EC 6701 - RF & Microwave ENGINEERING

UNIT – III
Passive Microwave Devices
Microwave Hybrid Circuits

- A microwave circuit ordinarily consists of several microwave devices connected in some way to achieve the desired transmission of a microwave signal. The interconnection of two or more microwave devices may be regarded as a microwave junction.

- Commonly used microwave junctions include such wave guide tees as the E Plane Tee (Series), H Plane Tee (Shunt), Magic Tee, Hybrid ring (rat -race circuit), and the circulator.

Wave guide Tees

1. A wave guide Tees may consists of the E plane tee, H Plane Tee, Magic Tee, Hybrid rings, Corners, bends, Twists. All such wave guide components are discussed in this section.

2. In microwave circuits, a wave guide or co-axial line junction with three independent ports is commonly referred to as a Tee junction.
1. A rectangular slot is cut along the broader dimension of a long wave guide & side arm is attached as shown in fig. Axis of the side arm is parallel to the E Field of main wave guide.

2. The wave incident at Port 3, will result in waves at Port 1 and Port 2, which are equal in magnitude but opposite in phase $S_{31} = S_{13} = -S_{23} = -S_{32}$
3. If the two in phase input waves are fed in to ports 1 & 2 of the collinear arms, the output waves at port 3 will be opposite in phase and subtractive. Sometimes this port is called difference arm.

4. All the diagonal elements of the S matrix of an E plane Tee cannot be zero simultaneously since the tee junction cannot be matched to all the three arms simultaneously. Considering the port 3 as matched, then $S_{33} = 0$.

5. From symmetric property $S_{ij} = S_{ji}$

(i.e) $S_{12} = S_{21}, S_{13} = S_{31}, S_{23} = S_{32}$

Combining all these together,

$$[S] = \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix} \text{ becomes } \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{12} & S_{22} & -S_{13} \\
S_{13} & -S_{13} & 0
\end{bmatrix}$$
From unit property of S-matrix

\[ |S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = 1 \rightarrow (1) \]
\[ |S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1 \rightarrow (2) \]
\[ |S_{13}|^2 + |S_{13}|^2 = 1 \rightarrow (3) \]

From zero property of S-matrix

\[ S_{13} S_{11}^* - S_{13} S_{12}^* = 0 \rightarrow (4) \]

Equating (1) & (2)

\[ |S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = |S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1 \]
\[ |S_{11}|^2 = |S_{22}|^2 \Rightarrow S_{11} = S_{22} \rightarrow (5) \]

(3) \[ \rightarrow |S_{13}|^2 + |S_{13}|^2 = 1 \]
\[ 2 |S_{13}|^2 = 1 \]
\[ |S_{13}| = \frac{1}{\sqrt{2}} \]
Substituting all these values in $[S]$ matrix:

\[ S_{13}S_{11}^* - S_{13}S_{12}^* = 0 \]
\[ S_{13}(S_{11}^* - S_{12}^*) = 0 \]
\[ S_{13} \neq 0 \text{ & } S_{13} = \frac{1}{\sqrt{2}} \text{ So } S_{11}^* - S_{12}^* = 0 \]
\[ S_{11}^* = S_{12}^* \]
\[ S_{11} = S_{12} \]

So $S_{11} = S_{12} = S_{22}$

\[ (4) \rightarrow |S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = 1 \]

\[ |S_{11}|^2 + |S_{11}|^2 + \left(\frac{1}{\sqrt{2}}\right)^2 = 1 \]
\[ 2|S_{11}|^2 = 1 - \frac{1}{2} = \frac{1}{2} \]

\[ |S_{11}|^2 = \frac{1}{4} \Rightarrow S_{11} = \frac{1}{2} \]

Substituting all these values in $[S]$ matrix:

\[ [S] = \begin{bmatrix}
\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\
\frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\
\end{bmatrix} \]
H Plane Tee (Shunt Tee)

1. Axis of the side arm is “Shunting” the E field (or) parallel to the H field of the main wave guide.

2. If two input waves are fed into port 1 & port 2 of the collinear arm the output wave at port 3 will be additive & in Phase. So the third port is called as sum arm. On the other hand, if the input is fed in to port 3, the wave will split equally into port 1 & port 2 in phase and in the same magnitude. \[ S_{13} = S_{23} \].

3. All the diagonal elements of the S matrix of an E plane Tee cannot be zero simultaneously since the tee junction cannot be matched to all the three arms simultaneously. Considering the port 3 as matched, then \[ S_{33} = 0 \].

4. From symmetric property \( S_{ij} = S_{ji} \) (i.e) \[ S_{12} = S_{21}, S_{13} = S_{31}, S_{23} = S_{32} \].
5. Combining all the conditions,

\[
[S] = \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix} = \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{12} & S_{22} & S_{13} \\
S_{13} & S_{13} & 0
\end{bmatrix}
\]

From unit property of S-matrix

\[|S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = 1 \rightarrow (1)\]
\[|S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1 \rightarrow (2)\]
\[|S_{13}|^2 + |S_{13}|^2 = 1 \rightarrow (3)\]

From zero property of S-matrix

\[S_{13}S_{11}^* - S_{13}S_{12}^* = 0 \rightarrow (4)\]

Equating (1) & (2)

\[|S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = |S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 = 1\]
\[|S_{11}|^2 = |S_{22}|^2 \Rightarrow S_{11} = S_{22} \rightarrow (5)\]
\[(3) \rightarrow |S_{13}|^2 + |S_{13}|^2 = 1 \]

\[2 |S_{13}|^2 = 1 \quad \Rightarrow \quad |S_{13}|^2 = \frac{1}{\sqrt{2}}\]

\[(4) \rightarrow S_{13}S_{11}^* + S_{13}S_{12}^* = 0\]

\[S_{13}(S_{11}^* + S_{12}^*) = 0\]

But \(S_{13} \neq 0\), so \(S_{11}^* + S_{12}^* = 0\)

\[S_{11}^* = -S_{12}^* \quad \Rightarrow \quad |S_{11}|^2 = |S_{12}|^2\]

\[(1) \rightarrow |S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 = 1\]

\[|S_{11}|^2 + |S_{11}|^2 + \left(\frac{1}{\sqrt{2}}\right)^2 = 1\]

\[2 |S_{11}|^2 = 1 - \frac{1}{2} = \frac{1}{2}\]

\[|S_{11}|^2 = \frac{1}{4} \quad \Rightarrow \quad |S_{11}| = \frac{1}{2}\]

Substituting all these values in \([S]\) matrix

\[
[S] = \begin{bmatrix}
\frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \\
-\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0
\end{bmatrix}
\]
Magic Tee (Hybrid or E-H Plane Tee)

1. A hybrid junction is a four port network in which a signal incident on any one of the ports divided between 2 output ports, with the remaining port being isolated.

2. Combination of the E plane tee & H Plane tee

3. Port 1 & Port 2 are collinear arm, port 3 - H arm & port 4 - E arms.

4. If two waves of equal magnitude and the same phase are fed into port 1 & port 2, the output will be zero at port 4 and additive at Port3. Hence Port 4 is difference (or) E arm and port 3 is sum (or) H arm

5. If a wave is fed in to port 3 (H arm), it will be divided equally between port 1 and port 2 of the collinear arms with in phase and it will not appear at port 4 (E arm)

\[ S_{13} = S_{23} \]
6. If a wave is fed in to port 4 (E arm) it will produce an output of equal magnitude and opposite phase at port 1 and port 2. The output at port 3 is zero. \[ S_{34} = S_{43} = 0 \] \[ S_{14} = -S_{24} \]

7. If a wave is fed in to one of the collinear arms at port 1 or port 2, it will not appear in the other collinear arm at port 2 or port 1, because the E arm causes a phase delay, while the H arm causes a phase advance. \[ S_{12} = S_{21} = 0 \].

