9.2 Types of Transmission Lines

There are various types transmission lines available depending on the propagation constant, distance, power transmission etc.

The important types are explained below (Fig. 9.1).

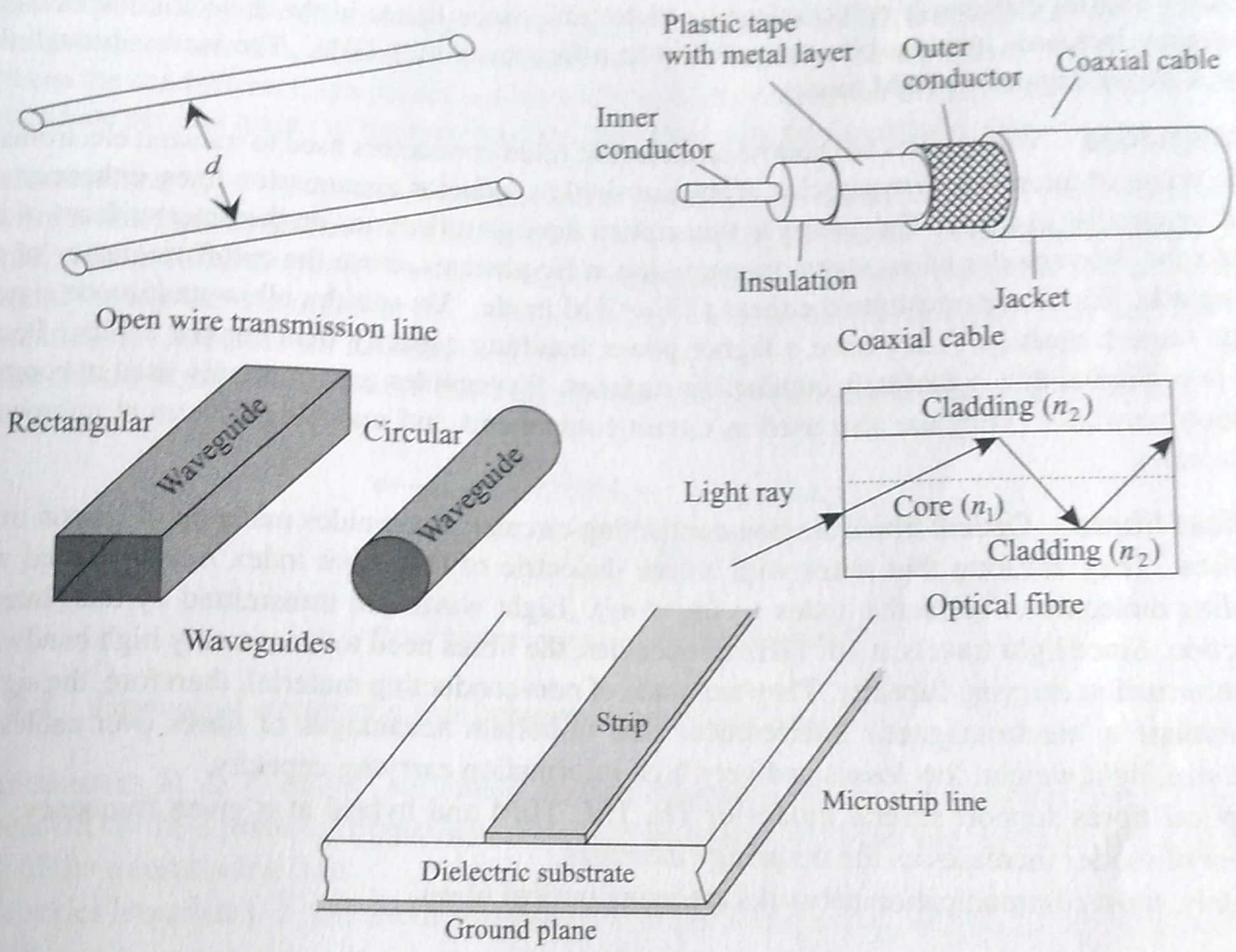

Fig. 9.1 *Types of transmission lines*

Open wire lines (parallel wire lines) An open wire line is a pair parallel conducting wires separated by a distance in free space and mounted on posts or on towers. Waves are transmitted in TEM mode. Open wire lines can be used for telephone lines, telegraphy lines and power lines.

