MODULE 1

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1.1 MICROWAVE TUBES: INTRODUCTION

For extremely high-frequency applications (above 1 GHz), the inter electrode capacitances and transit-time delays of standard electron tube construction become prohibitive. However, there seems to be no end to the creative ways in which tubes may be constructed, and several high-frequency electron tube designs have been made to overcome these challenges. It was discovered in 1939 that a toroid cavity made of conductive material called a cavity resonator surrounding an electron beam of oscillating intensity could extract power from the beam without actually intercepting the beam itself. The oscillating electric and magnetic fields associated with the beam "echoed" inside the cavity, in a manner similar to the sounds of traveling automobiles echoing in a roadside canyon, allowing radio-frequency energy to be transferred from the beam to a waveguide or coaxial cable connected to the resonator with a coupling loop.

1.2 OBJECTIVE

This module enables students Describe the microwave properties and its transmission media.

1.3REFLEX KLYSTRON OSCILLATOR

The electron gun emits the electron beam, which passes through the gap in the anode cavity. These electrons travel towards the Repeller electrode, which is at high negative potential. Due to the high negative field, the electrons repel back to the anode cavity. In their return journey, the electrons give more energy to the gap and these oscillations are sustained. The constructional details of this reflex klystron are as shown in the following Figure 1.1. It is assumed that oscillations already exist in the tube and they are sustained by its operation. The electrons while passing through the anode cavity, gain some velocity.

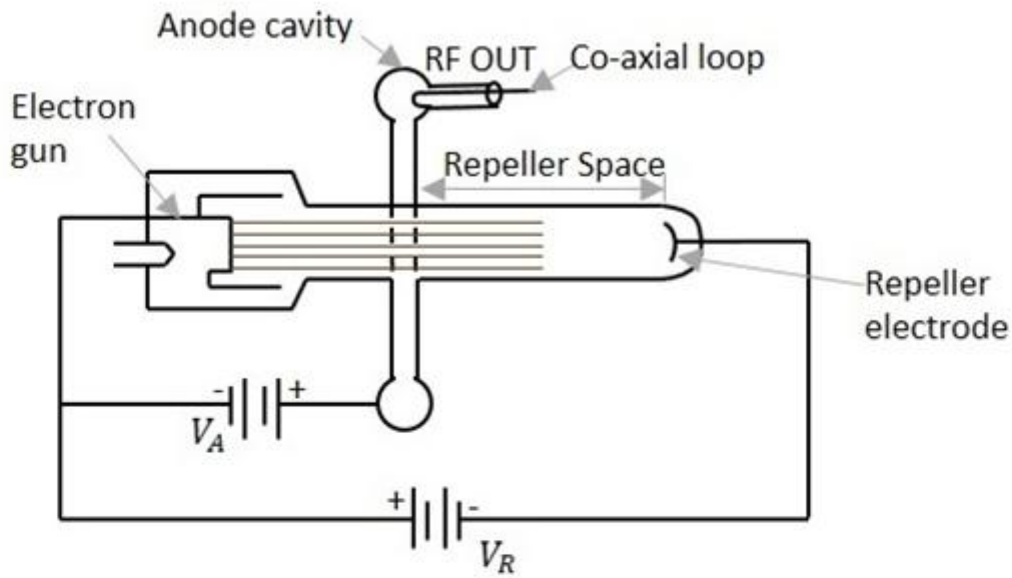


Figure 1.1: Construction details of Reflex Klystron

1.4 Mechanism of Oscillation

The mechanism of oscillation is explained in below figure 1.2. The operation of Reflex Klystron is understood by some assumptions. The electron beam is accelerated towards the anode cavity. Let us assume that a reference electron er crosses the anode cavity but has no extra velocity and it repels back after reaching the Repeller electrode, with the same velocity. Another electron, let's say ee which has started earlier than this reference electron, reaches the Repeller first, but returns slowly, reaching at the same time as the reference electron. We have another electron, the late electron el, which starts later than both erand ee, however, it moves with greater velocity while returning back, reaching at the same time as er and ee. Now, these three electrons, namely er, ee and el reach the gap at the same time, forming an electron bunch. This travel time is called as transit time, which should have an optimum value. The following figure illustrates this. The anode cavity accelerates the electrons while going and gains their energy by retarding them during the return journey. When the gap voltage is at maximum positive, this lets the maximum negative electrons to retard.

The optimum transit time is represented as

T=n+34wherenisanintegerT=n+34wherenisaninteger

This transit time depends upon the Repeller and anode voltages.

