15BEEC601 MICROWAVE ENGINEERING 3 2 0 4 100

OBJECTIVES

- To study passive microwave components and their S- Parameters.
- To study Microwave semiconductor devices & applications.
- To study Microwave sources and amplifiers.

INTENDED OUTCOMES:

- Gain Knowledge in passive microwave components and their S- Parameters.
- Gain Knowledge in Microwave semiconductor devices & applications.
- Gain Knowledge in Microwave sources and amplifiers.

UNIT-I INTRODUCTION

Microwave Frequencies, Microwave Devices, Microwave Systems, Microwave Units of Measure, Microwave Hybrid Circuits, Waveguide Tees, Magic Tees (Hybrid Trees), Hybrid Rings (Rat-Race Circuits), Waveguide Corners, Bends and Twists, Directional Couplers, Two-Hole Directional Couplers, Z & ABCD Parameters-Introduction to S parameters, S Matrix of a Directional Coupler, Hybrid Couplers, Circulators and Isolators, Microwave Circulators, Microwave Isolators.

UNIT-II TRANSFERRED ELECTRON DEVICES (TEDs) and AVALANCHE TRANSIT-TIME DEVICES

Introduction, Gunn-Effect Diodes – GaAs Diode, Background, Gunn Effect, Ridely-Watkins-Hilsun (RWH) Theory, Differential Negative Resistance, Two-Valley Model Theory, High-Field Domain, Modes of Operation, LSA Diodes, InP Diodes, CdTe Diodes, Microwave Generation and Amplification, Microwave Generation, Microwave Amplification, Avalanche Transit-Time Devices, Introduction, Read Diode, Physical Description, Avalanche Multiplication, Carrier Current $I_o(t)$ and External Current $I_e(t)$, Output Power and Quality Factor, IMPATT Diodes, Physical Structures, Negative Resistance, Power Output and Efficiency, TRAPATT Diodes, Physical Structures, Principles of Operation, Power Output and Efficiency, BARITT Diodes, Physical Description, Principles of Operation, Microwave Performance, Parametric Devices, Physical Structures, Nonlinear Reactance and Manley – Rowe Power Relations, Parametric Amplifiers, Applications.

UNIT-III MICROWAVE LINEAR-BEAM TUBES (O TYPE) AND MICROWAVE CROSSED-FIELD TUBES (M-TYPE)

Klystrons, Reentrant Cavities, Velocity-Modulation Process, Bunching Process, Output Power and Beam Loading, State of the Art, Multicavity Klystron Amplifiers, Beam-Current Density, Output Current Output Power of Two-Cavity Klystron, Output Power of Four-Cavity Klystron, Reflex Klystrons, Velocity Modulation, Power Output and Efficiency, Electronic Admittance, Helix Traveling-Wave Tubes (TWTs), Slow-Wave structures, Amplification Process, Convection Current, Axial Electric Field, Wave Modes, Gain Consideration, Microwave Crossed-Field Tubes, Magnetron Oscillators, Cylindrical Magnetron, Coaxial Magnetron, Tunable Magnetron, Ricke diagram.

UNIT-IV STRIP LINES AND MONOLITHIC MICROWAVE INTEGRATED CIRCUITS

Introduction, Microstrip Lines, Characteristic Impedance of Microstrip Lines, Losses in Microstrip Lines, Quality Factor Q of Microstrip Lines, Parallel Strip Lines, Distributed Lines, Characteristic Impedance, Attenuation Losses, Coplanar Strip Lines, Shielded Strip Lines, References, Problems, Monolithic Microwave Integrated Circuits, Introduction, Materials, Substrate Materials, Conductor Materials, Dielectric Materials, Resistive Materials, Monolithic Microwave Integrated-Circuit Growth, MMIC Fabrication Techniques, Fabrication Example.

UNIT-V MICROWAVE MEASUREMENTS

Slotted line VSWR measurement, VSWR through return loss measurements, power measurement, impedance measurement insertion loss and attenuation measurements- measurement of scattering parameters – Measurement of 1 dB, dielectric constant measurement of a solid using waveguide.

TEXT BOOKS:

S.NO.	Author(s) Name	Title of the book	Publisher	Year of the publication
1.	Samuel.Y.Liao	Microwave Devices and Circuits	Prentice Hall of India	2003
2.	Annapurna Das and Sisir K.Das	Microwave Engineering	Tata McGraw-Hill	2000
3.	Annapurna Das and Sisir K.Das	Microwave Engineering	Tata McGraw-Hill	2015

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Faculty Incharge **HOD / ECE**

KARPAGAM ACADEMY OF HIGHER EDUCATION
(Deemed to be University Established Under Section 3 of UGC Act 1956) Pollachi Main Road, Eachanari Post, Coimbatore – 641 021
FACULTY OF ENGINEERING
LECTURE PLAN

Name of the staff : **P.SASIKALA** Class : **IV B.E ECE**
Subject Name : **Microwave Engineering** Subject Code : **14BEEC704**

S.No	TOPICS TO BE COVERED	Teaching Aids	Time Duration
	UNIT-I Microwave Devices		
1.	Microwave Frequencies, Microwave Devices, Microwave Systems, Microwave Units of Measure	T(1)-page No.19-21	1
2.	Microwave Hybrid Circuits, Waveguide Tees ,Magic Tees (Hybrid Trees)	T(1)-page No.22-23	1
3.	Hybrid Rings (Rat-Race Circuits)	R(1)-page No.1.27-1.29	1
4.	Waveguide - Corners, Bends and Twists	R(1)-page No.1.30-1.32	1
5.	Directional Couplers, Two-Hole Directional Couplers, S Matrix of a Directional Coupler	T(1)-page No.167-170	1
6.	Z & ABCD Parameters- Introduction to S parameters	R(1)-page No.1.10-1.14	2
7.	Hybrid Couplers	R(1)-page No.1.16-1.74	1
8.	Circulators and Isolators, Microwave Circulators, Microwave Isolators.	T(1)-page No.172-179	1
9.	Tutorial		1
	UNIT-II Transferred Electron Devices (TEDs) And Avalanche Transit-Time Devices		
10	Gunn-Effect Diodes – GaAs Diode, Background, Gunn Effect, Ridely-Watkins-Hilsun (RWH) Theory, Differential Negative Resistance, Two-Valley Model Theory	T(1)-page No.288-298	2
11	High-Field Domain, Modes of Operation	T(1)-page No. 298- 302 T(1)-page No. 302-308	1
12	LSA Diodes, InP Diodes, CdTe Diodes	T(1)-page No.306-314	1
13	Microwave Generation and Amplification, Microwave Generation, Microwave Amplification	T(1)-page No.306-31	1
	Avalanche Transit-Time Devices		
14	Read Diode, Physical Description, Avalanche Multiplication, Carrier Current $I_o(t)$ and External Current $I_e(t)$, Output Power and Quality Factor	T(1)-page No.322-326	1
15	IMPATT Diodes, Physical Structures, Negative Resistance, Power Output and Efficiency	T(1)-page No.327-331	1
16	TRAPATT Diodes, Physical Structures, Principles of Operation, Power Output and Efficiency	T(1)-page No.332-334	1

17	BARITT Diodes, Physical Description, Principles of Operation, Microwave Performance	T(1)-page No.335-338	1
18	Parametric Devices, Physical Structures, Nonlinear Reactance and Manley – Rowe Power Relations, Parametric Amplifiers, Applications	T(1)-page No.338-349	1
19	Tutorial		1
	UNIT-III Microwave Linear-Beam Tubes (Otype) & Microwave Crossed-Field Tubes (Mtype)		
20	Klystrons, Reentrant Cavities, Velocity-Modulation Process, Bunching Process, Output Power and Beam Loading, State of the Art Multicavity.	T(1)-page No.359-380	1
21	Klystron Amplifiers, Beam-Current Density, Output Current Output Power of Two-Cavity Klystron, Output Power of Four-Cavity Klystron	T(1)-page No.380-390	1
22	Reflex Klystrons, Velocity Modulation.	T(1)-page No.391-399	1
23	Power Output and Efficiency, Electronic Admittance.		1
	TWTs		
24	Helix Traveling-Wave Tubes (TWTs)	T(1)-page No.400-401	1
25	Slow-Wave structures, Amplification Process, Convection Current	T(1)-page No.402-410	1
26	Axial Electric Field, Wave Modes, Gain Consideration	T(1)-page No.410-415	1
	Microwave Crossed-Field Tubes		
27	Magnetron Oscillators	T(1)-page No.445-446	1
28	Cylindrical Magnetron, Coaxial Magnetron,	T(1)-page No.447-454	1
29	Tunable Magnetron, Ricke diagram.	T(1)-page No.460-462	1
30	Tutorial		1
	UNIT-IV Strip Lines and Monolithic Microwave Integrated Circuit		
31	Introduction to Strip Lines	http://www.microwaves101.com /encyclopedias/stripline	1
32	Microstrip Lines, Characteristic Impedance of Microstrip Lines,	T(1)-page No.490-497	1
33	Losses in Microstrip Lines, Quality Factor Q of Microstrip Lines	T(1)-page No.497-503	1
34	Parallel Strip Lines, Distributed Lines, Characteristic Impedance, Attenuation Losses	T(1)-page No.503-505	1
35	Coplanar Strip Lines, Shielded Strip Lines	T(1)-page No.506-508	1
	Monolithic Microwave Integrated Circuits		
36	MMIC Introduction, Materials, Substrate Materials, Conductor Materials,	T(1)-page No.513-519	1

37	Dielectric Materials, Resistive Materials		1
38	MMIC Growth, MMIC Fabrication Techniques, Fabrication Example.	T(1)-page No.519-522	1
39	Tutorial		1
	UNIT-V Microwave Measurements		
40	Slotted line VSWR measurement	R(1)-page No. 501-502	1
41	VSWR through return loss measurements	R(1)-page No. 503-505	1
42	Power measurement	R(1)-page No. 507-509	1
43	Impedance measurement	R(1)-page No. 511-513	1
44	Insertion loss and attenuation measurements	R(1)-page No. 514-516	2
45	Measurement of scattering parameters – Measurement of 1 dB	R(1)-page No. 520-521	1
46	Dielectric constant measurement of a solid using waveguide	R(1)-page No. 522-524	1
47	Tutorial		1

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Faculty In-charge **HOD/ECE**

MICROWAVE ENGINEERING

15BEEC601

LECTURE NOTES

Mrs.P.SASIKALA

DEPARTMENT OF ELECRONICS AND COMMUNICATION ENGINEERING

FACULTY OF ENGINEERING

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13BEEC705 MICROWAVE ENGINEERING 3 0 0 3

AIM

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CONTENTS

UNIT-V Microwave Measurements

UNIT-I
Microwave Devices

1.1. MICROWAVE FREQUENCIES

The microwave range includes ultra-high frequency (UHF) (0.3–3 GHz), super high frequency (SHF) (3–30 GHz), and extremely high frequency (EHF) (30–300 GHz) signals.

Above 300 GHz, the absorption of electromagnetic radiation by Earth's atmosphere is so great that it is effectively opaque, until the atmosphere becomes transparent again in the so-called infrared and optical window frequency ranges.

1.2. MICROWAVE DEVICES

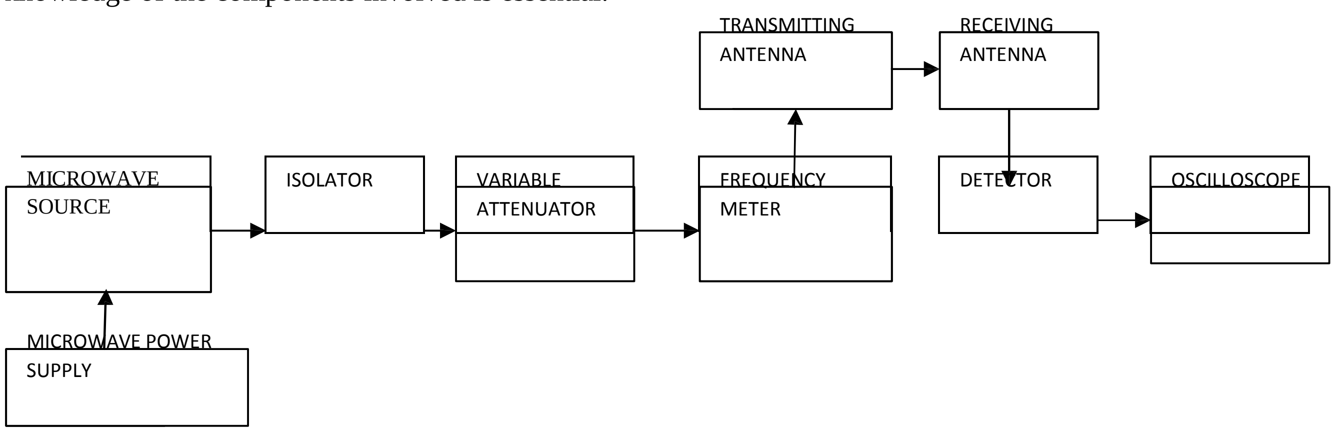
Vacuum tube based devices operate on the ballistic motion of electrons in a vacuum under t he influence of controlling electric or magnetic fields, and include the magnetron, klystron, travelling wave tube (TWT), and gyrotron. These devices work in the density modulated mode, rather than the current modulated mode. This means that they work on the basis of clumps of electrons flying ballistically through them, rather than using a continuous stream.

A maser is a device similar to a laser, except that it works at microwave frequencies.

Solid-state sources include the field-effect transistor, at least at lower frequencies, tunnel diodes and Gunn diodes

1.3. MICROWAVE SYSTEMS

A microwave system normally consists of a transmitter subsystem, including a microwave oscillator, waveguides, and a transmitting antenna, and a receiver sub system that includes a receiving antenna, transmission line or waveguide, a microwave amplifier, and a receiver. Figure 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.



1.4. MICROWAVE UNITS OF MEASURE

Microwave measures can be expressed in different units, such as the CGS (centimeter-gram-second) unit, MKS (meter-kilogram-second) unit, or another unit. Themeter-kilogram-second units (the International System of Units) are used throughoutunless otherwise indicated.

MKS UNITS

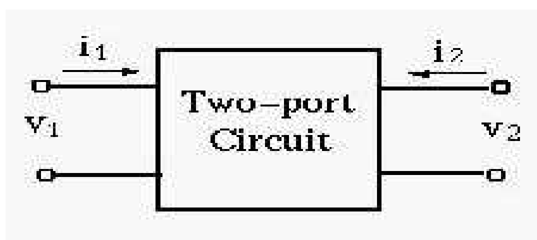
Capacitance	farad = coulomb per volt	F
Charge	coulomb: *A - s*	*Q*
Conductance	mhos	u
Current	ampere = coulomb per second	A
Energy	joule	J
Field	volt per meter	E
Flux linkage	weber = volt · second	φ
Frequency	cycle per second	Hz
Inductance	henry = *(V - s)/ A*	H
Length	meter	m
Power	watt = joule per second	w
Resistance	ohm	Ω
Time	second	s
Velocity	meter per second	*v*

1.5. MICROWAVE HYBRID CIRCUITS

Scattering is an idea taken from billiards, or pool. One takes a cue ball and fires it up the table at a collection of other balls. After the impact, the energy and momentum in the cue ball is divided between all the balls involved in the impact. The cue ball "scatters" the stationary target balls and in turn is deflected or "scattered" by them.

Formally, s-parameters can be defined for any collection of linear electronic components, whether or not the wave view of the power flow in the circuit is necessary. They are algebraically related to the impedance parameters (z-parameters), also to the admittance parameters (y-parameters) and to a notional characteristic impedance of the transmission lines.

Two Port Network



the matrix equations for a 2-port are

b1 = s11 a1 + s12 a2

b2 = s21 a1 + s22 a2

1.5.1 WAVEGUIDE TEE

A waveguide or coaxial-line junction with three independent ports Matrix of third order, containing nine elements, six of which should be independent. The characteristics of a three port junction can be explained by three theorems of the tee junction. These theorems are derived from the equivalent-circuit representation of the tee junction.

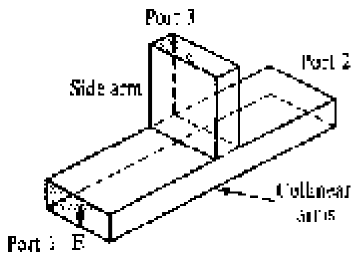
The two basic types are

1)E-plane Tee

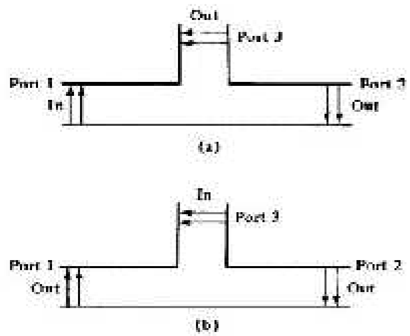
2)H-plane Tee

E-plane Tee

A waveguide tee in which the axis of its side arm is parallel to the E-field of the main guide



If the collinear arms are symmetric about the side arm, there are two different transmission characteristics.



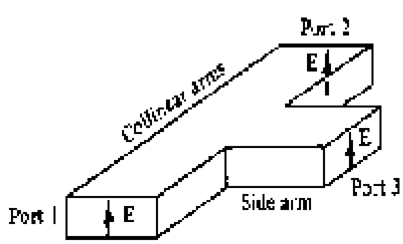
Two way Transmission of E-plane tee

a) i/p-main arm
b) i/p-side arm

If E-plane tee is perfectly matched with the aid of screw tuners or inductive or capacitive windows at the junction, the diagonal components of the S-matrix, S11, S22 and S33 are zero because there will be no reflection. When the waves are fed into the side arm (port 3), the waves appearing at port1 and port2 of the collinear arm will be in the opposite phase and in the same magnitude. Therefore, S13 = -S23 (both have opposite signs)

H-PLANE TEE

A waveguide tee in which the axis of its side arm is "shunting" the E-field or parallel to the H-field of the main guide.



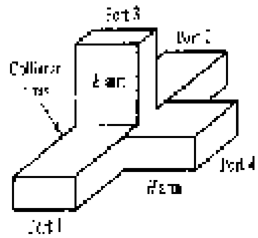
If two input waves are fed into port 1 and port 2 of the collinear arm, the output wave at port 3 will be in phase and additive.

If the input is fed into port 3, the wave will split equally into port 1 and port 2 in phase and in the same magnitude.

Therefore the S matrix of H-plane tee is similar to E-plane tee except S13 = S23

1.5.2 MAGIC TEE (HYBRID TEES)

Combination of E-plane tee and H-plane tee.

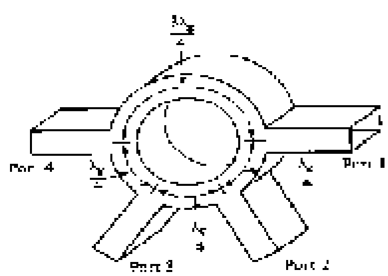


1. If two waves of equal magnitude and the same phase are fed into port 1 and port 2, the output will be zero at port 3 and additive at port 4
2. If a wave is fed into port 4 (H arm), it will be divided equally between port 1 and port 2 of the collinear arms and will not appear at port 3 (E arm).
3. If a wave is fed into port 3 (E arm), it will produce an output of equal magnitude and opposite phase at port 1 and port 2. Output at port 4 is zero i.e S43 = S34 = 0.
4. If a wave is fed into 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 be0cause the E arm causes a phase delay while the H arm causes the phase advance. i.e S12 = S21 = 0.
5. S matrix of magic tee is

$$S = \begin{bmatrix} 0 & 0 & S_{13} & S_{14} \\ 0 & 0 & S_{23} & S_{24} \\ S_{31} & S_{32} & 0 & 0 \\ S_{41} & S_{42} & 0 & 0 \end{bmatrix}$$

1.6 Hybrid Rings (Rat-Race Circuits)

Annular line of proper electrical length to sustain standing waves, to which four arms are connected at proper intervals by means of series or parallel junctions.



Hybrid ring with series junctions

Characteristics similar to hybrid tee. When a wave is fed into port 1, it will not appear at port 3 because the difference of phase shifts for the waves travelling in the clockwise and anticlockwise directions is 180.Thus the waves are cancelled at port 3.Similarly the waves fed into port 2 will not emerge at port 4 and so on.

Phase cancellation occurs only at designated frequency or an ideal hybrid ring. In actual hybrid rings there are small leakage couplings, and hence the zero elements in the matrix above are not quite equal to zero. S matrix for an ideal hybrid ring

$$S = \begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{21} & 0 & S_{23} & 0 \\ 0 & S_{32} & 0 & S_{34} \\ S_{41} & 0 & S_{43} & 0 \end{bmatrix}$$

1.7 WAVEGUIDE CORNERS, BENDS AND TWISTS

These waveguide components are normally used to change the direction of the guide through an arbitrary angle.In order to minimize reflections from the discontinuities, it is desirable to have the mean length L between continuities equal to an odd number of quarter wavelengths.

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

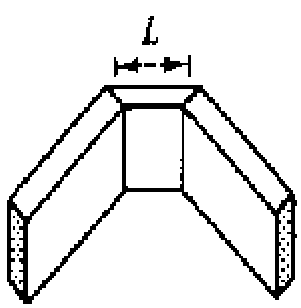
If the mean length L is an odd number of quarter wavelengths, the reflected waves from both ends of the waveguide section are completely cancelled.

For the waveguide bend, the minimum radius of curvature for a small reflection is given by Southworth as

R=1.5b for an E bend

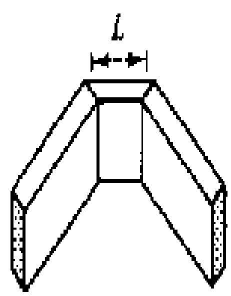
R=1.5a for an H bend

Where a and b are the dimensions of the bend.