8. A magic T can be matched by putting tuning screws suitably in the E and H arms without destroying the symmetry of the junctions. Therefore an ideal loss less magic T matched at ports 3 and Port 4. \[ S_{33} = S_{44} = 0 \]

9. From symmetric property \( S_{ij} = S_{ji} \).

\[ S_{12} = S_{21}, S_{13} = S_{31}, S_{14} = S_{41}, S_{23} = S_{32}, S_{24} = S_{42}, S_{34} = S_{43} \]

Combining all these

\[
[S] = \begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix} = \begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{12} & S_{22} & S_{13} & -S_{14} \\
S_{13} & S_{13} & 0 & 0 \\
S_{14} & -S_{14} & 0 & 0
\end{bmatrix}
\]
From unit property of S-matrix

\[ |S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 + |S_{14}|^2 = 1 \rightarrow (1) \]
\[ |S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 + |S_{14}|^2 = 1 \rightarrow (2) \]
\[ |S_{13}|^2 + |S_{13}|^2 = 1 \rightarrow (3) \]
\[ |S_{14}|^2 + |S_{14}|^2 = 1 \rightarrow (4) \]

Equating (1) & (2)

\[ |S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 + |S_{14}|^2 = |S_{12}|^2 + |S_{22}|^2 + |S_{13}|^2 + |S_{14}|^2 = 1 \]
\[ |S_{11}|^2 = |S_{22}|^2 \Rightarrow S_{11} = S_{22} \]

(3) \[|S_{13}|^2 + |S_{13}|^2 = 1 \]
\[ 2|S_{13}|^2 = 1 \]
\[ S_{13} = \frac{1}{\sqrt{2}} \]

(4) \[|S_{14}|^2 + |S_{14}|^2 = 1 \]
\[ 2|S_{14}|^2 = 1 \]
\[ S_{14} = \frac{1}{\sqrt{2}} \]
(1) \rightarrow |S_{11}|^2 + |S_{12}|^2 + |S_{13}|^2 + |S_{14}|^2 = 1

|S_{11}|^2 + |S_{12}|^2 + \left( \frac{1}{\sqrt{2}} \right)^2 + \left( \frac{1}{\sqrt{2}} \right)^2 = 1

since \quad S_{13} = S_{14} = \frac{1}{\sqrt{2}}

|S_{11}|^2 + |S_{12}|^2 + \frac{1}{2} + \frac{1}{2} = 1 \quad \Rightarrow \quad |S_{11}|^2 + |S_{12}|^2 = 0

which is valid if \( S_{11} = S_{12} = 0 \)

\[
[S] = \begin{bmatrix}
0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0
\end{bmatrix}
\]

Applications

1. Mixing
2. Duplexing
3. Impedance measurement
E Plane Tee

H Plane Tee

Magic Tee
Circulator

- A circulator is a multiport junction, in which the wave can travel from nth port to the \((n + 1)th\) port in one direction only.

- It means the wave cannot travel from \((n+1)th\) to nth port in opposite direction.

- Commonly used circulators are 3 port or 4 port devices, although more number of ports are possible.
1. A 4 port circulator may be constructed from combination of 2, 3dB side hole directional couplers & rectangular wave guide with two non-reciprocal phase shifters.

2. Each of the two 3dB couplers in the circulator introduces a phase shift of 90°.

3. Two phase shifter produces a certain phase shift in certain direction as indicated in the figure.

Figure 4-6-3  Schematic diagram of four-port circulator.
4. When a wave is incident to port 1, the wave split in to two components by coupler 1. The wave in the primary guide arrives at port 2 with a relative phase change of 180°.

5. The second wave propagates through the two couplers & the secondary guide and arrives at port 2 with a relative phase shift of 180°.

6. Since the two waves reaching port 2 are in phase, the power is transmitted from port 1 to port2.

7. However, the wave propagates through the primary guide, phase shifter and coupler 2 and arrives at port 4 with a phase change of 270°. The wave travel through a coupler 1 & the secondary guide & it arrives at port 4 with a phase shift of 90°. The two waves reaching port 4 are out of phase by 180° and the power transmission from port 1 to port 4 is zero.
Circulator can also be constructed using Two magic Tees and a non reciprocal phase shifter.
1. Input signal at port 1 (Encircled in figure) from magic Tee (T1) is split into two in phase and equal amplitude waves in 'b' & 'd': Now 'a' & 'c' will be same phase due to 0° phase shift. So the added output will be at port 2.

2. When input is in port 2, it is split into 'a' & 'e' in same phase, due to 180° phase shifter 'b' & 'd' will be out of phase. So the output will be at port 3.

3. When input is in port 3, the wave is split into 'b' & 'd' with opposite phase & 'a' & 'c' also out of phase. So there will be output in port 4.

4. When input is in port 4, 'a' & 'c' will be out of phase. 'b' & 'd' become in phase, when 'a' pass through 180° phase shifter. Now the added output will be in port 1.
Since all the ports are perfectly matched

\[
[S] = \begin{bmatrix}
0 & S_{12} & S_{13} & S_{14} \\
S_{21} & 0 & S_{23} & S_{24} \\
S_{31} & S_{32} & 0 & S_{34} \\
S_{41} & S_{42} & S_{43} & 0
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\]

3 Port Circulator

1. Formed by a 120° H plane wave guide or strip line symmetrical Y junction with a central ferrite post or disc.

2. A steady magnetic field \( H_0 \) is applied along the axis of the disc.

3. Depending upon the polarization of the incident wave and the direction of \( H_0 \), the microwave signal travels from on port to the immediate next one only.
By considering circulator as a perfectly matched, lossless and non-reciprocal device, its $[S]$ matrix can be written as

$$
[S] = \begin{bmatrix}
0 & 0 & S_{13} \\
S_{21} & 0 & 0 \\
0 & S_{32} & 0
\end{bmatrix}
$$

If the terminal planes are properly chosen to make the phase angles $S_{13}$, $S_{21}$ and $S_{32}$ zero, then $S_{13} = S_{21} = S_{32} = 1$

Insertion loss $< 1$ dB
Isolation $= 30 – 40$ dB
VSWR $< 1.5$
An isolator is a non-reciprocal transmission device that is used to isolate one component from reflections of other components in the transmission line.

An ideal isolator completely absorbs the power for propagation in one direction and provides lossless transmission in the opposite direction. Thus the isolator is usually called as a uni line.

An isolators are generally used to improve the frequency stability of microwave generators such as Klystrons and magnetrons, in which the reflection from the load affects the generating frequency.

Construction:
• Made by terminating port 3 & 4 of a four port circulator with matched loads.
• Made by inserting a ferrite rod along the axis of a rectangular waveguide. Here the isolator is called as Faraday rotation isolator.
Faraday Rotation:

The rotation of the direction of E field of linearly polarized wave passing through a magnetized ferrite medium is known as Faraday rotation.

Figure 4-6-5  Faraday-rotation isolator.
1. The input resistive card is in the Y-Z plane & the output resistive card is displaced 45° w.r.t the input card.
2. The de magnetic field, which is applied longitudinally to the ferrite rod rotates the wave plane of polarization by 45°. The degree of rotation depends on the length & diameter of the rod and on the applied dc magnetic field.
3. An input TE$_{10}$ dominant mode is incident to the left end of the isolator.
4. TE$_{10}$ mode wave is perpendicular to the input resistive card. So the wave passes through the ferrite rod without attenuation.
5. The wave in the ferrite rod section is rotate clockwise by 45° & is normal to the output resistive card. As a result of rotation, the wave arrives at the output end without attenuation.
6. A reflected wave from the output end is similarly rotated clockwise 45° by the ferrite rod. Since the reflected wave is parallel to the input resistive card the wave absorbed by the input card.

\[
S = \begin{bmatrix}
0 & 0 \\
1 & 0 
\end{bmatrix}
\]

**Characteristics of the isolator**
- Insertion loss : 1dB
- Isolation : 20 - 30dB
A directional coupler is a four-port waveguide junction as shown in Fig. 4-5-1. It consists of a primary waveguide 1–2 and a secondary waveguide 3–4. When all ports are terminated in their characteristic impedances, there is free transmission of power, without reflection, between port 1 and port 2, and there is no transmission of power between port 1 and port 3 or between port 2 and port 4 because no coupling exists between these two pairs of ports. The degree of coupling between port 1 and port 4 and between port 2 and port 3 depends on the structure of the coupler.
Coupling factor (dB) = 10 \log_{10} \frac{P_1}{P_4}

Directivity (dB) = 10 \log_{10} \frac{P_4}{P_3}

where \( P_1 \) = power input to port 1
\( P_3 \) = power output from port 3
\( P_4 \) = power output from port 4

It should be noted that port 2, port 3, and port 4 are terminated in their characteristic impedances. The coupling factor is a measure of the ratio of power levels in the primary and secondary lines. Hence if the coupling factor is known, a fraction of power measured at port 4 may be used to determine the power input at port 1. This significance is desirable for microwave power measurements because no disturbance, which may be caused by the power measurements, occurs in the primary line. The directivity is a measure of how well the forward traveling wave in the primary waveguide couples only to a specific port of the secondary waveguide.
1. Two-hole directional coupler