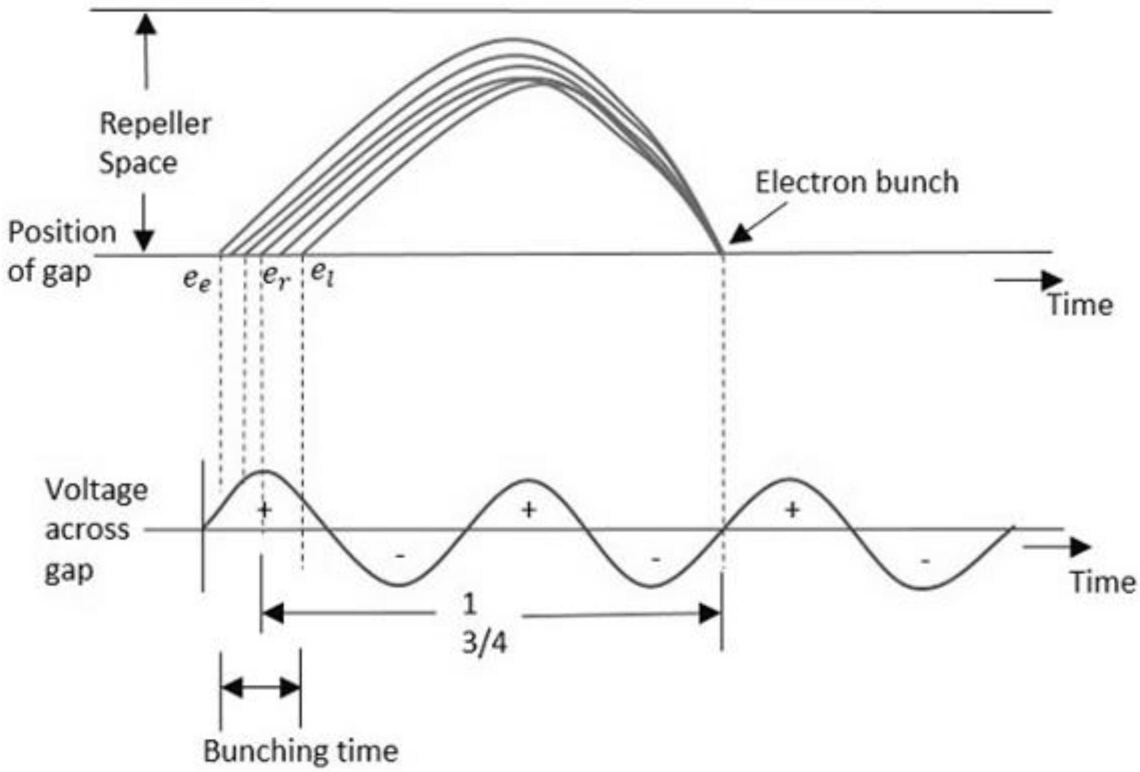


Figure1.2: Mechanism of Oscillation

1.5 Modes of Oscillation

The electrons should return after 1¾, 2 ¾ or 3 ¾ cycles – most optimum departure time. If T is the time period at the resonant frequency, to is the time taken by the reference electron to travel in the repelled space between entering the repelled space and returning to the cavity at positive peak voltage on formation of the bunch

Then, to = (n + ¾)T = NT

Where N = n + ¾, n = 0,1,2,3…….

N – mode of oscillation.

The mode of oscillation is named as N = ¾, 1 ¾   2 ¾ etc for modes n = 0,1,2……resp.

1.6 Mode Curve (Qualitative Analysis only)

Since the output power and Frequency can be Electronically Controlled by varying the repeller voltage, expansions for those parameters in terms of repeller voltage are important to draw mode curves. Figure 1.3 shows mode curve. PRF= 0.3986V0 I0(V0+VR)sqrt(e/2mV0)/2*f*L