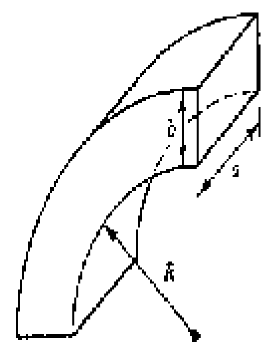
(a)

E plane Corner



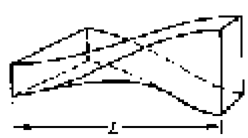
(a)

H-plane corner



(c)

Bend

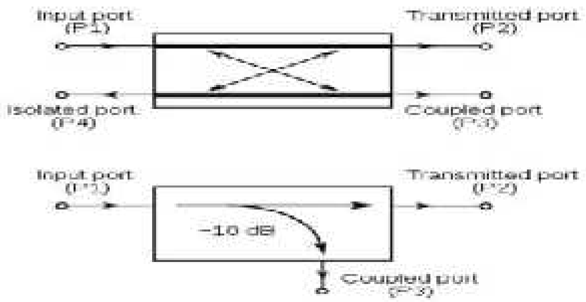


(d)

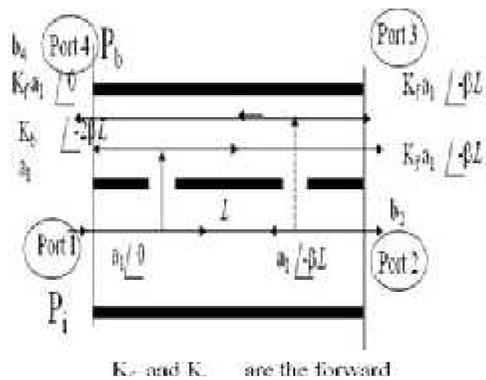
Continuous twist

1.8 DIRECTIONAL COUPLERS

Directional couplers are passive devices used in the field of radio technology. They couple part of the transmission power in a transmission line by a known amount out through another port, often by using two transmission lines set close enough together such that energy passing through one is coupled to the other. As shown in Figure the device has four ports: input, transmitted, coupled, and isolated. The term "main line" refers to the section between ports 1 and 2. On some directional couplers, the main line is designed for high power operation (large connectors), while the coupled port may use a small SMA connector. Often the isolated port is terminated with an internal or external matched load (typically 50 ohms). It should be pointed out that since the directional coupler is a linear device, the notations are arbitrary. Any port can be the input, which will result in the directly connected port being the transmitted port, the adjacent port being the coupled port, and the diagonal port being the isolated port.



1.8.1 Two-Hole Directional Couplers



The coupling C is :

$$C = -20\ \log\ 2|K_f|$$

The directivity D is :

$$D = 20\log\frac{2|K_f|}{K_r\ |1+e^{-2j\ L}|} = 20\log\frac{|K_f|}{K_r\ |\cos\ \ L|}$$

$$= 20\log\frac{|K_f|}{|K_r|} + 20\log|\sec\ \ L|$$

The directivity is the sum of the directivity of the single aperture plus a directivity associated with the array.

1.9 Z & ABCD Parameters- Introduction to S parameters

Z-parameters are also known as open-circuit impedance parameters as they are calculated under open circuit conditions. i.e., I_x=0, where x=1,2 refer to input and output currents flowing through the ports (of a two-port network in this case) respectively. For all ports the voltages may be defined in terms of the Z-parameter matrix and the currents by the following matrix equation:

$$V = ZI$$

where Z is an $N \times N$ matrix the elements of which can be indexed using conventional matrix notation.

The *ABCD*-parameters are known variously as chain, cascade, or transmission line parameters. There are a number of definitions given for *ABCD* parameters, the most common is,

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}$$

For reciprocal networks $AD-BC=1$. For symmetrical networks $A=D$. For networks which are reciprocal and lossless, *A* and*D* are purely real while *B* and *C* are purely imaginary.

This representation is preferred because when the parameters are used to represent a cascade of two-ports, the matrices are written in the same order that a network diagram would be drawn, that is, left to right. However, the examples given below are based on a variant definition;

$$\begin{bmatrix} V_2 \\ I'_2 \end{bmatrix} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix}$$

where

$$A' \stackrel{\text{def}}{=} \left.\frac{V_2}{V_1}\right|_{I_1=0} \qquad B' \stackrel{\text{def}}{=} \left.\frac{V_2}{I_1}\right|_{V_1=0}$$

$$C' \stackrel{\text{def}}{=} \left.-\frac{I_2}{V_1}\right|_{I_1=0} \qquad D' \stackrel{\text{def}}{=} \left.-\frac{I_2}{I_1}\right|_{V_1=0}$$

The negative signs in the definitions of parameters C' and D' arise because I'_2 is defined with the opposite sense to I_2, that is, $I'_2=-I_2$. The reason for adopting this convention is so that the output current of one cascaded stage is equal to the input current of the next. Consequently, the input voltage/current matrix vector can be directly replaced with the matrix equation of the preceding cascaded stage to form a combined $A'B'C'D'$ matrix.

The terminology of representing the $ABCD$ parameters as a matrix of elements designated a_{11} etc. as adopted by some authors and the inverse $A'B'C'D'$ parameters as a matrix of elements esignated b_{11} etc. is used here for both brevity and to avoid confusion with circuit elements.

$$[\mathbf{a}] = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

$$[\mathbf{b}] = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix}$$

S Matrix of a Directional Coupler

A directional coupler is a 4-port network that is designed to divide and distribute power.

1.10 Hybrid Couplers

The hybrid ring coupler, also called the rat-race coupler, is a four-port 3 dB directional coupler consisting of a 3λ/2 ring of transmission line with four lines at the intervals shown in figure 12. Power input at port 1 splits and travels both ways round the ring. At ports 2 and 3 the signal arrives in phase and adds whereas at port 4 it is out of phase and cancels. Ports 2 and 3 are in phase with each other, hence this is an example of a 0° hybrid. Figure 12 shows a planar implementation but this design can also be implemented in coax or waveguide. It is possible to produce a coupler with a coupling factor different from 3 dB by making each $\lambda/4$ section of the ring alternately low and high impedance but for a 3 dB coupler the entire ring is made $\sqrt{2}$ of the port impedances – for a 50 Ω design the ring would be approximately 70 Ω.

1.11 Circulators and Isolators

1.11.1 Microwave Circulators

A **circulator** is a passive non-reciprocal three- or four-port device, in which a microwave or radio frequency signal entering any port is transmitted to the next port in rotation (only). A *port* in this context is a point where an external waveguide or transmission line (such as a microstrip line or a coaxial cable), connects to the device. For a three-port circulator, a signal applied to port 1 only comes out of port 2; a signal applied to port 2 only comes out of port 3; a signal applied to port 3 only comes out of port 1, so to within a phase-factor, the scattering matrix for an ideal three-port circulator is

$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

1.11.2 Microwave isolator

An **isolator** is a two-port device that transmits microwave or radio frequency power in one direction only. It is used to shield equipment on its input side, from the effects of conditions on its output side; for example, to prevent a microwave source being detuned by a mismatched load.

An isolator is a non-reciprocal device, with a non-symmetric scattering matrix. An ideal isolator transmits all the power entering port 1 to port 2, while absorbing all the power entering port 2, so that to within a phase-factor its S-matrix is

$$S = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

To achieve non-reciprocity, an isolator must necessarily incorporate a non-reciprocal material. At microwave frequencies this material is invariably a ferrite which is biased by a static magnetic field. The ferrite is positioned within the isolator such that the microwave signal presents it with a rotating magnetic field, with the rotation axis aligned with the direction of the static bias field. The behaviour of the ferrite depends on the sense of rotation with respect to the bias field, and hence is different for microwave signals travelling in opposite directions. Depending on the exact operating conditions, the signal travelling in one direction may either be phase-shifted, displaced from the ferrite or absorbed.

UNIT-II
Transferred Electron Devices (TEDs) and Avalanche Transit-Time Devices

INTRODUCTION

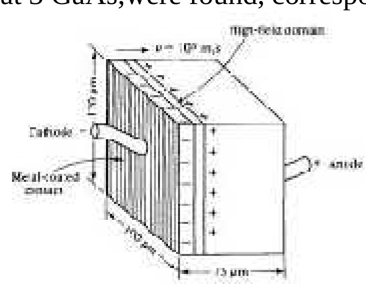
The application of two-terminal semiconductor devices at microwave frequencies has been increased usage during the past decades. The CW, average, and peak power outputs of these devices at higher microwave frequencies are much larger than those obtainable with the best power transistor. The common characteristic of all active two-terminal solid-state devices is their negative resistance. The real part of their impedance is negative over a range of frequencies. In a positive resistance the current through the resistance and the voltage across it are in phase. The voltage drop across a positive resistance is positive and a power of (2 R) is dissipated in the resistance. In a negative resistance, however, the current and voltage are out of phase by 180°. The voltage drop across a negative resistance is negative, and a power of (2 R) is generated by the power supply associated with the negative resistance. In other words, positive resistances absorb power (passive devices), whereas negative resistances generate power (active devices). In this chapter the transferred electron devices (TEDs) are analyzed. The differences between microwave transistors and transferred electron devices (TEDs) are fundamental. Transistors operate with either junctions or gates, but TEDs are bulk devices having no junctions or gates. The majority of transistors are fabricated from elemental semiconductors, such as silicon or germanium, whereas TEDs are fabricated from compound semiconductors, such as gallium arsenide(GaAs), indium phosphide (InP), or cadmium telluride (CdTe).

2.1 Gunn-Effect Diodes – GaAs Diode

Gunn-effect diodes are named after J. B. Gunn, who in 1963 discovered a periodic fluctuations of current passing through then-type gallium arsenide (GaAs) specimen when the applied voltage exceeded a certain critical value. Two years later, in 1965,B. C. DeLoach, R. C. Johnston, and B. G. Cohen discovered the impact ionization avalanche transit-time (IMPATT) mechanism in silicon, which employs the avalanching and transit-time properties of the diode to generate microwave frequencies. In later years the limited space-charge-accumulation diode (LSA diode) and the indium phosphide diode (InP diode) were also successfully developed. These are bulk devices in the sense that microwave amplification and oscillation are derived from the bulk negative-resistance property of uniform semiconductors rather than from the junction negative-resistance property between two different semiconductors, as in the tunnel diode.

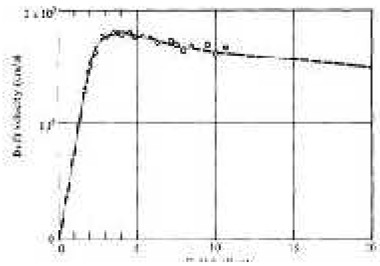
2.1.1 Gunn Effect

Above some critical voltage, corresponding to an electric field of 2000-4000 volts/cm,the current in every specimen became a fluctuating function of time. In the GaAs specimens, this fluctuation took the form of a periodic oscillation superimposed upon the pulse current. The frequency of oscillation was determined mainly by the specimen,and not by the external circuit. The period of oscillation was usually inversely proportional to the specimen length and closely equal to the transit time of electrons between the electrodes, calculated from their estimated velocity of slightly over 107 cm/s . The peak pulse microwave power delivered by the GaAs specimens to a matched load was measured. Value as high as 0.5 Wat l GaAs, and 0.15 Wat 3 GaAs,were found, corresponding to 1-2% of the pulse input power.



Schematic diagram for n type GaAs diode

From Gunn's observation the carrier drift velocity is linearly increased from zero to a maximum when the electric field is varied from zero to a threshold value. When the electric field is beyond the threshold value of 3000 V/cm for the n-type GaAs, the drift velocity is decreased and the diode exhibits negative resistance.



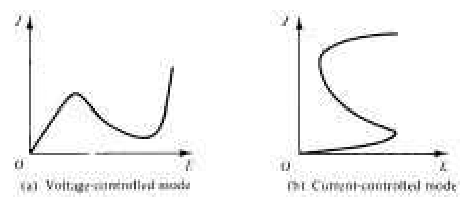
Drift velocity of electrons in n-type GaAs versus electric field.

2.2 Ridely-Watkins-Hilsun (RWH) Theory:

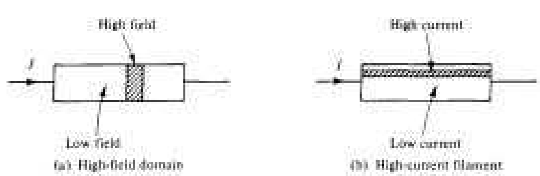
In 1964 Kroemer suggested that Gunn's observations were in complete agreement with the Ridley Watkins Hilsum (RWH) theory.

2.2.1 Differential Negative Resistance

The fundamental concept of the Ridley-Watkins-Hilsum (RWH) theory is the differential negative resistance developed in a bulk solid-state III-V compound when either a voltage (or electric field) or a current is applied to the terminals of the sample. There are two modes of negative-resistance devices: voltage-controlled and current controlled modes.

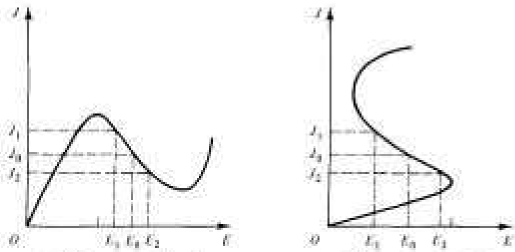


In the voltage-controlled mode the current density can be multivalued,whereas in the current-controlled mode the voltage can be multivalued. The major effect of the appearance of a differential negative-resistance region in the current density- field curve is to render the sample electrically unstable. As a result, the initially
homogeneous sample becomes electrically heterogeneous in an attempt to reach stability. In the voltage-controlled negative-resistance mode high-field domains are formed, separating two low-field regions. The interfaces separating lowand high-field domains lie along equipotentials; thus they are in planes perpendicular
to the current direction In the current-controlled negative-resistance mode splitting the sample results in high-current filaments running along the field direction .



Expressed mathematically, the negative resistance of the sample at a particular region is *di dJ* . .
$dV = dE$ = negative resistance

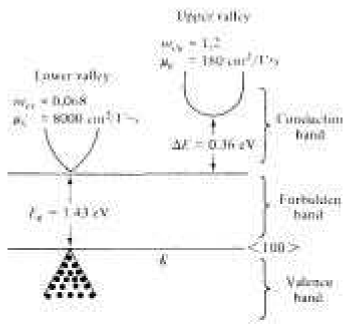
If an electric field *Eo* (or voltage *Vo)* is applied to the sample, for example, the current density *lo* is generated. As the applied field (or voltage) is increased to *E2* (or *Vi),* the current density is decreased to *12.* When the field (or voltage) is decreased to *E1* (or Vi), the current density is increased to 11.



(a) Voltage-controlled mode (b) Current-controlled mode

2.2.2 Two-Valley Model Theory

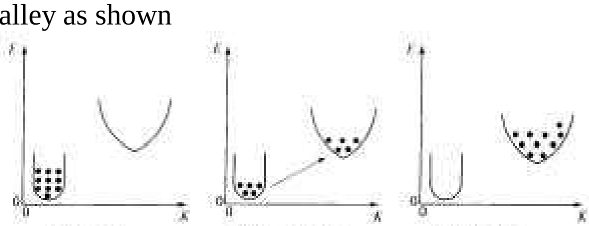
According to the energy band theory of then-type GaAs, a high-mobility lower valley is separated by an energy of 0.36 eV from a low-mobility upper valley as shown



This shows the data for two-valley semiconductors. 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 < Ee), no electrons will transfer to the upper valley as shownWhen the applied electric field is higher than that of the lower valley and lower than that of the upper valley (Ee < E < Eu), electrons will begin to transfer to the upper valley as shown .

Valley	Effective Mass M_e	Mobility μ	Separation ΔE
Lower	$M_{el} = 0.068$	$\mu_l = 8000$ cm²/V-sec	$\Delta E = 0.36$ eV
Upper	$M_{eu} = 1.2$	$\mu_u = 180$ cm²/V-sec	$\Delta E = 0.36$ eV

And when the applied electric field is higher than that of the upper valley *(Eu < E),* all electrons will transfer to the upper valley as shown



(a) $E < E_l$ (b) $E_l < E < E_u$ (c) $E_u < E$

If electron densities in the lower and upper valleys are *nc* and *nu* , the conductivity of the *n* -type GaAs is

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

where e = the electron charge
μ =the electron mobility
n =nc + nu is the electron density

2.3 High-Field Domain

In the n-type GaAs diode the majority carriers are electrons. When a smallvoltage is applied to the diode, the electric field and conduction current density areuniform throughout the diode. At low voltage the GaAs is ohmic, since the drift velocityof the electrons is proportional to the electric field. The conduction current density in the diode is given by

$$\mathbf{J} = \sigma \mathbf{E}_x = \frac{\sigma V}{L}\mathbf{U}_x = \rho v_x \mathbf{U}_x$$

where **J** = conduction current density
a = conductivity
Ex = electric field in the x direction
L = length of the diode
V = applied voltage
p = charge density
v = drift velocity
U = unit vector

The current is carried by free electrons that are drifting through a back ground of fixed positive charge. The positive charge, which is due to impurity atoms that have donated an electron (donors), is sometimes reduced by impurity atoms that have accepted an electron (acceptors). As long as the fixed charge is positive, the semiconductor is n type, since the principal carriers are the negative charges. The density of donors less the density of acceptors is termed doping. When the space charge is zero, the carrier density is equal to the doping. When the applied voltage is above the threshold value, which was measured at about 3000 V/cm times the thickness of the GaAs diode, a high-field domain is formed near the cathode that reduces the electric field in the rest of the material and causes the current to drop to about two-thirds of its maximum value. This situation occurs because the applied voltage is given by

$$V = -\int_0^L E_x \, dx$$

For a constant voltage V an increase in the electric field within the specimen must be accompanied by a decrease in the electric field in the rest of the diode. The high field domain then drifts with the carrier stream across the electrodes and disappears at the anode contact. When the electric field increases, the electron drift velocity decreases and the GaAs exhibits negative resistance.

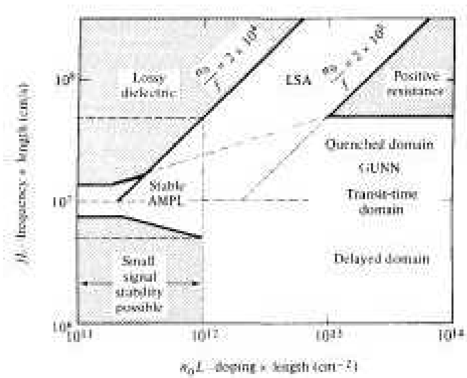
In general, the high-field domain has the following properties

1. 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.
2. 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.
3. A domain will not disappear before reaching the anode unless the voltage is dropped appreciably

2.4 Modes of Operation

Since Gunn first announced his observation of microwave oscillation in the n-type GaAs and n-type InP diodes in 1963, various modes of operation have been developed, depending on the material parameters and operating conditions. As noted, the formation of a strong space-charge instability depends on the conditions that enough charge is available in the crystal and that the specimen is long enough so that the necessary amount of space charge can be built up within the transit time of the electrons. This requirement sets up a criterion for the various modes of operation of bulk negative-differential-resistance devices. Copeland proposed four basic modes of operation of uniformly doped bulk diodes with low-resistance contacts as shown

1. Gunn oscillation mode: This mode is defined in the region where the product of frequency multiplied by length is about 107 cm/s and the product of doping multiplied by length is greater than l012/cm2
• In this region the device is unstable because of the cyclic formation of either the accumulation layer or the high-field domain. In a circuit with relatively low impedance the device operates in the high-field domain mode and the frequency of oscillation is near the intrinsic frequency. When the device is operated in a relatively high-Q cavity and coupled properly to the load, the domain is quenched or delayed (or both) before nucleating. In this case, the oscillation frequency is almost entirely determined by the resonant frequency of the cavity and has a value of several times the intrinsic frequency.



2. Stable amplification mode: This mode is defined in the region where the product of frequency times length is about 107 cm/s and the product of doping times length is between 1011 and l012/cm2
3. LSA oscillation mode: This mode is defined in the region where the product of frequency times length is above 107 cm/s and the quotient of doping divided by frequency is between 2 x 104 and 2 x 105
4. Bias-circuit oscillation mode: This mode occurs only when there is either Gunn or LSA oscillation, and it is usually at the region where the product of frequency times length is too small to appear in the figure. When a bulk diode is biased to threshold, the average current suddenly drops as Gunn oscillation begins. The drop in current at the threshold can lead to oscillations in the bias circuit that are typically 1 kHz to 100 MHz

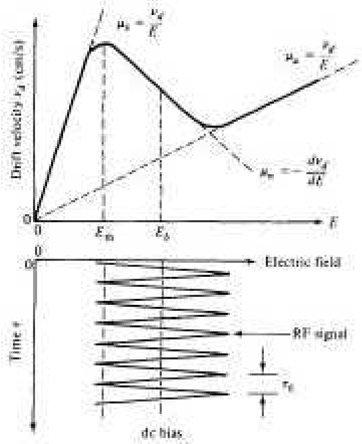
2.5 LSA Diodes:

The abbreviation LSA stands for the limited space-charge accumulation mode of the Gunn diode. As described previously, if the product no L is larger than l0 12/cm^2 and if the ratio of doping no to frequency f is within 2 x 105 to 2 x 104 s/cm3, the high field domains and the space-charge layers do not have sufficient time to build up. The magnitude of the RF voltage must be large enough to drive the diode below threshold during each cycle in order to dissipate space charge. Also, the portion of each cycle during which the RF voltage is above threshold must be short enough to prevent the domain formation and the space-charge accumulation. Only the primary accumulation layer forms near the cathode; the rest of the sample remains fairly homogeneous.

Thus with limited space-charge formation the remainder of the sample appears as a series negative resistance that increases the frequency of the oscillations in the resonant circuit. Copeland discovered the LSA mode of the Gunn diode in 1966 In the LSA mode the diode is placed in a resonator tuned to an oscillation frequency of

$$f_0 = \frac{1}{\tau_0}$$

The device is biased to several times the threshold voltage As the RF voltage swings beyond the threshold, the space charge starts building up at the cathode. Since the oscillation period To of the RF signal is less than the domain-growth time constant T8, the total voltage swings below the threshold before the domain can form. Furthermore, since To is much greater than the dielectric relaxation time Td, the accumulated space charge is drained in a very small fraction of the RF cycle. Therefore the device spends most of the RF cycle in the negative-resistance region, and the space charge is not allowed to build up. The frequency of oscillation in the LSA mode is independent of the transit time of the carriers and is determined solely by the circuit external to the device. Also, the power-impedance product does not fall off as 1 / J6; thus the output power in the LSA mode can be greater than that in the other modes.