Open wire lines are simple, low cost and easy to maintain for short distances. They have less capacitance effect compared to other types and are best suited for low frequency short and medium distance transmission. As distance increases, the cost becomes high as more number of posts and towers have to be erected. Open wire lines are badly affected by atmospheric conditions.

Short length lines at high frequency can be used as antenna feeders or matching lines. Open wires are used up to 100 MHz. Energy loss due to radiation is severe beyond 100 MHz.

Cables A cable consists of a number of twisted insulated wires in pairs protected by a lead or plastic sheath. Cables are generally laid underground or undersea, for example, telephone cables, electrical power transmission cables etc.

Coaxial cables When two conductors are placed coaxially and filled with dielectric material, the cable is called a coaxial cable. Coaxial cables can be used as TV cables and telephone cables. The dielectric inside the cables may be air, gas or solid. Coaxial cables have less attenuation, low interface and negligible radiation compared to open wire lines. It provides EM shielding against external fields as the EM fields are confined within the cable. Two strand pairs and coaxial cables are used in computer networks.

Most coaxial cables use polyethylene as dielectric. Since losses in the dielectric increases as frequency increases, these cables are used up to a frequency of 1 GHz. The waves through the cables are transmitted in TEM mode.

Waveguides Waveguides are hollow or dielectric filled conductors used to transmit electromagnetic waves at microwave frequencies. They are single conductor transmission lines, either rectangular or circular in shape. The energy is transmitted through reflections on the inner surfaces of the conductor. Waveguides allow signal transmission at frequencies above the cutoff frequency of the waveguide. Waves are transmitted either in TE or TM mode. Waveguides allow multimode signals at the same frequency. They have a higher power handling capacity than coaxial cables. Power loss is negligible due to perfectly conducting surfaces. Waveguides are commonly used in communication networks. They are also used as circuit components and matching devices at microwave frequencies.

Optical fibres Optical fibres are non-conducting circular waveguides made up of silicon oxide or silica. They are long thin wires with a core dielectric of refractive index n_1 and coated with cladding dielectric of refractive index n_2 ($n_2 < n_1$). Light waves are transmitted by total internal reflection. Since light travels at 10^5 GHz frequencies, the fibres need to have a very high bandwidth and information carrying capacity. They are made of non-conducting material, therefore, the signals are immune to electromagnetic interference. The important advantages of fibres over cables are small size, light weight, low losses and very high information carrying capacity.

Optical fibres support several modes of TE, TM, TEM and hybrid at a given frequency. The number of modes increases as the frequency increases.

Lately, most communication networks are using optical fibres.

Microstrip lines Microstrip line is a parallel plate transmission line consisting of a conducting strip and a ground plane separated by a dielectric substrate. A very thin copper sheet is used as a strip and the ground plane is fabricated using printed circuit board technology. The fields are confined in the dielectric substrate between the strip and the ground plane. Microstrip lines are lighter, more compact and flexible than other types of transmission lines, but they have low power handling capacity. They are used to transmit micowave signals and can be used as microwave components such as antennas, direction couplers, filters, circulators, etc. For example, high speed digital circuits and antennas in smart phones are designed by using microstrip line technology.