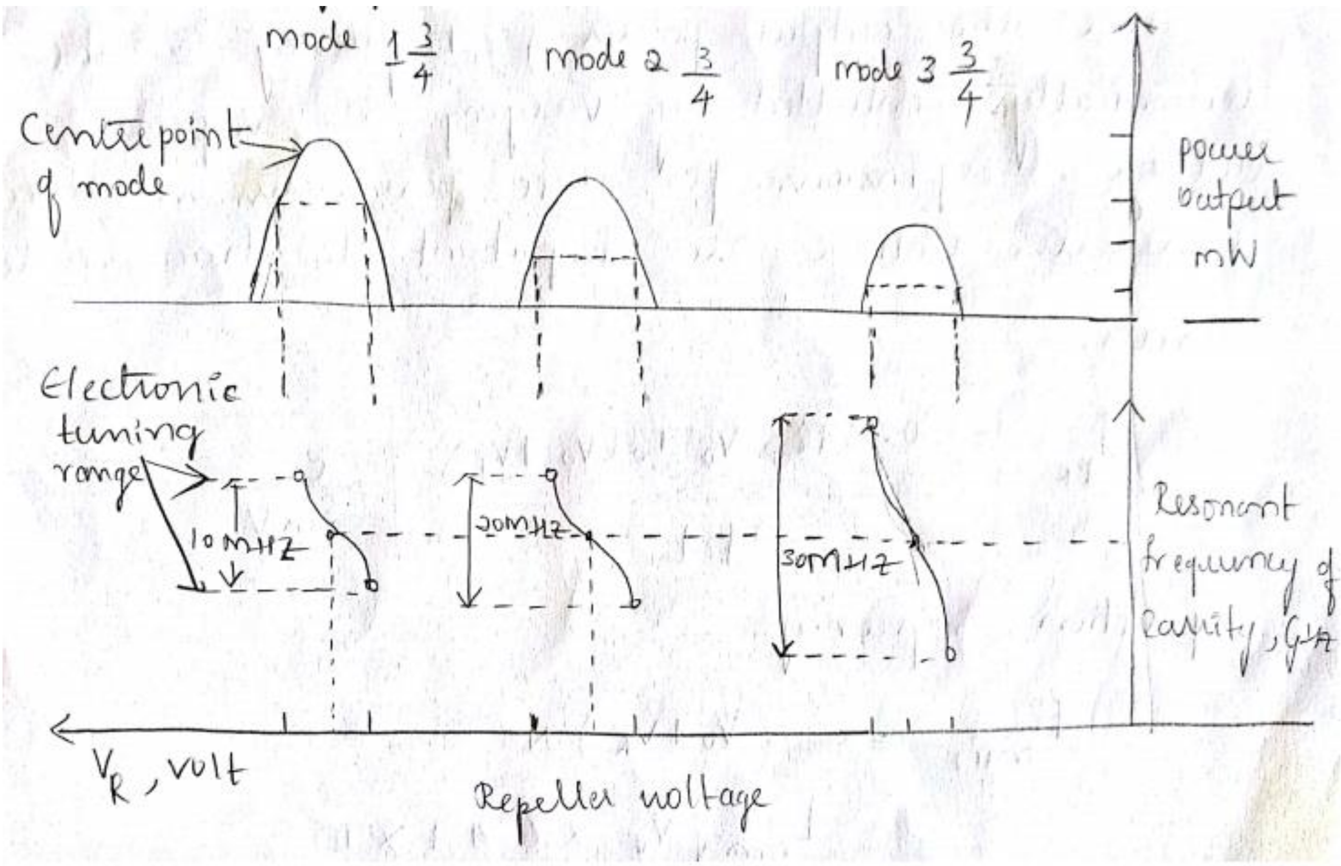


Figure 1.3: Electronic tuning and output mode power of a reflex Klystron

1.7 MICROWAVE FREQUENCIES

The term microwave frequencies are generally used for those wavelengths measured in centimetres, roughly from 30 cm to 1 mm (1 to 300 GHz). However, microwave really indicates the wavelengths in the micron ranges. This means microwave frequencies are up to infrared and visible-light regions. In this revision, microwave frequencies refer to those from 1 GHz up to 106 GHz.

Designation	Frequency range in gigahertz
HF	0.003– 0.030
VHF	0.030– 0.300
UHF	0.300– 1.000
L band	1.000– 2.000
S band	2.000– 4.000
C band	4.000– 8.000
X band	8.000– 12.000
Ku band	12.000– 18.000
K band	18.000– 27.000
Ka band	27.000– 40.000
Millimeter	40.000–300.000
Submillimeter	>300.000

1.8 MICROWAVE DEVICES

In the late 1930s it became evident that as the wavelength approached the physical dimensions of the vacuum tubes, the electron transit angle, interelectrode capacitance, and lead inductance appeared to limit the operation of vacuum tubes in microwave frequencies. In 1935 A. A. Heil and 0. Heil suggested that microwave voltages be generated by using transit-time effects together with lumped tuned cirSec. 0.3 Microwave Systems circuits. In 1939 W. C. Hahn and G. F. Metcalf proposed a theory of velocity modulation for microwave tubes. Four months later R. H. Varian and S. F. Varian described a two-cavity klystron amplifier and oscillator by using velocity modulation. In 1944 R. Kompfner invented the helix-type traveling-wave tube (TWT). Ever since then the concept of microwave tubes has deviated from that of conventional vacuum tubes as a result of the application of new principles in the amplification and generation of microwave energy. Historically microwave generation and amplification were accomplished by means of velocity-modulation theory. In the past two decades, however, microwave solid-state devices-such as tunnel diodes, Gunn diodes, transferred electron devices (TEDs), and avalanche transit-time devices have been developed to perform these functions. The conception and subsequent development of TEDs and avalanche transit-time devices were among the outstanding technical achievements. B. K. Ridley and T. B. Watkins in 1961 and C. Hilsum in 1962 independently predicted that the transferred electron effect would occur in GaAs (gallium arsenide). In 1963 J. B.

Gunn reported his "Gunn effect." The common characteristic of all microwave solid-state devices is the negative resistance that can be used for microwave oscillation and amplification. The progress of TEDs and avalanche transit-time devices has been so swift that today they are firmly established as one of the most important classes of microwave solid-state devices.

1.9 MICROWAVE SYSTEMS

A microwave system normally consists of a transmitter subsystem, including a microwave oscillator, waveguides, and a transmitting antenna, and a receiver subsystem that includes a receiving antenna, transmission line or waveguide, a microwave amplifier, and a receiver. Figure 1.4 shows a typical microwave system. In order to design a microwave system and conduct a proper test of it, an adequate knowledge of the components involved is essential. Besides microwave devices, the text therefore describes microwave components, such as resonators, cavities, microstrip lines, hybrids, and microwave integrated circuits.

