x) = \frac{V(x)}{I(x)} = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \qquad (12a)$$

This is defined as the impedance of the transmission line at location x. Units of Z are Ohms.

The parameters R, L, G and C depend on the geometry (shape, width, etc.) of the relevant PCB conductors forming the transmission line and the properties of the conductors and dielectric materials used in the PCB.

If the material and the geometrical properties are assumed to be uniform along the length of the transmission line, and the PCB materials are considered homogeneous, then R, L, G and C have the same value at every location along the length of the transmission line. This means that the above impedance has the same value for all values of x along the transmission line. This kind of transmission line is called a uniform transmission line and its impedance is:

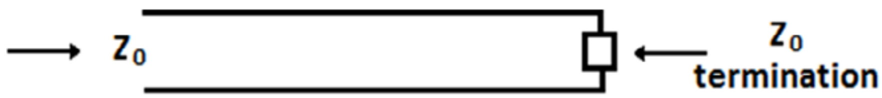
$$Z = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \qquad (12b)$$

This is the characteristic impedance of the uniform transmission line and it is its most important property from the signal integrity perspective. In the PCB industry, we generally refer to characteristic impedance as just "the impedance" of the transmission line.

Notes

If the PCB manufacturing process is such that we are able to control the geometry of the PCB transmission lines within a specified tolerance range, then we could obtain the impedance value of the PCB transmission line at every location along its length within a specified tolerance of a desired value. This way, the PCB transmission line has a controlled impedance and is called a controlled impedance PCB.

If we look at an infinite transmission line of characteristic impedance Z_0 from the left side at any point, we can see an impedance of Z_0. Therefore, if we take a finite length transmission line of impedance Z_0 and terminate it on the right by an impedance of value Z_0, and if we look at the finite transmission line from the left, it will appear as an infinite transmission of impedance Z_0 from the impedance perspective:



4.2 Lossless uniform transmission line

As the equation $Z = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$ shows, the impedance Z is a function of the signal frequency ω.

Practically speaking, R << ω L and G << ω C at signal frequencies of our interest. If we ignore R and G in this formulation, we get a lossless transmission line.

The impedance of a lossless uniform transmission line is given by:

$$Z_C = \sqrt{\frac{L}{C}} \quad ; \text{ (as R = 0 and G = 0)} \qquad \text{(12c)}$$

The impedance of a lossless transmission line is no longer a direct function of frequency, which means it has the same value $\sqrt{\frac{L}{C}}$ all signal frequencies. Note that $\sqrt{\frac{L}{C}}$ has units of Ohms.

In a lossless transmission line (R = 0, G = 0),

$$a = j\omega\sqrt{LC} \qquad (13)$$

The voltages and currents, taking into account of Equations 11, are given by:

$$V(x,t) = V(0)e^{j\omega(t-\sqrt{LC}x)} \qquad (14a)$$

And $$I(x,t) = \frac{V(0)}{Z_C}e^{j\omega(t-\sqrt{LC}x)} \qquad (14b)$$

These relations represent voltage and current waves traveling in the positive x direction with a speed $V = \frac{x}{t}$ and the propagation delay t_{pd} per unit length given by:

Notes

4.3 Estimation of L and C if Z_C and t_{pd} are known

The parameters V and t_{pd} depend on the dielectric constant of the PCB material and these parameters can be calculated separately as we have described in the section about signal speed and propagation delay in a transmission line above. Therefore, if we know t_{pd} and Z_C, we can calculate L and C per unit length values from the relations Equation 12 and Equation 15 as follows:

$$C = \frac{t_{pd}}{Z_C} \text{ Farads / unit length} \qquad (16a)$$

And $$L = t_{pd}\, Z_C \text{ Henrys / unit length} \qquad (16b)$$

Example:

For a microstrip transmission line in a PCB material of FR4 having Er = 4, if Z_C=50 $Ohms$ and t_{pd} = 145 psec/inch, we get:

$$C = \frac{145}{50} = 2.9\ pF/inch$$

And $$L = 145 \times 50 = 7250\,\frac{pH}{inch} = 7.25\ nH/inch$$

Notes

Summary

A transmission line comprises of at least two conductors – one for the signal and another for the signals' return path.

At high-speed or high-frequency signals, we can't ignore the transmission line effects. On a transmission line, time varying electrical signals – voltages and currents – propagate as waves – accompanied by analogous wave propagation of their electrical and magnetic fields.

For a uniform transmission line, we investigated its two most important parameters – its characteristic impedance and signal velocity / propagation delay.

Given a digital signals' rise/fall time or clock frequency or data transfer rate or the maximum frequency of an analog signal, and the dielectric constant of the material (or the medium) in which the line exists, we defined a concept called critical length l_c which clearly helps us in a real life situation as to whether we should design the PCB interconnects as controlled impedance transmission lines or not.

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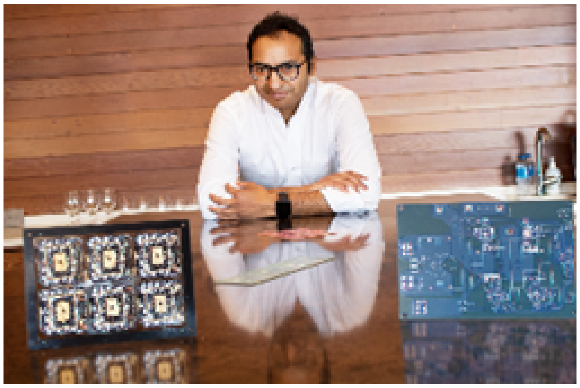

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