Chapter 3 – *Transmission Lines and Waveguides*

First, some **definitions**:

Transmission Line – A **two** conductor structure that **can** support a TEM wave.

Waveguide – A **one** conductor structure that **cannot** support a TEM wave.

Q: *What is a **TEM** wave?*

A: An electromagnetic wave wherein **both** the electric and magnetic fields are **perpendicular** to the direction of wave propagation.

HO: WAVEGUIDE

3.5 Coaxial Line

Reading Assignment: ***p. 130***

The most **prevalent** type of transmission line is the **coaxial** transmission line.

HO: COAXIAL TRANSMISSION LINES

Coaxial transmission lines are attached to devices using microwave **connectors**.

HO: COAXIAL CONNECTORS

3.7 Stripline

Reading Assignment: ***pp. 137-140***

Often, microwave devices or networks are built on dielectric substrates (e.g., "**printed circuit boards**"). Connecting these devices require printed circuit board **transmission lines**.

HO: PRINTED CIRCUIT BOARD TRANSMISSION LINES

One of the most popular PCB transmission lines is **stripline**.

HO: STRIPLINE

3.8 Microstrip

Reading Assignment: ***pp. 143-146***

Another popular PCB transmission line is **microstrip**.

HO: MICROSTRIP

3.11 Summary of Transmission Lines and Waveguides

Reading Assignment: ***pp. 154-157***

Let's **compare** transmission line characteristics!

HO: A COMPARISON OF COMMON TRANSMISSION LINES AND WAVEGUIDES

Waveguide

A waveguide is not considered to strictly be a transmission line, as it is **not** constructed with **two** separate conductors. As such, it can **not** support a TEM wave!

Instead, a waveguide will propagate "higher-order" **modes**, which are classified as either transverse magnetic (**TM**) or transverse electric (**TE**).

There are **two** problems with propagating higher-order modes!

1. TE and TM modes have a **limited bandwidth**. In fact, none of these modes can propagate at frequencies below a minimum frequency known as the **cutoff** frequency.

2. TE and TM modes are **dispersive**. That is, the phase velocity is dependent on frequency—for some modes highly dependent!

Q: *Yikes! So why would we ever use a waveguide?*

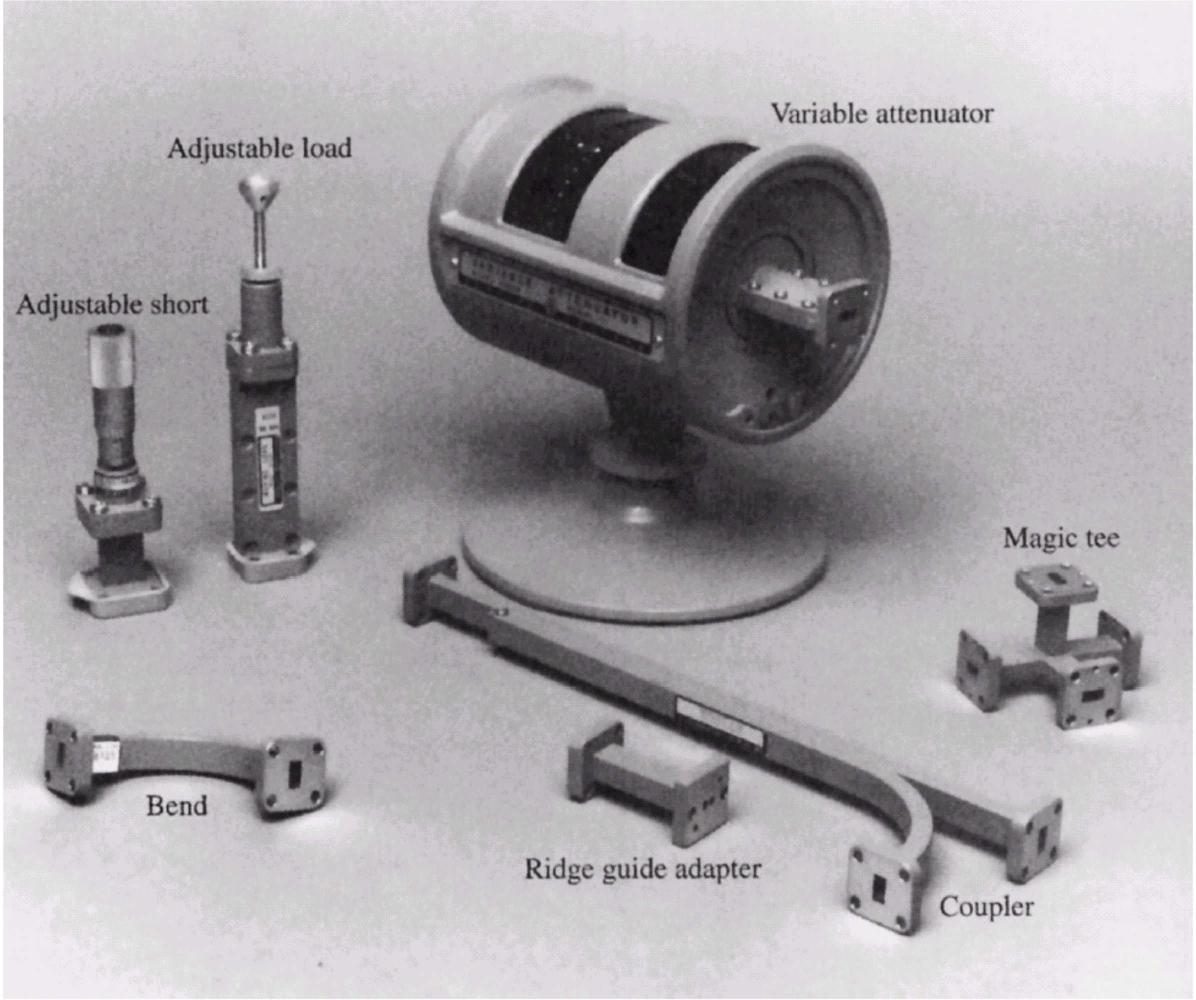
A: A waveguide likewise has **two** important **advantages**!

