Microwave Engineering

(EC0505)

Unit-1

B.Tech. (Electronics and Communication)

Semester-V

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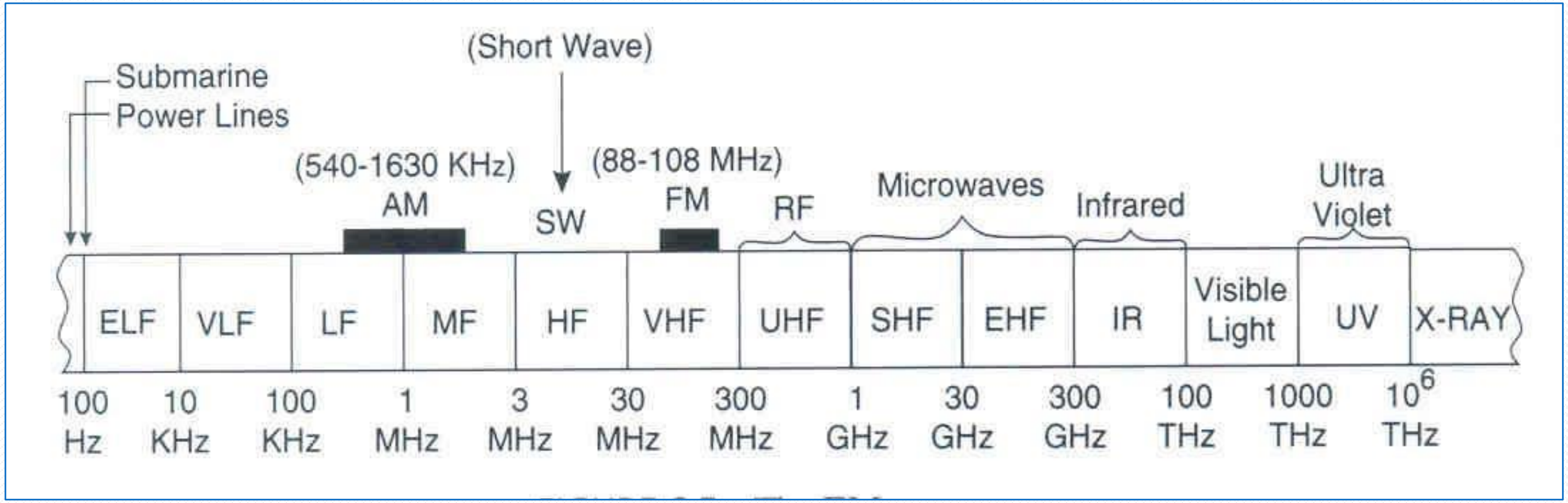
Academic Year 2019-2020

Introduction to Microwave Engineering and EM wave Propagation

Microwaves

- **Microwaves** are a form of electromagnetic radiation **with wavelengths ranging from one meter to one millimeter**; with frequencies between 300 MHz (100 cm) and 300 GHz (0.1 cm)



IEEE specified Microwave Bands

Designation	Frequency range	Typical uses
L band	1 to 2 GHz	military telemetry, GPS, mobile phones (GSM), amateur radio
S band	2 to 4 GHz	weather radar, surface ship radar, and some communications satellites (microwave ovens, microwave devices/communications, radio astronomy, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS, amateur radio)
C band	4 to 8 GHz	long-distance radio telecommunications
X band	8 to 12 GHz	satellite communications, radar, terrestrial broadband, space communications, amateur radio
K_u band	12 to 18 GHz	satellite communications

K band	**18 to 26.5 GHz**	**radar, satellite communications, astronomical observations**
K_a band	**26.5 to 40 GHz**	**satellite communications**
Q band	**33 to 50 GHz**	**satellite communications, terrestrial microwave communications, radio astronomy**
U band	**40 to 60 GHz**	**millimeter wave radar research and other kinds of scientific research**
V band	**50 to 75 GHz**	**millimeter wave radar research and other kinds of scientific research**
W band	**75 to 110 GHz**	**satellite communications, millimeter-wave radar research, military radar targeting and tracking applications**

Microwave Applications

- Today, the majority of applications of microwaves are related to ***radar and communication systems.***

- ***Radar systems*** are used for detecting and locating targets and for air traffic control systems, missile tracking radars, automobile collision avoidance systems, weather prediction, motion detectors, and a wide variety of remote sensing systems.

- Microwave communication systems handle a large fraction of the world's international and other long haul ***telephone, data and television transmissions.***

- Most of the currently developing wireless telecommunications systems, such as ***direct broadcast satellite (DBS) television, personal communication systems (PCSs), wireless local area networks (WLANS), cellular video (CV) systems, and global positioning satellite (GPS) systems*** rely heavily on microwave technology.

ADVANTAGES OF MICROWAVE ENGINEERING

- Antenna gain is proportional to the electrical size of the antenna. At higher frequencies, more antenna gain is therefore possible for a given physical antenna size, which has important consequences for implementing ***miniaturized microwave*** systems.

- ***More bandwidth*** can be realized at higher frequencies. Bandwidth is critically important because available frequency bands in the electromagnetic spectrum are being rapidly depleted.

- Microwave signals travel by ***line of sight &*** are not bent by the ionosphere and thus satellite and terrestrial communication links with very high capacities are possible.

- Various molecular, atomic, and nuclear ***resonances occur at microwave frequencies,*** creating a variety of unique applications in the areas of basic science, remote sensing, medical diagnostics and treatment, and heating methods.

Advantages in using Microwaves:

- ➢ Wider bandwidth due to higher frequency
- ➢ Smaller component size leading to smaller systems
- ➢ More available frequency spectrum with low interference.
- ➢ High antenna gain possible in a smaller space

Some Disadvantages in using Microwaves:

- ➢ More expensive components
- ➢ Existence of higher signal losses
- ➢ Use of high-speed semiconductor devices

A SHORT HISTORY OF MICROWAVE ENGINEERING

- Modern electromagnetic theory was formulated in 1873 by James Clerk Maxwell solely from mathematical considerations.
- Maxwell's formulation was cast in its modern form by Oliver Heaviside, during the period 1885 to 1887.
- Heinrich Hertz, a German professor of physics understood the theory published by Maxwell, carried out a set of experiments during 1887-1891 that completely validated Maxwell's theory of electromagnetic waves.
- It was only in the 1940's (World War II) that microwave theory received substantial interest that led to radar development.
- Communication systems using microwave technology began to develop soon after the birth of radar.
- The advantages offered by microwave systems, wide bandwidths and line of sight propagation, provides an impetus for the continuing development of low cost miniaturized microwave components.

Maxwell's equations

- **For Static fields ($\delta/\delta t=0$) Maxwell's equations are:**

$$\nabla \bullet D = \rho; \quad \nabla \bullet B = 0; \quad \nabla \times E = 0; \quad \nabla \times H = J$$

- **For Time varying fields Maxwell's equations are:**

$$\nabla \bullet D = \rho; \quad \nabla \bullet B = o; \quad \nabla \times E = - \delta B/\delta t; \quad \nabla \times H = J + \delta D/\delta t$$

- Faradays Law($\nabla \times E = - \delta B/\delta t$) shows that time-varying H-field is a source of electric field (E).

- Ampere's Law ($\nabla \times H = J + \delta D/\delta t$) shows that both electric-current (J) or time-varying E-field are sources for the magnetic field (H).

- Thus, in source-free region ($\rho=0$ and $J=0$), time varying electric and magnetic fields can generate each other.

- Consequently, EM fields are self sustaining,thus predicting the phenomenon of EM wave propagation.

THE WAVE EQUATION

- In a source-free, region, Maxwell's curl equations are

$$\nabla \times \bar{E} = -j\omega\mu\bar{H},$$
$$\nabla \times \bar{H} = j\omega\epsilon\bar{E},$$

- Take curl on both the side,

$$\nabla \times \nabla \times \bar{E} = -j\omega\mu\nabla \times \bar{H} = \omega^2\mu\epsilon\bar{E},$$

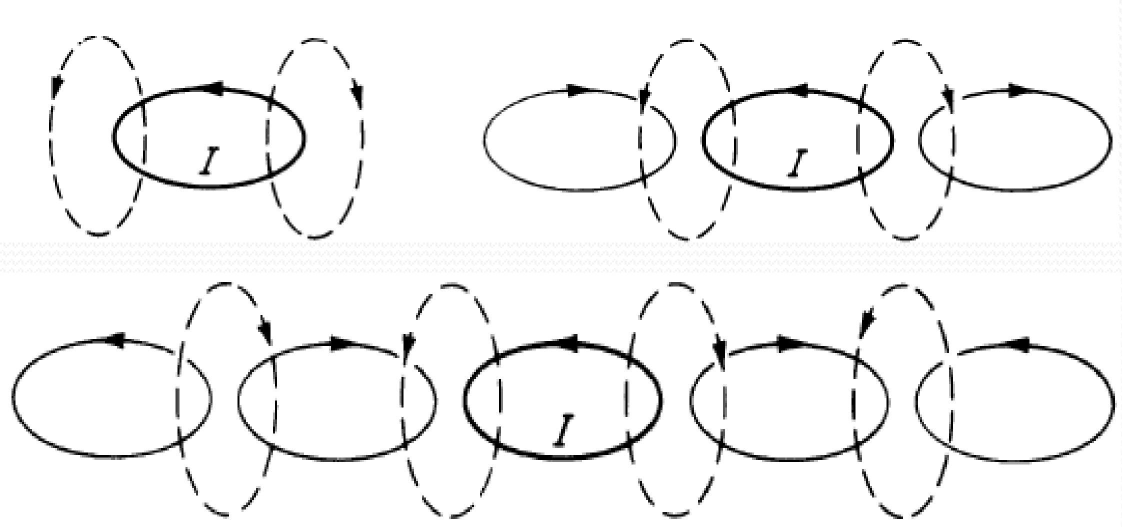
$$\nabla^2\bar{E} + \omega^2\mu\epsilon\bar{E} = 0,$$

- The above equation is the wave equation, or Helmholtz equation, for E

- An identical equation for *H can be*

$$\nabla^2 \bar{H} + \omega^2 \mu \epsilon \bar{H} = 0.$$

- Consider a loop of wire in which a current varying with time flows as in Fig.



- The conduction current causes a circulation, or curling, of the magnetic field around the current loop

- The changing magnetic field in turn creates a circulating, or curling, electric field, with field lines that encircle the magnetic field lines.
- This changing electric field creates further curling magnetic field lines.
- The net result is the continual growth and spreading of the electromagnetic field into all space surrounding the current loop.