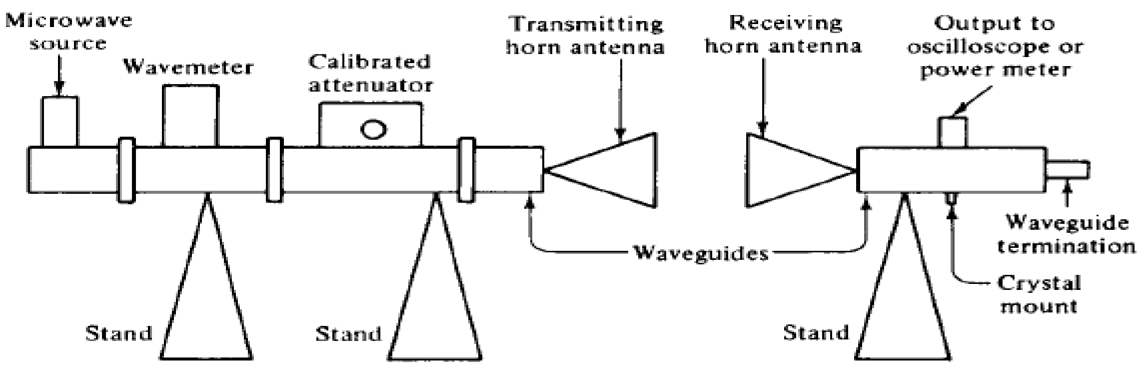


Figure 1.4: Electronic tuning and output mode power of a reflex Klystron

1.10 TRANSMISSION LINE EQUATIONS AND SOLUTIONS

A transmission line can be analysed either by the solution of Maxwell's field equations or by the methods of distributed-circuit theory. The solution of Maxwell's equations involves three space variables in addition to the time variable. The distributed-circuit method, however, involves only one space variable in addition to the time variable. Here latter method is used to analyse a transmission line in terms of the voltage, current, impedance, and power along the line. Based on uniformly distributed-circuit theory, the schematic circuit of a conventional two-conductor transmission line with constant parameters R, L, G, and C. The parameters are expressed in their respective names per unit length, and the wave propagation is assumed in the positive z direction.

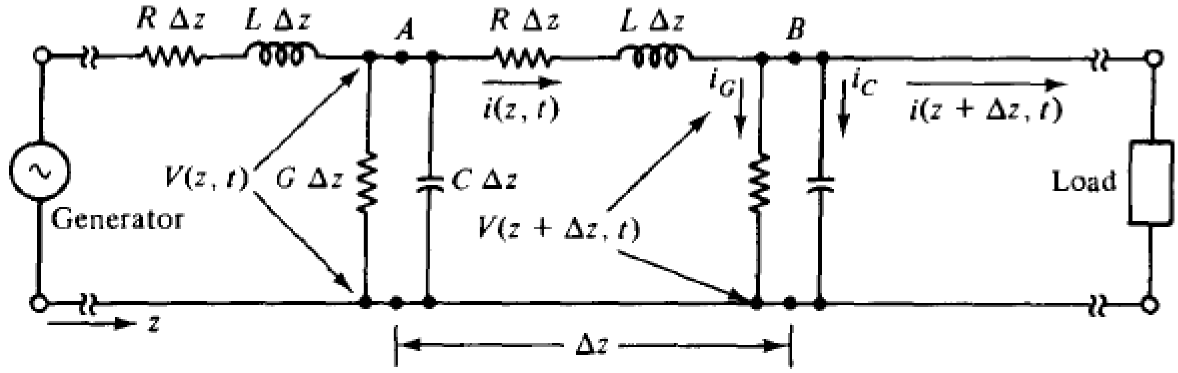


Figure 1.5: Elementary Section of Transmission Line

By Kirchhoff's voltage law, the summation of the voltage drops around the central loop is given by

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

Rearranging this equation, dividing it by Az, and then omitting the argument (z, *t),* which is understood, we obtain

$$-\frac{\partial v}{\partial z} = Ri + L\frac{\partial i}{\partial t}$$

Using Kirchhoff's current law, the summation of the currents at point *B, we obtain*

$$-\frac{\partial i}{\partial z} = Gv + C\frac{\partial v}{\partial t}$$

All these transmission-line equations are applicable to the general transient solution. The voltage and current on the line are the functions of both position *z* and time *t.* The instantaneous line voltage and current can be expressed as

$$v(z,\ t) = \text{Re}\ \mathbf{V}(z)e^{j\omega t}$$

$$i(z,\ t) = \text{Re}\ \mathbf{I}(z)e^{j\omega t}$$

$$\mathbf{V}(z) = \mathbf{V}_+ e^{-\gamma z} + \mathbf{V}_- e^{\gamma z}$$

$$\mathbf{I}(z) = \mathbf{I}_+ e^{-\gamma z} + \mathbf{I}_- e^{\gamma z}$$

$$\gamma = \alpha + j\beta \qquad \text{(propagation constant)}$$

Where V+ and I+ indicate complex amplitudes in the positive *z* direction, V- and **L** signify complex amplitudes in the negative *z* direction, *a* is the attenuation constant in nepers per unit length, and *f3* is the phase constant in radians per unit length. If we substitute *jw* for *a/at* and divide each equation by *jw*, the transmission-line equations in phasor form of the frequency domain become.