9.8 Relationship between Group Velocity and Phase Velocity

We know that when a wave travels along a line, the phase velocity is

$$v_p = \frac{\omega}{\beta}.$$

Differentiating with respect to frequency,

$$\frac{dv_p}{d\omega} = \frac{\beta - \omega\frac{d\beta}{d\omega}}{\beta^2} = \frac{1}{\beta} - \frac{\omega}{\beta^2}\frac{d\beta}{d\omega}.$$

$$\frac{dv_p}{d\omega} = \frac{1}{\beta} - \frac{v_p}{\beta}\frac{d\beta}{d\omega}.$$

But we know that the group velocity is $v_g = \dfrac{d\omega}{d\beta}$.

$$\therefore \qquad \beta \frac{dv_p}{d\omega} = 1 - \frac{v_p}{v_g} \tag{9.54}$$

or $$v_p = v_g \left(1 - \beta \frac{dv_p}{d\omega}\right). \tag{9.55}$$

If v_p is constant with respect to ω, then

$$\frac{dv_p}{d\omega} = 0.$$

From Eq. (9.55), $v_p = v_g$.

Thus if the phase velocity is independent of frequency, it becomes group velocity.

Condition for lossless transmission

We know that

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

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

By substituting $R = G = 0$,

$$\alpha + j\beta = \sqrt{j\omega L \times j\omega C} = j\sqrt{LC}.$$

$$Z_0 = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{\frac{L}{C}}.$$

Thus, $\alpha = 0$, $\beta = \omega\sqrt{LC}$ and $Z_0 = \sqrt{\frac{L}{C}}$.

Phase velocity $v_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{LC}}$.

Since $v_p = \frac{1}{\sqrt{\mu\varepsilon}}$,

$$\therefore \quad LC = \mu\varepsilon.$$

Here phase velocity and characteristic impedance depend only on L and C values.

9.2.1 Transmission Line Parameters

The equivalent electric circuit of a transmission line consists of series resistance, series inductance, shunt capacitance and shunt conductance along the length. These parameters are calculated per unit length of the transmission line.

Resistance (R) A series resistance is due to the intemal resistance of the conductors of a transmission line. It is uniformly distributed along the line and depends on the conductivity and cross-sectional area of the conductors. But at high frequencies, it depends on skin depth. It is measured as loop resistance per unit length of the line. Its units are ohms/m or Ω/m.

Inductance (L) A series or loop inductance is due to the magnetic flux density produced around the conductors of a transmission line. It is uniformly distributed along the line. The flux linkages per unit current gives the inductance of the transmission line. It is measured as loop inductance per unit length of the transmission line and its units are henries/m or H/m.

Capacitance (C) Two parallel conductors or coaxial conductors of a transmission line separated by a distance d acts as a capacitor. Thus, a shunt capacitance is formed due to the electric field between the conductors. Capacitance is distributed uniformly along the line. It is measured as shunt capacitance per unit length of the transmission line. The units are farads/m or F/m.

Conductance (G) A shunt conductance is due to the leakage current between the conductors of a transmission line. Since the dielectric or insulation material around the conductors is not perfect, a small amount of current flows through the dielectric material. The conductance is also distributed uniformly along the transmission line. It is measured as shunt conductance per unit length of the transmitted line. Its units are mhos/m or S/m.

The electric equivalent circuit of the transmission line per unit length in shown in Fig.9.2.

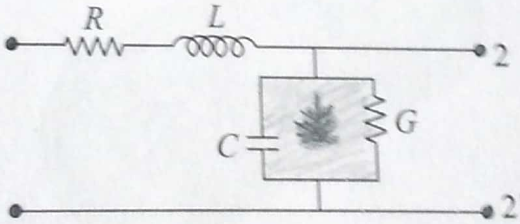

Fig. 9.2 *Equivalent circuit of a transmission line per unit length*

The parameters R, L, G and C are called primary constants of the transmission line. They are independent of the operating frequency. They are measured in either per metre or per kilometre length of the transmission line.

The series impedance Z and shunt admittance Y of the line per unit length can be expressed as

$$Z = R + j\omega L.$$

$$Y = G + j\omega C.$$

9.5 Transmission Line Terminated with Characteristic Impedance Z_0

Consider a line of length l which is terminated with characteristic impedance Z_0 as shown in Fig. 9.6.