- Consists of primary wave guide 1-2 & a secondary with 3-4 with two small holes. Spacing between the centers of two holes must be

$$L = (2n + 1) \frac{\lambda g}{4}$$

- A Fraction of wave energy entered in to port 1 passes through the holes and is radiated in to the secondary guide as the holes act as slot antennas.
- The forward waves in the secondary guide are in the same phase, and are added at port 4. The backward waves in the secondary guides (wave progressing from right to left) are out of phase and cancelled at port 3.
$\textbf{S matrix of a directional coupler}$

$S$ is, $4 \times 4$ matrix

$$
[S] = 
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix}
$$

(a) All four ports are completely matched. Thus the diagonal elements are zero.

$$S_{11} = S_{22} = S_{33} = S_{44} = 0$$

(b) No coupling between port 1 and port 3 and port 2 and port 4

$$S_{13} = S_{31} = 0 \quad \& \quad S_{24} = S_{42} = 0$$

(c) By using symmetry property, $[S_{ij} = S_{ji}, (i \neq j)]$, we can write

$$
\begin{align*}
S_{12} &= S_{21} \\
S_{13} &= S_{31} \\
S_{14} &= S_{41} \\
S_{23} &= S_{32} \\
S_{24} &= S_{42} \\
S_{34} &= S_{43}
\end{align*}
$$
Substituting all these conditions,

\[
[S] = \begin{bmatrix}
0 & S_{12} & 0 & S_{14} \\
S_{12} & 0 & S_{23} & 0 \\
0 & S_{23} & 0 & S_{34} \\
S_{14} & 0 & S_{34} & 0
\end{bmatrix}
\]

By unit property of S matrix:

\[|S_{12}|^2 + |S_{14}|^2 = 1\]  \hspace{1cm} (1)

\[|S_{12}|^2 + |S_{23}|^2 = 1\]  \hspace{1cm} (2)

\[|S_{23}|^2 + |S_{34}|^2 = 1\]  \hspace{1cm} (3)

By zero property of S matrix:

\[S_{12} S_{23}^* + S_{14} S_{34}^* = 0\]  \hspace{1cm} (4)
Comparing equation (1) and (2)

\[ |S_{12}|^2 + |S_{14}|^2 = |S_{12}|^2 + |S_{23}|^2 \]

\[ |S_{14}|^2 = |S_{23}|^2 \]

\[ S_{14} = S_{23} \] \hspace{1cm} (5)

Comparing equation (2) and (3)

\[ |S_{12}|^2 = |S_{34}|^2 \]

\[ S_{12} = S_{34} \]

→ Let \( S_{12} = S_{34} = P \), where \( P \) is real and positive number

\[ S_{12} = S_{34} = S_{12}^* = S_{34}^* = P \] \hspace{1cm} (6)
→ Substitute (6) in (4) we get

\[ S_{12}S_{23}^* + S_{14}S_{34}^* = 0 \]
\[ PS_{23}^* + S_{23}P = 0 \]
\[ \text{(i.e)} \quad P(S_{23}^* + S_{23}) = 0 \]
\[ P \neq 0, \quad S_{23}^* + S_{23} = 0 \]
\[ \Rightarrow \quad \text{(i.e)} - S_{23} = S_{23}^* \]

We can conclude that \( S_{23} \) is imaginary number

\[ S_{14} = S_{23} = jq \& S_{12} = S_{34} = P \]

Substituting all these together

\[ [S] = \begin{bmatrix}
0 & P & 0 & jq \\
P & 0 & jq & 0 \\
0 & jq & 0 & P \\
jq & 0 & P & 0
\end{bmatrix} \]
Matched Termination

- Matched terminations are used in coaxial lines, strip lines and wave guide to absorb the incident power without appreciable reflection and radiation.
- A tapered lossy dielectric is placed at the end of the shorted line as shown in the figure to form a matched termination.
- The length of the tapered section is kept about one to two wavelengths at the lowest frequency of operation for effective absorption power.
- To increase the power dissipation, aquadag-coated sand is used as lossy material.
- High power (> 1W) terminations use outer cooling fins for heat dissipation.
- Practical VSWR of these loads is the range of 1.02-1.05 over the frequency bandwidth of the order of 20-30% of the centre frequency.

Waveguide Matched termination

Photo of Waveguide Matched termination
Attenuators

1. Attenuators are passive devices used to control power levels in a microwave system by partially absorbing the transmitted signal wave.
2. Both the fixed and variable attenuators are designed using resistive films (Aquadag coated dielectric sheet)

Waveguide Fixed Attenuator

Coaxial Fixed Attenuator

It uses a film with losses on the center conductor to absorb some of the power

1. This type consists of thin dielectric strip coated with resistive film & placed at the center of the waveguide parallel to the E field.
2. Induced current on the resistive film due to the incident wave results in power dissipation, leading to attenuation of microwave energy.
3. Dielectric strip is tapered at both ends up to a length of more than half wavelength to reduce reflections.
4. The resistive vane is supported by dielectric rods separated by an odd multiple of quarter wavelength & perpendicular to the electric field.
**Waveguide variable type Attenuator**

A variable type attenuator can be constructed by moving the resistive vane by means of micrometer screw from one side of the narrow wall to the center or by changing the depth of insertion of resistive vane through a longitudinal slot at the middle of the broad wall.

Maximum attenuation: 90dB & VSWR : 1.05

**Waveguide Precision Type Variable Attenuator**

1. It makes use of a circular section (C) containing a very thin tapered resistive card R2 to both sides of which are connected as symmetric sections of circular to rectangular waveguide tapered transitions (RC1 & RC2)

2. The center circular section with the resistive card can be precisely rotated by 360° w.r.t the two fixed sections of circular to rectangular waveguide transition.

3. The induced current on the resistive card $R_2$ due to the incident signal is dissipated as heat-producing attenuation of the transmitted signal.
4. The incident TE10 dominant wave in rectangular wave guide is converted into a dominant TE11 mode in the circular wave guide.

5. The tapered resistive card is placed perpendicular to the E field at the circular end of each transition section. It has negligible effect on the field perpendicular to it. But absorbs any component parallel to it. Therefore a pure TE11 mode is excited in the middle section.

6. If the resistive card (R2) in the center section is kept at an angle $\theta$, relative to the E field direction of the TE11 mode, the component $E \cos \theta$ parallel to the card gets absorbed, while the component $E \sin \theta$ is transmitted without attenuation.

7. This later component finally appears as electric field component $E \sin 2\theta$ in a rectangular output guide.

8. Therefore the attenuation of the incident wave is

$$\alpha = \frac{E}{E \sin^2 \theta} = \frac{1}{\sin^2 \theta} = \frac{1}{|S_{21}|}$$

$$\alpha (dB) = -40 \log (\sin \theta) = -20 \log |S_{21}|$$

9. Therefore the attenuation depends only on the angle of rotation $\theta$ of the resistive card w.r.t the incident wave polarization.

Normally reciprocal devices $|S_{12}| = |S_{21}|$

$$[S] = \begin{bmatrix}
0 & \sin^2 \theta \\
\sin^2 \theta & 0
\end{bmatrix}$$
Phase Shifters

1. A phase shifter is a two port passive device that produces a variable change in phase of the wave transmitted through it.

2. Phase shifter can be realized by placing a loss less dielectric slab with in a wave guide parallel to it.

3. A differential phase change is produced due to the change of wave velocity through the dielectric slab, compared to that through an empty wave guide.

4. The propagation constant through a length ‘ℓ’ of a dielectric slab and of an empty guide are respectively,

\[
\beta_1 = \frac{2\pi}{\lambda_{g_1}} = \frac{2\pi}{\lambda_0/\sqrt{\varepsilon_r}} \sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2} \\
\beta_2 = \frac{2\pi}{\lambda_{g_2}} = \frac{2\pi}{\lambda_0/\sqrt{\varepsilon_r}} \sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2}
\]

5. Thus the differential phase shift produced by the phase shifter is ‘Δφ = (β₁ ~ β₂) ℓ’. By adjusting the length ℓ different phase shifts can be produced.

\[
[S] = \begin{bmatrix} 0 & e^{-j\Delta\phi} \\ e^{-j\Delta\phi} & 0 \end{bmatrix}
\]
Precision Phase Shifter

1. This uses a section of circular waveguide containing a loss less dielectric plate of length $2\ell$ called half wave $180^\circ$ section. This section can be rotated over $360^\circ$ between two sections of circular to rectangular wave guide transitions, each containing loss less dielectric plate of length $\ell$ called quarter wave $(90^\circ)$ section oriented an angle of $45^\circ$ w.r.t. the broad wall of the rectangular waveguide.

