MALLA REDDY INSTITUTE OF TECHNOLOGY & SCIENCE
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Approved by UK Accreditation CentreGranted Status of 2(f) & 12(b) under UGC Act. 1956, Govt. of India.

MICROWAVE AND OPTICAL COMMUNICATIONS
COURSE FILE

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING
(2022-2023)

Faculty In-Charge	**HOD-ECE**
CH.RAJASHEKAR	**Dr.R.Prabhakar**

COURSE FILE

SUBJECT: MICROWAVE AND OPTICAL COMMUNICATIONS

ACADEMIC YEAR: 2022-2023.

REGULATION: R18

NAME OF THE FACULTY: CH.RAJASHEKAR

DEPARTMENT: ECE

YEAR & SECTION: IV ECE A,B,C

SUBJECT CODE:

INDEX

COURSE FILE

MICROWAVE AND OPTICAL COMMUNICATIONS

1.PEO'S, PO'S, PSO'S

PROGRAM EDUCATIONAL OBJECTIVES:

PEO1: To excel in different fields of electronics and communication as well as in multidisciplinary areas. This can lead to a new era in developing a good electronic product.
PEO2: To increase the ability and confidence among the students to solve any problem in their profession by applying mathematical, scientific and engineering methods in a better and efficient way.
PEO3: To provide a good academic environment to the students which can lead to excellence, and stress upon the importance of teamwork and good leadership qualities, written ethical codes and guide lines for lifelong learning needed for a successful professional career.
PEO4: To provide student with a solid foundation to students in all areas like mathematics, science and engineering fundamentals required to solve engineering problems, and also to pursue higher studies.
PEO5: To expose the student to the state of art technology so that the student would be in a position to take up any assignment after his graduation.

PROGRAM OUTCOMES:-

Engineering knowledge: Apply the knowledge of mathematics, science, engineering fundamentals,and an engineering specialization to the solution of complex engineering problems.
Problem analysis: Identify, formulate, review research literature, and analyze complex engineeringproblems reaching substantiated conclusions using first principles of mathematics, natural sciences,and engineering sciences.
Design/development of solutions: Design solutions for complex engineering problems and designsystem components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.
Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of theinformation to provide valid conclusions.
Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with anunderstanding of the limitations.
The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal,health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.
Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.
Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms ofthe engineering practice.
Individual and team work: Function effectively as an individual, and as a member or leader indiverse teams, and in multidisciplinary settings.
Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reportsand design

documentation, make effective presentations, and give and receive clear instructions.

Project management and finance: Demonstrate knowledge and understanding of the engineering and management principles and apply these to one’s own work, as a member and leader in a team, tomanage projects and in multidisciplinary environments.

Life-long learning: Recognize the need for, and have the preparation and ability to engage inindependent and life-long learning in the broadest context of technological change.

PROGRAM SPECIFIC OUTCOMES:

PSO1: The ability to absorb and apply fundamental knowledge of core Electronics and Communication Engineering subjects in the analysis, design, and development of various types of integrated electronic systems as well as to interpret and synthesize the experimental data leading to valid conclusions.

PSO2: Competence in using electronic modern IT tools (both software and hardware) for the design and analysis of complex electronic systems in furtherance to research activities.

PSO3: Excellent adaptability to changing work environment, good interpersonal skills as a leader in a team in appreciation of professional ethics and societal responsibilities.

EC701PC: MICROWAVE AND OPTICAL COMMUNICATIONS (PC)

B.Tech. IV Year I Semester	**L**	**T**	**P**	**C**
	3	0	0	3

Prerequisite: Antennas and Propagation

Course Objectives:

- To get familiarized with microwave frequency bands, their applications and to understand the limitations and losses of conventional tubes at these frequencies.
- To distinguish between different types of microwave tubes, their structures and principles of microwave power generation.
- To impart the knowledge of Scattering Matrix, its formulation and utility, and establish the S-Matrix for various types of microwave junctions.
- Understand the utility of Optical Fibres in Communications.

