Benha University
Faculty of Engineering at Shoubra

Post-Graduate
ECE-601
Active Circuits

Lecture #3
Microstrip lines

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November 2014

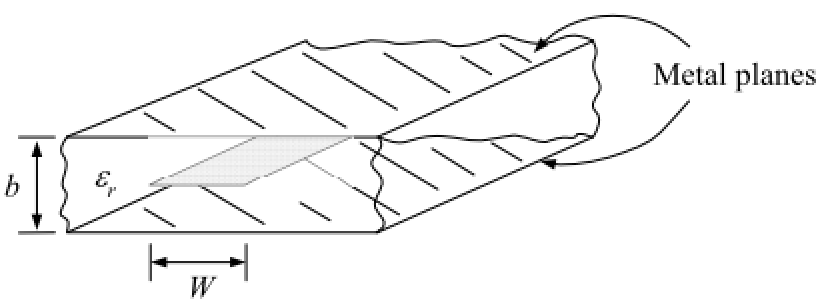
Agenda

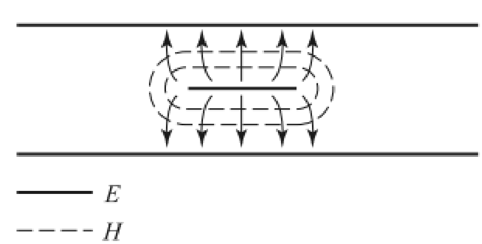
- Striplines
- Forward & Reverse Striplines Design
- Microstrip lines
- Design of Microstrip lines
- Multi-layer Microstrip lines

STRIPLINES

Stripline Transmission Lines

- Microwave circuits that supports TEM or “quasi-TEM” modes are:
  - Microstrip and covered microstrip
  - Stripline
  - Slotline
  - Coplanar waveguide.
- Stripline has one or more interior strip conductors immersed in a dielectric with ground planes above and below.





Formulas for Propagation Constant, Characteristic Impedance, and Attenuation

- Stripline can support the TEM mode exclusively provided that $b \lesssim \lambda/4$ where $\lambda = \lambda_0/\sqrt{\varepsilon_r}$.
- At higher frequencies, TE and TM modes may also propagate, which leads to signal distortion and other undesirable effects. This is called an "over-moded" waveguide.
- We'll assume that the (carrier) frequency is "low" enough that $b \lesssim \lambda/4$ and only the TEM mode propagates. As with any TEM mode, in a stripline with $\mu = \mu_0$:

phase velocity • $v_p = \dfrac{1}{\sqrt{LC}} = \dfrac{c_0}{\sqrt{\varepsilon_r}}$

propagation constant • $\beta = \dfrac{\omega}{v_p} = k_0\sqrt{\varepsilon_r}$

characteristic impedance of a transmission line • $Z_0 = \sqrt{\dfrac{L}{C}} = \dfrac{\sqrt{LC}}{C} = \dfrac{1}{v_p C}$

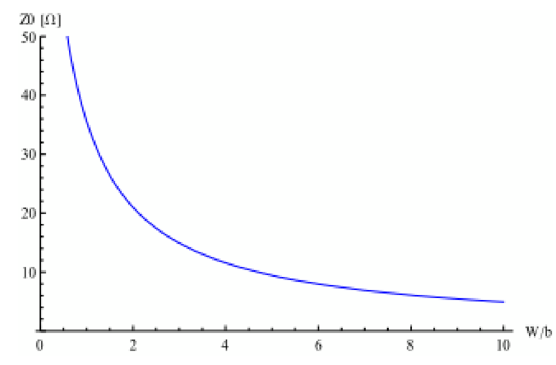
none of these quantities depend on frequency for a TEM mode.