2. The incident $TE_{10}$ wave in the rectangular wave guide is converted in to a dominant $TE_{11}$ mode in the circular wave guide.

3. The half wave section produces a phase shift equal to twice it rotation angle $\theta$ w.r.t the quarter wave section.

4. The dielectric plates are tapered through a length of quarter wavelength at both ends for reducing reflection due to discontinuity.
Power Dividers

1. A power divider is a device to split the input power into a number of smaller amounts of power at multiple ports (N) to feed N number of branching circuits with isolation between the output ports.

2. Loss less T junction Divider: It suffers from the problem of not being matched at all ports. In addition, it does not have any isolation between output ports.

3. Resistive Divider: It can be matched at all ports, but even though it is loss less, isolation is still not achieved.

4. Wilkinson Power Divider:
   It is a network with the useful property of being loss less, when the output ports are matched.

5. This divider is often made in micro strip or strip line form as shown in fig.
1. The characteristics impedance of input line is $Z_o$.

2. For equal power division, the device consists of two quarter wave sections with characteristics impedance $\sqrt{2}Z_o$.

3. The input impedance at port 1 is $Z_o/2$. With the help of quarter wave transformer, the characteristics impedance of port 1 is transformed into feeder line impedance $Z_o$.

4. A resistor $R = 2Z_o$ is connected between Port 2 and 3 which are matched terminated.

5. When a signal enters port 1, it splits into equal-amplitude, equal-phase output signals at ports 2 and 3. Since each end of the isolation resistor, between ports 2 and 3 is at the same potential, no current flows through it and therefore the resistor is decoupled from the input.

6. With a help of even and odd mode analysis, it can be shown that the power applied to port 1 divides equally between ports 2 & 3 with zero loss in the balancing resistor $R$, and the voltage at either output port lags that at the input port by 90°.

Thus the device is a 3dB, 90° divider. It can also shown that the configuration also acts as a 3 dB power combiner when fed from the ports 2 and 3 with the output taken at port 1.
**Tuning Screw**

A tuning screw is used as a toning device for impedance matching on account of the reactive nature of the screw.

A tuning screw is a metal rod or probe inserted into a rectangular waveguide through the center of a broad wall perpendicularly. This probe provides a reactance across the guide which can be varied from capacitive to inductive by changing the depth of penetration.

To avoid power leakage through the screw gap, a half wave length choke is used at the screw insertion junction, where the leakage signal sees zero impedance due to $\lambda_g/2$ short circuited line.

*Photo of Slide Screw Tuner*
The tuning screw can also be slid along the axis of the waveguide through a narrow longitudinal slot at the center of the broad wall. This helps varying both penetration and position of the tuning screw along a longitudinal distance of the half guide wavelength for better matching with ease. Such devices are called Slide Screw tuners.

Since the position of the screw is adjustable over at least a half guide wavelength, this probe provides a reactance across the guide which can be varied from capacitive to inductive by changing the depth of penetration. When a depth of penetration $h < \lambda g/4$, the reactance is capacitive, when it $> \lambda g/4$, the reactance is inductive and when $h \approx \lambda g/4$, the reactance is infinite.

A single screw reactance provides very narrow band impedance matching. A greater frequency range of impedance matching can be achieved with three fixed screws placed $3\lambda g/8$ apart as shown in the figure, whose depth of penetration can be varied independently for matching.
Quarter Wave Transformers

Quarter wave Transformers are primarily used as intermediate matching sections, when it is desired to connect two wave guiding systems of different characteristics impedance.

Examples
• Connection of two transmission lines with different characteristics impedance
• Connection of empty wave guide to a wave guide partially or completely filled with dielectric
• Connection of two wave guides of different width, height or both
• Matching of a dielectric medium such as a microwave lens to free space.

Here consider, the problem of matching a transmission line of characteristics impedance \( Z_1 \) to a pure resistive load impedance \( Z_L \) as shown in
If an intermediate section of transmission line with a characteristic impedance $Z_2$ and a quarter wave length long is connected between the main line & the load, the effective load impedance presented to the main line is

$$Z = Z_2 \frac{Z_L + jZ_2 \tan (B\lambda/4)}{Z_2 + jZ_L \tan (B\lambda/4)} = \frac{Z_2^2}{Z_L}$$

If $Z_2 = \sqrt{Z_1 Z_L}$ then $Z = Z_1$ & the load is matched to the main line.

Therefore, the matching line is called Quarter wave transformer.

To match over a narrow band frequency, a single section transformer may be used. To obtain a good match over a broad band of frequencies, two, three or even more intermediate quarter wave transformers are commonly used.
Active Microwave Devices & MMIC
Microwave Semiconductor Devices

A wide range of microwave semiconductor devices have been developed for

- Detection
- Mixing
- Frequency Multiplication
- Phase Shifting
- Attenuation
- Switching
- Limiting
- Amplification
- Oscillation.

In most of the low power applications, solid state devices have replaced electron beam devices, because of the advantages of their small size, light weight, high reliability, low cost & capability of being incorporated in to microwave integrated circuits.
Diodes

- Microwave diodes are classified as crystal diodes and Schottky diodes for mixing & detection.
- PIN diode for attenuation modulation, switching phase shifting & limiting.
- Varactor diode for frequency multiplication, parametric amplification & tuning.
- Tunnel diode & Gunn diode for oscillation.
- Read (IMPATT, TRAPATT & BARITT) diodes for amplification & oscillation.
- An important consideration of frequency & power limitations of these diodes is the requirement of reduced thickness of the active layer to minimize the transits time effect.

Crystal Diode

![Crystal Diode Diagram](image-url)
The diode consists of a pointed tungsten wire (~0.08 mm dia) made in the form of a spring that presses against the surface of a silicon (p type) wafer (~1.6 mm square) suitably doped with impurities making a rectifying contact.

**Schottky Diode**

1. Schottky diodes are metal semiconductor barrier diodes as shown in Figure.

2. The diode is constructed on thin silicon (n⁺ type) substrate by growing epitaxially on n type active layer of about two micron thickness. A thin SiO₂ layer is grown thermally over this active layer.

3. Metal- semiconductor junction is formed by depositing metal over SiO₂.

4. Schottky diodes also exhibit a square law characteristic & have a higher burn out rating, lower (1/f) noise & better reliability than point contact diodes.
5. When the device is forward biased, the major carrier (electrons) can be easily injected from the highly doped n type semiconductor material into the metal. When it is reverse biased, the barrier height becomes too high for the electrons to cross & no conduction takes place.

6. RF Power flow in the device is limited by power dissipation in Rs & is shorted across $C_j$.

7. $C_c$ & $L_s$ produce RF mismatch & can be matched by external circuit. 00
Diode Detector Circuit

1. The Microwave diode can be used for detection of microwave signal.
2. For input signal Power (< 10 W) the forward IV characteristic is approximately parabolic and follows the square law: \( I \propto V^2 \) as shown in Figure.

These detector diodes are sensitive & operate with RF signal without any dc bias.

The diode is mounted in a waveguide or a coaxial line which contains matching elements. So that VSWR < 1.3 & microwave power is absorbed without reflection.
Tunable probes are very useful devices to measure the SWR and Impedances. Tunable probe is consists of a crystal detector and a small wire antenna in coaxial housing. Its depth of penetration into the slotted section is variable.

The crystal detector can be used for the detection of microwave signal. At low level of microwave power, the response of each detector approximates to square law characteristics and may be used with a high gain selective amplifier having a square law meter calibration.
1. The figure shows a schematic circuit of a co-axial line broad band mixer used up to frequencies of about 3GHz.

2. At frequencies above about 1GHz, a silicon crystal diode can be used as a mixer to produce a lower frequency IF signal. It has low conversion loss, low noise, & ability to stand momentary overloads.

3. Single diode mixers are useful when the signal level is relatively large compared to noise.
PIN Diode & its Applications

A PIN diode consists of a high resistivity intrinsic semiconductor layer between two highly doped $p^+$ & $n^+$ Si layers.