Plane Waves in a Lossless Medium

- In a lossless medium, ε and μ are real numbers, and so k is real.
- A basic plane wave solution to the above wave equations can be found by considering an **electric field with only an x component and uniform (no variation) in the x and y directions.**
- The Wave equation reduces to

$$\frac{\partial^2 E_x}{\partial z^2} + k^2 E_x = 0.$$

- The two independent solutions to this equation are easily obtained

$$E_x(z) = E^+ e^{-jkz} + E^- e^{jkz},$$

- In the time domain, this result is written as

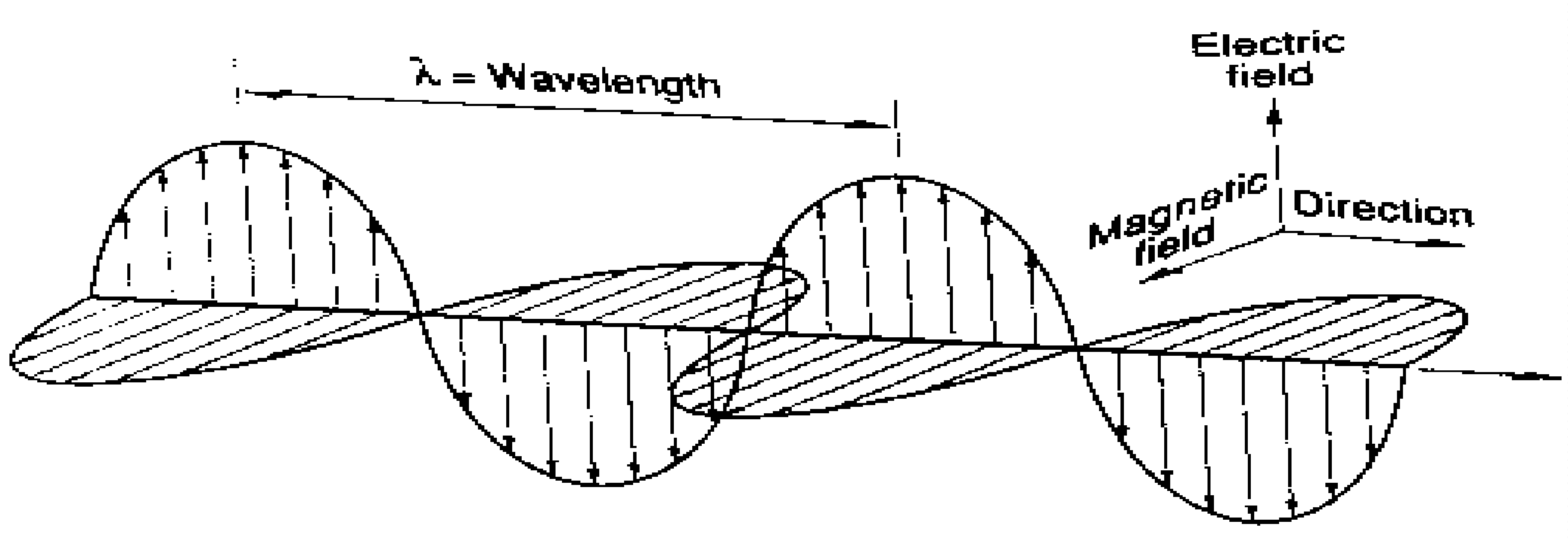
$$\mathcal{E}_x(z,\ t) = E^+ \cos(\omega t - kz) + E^- \cos(\omega t + kz),$$

- Consider the first term, this term represents a wave traveling in the +z direction and second term represents a wave traveling in the -z direction.

- **The velocity at which a fixed phase point on the wave travels is called the phase velocity,**

$$v_p = \frac{dz}{dt} = \frac{d}{dt}\left(\frac{\omega t - \text{constant}}{k}\right) = \frac{\omega}{k} = \frac{1}{\sqrt{\mu\epsilon}}$$

Plane TEM wave:



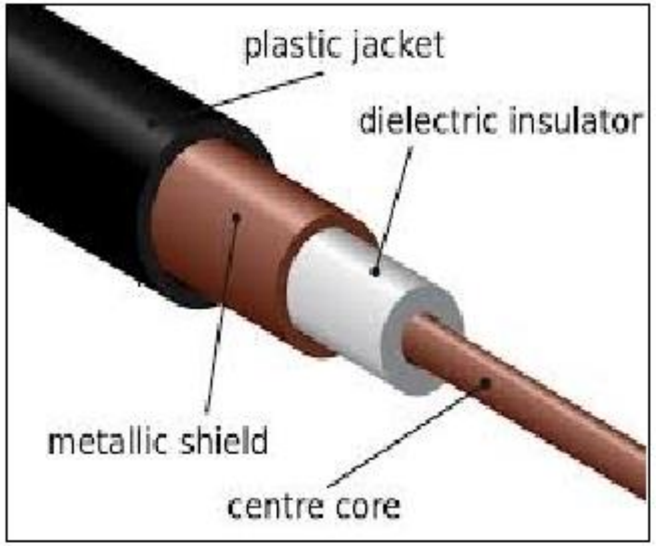
RF/MW versus DC/Low-AC signals:

- In LF, mostly *l*<<λ , thus I & V are constant in line. (*l*=device length)

  In HF, mostly *l*>> λ, thus I & V are not constant in the line.

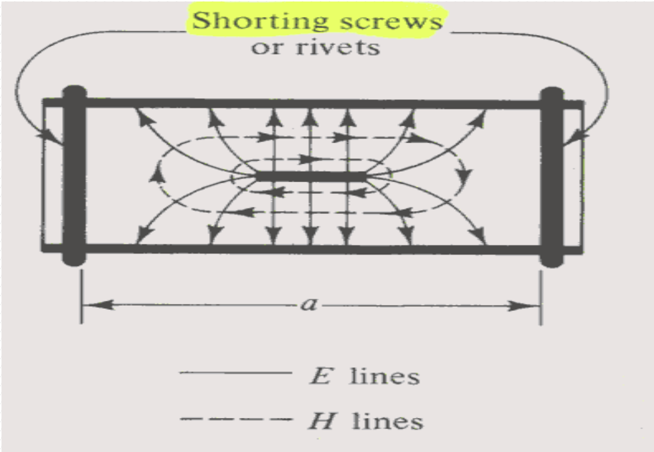
Low frequency Electronics	High frequency Electronics
Lumped Parameter Analysis	Distributed Parameter Analysis
Length is small compared to wavelength	Length is large compared to wavelength
Propagation delay is not comparable to period of oscillation of signal	Propagation delay is comparable to period of oscillation of signal
Voltage & Current are time harmonic only, they are called phasors.	Voltage & current are time & distance harmonic, they are called travelling waves.
Analysis using KCL, KVL and Ohm's law	Analysis using Maxwell's Equations
Circuit Components: R,L,C, transistor, diode	Circuit Components: Transmission line, waveguide, Tee junctions.
If load mismatches, Power remains stored in L & C components.	If load mismatches, Power remains stored as standing wave pattern on the line.

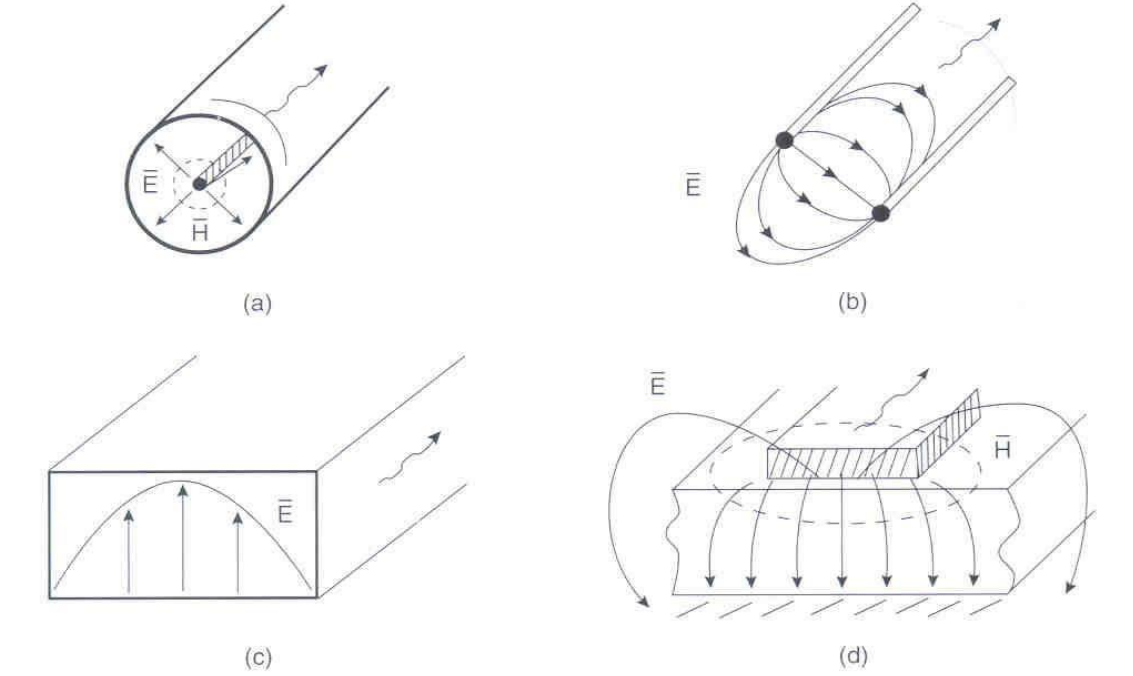
Rigid & Flexible Co-axial lines



Guided Transmission Media

- Coaxial TL: Low radiation, freq. range up to 3GHz, support TEM mode
- Two-wire TL: Low radiation, freq. up to 300 MHz, support TEM mode
- Waveguide: For high freq. high power signals, Support **TE/TM** modes.
- Microstrip: Losy, quasi-TEM modes, high bandwidth, easy integration
- Stripline: Less losy, **TEM**, high bandwidth, low power capacity





TEM: E.& H.field comp. are ⊥ to each other and also to direc. of prop.

The transverse modes are classified into different types:

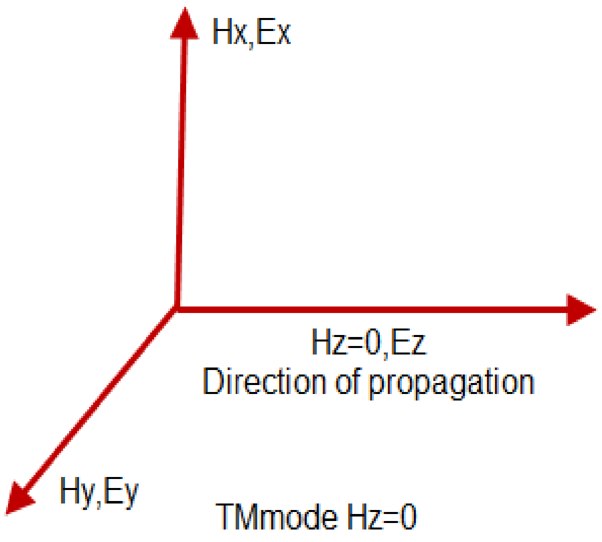
• TE modes (Transverse Electric) have no electric field in the direction of propagation.

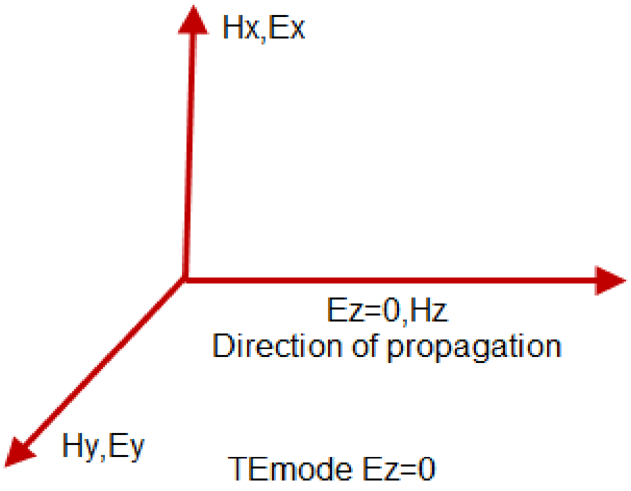
•TM modes (Transverse Magnetic) have no magnetic field in the direction of propagation.

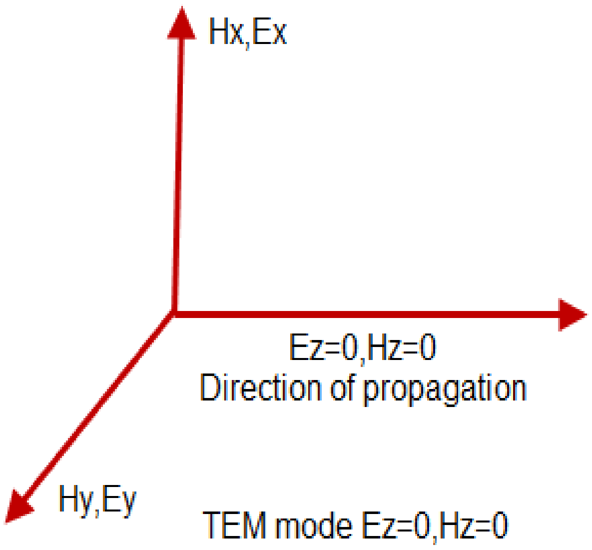
•TEM modes (Transverse Electromagnetic) have no electric nor magnetic field in the direction of propagation.