FORWARD & REVERSE STRIPLINES DESIGN

Forward Stripline Design

- We will need to design stripline with a specific Z_0.
- Determining the C value is the problem. There is no simple, exact analytical solution for stripline (or microstrip, for that matter).
- But extremely accurate numerical solutions can be found using a number of techniques including the method of moments and the finite element method, among others.
- By curve fitting to these numerical solutions, it can be shown that for a stripline:

$$\boxed{Z_0 \approx \frac{30\pi}{\sqrt{\varepsilon_r}} \frac{b}{W_e + 0.441b} \quad \Omega}$$



where W_e is called an "effective strip width" given by

$$\frac{W_e}{b} = \frac{W}{b} - \begin{cases} 0 & \dfrac{W}{b} \ge 0.35 \\ \left(0.35 - \dfrac{W}{b}\right)^2 & \dfrac{W}{b} < 0.35 \end{cases}$$

*These formulas assume a strip with zero thickness and are quoted as being accurate to about 1% of the exact results.

Reverse Stripline Design

- One can determine the “inverse” of Z_0, so that W/b can be determined once ε_r and the required Z_0 are specified:

$$\boxed{\frac{W}{b} = \begin{cases} x & Z_0\sqrt{\varepsilon_r} \le 120 \\ 0.85 - \sqrt{0.6 - x} & Z_0\sqrt{\varepsilon_r} > 120 \end{cases}}$$

where $x = \dfrac{30\pi}{Z_0\sqrt{\varepsilon_r}} - 0.441.$

- For example, with $\varepsilon_r = 3.38$ and $Z_0 = 50\ \Omega$, $50\sqrt{3.38} = 91.92$.

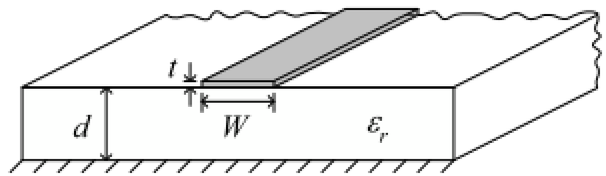
$$\frac{W}{b} = \frac{30\pi}{50\sqrt{3.38}} - 0.441 = 0.5843$$

This is very close to the graphical solution we just obtained.

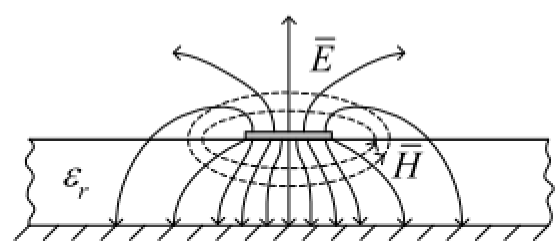
MICROSTRIP LINES

Microstrip lines

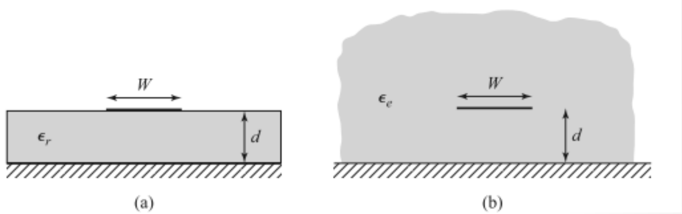
- One of the most widely used planar microwave circuit interconnections is microstrip. These are commonly formed by a strip conductor (land) on a dielectric substrate, which is backed by a ground plane.



- We will often assume the land has zero thickness, t.
- In practical circuits there will often be metallic walls and covers to protect the circuit. We will ignore these effects.
- Unlike stripline, a microstrip has more than one dielectric in which the EM fields are located.
- This presents a difficulty.



Microstrip lines..



- If the field propagates as a TEM wave, then $v_p = \dfrac{c_0}{\sqrt{\varepsilon_r}}$
- But which ε_r do we use?
- The answer is neither because there is actually no purely TEM wave on the microstrip, but something that closely approximates it called a "quasi-TEM" mode.
- At low frequency, this mode is almost exactly TEM.
- Conversely, when the frequency becomes too high, there are axial components of E and/or H making the mode no longer quasi-TEM.
- This property leads to dispersive behavior.
- Numerical and other analysis have been performed on microstrip since approximately 1965.
- Some techniques, such as the method of moments, produce very accurate numerical solutions to equations derived directly from Maxwell's equations and incorporate the exact cross-sectional geometry and materials of the microstrip.