1. It can typically handle very **large power** (e.g., kilowatts).

2. It can have very **low loss** (low value of α).

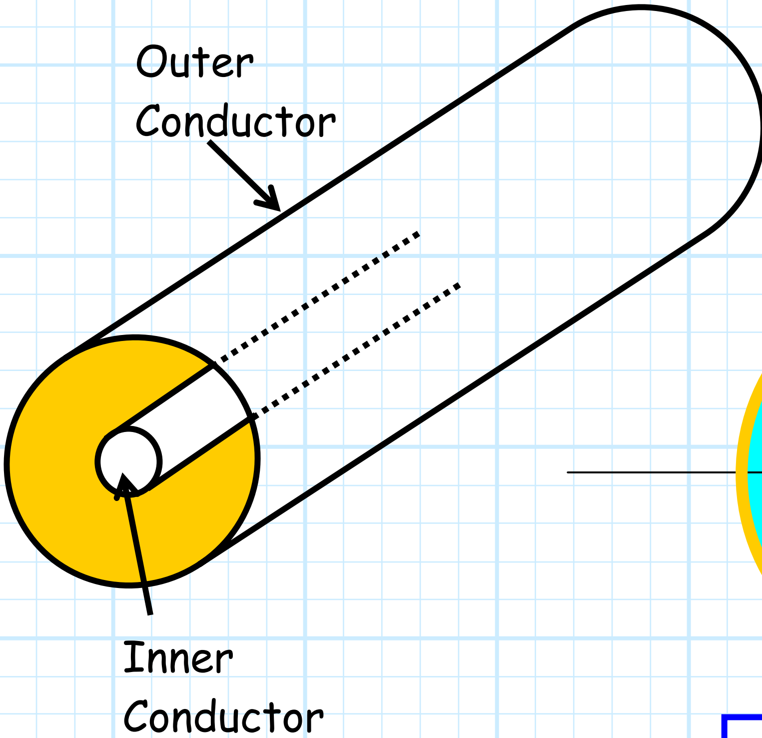
Thus, waveguide is typically used for **high-power** applications, such as high-power microwave **transmitters**.