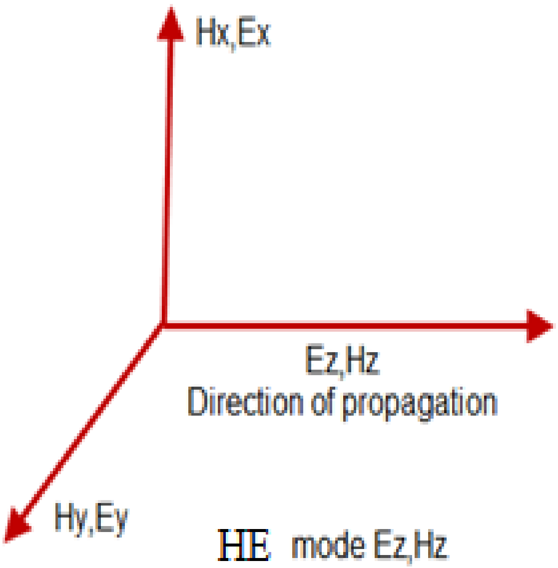
•Hybrid modes have both electric and magnetic field components in the direction of propagation.

TEM mode is only possible with two conductors and cannot exist in a waveguide.


Hx,Ex
Hz=0,Ez
Direction of propagation
Hy,Ey
TMmode Hz=0


Hx,Ex
Ez=0,Hz
Direction of propagation
Hy,Ey
TEmode Ez=0


Hx,Ex
Ez=0,Hz=0
Direction of propagation
Hy,Ey
TEM mode Ez=0,Hz=0


Hx,Ex
Ez,Hz
Direction of propagation
Hy,Ey
HE mode Ez,Hz

Transmission Lines

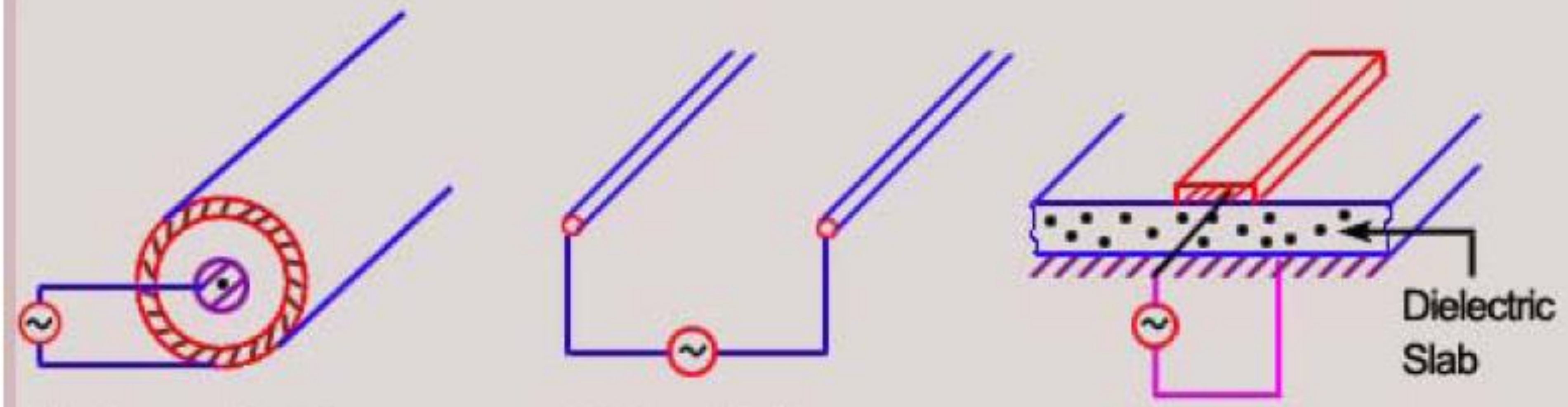
What is Transmission Line?

- It is the guided media through which electrical signal at high frequency (i.e. RF signal) can be transported from one point to another.
- They propagate the RF signal in form of guided Electromagnetic fields.

❖ Applications:

1. As feed lines to connect the transmitter and receiver with Tx & Rx Antennas respectively
2. To distribute the TV & Power signals
3. For the computer network connections

Various Types Of Transmission Lines

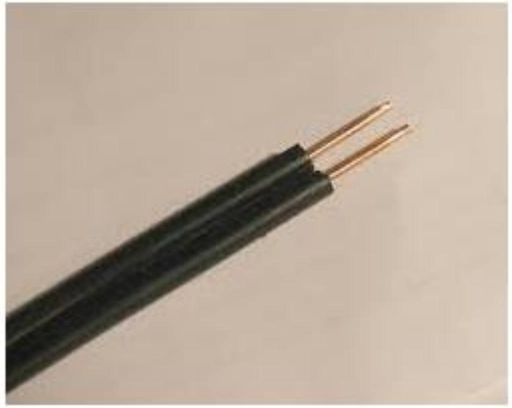


(a) Co - axial cable

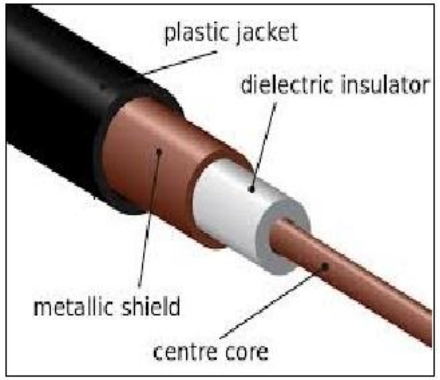
(b) Parallel wire Transmission line

(c) Microstrip line

Twin lead line & Co-axial lines

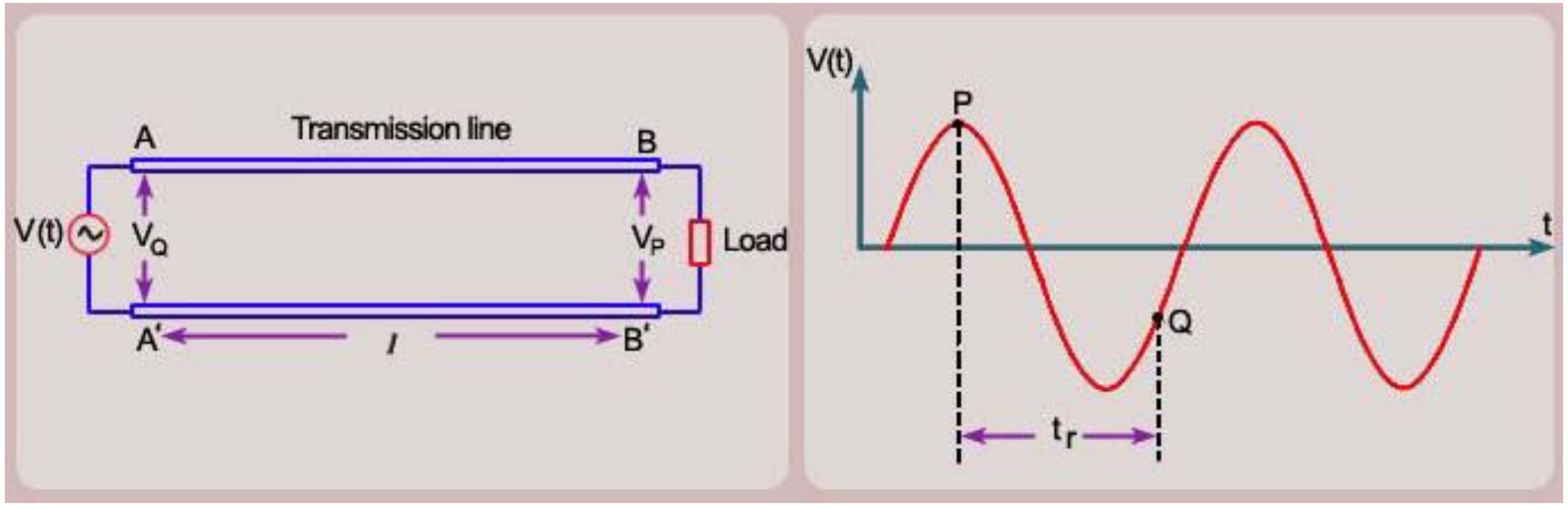


2 wire parallel transmission line



Flexible & rigid co-axial line

Transit Time Effect



- Transit time is **time delay required by signal to propagate from source to the load terminals of transmission line.**

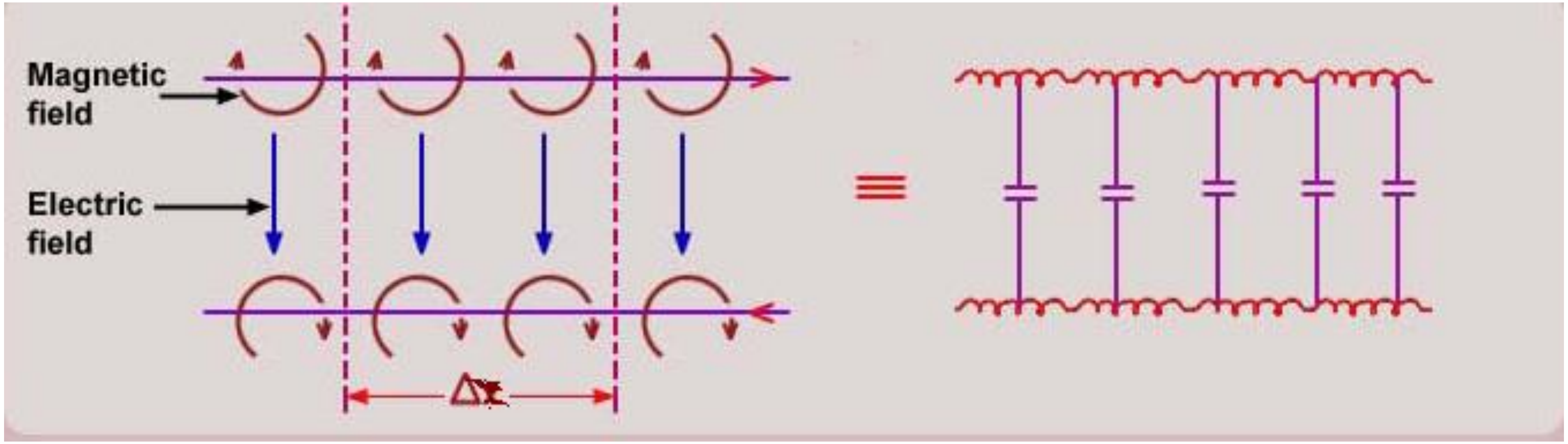
- Transit time effect is important when **period of oscillation of signal is comparable to the transit time delay.**

- That is when length of the circuit is larger than the signal wavelength ; $l >> \lambda$

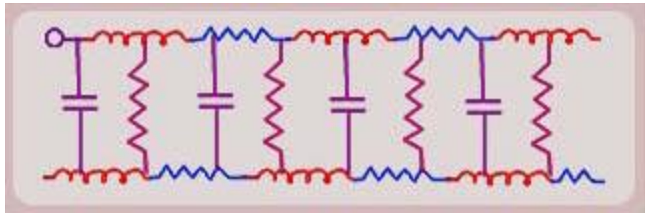
Field Theory	Circuit Theory
❑The dimensions are fraction of a wavelength or many wavelengths ,in size.	❑The physical dimensions of the network is very less comparatively with the wavelength.
❑distributed parameter network, where the voltages & currents can vary in magnitude and phase over its length.	❑Lumped parameter network, where voltages and currents are constant over the length of the circuit. They may be time harmonic but not distance dependant.
❑Analysis based on Maxwell's equations	❑Analysis based on Kirchoff's laws and Ohm's law.
❑Useful for RF and micorwave signals (range from MHz to GHz)	❑Useful for low frequency electrical signals (range up to few KHz)