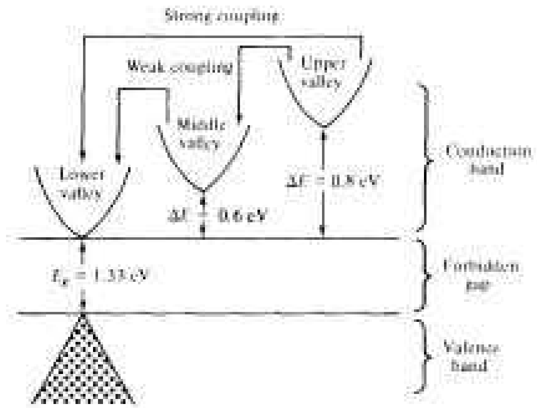
The LSA mode does have limitations. It is very sensitive to load conditions, temperatures, and doping fluctuations .In addition, the RF circuit must allow the field to build up quickly in order to prevent domain formation. The power output of an LSA oscillator can be simply written as

$$P = \eta V_0 I_0 = \eta (M E_{th} L)(n_0 e v_0 A)$$

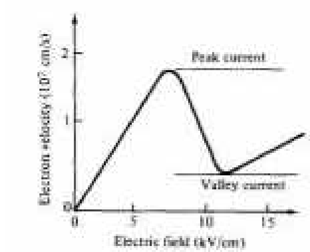
Where, ri =de-to-RF conversion efficiency (primarily a function of material and circuit considerations)
Vo =operating voltage
Io =operating current
M =multiple of the operating voltage above negative-resistance threshold voltage
E,h =threshold field (about 3400 V/cm)
L =device length (about 10 to 200 ,um)
n_o =donor concentration (about 10^{15} e /cm3)
e =electron charge (1.6 x 10^{-19} C)
A =device area (about 3 x 10-4 to 20 x 10^{-4} cm2)

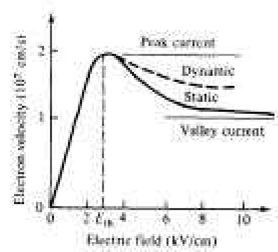
2.6 InP Diodes

Both the GaAs diode and the InP diode operate basically the same way in a circuit with the voltage applied at the electrodes. In the ordinary Gunn effect in the n-type GaAs, the two-valley model theory is the foundation for explaining the electrical behavior of the Gunn effect. However, Hilsum proposed that indium phosphide and some alloys of indium gallium antimonide should work as three-level devices .It can be seen that InP, besides having an upper-valley energy level and a lower-valley energy level similar to the model shown in the below figure for n-type GaAs, also has a third middle-valley energy level. In GaAs the electron transfer process from the lower valley to the upper valley is comparatively slow. At a particular voltage above threshold current flow consists of a larger contribution of electrons from the lower valley rather than from the upper valley. Because of this larger contribution from the lower-energy level, a relatively low peak-to-valley current ratio results the InP diode has a larger peak-to-valley current ratio because an electron transfer proceeds rapidly as the field increases. This situation occurs because the coupling between the lower valley and upper valley in InP is weaker than in GaAs. The middle-valley energy level provides the additional energy loss mechanism required to avoid breakdown caused by the high energies acquired by the lower-valley electrons from the weak coupling that the lower valley is weakly coupled to the middle valley but strongly coupled to the upper valley to prevent breakdown. This situation ensures that under normal operating conditions electrons concentrate in the middle valley.



Three-valley-model energy level for InP diode.





Because InP has a greater energy separation between the lower valley and the hearest energy levels, the thermal excitation of electrons has less effect, and the degradation of its peak-to valley current ratio is about four times less than in GaAs .

2.7 CdTe Diodes

The Gunn effect, first observed by Gunn as a time variation in the current through samples of n -type GaAs when the voltage across the sample exceeded a critical value, has since been observed inn-type InP, n-type CdTe, alloys of n-GaAs and nGaP, and in In As. In n-type cadmium telluride (CdTe), the Gunn effect was first seen by Foyt and McWhorter who observed a time variation of the current through samples 250 to 300 µ,m long with a carrier concentration of 5 x l014/cm3and a room temperature mobility of 1000 cm2/V · s. Ludwig, Halsted, and Aven confirmed the existence of current oscillations in n-CdTe, and Ludwig has further reported studies of the Gunn effect in CdTe over a wider range of sample doping levels and lengths .It has been confirmed that the same mechanism-the field induced transfer of electrons to a higher conduction band minimum (Gunn effect) applies in CdTe just as it does in GaAs. From the two-valley model theory in CdTe,as in GaAs, the (000) minimum is the lowest in energy. The effective mass m_{eff} = 0.11 m (electron mass) and the intrinsic mobility µ, = 1100 cm2/V · sat room temperature. Hilsum has estimated that minima are the next lowest in energy, being0.51 eV higher than (000) minimum. In comparing the Gunn effect in CdTe to that in GaAs, a major difference is the substantially higher threshold field, about 13 kV/cm for CdTe compared with about 3 kV/cm for GaAs. Qualitatively, the higher threshold can be thought of as associated with the relatively strong coupling of the electrons to longitudinal optical phonons, which limits the mobility-and hence the rate of energy acquisition from the applied field-and also provides an efficient mechanism for transferring energy to the lattice, thereby minimizing the kineticenergy in the electron distribution.

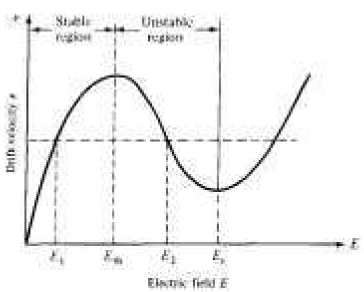
The ratio of peak-to-valley current is another parameter of interest. In CdTe, as in GaAs, the spike amplitude can be as large as 50% of the maximum total current. A similar maximum efficiency for CdTe and GaAs can be expected. Since the domain velocities in CdTe and GaAs are approximately equal, samples of the same length will operate at about the same frequency in the transit-time mode. The high threshold field of CdTe combined with its poor thermal conductivity creates a heating problem. If sufficiently short pulses are used so that the heat can be dissipated, however, the high operating field of the sample can be an advantage.

2.8 Microwave Generation and Amplification

2.8.1 Microwave Generation

If the applied field is less than threshold the specimen is stable. If, however, the field is greater than threshold, the sample is unstable and divides up into two domains of different conductivity and different electric field but the same drift velocity. At the initial formation of the accumulation layer, the field behind the layer decreases and the field in front of it increase. This process continues as the layer travels from the cathode toward the anode. As the layer approaches the anode, the field behind it begins to increase again; and after the layer is collected by the anode, the field in the whole sample is higher than threshold. When the high-field domain disappears at the anode, a new dipole field starts forming again at the cathode and the process repeats itself. Since current density is proportional to the drift velocity of the electrons, a pulsed current output is obtained. The oscillation frequency of the pulsed current is given by

$$f = \frac{v_d}{L_{eff}}$$



2.8.2 Microwave Amplification

When an RF signal is applied to a Gunn oscillator, amplification of the signal occurs, provided that the signal frequency is low enough to allow the space charge in the domain to readjust itself. There is a critical value of JL above which the device will not amplify. Below this frequency limit the sample presents an impedance with a negative real part that can be utilized for amplification. If no L becomes less than$10^{12}/cm^2$, domain formation is inhibited and the device exhibits a non uniform field distribution that is stable with respect to time and space. Such a diode can amplify signals in the vicinity of the transit-time frequency and its harmonics without oscillation. If this device is used in a circuit with enough positive feedback, it will oscillate. Hakki has shown that the oscillation diode can amplify at nearby frequencies or can be used simultaneously as an amplifier and local oscillator However, the output power of a stable amplifier is quite low because of the limitation imposed by the value of no L.

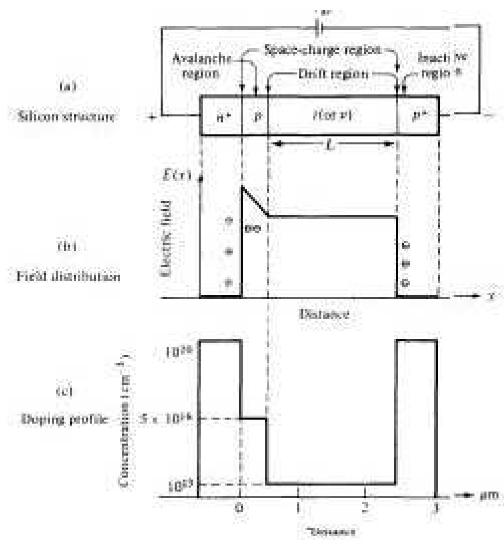
Avalanche Transit-Time Devices

Avalanche transit-time diode oscillators rely on the effect of voltage break down across a reverse-biased p-n junction to produce a supply of holes and electrons. Ever since the development of modern semiconductor device theory scientists have speculated on whether it is possible to make a two-terminal negative-resistance device. The tunnel diode was the first such device to be realized in practice. Its operation depends on the properties of a forward-biased p-n junction in which both the p and n regions are heavily doped. The other two devices are the transferred electron devices and the avalanche transit-time devices.

2.9 Read Diode

Physical Description

The basic operating principle of IMPATT diodes can be most easily understood byreference to the first proposed avalanche diode, the Read diode .The theory ofthis device was presented by Read in 1958, but the first experimental Read diodewas reported by Lee et al. in 1965 A mode of the original Read diode with a
doping profile and a de electric field distribution that exists when a large reverse biasis applied across the diode.



The Read diode is an *n+ -p-i-p+* structure, where the superscript plus sign denotes very high doping and the i or *v* refers to intrinsic material. The device consists essentially of two regions. One is the thin *p* region at which avalanche multiplication occurs. This region is also called the high-field region or the avalanche region. The other is the *i* or *v* region through which the generated holes must drift in moving to the *p+* contact. This region is also called the intrinsic region or the drift region. The *p* region is very thin. The space between the *n+ -p* junction and the *i-p+* junction is called the space-charge region. Similar devices can be built in the *p+ -n-i-n+* structure, in which electrons generated from avalanche multiplication drift through the I region. The Read diode oscillator consists of an *n+ -p-i-p+* diode biased in reverse and mounted in a microwave cavity. The impedance of the cavity is mainly inductive and is matched to the mainly capacitive impedance of the diode to form a resonant circuit. The device can produce a negative ac resistance that, in turn, delivers power from the de bias to the oscillation.

2.9.1 Avalanche Multiplication

When the reverse-biased voltage is well above the punch through or breakdown voltage, the space-charge region always extends from the *n+ -p* junction through the *p* and i regions to the *i-p+* junction. The fixed charges in the various regions are shown. A positive charge gives a rising field in moving from left to right. The maximum field, which occurs at the *n+ -p* junction, is about several hundred kilovolts per centimeter. Carriers (holes) moving in the high field near *then+ -p* junction acquire energy to knock valence electrons into the conduction band, thus producing hole-electron pairs. The rate of pair production, or avalanche multiplication, is a sensitive nonlinear function of the field. By proper doping, the field can be given a relatively sharp peak so that avalanche multiplication is confined to a very narrow region at the *n+ -p* junction. The electrons move into the *n+* region and the holes drift through the space-charge region to the *p+* region with a constant velocity *VJ* of about 107 *emfs* for silicon. The field throughout the space-charge region is above about 5 kV/cm. The transit time of a hole across the drift i-region *L* is given by

$$\tau = \frac{L}{v_d}$$

and the avalanche multiplication factor is

$$M = \frac{1}{1 - (V/V_b)^n}$$

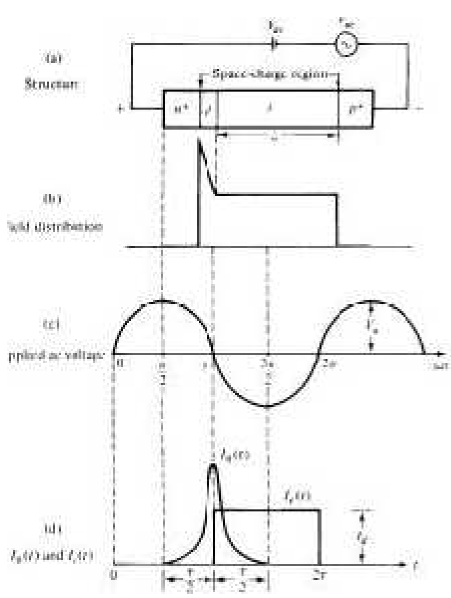
where *V* = applied voltage
vb = avalanche breakdown voltage
n = 3-6 for silicon is a numerical factor depending on the doping of *p+ -nor*
n+ -p junction
The breakdown voltage for a silicon *p+ -n* junction can be expressed as

$$|V_b| = \frac{\rho_n \mu_n \epsilon_s |E_{max}|^2}{2}$$

Where, *Pn* = resistivity
JLn = electron mobility
I *vb* I = *PnJLnEsl* Emax
Es = semiconductor permittivity
Emax = maximum breakdown of the electric field

2.9.2 Carrier Current Io(t) and External Current Ie(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 the de and ac fields. This total field causes breakdown at then + -p junction during the positive half of the ac voltage cycle if the field is above the breakdown voltage, and the carrier current (or the hole current in this case) Io(t) generated at the n+ -p junction by the avalanche multiplication grows exponentially with time while the field is above the critical value. During the negative half cycle, when the field is below the breakdown voltage, the carrier current fo(t)decays exponentially to a small steady-state value. The carrier current fo(t) is the current at the junction only and is in the form of a pulse of very short duration as shown Therefore the carrier current fo(t) reaches its maximum in the middle of the ac voltage cycle, or one-quarter of a cycle later than the voltage. Under the influence of the electric field the generated holes are injected into the space-charge region toward the negative terminal. As the injected holes traverse the drift space, they induce a current le(t) in the external circuit



2.9.3 Output Power and Quality Factor Q

The external current I,(t) approaches a square wave, being very small during the positive half cycle of the ac voltage and almost constant during the negative half cycle. Since the direct current Id supplied by the de bias is the average external current or conductive current, it follows that the amplitude of variation of I,(t) is approximately equal to Id. If Va is the amplitude of the ac voltage, the ac power delivered is found to be

$$P = 0.707 V_a I_d \qquad \text{W/unit area}$$

The quality factor *Q* of a circuit is defined as

$$Q = \omega \frac{\text{maximum stored energy}}{\text{average dissipated power}}$$

Since the Read diode supplies ac energy, it has a negative Qin contrast to the positive *Q* of the cavity. At the stable operating point, the negative *Q* of the diode is equal to the positive *Q* of the cavity circuit. If the amplitude of the ac voltage increases, the stored energy, or energy of oscillation, increases faster than the energy.

2.10 IMPATT DIODES

Physical Structures

A theoretical Read diode made of an *n+ -p-i-p+* or *p+ -n-i-n+* structure has been analyzed. Its basic physical mechanism is the interaction of the impact ionization avalanche and the transit time of charge carriers. Hence the Read-type diodes are called IMPATT diodes. These diodes exhibit a differential negative resistance by two effects:

1. The impact ionization avalanche effect, which causes the carrier current fo(t) and the ac voltage to be out of phase by 90°
2. The transit-time effect, which further delays the external current *I.(t)* relative to the ac voltage by 90°

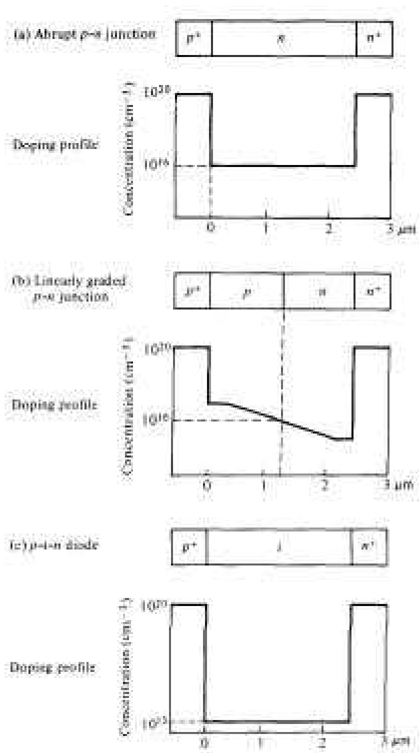
The first IMPATT operation as reported by Johnston et al. in 1965 however, was obtained from a simple *p-n* junction. The first real Read-type IMPATT diode was reported by Lee et al. [3], as described previously. From the small-signal theory developed by Gilden it has been confirmed that a negative resistance of the IMPATT diode can be obtained from a junction diode with any doping profile. Many IMPATT diodes consist of a high doping avalanching region followed by a drift region where the field is low enough that the carriers can traverse through it without avalanching. The Read diode is the basic type in the IMPATT diode family. The others are the one-sided abrupt *p-n* junction, the linearly graded *p-n* junction (or double-drift region), and the *p-i-n* diode, all of which are shown. The principle of operation of these devices, however, is essentially similar to the mechanism described for the Read diode.

2.10.1 Negative Resistance

Small-signal analysis of a Read diode results in the following expression for the real part of the diode terminal impedance

$$R = R_s + \frac{2L^2}{v_d \epsilon_s A} \frac{1}{1 - \omega^2/\omega_r^2} \frac{1 - \cos\theta}{\theta}$$

Where, *Rs* = passive resistance of the inactive region
vd = carrier drift velocity
L = length of the drift space-charge region
A = diode cross section
es = semiconductor dielectric permittivity



2.10.2 Power Output and Efficiency

At a given frequency the maximum output power of a single diode is limited by semiconductor materials and the attainable impedance levels in microwave circuitry. For a uniform avalanche, the maximum voltage that can be applied across the diode is given by

$$V_m = E_m L$$

Where, *Ls* the depletion length and

Em is the maximum electric field.

This maximum applied voltage is limited by the breakdown voltage. Furthermore, the maximum current that can be carried by the diode is also limited by the avalanche breakdown process, for the current in the space-charge region causes an increase in the electric field. The maximum current is given by

$$I_m = J_m A = \sigma E_m A = \frac{\epsilon_s}{\tau} E_m A = \frac{v_d \epsilon_s E_m A}{L}$$

2.11 TRAPATT DIODES

2.11.1 Physical Structures

The abbreviation TRAPATT stands for trapped plasma avalanche triggered transit mode, a mode first reported by Prager. It is a high-efficiency microwave generator capable of operating from several hundred megahertz to several giga hertz. The basic operation of the oscillator is a semiconductor p-n junction diode reverse biased to current densities well in excess of those encountered in normal avalanche operation. High-peak-power diodes are typically silicon n+ -p-p+ (or p+ -n-n+) structures with then-type depletion region width varying from 2.5 to 12.5 µ,m. The doping of the depletion region is generally such that the diodes are well "punched through" at breakdown; that is, the de electric field in the depletion region just prior to breakdown is well above the saturated drift-velocity level. The device's p+ region is kept as thin as possible at 2.5 to 7.5 µ,m. The TRAPATT diode's diameter ranges from as small as 50 µ,m for CW operation to 750 µ,mat lower frequency for high• peak-power devices.

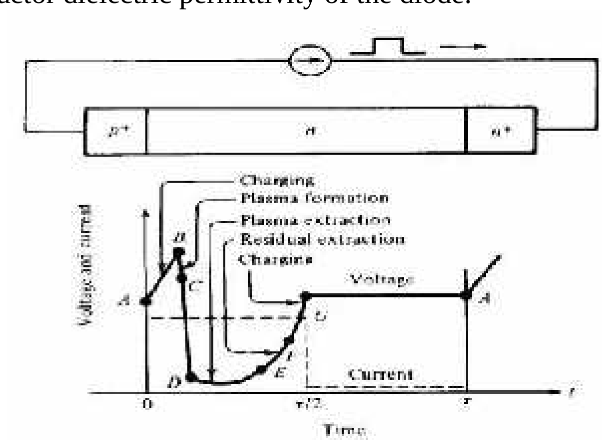
2.11.2 Principles of Operation:

Approximate analytic solutions for the TRAPATT mode in p+ -n-n+ diodes have been developed by Clorfeine and DeLoach among others. These analyses have shown that a high-field avalanche zone propagates through the diode and fills the depletion layer with dense plasma of electrons and holes that become trapped in the low-field region behind the zone. A typical voltage waveform for the TRAPATT mode of an avalanche p+ -n-n+ diode operating with an assumed square wave current drive is shown in below figure. At point A the electric field is uniform throughout the sample and its magnitude is large but less than the value required for avalanche breakdown.

The current density is expressed by

$$J = \epsilon_s \frac{dE}{dt}$$

Where, Es is the semiconductor dielectric permittivity of the diode.



Voltage and current waveforms for TRAPATT diode

At the instant of time at point A, the diode current is turned on. Since the only charge carriers present are those caused by the thermal generation, the diode initially charges up like a linear capacitor, driving the magnitude of the electric field above the breakdown voltage. When a sufficient number of carriers is generated, the particle current exceeds the external current and the electric field is depressed throughout the depletion region, causing the voltage to decrease. This portion of the cycle is shown by the curve from point B to point C. During this time interval the electric field is sufficiently large for the avalanche to continue, and dense plasma of electrons and holes is created. As some of the electrons and holes drift out of the ends of the depletion layer, the field is further depressed and "traps" the remaining plasma. The voltage decreases to point D. A long time is required to remove the plasma because the total plasma charge is large compared to the charge per unit time in the external current. At point E the plasma is removed, but a residual charge of electrons remains in one end of the depletion layer and a residual charge of holes in the other end. As the residual charge is removed, the voltage increases from point E to point F. At point Fall the charge that was generated internally has been removed. This charge must be greater than or equal to that supplied by the external current; otherwise the voltage will exceed that at point A. From point F to point G the diode charges up again like a fixed capacitor. At point G the diode current goes to zero for half a period and the voltage remains constant at VA until the current comes back on and the cycle repeats.

TRAPATT mode can operate at comparatively low frequencies, since the discharge time of the plasma-that is, the rate Q/ I of its charge to its current can be considerably greater than the nominal transit time Ts of the diode at high field. Therefore the TRAPATT mode is still a transit-time mode in the real sense that the time delay of carriers in transit (that is, the time between injection and collection) is utilized to obtain a current phase shift favorable for oscillation.

2.11.3 Power Output and Efficiency: RF power is delivered by the diode to an external load when the diode is placed in a proper circuit with a load. The main function of this circuit is to match the diode effective negative resistance to the load at the output frequency while reactively terminating (trapping) frequencies above the oscillation frequency in order to ensure TRAPATT operation. To date, the highest pulse power of 1.2 kW has been obtained at l. l GHz (five diodes in series) [10], and the highest efficiency of 75% has been achieved at 0.6 GHz. The TRAPATT operation is a rather complicated means of oscillation, however, and requires good control of both device and circuit properties. In addition the TRAPATT mode generally exhibits a considerably higher noise figure than the IMPATT mode, and the upper operating frequency appears to be practically limited to below the millimeter wave region.

2.12 BARITT DIODES

2.12.1 Physical Description

BARITT diodes, meaning barrier injected transit-time diodes, are the latest addition to the family of active microwave diodes. They have long drift regions similar to those of IMPATT diodes. The carriers traversing the drift regions of BARITT diodes, however, are generated by minority carrier injection from forward-biased junctions instead of being extracted from the plasma of an avalanche region. Several different structures have been operated as BARITT diodes, including p-n-p, p-n-v-p, p-n-metal, and metal-n-metal. For a p-n-v-p BARITT diode, the forward-biased p-n junction emits holes into the v region. These holes drift with saturation velocity through the v region and are collected at the p contact. The diode exhibits a negative resistance for transit angles between 1T and 27T. The optimum transit angle is approximately 1.67r. Such diodes are much less noisy than IMPATT diodes. Noise figures are as low as 15 dB at C-band frequencies with silicon BARITT amplifiers. The major disadvantages of BARITT diodes are relatively narrow bandwidth and power outputs limited to a few milliwatts.