Microstrip lines…

- From these solutions, simple and quite accurate analytical expressions for Z_0, υ_p etc. have been developed primarily by curve fitting.
- The result of these analyses is that at relatively "low" frequency, the wave propagates as a quasi-TEM mode with an effective relative permittivity, $\varepsilon_{r,e}$:

$$\boxed{\varepsilon_{r,e} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12d/W}}}$$

- The phase velocity and phase constant, respectively, are:

$$v_p = \frac{c_0}{\sqrt{\varepsilon_{r,e}}}$$

as for a typical TEM mode.

$$\beta = k_0 \sqrt{\varepsilon_{r,e}}$$

- In general, $\boxed{1 \le \varepsilon_{r,e} \le \varepsilon_r}$
- The upper bound occurs if the entire space above the microstrip has the same permittivity as the substrate, while the lower bound occurs if in this situation the material is chosen to be free space.

Microstrip lines….

- The characteristic impedance of the quasi-TEM mode on the microstrip can be approximated as

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_{r,e}}} \ln\left(\dfrac{8d}{W} + \dfrac{W}{4d}\right) & \dfrac{W}{d} \le 1 \\ \dfrac{120\pi}{\sqrt{\varepsilon_{r,e}}\left[\dfrac{W}{d} + 1.393 + 0.667 \ln\left(\dfrac{W}{d} + 1.444\right)\right]} & \dfrac{W}{d} > 1 \end{cases}$$

Alternatively, given a desired Z_0 and ε_r, the necessary W/d can be computed from (3.197).

$$\frac{W}{d} = \begin{cases} \dfrac{8e^A}{e^{2A} - 2} & \text{for } W/d < 2 \\ \dfrac{2}{\pi}\left[B - 1 - \ln(2B - 1) + \dfrac{\epsilon_r - 1}{2\epsilon_r}\left\{\ln(B - 1) + 0.39 - \dfrac{0.61}{\epsilon_r}\right\}\right] & \text{for } W/d > 2, \end{cases} \tag{3.197}$$

$$A = \frac{Z_0}{60}\sqrt{\frac{\epsilon_r + 1}{2}} + \frac{\epsilon_r - 1}{\epsilon_r + 1}\left(0.23 + \frac{0.11}{\epsilon_r}\right)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\epsilon_r}}.$$

- the attenuation due to dielectric loss

$$\alpha_d = \frac{k_0 \epsilon_r (\epsilon_e - 1) \tan\delta}{2\sqrt{\epsilon_e}(\epsilon_r - 1)} \text{ Np/m},$$

where $\tan\delta$ is the loss tangent of the dielectric.

- The attenuation due to conductor loss

$$\alpha_c = \frac{R_s}{Z_0 W} \text{ Np/m},$$

$R_s = \sqrt{\omega\mu_0/2\sigma}$ is the surface resistivity of the conductor.

DESIGN OF MICROSTRIP LINES

Design Example

EXAMPLE 3.7 MICROSTRIP LINE DESIGN

Design a microstrip line on a 0.5 mm alumina substrate ($\epsilon_r = 9.9$, $\tan\delta = 0.001$) for a 50 Ω characteristic impedance. Find the length of this line required to produce a phase delay of 270° at 10 GHz, and compute the total loss on this line, assuming copper conductors. Compare the results obtained from the approximate formulas of (3.195)–(3.199) with those from a microwave CAD package.

Solution

First find W/d for $Z_0 = 50\ \Omega$, and initially guess that $W/d < 2$. From (3.197),

$$A = 2.142, \qquad W/d = 0.9654.$$

So the condition that $W/d < 2$ is satisfied; otherwise we would use the expression for $W/d > 2$. Then the required line width is $W = 0.9654d = 0.483$ mm. From (3.195) the effective dielectric constant is $\epsilon_e = 6.665$. The line length, ℓ, for a 270° phase shift is found as

$$\phi = 270° = \beta\ell = \sqrt{\epsilon_e}k_0\ell,$$

$$k_0 = \frac{2\pi f}{c} = 209.4\ \mathrm{m}^{-1},$$

$$\ell = \frac{270°(\pi/180°)}{\sqrt{\epsilon_e}k_0} = 8.72\ \mathrm{mm}.$$

Attenuation due to dielectric loss is found from (3.198) as $\alpha_d = 0.255$ Np/m = 0.022 dB/cm. The surface resistivity for copper at 10 GHz is 0.026 Ω, and the attenuation due to conductor loss is, from (3.199), $\alpha_c = 0.0108$ Np/cm = 0.094 dB/cm. The total loss on the line is then 0.101 dB.