Distributed Circuit Elements

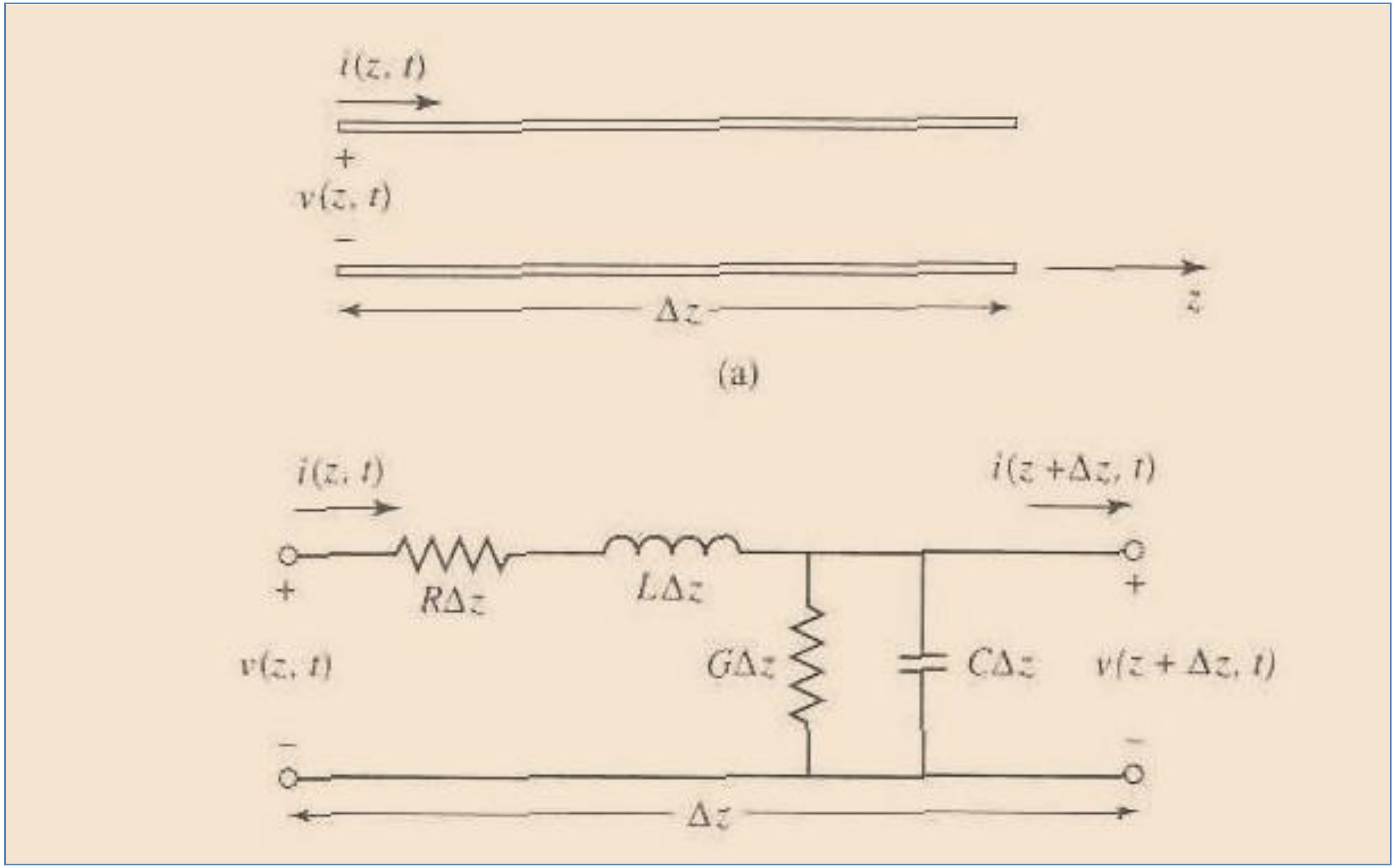
- Consider a small section of the line such that its length $\Delta z << \lambda$, the transit time effect would be negligible and consequently the Kirchoff's laws can be applied.



Electromagnetic fields on 2- wire line



Equivalent Lumped circuit Model



- **<u>Distribute parameters can be defined per unit length of the line.</u>**

  R = Resistance of both conductors together for unit length of the line (ohms/m)

  L = Inductance (self and mutual) for both conductors together for unit length of the line (Henery/m)

  C = Capacitance between two conductors for unit length of the line (Farad/m)

  G = Leakage conductance between two conductors for unit length of the line (Mho/m).

- By KVL in the circuit

$$v(z,t) - R\Delta z i(z,t) - L\Delta z \frac{\partial i(z,t)}{\partial t} - v(z+\Delta z, t) = 0.$$

- By KCL in the circuit,

$$i(z,t) - G\Delta z v(z+\Delta z,t) - C\Delta z \frac{\partial v(z+\Delta z,t)}{\partial t} - i(z+\Delta z,t) = 0.$$

- By dividing the above two equations by Δz and taking Δz ⟶ 0

$$\frac{\partial v(z,t)}{\partial z} = -Ri(z,t) - L\frac{\partial i(z,t)}{\partial t},$$

$$\frac{\partial i(z,t)}{\partial z} = -Gv(z,t) - C\frac{\partial v(z,t)}{\partial t}.$$

- These equations are the time domain form of the transmission line. (**Telegrapher Equations)**

- **The wave equations for V(z) and I(z) can be written as,**

$$\frac{d^2V(z)}{dz^2} - \gamma^2 V(z) = 0,$$

$$\frac{d^2I(z)}{dz^2} - \gamma^2 I(z) = 0,$$

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

Where, γ is the complex propagation constant.

- The solution of the above equations are,

$$V(z) = V_o^+ e^{-\gamma z} + V_o^- e^{\gamma z},$$

$$I(z) = I_o^+ e^{-\gamma z} + I_o^- e^{\gamma z},$$

- From the above equations, we get,

$$I(z) = \frac{\gamma}{R + j\omega L}\left[V_o^+ e^{-\gamma z} - V_o^- e^{\gamma z}\right].$$

- And the characteristic impedance is given by,

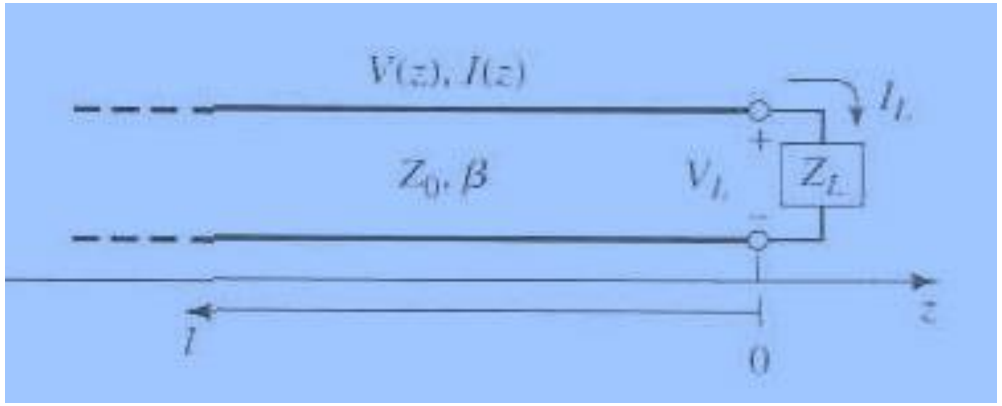
$$Z_0 = \frac{R + j\omega L}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}},$$

- For lossless, transmission line,

$$Z_0 = \sqrt{\frac{L}{C}},$$

Transmission Line and Reflection Coefficient

- A lossless transmission line terminated in an arbitrary load impedance Z_L.
- An incident wave of the form is generated from the source and the ratio of voltage to current for such a traveling wa $V_0^+ e^{-j\beta z}$
- But when the line is terminated in an arbitrary load $Z_L = Z_0$, the ratio of voltage to current at the load must be Z_L.



- **Thus, a reflected wave must be excited with appropriate amplitude to satisfy this condition.**
- The total voltage on the line is sum of incident and reflected waves.

$$V(z) = V_o^+ e^{-j\beta z} + V_o^- e^{j\beta z}.$$

- Similarly, the total current on the line is,

$$I(z) = \frac{V_o^+}{Z_0} e^{-j\beta z} - \frac{V_o^-}{Z_0} e^{j\beta z}.$$

- The total voltage and current at the load are related by the load impedance.

$$Z_L = \frac{V(0)}{I(0)} = \frac{V_o^+ + V_o^-}{V_o^+ - V_o^-} Z_0.$$

- This gives,

$$V_o^- = \frac{Z_L - Z_0}{Z_L + Z_0} V_o^+.$$

- **The amplitude of the reflected voltage wave to the amplitude of the incident voltage wave is defined as the voltage reflection coefficient Γ at load end (z=0).**

$$\Gamma = \frac{V_o^-}{V_o^+} = \frac{Z_L - Z_0}{Z_L + Z_0}.$$

- **The transmission line provides a medium of impedance Zo for the energy flow. Any departure from Zo disrupts the smooth flow of energy and the part of the energy is reflected. Larger the impedance step more is the reflected energy and higher the reflection coefficient.**
- The total voltage and current waves on the line are,

$$V(z) = V_o^+ \left[e^{-j\beta z} + \Gamma e^{j\beta z}\right],$$

$$I(z) = \frac{V_o^+}{Z_0} \left[e^{-j\beta z} - \Gamma e^{j\beta z}\right].$$

- **It is seen that the voltage and current on the line consist of a superposition of an incident and reflected wave; such wave are called standing waves.**

- **Only when Γ=0, there is no reflected wave. To obtain Γ=0, the load impedance must be equal to the characteristic impedance of the transmission line.**
- Such a load is then said to be matched load and there is no reflection of the incident wave. (flat line)
- The time average power flow along the line,

$$P_{av} = \frac{1}{2}\text{Re}\left[V(z)I(z)^*\right] = \frac{1}{2}\frac{|V_o^+|^2}{Z_0}\text{Re}\left\{1 - \Gamma^* e^{-2j\beta z} + \Gamma e^{2j\beta z} - |\Gamma|^2\right\},$$

- The middle two terms are of the form $A-A^* = 2j\,\text{Im}(A)$ means purely imaginary.

$$P_{av} = \frac{1}{2}\frac{|V_o^+|^2}{Z_0}\left(1 - |\Gamma|^2\right)$$

- **Which shows that the average power flow is constant at any point on the line. Total power delivered to load is equal to the incident power minus reflected power.**

- $\Gamma=0$, the maximum power is delivered to the load, while no power is delivered for $\Gamma=-1$ or 1.