2.12.2 Principles of Operation

A crystal n-type silicon wafer with 11 H-cm resistivity and 4 x 10 per cubic centimeter doping is made of a 10-µm thin slice. Then then-type silicon wafer is sandwiched between two PtSi Schottky barrier contacts of about 0.1 µm thickness. A schematic diagram of a metal-n-metal structure is shown in below figure. The energy-band diagram at thermal equilibrium is shown in below figure. Where, n1 and n2 are the barrier heights for the metal-semiconductor contacts, respectively. For the PtSi-Si-PtSi structure mentioned previously, n1 = n2 0.85 eV. The hole barrier height for the forward-biased contact is about 0.15 eV. Below figure shows the energy-band diagram when a voltage is applied.

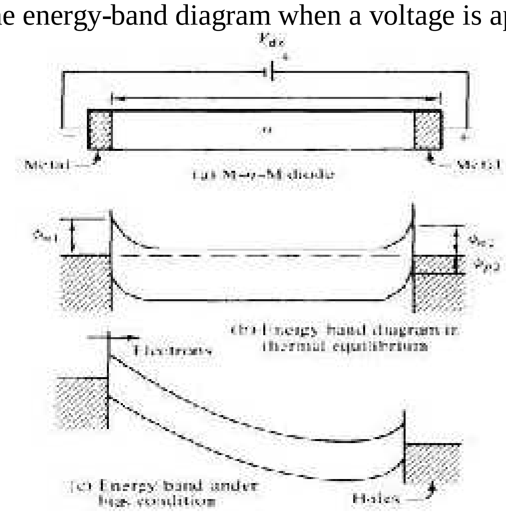


Figure M-n-M diode

The mechanisms responsible for the microwave oscillations are derived from:

1. The rapid increase of the carrier injection process caused by the decreasing potential barrier of the forward-biased metal-semiconductor contact.

2. An apparent 3Pi /2 transit angle of the injected carrier that traverses the semiconductor depletion region The rapid increase in terminal current with applied voltage (above 30 V) as shown in below figure is caused by thermionic hole injection into the semiconductor as the depletion layer of the reverse-biased contact reaches through the entire device thickness.

2.12.3 Microwave Performance

Continuous-wave (CW) microwave performance of the M-n-M-type BARITT diode was obtained over the entire C band of 4 to 8 GHz. The maximum power observed was 50 mW at 4.9 GHz. The maximum efficiency was about 1.8%. The FM single sideband noise measure at 1 MHz was found to be 22.8 dB at a 7-mA bias current. This noise measure is substantially lower than that of a silicon IMPATT diode and is comparable to that of a GaAs transfer-electron oscillator. Figure 8-4-3 shows some of the measured microwave power versus current with frequency of operation indicated on each curve for three typical devices tested. The voltage enclosed in parentheses for each curve indicates the average bias voltage at the diode while the diode is in oscillation. The gain-bandwidth product of a 6-GHz BARITT diode was measured to be 19-dB gain at 5-mA bias current at 200 MHz. The small-signal noise measure was about 15 dB.

2.13 Parametric Devices

2.13.1 Physical Structures:

A parametric device is one that uses a nonlinear reactance (capacitance or inductance) or a time-varying reactance. The capacitance or inductance, which is a reactive parameter, can be used to produce capacitive or inductive excitation. Parametric excitation can be subdivided into parametric amplification and oscillation.

2.13.2 Nonlinear Reactance

Reactance: A reactance is defined as a circuit element that stores and releases electromagnetic energy as opposed to a resistance, which dissipates energy.

Capacitive: If the stored energy is predominantly in the electric field, the reactance is said to be capacitive

Inductive: If the stored energy is predominantly in the magnetic field, the reactance is said to be inductive.

$C = Q/V$

If the ratio is not linear, the capacitive reactance is said to be nonlinear. In this case it is convenient to define a non linear capacitance as the partial derivative of charge with respect to voltage.

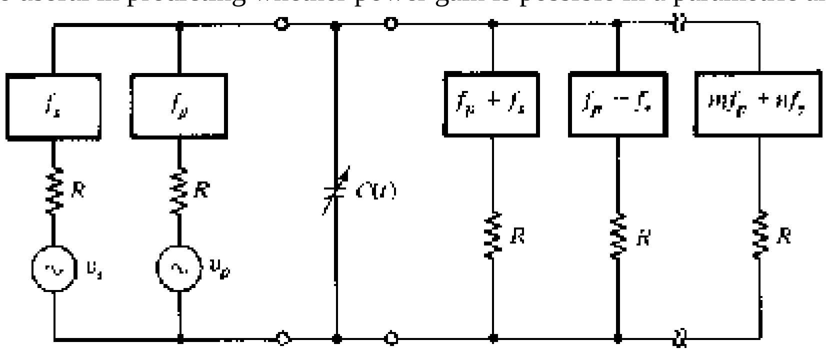
(i.e) $C(v) = dQ/dt$

The analogous definition of non linear inductance is $L(i) = d\Phi/di$.

2.13.3 Manley – Rowe Power Relations

Derived a set of general energy relations regarding power flowing into and out of an ideal nonlinear reactance.

These relations are useful in predicting whether power gain is possible in a parametric amplifier.



Equivalent circuit for Manley-Rowe derivation

One signal generator and one pump generator at their respective frequencies f_s and f_p together with

associated series resistances and bandpass filters, are applied to a nonlinear capacitance C(t).
These resonating circuits of filters are designed to reject power at all frequencies other than their respective signal frequencies. In the presence of two applied frequencies f_s and f_p an infinite number of resonant frequencies of $mf_p + nf_s$ are generated, where m and n are any integers.
Each of the resonating circuits is assumed to be ideal.
The power loss by the nonlinear susceptance is negligible. That is the power entering the nonlinear capacitor at the pump frequency is equal to the power leaving the capacitor at the other frequencies through the nonlinear interaction.

Manley and Rowe established the power relations between the input power at the frequencies f_s and f_p and the output power at the other frequencies $mf_p + nf_s$.

It is assumed that the signal voltage vs is much smaller than the pumping voltage v_p, and the total voltage across the nonlinear capacitance C(t) is given by

$$v = v_p + v_s = \frac{V_p}{2}(e^{j\omega_p t} + e^{-j\omega_p t}) + \frac{V_s}{2}(e^{j\omega_s t} - e^{-j\omega_s t})$$

The general expression of the charge Q deposited on the capacitor is given by

$$Q = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} Q_{m,n} e^{j(m\omega_p t + n\omega_s t)}$$

For Q to be real,

$$Q_{m,n} = Q^*_{-m,-n}$$

The total voltage v can be expressed as a function of the charge Q.
A similar taylor series expression of v(Q) shows that

$$v = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} V_{m,n} e^{j(m\omega_p t + n\omega_s t)}$$

V to be real,

$$V_{m,n} = V^*_{-m,-n}$$

The current flowing through C(t) is the total derivative of Q w r t time. Hence

$$i = \frac{dQ}{dt} = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} j(m\omega_p + n\omega_s) Q_{m,n} e^{j(m\omega_p t + n\omega_s t)}$$

$$= \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} I_{m,n} e^{j(m\omega_p t + n\omega_s t)}$$

Where,

$$I_{m,n} = j(m\omega_p + n\omega_s) Q_{m,n} \text{ and } I_{m,n} = I^*_{-m,-n}$$

Since the capacitance C(t) is assumed to be pure reactance, the average power at the frequencies is

$$P_{m,n} = (V_{m,n} I^*_{m,n} + V^*_{m,n} I_{m,n})$$

$$= (V^*_{-m,-n} I_{-m,-n} + V_{-m,-n} I^*_{-m,-n}) = P_{-m,-n}$$

Then conservation of power can be written

$$\sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} P_{m,n} = 0$$

Multiply the above equation by a factor of

$(m\omega_p + n\omega_s)/(m\omega_p + n\omega_s)$ and rearrangement of the resultant into two parts yield

$$\omega_p \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \frac{mP_{m,n}}{m\omega_p + n\omega_s} + \omega_s \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \frac{nP_{m,n}}{m\omega_p + n\omega_s} = 0$$

Consequently, the frequencies fp and fs can be arbitrarily adjusted in order to require

$$\sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \frac{mP_{m,n}}{m\omega_p + n\omega_s} = 0$$

$$\sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \frac{nP_{m,n}}{m\omega_p + n\omega_s} = 0$$

Equation can be expressed as

$$\sum_{m=0}^{\infty} \sum_{n=-\infty}^{\infty} \frac{mP_{m,n}}{m\omega_p + n\omega_s} + \sum_{m=0}^{\infty} \sum_{n=-\infty}^{\infty} \frac{-mP_{m,n}}{-m\omega_p - n\omega_s} = 0$$

Since,

$$P_{m,n} = P_{-m,-n}$$

then

$$\sum_{m=0}^{\infty} \sum_{n=-\infty}^{\infty} \frac{mP_{m,n}}{mf_p + nf_s} = 0$$

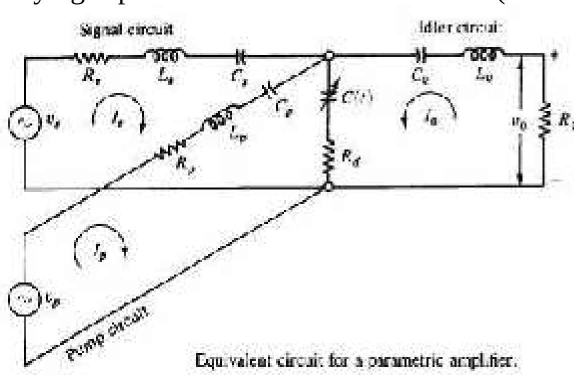
Similarly,

$$\sum_{m=-\infty}^{\infty} \sum_{n=0}^{\infty} \frac{nP_{m,n}}{mf_p + nf_s} = 0$$

Where w_p and w_s are replaced by f_p and f_s respectively.
The above equations are standard forms for the Manley-Rowe power relations.

2.13.4 Parametric Amplifiers:

In a super heterodyne receiver a radio frequency signal may be mixed with a signal from the local oscillator in a nonlinear circuit (the mixer) to generate the sum and difference frequencies. In a parametric amplifier the local oscillator is replaced by a pumping generator such as a reflex klystron and the nonlinear element by a time varying capacitor such as a varactor diode (or inductor).



Equivalent circuit for a parametric amplifier.

Parametric up-converter: A parametric up-converter has the following properties:

1. The output frequency is equal to the sum of the signal frequency and the pump frequency.
2. There is no power flow in the parametric device at frequencies other than the signal, pump, and output frequencies.

Parametric down-converter: If a mode of down conversion for a parametric amplifier is desirable, the signal frequency ls must be equal to the sum of the pump frequency f, and the output frequency f_o . This means that the input power must feed into the idler circuit and the output power must move out from the signal circuit.

2.13.5 Applications:

The choice of which type of parametric amplifier to use depends on the microwave system requirements. The up-converter is a unilateral stable device with a wide bandwidth and low gain. The negative-resistance amplifier is inherently a bilateral and unstable device with narrow bandwidth and high gain. The degenerate parametric amplifier does not require a separate signal and idler circuit coupled by the diode and is the least complex type of parametric amplifier.

In general, the up-converter has the following advantages over the negative resistance parametric amplifier:

1. A positive input impedance
2. Unconditionally stable and unilateral
3. Power gain independent of changes in its source impedance
4. No circulator required
5. A typical bandwidth on the order of 5%

At higher frequencies where the up-converter is no longer practical, the negative resistance parametric amplifier operated with a circulator becomes the proper choice. When a low noise figure is required by a system, the degenerate parametric amplifier may be the logical choice, since its double-sideband noise figure is less than the optimum noise figure of the up-converter or the no degenerate negative-resistance parametric amplifier. Furthermore, the degenerate amplifier is a much simpler device to build and uses a relatively low pump frequency. In radar systems the negative-resistance parametric amplifier may be the better choice, since the frequency required by the system may be higher than the X band. However, since the parametric amplifier is complicated in fabrication and expensive in production, there is a tendency in microwave engineering to replace it with the GaAs metal-semiconductor field-effect transistor amplifier in airborne radar systems.

UNIT-III

Microwave Linear-Beam Tubes (Otype) & Microwave Crossed-Field Tubes (Mtype)

3.1 Klystron

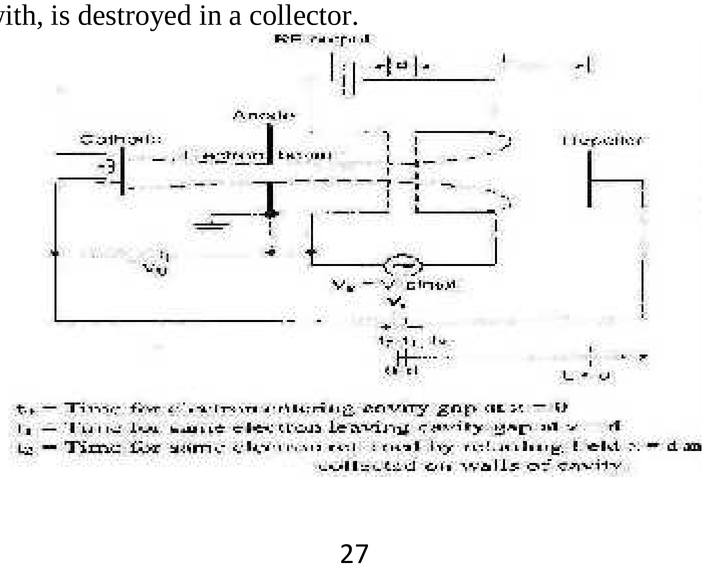
A klystron is a specialized linear-beam vacuum tube (evacuated electron tube). The pseudo-Greek word klystron comes from the stem form κλυσ (klys) of a Greek verb referring to the action of waves breaking against a shore, and the end of the word electron.

The brothers Russell and Sigurd Varian of Stanford University are generally considered to be the inventors of the klystron. Their prototype was completed in August 1937. Upon publication in 1939, news of the klystron immediately influenced the work of US and UK researchers working on radar equipment. The Variants went on to found Varian Associates to commercialize the technology (for example to make small linear accelerators to generate photons for external beam radiation therapy). In their 1939 paper, they acknowledged the contribution of A. Arsenjewa-Heil and O. Heil (wife and husband) for their velocity modulation theory in 1935.

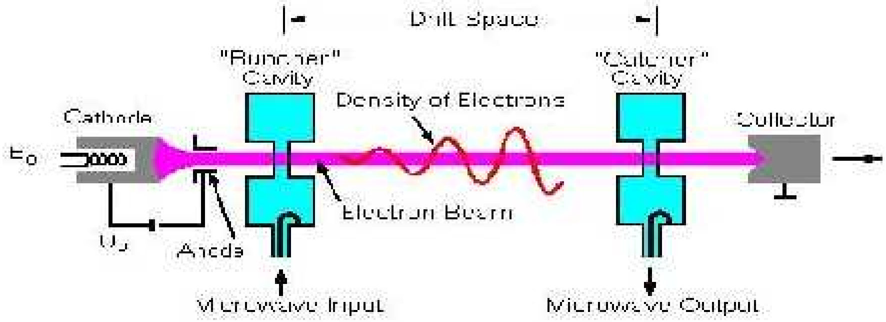
During the second World War, the Axis powers relied mostly on (then low-powered) klystron technology for their radar system microwave generation, while the Allies used the far more powerful but frequency-drifting technology of the cavity magnetron for microwave generation. Klystron tube technologies for very high-power applications, such as synchrotrons and radar systems, have since been developed.

Klystrons are used as an oscillator (such as the reflex klystron) or amplifier at microwave and radio frequencies to produce both low-power reference signals for super heterodyne radar receivers and to produce high-power carrier waves for communications and the driving force for linear accelerators. All modern klystrons are amplifiers, since reflex klystrons have been surpassed by alternative technologies. Klystron amplifiers have the advantage (over the magnetron) of coherently amplifying a reference signal so its output may be precisely controlled in amplitude, frequency and phase. Many klystrons have a waveguide for coupling microwave energy into and out of the device, although it is also quite common for lower power and lower frequency klystrons to use coaxial couplings instead. In some cases a coupling probe is used to couple the microwave energy from a klystron into a separate external waveguide.

Klystrons amplify RF signals by extracting energy from a DC electron beam. A beam of electrons is produced by a thermionic cathode (a heated pellet of low work function material), and accelerated to high voltage (typically in the tens of kilovolts). This beam is then passed through an input cavity. RF energy is fed into the input cavity at, or near, its natural frequency to produce a voltage which acts on the electron beam. The electric field causes the electrons to bunch: electrons that pass through during an opposing electric field are accelerated and later electrons are slowed, causing the previously continuous electron beam to form bunches at the input frequency. To reinforce the bunching, a klystron may contain additional "buncher" cavities. The electron bunches excite a voltage on the output cavity, and the RF energy developed flows out through a waveguide. The spent electron beam, which now contains less energy than it started with, is destroyed in a collector.



Two-cavity klystron amplifier



In the two-chamber klystron, the electron beam is injected into a resonant cavity. The electron beam, accelerated by a positive potential, is constrained to travel through a cylindrical drift tube in a straight path by an axial magnetic field. While passing through the first cavity, the electron beam is velocity modulated by the weak RF signal. In the moving frame of the electron beam, the velocity modulation is equivalent to a plasma oscillation, so in a quarter of one period of the plasma frequency, the velocity modulation is converted to density modulation, i.e. bunches of electrons. As the bunched electrons enter the second chamber they induce standing waves at the same frequency as the input signal. The signal induced in the second chamber is much stronger than that in the first.

Two-cavity klystron oscillator

The two-cavity amplifier klystron is readily turned into an oscillator klystron by providing a feedback loop between the input and output cavities. Two-cavity oscillator klystrons have the advantage of being among the lowest-noise microwave sources available, and for that reason have often been used in the illuminator systems of missile targeting radars. The two-cavity oscillator klystron normally generates more power than the reflex klystron—typically watts of output rather than milliwatts. Since there is no reflector, only one high-voltage supply is to cause the tube to oscillate, the voltage must be adjusted to a particular value. This is because the electron beam must produce the bunched electrons in the second cavity in order to generate output power. Voltage must be adjusted by varying the velocity of the electron beam to a suitable level due to the fixed physical separation between the two cavities. Often several "modes" of oscillation can be observed in a given klystron.

3.2 Multicavity Klystron Amplifiers

Multicavity klystron: In all modern klystrons, the number of cavities exceeds two. A larger number of cavities may be used to increase the gain of the klystron, or to increase the bandwidth.

Tuning a klystron: Some klystrons have cavities that are tunable. Tuning a klystron is delicate work which, if not done properly, can cause damage to equipment or injury to the technician. By changing the frequency of the individual cavities, the technician can change the operating frequency, gain, output power, or bandwidth of the amplifier. The technician must be careful not to exceed the limits of the graduations, or damage to the klystron can result.

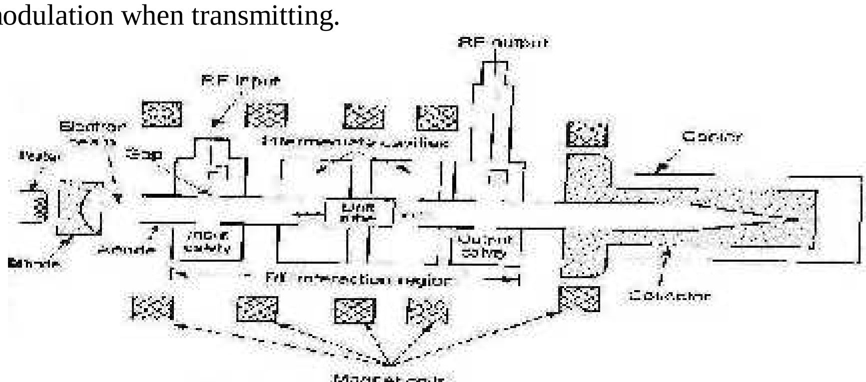
Manufacturers generally send a card with the unique calibrations for a klystron's performance characteristics, that lists the graduations that are to be set, for any given frequency. No two klystrons are alike (even when comparing like part/model number klystrons) so that every card is specific to the individual unit. Klystrons have serial numbers on each of them that distinguishes them uniquely, and for which manufacturers may (hopefully) have the performance characteristics in a database. If not, loss of the calibration card may be an insoluble problem, making the klystron unusable or perform marginally un-tuned.

Other precautions taken when tuning a klystron include using nonferrous tools. If ferrous (magnetically reactive) tools come too close to the intense magnetic fields that contain the electron beam (some klystrons employ permanent magnets, which cannot be turned off) the tool can be pulled into the unit by

the intense magnetic force, smashing fingers, hurting the technician, or damaging the klystron. Special lightweight nonmagnetic tools made of beryllium alloy have been used for tuning U.S. Air Force klystrons.
Precautions are routinely taken when transporting klystron devices in aircraft, as the intense magnetic field can interfere with magnetic navigation equipment. Special over packs are designed to help limit this field "in the field," and thus transport the klystron safely.

Optical klystron: In an optical klystron the cavities are replaced with undulators. Very high voltages are needed. The electron gun, the drift tube and the collector are still used.

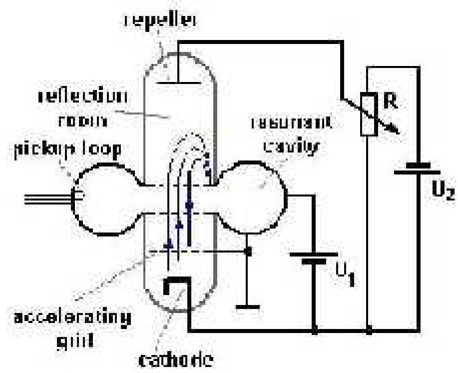
Floating drift tube klystron: The floating drift tube klystron has a single cylindrical chamber containing an electrically isolated central tube. Electrically, this is similar to the two cavity oscillator klystron with a lot of feedback between the two cavities. Electrons exiting the source cavity are velocity modulated by the electric field as they travel through the drift tube and emerge at the destination chamber in bunches, delivering power to the oscillation in the cavity. This type of oscillator klystron has an advantage over the two-cavity klystron on which it is based. It only needs one tuning element to effect changes in frequency. The drift tube is electrically insulated from the cavity walls, and DC bias is applied separately. The DC bias on the drift tube may be adjusted to alter the transit time through it, thus allowing some electronic tuning of the oscillating frequency. The amount of tuning in this manner is not large and is normally used for frequency modulation when transmitting.