- The device acts as an electrically variable resistor related to the '$i'$ layer thickness. The intrinsic layer has a very large resistance in reverse bias & it decreases in forward bias.
- When mobile carriers from $p$ & $n$ regions are injected into the '$i'$ layer, carriers take time such that the diode ceases to act as rectifier at microwave frequency & appear as a linear resistance. This property makes it usable as variable attenuator at microwave frequency.

\[
R_j \cdot C_j = \text{junction resistance, capacitance of 'i' layer} \\
R_S = \text{Bulk semiconductor layer & contact resistance.} \\
L_P, C_P : \text{Package Inductance & capacitance} \\
R_j : \text{variable, } C_j = 0.2\text{pf at freq > 1GHz} \\
R_S : 1\text{ohm} \\
\text{resistivity of 'i' layer = } 1000\Omega - \text{cm} \\
L_P & C_P \text{ may be omitted, when the diode is directly mounted in chip.}
\]
1. Because of the large breakdown voltage ($V_r = -500V$) compared to an ordinary PN junction, PIN diode can be biased at a high negative region. So that large AC signal super imposed on dc cannot make the device forward biased.

2. For the device to remain in the high impedance state in the presence of a large microwave signal, the dc reverse voltage must be high.

3. At high power applications, the $i$ region width $W$ should be wide but less than diffusion length $L_d$, otherwise the center layer voltage drop will increase & the forward bias impedance will become high.

**PIN Switch**

1. PIN device is designed such that under reverse or zero biasing, $R_j$ is extremely large & $C_j(0.02 - 2pF)$ plays the dominant role. $C_p$, $L_p$ & $R_s$ are negligibly small.

2. For forward biasing, $R_j$ is very small. (i.e) $\left(<< \frac{1}{jW C_j}\right)$ & $R_f = (0.1 - 2$ ohms$) = R_j + R_s$

3. Therefore for reverse bias, a high impedance is presented to the microwave signal & for forward bias, the diode represents a very low resistance. Thus by changing the bias it acts as a switch.
PIN diode – Single Switch

AC blocking inductor is realized from a high impedance strip line section & DC blocking capacitor is realized from a gap in the line.

For shunt configuration,
Reverse biasing produces transmission ON due to high impedance shunt
Forward biasing produces transmission OFF due to low impedance shunt.

For Series Configuration,
Reverse biasing produces transmission OFF due to low impedance shunt.
Forward biasing produces transmission ON due to high impedance shunt.

Because of the large break down voltage, compared to ordinary diode, PIN diode can be biased at high -ve region, so that large ac signal superimposed
Pin diode modulators are used to provide amplitude or pulse modulation in wide range of microwave to study many applications. These modulators use PIN diode which is mounted across the waveguide line with RF isolated DC bias lead passing to an external TNC(F).
1. The application of two terminal semiconductor devices at microwave frequency has been increased due to the larger values of average and peak power outputs compared to the power transistor.

2. The common characteristics of all active two terminal solid state device is their negative resistance. (i.e) The real part of the impedance is negative over a range of frequencies.

3. In a positive resistance, current through resistance and the voltage are in phase. The voltage drop across resistance is positive and a power is dissipated in resistance. In a negative resistance, current through resistance and the voltage are out of phase. The voltage drop across resistance is negative and a power is generated by the resistance.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Gunn diode</th>
<th>Microwave Transistor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Not having junction or gate</td>
<td>Operate with either junction (or) gate</td>
</tr>
<tr>
<td>2.</td>
<td>Fabricated from compound semiconductors such as Gallium Arsenide (GaAs), Indium Phosphide (InP), or Cadmium Telluride (CdTe)</td>
<td>Fabricated from semiconductors such as silicon and Gallium</td>
</tr>
<tr>
<td>3.</td>
<td>Operated with hot electrons whose energy is very much greater than thermal energy</td>
<td>Operated with warm electrons whose energy is not much greater than thermal energy.</td>
</tr>
</tbody>
</table>
Gunn Diodes- GaAS Diodes

Gunn Diodes are negative resistance devices, which are normally used as low power oscillator at microwave frequencies in transmitter and also as local oscillators at receiver ends.

**Construction**

![Schematic diagram for ntype GaAs diode.](image)

**Equivalent circuit**

![Equivalent circuit](image)

**Symbol**

![Symbol](image)

$C_j$ and $-R_j$ are the diode capacitance and resistance, respectively. $R_s$ includes the total resistance of lead, ohmic contacts, and bulk resistance of the diode. $C_p$ and $L_p$ are the package capacitance and inductance respectively.

Although there is no junction, this is called as a diode with reference to the positive end (anode) and negative end (cathode), when the DC voltage applied across it.
RWH Theory
1. Differential Negative Resistance
• The fundamental concept of RWH theory is differential negative resistance, developed in bulk solid state III-V compounds, when either voltage or current is applied to the samples.
• There are two modes of negative resistance devices: Voltage controlled and current controlled modes.

1) Voltage controlled mode

- Current density can be multi valued
- High field domains are formed, separating two low field regions.
- The interface separating low field and high field domains are in plane, perpendicular to the current direction.
2) \textit{Current controlled mode}

- Voltage can be multi valued.
- Splitting the sample results in high current filaments running along the field direction.

- The negative resistance of the sample at a particular region is expressed mathematically as $\frac{dI}{dV} = \frac{dJ}{dE} = \text{negative resistance}$.

If an electric field $E_o$ (or voltage $V_o$) is applied to the sample, the current density $J_o$ is generated. When the voltage is increased to $E_2$ (or $V_2$), current density is decreased to $J_2$. When the field is decreased to $E_1$ (or $V_1$), the current density is increased to $J_1$. Similarly for the current controlled mode.
Two-valley model of electron energy versus wave number for n-type GaAs.

Upper valley

\[ m_{cu} = 1.2 \]
\[ \mu_{cu} = 180 \text{ cm}^2/\text{V} \cdot \text{s} \]

\[ \Delta E = 0.36 \text{ eV} \]

Conduction band

\[ E_g = 1.43 \text{ eV} \]

Forbidden band

Valence band

\[ m_{eV} = 0.068 \]
\[ \mu_{eV} = 8000 \text{ cm}^2/\text{V} \cdot \text{s} \]
**Transferred Electron Effect**

- At low bias voltage, the high mobility electron in the lower valley increases the conductivity of the material and hence, the current increases with the applied field.

- As the applied voltage increases, more and more electrons are transferred from higher mobility lower valley to lower mobility upper valley resulting in a decrease of conductivity. This results in a decrease of current.

- Thus the device behaves as differential negative resistance. This is called transferred electron effect and the device is called transferred electron Device (TED)

**Current versus field characteristic of a two-valley semiconductor**

![Graph showing the current density J as a function of the electric field E. The graph illustrates the transferred electron effect, with a peak at J<sub>th</sub> and a negative resistance region between E<sub>v</sub> and E<sub>u</sub>.]
Transfer of electron densities.

According to the energy band theory of n-type GaAs, a high-mobility lower valley is separated by an energy of 0.36 eV from a low-mobility upper valley as shown in Fig.

Electron densities in the lower and upper valleys remain the same under an equilibrium condition. When the applied electric field is lower than the electric field of the lower valley \((E < E_l)\), no electrons will transfer to the upper valley.

When the applied electric field is higher than that of the lower valley and lower than that of the upper valley \((E_l < E < E_u)\), electrons will begin to transfer to the upper valley.