- When the load is mismatched, not all of the available power from the generator is delivered to the load. **This "loss" is called return loss RL and it is given by,**

$$RL = -20 \log |\Gamma| \text{ dB},$$

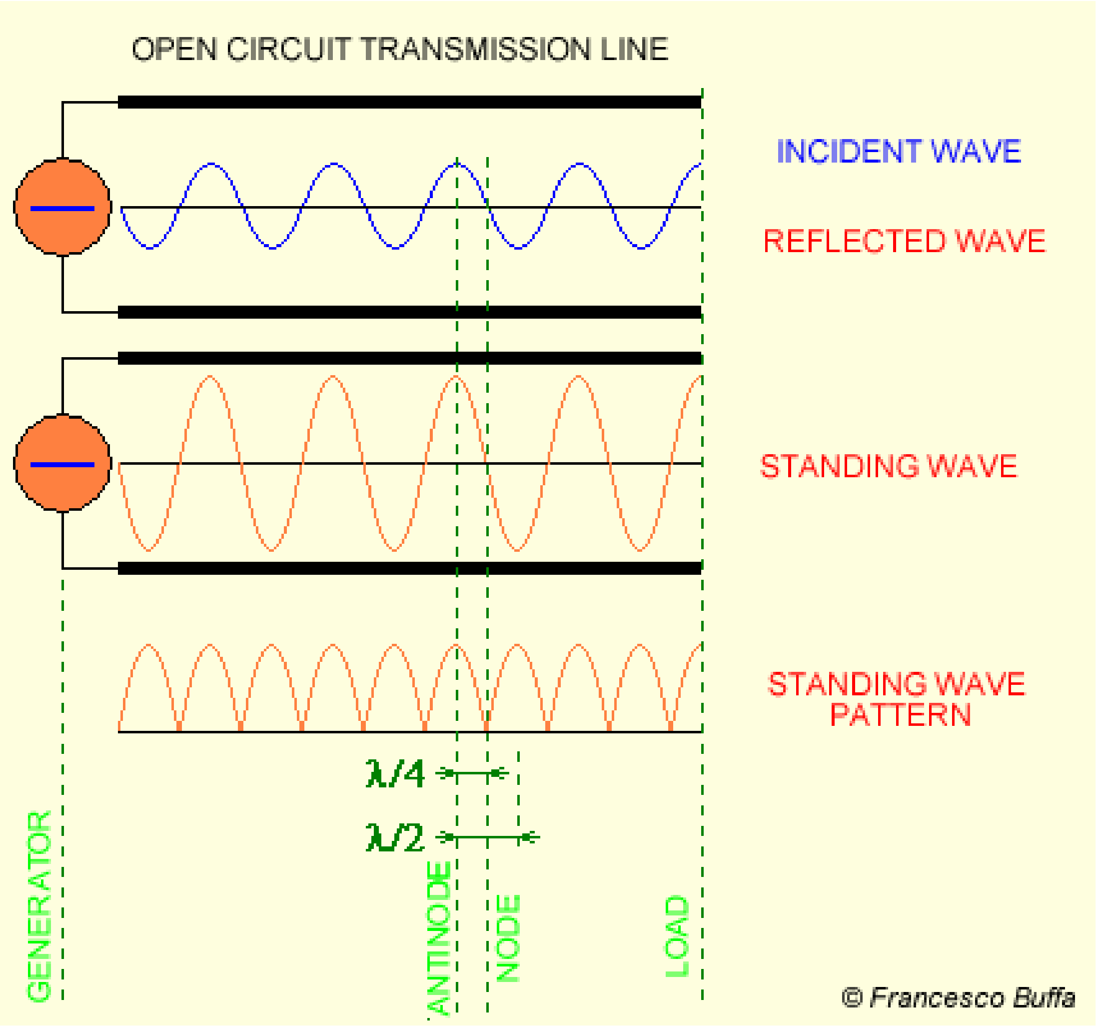
- **The return loss indicates the factor by which the reflected signal is down compared to the incident signal.**

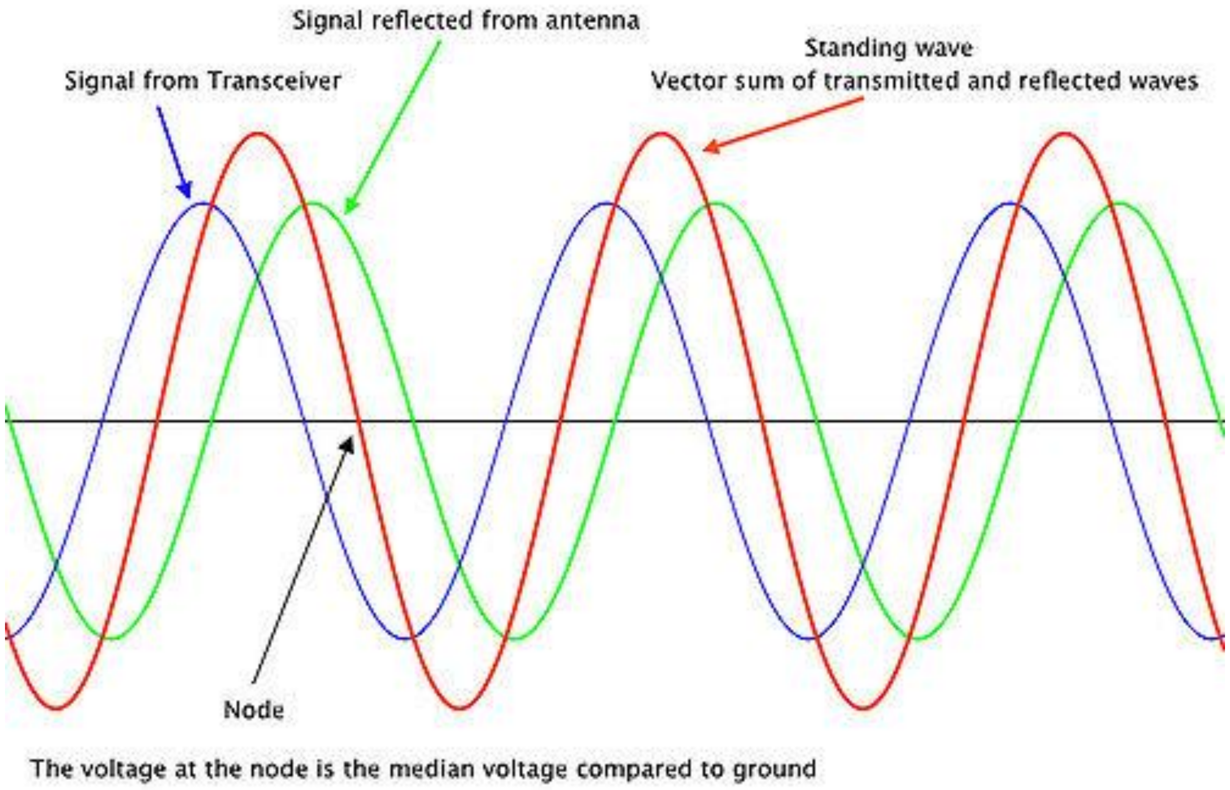
- So matched load ($\Gamma=0$) has return loss of ∞ dB (no reflected power) whereas total reflection ($\Gamma=-1$ or 1) has a return loss of 0 dB (all incident power is reflected).

Standing Wave

- When the load $\mathbf{Z_L}$ is different from $\mathbf{Z_0}$, then it is established along the line, a system of standing waves.
- The two waves put one upon the other, the incident and the reflected wave propagating in opposite directions.
- **Antinodes**, where the incident waves and the reflected waves will meet always in **phase** and so the total voltage is **maximum.**
- **Nodes,** where the two waves meet always in phase opposition and where the voltage has a **minimum** value.

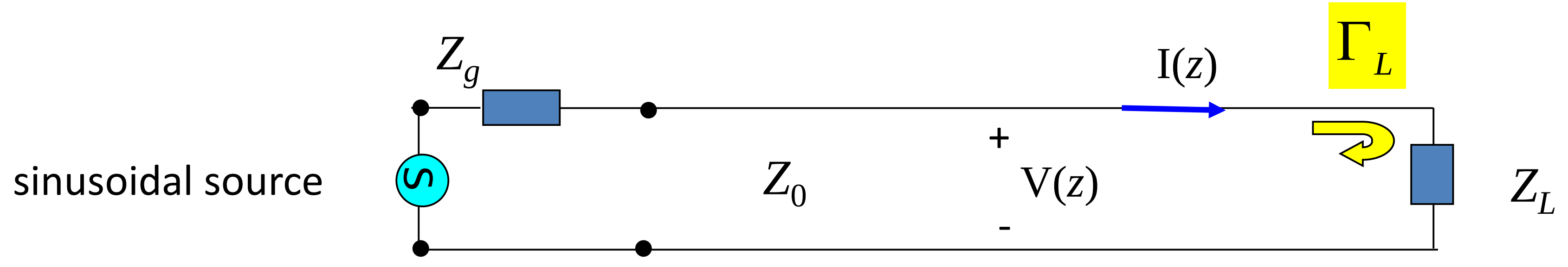
Standing Wave




Signal reflected from antenna
Standing wave
Vector sum of transmitted and reflected waves
Signal from Transceiver
Node
The voltage at the node is the median voltage compared to ground

Standing Wave Ratio

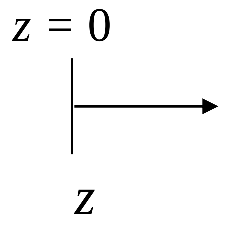
Consider a lossless transmission line that is terminated with a load:



$\gamma = j\beta$

$$Z_0 = \sqrt{\frac{L}{C}}$$

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$$



$$V(z) = V^+\left(e^{-j\beta z} + \Gamma_L e^{+j\beta z}\right)$$

$$I(z) = \frac{1}{Z_0} V^+\left(e^{-j\beta z} - \Gamma_L e^{+j\beta z}\right)$$

$$V(z) = V^+ e^{-j\beta z}\left(1 + \Gamma_L e^{+j2\beta z}\right)$$

$$I(z) = \frac{1}{Z_0} V^+ e^{-j\beta z}\left(1 - \Gamma_L e^{+j2\beta z}\right)$$

Standing Wave Ratio (cont.)

$$V(z) = V^{+} e^{-j\beta z} \left(1 + \Gamma_L e^{+j2\beta z}\right)$$

Denote $\Gamma_L = |\Gamma_L| e^{j\phi}$

Then we have $V(z) = V^{+} e^{-j\beta z} \left(1 + |\Gamma_L| e^{+j(\phi + 2\beta z)}\right)$

The magnitude is $|V(z)| = |V^{+}| \left|1 + |\Gamma_L| e^{+j(\phi + 2\beta z)}\right|$

Maximum voltage: $|V(z)|_{max} = V_{max} = |V^{+}| \left(1 + |\Gamma_L|\right)$ $\qquad \phi + 2\beta z = 2\pi m$

Minimum voltage: $|V(z)|_{min} = V_{min} = |V^{+}| \left(1 - |\Gamma_L|\right)$ $\qquad \phi + 2\beta z = \pi + 2\pi n$

$$m, n = 0, \pm 1, \pm 2, \ldots$$

Standing Wave Ratio (cont.)

The voltage standing wave ratio is the ratio of V_{max} to V_{min} .

$$VSWR \equiv \frac{V_{\max}}{V_{\min}}$$

We then have

$$VSWR = \frac{1+|\Gamma_L|}{1-|\Gamma_L|}$$

$$1 \leq VSWR \leq \infty$$

Input Impedance

- **Real power flow on the line is constant but voltage amplitude is oscillatory with position on the line. Therefore, impedance seen looking into line must vary with position.**
- At the distance l=-Z from the load, the input impedance seen looking toward the load is,

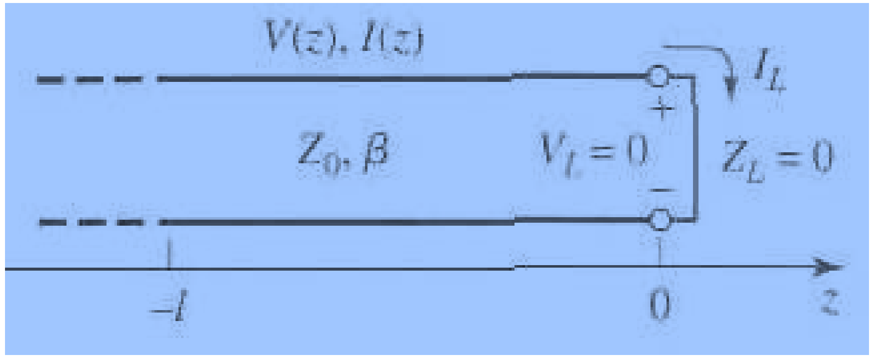
$$Z_{in} = \frac{V(-\ell)}{I(-\ell)} = \frac{V_o^+\left[e^{j\beta\ell} + \Gamma e^{-j\beta\ell}\right]}{V_o^+\left[e^{j\beta\ell} - \Gamma e^{-j\beta\ell}\right]} Z_0$$

$$Z_{in} = Z_0 \frac{(Z_L + Z_0)e^{j\beta\ell} + (Z_L - Z_0)e^{-j\beta\ell}}{(Z_L + Z_0)e^{j\beta\ell} - (Z_L - Z_0)e^{-j\beta\ell}}$$

$$= Z_0 \frac{Z_L \cos\beta\ell + jZ_0 \sin\beta\ell}{Z_0 \cos\beta\ell + jZ_L \sin\beta\ell}$$

$$= Z_0 \frac{Z_L + jZ_0 \tan\beta\ell}{Z_0 + jZ_L \tan\beta\ell}.$$

Short Circuited Load



- As shown in figure the line is terminate in short circuit Z_L=0.
- The reflection coefficient for the short circuit is -1 & VSWR=∞.
- The voltage and current on the line are,