Collector: After the RF energy has been extracted from the electron beam, the beam is destroyed in a collector. Some klystrons include depressed collectors, which recover energy from the beam before collecting the electrons, increasing efficiency. Multistage depressed collectors enhance the energy recovery by "sorting" the electrons in energy bins.

3.3 Reflex klystron:

In the reflex klystron (also known as a 'Sutton' klystron after its inventor), the electron beam passes through a single resonant cavity. The electrons are fired into one end of the tube by an electron gun. After passing through the resonant cavity they are reflected by a negatively charged reflector electrode for another pass through the cavity, where they are then collected. The electron beam is velocity modulated when it first passes through the cavity. The formation of electron bunches takes place in the drift space between the reflector and the cavity. The voltage on the reflector must be adjusted so that the bunching is at a maximum as the electron beam re-enters the resonant cavity, thus ensuring a maximum of energy is transferred from the electron beam to the RF oscillations in the cavity. The voltage should always be switched on before providing the input to the reflex klystron as the whole function of the reflex klystron would be destroyed if the supply is provided after the input. The reflector voltage may be varied slightly from the optimum value, which results in some loss of output power, but also in a variation in frequency.



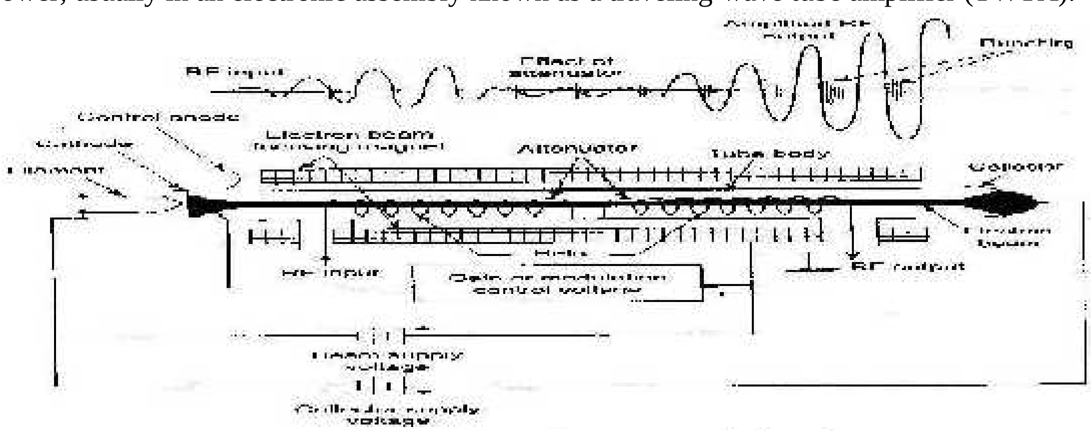
Reflex klystron

This effect is used to good advantage for automatic frequency control in receivers, and in frequency modulation for transmitters. The level of modulation applied for transmission is small enough that the power output essentially remains constant. At regions far from the optimum voltage, no oscillations are obtained at all. This tube is called a reflex klystron because it repels the input supply or performs the opposite function of a Klystron.

There are often several regions of reflector voltage where the reflex klystron will oscillate; these are referred to as modes. The electronic tuning range of the reflex klystron is usually referred to as the variation in frequency between half power points—the points in the oscillating mode where the power output is half the maximum output in the mode. It should be noted that the frequency of oscillation is dependent on the reflector voltage, and varying this provides a crude method of frequency modulating the oscillation frequency, albeit with accompanying amplitude modulation as well. Modern semiconductor technology has effectively replaced the reflex klystron in most applications.

3.4 Helix Traveling-Wave Tubes (TWTs)

A traveling-wave tube (TWT) is an electronic device used to amplify radio frequency signals to high power, usually in an electronic assembly known as a traveling-wave tube amplifier (TWTA).



TWT amplifier tube and circuit

The TWT was invented by Rudolf Kompfner in a British radar lab during World War II, and refined by Kompfner and John Pierce at Bell Labs. Both of them have written books on the device. In 1994, A.S. Gilmour wrote a modern TWT which is widely used.

Cutaway view of a TWT. 1) Electron gun 2) RF input 3) Magnets 4) Attenuator 5) Helix coil 6) RF output 7) Vacuum tube 8) Collector.

The device is an elongated vacuum tube with an electron gun (a heated cathode that emits electrons) at one end. A magnetic containment field around the tube focuses the electrons into a beam, which then passes down the middle of a wire helix that stretches from the RF input to the RF output, the electron beam finally striking a collector at the other end. A directional coupler, which can be either a waveguide or an electromagnetic coil, fed with the low-powered radio signal that is to be amplified, is positioned near the emitter, and induces a current into the helix. The helix acts as a delay line, in which the RF signal travels at near the same speed along the tube as the electron beam. The electromagnetic field due to the current in the helix interacts with the electron beam, causing bunching of the electrons (an effect called velocity modulation), and the electromagnetic field due to the beam current then induces more current back into the helix (i.e. the current builds up and thus is amplified as it passes down).A second directional coupler, positioned near the collector, receives an amplified version of the input signal from the far end of the helix. An attenuator placed on the helix, usually between the input and output helicies, prevents reflected wave from travelling back to the cathode. The bandwidth of a broadband TWT can be as high as three octaves, although tuned (narrowband) versions exist, and operating frequencies range from 300 MHz to 50 GHz. The voltage gain of the tube can be of the order of 70 decibels. A TWT has sometimes been referred to as a traveling-wave amplifier tube (TWAT), although this term was never really adopted.

Coupled-cavity TWT:

Helix TWTs are limited in peak RF power by the current handling (and therefore thickness) of the helix wire. As power level increases, the wire can overheat and cause the helix geometry to warp. Wire thickness can be increased to improve matters, but if the wire is too thick it becomes impossible to obtain the required helix pitch for proper operation. Typically helix TWTs achieve less than 2.5 kW output power.

The coupled-cavity TWT overcomes this limit by replacing the helix with a series of coupled cavities arranged axially along the beam. Conceptually, this structure provides a helical waveguide and hence amplification can occur via velocity modulation. Helical waveguides have very nonlinear dispersion and thus are only narrowband (but wider than klystron). A coupled-cavity TWT can achieve 15 kW output power.

Operation is similar to that of a klystron, except that coupled-cavity TWTs are designed with attenuation between the slow-wave structure instead of a drift tube. The slow-wave structure gives the TWT its wide bandwidth. A free electron laser allows higher frequencies.

Traveling-wave tube amplifier:

A TWT integrated with a regulated power supply and protection circuits is referred to as a traveling wave tube amplifier. It is used to produce high-power radio frequency signals. The bandwidth of a broadband TWTA can be as high as one octave, although tuned (narrowband) versions exist; operating frequencies range from 300 MHz to 50 GHz.

A TWTA consists of a traveling-wave tube coupled with its protection circuits (as in klystron) and regulated power supply (EPC, electronic power conditioner), which may be supplied and integrated by a different manufacturer. The main difference between most power supplies and those for vacuum tubes is that efficient vacuum tubes have depressed collectors to recycle kinetic energy of the electrons and therefore the secondary winding of the power supply needs up to 6 taps of which the helix voltage needs precise regulation. The subsequent addition of a linearizer (as for inductive output tube) can, by complementary compensation, improve the gain compression and other characteristics of the TWTA; this combination is called a linearized TWTA.

Broadband TWTAs generally use a helix TWT, and achieve less than 2.5 kW output power. TWTAs using a coupled cavity TWT can achieve 15 kW output power, but at the expense of bandwidth.

Uses

TWTAs are commonly used as amplifiers in satellite transponders, where the input signal is very weak and the output needs to be high power.

A TWTA whose output drives an antenna is a type of transmitter. TWTA transmitters are used extensively in radar, particularly in airborne fire-control radar systems, and in electronic warfare and self-protection systems. In these types of applications, a control grid is typically introduced between the TWT's electron gun and slow-wave structure to allow pulsed operation. The circuit that drives the control grid is usually referred to as a grid modulator.

Another major use of TWTAs is for the electromagnetic compatibility (EMC) testing industry for immunity testing of electronic devices.

3.4.1 Slow-wave structures:
Slow-wave structures are special circuits that are used in microwave tubes to reduce the wave velocity in a certain direction so that the electron beam and the signal wave can interact. The phase velocity of a wave in ordinary waveguides is greater than the velocity of light in a vacuum. In the operation of traveling-wave and magnetron-type devices, the electron beam must keep in step with the microwave signal. Since the electron beam can be accelerated only to velocities that are about a fraction of the velocity of light, a slow-wave structure must be incorporated in the microwave devices so that the phase velocity of the microwave signal can keep pace with that of the electron beam for effective interactions.

3.4.2 Amplification Process: The magnitude of the velocity fluctuation of the electron beam is directly proportional to the magnitude of the axial electric field.

3.4.3 Conventional current:
The conventional current induced in the electron beam by the axial electric field.
Space charge effect: Periodic fluctuation in beam velocity take place when the beam is under the influence of a longitudinal RF electric field. Also coupled to these velocity fluctuation are charge density fluctuation and current density fluctuation. These are known as Space charge effect.

3.4.4 Axial Electric Field: The convection current in the electron beam induces an electric field in the slow wave circuit. This induced field adds to the field already present in the circuit and causes the circuit power to increase with distance.
The axial electric field is given by

$$E_1 = -\frac{\gamma^2 \gamma_0 Z_0}{\gamma^2 - \gamma_0^2} i$$

This equation is called the circuit equation because it determines how the axial electric field of the slow-wave helix is affected by the spatial ac electron beam current.

3.4.5 Wave Modes: The wave modes of a helix-type traveling-wave tube can be determined by solving the electronic and circuit equations simultaneously for the propagation constants. Each solution for the propagation constants represents a mode of traveling wave in the tube.

3.4.6 Gain Consideration: For simplicity, it is assumed that the structure is perfectly matched so that there is no backward traveling wave. Such is usually the case. Even though there is a reflected wave from the output end of the tube traveling backward toward the input end, the attenuator placed around the center of the tube subdues the reflected wave to a minimum or zero level. Thus the total circuit voltage is the sum of three forward voltages corresponding to the three forward traveling waves.

Microwave Crossed-Field Tubes
Crossed-field tubes derive their name from the fact that the dc electric field and the dc magnetic field are perpendicular to each other. They are also called M –type tubes. In a crossed-field tube, the electrons emitted by the cathode are accelerated by the electric field and gain velocity, but the greater their velocity, the more their path is bent by the magnetic field. If an RF field is applied to the anode circuit, those electrons entering the circuit during the retarding field are decelerated and give up some of their energy to the RF field.
Consequently, their velocity is decreased, and these slower electrons will then travel the dc electric field far enough to regain essentially the same velocity as before. Because of the crossed-field interactions, only those electrons that have given up sufficient energy to the RF field can travel all the way to the anode. This phenomenon would make the M-type devices relatively efficient. Those electrons entering the circuit during the accelerating field are accelerated by means of receiving enough energy from the RF

field and are returned back toward the cathode. This back-bombardment of the cathode produces heat in the cathode and decreases the operational efficiency.

3.5 Magnetron Oscillators:

All magnetrons consist of some form of anode and cathode operated in a demagnetic field normal to a de electric field between the cathode and anode. Because of the crossed field between the cathode and anode, the electrons emitted from the cathode are influenced by the crossed field to move in curved paths. If the de magnetic field is strong enough, the electrons will not arrive in the anode but return in• stead to the cathode. Consequently, the anode current is cut off. Magnetrons can be

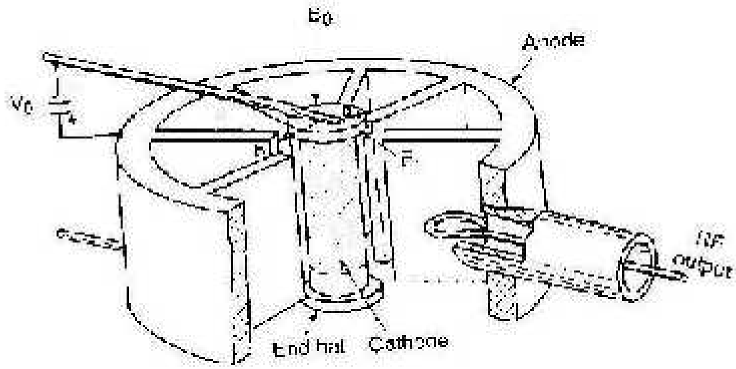
Classified into three types:

1. Split-anode magnetron:This type of magnetron uses a static negative resistance between two anode segments.
2. Cyclotron-frequency magnetrons: This type operates under the influence of synchronism between an alternating component of electric field and a periodic oscillation of electrons in a direction parallel to the field.
3. Traveling-wave magnetrons: This type depends on the interaction of electrons with a traveling electromagnetic field of linear velocity. They are customarily referred to simply as magnetrons.

Negative-resistance magnetrons ordinarily operate at frequencies below the microwave region. Although cyclotron-frequency magnetrons operate at frequencies in microwave range, their power output is very small (about 1 W at 3 GHz), and their efficiency is very low (about 10% in the split-anode type and 1 % in the single-anode type).

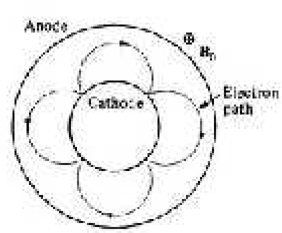
3.6 Cylindrical Magnetron:

A schematic diagram of a cylindrical magnetron oscillator is shown in below Figure.



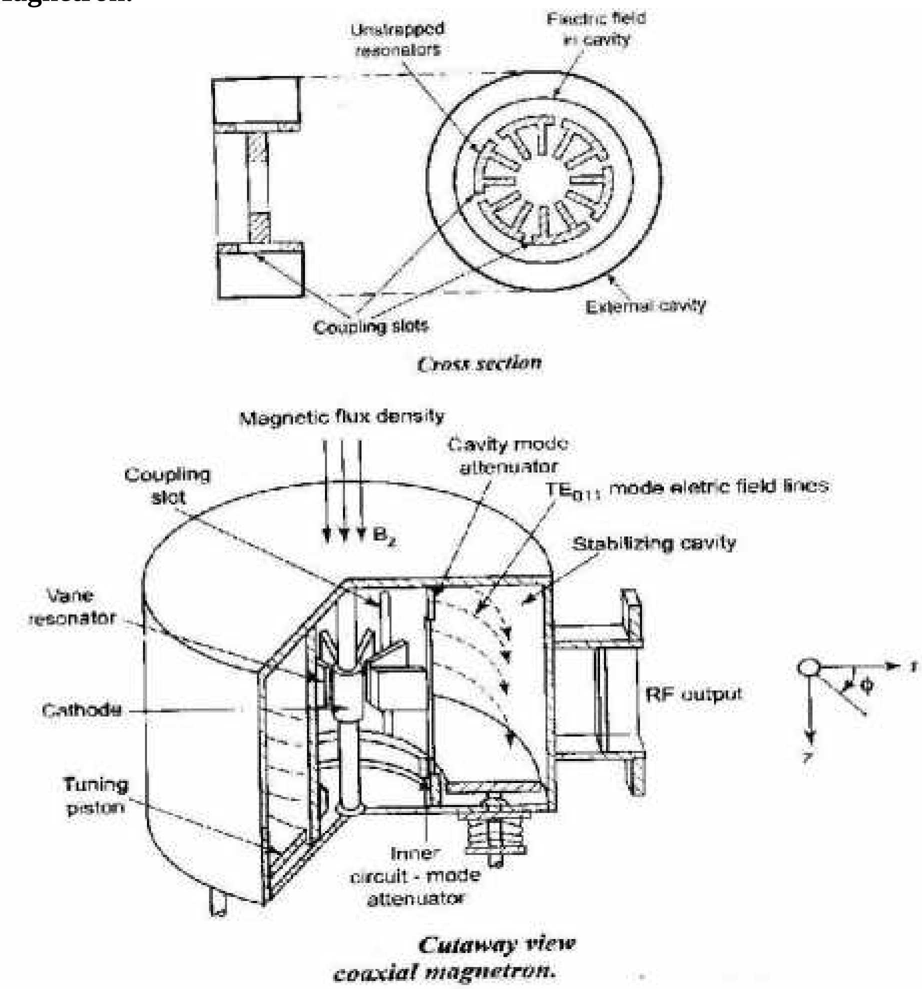
Schematic diagram of a cylindrical magnetron

This type of magnetron is also called a conventional magnetron. In a cylindrical magnetron, several reentrant cavities are connected to the gaps. The dc voltage V_0 is applied between the cathode and the anode. The magnetic flux density Bo is in the positive z direction. When the de voltage and the magnetic flux are adjusted properly, the electrons will follow cycloidal paths in the cathode• anode space under the combined force of both electric and magnetic fields as shown in Figure.



Electron path in a cylindrical magnetron

3.7 Coaxial Magnetron:

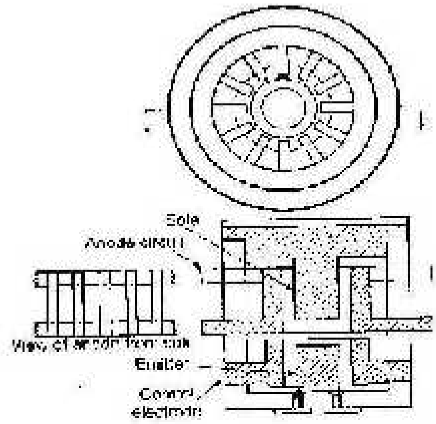


Cross section

Cutaway view coaxial magnetron.

The coaxial magnetron is composed of an anode resonator structure surrounded by an inner-single, high-Q cavity operating in the TEo11 mode as shown in above Figure. The slots in the back walls of alternate cavities of the anode resonator structure tightly couple the electric fields in these resonators to the surrounding cavity. In the Pi-mode operation, the electric fields in every other cavity are in phase, and so they couple in the same direction into the surrounding cavity. As a result, the surrounding coaxial cavity stabilizes the magnetron in the desired 1T-mode operation. In the desired TEo11 mode, the electric fields follow a circular path within the cavity and reduce to zero at the walls of the cavity. Current flow in the TE_o mode is in the walls of the cavity in circular paths about the axis of the tube. The undesired modes are damped out by the attenuator within the inner slotted cylinder near the ends of the coupling slots. The tuning mechanism is simple and reliable. As the straps are not required, the anode resonator for the coaxial magnetron can be larger and less complex than for the conventional strapped magnetron. Thus cathode loading is lower, and voltage gradients are reduced. The Varian SFD-333TM magnetron, as shown in above Figure is a typical X• band coaxial magnetron. It has a minimum peak power of 400 kW at a frequency range from 8.9 to 9.6 GHz. Its duty cycle is 0.0013. The nominal anode voltage is 32 kV, and the peak anode current is 32 A.

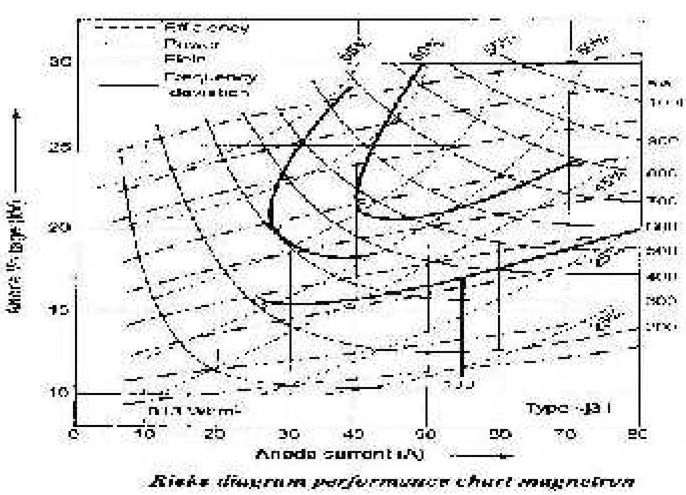
3.8 Voltage Tunable Magnetron



Cross section view of a voltage tunable magnetron.

The voltage-tunable magnetron is a broadband oscillator with frequency changed by varying the applied voltage between the anode and sole. As shown in above Figure the electric beam is emitted from a short cylindrical cathode at one end of the device. Electrons are formed into a hollow beam by the electric and magnetic forces near the cathode and then are accelerated radically outward from the cathode. The electron beam is then injected into the region between the sole and the anode. The beam rotates about the sole at the rate controlled by the axial magnetic field and the dc voltage applied between the anode and the sole. The voltage-tunable magnetron uses a low-Q resonator, and its bandwidth may exceed 50% at low-power levels. In the 1T-mode operation, the bunch process of the hollow beam occurs in the resonator, and the frequency of oscillation is determined by the rotational velocity of the electron beam. In other words, the oscillation frequency can be controlled by varying the applied dc voltage between the anode and sole. Power output can be adjusted to some extent through the use of the control electrode in the electron gun. At high-power levels and high frequencies, the band width percentage is limited. However, at low-power levels and low frequencies, the bandwidth may approach 70%.

3.9Ricke diagram



Rieke diagram performance chart magnetron

Rieke diagram is a graphical representation which is a method of representing the performance characteristics of magnetron. The operation condition of magnetron for a given load can be obtained from these diagrams which is basically a plot of anode voltage Vs current with power output, efficiency, flux density, frequency deviation as parameters. From these the best operating condition are selected. The frequency pushing and pulling effects can be easily determined from this diagram.

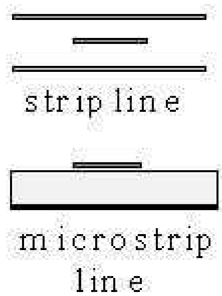
UNIT-IV

Strip Lines and Monolithic Microwave Integrated Circuit

4.1 Microstrip (Asymmetric Strip Transmission) Lines:

Strip Line:
Strip line is a three - conductor TEM mode transmission line.
It consists of a central conductor called strip and two ground plates.

Microstrip line is an unsymmetrical strip line.
This line consists of a single dielectric substrate with ground plane on one side and a strip on the other face. Modes on microstrip line are only quasi - transverse electric and magnetic (TEM). The microstrip line is also called an open - strip line. Microstrip circuits and components are fabricated using printed circuit techniques.