$$\frac{d\mathbf{V}}{dz} = -\mathbf{ZI}$$

$$\frac{d\mathbf{I}}{dz} = -\mathbf{YV}$$

$$\frac{d^2\mathbf{V}}{dz^2} = \gamma^2 \mathbf{V}$$

$$\frac{d^2\mathbf{I}}{dz^2} = \gamma^2 \mathbf{I}$$

in which the following substitutions have been made:

$$\mathbf{Z} = R + j\omega L \qquad \text{(ohms per unit length)}$$

$$\mathbf{Y} = G + j\omega C \qquad \text{(mhos per unit length)}$$

$$\gamma = \sqrt{ZY} = \alpha + j\beta \qquad \text{(propagation constant)}$$

For a lossless line, $R = G = 0$, and the transmission-line equations are expressed as

$$\frac{d\mathbf{V}}{dz} = -j\omega L\,\mathbf{I} \tag{1.1}$$

$$\frac{d\mathbf{I}}{dz} = -j\omega C\,\mathbf{V} \tag{1.2}$$

$$\frac{d^2\mathbf{V}}{dz^2} = -\omega^2 LC\,\mathbf{V} \tag{1.3}$$

$$\frac{d^2\mathbf{I}}{dz^2} = -\omega^2 LC\,\mathbf{I} \tag{1.4}$$

Solutions to Transmission Line: The one possible solution for Eq. 1.3

$$\mathbf{V} = \mathbf{V}_+ e^{-\gamma z} + \mathbf{V}_- e^{\gamma z} = \mathbf{V}_+ e^{-\alpha z} e^{-j\beta z} + \mathbf{V}_- e^{\alpha z} e^{j\beta z}$$

The one possible solution for Eq. 1.4

$$\mathbf{I} = \mathbf{Y}_0(\mathbf{V}_+ e^{-\gamma z} - \mathbf{V}_- e^{\gamma z}) = \mathbf{Y}_0(\mathbf{V}_+ e^{-\alpha z} e^{-j\beta z} - \mathbf{V}_- e^{\alpha z} e^{j\beta z})$$

At microwave frequencies it can be seen that $R \ll wL$ and $G \ll wC$

By using the binomial expansion, the propagation constant can be expressed as

$$\begin{aligned}
\gamma &= \sqrt{(R + j\omega L)(G + j\omega C)} \\
&= \sqrt{(j\omega)^2 LC}\sqrt{\left(1 + \frac{R}{j\omega L}\right)\left(1 + \frac{G}{j\omega C}\right)} \\
&\approx j\omega\sqrt{LC}\left[\left(1 + \frac{1}{2}\frac{R}{j\omega L}\right)\left(1 + \frac{1}{2}\frac{G}{j\omega C}\right)\right] \\
&\approx j\omega\sqrt{LC}\left[1 + \frac{1}{2}\left(\frac{R}{j\omega L} + \frac{G}{j\omega C}\right)\right] \\
&= \frac{1}{2}\left(R\sqrt{\frac{C}{L}} + G\sqrt{\frac{L}{C}}\right) + j\omega\sqrt{LC}
\end{aligned}$$

$$\alpha = \frac{1}{2}\left(R\sqrt{\frac{C}{L}} + G\sqrt{\frac{L}{C}}\right)$$

$$\beta = \omega\sqrt{LC}$$

$$\mathbf{Z}_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$
$$= \sqrt{\frac{L}{C}}\left(1 + \frac{R}{j\omega L}\right)^{1/2}\left(1 + \frac{G}{j\omega C}\right)^{-1/2}$$
$$\approx \sqrt{\frac{L}{C}}\left(1 + \frac{1}{2}\frac{R}{j\omega L}\right)\left(1 - \frac{1}{2}\frac{G}{j\omega C}\right)$$
$$\approx \sqrt{\frac{L}{C}}\left[1 + \frac{1}{2}\left(\frac{R}{j\omega L} - \frac{G}{j\omega C}\right)\right]$$
$$\approx \sqrt{\frac{L}{C}}$$

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

Problem on Line Characteristic Impedance:

A transmission line has the following parameters:

$$R = 2\ \Omega/\text{m} \qquad G = 0.5\ \text{mmho/m} \qquad f = 1\ \text{GHz}$$
$$L = 8\ \text{nH/m} \qquad C = 0.23\ \text{pF}$$

Calculate: **(a)** the characteristic impedance; **(b)** the propagation constant.