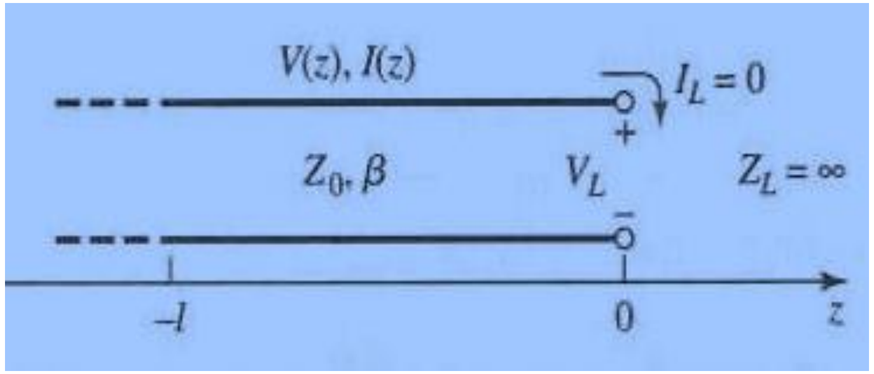
$$V(z) = V_o^+ \left[e^{-j\beta z} - e^{j\beta z}\right] = -2jV_o^+ \sin \beta z,$$

$$I(z) = \frac{V_o^+}{Z_0}\left[e^{-j\beta z} + e^{j\beta z}\right] = \frac{2V_o^+}{Z_0} \cos \beta z,$$

- The input impedance is

$$Z_{\text{in}} = jZ_0 \tan \beta \ell.$$

Open Circuited Load



- As shown in figure the line is terminate in short circuit Z_L=0.
- The reflection coefficient for the short circuit is -1 and VSWR=∞.
- The voltage and current on the line are,

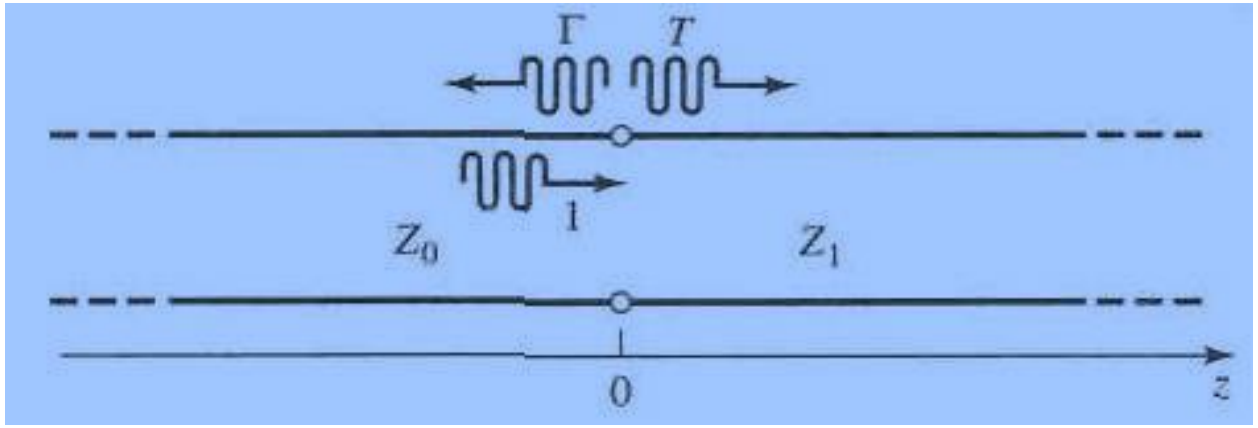
$$V(z) = V_o^+ \left[e^{-j\beta z} + e^{j\beta z}\right] = 2V_o^+ \cos \beta z,$$

$$I(z) = \frac{V_o^+}{Z_0} \left[e^{-j\beta z} - e^{j\beta z}\right] = \frac{-2jV_o^+}{Z_0} \sin \beta z.$$

$$Z_{\text{in}} = -jZ_0 \cot \beta \ell.$$

$$Z_0 = +\sqrt{Z_{\text{in}}^{\text{sc}} \; Z_{\text{in}}^{\text{oc}}} \,,$$

Reflection and Transmission Coefficient



- A transmission line of characteristic impedance Z_0 feeding a line of different characteristic impedance Z_1.
- The reflection coefficient is given by,

$$\Gamma = \frac{Z_1 - Z_0}{Z_1 + Z_0}.$$

- Not all of the incident wave is reflected; some of it is transmitted onto the second line with a voltage amplitude given by a transmission coefficient *T.*

- The voltage wave for Z > 0, in the absence of reflections, is outgoing only, and can be written as,

$$V(z) = V_0^+ T e^{-j\beta z}, \qquad \text{for } z > 0.$$

- The transmission coefficient *T* is,

$$T = 1 + \Gamma = 1 + \frac{Z_1 - Z_0}{Z_1 + Z_0} = \frac{2Z_1}{Z_1 + Z_0}.$$

- The transmission coefficient between two points in a circuit is often expressed in dB as insertion loss, *IL*

$$IL = -20 \log |T| \text{ dB}.$$

- **In telecommunication, the transmission coefficient is the ratio of the amplitude of the complex transmitted wave to that of the incident wave at a discontinuity in the transmission line.**

Impedance Matching

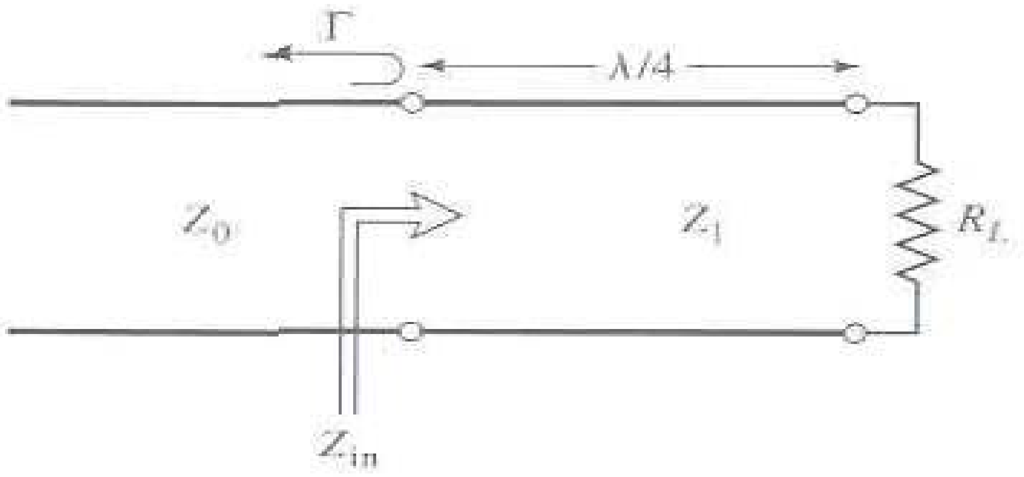
- For maximum power transfer from the source to load, the resistance of the load should be equal to that of the source.
- The reactance of the load should be equal to that of the source but opposite in sign, $R_L = R_S$ and jX=-jX, means if load is inductive , the source must be capacitive.

- **Transmission line having a length λ/4 and λ/2 have special property that can be employed for impedance matching purposes.**

- **Now let's look at the Z_{in} for some important load impedances and line lengths.**

The Quarter-Wave Transformer

- In the given figure, the load resistance R_L and the feed line characteristic impedance Z_0, are both real and assumed to be known.
- These two components are connected with a lossless piece of transmission line of (unknown) characteristic impedance of Z_1 and length λ/4.



- It is desired to match the load to the Z_0 line, by using $\lambda/4$ piece of line, and so make **Γ=0 we want Zin=Zo**

$$Z_{in} = Z_1 \frac{R_L + jZ_1 \tan \beta\ell}{Z_1 + jR_L \tan \beta\ell}.$$

- Here $l=\lambda/4$, so $\beta l=\pi/2$,

$$Z_{in} = \frac{Z_1^2}{R_L}.$$

- Putting Zin=Zo , the characteristic impedance Z_1 of quarter wave transformer is

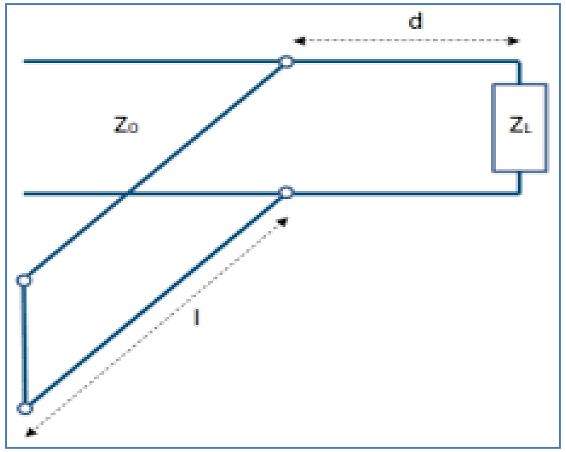
$$Z_1 = \sqrt{Z_0 R_L},$$

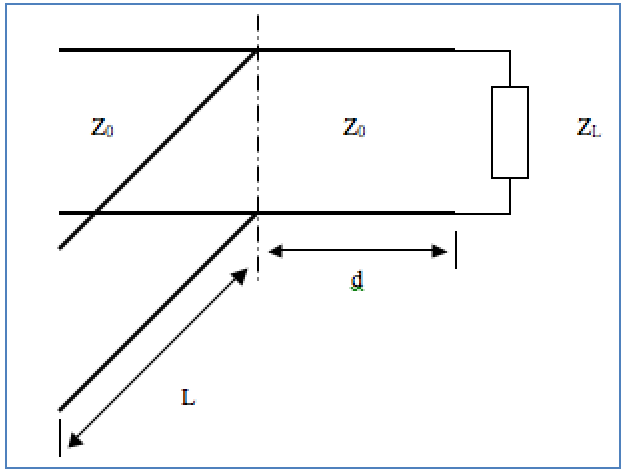
- Then there will be no standing waves on the feedline, although there will be standing waves on the $\lambda/4$ matching section.
- The above condition applies only when length of matching section is $\lambda/4$ or odd multiple of it, so perfect match may be achieved at one frequency, but mismatch will occur at other frequency.

Stub Matching

- For impedance matching, it is also possible to connect **sections of open or short circuited lines called stubs** in **shunt with the main line** at some point or points.

