# 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**

## 3.7 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!

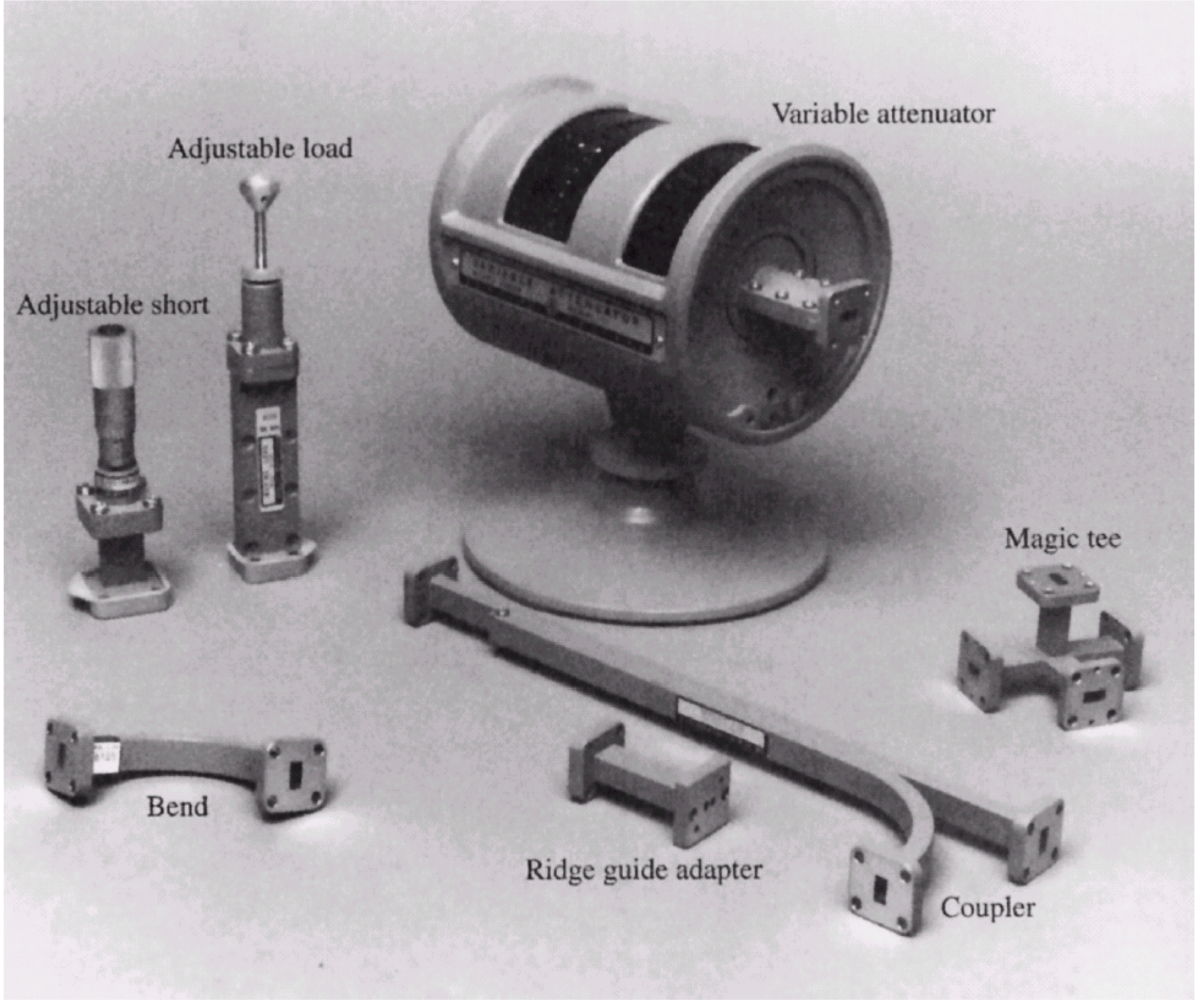
**Q:** *Yikes! So why would we ever use a waveguide?*