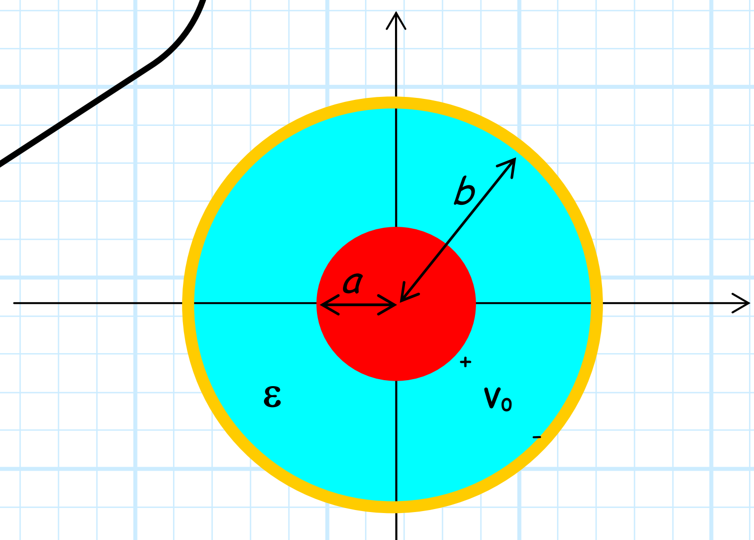
Waveguide appears at first to simply be a **pipe** (either circular or rectangular), and effectively it is—an **electromagnetic** pipe!



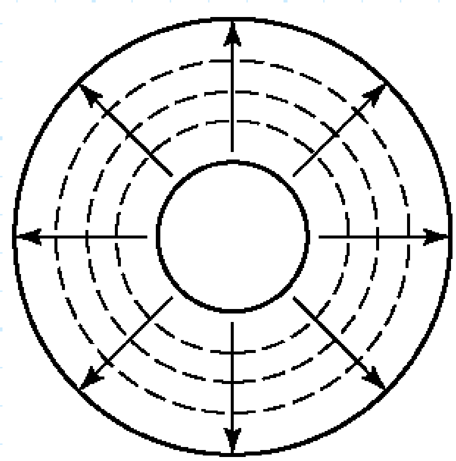
Coaxial Transmission Lines

The most **common** type of transmission line!





Coax Cross-Section



The **electric** field (⟶)points in the direction $\hat{a}_\rho$.

The **magnetic** field (- - - -)points in the direction $\hat{a}_\phi$.

E. M. Power flows in the direction $\hat{a}_z$.

→ A TEM wave!

Recall from EECS 220 that the **capacitance** per/unit length of a coaxial transmission line is:

$$C = \frac{2\pi\,\varepsilon}{\ln[b/a]} \qquad \left[\frac{\text{farads}}{\text{meter}}\right]$$

And that the **inductance** per unit length is :

$$L = \frac{\mu_0}{2\pi}\ln\left[\frac{b}{a}\right] \qquad \left[\frac{\text{Henries}}{\text{m}}\right]$$

Where of course the **characteristic impedance** is:

$$Z_o = \sqrt{\frac{L}{C}} = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon}}\ln\left[\frac{b}{a}\right]$$

and:

$$\beta = \omega\sqrt{LC} = \omega\sqrt{\mu_0\,\varepsilon}$$

Therefore the **propagation velocity** of each TEM wave within a coaxial transmission line is:

$$v_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{\mu_0\,\varepsilon}} = \frac{1}{\sqrt{\mu_0\,\varepsilon_0}}\frac{1}{\sqrt{\varepsilon_r}} = c\frac{1}{\sqrt{\varepsilon_r}}$$

where $\varepsilon_r = \varepsilon/\varepsilon_0$ is the relative dielectric constant, and c is the "speed of light" ($c = 3\times10^8\ m/s$).

Note then that we can likewise express β in terms ε_r:

$$\beta = \omega\sqrt{\mu_0\,\varepsilon} = \omega\sqrt{\mu_0\,\varepsilon_0}\sqrt{\varepsilon_r} = \frac{\omega}{c}\sqrt{\varepsilon_r}$$

Now, the **size** of the coaxial line (*a* and *b*) determines **more** than simply Z_0 and β (*L* and *C*) of the transmission line. Additionally, the line radius determines the **weight** and bulk of the line, as well as its **power handling** capabilities.

Unfortunately, these two characteristics **conflict** with each other!