4.1.1 Characteristic Impedance of Microstrip Lines:

Characteristic Impedance

A closed-form approximate expression for the quasi-static characteristic impedance of a microstrip line was developed by Wheeler:

$$Z_{\text{microstrip}} = \frac{Z_0}{2\pi\sqrt{2(1+\varepsilon_r)}} \ln\left(1 + \frac{4h}{w_{\text{eff}}}\left(\frac{14+\frac{8}{\varepsilon_r}}{11}\frac{4h}{w_{\text{eff}}} + \sqrt{\left(\frac{14+\frac{8}{\varepsilon_r}}{11}\frac{4h}{w_{\text{eff}}}\right)^2 + \pi^2\frac{1+\frac{1}{\varepsilon_r}}{2}}\right)\right)$$

where w_{eff} is the *effective width*, which is the actual width of the strip, plus a correction to account for the non-zero thickness of the metallization. The effective width is given by

$$w_{\text{eff}} = w + t\frac{1+\frac{1}{\varepsilon_r}}{2\pi}\ln\left(\frac{4e}{\sqrt{\left(\frac{t}{h}\right)^2 + \left(\frac{1}{\pi}\frac{1}{\frac{w}{t}+\frac{11}{10}}\right)^2}}\right)$$

with

Z_0 = impedance of free space,

ε_r = dielectric constant of substrate,

w = width of strip,

h = thickness ("height") of substrate and

t = thickness of strip metallization.

This formula is asymptotic to an exact solution in three different cases

1. $w \gg h$, any ε_r (parallel plate transmission line),
2. $w \ll h$, $\varepsilon_r = 1$ (wire above a ground-plane) and
3. $w \ll h$, $\varepsilon_r \gg 1$.

4.1.2 Losses in Microstrip Lines

The attenuation of a microstrip depends upon the electrical properties of the substrate and conductors and also on the frequency.

Types of loses:

a) Dielectric loss in the substrate

b) Ohmic skin loss in the strip conductor and the ground plane

c) Radiation losses.

4.1.3 Quality Factor Q of Microstrip Lines:

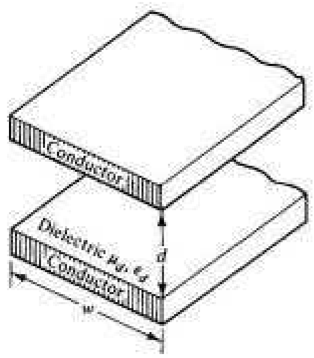
Many microwave integrated circuits require very high quality resonan circuits.

The quality factor Q of a microstrip line is very high, but it is limited the radiation losses of the substrates and with low dielectric constant.

The Q_d for the dielectric attenuation constant of a microstrip line is approximately the reciprocal of the dielectric loss tangent theta and is relatively constant with frequency.

4.2 Parallel Strip Lines:

A parallel strip line consists of two perfectly parallel strips separated by a perfect dielectric slab of uniform thickness. The plate width' is w, the separation distance is d, and the relative dielectric constant of the slab is E_{rd}. A parallel strip line is similar to a two - conductor transmission line, so it can support a quasi - TEM mode.



Parallel Strip lines

4.2.1 Distributed Lines:

Consider a TEM mode wave propagating in the positive z direction in a lossless strip line (R = G = 0).

The electric field is in the y direction, and the magnetic field is in the x direction.

If the width w is much larger than the separation distance d, the fringing, capacitance is negligible.

some parameters are

$$L = \frac{\mu_c d}{w} \qquad \text{H/m}$$

$$C = \frac{\epsilon_d w}{d} \qquad \text{F/m}$$

$$R = \frac{2R_s}{w} = \frac{2}{w}\sqrt{\frac{\pi f \mu_c}{\sigma_c}} \qquad \Omega/\text{m} \qquad G = \frac{\sigma_d w}{d} \qquad \mho/\text{m}$$

4.2.2 Characteristic impedances:

The characteristic impedance of a lossless parallel strip line is

$$Z_0 = \sqrt{\frac{L}{C}} = \frac{377}{\sqrt{\epsilon_{rd}}}\frac{d}{w} \qquad \text{for } w \gg d$$

4.2.3 Attenuation losses:

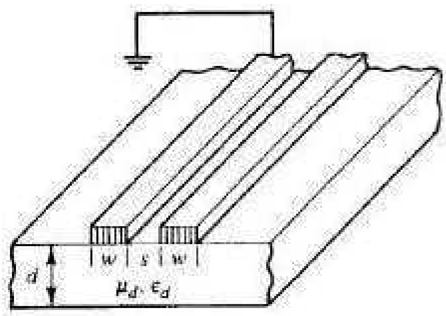
The propagation constant of a parallel strip line at microwave frequencies can be expressed by

$$v_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{LC}} = \frac{c}{\sqrt{\epsilon_{rd}}} \quad \text{m/s} \quad \text{for } \mu_c = \mu_0$$

4.3 Coplanar Strip Lines:

A coplanar strip line consists of two conducting strips on one substrate surface with one strip grounded . The coplanar line is often called a coplanar waveguide (CPW).
The propagating modes in coplanar lines are TE modes.

Coplanar striplines



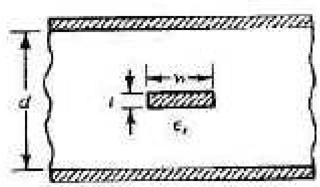
The characteristic impedance of a coplanar strip line is

$$Z_0 = \frac{2\, P_{avg}}{I_0^2}$$

4.4 Shielded Strip Lines

A partially shielded strip line has its strip conductor embedded in a dielectric medium, and its top and bottom ground planes have no connection.

Shielded striplines



The characteristic impedance is

$$Z_0 = \frac{94.15}{\sqrt{\epsilon_r}} \left(\frac{w}{d} K + \frac{C_f}{8.854\epsilon_r} \right)^{-1}$$

where $K = \frac{1}{1 - t/d}$

t = the strip thickness

d = the distance between the two ground planes

$C_f = \frac{8.854\epsilon_r}{\pi}[2K \ln (K + 1) - (K - 1) \ln (K^2 - 1)]$ and is the fringe capacitance in pF/m

4.5 Substrate Materials

A substrate of MMIC is a piece of substance on which an electronic devices are built.
The ideal characteristics of substrate material are
a) High dielectric constant,
b) Low dissipation factor or loss tangent.
c) Dielectric constant should remain constant over the frequency range and the temperature range.
d) High purity and constant thickness.
e) High surface smoothness
f) High resistivity
g) Dielectric strength and
h) High thermal conductivity.
The selection of a substrate material depends on the required circuit dissipation, it circuit function and the type of circuit to be used .
Alumina, beryllia, ferrite, GaAs, glass are used as substrate materials.

4.6 Conductor Materials

The ideal **characteristic** of a conductor material are
a) High conductivity.
b) Low temperature coefficient of resistance
c) Good etch ability and solderability and
d) Easily deposited or electroplated .
Alumina, copper, gold and silver are mainly used as conductor materials .
They are used to form both the conductor pattern and the bottom ground plane .

4.7 Dielectric Materials

To realize blockers, capacitors and couple - line structures, dielectric materials are used . The typical dielectric materials used in microcircuits are: SiO_2, SiO and Ta_2O_5 .
Thin film SiO is not very stable and can be used only in non critical applications, such bypass capacitors .
The desirable properties of dielectric materials are:
a) Good reproductivity
b) Capability of handling high voltages
c) Ability to undergo processes without developing pin holes and
d) Low RF dielectric loss .

4.8 Resistive Materials

For realizing bias network, terminations, and attenuators, resistive materials are employed.
The desirable properties of resistive materials are
a) Good stability.
b) Low temperature coefficient of resistance.
c) Adequate dissipation capability and
d) Sheet resistivities in the range of 10 to 1000 ohm per square.
The typical resistive materials are: Cr, Cr - SiO, NiCr, Ta and Ti.

4.9 MMIC Growth:

Monolithic microwave integrated circuits (MMICs) can be made in monolithic or hybrid form.
In a monolithic circuit, active devices are grown on or in a semi conducting substrate, and passive elements are either deposited on the substrate or grown in it. Monolithic integrated circuits have been successful in digital and linear applications in which all required circuit components can be simultaneously fabricated . Monolithic technology is not well suited to microwave integrated circuits because the processing difficulties, low yields and poor performance have seriously limited

their applications. The hybrid form of technology is used almost exclusively for integrated circuits in the frequency range of 1 to 15GHz. Hybrid MMICs are fabricated on a high quality ceramic, glass or substrate. The passive circuit elements are deposited on the substrate, active devices are mounted on the substrate and connected to the circuit. The resistivity of microwave integrated circuits should be much greater 1000 ohm - cm for good circuit performance.

4.10 MMIC Fabrication Techniques and its example.

MMICs can be fabricated by using different techniques such as
a) diffusion and ion implantation,
b) oxidation and film deposition,
c) epitaxial growth,
d) lithography,
e) etching and photoresist, and
f) deposition

a) Diffusion and ion implantation:
Diffusion and ion implantation are the two processes used in controlling amount of dopants in semiconductor device fabrications .The process of diffusion consists of diffusing impurities into a pure material in order to alter the basic electronic characteristics of the pure material.

Ion implantation is used to dope the substrate crystal with high energy ion impurities.
Both processes are used to dope selectively the semiconductor substrate to produce either an n or p type layer.
The advantages of the ion implantation method are:
i) Precise control of the total amount of dopants.
ii) The improvement of reproducibility and
iii) Reduced processing temperature .
Both diffusion and ion implantation can be used for fabricating discrete and integrated devices because these processes are generally complementary to one another.

b) Oxidation and film deposition:
To fabricate discrete and integrated devices or circuits many different types of thin films are used.
There are four groups of thin film
i) Thermal oxides
ii) Dielectric layers
iii) Polycrystalline silicon.
iv) Metal films.

c) Epitaxial growth:
In epitaxial technology, single crystal semiconductor layers grow on a single crystal semiconductor substrate .
The word epitaxy comes from the Greek epi (on) and taxis (arrangement).
The epitaxial process is controlling the doping profiles so device and circuit performances can be optimized .
There are three types of epitaxy
i) Vapor - Phase Epitaxy (VPE)
ii) Molecular - Beam Epitaxy (MBE)
iii) Liquid - Phase Epitaxy (LPE)

d) Lithography:

Lithography is the process of transferring patterns of geometric shapes on a mask to a thin layer of radiation sensitive material, which is known as resist, for covering the surface of a semiconductor wafer.

The resist patterns defined by the lithographic process are not permanent elements of the final device but only replicas of circuit features .

There are four types of lithography technology.

i) Electron-beam lithography

ii) Ion-beam lithography

iii) Optical lithography and

iv) X-ray lithography

e) Etching and photoresist:

In the processes of making MICs, a selective removal of SiO_2 is required in order to form openings through which impurities can be diffused. During the photolithographic process the substrate is coated with a uniform, film of Kodak Photo resist (KPR), which is a photo sensitive emulation. A mask for the desired openings is placed over the photo resist, and ultraviolet light exposes the photo resist through the mask. A polymerized photo resist is developed, and the unpolymerized portions are dissolved by using trichloro-ethylene after the mask is removed. The SiO_2, which is not covered by the photo resist, can be removed by hydrofluoric acid. The thick - film process usually involves the printing and silk screening of silver or gold through a metal mask in a glass which is applied on the ceramic and fired at 850°C. After firing, the initial layer may be covered with gold.

f) Deposition:

Three methods are commonly used for making MMICs.

i) Vacuum evaporation,

ii) Electron - beam evaporation, and

iii) DC sputtering

i) 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 a mask on it 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 while the heat is evaporating the impurities, and the impurity vapor deposits itself on the substrate, forming a polyerstalline layer on it.

ii) Electron - beam evaporation:

In another method of evaporating the impurity a narrow beam of electrons is generated to seen the substrate in the boat in order to vaporize the impurity.

iii) DC sputtering:

The third method of vacuum deposition is known as desputtering or cathod sputtering. In a vacuum, the crucible containing the impurity is used as the cathod and the substrate as the anode of a diode . A slight trace of argon gas IS introduced into the vacuum. When the applied voltage between cathod and anode is high enough, a glow discharge of argon gas is formed. The positive argon ions are accelerated toward the cathode, where they dislodge atoms of the impurity. The impurity atoms have enough energy to reach the substrate and adhere to it.

4.11 Fabrication Example:

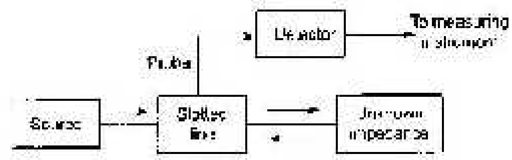
For example, the photoresist technique can be used to remove the oxide layer in related areas. The fabrication procedures include the following

i) Deposition: An oxide layer is deposited on the semiconductor material and then a photo resist layer is deposited to cover the oxide on top of the semiconductor chip.
ii) Mask: Ultraviolet light is used to shine through a precision photographic mask to the photoresist.
iii) Chemical etching: Chemical etching with hydrofluoric acid is used to remove the selected oxide region.
iv) Etching: The photo resist is finally dissolved with an organic solvent in the oxide leaving the desired opening.

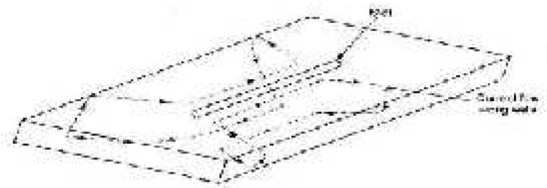
UNIT-V Microwave Measurements

5.1 Slotted line VSWR measurement:

Slotted line is a fundamental tool for microwave measurements. Slotted line consists of longitudinal slot. This slot is roughly 1mm wide allows an electric field probe to enter the waveguide for measurement of relative magnitude of filed at the location of the probe.

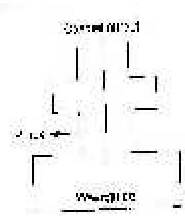


Connection of slotted line in microwave



Current flow in slotted line

The slot is located suitable in the wall of the waveguide such that the disturbance to the wall currents is minimum. For a rectangular waveguide operated in the dominant mode this location is in the middle of the broad wall.



Cross section of rectangular waveguide slotted line

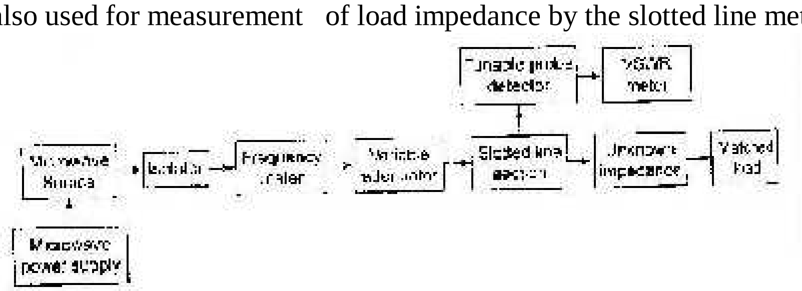
Slotted section is normally mounted in a 'carriage' which also supports the probe moving inside the slot. Probe is a thin conducting wire which passes through the slot in the slotted line and couples to the fields in the waveguide. Microwave signal is then applied to a detector. The slotted line actually measures standing wave. The slotted line section with tunable detectors is used to measure following parameters.

VSWR, Standing wave pattern, Wave length, Impedance, Reflection coefficient and Return loss measurements by the minima shift method.

VSWR Measurement:

VSWR and the magnitude of voltage reflection coefficient are very important parameters which determine the degree of impedance matching .

VSWR and I' are also used for measurement of load impedance by the slotted line method.



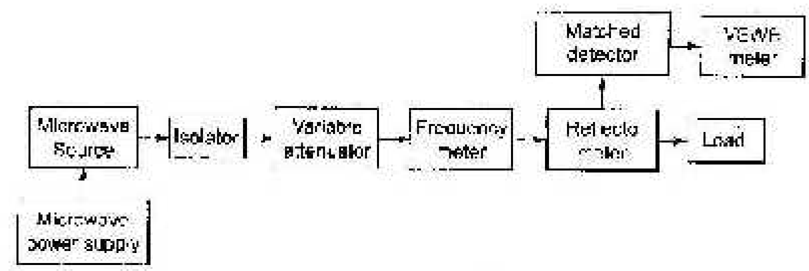
Slotted line method of VSWR measurement

Standing wave ratio (S) = V_{max} / V_{min}

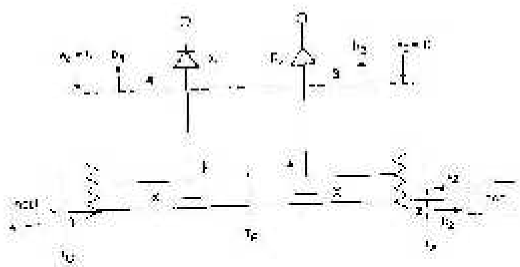
5.2 VSWR through return loss measurement

Return loss: The return loss is measure of the power reflected by a line or network or device.

Return loss (dB) = 10 log (Input energy to the device/ Re fleeted energy at the input of the device)



Experimental set up for a reflectometer



Reflectometer

The return loss and VSWR of a load can be determined by measuring the magnitude of the reflection coefficient with a reflectometer. In the internal block diagram of reflectometer, two identical directional couplers are connected opposite to each other. One coupler couples to the forward wave and the other to the reverse wave. Let us assume that the directional couplers have infinite directivity, a voltage coupling coefficient C. The main line VSWR1 and the detectors have constant impedance and perfect matching to the line.

5.3 Power measurement:

Power: Power is defined as the quantity of energy dissipated or stored per unit time. The microwave power inside a waveguide is invariant with position of measurement and the power measured is the average power.

Categories of power measurement:

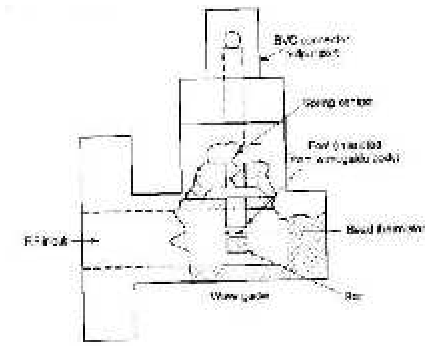
i) Measurement of low power (less than 10 mW)

ii) Measurement of medium power (from l0 mW to 10W) and

iii) Measurement of high power (> l0W)

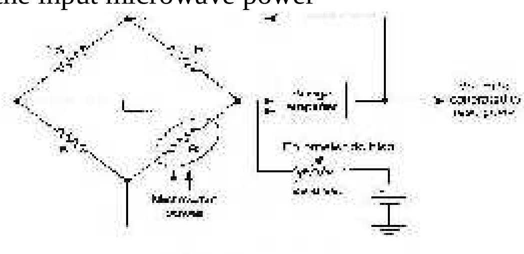
Average power: The average power is measured while propagation in a transmission medium.

Thermistor: The thermistor is a semiconductor sensor which has a negative temperature coefficient of resistance and can be easily mounted in microwave lines due to' its smaller and more compact size.



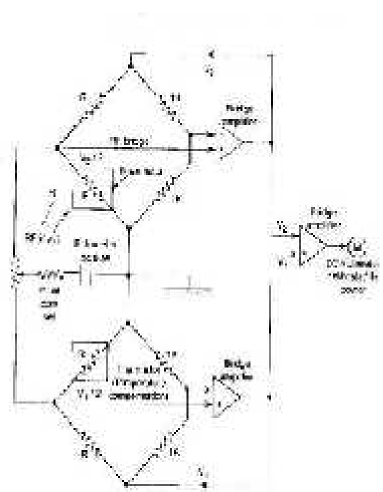
Power Measurement - Thermistor mount

Single bridge power meter: The microwave power applied to the arm will change the bolometer's resistance causing an unbalance in the bridge from its initial balance condition under zero incident power . Heating effect causes the bolometer's (thermistor) resistance to decrease and unbalances the bridge in proportion to the power applied. The non -zero output is recorded on a voltmeter which is calibrated to read the level of the input microwave power



Power meter using single bridge

Double bridge power meter: The upper bridge circuit measures the microwave and the lower bridge circuit compensates ambient temperature variation (V1 = V2). The added microwave power due to compensated automatically through a self -circuit by decreasing the de power V2 carried by the sensing thermistor until bridge balance is restored or net change in the thermistor resistance is zero due to negative dc feedback.



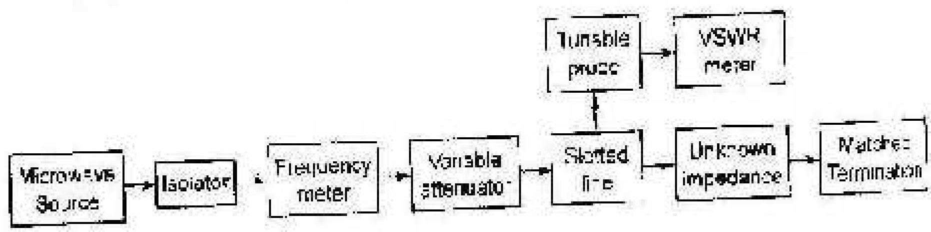
Power meter using double bridge for compensation

5.4 Impedance measurement:

Impedance at microwave frequencies can be measured using any of the following two methods.

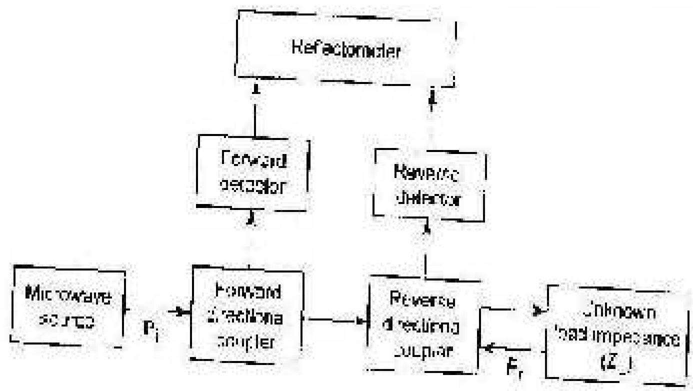
1) Using slotted line method and
2) Using reflectometer

Measurement of impedance using slotted line: This method is simplest for the measurement of impedance at microwave frequencies. The unknown impedance is connected at the end of a slotted line (or a slotted wave guide). Microwave power is fed from the other end of the coaxial line (waveguide). Unknown impedance reflects a part of this power. This reflection coefficient is measured by probing the standing fields in the slotted line.



Impedance measurement using reflectometer

Measurement of impedance using reflectometer: Two directional couplers are used to sample the incident power P_i the reflected power P_r from load. Both the directional couplers, identical (except their direction) .The magnitude of the reflection coefficient p, can be directly on the reflectometer from which impedance can be calculated.