**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 $\alpha$).

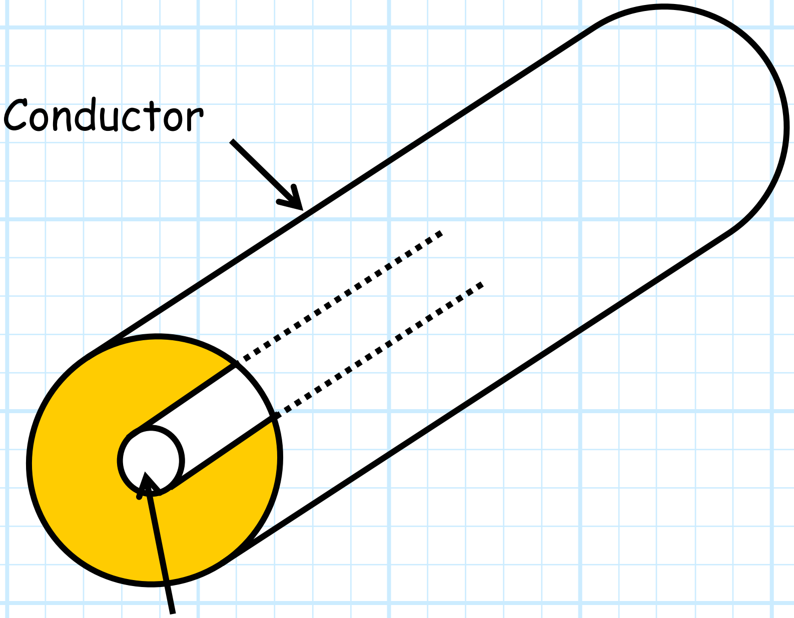
Thus, waveguide is typically used for **high-power** applications, such as high-power microwave **transmitters**.

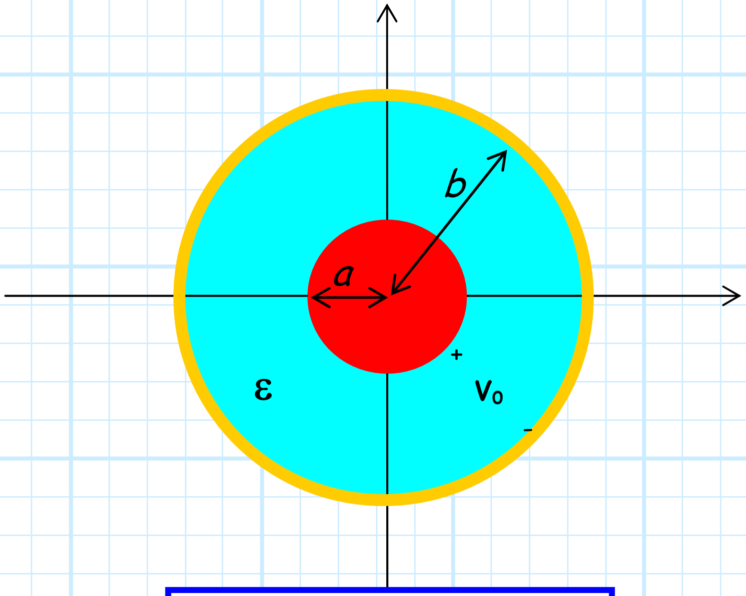
Waveguide appears at first to simply be a **pipe** (either circular or rectangular), and effectively it is—an **electromagnetic** pipe!



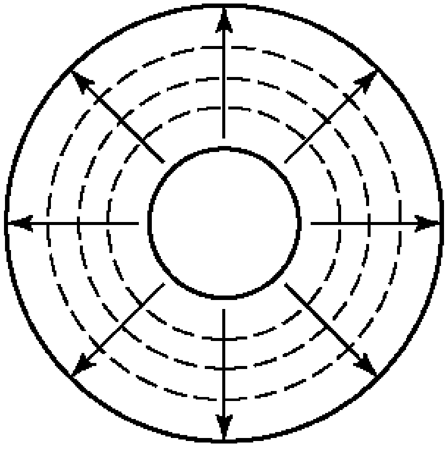
# Coaxial Transmission Lines

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!