- **Single Stub Matching – SC & OC stubs**

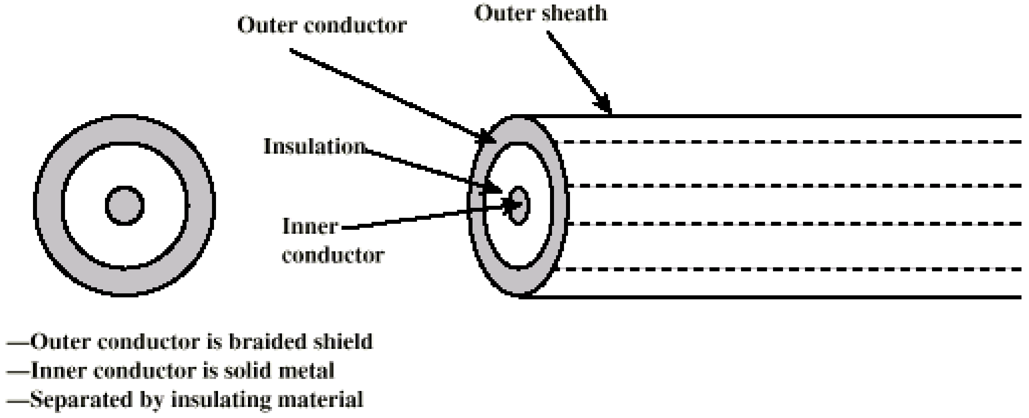




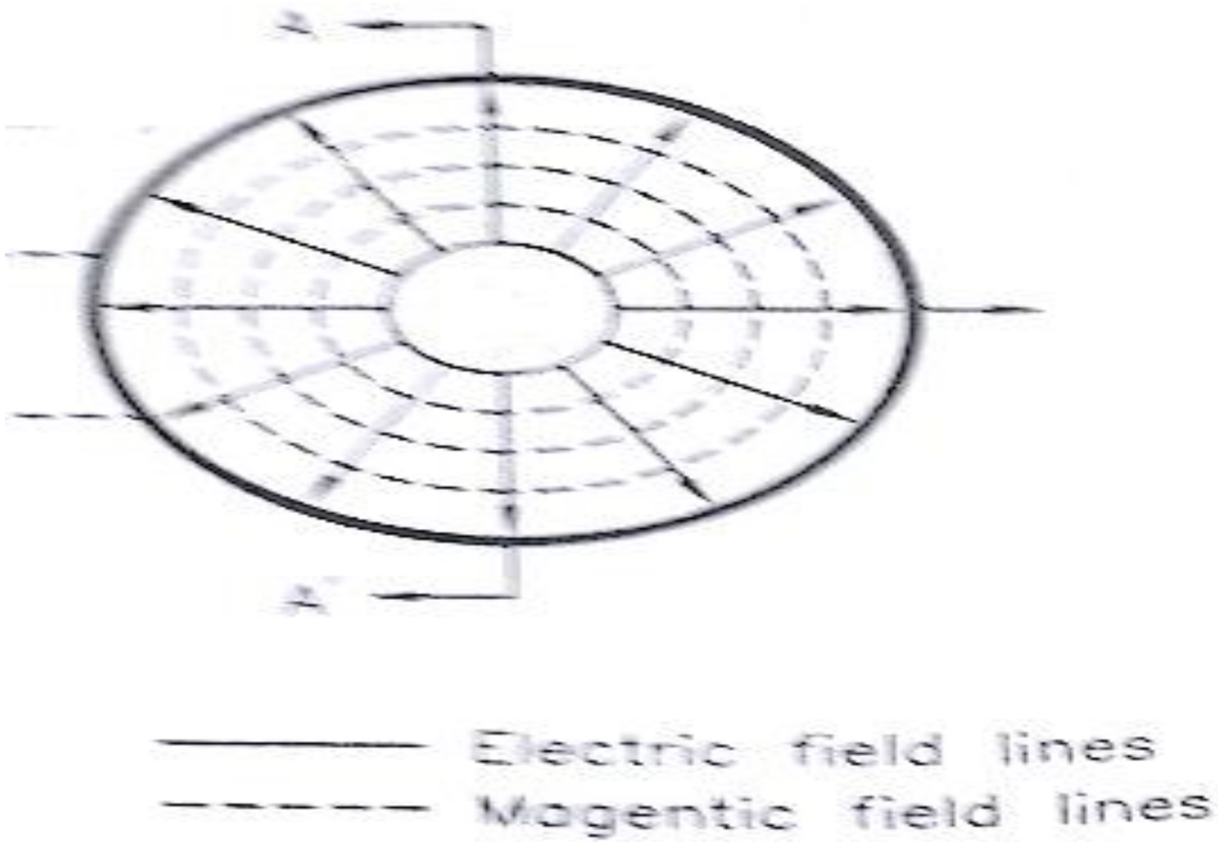
Coaxial Lines

- The coaxial line carries a **TEM waves, so it is a broadband device as TEM wave has no cut off frequency.**

- It consists of two conductors separated by a dielectric material (ε_r). The center conductor (dia d) and the outer conductor (dia D), are configured in such a way that they form concentric cylinders with a common axis. Hence the term and name co-axial.



- TEM wave in Co-axial Lines has EM fields confined in dielectric space between inner & outer conductor. Hence **Coaxial lines are less susceptible to EMI.**



As shown in the mode patterns, coaxial ...
he e.m. fields are confined in the insulator between the inner and outer onductors. Coaxial lines can operate well upto 40 GHz due to levelopment of precision connectors for smaller diameter coaxial cables.

The inductance and capacitance per unit length of a coaxial cable are given by

$$L = \frac{\mu}{2\pi} \ln \frac{D}{d} \text{ H/m} ; \quad C = \frac{2\pi\epsilon}{\ln (D/d)} \text{ F/m}$$

Since $\mu_r = 1$ and $\mu_0 = 4\pi \times 10^{-7}$ H/m and $\epsilon = \epsilon_r \epsilon_0$ and $\epsilon_0 = 8.854 \times 10^{-12}$ F/m

$$L = 2 \times 10^{-7} \ln \frac{D}{d} \text{ H/m and } C = 55.56 \times 10^{-12} \frac{\epsilon_r}{\ln (D/d)} \text{ F/m} \quad \ldots(4.1)$$

Hence the characteristic impedance of coaxial lines will be,

$$Z_0 = \sqrt{\frac{L}{C}} \Rightarrow \quad R_0 = \frac{1}{2\pi} \sqrt{\frac{\mu}{\epsilon}} \ln \left(\frac{D}{d} \right) \Omega$$

Since $\mu_r = 1$ for non-magnetic materials, substituting for ϵ_0 and μ we get

$$R_0 = \frac{60}{\sqrt{\epsilon_r}} \ln \left(\frac{D}{d} \right) \Omega \quad \ldots(4$$

The velocity of propagation for the coaxial cable is given by

$$v = \frac{1}{\sqrt{\mu\epsilon}} = \frac{c}{\sqrt{\mu_r \epsilon_r}} \text{ m/s}$$

Since $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$ and $\mu_r = 1$ for coaxial cables,

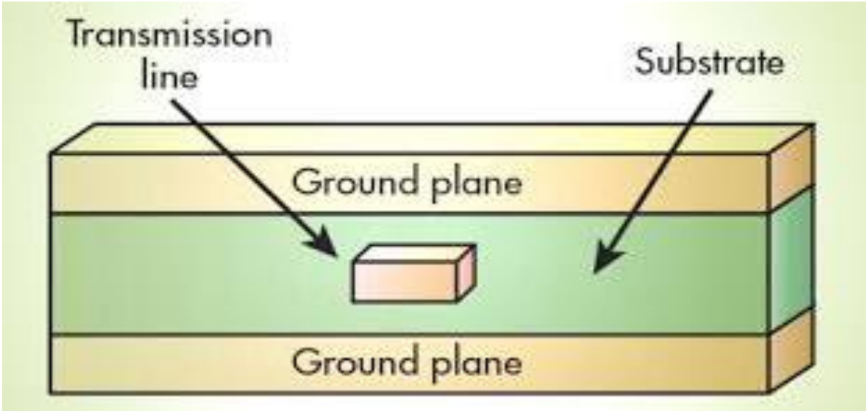
$$v = \frac{c}{\sqrt{\epsilon_r}} \text{ m/s} \quad \ldots($$

Strip lines

✓Strip lines are essentially modifications of the two wire lines and coaxial lines. These are basically planar transmission lines that are widely used at 100 MHz to 100 GHz.

✓A stripline circuit uses a flat strip of metal which is sandwiched between two parallel ground planes. The insulating material of the substrate forms a dielectric.

✓The width of the strip, the thickness of the substrate and the relative permittivity of the substrate determine the characteristic impedance of the strip which is a transmission line.

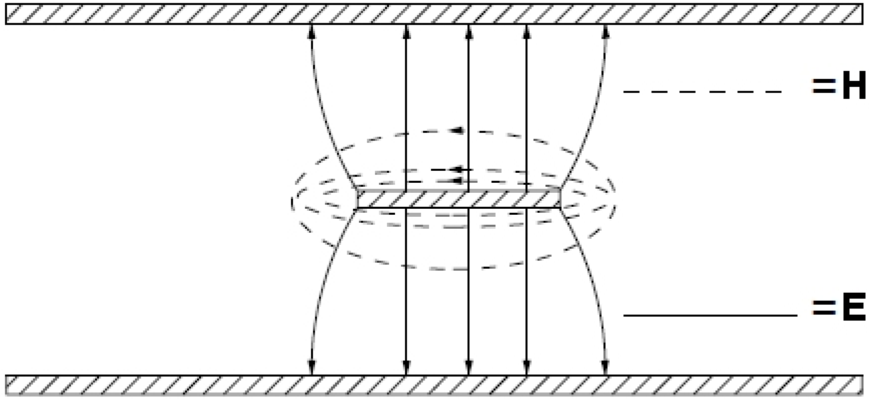


✓the central conductor need not be equally spaced between the ground planes. In the general case, the dielectric material may be different above and below the central conductor.

✓Like coaxial cable, stripline is non-dispersive (supports TEM wave), and has no cutoff frequency.

✓To prevent the propagation of unwanted modes, the two ground planes must be shorted together.

✓Stripline carries high frequency signal entirely contained inside the PCB thus minimizes RF emissions and provides enhanced noise immunity against incoming spurious signals, at the expense of slower propagation speeds.

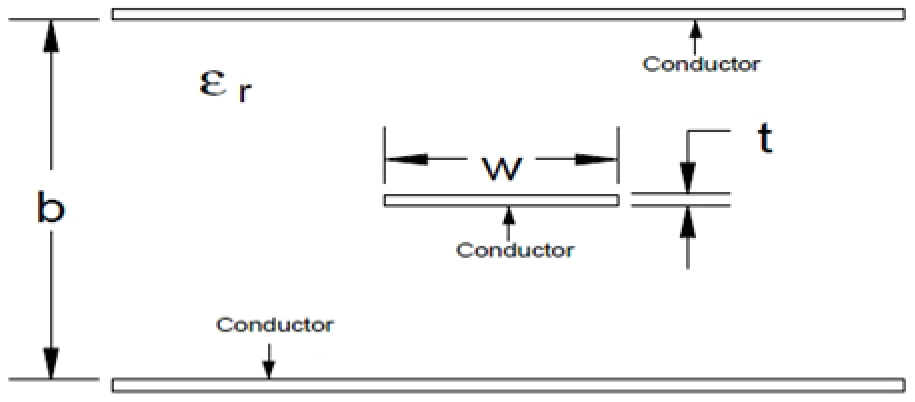


Design of Strip Line

- A strip line consists of a central thin conducting strip of width ‘w’ which is greater than the thickness ’t’, placed inside the low loss dielectric substrate of thickness ‘b’, between two wide ground plates.

- In this the thickness of the metallic central conductor and metallic ground planes are same.

- The width of the ground planes are at least five times greater than the distance between the plates.