Impedance measurement using reflectometer

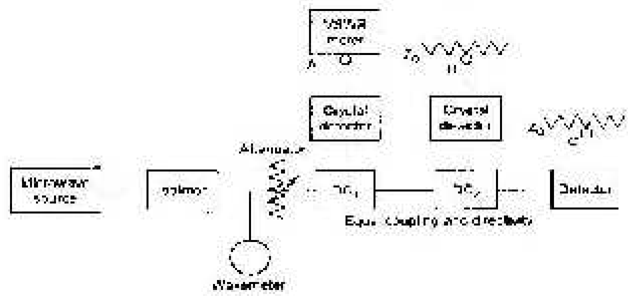
5.5 Insertion loss and attenuation measurements:

Insertion loss: The insertion loss is measure the loss of energy in transmission through a line or device compared to direct delivery of energy without the line or device.

Insertion loss (dB) = 10 log (Power received by load without line or device/ Power received by load with line or device)

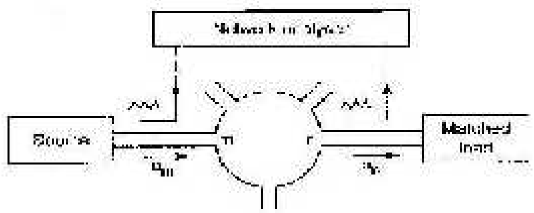
Attenuation loss: The attenuation loss is a measure of the power loss due to signal absorption in the device.

Attenuation loss (dB) = 10 log ((Input energy – Reflected energy at the Input) / Transmitted energy to the load)



Insertion loss and attenuation measurements

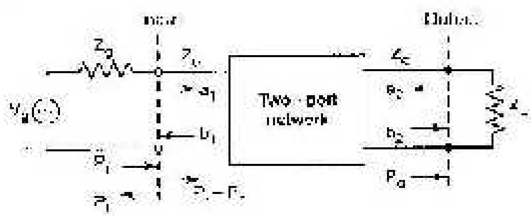
5.6 Measurement of scattering parameters – Measurement of 1 dB:
Scattering parameters are defined as the rations of the outgoing waves to the incident waves. The incident and reflected amplitudes of microwaves at any port are used to characterize a microwave circuit.



Two port network connected with network analyzer

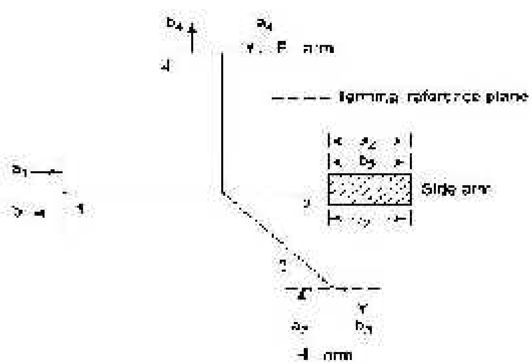
Now, we known the reflection and insertion loss, the attenuation loss ca be calculated using following relation.

Attenuation loss (dB) = Insertion loss (dB) - Reflection loss (dB)

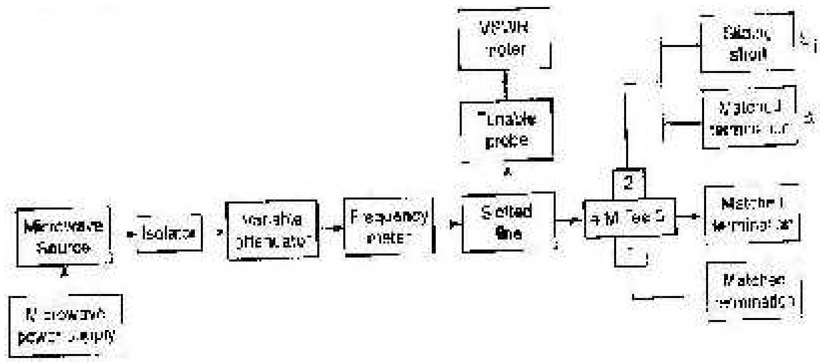


Two port network

S- Parameters of a magic T:
Magic Tee: The device magic Tee is a combination of the E and H plane. Arm the H - arm forms an H plane Tee and arm 4, the E - arm forms, E plane Tee in combination with arm 1 and 2 a side or collinear arms.



Magic Tee

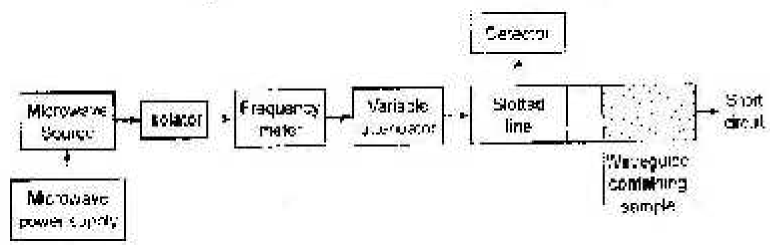


Experimental set up for S parameters measurement of magic T

Measurement of Sij:

The diagonal elements are determined from the slotted line measurement of the VSWR S, at the corresponding port with all other ports matched termination.

5.7 Dielectric constant measurement of a solid using waveguide:



Measurement of Dielectric constant

There are two methods are commonly used for dielectric constant measurement. They are waveguide method and Cavity perturbation method.

In electromagnetics and communications engineering, the term waveguide may refer to any linear structure that conveys electromagnetic waves between its endpoints. However, the meaning is a hollow metal pipe used to carry radio waves. This type of waveguide is used as a transmission line mostly at microwave frequencies, for such purposes as connecting microwave transmitters and receivers to their antennas in equipment such as microwave ovens, radar sets, satellite communications, and microwave radio links.

A dielectric waveguide employs a solid dielectric rod rather than a hollow pipe. An optical fiber is a dielectric guide designed to work at optical frequencies. Transmission lines such as microstrip, coplanar waveguide, strip line or coaxial cable may also be considered to be waveguides.

The electromagnetic waves in a (metal-pipe) waveguide may be imagined as travelling down the guide in a zigzag path, being repeatedly reflected between opposite walls of the guide. For the particular case of rectangular waveguide, it is possible to base an exact analysis on this view. Propagation in a dielectric waveguide may be viewed in the same way, with the waves confined to the dielectric by total internal reflection at its surface. Some structures, such as non radiative dielectric waveguides use both metal walls and dielectric surfaces to confine the wave.

Cavity perturbation theory describes methods for derivation of perturbation formulae for performance changes of a cavity resonator. These performance changes are assumed to be caused by either introduction of a small foreign object into the cavity or a small deformation of its boundary.

Reg. No…………………….
Subject Code: 09BEEC705

KARPAGAM UNIVERSITY

(Under section 3 of UGC Act 1956)

COIMBATORE - 641 021.

(For the candidate admitted from 2009 onwards) – FULL TIME

BE DEGREE EXAMINATIONS, NOV 2012

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

SEVENTH SEMESTER

MICROWAVE ENGINEERING

Time: 3 hours Maximum : 100 marks

PART - A (15 x 2 = 30 Marks)

Answer ALL the questions.

1) Define microwave.
2) Why is a magic tee referred to as E-H tee?
3) Define scattering matrix.
4) Compare voltage and current controlled modes.
5) What are the elements that exhibit Gunn effect?
6) Define LSA mode.
7) What is transit time?
8) Write the classification of microwave tubes.
9) What do you meant klystron?
10) What is strip line?
11) Define microstrip line.
12) What is parallel strip line?
13) What do you meant by slotted line?
14) What is voltage standing wave ratio?
15) Give a note on return loss.

PART - B (5 x 14 = 70 Marks)

Answer ALL the questions.

16) a) Explain the operation of H plane tee and derive the scattering matrix for it. (14)

(or)

b) Derive the expression for two port networks relating with H, Y, Z, ABCD parameter. Write the properties of S matrix. (14)

17) a) Explain briefly about limited space charge accumulation diode and indium phosphate diode. (14)

(or)

b) Explain and derive an expression for two valley model theory. (14)

18) a) Explain the principle of operation of multicavity klystron amplifier. (14)

(or)

b) Derive an expression for reflex klystron electron efficiency and draw it admittance spiral diagram.(14)

19) a) Explain briefly about strip lines and coplanar strip lines. (14)

(or)

b) Explain the basic materials for monolithic microwave integrated circuit. (14)

20) a) Explain the method of measuring impedance of a given load with suitable diagram. (14)

(or)

b) Explain VSWR through return loss measurement. (14)

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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

SEVENTH SEMESTER

MICROWAVE ENGINEERING

Time: 3 hours Maximum : 100 marks

PART - A (15 x 2 = 30 Marks)

Answer ALL the questions.

1) Why is a magic tee referred to as E-H tee?
2) What are the elements that exhibit Gunn effect?
3) Write the classification of microwave tubes.
4) Define microstrip line.
5) What is voltage standing wave ratio?
6) What is waveguide?
7) What are modes available in avalanche devices?
8) What is catcher cavity?
9) Define partially shielded strip line.
10) What are the methods to detect microwave power?
11) What is E-plane tee?
12) What is meant by capacitive.
13) What is travelling wave tube amplifier?
14) What is the need for dielectric materials?
15) What do you meant by reflection loss?

PART - B (5 x 14 = 70 Marks)

Answer ALL the questions.

16) a) Derive and describe briefly about Shunt tee with its scattering matrix. (14)

(or)

b) Explain the operation of magic tee and derive the scattering matrix for it. (14)

17) a) Explain briefly about impact ionization avalanche transit time device. (14)

(or)

b) Derive the Manley Rowe power relations. What are the condition for parametric up converter and down converter. (14)

18) a) Explain co-axail magnetron with suitable diagram. (14)

(or)

b) Describe briefly about four cavity klystron amplifier. (14)

19) a) Explain briefly about diffusion and ion implantation, oxidation and film deposition, epitaxial growth, lithography, etching and photo resist, deposition in monolithic microwave integrated circuit. (14)

(or)

b) List out the basic materials required for the manufactured of MMIC. (14)

20) a) Write short note on waveguide method and cavity perturbation method. (14)

(or)

b) Explain the measurements of scattering parameters of a network. (14)

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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

SEVENTH SEMESTER

MICROWAVE ENGINEERING

Time: 3 hours Maximum : 100 marks

PART - A (15 x 2 = 30 Marks)

Answer ALL the questions.

1) What are scattering coefficients?
2) What is waveguide?
3) Write the properties of S matrix.
4) Define avalanche transit time devices?
5) What are modes available in avalanche devices?
6) Define the reactance.
7) Define bunching.
8) What is catcher cavity?
9) State the power gain, power output and efficiency of two cavity klystron amplifier.
10) What do you meant by coplanar strip line?
11) Define partially shielded strip line.
12) Mention the materials used in MMICs.
13) Define power.
14) What are the methods to detect microwave power?
15) Name two methods to measure impedance.

PART - B (5 x 14 = 70 Marks)

Answer ALL the questions.

16) a) Explain and derive an open loop circuit and close loop circuit for two port network. (14)

(or)

b) Derive and describe briefly about series tee with its scattering matrix. (14)

17) a) Explain briefly about Ridley Watkins Hilsum theory and two valley model theory. (14)

(or)

b) Describe the operating principle of cadmium telluride diode and InP diode. (14)

18) a) Explain the operating principle of single cavity klystron with suitable diagram. (14)

(or)

b) Explain the working of a TWT amplifier with neat sketch. (14)

19) a) Derive an expression for distributed parameters, characteristic impedance and attenuation losses in parallel strip lines. (14)

(or)

b) Explain the fabrication techniques of a monolithic microwave integrated circuit. (14)

20) a) Describe briefly about insertion loss and attenuation measurements. (14)

(or)

b) Describe briefly about S-parameters of a two port network and S-parameters of magic T with suitable diagram. (14)

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BE DEGREE EXAMINATIONS, APRIL 2014

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

SEVENTH SEMESTER

MICROWAVE ENGINEERING

Time: 3 hours Maximum : 100 marks

PART - A (15 x 2 = 30 Marks)

Answer ALL the questions.

1) Define scattering matrix.
2) Define LSA mode.
3) What do you meant klystron?
4) What is parallel strip line?
5) Give a note on return loss.
6) Write the properties of S matrix.
7) Define the reactance.
8) State the power gain, power output and efficiency of two cavity klystron amplifier.
9) Mention the materials used in MMICs.
10) Name two methods to measure impedance.
11) Define tee - junction.
12) Define the indictive.
13) Write the application of TWT.
14) What is the need of resistive materials?
15) Define insertion loss.

PART - B (5 x 14 = 70 Marks)

Answer ALL the questions.

16) a) Explain the operation of E plane tee and derive the scattering matrix for it. (14)

(or)

b) Explain and derive the scattering matrix for Directional coupler. (14)

17) a) Describe the comparison between Gunn diode, IMPATT Diodes, TRAPATT Diodes and BARITT Diodes. (14)

(or)

b) Explain and derive nonlinear reactance and Manley Rowe power relations. (14)

18) a) Describe voltage tunable magnetron and its π mode operation with suitable diagram. (14)

(or)

b) Describe the operation of two cavity klystron with its characteristics and applications. (14)

19) a) Explain briefly about substrate material, conductor material, dielectric material and resistive material. (14)

(or)

b) Brief explain about parallel strip lines. (14)

20) a) Explain the experimental set up for a reflectometer in VSWR through return loss measurement. (14)

(or)

b) Explain insertion loss and attenuation measurements. (14)

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KARPAGAM UNIVERSITY

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BE DEGREE EXAMINATIONS, NOV 2014
DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING
SEVENTH SEMESTER
MICROWAVE ENGINEERING

Time: 3 hours Maximum : 100 marks

PART - A (15 x 2 = 30 Marks)
Answer ALL the questions.

1) What is H-plane tee?
2) What is E-plane tee?
3) Define tee - junction.
4) Define the indictive.
5) What is meant by capacitive.
6) Give Manley – Rowe relation.
7) Mention the applications of two cavity klystron.
8) What is travelling wave tube amplifier?
9) Write the application of TWT.
10) Define substrate.
11) What is the need for dielectric materials?
12) What is the need of resistive materials?
13) Define attenuation loss.
14) What do you meant by reflection loss?
15) Define insertion loss.

PART - B (5 x 14 = 70 Marks)
Answer ALL the questions.

16) a) Derive and explain E-H plane tee with suitable diagram. (14)
(or)
b) Explain the microwave isolator and faraday rotation isolator with suitable diagram. (14)
17) a) Describe the operating principle of InP diode and CdTe diode. (14)
(or)
b) What are avalanche transit device? Explain the operation, construction and application for IMPATT diode. (14)
18) a) Describe briefly about helix travelling wave tube with suitable diagram. (14)
(or)
b) Explain the construction and working of cylindrical magnetron. (14)
19) a) Describe MMIC fabrication techniques. (14)
(or)
b) Write short notes on coplanar strip lines and shielded strip lines. (14)
20) a) Describe briefly about impedance measurement using slotted line method and reflectometer.(14)
(or)
b) Derive and explain about voltage standing wave ratio through return loss measurement. (14)

Questions
What is the range of Microwave frequencies
What is the Length of Electro magnetic waves
Two - wire lines are used as
Circulators are created by
Directional coupler is
Coupling factor of Directional coupler is
The directivty of directional coupler is
Magic Tee can produce
Ferrite is a
Circulator is a
Directivity of a directional coupler is
Isolation of directional coupler is
S matrix is always a
Directivity of a directional coupler is always expressed in
Microwave wavelength is in the range of
Pick the microwave frequency band which is NOT included in the IEEE microwave bands
S band is in the range of ____ GHz
C band is in the range of ____ GHz
Submillimeter band of microwave frequencies comes in the range of ____ GHz
Millimeter band of microwave frequencies is in the range of ____ GHz
The microwave frequency band generally used in microwave laboratory experiments is
Reflex klystron is a _____ equipment
Microwave devices use hollow wave guides because
The variables in S matrix representation of a microwave circuit is
Microwave circuits can be analyzed using
The dependant variables in an S matrix is
A microwave circulator is a
The independent variables in an S matrix is
In an S matrix for a 2 port microwave network, the coefficient S_{11} implies
In an S matrix for a 2 port microwave network, the coefficient S_{22} implies
In S matrix representation of a microwave circuit, b_1/a_2 will give
In S matrix representation of a microwave circuit, b_2/a_1 will give
The S-parameters will generally be complex numbers because
If the S parameters of a microwave circuit is given _____ can be calculated directly
If a microwave circuit provide zero reflections, then the S matrix will be
For a reciprocal network the S matrix will be
For a 3 port microwave network the order of S matrix will be
A wave guide is a
If the frequency of an input signal to a wave guide is BELOW the cutoff frequency,
The mode of wave in a wave guide is indicated by TE_{mn}, the suffix ‘m’ indicates
The mode of wave in a wave guide is indicated by TE_{mn}, the suffix ‘n’ indicates
A circular wave guide is used in situations where _________ polarization is involved
A wave guide Flange is used in microwave circuits in order
A matched termination in a microwave circuit
A Plunger in a microwave circuit
A plunger is used in

In a choke plunger, the copper blocks are of the length
While making a short circuit plunger, the resistance condition for the block when it is moving along the direction of propagation of wave is

Opt 1
3-30 GHz
1 cm - 1 m
Radiator
2 wave guide
reciprocal device
pa/pi
pa f/pa r
Sum and difference of signal
highly resistance magnetic material
two port device
pr/pb
pb/pi
square matrix
nepers
Meters
K
1–2
1–2
1–2
18–27
L
Tube based
It is very easy to use
Voltages only
Z matrix
Amplitude of incident wave
Type of wave guide tee
Amplitude of incident wave
The reflection coefficient at port 1
The reflection coefficient at port 1
S_{11}
S_{11}
S-Matrix is just an imaginary concept
Frequency
Having all diagonal elements as Zero
Symmetric
2
Twisted pair of copper wire
The wave is very much attenuated
No: of halfwaves' intensity in 'x' direction
No: of halfwaves' intensity in 'x' direction
Vertical
To introduce resistance to energy flow
Reflects all incoming energy
Reflects all incoming energy
Microwave terminators

λ
Resistance should increase

Opt 2
1 - 300 GHZ
1cm - 100 m
transmission lines
2 magic Tees
non reciprocal device
pi/pa
pr/pi
oscillation
low resistance magnetic material
one port device
pb/pf
pi/pb
rectangular matrix
dB
Centimeters
X
2–4
2–4
8–12
27–40
S
Semiconductor based
Microwave current flow is enormous – needs a lot of space
Currents only
Y matrix
Amplitude of reflected wave
Non – reciprocal device
Amplitude of reflected wave
The reflectioncoefficient at port 2
The reflection coefficient at port 2
S_{22}
S_{22}
S-parameters depends on wave amplitudes alone
Input Voltage
Having all diagonal elements as imaginary
Skew symmetric
3
Co-axial cable
The wave can pass freely without being attenuated
No: of halfwaves' intensity in 'y' direction
No: of halfwaves' intensity in 'y' direction
Horizontal
To introduce capacitive impedance
Absorbs all energy without reflection
Absorbs all energy without reflection
Microwave attenuators

2λ
Resistance should decrease

Opt 3
1 - 300 MHZ
1 cm - 10 m
Filters
2 Transmission lines
an amplifier
pr/pi
pa/pi
only sum of signal
resistance
three port device
pi/pr
pr/pi
2 x 2
without unit
Kilometers
M
4–8
4–8
27–40
40–300
C
Transit time based
At microwave frequencies it is flow of energy not current
Voltages and currents
ABCD matrix
Voltage of incident wave
Reciprocal device
Voltage of incident wave
The attenuation coefficient when wave is travelling from port 1 to 2
The attenuation coefficient when wave is travelling from port 1 to 2
S_{12}
S_{12}
S-parameters depends on wave amplitudes and their respective phases
Input current
Symmetric
Identity matrix
4
Hollow metallic tube
The wave remains as TEM wave
No: of standing waves in ‘x’ direction
No: of standing waves in ‘x’ direction
E – plane
To introduce inductive impedance
Absorbs energy with partial reflections
Absorbs energy with partial reflections
Impedance measurements

$\lambda/2$
Resistance should remain constant

p
None of these
10cm - 100 cm
TEM wave generator
Circular wave guide
an oscillator
pi/pr
pi/pa
None of these
None of these
None of these
p1/p2
p1/p2
3 x 3
watts
Micrometers
L
8–12
8–12
>300
>300
X
Negative Resistance based Tube based
Statement is wrong – Microwave devices uses copper conductors only
Wave amplitudes only
S matrix
Voltage of reflected wave
Attenuator
Voltage of reflected wave
The attenuation coefficient when wave is travelling from port 2 to 1
The attenuation coefficient when wave is travelling from port 2 to 1
S_{21}
S_{21}
Microwave circuits are purely resistive
Transmission loss
Skew symmetric
Having Zero diagonal matrix
9
Microwave resistance device
Only TE waves can remain
No: of standing waves in ‘y’ direction
No: of standing waves in ‘y’ direction
Circular
To avoid leakage in circuit connections
Introduces circular polarization by faraday rotation principle
Introduces circular polarization by faraday rotation principle
VSWR meters

$\lambda/4$
Resistance should be absent

Op5 Op6

Answer
1 - 300 GHZ
1 cm - 1 m
transmission lines
2 magic Tees
reciprocal device
pi/pa
pa f/pa r
Sum and difference of signal
highly resistance magnetic material
None of these
pr/pb
pi/pb
square matrix
dB
Centimeters
M
2–4
4–8
>300
40-300
X
Tube based
At microwave frequencies it is flow of energy not current
Wave amplitudes only
S matrix
Amplitude of reflected wave
Non – reciprocal device
Amplitude of incident wave
The reflection coefficient at port 1
The reflection coefficient at port 2
S_{12}
S_{21}
S-parameters depends on wave amplitudes and their respective
Transmission loss
Having all diagonal elements as Zero
Symmetric
3
Hollow metallic tube
The wave is very much attenuated
No: of halfwaves' intensity in 'x' direction
No: of halfwaves' intensity in 'y' direction
Circular
To avoid leakage in circuit connections
Absorbs all energy without reflection
Reflects all incoming energy
Impedance measurements