# Remember EECS 220!!!

Recall from EECS 220 that we can use **electrostatics** to determine the **capacitance** per/unit length of a coaxial transmission line:

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

And from **magnetostatics** we find that the **inductance** per unit length is :

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

Combining these results, the **characteristic impedance** of a coaxial transmission line is:

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

and so:

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

# TEM Wave Propagation

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" ($c = 3 \times 10^8\ m/s$).Note then that we can likewise express $\beta$ in terms $\varepsilon_r$:

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

# Coax Geometry and Size

Now, the **size** of the coaxial line (*a* and *b*) determines **more** than simply $Z_0$ and $\beta$ (*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**; second, it can result in **dielectric breakdown**.

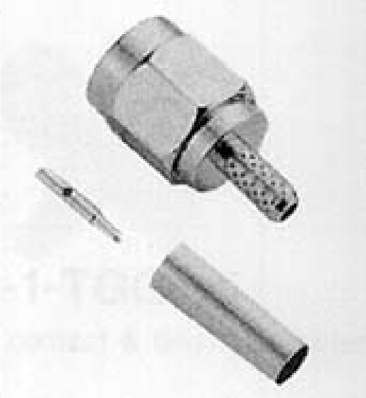
Dielectric breakdown results when the electric field within the transmission line becomes so large that the dielectric material is **ionized**. Suddenly, the dielectric becomes a **conductor**, and the value *G* gets **very** large!

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 $\ell$ 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**

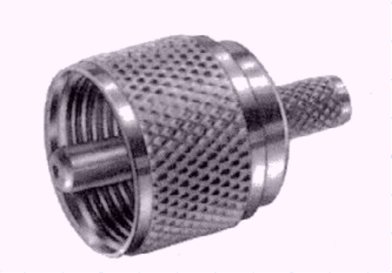
The workhorse **RF** connector. Relatively small and cheap, and easy to connect. Don't use this connector past 2 GHz!

**F**

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

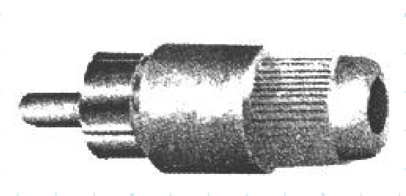
## N

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

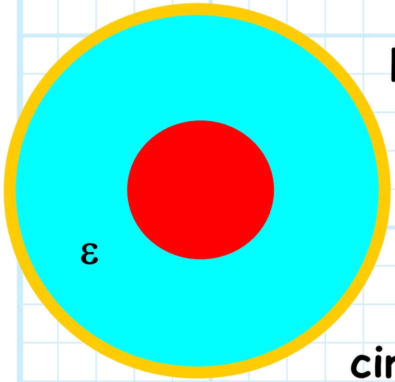
**Not really** an RF connector. Used primarily in consumer application for video and audio signals (i.e., <20 MHz). Cheap and easy to connect.

## 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

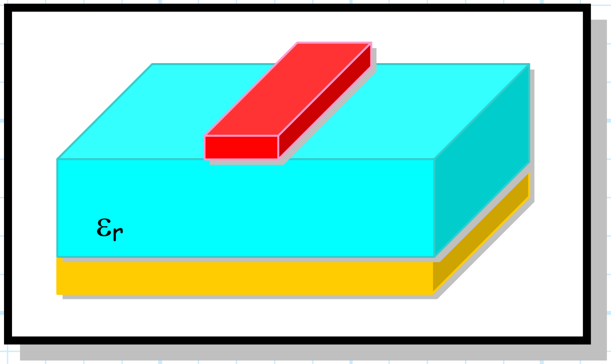
Recall that a transmission line **must** consist of **two separate conductors**. Typically, the volume between these conductors is filled with a very low-loss **dielectric**.



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.