CAD tool

- Many tools are available for microwave CAD.
- The Rogers ACM Division introduces a new design program that is **free to download** called the MWI-2010 Microwave Impedance Calculator, a transmission line modeling tool for electronics engineers.

- Link to download:
  - http://www.rogerscorp.com/acm/technology/index.aspx

- Design the previous Example using the MWI-2010 Microwave Impedance Calculator.

MULTI-LAYER MICROSTRIP LINES

Ref: K. R. Jha and G. Singh, Terahertz Planar Antennas for Next Generation Communication, DOI: 10.1007/978-3-319-02341-0_2, Springer International Publishing Switzerland 2014

Multi-layer Microstrip lines

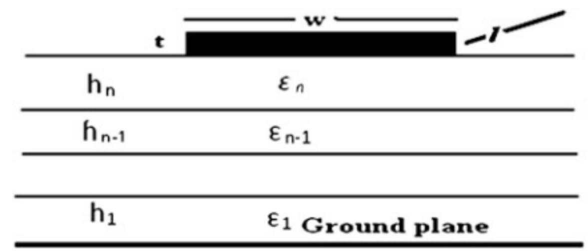
- In general, the microstrip line is used to conduct the electromagnetic wave at low frequency.
- Beyond 60 GHz, its application is restricted due to the losses in the line.
- Due to this, there is a general consideration that the use of microstrip transmission line at THz frequency is impractical.
- Moving away from this theory, the microstrip transmission line has successfully been used to transmit the THz wave.
- The transmission line parameters become frequency dependent and need the empirical formula to evaluate these parameters at such high frequency.

Necessity of Multilayer Microstrip Transmission Line

- A microstrip transmission line can be designed on the different configuration of the substrate layers which may be single, double, or the multilayered material.
- With the development in the technology and the need of the system-on-chip (SOC) requirement, the use of the multilayered substrate has increased at high frequency.
- The use of the multilayered substrate material microstrip transmission line has a numerous advantages such as:
  - Capability to reduce the losses and to control the coefficient of expansion.
  - It is also an alternative solution to circuit layout and the combination of the substrate and semiconductor layer gives the slow-wave structure.
  - The multilayered substrate is also used in the antenna design where it shows good surface wave immunity gain, and bandwidth enhancement apart from the good mechanical integration.

The **effective dielectric permittivity** of the multilayered substrate material is :

$$\varepsilon_{\mathrm{rc}} = \frac{|d_1| + |d_2| + \cdots + |d_n|}{\left|\frac{d_1}{\varepsilon_1}\right| + \left|\frac{d_2}{\varepsilon_2}\right| + \cdots + \left|\frac{d_n}{\varepsilon_n}\right|} \quad \text{for } h_n + h_{n-1} + \cdots + h_1 \cong \lambda/10$$



where

$$d_1 = \frac{K(k_1)}{K'(k_1)}$$

$$d_2 = \frac{K(k_2)}{K'(k_2)} - \frac{K(k_1)}{K'(k_1)}$$

$$d_3 = \frac{K(k_3)}{K'(k_3)} - \frac{K(k_2)}{K'(k_2)} - \frac{K(k_1)}{K'(k_1)}$$

$$d_n = \frac{K(k_n)}{K'(k_n)} - \frac{K(k_{n-1})}{K'(k_{n-1})} - \cdots - \frac{K(k_1)}{K'(k_1)}$$

and in general,

$$k_n = \frac{1}{\cosh\left(\frac{\pi w}{4(h_n + h_{n-1} + h_{n-2} + \cdots + h_1)}\right)} \quad \text{for } n = 1, 2, 3 \ldots$$