$\lambda/4$
Resistance should remain constant

Questions	Opt 1
The operation of the microwave transistor depends on	Transit time
The microwave bipolar transistor is operated in	Class A
The operation of FET depends on	Varying conductivity of semi
FET is used as	Oscillator
TED is a	FET
TED is used as	Switch
Gunn Diode is a	Negative Resistance device
LSA diode is an example of	TED
IMPATT diode is an	Avalanche transit time device
IMPATT diode is an	A narrow band device
TRAPATT diode has	PNN structure
TRAPATT diode is	High efficiency oscillator
TRAPATT is used as	Local oscillator in RADAR
BARITT diode has	PNN structure
PIN diode is	Phase shifter
TED is a bulk device and has	1 junction
At microwave frequencies PIN diode acts as	Variable resistance
MOSFET is a	four terminal device
phase shift is	not a function of frequency
probe is	short antenna
One advantage of microwave SSDs over tube type devices are	High Power output capacity
Pick the odd one out	Microwave BJT
Pick the odd one out	JFET
Pick the odd one out	Gunn diode
Pick the odd one out	Read diode
Which of the following is NOT a microwave TED device?	CdTe diode
The Charge Coupled Devices comes under the category	BJT
In a semiconductor the energy band gap is defined as	Space between P and N type
Pick from the following a voltage controlled device	BJT
The microwave BJTs are mostly npn transistors because	It is cheaper
The ________ surface geometry BJT can handle small signal a	Interdigitated
The best transistor amplifier configuration is	CB
The ______ configuration of the BJT cannot be used as an amp	CB
In a grounded emitter configuration the ______ terminal is con	Base
The _______ configuration of BJT has moderate input and out	CB
The microwave BJT can work in normal mode when	J_E is forward biased; J_C is For
The microwave BJT can work in cutoff mode when	J_E is forward biased; J_C is For
The inverse mode of operation is used in ______ circuits	Amplifier
The current gain of a transistor when working in CB configura	α

The current gain of a transistor when working in CE configurat	α
The current gain of a transistor when working in CC configura	α
For a BJT one of the following can be justified	α = β
The ______ configuration of a BJT is used as for impedance m	CB
In a microwave BJT the heavily doped region is always	Emitter
In a microwave BJT, the thinnest part will be	Emitter
The transistor equation is given by	$I_E = I_B + I_C$
One of the following devices can be used a Voltage Variable R	BJT
In the output characteristics of a BJT, the constant output curr	Channel cutoff
Which of the following is a negative resistance device?	FET

Opt 2	Opt 3	Opt 4	Op5
PN Junction thickness	Transit time & PN Junction tl	The base width	
Class B	Class AB	Class D	
Transit time	Frequency	Pinch off voltage	
Amplitude limiter	rectifier	switch	
Gunn diode	Tunnel diode	BARITT diode	
An Oscillator	A Clipper	A Rectifier	
Positive resistance device	high noise device	low frequency device	
PN diode	PNP Diode	PNPN diode	
Low frequency device	High efficiency device	used as switch	
A white band device	noise less device	low frequency device	
NPN structure	PNP Structure	none of the above	
low efficiency oscillator	A switch	Rectifier	
Amplifier in RADARS	switch in communication tran	low frequency oscillator	
NPN structure	PNP Structure	none of the above	
Oscillator	Rectifier	Amplifier	
2 junction	3 junction	No junction	
filter	oscillator	switch	
three terminal device	two terminal device	two junction device	
function of frequency	obtained from resistance	obtained from magnetic materials	
a filter	an amplifier	an oscillator	
Very stable against voltage fluc	Ability to act as a microwave	Low power consumption	
JFET	HBT	Tunnel diode	
MESFET	MOSFET	HBT	
LSA diode	InP diode	Tunnel diode	
Gunn diode	IMPATT diode	TRAPATT diode	
Read diode	LSA diode	Gunn Diode	
FET	TED	ATT	
Space in the diode where recor	Space between the conductio	The energy emitted when a hole reco	
HBT	MESFET	Tunnel diode	
It is easier to make	Electron has more mobility th	It has more stability	
Overlay	Matrix	Surface metalized	
CE	CC	Grounded Base	
CE	CC	Grounded emitter	
Emitter	Collector	Substrate	
CE	CC	Emitter follower	
J_E is forward biased; J_C is rever	J_E is reverse biased; J_C is reve	J_E is reverse biased; J_C is Forward Bi	
J_E is forward biased; J_C is rever	J_E is reverse biased; J_C is reve	J_E is reverse biased; J_C is Forward Bi	
Switching	Oscillating	TTL	
β	γ	I_B	

β	γ	I_E
β	γ	I_C
$\beta = \gamma$	$\gamma = \alpha$	$\alpha = \gamma\beta$
CE	CC	Inverse mode of operation
Base	Collector	Collector junction
Base	Collector	Substrate
$I_B = I_E + I_C$	$I_C = I_E + I_B$	$I_E = I_C / I_B$
HBT	FET	Read diode
Channel pinchoff	Effective base width reducing	Base current approaching emitter cur
CCD	HBT	Tunnel Diode

Op6	Answer
	Transit time & PN Junction thickness
	depletion region
	Class B
	Varying conductivity of semiconductor material
	Oscillator
	Gunn diode
	An Oscillator
	Negative Resistance device
	TED
	Avalanche transit time device
	A white band device
	PNN structure
	High efficiency oscillator
	Local oscillator in RADAR
	PNP Structure
	Phase shifter
	No junction
	Variable resistance
	four terminal device
	function of frequency
	short antenna
	Low power consumption
	JFET
	HBT
	Tunnel diode
	Gunn diode
	Read diode
	FET
mbines wi	Space between the conduction band and valence band where no electrons can stay
	MESFET
	Electron has more mobility than holes
	Interdigitated
	CE
	CC
	Emitter
	CE
ased	J_E is forward biased; J_C is reverse Biased
ased	J_E is reverse biased; J_C is reverse Biased
	TTL
	α

	β
	γ
	β = γ
	CC
	Emitter
	Base
	$I_E = I_B + I_C$
	FET
rent	Effective base width reducing to zero
	Tunnel Diode

Questions	Opt 1
Pick the device which works on the principle of a parallel plate capacitor	Microwave BJT
The input resistance of a MOSFET is ideally	Zero
CCDs are an array of	Microwave BJTs
When the implementation in silicon is considered, which on has smaller size?	Microwave BJT
Most of the microwave SSDs is of N type semiconductor. This is because	It is cheaper
Which of the following is NOT a negative resistance device?	Tunnel diode
Klystron cavity works on the principle of	Negative resistance
Pick the term which is NOT related to a two-cavity klystron	Velocity modulation
Velocity modulation in a klystron happens in ________	The first cavity
In a two-cavity klystron, the electron density is NOT constant near	Electron gun
In a two cavity klystron, the kinetic energy from the electron is transferred to the field near ____	Electron gun
The efficiency of the two cavity klystron is about ____	0.3
The power gain of a two-cavity klystron is about ____dB	10
In a two-cavity klystron, the amplitude of the input signal is _______ than the dc accelerating voltage	Greater
A re-entrant cavity is one in which the metallic boundaries extend into the _____ of the cavity	Interior
The microwave tubes differ from the other vacuum tubes in that, they use the _____________ for microwave oscillations	Velocity
Pick the odd one out	Reflex klystron
Pick the crossed field device form the following	Reflex klystron
Pick from the following which can be used as a microwave amplifier	Reflex klystron
Which of the following CAN NOT be used as a microwave amplifier?	Microwave BJT
A steady microwave oscillation is generated from the reflex klystron when the power loss in the cavity _______ power delivered by the system	Equal
Vacuum triodes are suitable at	Low and high frequencies
At high frequencies, conventional vacuum tubes have limitations with the presence of	Transit time effects
The linear beam tube (O type) is	Reflex klystron
Microwave M-type tube is	Klystron
Slow-wave structure is	Klystron
The unit of electron transit angle is	Radian
The unit of transit angle is	Sec/m
Feed back in klystron is by	Using three cavities

The re-entrant cavities in klystron can be	Circular
The velocity modulation in klystron is represented by	Equivalent circuit
The velocity of electron in klystron is proportional to	Square root of beam voltage
Beam coupling co-efficient in klystron is a function of	Beam voltage
The transit angle is proportional to	Space between the cavities
The bunching parameter in klystron is proportional to	Beam coupling
The mode number in reflex klystron is	Nn = (n + 1/4)
The electronic tuning range in reflex klystron is	Total change in frequency from one
The output efficiency of reflex klystron is the ratio of	Output RF power to input RF power
TWYSTRON is a combination of	Klystron and magnetron
Magnetron is	O-type tube
Magnetron is	Low frequency oscillator
BWO is	Continuous wave oscillator
The electron velocity in reflex klystron is	$\sqrt{(2(e/m)(1/V_b))}$
TWT is	M-type tube
The force on the electron by the magnetic field in a magnetron is	$F = -e (V \times B)$
Transit angle in a vacuum tube is	$\omega d / v_e$
The electron velocity in a tube is	$0.593 \times 10^6 V_b$
The beam coupling co-efficient is	$(\text{Sin} (T_t / 2)) / (T_t / 2)$
The bunching parameter of a klystron is	$((\beta_c V_m) / 2V_b) \theta_t$
The dc transit angle between cavities is	$(\omega L) / v_e$
The mutual conductance of a klystron amplifier is the ratio of	Beam current to beam voltage
g_m of a klystron is	$2\beta_c I_b J_1(X) / V_m$

Opt 2	Opt 3	Opt 4	Op5	Op6
HBT	Tunnel diode	MOSFET		
Matched	Infinity	100 Ω		
HBTs	FETs	MOS capacitors		
Low frequency BJT	FET	Klystron		
It is easy to construct	Electron mobility is faster than hole mobility	P type becomes unstable at microwave frequencies		
Gunn diode	TED	FET		
Temperature dependence	Velocity modulation	Avalanche breakdown		
Current modulation	Voltage modulation	Electron gun		
The second cavity	Near the electron gun	Near the repeller		
First cavity	Second cavity	Input modulation		
First cavity	Second cavity	Repeller plate		
0.4	0.5	1		
20	30	90		
Lesser	Equal	Much lesser		
Exterior	Center	Tangent		
Current	Transit time	Gunn effect		
Two-cavity klystron	TWT	Magnetron		
Two-cavity klystron	TWT	Magnetron		
Magnetron	Gunn diode	TWT		
Two cavity klystron	Reflex Klystron	TWT		
Double	Half	Square		
Low frequencies	High frequencies	X band only		
Low bandwidth	High noise	Vacuum		
Amplitron	Gyrotrons	Magnetron		
TWT	Magnetron	BWA		
Magnetron	Dematron	TWT		
Radian / m	Radian / sec	Radian – sec		
Second	Sec/radian	Sec/degree		
Re-entrant	Using four cavities	Anode		

Rectangular	Elliptical	Toroidal
Applegate diagram	Output voltage	Output power
Electron charge	Electron mass	Square root of mass of the electron
Transit angle	Input signal	Depth of velocity modulation
V_e	e	$1/\omega$
$1/\theta_t$	V_s	$1/T_t$
Nn = (n + 3/4)	Nn = (n)	Nn = (n – 3/4)
Total change in frequenc	Total change in frequency	Total change in frequency with transit angle
Output RF power to inpu	Output dc power to input	Output dc power to input RF power
Klystron and TWT	Klystron and BWA	Klystron and BWO
An oscillator	An amplifier	A detector
Low power device	High power device	Low gain amplifier
Pulse generator	Square wave generator	Amplifier
$\sqrt{(2(e/m)V_b)}$	$\sqrt{(2(m/e)V_b)}$	$\sqrt{((1/2)(e/m)V_b)}$
Amplifier	O-type tube	Cross field tube
$F = (V \times B)$	$F = -e (B \times V)$	$F = -e (V . B)$
$v_e d / \omega$	$\omega / d v_e$	fd / v_e
$0.593 \times 10^6 \sqrt{(V_b)}$	$0.593 \times \sqrt{(V_b)}$	$0.953 \times 10^6 \sqrt{(V_b)}$
$\theta_t / 2$	$(\text{Sin} (\theta_t / 2)) / (\theta_t / 2)$	$(\omega \text{ Sin} (\theta_t / 2)) / (\theta_t / 2)$
$(V_m / 2V_b) \theta_t$	$((\beta_c V_m) / 2V_b) T_t$	$((\beta_c V_m) / 2V_b)$
$- v_e / \omega L$	ω / v_e	L / v_e
Induced current to induce	Beam voltage to beam curr	Input voltage to input current
$2I_b J_1(X) / V_m$	$2\beta_c J_1(X) / V_m$	$2\beta_c I_b J_1(X)$

Answer

MOSFET
Infinity
MOS capacitors

FET
Electron mobility is faster than hole mobility

FET
Velocity modulation

Voltage modulation
The first cavity

Second cavity

Second cavity
0
30

Much lesser

Interior

Transit time
Magnetron
Magnetron

TWT

Reflex Klystron

Equal
Low frequencies

Transit time effects
Reflex klystron
Magnetron
TWT
Radian
Second
Re-entrant

Toroidal
Applegate diagram
Square root of beam voltage
Transit angle
Space between the cavities
Beam coupling
Nn = (n + 3/4)
Total change in frequency from one end of the mode to the other

Output RF power to input dc power
Klystron and TWT
An oscillator
High power device
Continuous wave oscillator
$\sqrt{(2(e/m)V_b)}$
O-type tube

$F = -e (V \times B)$
$\omega d / v_e$
$0.593 \times 10^6 \sqrt{(V_b)}$
$(\sin (\theta_t / 2)) / (\theta_t / 2)$
$((\beta_c V_m) / 2V_b) \theta_t$
$(\omega L) / v_e$

Induced current to induced voltage
$2\beta_c I_b J_1(X) / V_m$

Questions	Opt 1
Characteristic impedance of microstrip is also a function of the ratio of	Height
MMIC stands for	Multiple Microwave IC
A horizontal polarized wave is given as input to a wave guide twist the output polarization will be	Horizontal
In a wave guide twist; the length of the twist is kept to an odd multiple of ______	λ
The microwave circuit component which is similar to a resistor used in lower frequencies is	Isolator
The microwave circuit component which is similar to a pn junction diode used in lower frequencies is	Isolator
The material commonly used to make microwave attenuators are	Copper
In a wave guide attenuator, the resistive film is kept	Parallel to E field
In a wave guide, the maximum E field will be available	At the center of the wave guide
Microwave isolator is a	Reciprocal device
Microwave isolators works on the principle of	orizontal polarization
________ polarized waves experiences maximum attenuation near the ferrite material in an isolator	Positive circular
Pick the S matrix for an isolator	$S_{11} = 0$, $S_{12} = 1$, $S_{21} = 0$, $S_{22} = 0$
In microwave circuits, a junction with three independent ports are usually called as	Directional Coupler
One theorem for wave guide tees states that, “a short circuit can always be placed in one of the arms, in such a way that _______ power can be transmitted through the other 2 arms”	Maximum
The statement “it is impossible for a general 3 port junction to present matched impedance at all three arms” is	Always true
_______ wave guide tee is known as series tee	E Plane
_______ wave guide tee is known as parallel tee	E Plane
The diagonal elements in the S matrix for an E plane tee will always be	0
Isolator is made of	non ferrite
Faraday rotation produces	isolation
Directional coupler produces	division of power
In a two-cavity klystron, the _______ cavity is the input cavity	Buncher

In a two-cavity klystron, the _______ cavity is the output cavity	Buncher
_____ uses slow wave principle	Klystron
The general life of a TWT is about ____ hours	50
Cross field devices are also known as ______ type devices	O
The theoretical efficiency of a reflex klystron is around ___ %	10
The Q values of the cavities in a magnetron is _____	Very low
The TWT is a ____ device	Broad band
A slow wave device is a device in which	Electron beam is velocity modulated without a resonant cavity.
Strip lines was invented by	Wilhelm Rontgen
Strip lines and Micro Strip lines are	Wave giude
Wave guides conduct microwave energy at -------- than coaxial cables	higher loss
In strip line middle conductor is sandwiched between	Loss less cable
In an S matrix for a 2 port microwave network, the coefficient S_{21} implies	The reflection coefficient at port 1
In an S matrix for a 2 port microwave network, the coefficient S_{11} implies	The reflection coefficient at port 1
Attenuation is measured in	Volts

Opt 2	Opt 3	Opt 4	Op5	Op6
width	length	height to the width		
Monolithic Microwave IC	Microwave Monolithic IC	Measurement of Microwave IC		
Vertical	Circular	Elliptical		
2λ	λ/2	λ/4		
Plunger	Choke plunger	Attenuator		
Plunger	Choke plunger	Attenuator		
Carbon	Ceramic	Aquadag		
Perpendicular to E field	Parallel to H field	Perpendicular to H field		
At a distance λ from the walls	At a distance 2λ from the walls	Near the walls of the wave guide		
Non-reciprocal device	Resistive device	Capacitive device		
Faraday rotation	Poynting vector theorem	Permanent magnetism		
Negative circular	Horizontal	Vertical		
$S_{11} = 1, S_{12} = 0, S_{21} = 0, S_{22} = 1$	$S_{11} = 0, S_{12} = 1, S_{21} = 1, S_{22} = 0$	$S_{11} = 0, S_{12} = 0, S_{21} = 0, S_{22} = 0$		
Plunger	Isolator	Wave guide Tee		
Minimum	No	180 degree out of phase		
Always false	Depends on construction of junction	Cannot say with the data given		
H plane	Magic	Hybrid ring		
H plane	Magic	Hybrid ring		
Imaginary	Non-zero	1		
ferrite	Si	Ge		
circular properties	matching properties	transmission properties		
amplification	generator of power	reduction of power		
Catcher	Repeller	Modulation		

Catcher	Repeller	Modulation
Magnetron	TWT	Microwave Amplifier
500	5000	50000
M	TWT	Hybrid
20	30	50
Low	High	Always 0
Narrow band	Frequency independent	Highly frequency selective
The beam is slowed down by an opposite field	Two cavities are used to slow down the wave	Four cavities are used to slow down the wave
Robert M. Barrett	shockley	none of the option
Transmission line	Microwave Monolithic IC	Microwave measurement device
lower loss	low frequency	none of the option
ground planes	two cavity	Two dielectric
The reflection coefficient at port 2	The attenuation coefficient when wave is travelling from port 1 to 2	The attenuation coefficient when wave is travelling from port 2 to 1
The reflection coefficient at port 2	The attenuation coefficient when wave is travelling from port 1 to 2	The attenuation coefficient when wave is travelling from port 2 to 1
Ampere	Decibels	watt

Answer

height to the width

Monolithic Microwave IC
Vertical

λ/4

Attenuator

Isolator

Aquadag

Parallel to E field

At the center of the wave guide
Non-reciprocal device

Faraday rotation
Negative circular

$S_{11} = 0$, $S_{12} = 1$, $S_{21} = 0$, $S_{22} = 0$
Wave guide Tee

No

Always true

E Plane
H plane
Non-zero

ferrite
circular properties
division of power

Buncher

Catcher
TWT
50000
M

20
High

Broad band

Electron beam is velocity modulated without a resonant cavity.
Robert M. Barrett

Transmission line

lower loss
ground planes

The attenuation coefficient when wave is travelling from port 2 to 1

The attenuation coefficient when wave is travelling from port 1 to 2
Decibels

Questions	Opt 1
VSWR meter measures the	Power
Which device is not used for microwave applicatoin	IMPATT diode
For a short circuit plunger, __________ resistance between the copper block and the guide wall is desired	Low
In a wave guide corner reflections __________	Are present
A wave guide corner is used to alter the guide direction by ______ degree	90
The mean length L between junctions in a wave guide bend is kept at an odd multiple of $\lambda/4$ in order to	Double the transmission rate
Wave guide bends is used to alter the direction of a wave guide by ______ degree	45
Which of the following does not have a P-N junction?	FET
In a tunnel diode, the doping level is	Very low
Which of the following can be used as a high speed switch/	FET
Which of the following cannot be used as a microwave amplifier?	BJT
READ diode is a	Practical diode
In GaAs diode ------- number of conduction band valleys are there	4
IMPATT stands for	IMPact ionization Avalanche Transit-Time diode
Plasma is a	state of matter
Plasma are	mixture of liquid and solid
TRAPATT stands for	TRApped, Plasma Avalanche Triggered Transit diode
Insertion loss is the loss of signal power resulting from	Improper initial setting
L band is in the range of ____ GHz	1–2
X band is in the range of ____ GHz	1–2
The maximum electronic efficiency of a reflex klystron is ______ %	40
The vacuum tubes used in microwave frequencies is	Similar to low frequency tubes
The limitations of ordinary vacuum tubes are	Lead inductance
_____ cavity klystron is generally used	2
The power gain of a klystron is about ___ dB	30
2–4 GHz is the frequency of --- band	L

4-8 GHz is the frequency of --- band	L
Which is not a negative resistance diode	tunnel diode
S-parameters is	Impedance parameter
S-parameters use ----- conditions to characterize electrical network	open circuit
Network analyzer is used for measuring	Voltage
4-8 GHz is the frequency of --- band	L

Opt 2	Opt 3	Opt 4	Op5	Op6
standing wave ratio	Amplitude	none of the option		
TRAPATT diode	Gunn diode	Zener diode		
High	Zero	Infinitely high		
Are absent	Are enormous	Cancel from both directions		
60	Any convenient	45		
Cancel the reflections from either side	Avoid any possible reflections	To change polarization		
60	90	Any convenient		
BJT	Tunnel diode	TEDs		
Very high	Moderate	Same as that of an intrinsic material		
Read diode	CCD	Tunnel diode		
FET	Tunnel Diode	Gunn diode		
Theoretical doide	Tunnel Diode	MMIC diode		
3	2	more than 2		
IMpact Polarization Avalanche Transit-Time diode	IMpact Polarization Anode Transit-Time diode	none		
outer layer	mixture of liquid and solid	none of the options		
electrically conductive	insulators	semisolid		
TRApped, Plasma Anode Triggered Transit diode	Transsion Read Avalanche Plasma Anode Triggered Transit diode	none of the options		
insertion of a device in a transmission line	insertion of a klystron oscillator	none of the options		
2–4	4–8	8–12		
2–4	4–8	8–12		
50	22.7	35		
Similar to semiconductor devices	Similar to a vacuum diode	Different from that of low frequency vacuum tubes		
Inter electrode capacitance	Effect of transit time	All the above		
4	6	8		
-30	60	-60		
X	O	S		

C	O	S
Gunn diode	thyristors	zener diode
Admittance parameter	Current parameter	Scattering parameters
Matched loads	Short circuit	closed circuit
loss in medium	S-parameters	non of the option
X	O	non of the option

Answer
standing wave ratio
Zener diode
Low

Are present
90

Cancel the reflections from
either side

Any convenient

TEDs

Very high
Tunnel diode
Gunn diode
Theoretical doide
2

IMPact
ionization Avalanche Transit
-Time diode

state of matter

electrically conductive

TRApped, Plasma
Avalanche Triggered
Transit diode

insertion of a device in a
transmission line
1-2
8–12
23

Different from that of low
frequency vacuum tubes

All the above
2
30
S

C
zener diode

Scattering parameters
Matched loads
S-parameters
non of the option