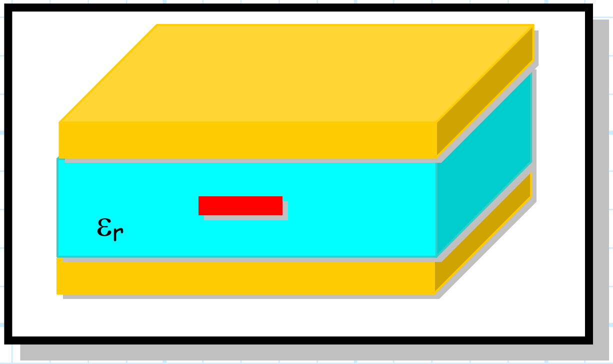
However, we can likewise construct a transmission line using **printed circuit board** technology. The **substrate** of the circuit board is the dielectric that separates two conductors. The first conductor is typically a **narrow** etch that provides the **connection** between two components, while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

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



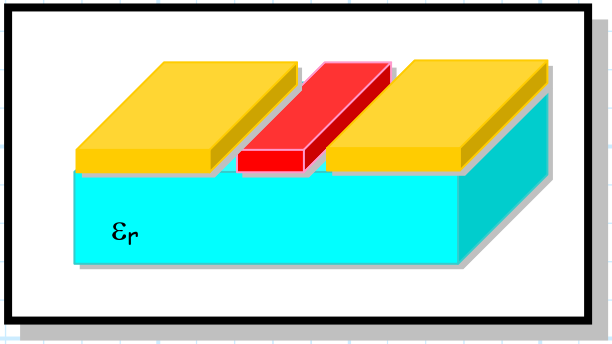
## Microstrip

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



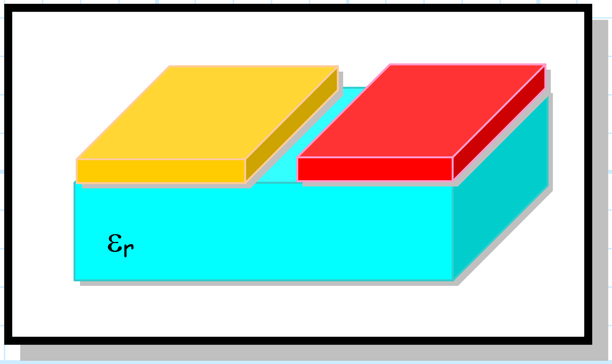
## Stripline

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



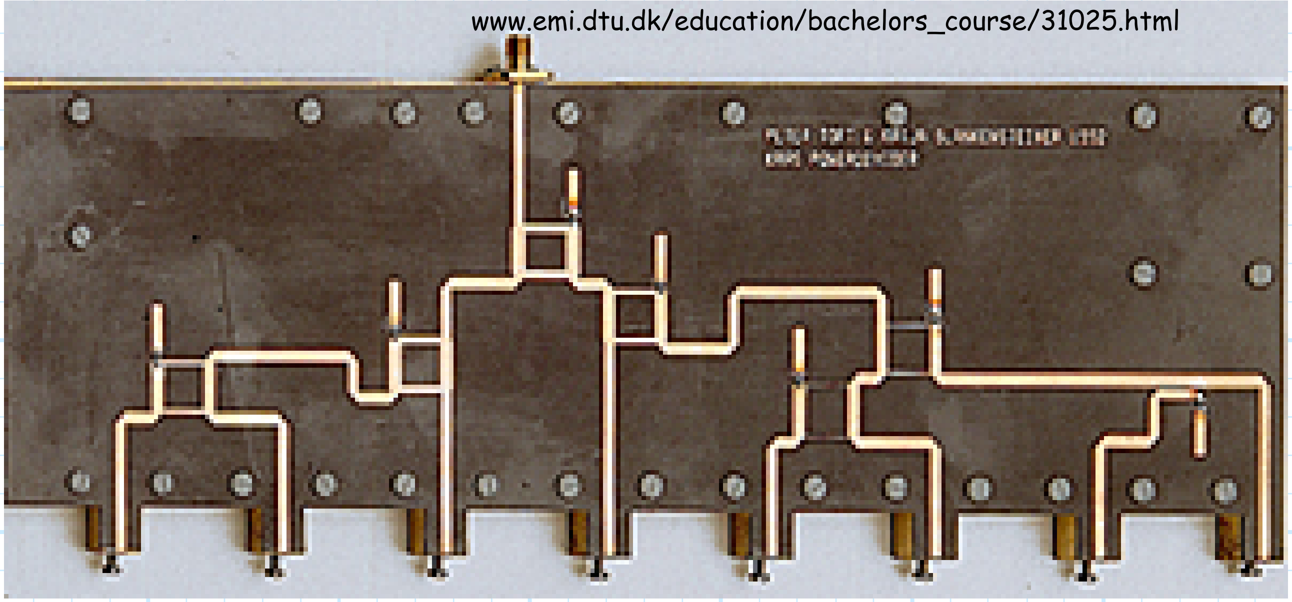
## Coplanar Waveguide

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