1. Obviously, to **minimize** the weight and bulk of a coaxial transmission line, we should make *a* and *b* as **small** as possible.

2. However, for a given line voltage, reducing *a* and *b* causes the **electric field** within the coaxial line to **increase** (recall the units of electric field are *V/m*).

A higher electric field causes **two** problems: first, it results in greater **line attenuation** (larger α); second, it can result in **dielectric breakdown**.

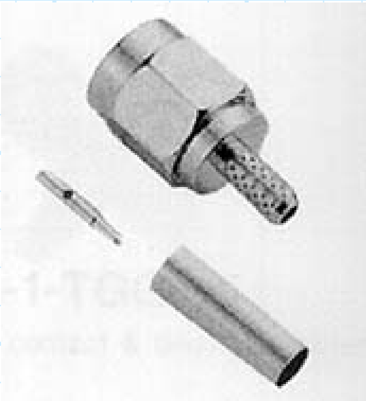
Dielectric breakdown results when the electric field within the transmission line becomes so large that the dielectric material is **ionized**. Suddenly, the dielectric becomes a **conductor**, and the value *G* gets **very** large!

This generally results in the **destruction** of the coax line, and thus must be **avoided**. Thus, **large** coaxial lines are required when extremely **low-loss** is required (i.e., line length ℓ is large), **or** the delivered **power** is large.

Otherwise, we try to keep our coax lines as **small** as possible!

Coaxial Connectors

There are many types of **connectors** that are used to connect coaxial lines to RF/microwave devices. They include:



SMA

The workhorse **microwave** connector. Small size, but works well to > 20 GHz. By microwave standards, moderately priced.

BNC

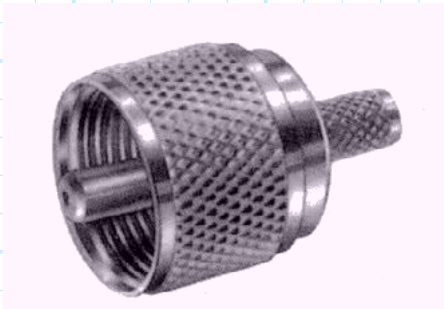
The workhorse **RF** connector. Relatively small and cheap, and easy to connect. Don't use this connector past 2 GHz!

F

A poorman's BNC. The RF connector used on most consumer products such as **TVs**. Cheap, but difficult to connect and not reliable.

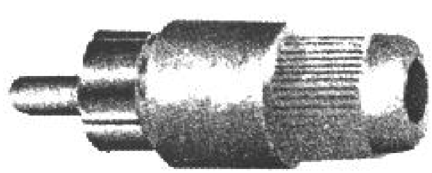
N

The **original** microwave connector. Good performance (up to 18GHz), and moderate cost, but large (about 2 cm in diameter) ! However, can handle greater **power** than SMA.



UHF

The poorman's **N.** About the same size, although **reduced** reliability and performance.



RCA

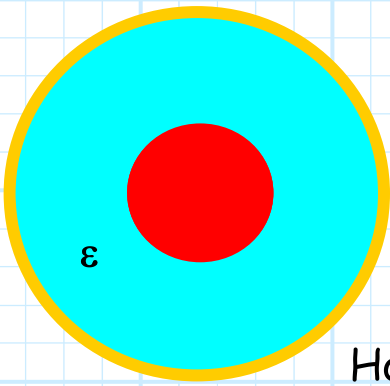
Not really an RF connector. Used primarily in consumer application for video and audio signals (i.e., <20 MHz). Cheap and easy to connect.

APC-7 and APC-3.5

The top of the line connector. Best performance, but cost **big $$$**. Used primarily in test equipment (e.g., network analyzers). 3.5 can work to nearly 40 GHz.

Printed Circuit Board Transmission Lines

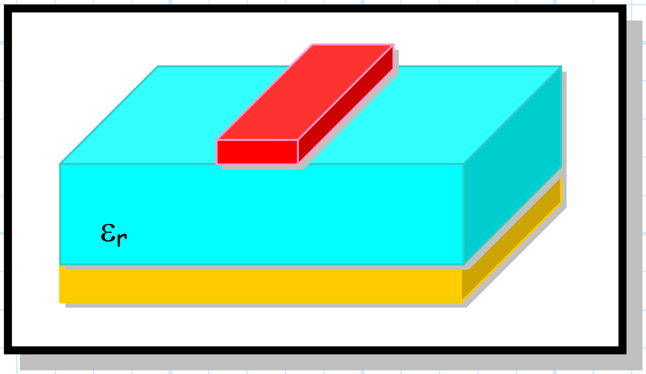
Recall that a transmission line **must** consist of **two separate conductors**. Typically, the volume between these conductors is filled with a very low-loss **dielectric**.