And when the applied electric field is higher than that of the upper valley \((E_u < E)\), all electrons will transfer to the upper valley.
If electron densities in the lower and upper valleys are \( n_\ell \) and \( n_u \), the conductivity of the \( n \)-type GaAs is

\[
\sigma = e(\mu_\ell n_\ell + \mu_u n_u)
\]

where \( e \) = the electron charge
\( \mu \) = the electron mobility
\( n = n_\ell + n_u \) is the electron density

Electron density \( n \) & mobility \( \mu \) are both functions of electric field \( E \).

\[
\frac{d\sigma}{dE} = e \left( \mu_\ell \frac{dn_\ell}{dE} + \mu_u \frac{dn_u}{dE} \right) + e \left( n_\ell \frac{d\mu_\ell}{dE} + n_u \frac{d\mu_u}{dE} \right)
\]

It is assumed that \( \mu_\ell \) & \( \mu_u \) are proportional to \( E^P \), where \( P \) is constant

\[
\frac{d}{dE} (n_\ell + n_u) = \frac{dn}{dE} = 0
\]

\[
\Rightarrow \frac{dn_\ell}{dE} = \frac{-dn_u}{dE}
\]
\[
\text{since } \mu \alpha E^p \Rightarrow \frac{d\mu}{dE} \alpha \frac{dE^p}{dE} = PE^{p-1} = \frac{PE^p}{E} \alpha \frac{P\mu}{E} \\
\frac{d\sigma}{dE} = e \left[ \mu \ell \frac{dn_\ell}{dE} + \mu_u \left( \frac{-dn_\ell}{dE} \right) \right] + e \left[ n\ell \frac{P\mu_\ell}{E} + n_u \frac{P\mu_u}{E} \right] \\
= e \left( \frac{dn_\ell}{dE} \right) (\mu \ell - \mu_u) + e (n\ell \mu_\ell + n_u \mu_u) \frac{P}{E}
\]

Substituting in to (3) to (5)

w.k.t Ohm's law \( J = \sigma E \)

\[
\frac{dJ}{dE} = \sigma \frac{dE}{dE} + E \frac{d\sigma}{dE} = \sigma + E \frac{d\sigma}{dE} = \sigma \left( 1 + \frac{E \frac{d\sigma}{dE}}{\sigma \frac{dE}{dE}} \right) \\
\frac{dJ}{dE} = \frac{1}{\sigma} \frac{E \frac{d\sigma}{dE}}{\sigma \frac{dE}{dE}} = 1 + \frac{d\sigma / dE}{\sigma / E}
\]

For negative resistance, current density \( J \) must be decrease with increasing field \( E \) (or) the ratio of \( \frac{dJ}{dE} \) must be negative.

\[
\frac{-d\sigma / dE}{\sigma / E} > 1
\]

Condition for negative resistance is given by \( \frac{-d\sigma / dE}{\sigma / E} > 1 \)
Substitute the values of $\sigma$ and $d\sigma/dE$ with $f = nu/nl$, now the condition for negative resistance becomes,

$$\left( \frac{-E dn_\ell}{nl dE} \right) \left( \frac{\mu_\ell - \mu_u}{\mu_\ell + \mu_u f} \right) - P > 1$$

To satisfy above

$$\frac{\mu_\ell - \mu_u}{\mu_\ell + \mu_u f} > 0 \text{ (i.e.) } (+V_e) \& \mu_\ell > \mu_u$$

$$\frac{dn_\ell}{dE} < 0$$

On the basis of RWH theory, the band structure of a semiconductor must satisfy three criteria to exhibit negative resistance.

(a) The separation energy between the bottom of the lower valley and the bottom of the upper valley must be several times larger than the thermal energy $\Delta E > KT$ or $\Delta E > 0.026\text{ ev}$

(b) Separation energy between the valleys must be smaller than the gap energy ($E_g$) between the conduction band & valence bands. This means $\Delta E < E_g$.

(c) Electrons in lower valley must have high mobility, small effective mass & low density of state, where as those in upper valley must have low mobility, high effective mass, & a high density of state.
High field domain

1. Decrease in drift velocity with increasing electric field can lead to the formation of a high field domain for microwave generation and amplification.

2. When positive and negative charges are separated by a small distance, then a dipole domain is formed.

3. Then the dipole field reaches a stable condition & moves through the specimen toward the anode. When the high field domain disappears at the anode, a new dipole field starts forming at the cathode & the process is repeated.

4. A domain will start to form whenever the electric field in a region of the sample increases above the threshold electric field and will drift with the carrier stream through the device. When the electric field increases, the electron drift velocity decreases and the GaAs diode exhibits negative resistance.

5. If additional voltage is applied to a device containing a domain, the domain will increase in size and absorb more voltage than was added and the current will decrease.

6. A domain will not disappear before reaching the anode unless the voltage is dropped appreciably below threshold (for a diode with uniform doping and area).

7. The domain's length is generally inversely proportional to the doping.
MODES OF OPERATION

1. Gunn oscillation mode: This mode is defined in the region where the product of frequency multiplied by length is about $10^7$ cm/s and the product of doping multiplied by length is greater than $10^{12}$/cm$^2$. In this region the device is unstable because of the cyclic formation of either the accumulation layer or the high-field domain.

The frequency of oscillation is given by $f = \frac{v_{\text{dom}}}{L_{\text{eff}}}$

where $v_{\text{dom}}$ is the domain velocity and $L_{\text{eff}}$ is the effective length that the domain travels from the time it is formed until the time that a new domain begins to form.

Gunn oscillation mode is operated with the electric field greater than the threshold field ($E > E_{\text{th}}$) and the high field domain drifts along the specimen until it reaches the anode or until the low field value drops below the sustaining field $E_s$, required to maintain $v_s$. The sustaining drift velocity for GaAs is $v_s = 10^7$ cm/s. There are three possible modes

1. Transit-time domain mode ($fL \approx 10^7$ cm/s):

(a) When the electron drift velocity $v_d$ is equal to the sustaining velocity $v_s$, the high field domain is stable. (i.e) $v_d = v_s = fL \approx 10^7$ cm/s.

(b) Oscillation period $\tau_o$ is equal to the transit time $\tau_t$. Where $\tau_t$ is the time taken by the dipole domain to travel from cathode to anode.

(c) Efficiency is below 10%, because the current is collected only when the domain arrives at the anode as shown in Figure 3.48.(a).
2. Delayed domain mode $(10^6 \text{cm/s} < f_L < 10^7 \text{cm/s})$:

   (a) When the transit time is chosen (Oscillation Period $\tau_o$) > (transit time $\tau_t$), so that the domain is collected while $E < E_{th}$ as shown in Fig-

   (b) New domain cannot form until the field rises above threshold again.
   (c) This delayed mode is called inhibited mode
   (d) Efficiency is about 20%

3. Quenched domain mode $(f_L > 10^7 \text{cm/s})$

   (a) If the bias field drop below the sustaining field $E_s$ during the negative half cycle the domain collapses before it reaches the anode.

   (b) When the bias field swings back above a threshold, a new domain is nucleated and the process is repeated.

   (c) Therefore the oscillation occur at the frequency of the resonant frequency rather than the transit time frequency. The resonant frequency is several times the transit time frequency

   (d) Efficiency is about 13%
(a) Transit time mode
\( \tau_0 = \tau_t \)

(b) Delayed mode
\( \tau_0 > \tau_t \)

(c) Quenched mode
\( \tau_0 < \tau_t \)

DC bias

V

Es

Eth

\( \tau_t \)

\( \tau_0 = 3\tau_d \)

LSA mode

\( \tau_0 < \tau_t \)
4. Limited - Space - Charge Accumulation (LSA) mode:

\[ fL > 10^7 \text{ cm/s} \quad \& \quad 2 \times 10^4 \leq \frac{no}{f} \leq 2 \times 10^5 \]

(a) When the frequency is very high, the dipole domains do not have sufficient time to form, while the field is above the threshold.

(b) As a result, most of the domains are maintained in the negative conductance state during large fraction of the voltage cycle.

(c) Any accumulation of electrons near the cathode has time to collapse while the signal is below threshold.

(d) Current in the device is proportional to the drift velocity.

(e) Efficiency of LSA mode can reach 20%.

5. Stable Amplification mode

(a) When the \( noL < 10^{12} / \text{ cm}^2 \), the device exhibits amplification at the transit time frequency rather than spontaneous oscillation. This situation occurs because the negative conductance is utilized without domain formation.

(b) There are too few carriers for domain formation within the transit time. Therefore amplification of signals near the transit time frequency can be achieved.
**Avalanche Transit Time Devices**

1. Avalanche transit time diode oscillators rely on the effect of voltage breakdown across a reverse biased p-n junction to produce a supply of holes and electrons.

2. Avalanche diode oscillator uses carrier impact ionization and drift in the high field region of a semiconductor junction to produce a negative resistance at microwave frequency.

**IMPATT Diode:**

- Impact Ionization Avalanche transit time operation.
- DC to RF conversion efficiency is 5% to 10%.
- Generated frequency are as high as 100GHz with silicon diodes.
- Have many forms like n^+p^+ (or) p^+n^+ read device, p^+nn^+ abrupt junction, p^+in^+ diode which are shown in figure together with their doping profiles.
- Such diodes can be manufactured from Ge, Si, GaAs or InP.
- However GaAs provides the highest operating frequency, highest efficiency and least noise figure.
These diodes exhibit a differential negative resistance by two effects.

- The impact ionization avalanche effect, which causes the carrier current $I_o(t)$ and the AC voltage to be out of phase by 90°.