Solution

a. From Eq. (3-1-25) the line characteristic impedance is

$$\mathbf{Z}_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = \sqrt{\frac{2 + j2\pi \times 10^9 \times 8 \times 10^{-9}}{0.5 \times 10^{-3} + j2\pi \times 10^9 \times 0.23 \times 10^{-12}}}$$
$$= \sqrt{\frac{50.31\angle 87.72^\circ}{15.29 \times 10^{-4}\angle 70.91^\circ}} = 181.39\angle 8.40^\circ = 179.44 + j26.50$$

b. From Eq. (3-1-18) the propagation constant is

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \sqrt{(50.31\angle 87.72^\circ)(15.29 \times 10^{-4}\angle 70.91^\circ)}$$
$$= \sqrt{769.24 \times 10^{-4}\angle 158.63^\circ}$$
$$= 0.2774\angle 79.31^\circ = 0.051 + j0.273$$

1.11 REFLECTION COEFFICIENT

In the analysis of the solutions of transmission-line equations in 1.10, the traveling wave along the line contains two components: one traveling in the positive z direction and the other traveling the negative z direction. If the load impedance is equal to the line characteristic impedance, however, the reflected traveling wave does not exist. Figure 1.5 shows a transmission line terminated in impedance Ze. It is usually more convenient to start solving the transmission-line problem from the receiving rather than the sending end, since the voltage-to-current relationship at the load point is fixed by the load impedance. The incident voltage and current waves traveling along the transmission line are given by

The reflection coefficient, which is designated by r (gamma), is defined as,

$$\text{Reflection coefficient} \equiv \frac{\text{reflected voltage or current}}{\text{incident voltage or current}}$$

$$\mathbf{\Gamma} \equiv \frac{\mathbf{V}_{ref}}{\mathbf{V}_{inc}} = \frac{-\mathbf{I}_{ref}}{\mathbf{I}_{inc}}$$

TRANSMISSION COEFFICIENT

A transmission line terminated in its characteristic impedance Zo is called a properly terminated line. Otherwise it is called an improperly terminated line. As described earlier, there is a reflection coefficient r at any point along an improperly terminated line. According to the principle of conservation of energy, the incident power minus the reflected power must be equal to the power transmitted to the load. This can be expressed as,

$$\mathbf{T} \equiv \frac{\text{transmitted voltage or current}}{\text{incident voltage or current}} = \frac{\mathbf{V}_{tr}}{\mathbf{V}_{inc}} = \frac{\mathbf{I}_{tr}}{\mathbf{I}_{inc}}$$

A certain transmission line has a characteristic impedance of $75 + j0.01\ \Omega$ and is terminated in a load impedance of $70 + j50\ \Omega$. Compute **(a)** the reflection coefficient; **(b)** the transmission coefficient. Verify: **(c)** the relationship shown in Eq. (3-2-21); **(d)** the transmission coefficient equals the algebraic sum of 1 plus the reflection coefficient as shown in Eq. (2-3-18).

Solution

a. From Eq. (3-2-17) the reflection coefficient is

$$\Gamma = \frac{Z_\ell - Z_0}{Z_\ell + Z_0} = \frac{70 + j50 - (75 + j0.01)}{70 + j50 + (75 + j0.01)}$$

$$= \frac{50.24\angle 95.71^\circ}{153.38\angle 19.03^\circ} = 0.33\angle 76.68^\circ = 0.08 + j0.32$$

b. From Eq. (3-2-18) the transmission coefficient is

$$T = \frac{2Z_\ell}{Z_\ell + Z_0} = \frac{2(70 + j50)}{70 + j50 + (75 + j0.01)}$$

$$= \frac{172.05\angle 35.54^\circ}{153.38\angle 19.03^\circ} = 1.12\angle 16.51^\circ = 1.08 + j0.32$$

c.

$$T^2 = (1.12\angle 16.51^\circ)^2 = 1.25\angle 33.02^\circ$$

$$\frac{Z_\ell}{Z_0}(1 - \Gamma^2) = \frac{70 + j50}{75 + j0.01}[1 - (0.33)\angle 76.68^\circ)^2]$$

$$= \frac{86\angle 35.54^\circ}{75\angle 0^\circ} \times 1.10\angle -2.6^\circ = 1.25\angle 33^\circ$$

Thus Eq. (3-2-21) is verified.

d. From Eq. (2-3-18) we obtain

$$T = 1.08 + j0.32 = 1 + 0.08 + j0.32 = 1 + \Gamma$$

1.13 STANDING WAVE AND STANDING WAVE RATIO

The general solutions of the transmission-line equation consist of two waves traveling in opposite directions with unequal amplitude as shown in Eq 1.3 and 1.4.

$$\begin{aligned} V &= V_+ e^{-\alpha z} e^{-j\beta z} + V_- e^{\alpha z} e^{j\beta z} \\ &= V_+ e^{-\alpha z}[\cos(\beta z) - j\sin(\beta z)] + V_- e^{\alpha z}[\cos(\beta z) + j\sin(\beta z)] \\ &= (V_+ e^{-\alpha z} + V_- e^{\alpha z})\cos(\beta z) - j(V_+ e^{-\alpha z} - V_- e^{\alpha z})\sin(\beta z) \end{aligned}$$