For example, a **coaxial** line has an inner conductor (conductor #1) and an outer conductor (conductor #2), with the cylindrical space between filled with dielectric.

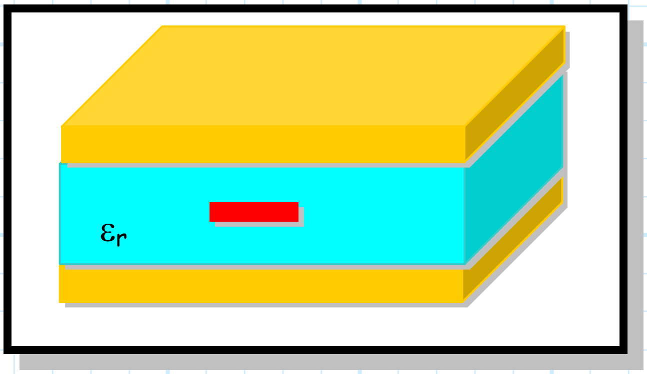
However, we can likewise construct a transmission line using **printed circuit board** technology. The **substrate** of the circuit board is the dielectric that separates two conductors. The first conductor is typically a **narrow** etch that provides the **connection** between two components, while the second conductor is typically a **ground plane**.

Below are some of the most popular types of printed circuit board transmission lines:



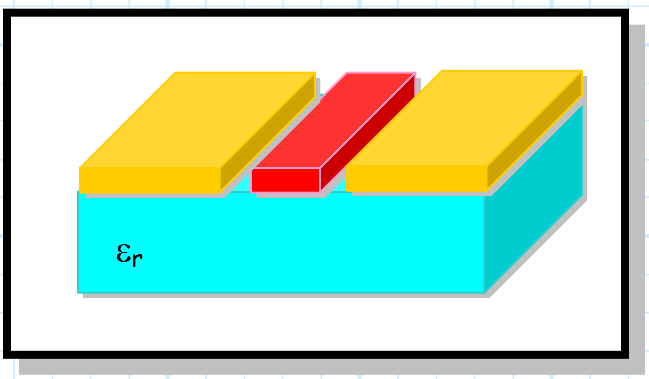
Microstrip

Probably most **popular** PCB transmission line. Easy fabrication and connection, yet is **slightly** dispersive, lossy, and difficult to analyze.



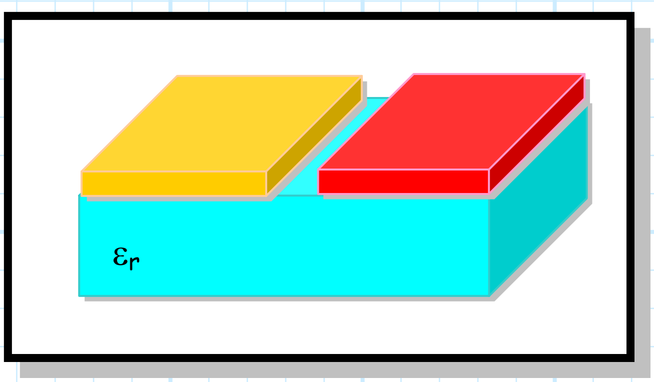
Stripline

Better than microstrip in that it is **not** dispersive, and is more easily analyzed. However, fabrication and connection is more difficult.