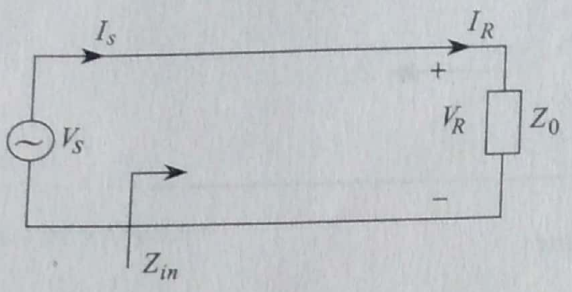

Fig. 9.6 *Transmission line with Z_0*

Let V_R = Voltage at termination,
I_R = Current at termination,
V_S = Source voltage and
I_S = Source current.

We know from Eq. (9.31) and Eq. (9.32) that the line equations are

$$V = V_S \cosh \gamma x - I_S Z_0 \sinh \gamma x \quad \text{and}$$

$$I = I_S \cosh \gamma x - \frac{V_S}{Z_0} \sinh \gamma x.$$

At distance $x = l$,

$$V = V_R \text{ and } I = I_R.$$

$$V_R = V_S \cosh \gamma l - I_S Z_0 \sinh \gamma l.$$

$$I_R = I_S \cosh \gamma l - \frac{V_S}{Z_0} \sinh \gamma l.$$

From Fig. 9.6, we know that $Z_0 = \dfrac{V_R}{I_R}$

$$Z_0 = \frac{V_S \cosh \gamma l - I_S Z_0 \sinh \gamma l}{I_S \cosh \gamma l - \dfrac{V_S}{Z_0} \sinh \gamma l}$$

$$Z_0 I_S \cosh \gamma l - V_S \sinh \gamma l = V_S \cosh \gamma l - I_S Z_0 \sinh \gamma l$$

$$Z_0 I_S (\cosh \gamma l + \sinh \gamma l) = V_S (\cosh \gamma l + \sinh \gamma l)$$

$$Z_0 I_S = V_S$$

$$Z_0 = \frac{V_S}{I_S}.$$

But $\frac{V_S}{I_S} = Z_{in}$ is the input impedance of the transmission line.

$$\therefore \quad Z_{in} = Z_0. \tag{9.38}$$

Hence, the input impedance Z_{in} of a finite length line terminated with its characteristic impedance Z_0 is equal to Z_0. Thus a line is matched when the termination impedance is equal to its characteristic impedance Z_0 (not the complex conjugate of the characteristic impedance as in circuit theory).

That is, $\quad Z_R = Z_0 = Z_{in}\ \Omega.$

For an open wire line
Characteristic impedance for an open wire system is

$$Z_0 = 276 \log_{10}\left(\frac{d}{r}\right)\ \Omega, \tag{9.39}$$

where $\quad r =$ radius of the wire
$\qquad d =$ separation between two wires

For a coaxial cable

$$Z_0 = \frac{138}{\sqrt{\varepsilon_r}} \log_{10}(b/a)\ \Omega, \tag{9.40}$$

where $\quad b =$ radius of the outer conductor,
$\qquad a =$ radius of the inner conductor and
$\qquad \varepsilon_r =$ dielectric constant.

Transmission line with source generator: Consider a line length l terminated with characteristic impedance Z_0 and fed with a generator having source voltage V_g and internal impedance Z_g. If Z_s is the input impedance line, then $Z_s = Z_0$.

The input current $I_s = \dfrac{V_g}{Z_g + Z_s}$, input voltage $V_s = I_s Z_s$ and average input power $P_s = |I_s||V_s| \cos\theta$

Load voltage $V_L = V_s e^{-\gamma l}$, load current $I_L = I_s e^{-\gamma l}$ and

average load power $P_L = P_s e^{-2\alpha l} = |I_L||V_L| \cos\theta$, where θ is the angle between voltage and curren

Frequency distortion Frequency distortion occurs due to variation of attenuation with frequency. Each frequency component of the wave undergoes different attenuation. At the receiver end, the wave contains different amplitudes at different frequencies resulting in frequency distortion.