- The transit time effect, which further delays the external current $I_e(t)$ relative to the ac voltage by 90°.

**Construction of $n^+ - p - i - p^+$ IMPATT diodes:**

(a) In this structure, the superscript plus sign denotes very high doping and the 'i' or 'v' refers to intrinsic material.

(b) The device consists of two regions. One is the thin pregion at which avalanche multiplication occurs. This region is called the high field region or the avalanche region.

(c) The other region is the 'i' or 'v' through which the generated holes must drift in moving to $p^+$ contact. This region is also called the intrinsic region or drift region.

(d) The $p$ region is very thin. The space between the $n^+ - p$ junction and the $i - p^+$ junction is called the space charge region.

(e) Similar devices can be built in the $p^+ - n - i - n^+$ structure, in which electrons generated from avalanche multiplication drift through the 'i' region.
Figure 8-1-3 Field, voltage, and currents in Read diode. (After Read [1]; reprinted by permission of the Bell System, AT&T Co.)
Operating Principle:
(a) During reverse bias, space charge region will form in \( n^+p \) junction. When the reverse biased voltage is well above the punch through or breakdown voltage, the space charge region extends from \( n^+ - p \) junction through the \( p \) and \( i \) regions to the \( i - p^+ \) junction.

(b) A positive charge gives a rising field in moving from left to right. The carriers moving in the high field near the \( n^+ - p \) junction get energy to knock valence electrons in to the conduction band, thus producing hole-electron pairs.

(c) The rate of pair production or avalanche multiplication is a sensitive nonlinear function of the field. By proper doping, the field can be given relatively sharp peak so that avalanche multiplication is restricted to a very narrow region at the \( n^+ - p \) junction.

(d) The field throughout the space charge region is 5 kV/cm. The electrons move in the \( n^+ \) region & holes drift through the space charge region to the \( p^+ \) region with a constant velocity \( v_d \) of about \( 10^7 \) cm/s for silicon. The transit time for a hole across the drift region \( L \) is given as \( \tau = L / v_d \)

(e) Avalanche Multiplication Factor \( M = 1/(1 - (V/Vb)^n) \) Where \( V = \) applied voltage, \( V_b = \) avalanche break down voltage, \( n = 3 - 6 \) for silicon is a numerical factor depending on the doping of \( p^+ - n \) or \( n^+ - p \) junction.

Where break down voltage for a silicon \( p^+n \) junction

\[
|V_b| = \left( \frac{\rho_n \mu_n \varepsilon_s |E_{max}|^2 b}{2} \right)
\]

\( \rho_n \) : resistivity, \( \mu_n \) : electron mobility, 
\( \varepsilon_s \) : permittivity of Semi Conductor 
\( E_{max} \) : maximum breakdown of Electric field
Carrier current $I_o(t)$ and external current $I_e(t)$:

- An Ac voltage can be maintained at a given frequency in the circuit, and the total field across the diode is the sum of de and ac field.

- This total field causes break down at the $n^+ - p$ junction during the positive half of the voltage cycle, if the field is above the break down voltage and the carrier current $I_o(t)$ generated at the $n^+ - p$ junction by the avalanche multiplication grows exponentially.

- During the negative half cycle, when the field is below the break down voltage, the carrier current $I_o(t)$ decays exponentially to a small steady state value.

- $I_o(t)$ is in the form of a pulse for very short duration. It reaches its maximum the middle of ac voltage cycle, or one quarter of a cycle later than the voltage.

- Under the influence of electric field, the generated holes are injected in to the space charge region and traverse the drift space and induce a current $I_e(t)$ in the external circuit.

\[
I_e(t) = \frac{Q}{\tau} = \frac{\vartheta_d Q}{L}, \text{where}
\]

- $Q$: total charge of moving holes
- $\vartheta_d$: hole drift velocity
- $L$: Length of drift region
Advantages

1. Potentially reliable,
2. Compact
3. inexpensive
4. moderately efficient microwave Power Source.

Applications

1. Microwave generators
2. Modulated output Oscillations
3. Parametric amplifier Pumps
4. Suitable for negative resistance Amplifications

\[ I_e(t) \text{ is delayed by } 90^\circ \text{ or } \tau/2 \text{ relative to } I_0(t) \text{ because of moving holes.} \]
\[ I_0(t) \text{ is delayed by } 90^\circ \text{ relative to the A.C voltage. So the AC voltage} \]
\[ \& I_e(t) \text{ are out of phase by } 180^\circ. \]

Thus a 180° phase shift between the external current and the AC microwave voltage provides a negative resistance for sustained oscillation. Therefore the fundamental frequency of microwave oscillation

\[ f = \frac{V_d}{2l} \]

Efficiency \( \eta = \frac{P_{ac}}{P_{dc}} = \frac{RF \text{ Power Output}}{DC \text{ Input Power}} = 30\% \)

In practical efficiency is less than 30% because of space charge effect, the reverse saturation current effect, high frequency skin effect and the ionization saturation effect.
**IMPATT Diode Power Amplifier**

1. The IMPATT diode can be used as amplifier with the same basic circuit arrangement as oscillator provided $R_L > |R_d|$ & a circulator is incorporated as shown in Figure.3.52.

2. The negative resistance is used to terminate one port of the circulator & the actual load is connected to other port. The input RF power is fed from the remaining port.

![Figure 3.52](image)
3. The negative resistance results in voltage reflection coefficient at the port greater than unity.

4. Thus the average power from the source $P_{av}$ circulates to the negative resistance port & the reflected power is greater than the incident power. The reflected power is delivered to the load. The power gain is

$$G_P = \frac{|\Gamma|^2 P_{av}}{P_{av}} = |\Gamma|^2 > 1 = \left| \frac{-|R_d| - R_L}{|-R_d| + R_L} \right|^2$$

if $R_d = -20\, \text{ohm}$, & $R_L = 30\, \text{ohm}$

$$G_P = \left| \frac{-5}{1} \right|^2 = 25$$
Varactor Diode

1. Can be used as Variable capacitor. Also called as variable reactor (Varactor) & Varicap (Variable Capacitor)

2. All PN junction diodes exhibit the variable junction capacitance phenomena to some extent.

Symbol

Principle of Operation
1. During Forward bias, the charge carriers are forced to cross the junction, causing a current flow. During reverse bias, charge carriers are drawn away from the junction & forming a high resistance depletion region at junction interface.

2. Depletion region width is increased by increasing the reverse bias potential which is equivalent to the separation between the plates increased & the capacitance decreases.

3. Reducing the reverse bias potential, reduces the Depletion region width & increases the capacitance.
Applications
(a) Used in TV receivers, HFC Circuit adjustable BPF
(b) Used in PLL & FLL
(c) Frequency modulation
(d) High frequency multipliers
(e) Very low noise microwave parametric amplifier.

Diode Capacitance

\[ C_j = \frac{C_K}{(V_b - V)^m} \]

(neglecting stray capacitance)

\( C_j \): Diode Capacitance
\( C \): Diode Capacitance when the device is unbiased
\( V \): Applied reverse bias potential
\( V_b \): Barrier Potential at the junction (0.55 - 0.7V in Si)
\( m \): Constant (material dependent)
\( K \): Constant (Often 1)

5. Equivalent Circuit: The equivalent circuit is shown in fig.3.39.
Monolithic Microwave Integrated Circuits

1. Extension of integrated circuit to microwave frequency.

2. Monolithic integrated circuit is built on a single crystal. Such circuits are produced by the processes of epitaxial growth, masked impurity diffusion, oxidation growth, and oxide etching.

3. Conventional IC require high packing density, whereas MMIC needs low packing density.

4. Formed on an insulating substrate, such as glass or ceramic called of film integrated circuits.

Advantages

(a) Low cost
(b) Small size
(c) Light weight
(d) High reliability
(e) Improved reproducibility
(f) Improved performance
5. Used in Space & Military applications since they meet the requirements for shock, temperature conditions & severe Vibration.