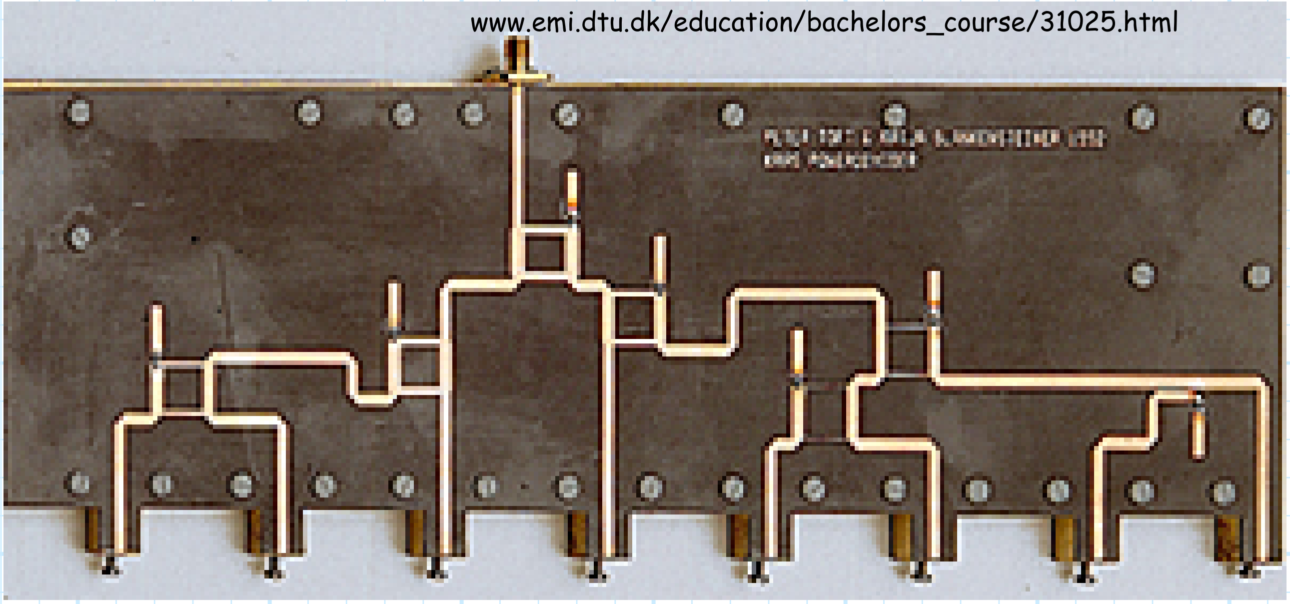
Coplanar Waveguide

The **newest** technology. Perhaps easiest to fabricate and connect components, as **both** ground and conductor are on one side of the board.