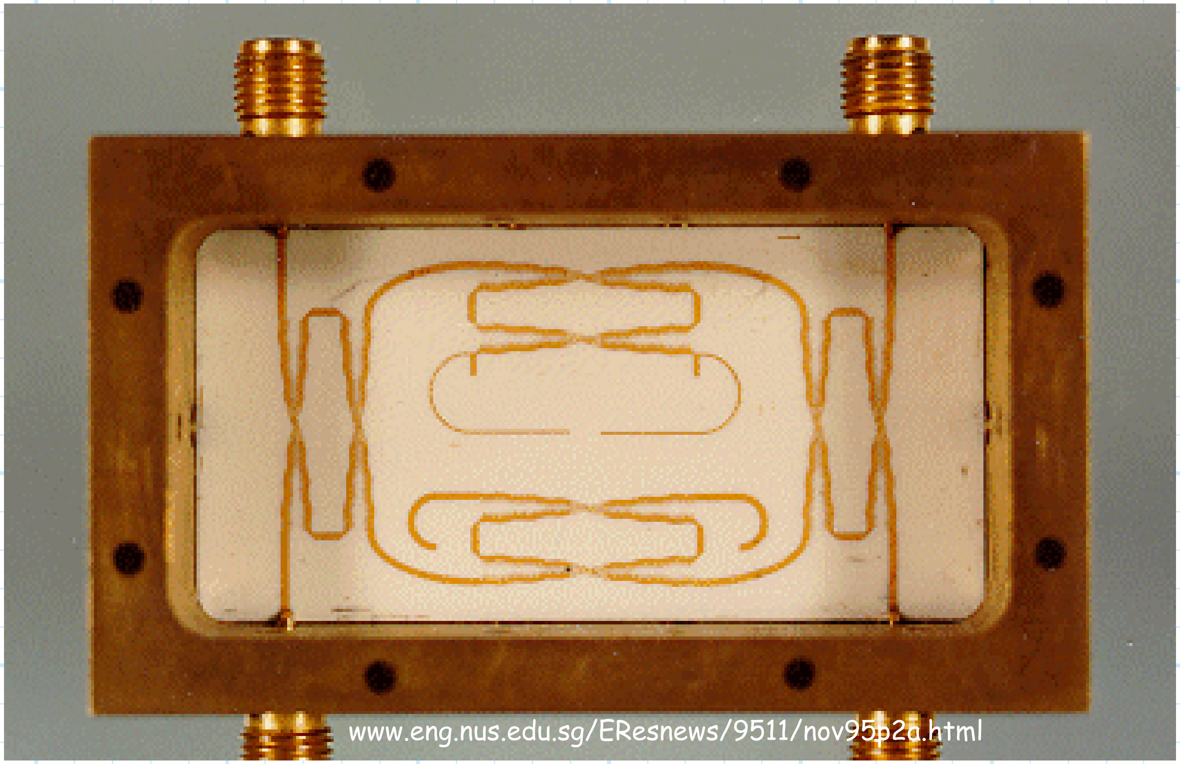
## Slotline

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



www.emi.dtu.dk/education/bachelors_course/31025.html

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

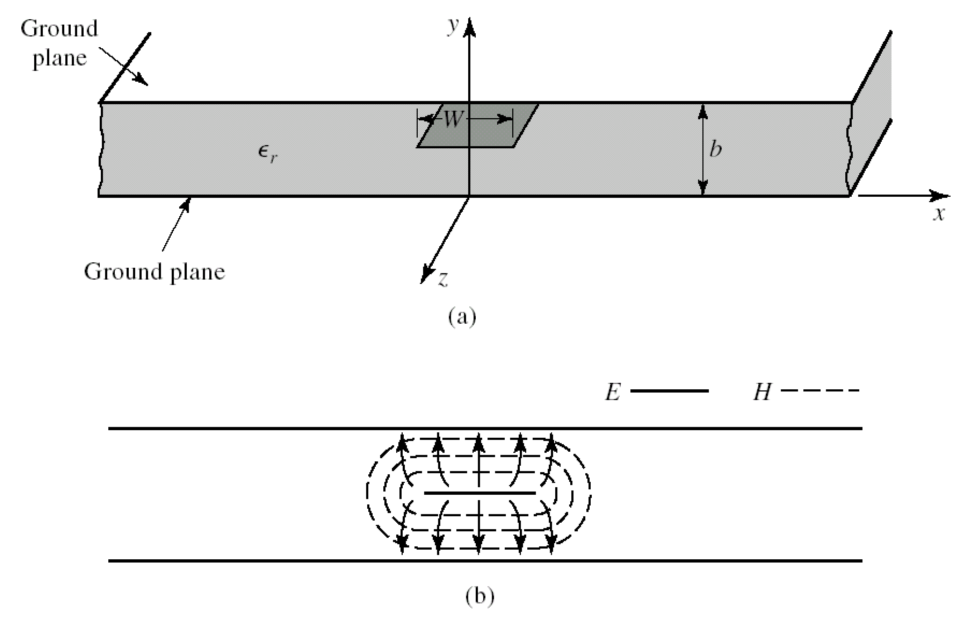


www.eng.nus.edu.sg/EResnews/9511/nov95b2a.html

A wideband **microstrip** coupler.

# Stripline Transmission Lines

Stripline—a **TEM** transmission line!



The characteristic impedance **is** therefore:

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

and:

$$\beta = \omega\sqrt{LC} = \omega\sqrt{\varepsilon\mu} = \frac{\omega}{c}\sqrt{\varepsilon_r}$$

**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:

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

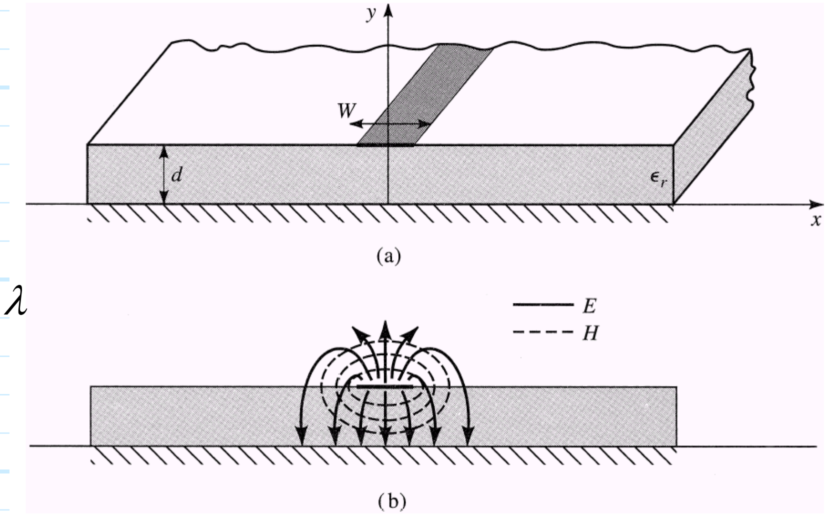
Note that $Z_0$ is expressed in terms of the **unitless** parameter $W/b$, a coefficient value **analogous** to the ratio $a/b$ used to describe **coaxial** transmission line geometry.

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!

$d \ll \lambda$



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 $\beta$ of a microstrip line is related to its **effective relative dielectric** $\varepsilon_e$:

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

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**:

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_e}}\, ln\left(\dfrac{8d}{W} + \dfrac{W}{4d}\right) & \text{for } W/d \leq 1 \\[2ex] \dfrac{120\pi}{\sqrt{\varepsilon_e}\left[W/d + 1.393 + 0.667\, ln\left(W/d + 1.444\right)\right]} & \text{for } W/d \geq 1 \end{cases}$$

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 |