With no loss in generality it can be assumed that *V+e-az* and V-e'" are real. Then the voltage-wave equation can be expressed as

$$\mathbf{V}_s = \mathbf{V}_0 e^{-j\phi}$$

This is called the *equation of the voltage standing wave,* where

$$\mathbf{V}_0 = [(\mathbf{V}_+ e^{-\alpha z} + \mathbf{V}_- e^{\alpha z})^2 \cos^2(\beta z) + (\mathbf{V}_+ e^{-\alpha z} - \mathbf{V}_- e^{-\alpha z})^2 \sin^2(\beta z)]^{1/2}$$

$$\phi = \arctan\left(\frac{\mathbf{V}_+ e^{-\alpha z} - \mathbf{V}_- e^{\alpha z}}{\mathbf{V}_+ e^{-\alpha z} + \mathbf{V}_- e^{\alpha z}} \tan(\beta z)\right)$$

which is called the *phase pattern of the standing wave.*

By doing so and substituting the proper values of *f3z* in the equation, we find that,

1. The maximum amplitude is

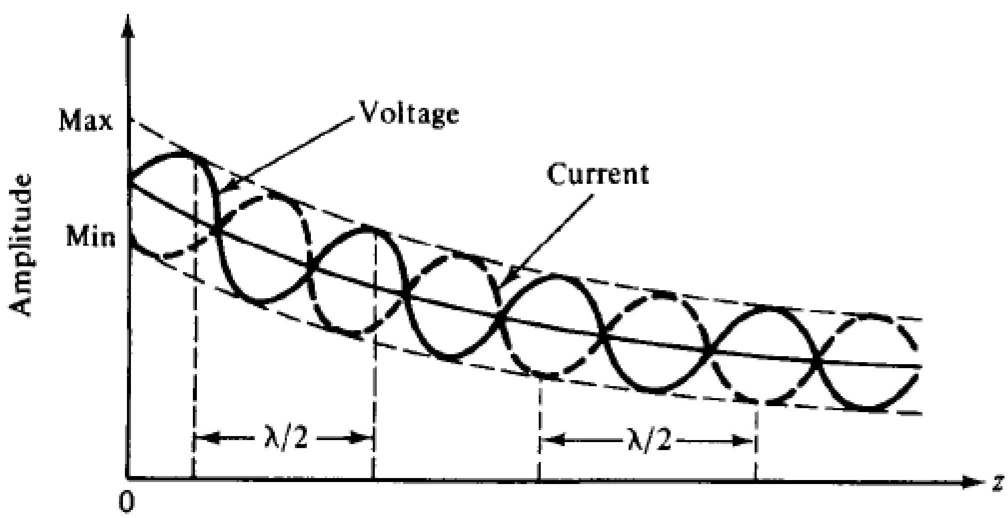
$$\mathbf{V}_{max} = \mathbf{V}_+ e^{-\alpha z} + \mathbf{V}_- e^{\alpha z} = \mathbf{V}_+ e^{-\alpha z}(1 + |\Gamma|)$$

   and this occurs at $\beta z = n\pi$, where $n = 0, \pm 1, \pm 2, \ldots$.

2. The minimum amplitude is

$$\mathbf{V}_{min} = \mathbf{V}_+ e^{-\alpha z} - V_- e^{\alpha z} = \mathbf{V}_+ e^{-\alpha z}(1 - |\Gamma|)$$

   and this occurs at $\beta z = (2n - 1)\pi/2$, where $n = 0, \pm 1, \pm 2, \ldots$.



Standing waves result from the simultaneous presence of waves traveling in opposite directions on a transmission line. The ratio of the maximum of the standing-wave pattern to the minimum is defined as the standing-wave ratio, designated by *p*. That is,

$$\text{Standing-wave ratio} \equiv \frac{\text{maximum voltage or current}}{\text{minimum voltage or current}}$$

$$\rho \equiv \frac{|\mathbf{V}_{max}|}{|\mathbf{V}_{min}|} = \frac{|\mathbf{I}_{max}|}{|\mathbf{I}_{min}|}$$

1.12 SMITH CHART

Many of the computations required to solve transmission-line problems involve the use of rather complicated equations. The solution of such problems is tedious and difficult because the accurate manipulation of numerous equations is necessary. To simplify their solution, we need a graphic method of arriving at a quick answer. A number of impedance charts have been designed to facilitate the graphic solution of transmission-line problems. Basically all the charts are derived from the fundamental relationships expressed in the transmission equations. The most popular chart is that developed by Phillip H. Smith [l]. The purpose of this section is to present the graphic solutions of transmission-line problems by using the Smith chart. The Smith chart consists of a plot of the normalized impedance or admittance with the angle and magnitude of a generalized complex reflection coefficient in a unity circle. The chart is applicable to the analysis of a lossless line as well as a lossy line. By simple rotation of the chart, the effect of the position on the line can be determined.