If the attenuation α is made independent of frequency, frequency distortion will not exist on transmission lines.

Delay distortion Delay distortion occurs due to variation of time delay with frequency. If the time required to transmit various frequency components of the wave is not the same, then delay distortion occurs. Delay depends on phase velocity. If the phase velocity of the wave is constant with frequency, then all the frequency components of the wave will reach at the same time and delay distortion will not occur. Since $v_p = \frac{\omega}{\beta}$, if β varies linearly with ω, the phase velocity becomes constant with frequency and we can achieve a transmission without delay distortion. Delay distortion is also called phase distortion.

In general, attenuation and phase constants of the line from Eq. (9.43) and Eq. (9.44) are given by

$$\alpha = \sqrt{\frac{1}{2}\left[(RG - \omega^2 LC) + \sqrt{(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)}\right]}, \tag{9.78}$$

$$\beta = \sqrt{\frac{1}{2}\left[(RG + \omega^2 LC) - \sqrt{(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)}\right]}. \tag{9.79}$$

Thus if α is independent of frequency and β varies linearly with ω (β is a constant multiplied by ω), no distortions occur in transmission.

Here p...

9.10 Distortionless Transmission Line

A line is said to be a distortionless transmission line if the attenuation constant α is independent of frequency ω and β varies linearly with frequency.

Condition for distortionless transmission

We know that

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \sqrt{L\left(\frac{R}{L} + j\omega\right)C\left(\frac{G}{C} + j\omega\right)}.$$

$$\alpha + j\beta = \sqrt{LC}\sqrt{\left(\frac{R}{L} + j\omega\right)\left(\frac{G}{C} + j\omega\right)}.$$

To make the α in the above equation independent of frequency, let $\dfrac{R}{L} = \dfrac{G}{C}$. (9.58)

Then $\alpha + j\beta = \sqrt{LC}\sqrt{\left(\frac{R}{L} + j\omega\right)\left(\frac{R}{L} + j\omega\right)} = \sqrt{LC}\left(\frac{R}{L} + j\omega\right).$

Equating real and imaginary terms,

$$\alpha = \sqrt{LC}\frac{R}{L} = R\sqrt{\frac{C}{L}} \quad \text{and} \quad \beta = \omega\sqrt{LC}. \tag{9.59}$$

Also, $$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega L}} = \sqrt{\frac{L\left(\frac{R}{L} + j\omega\right)}{C\left(\frac{G}{C} + j\omega\right)}} = \sqrt{\frac{L}{C}}. \tag{9.60}$$

Therefore for distortionless transmission,

$$\alpha = R\sqrt{\frac{C}{L}} = G\sqrt{\frac{L}{C}} \tag{9.61}$$

or $\quad \alpha = \dfrac{R}{Z_0}$ or GZ_0

and $\quad \beta = \omega\sqrt{LC}, \quad v_p = \dfrac{1}{\sqrt{LC}}. \qquad (9.62)$

Therefore, the condition for distortionless transmission is

$$\frac{R}{L} = \frac{G}{C} \quad \text{or} \quad RC = LG. \tag{9.63}$$

In a distortionless line, the attenuation, characteristic impedance and phase velocity are independent of frequency. Phase shift constant varies linearly with frequency.

Note: For a lossless line, $\alpha = 0$, $\beta = \omega\sqrt{LC}$, $Z_0 = \sqrt{\dfrac{L}{C}}$, and $v_p = \dfrac{1}{\sqrt{LC}}$.

That is, the resistive components $R = G = 0$.
Hence, the lossless line is distortionless.

10. For distortion less transmission line,

$$RC = LG, \quad Z_0 = \sqrt{\frac{L}{C}}, \quad \alpha = \frac{R}{Z_0} \text{ or } GZ_0, \quad \beta = \omega\sqrt{LC} \quad \text{and} \quad v_p = \frac{1}{\sqrt{LC}}.$$