- The phase velocity of a TEM waves in the strip line is,

$$v_p = 1/\sqrt{\mu_0 \epsilon_0 \epsilon_r} = c/\sqrt{\epsilon_r},$$

- The propagation constant of the strip line is,

$$\beta = \frac{\omega}{v_p} = \omega\sqrt{\mu_0 \epsilon_0 \epsilon_r} = \sqrt{\epsilon_r} k_0.$$

- The characteristic impedance is,

$$Z_0 = \frac{30\pi}{\sqrt{\epsilon_r}} \frac{b}{W_e + 0.441b},$$

where, We is the effective width of the center conductor and is given by,

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

Microstrip lines

- Coaxial Line was very suitable, since it possessed a dominant mode with zero cut-off frequency, providing two important characteristics: **very wide bandwidth, and the capability of miniaturization.**

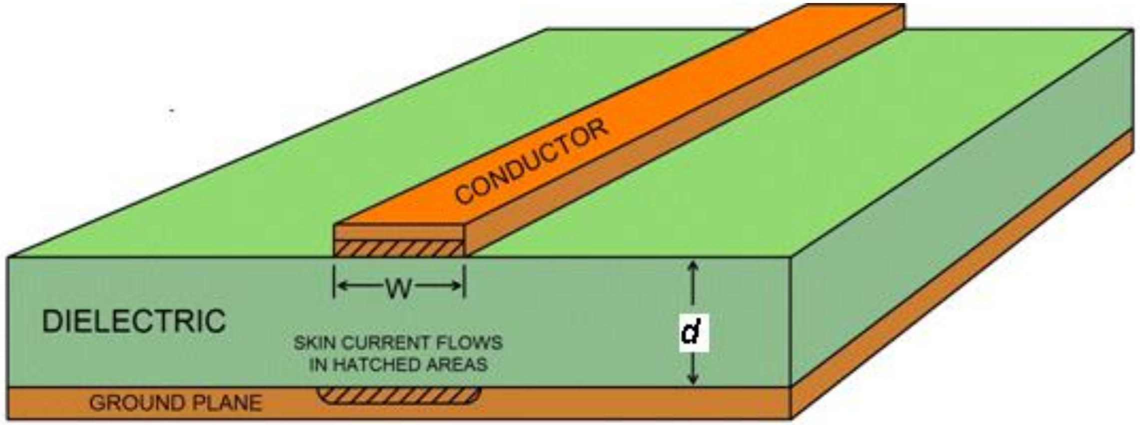
- In addition, those **components were expensive to fabricate.**

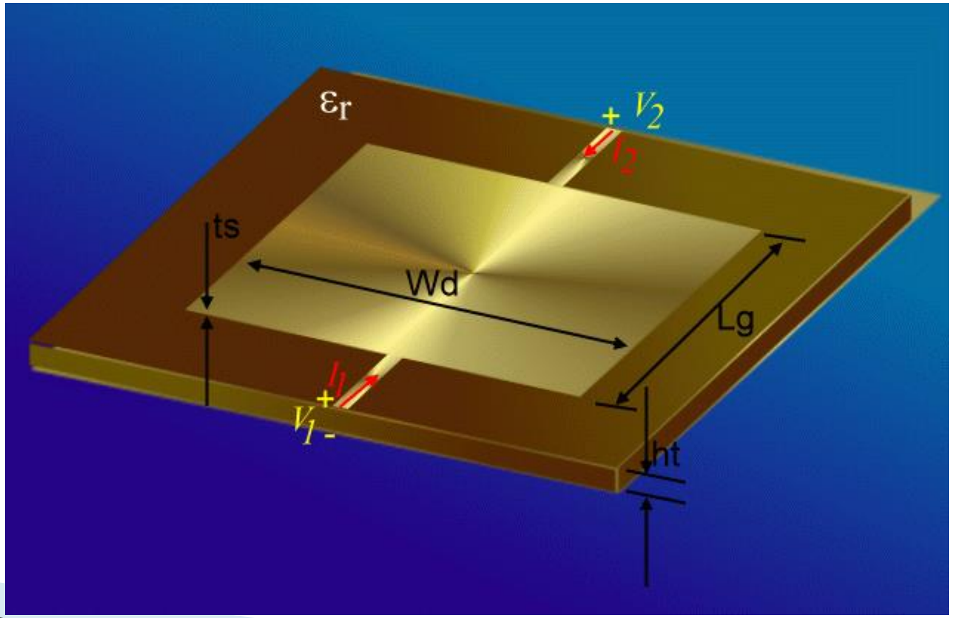
- In an attempt to overcome these fabrication difficulties, the center conductor of the coaxial line was flattened into a strip and the outer conductor was changed into a rectangular box, and then fitted with connectors for use with regular coaxial line.

- A modification that emerged almost in the same time involved removing the top plate leaving only the strip and the bottom plate with a dielectric layer between them to support the strip. That structure was named ***Microstrip.***

- Microstrip line is one of the most popular types of planar transmission lines, primarily because it can be fabricated by **photolithographic processes and is easily integrated with other passive and active microwave devices.**

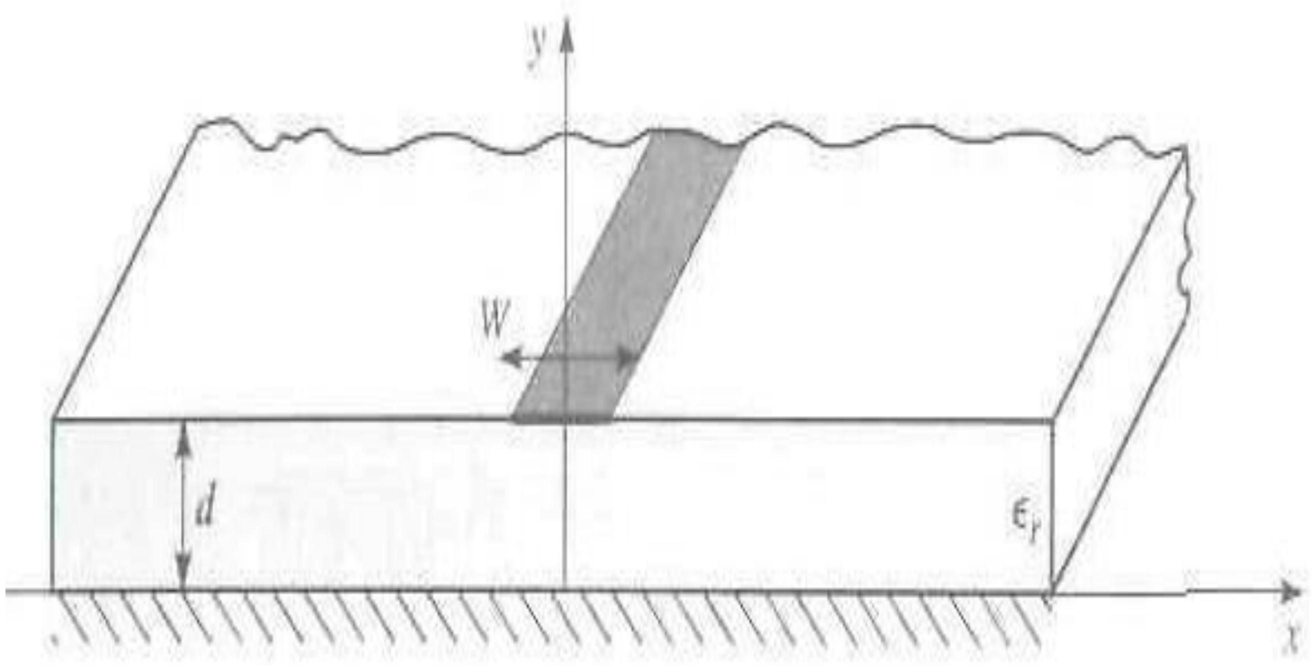
Design of Microstrip Lines





Construction of Microstrip Lines

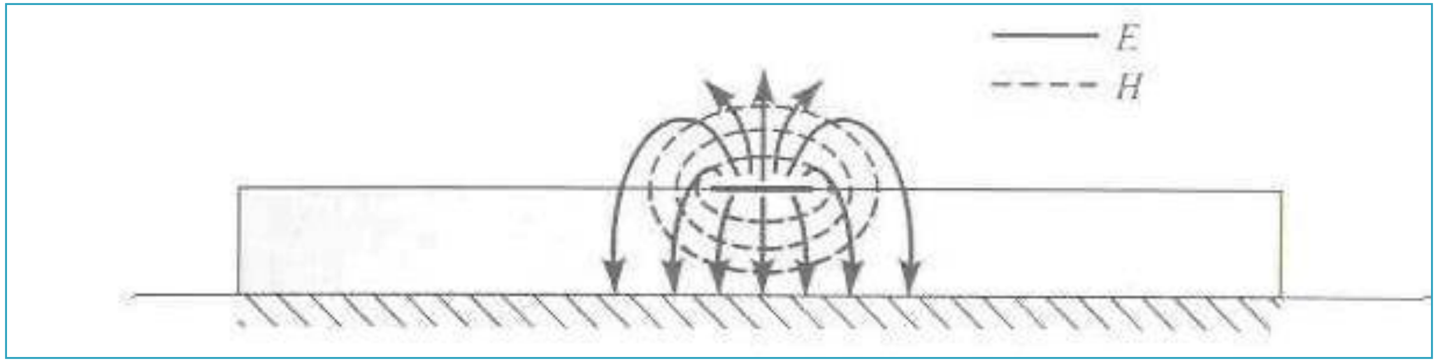
- A conductor of width 'W' is printed on a thin, metallic grounded dielectric substrate of thickness 'd' and relative permittivity ϵr.



- Unlike strip line, where all the fields are contained within a homogeneous dielectric region, microstrip line has some of its field lines in the dielectric region, concentrated between the strip conductor and the ground plane and some fraction in the air region above the substrate.

- For this reason the microstrip line cannot support a pure TEM wave, since phase velocity of TEM wave in the dielectric region would be $c/\sqrt{\epsilon_r}$, but the phase velocity of TEM fields in the air region would be ‘c’.

- Thus, a phase match at the dielectric-air interface would be impossible to attain for a TEM-type of wave. However, the dielectric substrate is electrically very thin, and so the **fields are quasi-TEM** as shown in figure.



- The phase velocity and propagation constant can be expressed as,

$$v_p = \frac{c}{\sqrt{\epsilon_e}},$$

$$\beta = k_0\sqrt{\epsilon_e}.$$

where ϵ_e is the effective dielectric constant of microstrip line.

- **Since some of the field lines are in the dielectric region and some are in air, the effective dielectric constant satisfied the relation,**

$$1 < \epsilon_e < \epsilon_r.$$

- The effective dielectric constant is given by,

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12d/W}}.$$

Applications of Microstrip lines & comparison with waveguide

- Microwave components such as antennas, couplers, filters, power dividers etc. can be formed from microstrip, with the **entire device existing as the pattern of metallization on the substrate.**

- **Microstrip is thus much less expensive than traditional waveguide technology, as well as being far lighter and more compact.**

- The disadvantages of microstrip compared with waveguide are the generally lower power handling capacity, and higher losses. Also, unlike waveguide, microstrip is not enclosed, and is therefore susceptible to cross-talk and unintentional radiation.

Pros & Cons of Micorstrip Lines

- The Microstrip line it has become the best known and most widely used planar transmission line for RF and Microwave circuits. (300 MHz to 300 GHz)

- This popularity and widespread use are due to its planar nature, ease of fabrication using various processes, easy integration with solid-state devices, good heat sinking, and good mechanical support.

- Microstrip is the printed circuit version of a wire over a ground plane, and thus it tends to radiate as the spacing between the ground plane and the strip increases.

- A substrate thickness of a few percent of a wavelength (or less) minimizes radiation without forcing the strip width to be too narrow.

- In contrast to Stripline, the two-media nature (substrate discontinuity) of Microstrip causes its dominant mode to be hybrid (Quasi-TEM) not TEM, with the result **that the phase velocity, characteristic impedance, and field variation in the guide cross section all become mildly frequency dependent.**

- Waveguides and Striplines have no radiation losses, while in Microstrip case (since the Microstrip is an open transmission line) radiation effects are present at any discontinuity section.

- Microstrip's primary advantages of low cost and compact size are offset by its tendency to be more lossy than Coaxial Line, Waveguide, and Stripline.

- **Radiation Losses depend on the dielectric constant, substrate thickness, and the circuit geometry.**

- The lower the dielectric constant, the less the concentration of energy in the substrate region, and, hence, the greater the radiation losses.

- The real benefit in having a higher dielectric constant is not only reducing radiation losses but also that the package size decreases by approximately the square root of the dielectric constant.