In the above equations, h_n, h_{n-1}, … h_1 represents the individual substrate layer thickness starting from the top layer. Further, $\varepsilon_n, \varepsilon_{n-1}, \ldots \varepsilon_1$ are the complex relative dielectric permittivity of the respective substrate layer, and λ_0 is the free-space wavelength. The value of $\frac{K()}{K'()}$ is given by the following formula

$$\frac{K(k_n)}{K'(k_n)} = \frac{1}{\pi} \ln\left(2 \frac{1 + \sqrt{k_n}}{1 - \sqrt{k_n}}\right) \quad \text{for } 0.7 \le k_n \le 1$$

Characteristic Impedance

The dispersive behavior of characteristic impedance on the multilayered substrate material is obtained by

$$Z_c(f) = Z_c \frac{\varepsilon_e(f) - 1}{\varepsilon_e(0) - 1} \sqrt{\frac{\varepsilon_e(0)}{\varepsilon_e(f)}}$$

where

$$Z_c = \frac{120\pi}{2\sqrt{\varepsilon_r(0)}} \ln\left(\frac{8h}{w_e} + 0.25\frac{w_e}{h}\right) \quad \text{for } \frac{w_e}{h} \leq 1$$

and

$$w_e = \frac{w}{h} + \frac{1.25t}{\pi h}\left(1 + \ln\frac{4\pi w}{t}\right) \quad \text{for } \frac{w}{h} \leq 0.5\pi$$

Effect of Substrate Layers on the Characteristic Impedance

Table 2.1 Multilayered substrate material transmission line

Four-layered substrate				Five-layered substrate			
Layer no.	Thickness (μm)	ε_r	$\tan\delta$	Layer no.	Thickness (μm)	ε_r	$\tan\delta$
h4	10.0	7.0	0.001	h5	10.0	7.0	0.001
h3	5.0	6.15	0.0025	h4	5.0	6.15	0.0025
h2	40.0	2.2	0.0009	h3	20.0	4.5	0.0009
h1	5.0	2.45	0.0013	h2	20.0	2.2	0.0009
				h1	5.0	2.45	0.0019

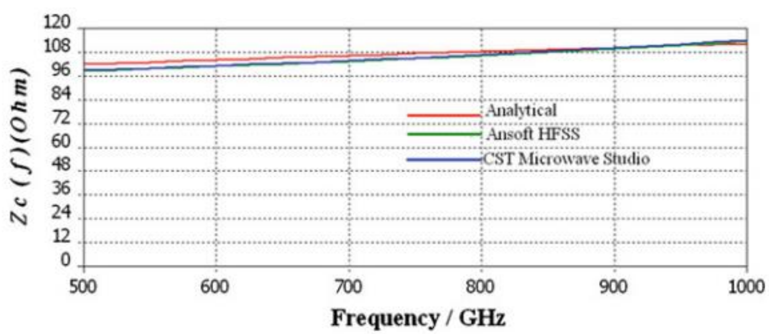


Fig. 2.5 Characteristic impedance of the four-layered substrate material transmission line

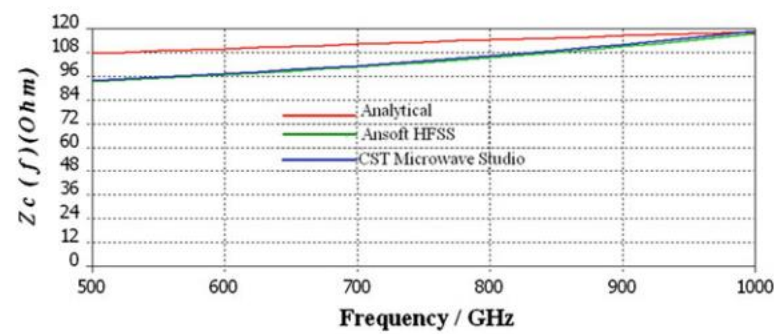


Fig. 2.6 Characteristic impedance of the five-layered substrate material transmission line

- For more details, refer to:
  - Chapters 3, Microwave Engineering, David Pozar_4ed.
  - Lecture Notes of , EE 481 - Microwave Engineering Course, Laboratory for applied electromagnetic and communications, South Dakota school for mines and technology, 2013.
- The lecture is available online at:
  - http://bu.edu.eg/staff/ahmad.elbanna-courses/11983
- For inquires, send to:
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