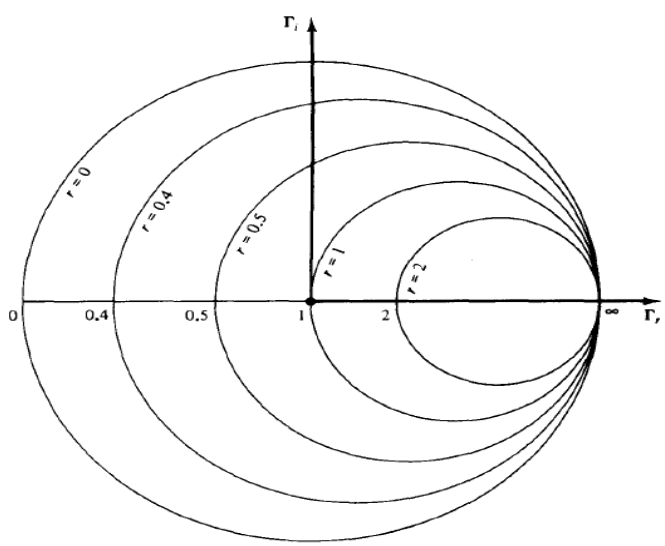


Figure: Constant r (Resistance) Circle

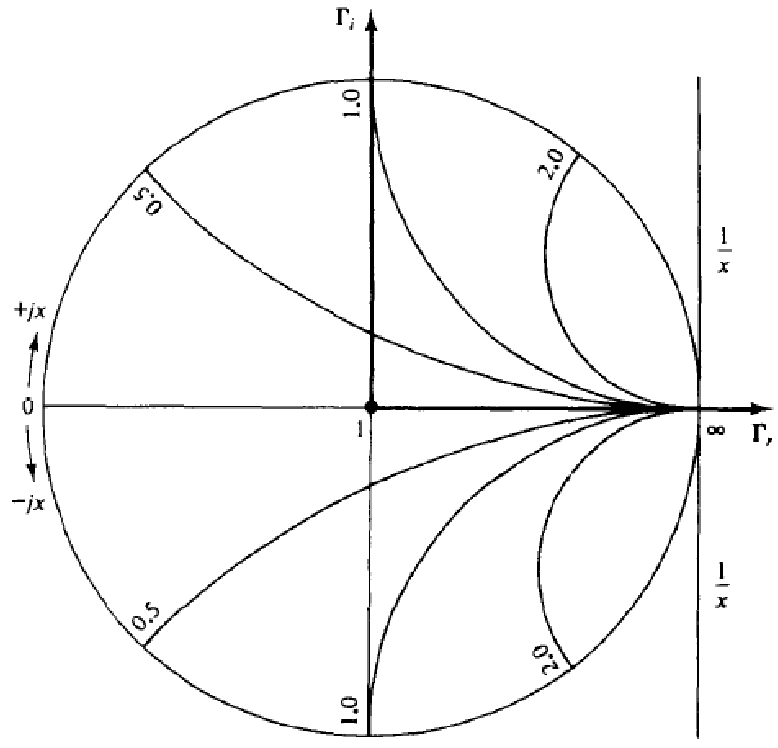


Figure: Constant x (Reactance) Circle

The characteristics of the Smith chart are summarized as follows:

1. The constant *r* and constant *x* loci form two families of orthogonal circles in the chart.

2. The constant *r* and constant *x* circles all pass through the point (L = 1,f; = O).

3. The upper half of the diagram represents + *jx.*

4. The lower half of the diagram represents - *jx.*

5. For admittance the constant *r* circles become constant *g* circles, and the constant *x* circles become constant susceptance *b* circles.

6. The distance around the Smith chart once is one-half wavelength (A/2).

7. At a point of Zmin = 1 / *p*, there is a Vmin on the line.

8. At a point of Zmax = *p'* there is a Vmax on the line.

9. The horizontal radius to the right of the chart center corresponds to Vmax, /min, Zmax, and *p* (SWR).

10. The horizontal radius to the left of the chart center corresponds to Vmin, *I* max, Zmin, and l/p.

11. Since the normalized admittance y is a reciprocal of the normalized impedance z, the corresponding quantities in the admittance chart are 180° out of phase with those in the impedance chart.

12. The normalized impedance or admittance is repeated for every half wavelength of distance.

13. The distances are given in wavelengths toward the generator and also toward the load.

1.14 SINGLE STUB MATCHING

Although single-lumped inductors or capacitors can match the transmission line, it is more common to use the susceptive properties of short-circuited sections of transmission lines. Short-circuited sections are preferable to open-circuited ones because a good short circuit is easier to obtain than a good open circuit. For a lossless line with *Y8* = Yo, maximum power transfer requires Y11 = Yo, where Y11 is the total admittance of the line and stub looking to the right at point 1-1 (see Fig. 3-6-2). The stub must be located at that point on the line where the real part of the admittance, looking toward the load, is Yo. In a normalized unit *Y11* must be in the form.

$$Y11 = Yd \pm Ys = 1$$

A lossless line of characteristic impedance Ro = 50 fl is to be matched to a load *Ze* = 50/[2 + j(2 + \/3)] fl by means of a lossless short-circuited stub. The characteristic impedance of the stub is 100 fl. Find the stub position (closest to the load) and length so that a match is obtained.

OUTCOME:

Student will be able to,

- Describe the use and advantages of microwave transmission and analyze various parameters related to microwave transmission lines and waveguides

RECOMMENEDED QUESTIONS:

1 What is Microwave system?
2 What are Microwave Frequencies?
3 What is Smith Chart and Single Stub Matching?
4 Derive equation for Reflection Coefficient.
5 Derive Equation for Transmission Coefficient.
6 Define SWR and derive the same.