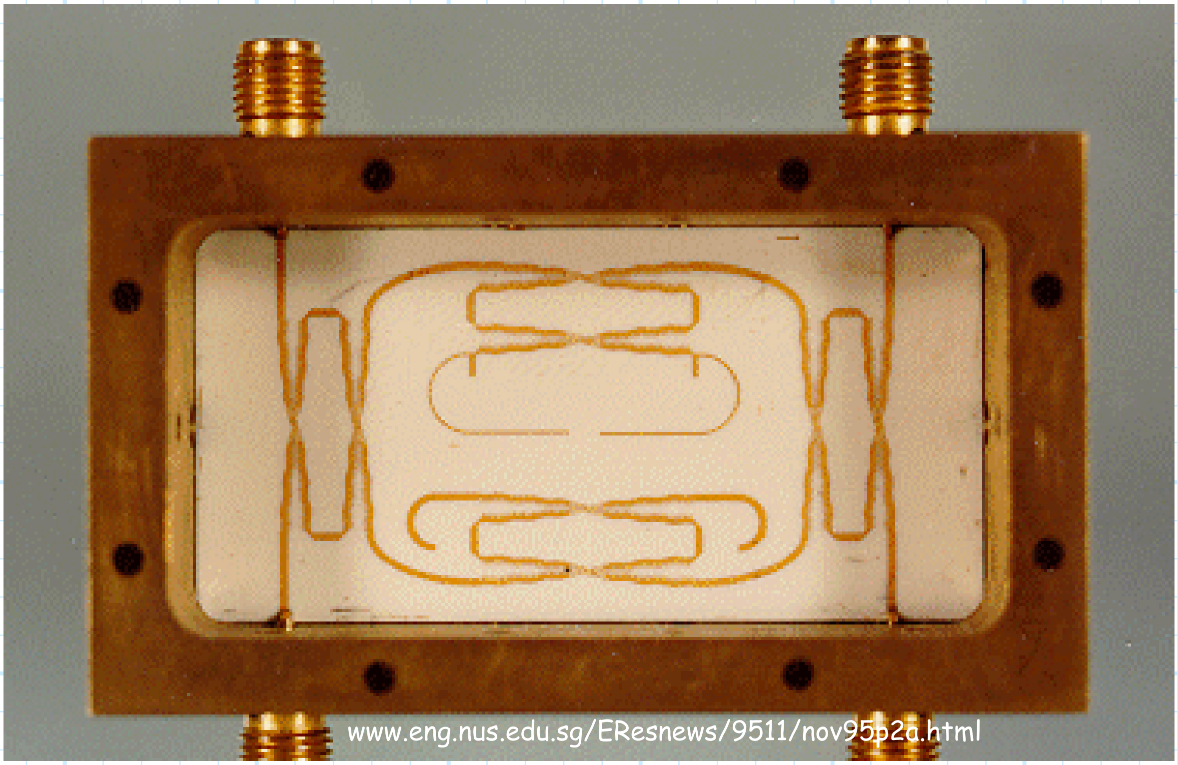


Slotline

Essentially, a dual wire tranmission line. Best for **"balanced"** applications. Not used much.



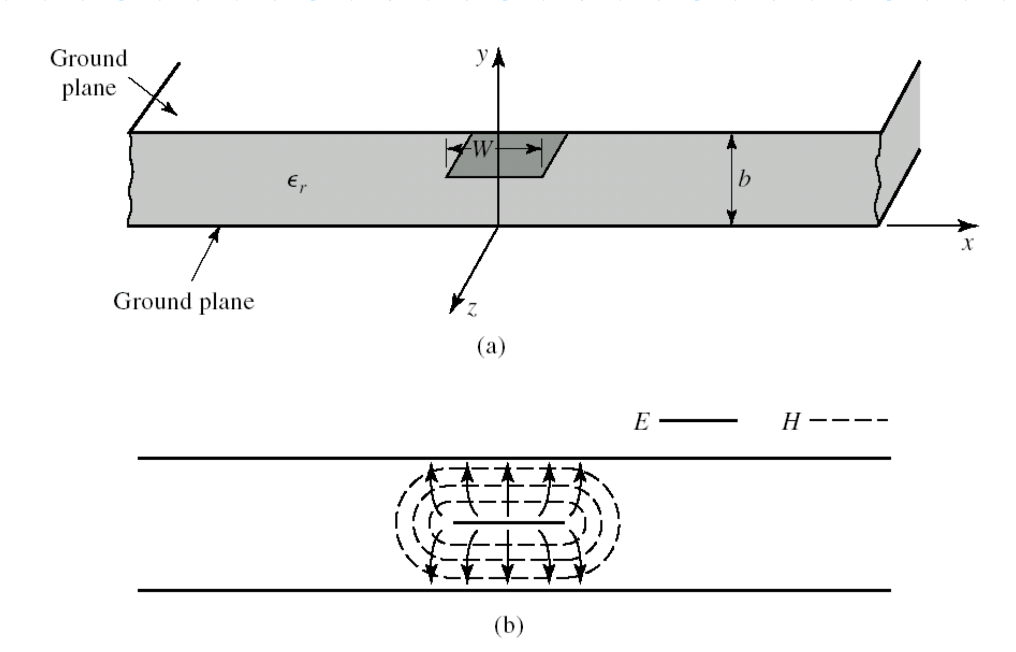
An antenna array feed, constructed using **microstrip** transmission lines and circuits.



A wideband **microstrip** coupler.

Stripline Transmission Lines

Stripline—a **TEM** transmission line!



The characteristic impedance is therefore:

$$Z_o = \sqrt{\frac{L}{C}}$$

and:

$$\begin{aligned}\beta &= \omega\sqrt{LC} \\ &= \omega\sqrt{\varepsilon\mu} \\ &= \frac{\omega}{c}\sqrt{\varepsilon_r}\end{aligned}$$

However, there are no **exact** analytic solutions for the capacitance and inductance of stripline—they must be numerically analyzed. However, we can use those results to form an analytic **approximation** of characteristic impedance:

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_e}} \frac{b/W_e}{1+0.441\ b/W_e}$$

where W_e is a value describing the **effective width** of the center conductor:

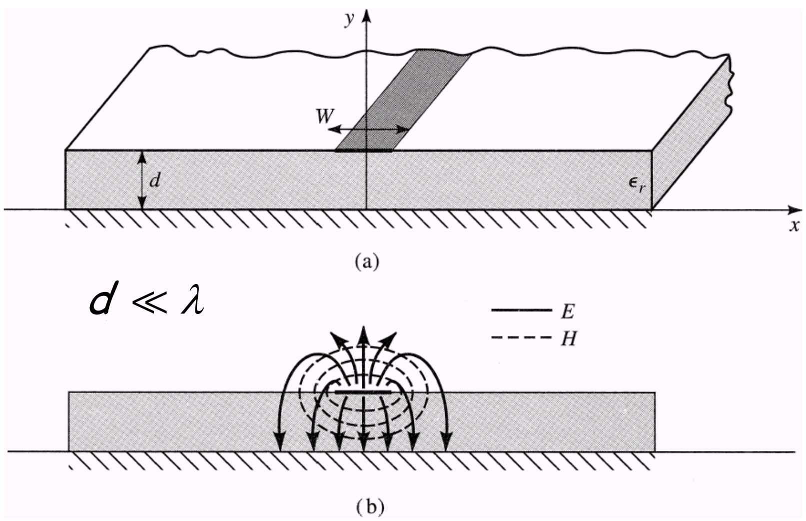
$$\frac{W_e}{b} = \frac{W}{b} - \begin{cases} 0 & \text{for } W/b > 0.35 \\ (0.35 - W/b)^2 & \text{for } W/b < 0.35 \end{cases}$$

Note that Z_0 is expressed in terms of the **unitless** parameter W/b, a coefficient value **analogous** to the ratio a/b used to describe **coaxial** transmission line geometry.

From the standpoint of stripline **design**, we typically want to determine the value W/b for a desired value Z_0 (i.e., the **inverse** of the equation above). This result is provided by equation 3.180 of your **textbook**.

Microstrip Transmission Lines

Microstrip—a **quasi**-TEM transmission line!



There are no **exact** analytic solutions for a microstrip transmission line—they must be **numerically** analyzed. However, we can use those results to form an analytic **approximation** of microstrip transmission line behavior.

The propagation constant β of a microstrip line is related to its **effective relative dielectric** ε_e:

$$\beta = \frac{\omega}{c}\sqrt{\varepsilon_e}$$

where:

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 12\, d/W}}$$

Note that $\varepsilon_e \neq \varepsilon_r$; in fact, $1 < \varepsilon_e < \varepsilon_r$.

Likewise, the characteristic impedance of a microstrip line is **approximately**:

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_e}} \ln\left(\dfrac{8d}{W} + \dfrac{W}{4d}\right) & \text{for } W/d \leq 1 \\ \\ \dfrac{120\pi}{\sqrt{\varepsilon_e}\left[W/d + 1.393 + 0.667 \ln\left(W/d + 1.444\right)\right]} & \text{for } W/d \geq 1 \end{cases}$$

Note that both transmission line parameters are expressed in terms of the **unitless** parameter W/d, a coefficient value **analogous** to the ratio a/b used to describe **coaxial** transmission line geometry.

From the standpoint of microstrip **design**, we typically want to determine the value W/d for a desired value Z_0 (i.e., the **inverse** of the equation above). This result is provided by equation 3.197 of your **textbook**.

A Comparison of Common Transmission Lines and Waveguides

Q: *Why don't we simply pick the **best** transmission line, and use it for **all** applications?*

A: **Every** transmission line design has its pros and cons—**none** is the best for all applications, and each is best for **some** applications.

Table 3.6 provides an accurate list of these pros and cons:

Characteristic	Coax	Waveguide	Stripline	Microstrip
Preferred Mode	TEM	TE_{10}	TEM	Quasi-TEM
Other Modes	TM, TE	TM, TE	TM, TE	TM, TE
Dispersion	None	Medium	None	Low
Bandwidth	High	Low	High	High
Loss	Medium	Low	High	High
Power Capacity	Medium	High	Low	Low
Physical Size	Large	Real Large	Medium	Small
Fabrication Ease	Medium	Medium	Easy	Real Easy
Component Integration	Hard	Hard	Fair	Easy