6. Basic Materials for monolithic microwave integrated circuits are
- Substrate Materials
- Conductor materials
- Dielectric Materials
- Resistive Materials

**1. Substrate Materials**
- Piece of substance, on which an electronic devices are built
- Ideal characteristics of substrate materials are
  1. High dielectric constant & it should remain constant over frequency & temperature
  2. Low dissipation factor
  3. High Purity & Constant thickness.
  4. High surface smoothness.
  5. High Resistivity
  6. High dielectric strength
  7. High thermal conductivity
- Alumina, beryllia ferrite/garnet, GaAs, glass rutile & sapphire materials are used
2. **Conductor Material**

1. Can be deposited and are capable of being photo etched
2. Used to form conductor pattern & bottom ground plane
3. Characteristics:
   (a) High Conductivity
   (b) Low temperature coefficient of resistance.
   (c) Good adhesion to the substrate
   (d) Good etch ability & solder ability
   (e) Easily deposited (or) electroplated.
4. Alumina, copper gold & silver are the materials used in conductor.

3. **Dielectric Material**

1. Used in blockers, capacitors and in couple-line structures
2. Characteristics:
   (a) Good reproductively
   (b) Capability of handling high voltages
   (c) Ability to undergo process without developing pin hides
   (d) Low RF dielectric Loss
3. AlN, SiO2, Si3N4 & Ta2O5 are the materials used.
4. Resistive Materials

- For realizing bias networks, attenuators & terminators.
- Characteristics
  1. Good Stability
  2. Low temperature coefficient of resistance.
  3. Adequate dissipation Capability
  4. Sheet resistivity's in the range of 10 to 1000 per square

- Cr, Cr-SiO, NiCr, Ta & Ti are the materials used.

MMIC Fabrication Techniques:

1. Diffusion & ion implantation
2. Oxidation & film deposition
3. Epitaxial growth
4. Lithography
5. Etching & Photo resist
6. Deposition.
1. **Diffusion & ion implantation**

   These are the two processes, used in controlling amount of dopants in semiconductor device fabrication i.e. used to dope the impurities to produce n or p type layer.

   - Diffusion is the process of Diffusing impurities to alter the basic electronic characteristics of the pure material.
   - Ion Implantation: Dope the substrate crystal with high energy ion impurities

**Advantages of ion implantation methods:**

1. Precise control of total amount of dopants
2. Improvement of reproducibility
3. Reduced Processing temperature.

2. **Oxidation & film deposition:**

   Different types of thin films are used

   1. Thermal oxides
   2. Dielectric layers
   3. Polycrystalline silicon
   4. Metal films
3. Epitaxial growth:

In epitaxial technology, single crystal semiconductor layers grow on a single crystal semiconductor substrate.

- There are three types of epitaxy:

1. Vapor Phase Epitaxy (VPE)

Used for silicon and GaAs device.

2. Molecular-Beam Epitaxy (MBE)

Process involving the reaction of one or more thermal beams of atoms or molecules with a crystalline surface, under ultrahigh vacuum conditions.

3. Liquid-Phase Epitaxy (LPE):
   (a) Growth of epitaxial layers on crystalline substrates by direct precipitation from the liquid phase.
   (b) Useful for growing & related III-V compounds.
   (c) Suited to grow thin epitaxial layers ($\geq 0.2$ micrometer) because it has a slow growth rate.
   (d) Useful to grow multilayered structures, in which precision doping is required.
4. Lithography:

- Process of transferring Patterns of geometric shape on a mark to a thin layer of radiation sensitive material known as resist. Photo resist will cover the surface of a semiconductor wafer.  
- Four types of lithography technology
  1. Electron beam lithography  
  2. Icon beam lithography  
  3. Optical lithography  
  4. X ray lithography.

5. Etching the photo resist:

1. In the process of making MICs, a selective removal of is required in order to form openings through which impurities can be diffused is called as etching. During photolithographic Process, substrate is coated with a uniform film of Kodak photo resist (KPR)  
2. A mask for the desired openings is placed over the photo resist & ultraviolet light exposes the photo resist through the mask.  
3. Due to this ultraviolet light polymerized photo resist is developed & the polymerized positions are dissolved by tri-chloro-ethylene after the mark is removed.  
4. Which is not covered by the photo resist can be removed by hydrofluoric acid.
3. Deposition:
The methods are commonly used for making MMICs
1. Vacuum evaporation
2. Electron beam evaporation
3. DC sputtering
1. Vacuum evaporation
   • Here the impurity material to be evaporated is placed in a metallic boat through which a high current is passed
   • The substrate with mask and the heated boat are located in a glass tube, in which a high vacuum at a pressure of 10^{-6} to 10^{-8} torr is maintained.
   • The substrate is heated slightly. The heat is evaporating the impurities & the impurity vapor deposits itself on the substrate forming a polycrystalline layer on it.
2. Electron beam evaporation

- A narrow beam of electrons is generated to scan the substrate in the boat in order to vaporize the impurity

3. DC sputtering

- In a vacuum, the crucible containing the impurity, which is used as a cathode & the substrate act as anode of diode

- A slight trace of organ gas is introduced in to the vacuum. When the applied voltage between cathode & anode is high a discharge of argon gas is formed. The positive argon ions are accelerated towards the cathode where they dislodge atoms of impurity.

- The impurity atoms have enough energy to reach the substrate & adhere to it.
1. A matched isolator has insertion loss of 0.5 dB and an isolation of 25 dB. Find the S parameters.

Insertion loss = 0.5 dB = 20 \log \left| S_{21} \right|

- 20 \log \left| S_{21} \right| = 0.5 \implies S_{21} = 10^{-0.5/20} = 0.944

Isolation = 25 dB = 20 \log \left| S_{12} \right|

- 20 \log \left| S_{12} \right| = 25 \implies S_{12} = 10^{-25/20} = 0.056.

Since it is a matched isolator, S_{11} = S_{22} = 0.

\[ S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} 10^{-0.5/20} & 0.056 \\ 0.944 & 0 \end{bmatrix} \]
2. Power at the input port is $900 \text{ mw}$. If this power is incident on a $20 \text{ dB}$ coupler with directivity of $40 \text{ dB}$, what is the coupled power and transmitted power?

\[ P_1 = 900 \text{ mw}, \quad C = 20 \text{ dB}, \quad D = 40 \text{ dB}. \]

\[ C = 10 \log \frac{P_1}{P_4} = 20 \]

\[ \frac{P_1}{P_4} = 10^{20/10} = 10^2 = 100 \]

\[ P_4 = \frac{P_1}{100} = \frac{900 \text{ mw}}{100} = 9 \text{ mw} \]

\[ D = 10 \log \frac{P_4}{P_3} = 40 \]

\[ \frac{P_4}{P_3} = 10^{40/10} = 10000 \]

\[ \Rightarrow P_3 = \frac{P_4}{10000} = \frac{9 \text{ mw}}{10^4} = 0.9 \text{ mw}. \]
Transmitted power \( P_2 = P_1 - P_4 - P_3 \)

\[ P_2 = 980 \text{ mW} - 9 \text{ mW} - 0.9 \mu \text{W} = 890.99 \text{ mW} \]

3. A three port circulator has an insertion loss of 1 dB, isolation 30 dB and VSWR = 1.5, find the S-matrix.

\[
S = \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix}
\]

Insertion loss = \(-20 \log |S_{21}| = 1\) dB.

\[ S_{21} = 10^{-\frac{1}{20}} = 0.89 \]

Insertion loss is same for other ports 1 & 2, 2 & 3, \( S_{21} \). \( S_{21} = S_{32} = S_{13} = 0.89 \).
Isolation: \(-20 \log |S_{31}| = 30\)

\[ |S_{31}| = 10^{-30/20} = 0.032 \]

dane isolation for other ports.

\[ \therefore S_{31} = S_{23} = S_{12} \]

Given VSWR \( S = 1.5 \),

\( \Gamma = \frac{S-1}{S+1} = \frac{1.5-1}{1.5+1} = 0.2 \)

\( \Gamma = S_{11} = 0.2 \)

same reflection coefficient for other ports

\[ \therefore S_{11} = S_{22} = S_{33} = 0.2 \]
4. In a waveguide termination having VSWR of 1.1 is used to dissipate 100 watts of power. Find the reflected power.

\[ \Gamma = \frac{S-1}{S+1} = \frac{1.1-1}{1.1+1} = 0.04762 \]

\[ \Gamma = S_{11} = \frac{b_1}{a_1} = \frac{1}{8} \]

\[ P_i = \frac{1}{2} |a_1|^2 \]

\[ P_r = \frac{1}{2} |b_1|^2 \]

\[ \frac{|b_1|^2}{|a_1|^2} = \frac{P_r}{P_i} \]

\[ P_r = \Gamma^2 P_i = \left(0.0476\right)^2 \times 100 = 0.226 \text{ W.} \]
THANK YOU !!!