Course Outcomes: Upon completing this course, the student will be able to

- Known power generation at microwave frequencies and derive the performance characteristics.
- realize the need for solid state microwave sources and understand the principles of solid state devices.
- distinguish between the different types of waveguide and ferrite components, and select proper components for engineering applications
- understand the utility of S-parameters in microwave component design and learn the measurement procedure of various microwave parameters.
- Uunderstand the mechanism of light propagation through Optical Fibres.

UNIT - I

Microwave Tubes: Limitations and Losses of conventional Tubes at Microwave Frequencies, Microwave Tubes – O Type and M Type Classifications, O-type Tubes: 2 Cavity Klystrons – Structure, Reentrant Cavities, Velocity Modulation Process and Applegate Diagram, Bunching Process and Small Signal Theory – Expressions for O/P Power and Efficiency. Reflex Klystrons – Structure, Velocity Modulation and Applegate Diagram, Mathematical Theory of Bunching, Power Output, Efficiency, Oscillating Modes and O/P Characteristics.

Helix TWTs: Types and Characteristics of Slow Wave Structures; Structure of TWT and Amplification Process (qualitative treatment), Suppression of Oscillations, Gain Considerations.

UNIT - II

M-Type Tubes:

Introduction, Cross-field Effects, Magnetrons – Different Types, Cylindrical Traveling Wave Magnetron

– Hull Cut-off and Hartree Conditions, Modes of Resonance and PI-Mode Operation, Separation of PI-Mode, o/p characteristics,

Microwave Solid State Devices: Introduction, Classification, Applications. TEDs – Introduction, GunnDiodes – Principle, RWH Theory, Characteristics, Modes of Operation - Gunn Oscillation Modes, Principle of operation of IMPATT and TRAPATT Devices.

UNIT - III

Waveguide Components: Coupling Mechanisms – Probe, Loop, Aperture types. Waveguide Discontinuities – Waveguide Windows, Tuning Screws and Posts, Matched Loads. Waveguide Attenuators – Different Types, Resistive Card and Rotary Vane Attenuators; Waveguide Phase Shifters
– Types, Dielectric and Rotary Vane Phase Shifters, Waveguide Multiport Junctions - E plane and H plane Tees. Ferrites– Composition and Characteristics, Faraday Rotation, Ferrite Components – Gyrator, Isolator,

UNIT - IV

Scattering matrix: Scattering Matrix Properties, Directional Couplers – 2 Hole, Bethe Hole, [s] matrix of Magic Tee and Circulator.

Microwave Measurements: Description of Microwave Bench – Different Blocks and their Features, Errors and Precautions, Measurement of Attenuation, Frequency. Standing Wave Measurements, measurement of Low and High VSWR, Cavity Q, Impedance Measurements.

UNIT - V

Optical Fiber Transmission Media: Optical Fiber types, Light Propagation, Optical fiber Configurations, Optical fiber classifications, Losses in Optical Fiber cables, Light Sources, Optical Sources, Light Detectors, LASERS, WDM Concepts, Optical Fiber System link budget.

TEXT BOOKS:

1. Microwave Devices and Circuits – Samuel Y. Liao, Pearson, 3rd Edition, 2003.
2. Electronic Communications Systems- Wayne Tomasi, Pearson, 5th Edition

REFERENCE BOOKS:

1. Optical Fiber Communication – Gerd Keiser, TMH, 4th Ed., 2008.
2. *Microwave Engineering - David M. Pozar, John Wiley & Sons (Asia) Pvt Ltd., 1989, 3r ed., 2011 Reprint.*
3. Microwave Engineering - G.S. Raghuvanshi, Cengage Learning India Pvt. Ltd., 2012.
4. Electronic Communication System – George Kennedy, 6th Ed., McGrawHill.

3.Class Time Table & Individual Time Table

III-I ECE-A,B,C

Individual Time Table

	9.15-10.15	**10.15-11.15**	**11.15-12.15**	**12.15-1.15**	**1.15-2.00**	**2.00-3.00**	**3.00-4.00**
MON	MWOC(A)			MWOC(B)	**LUNCH**	**MWOC LAB (A) IST BATCH**	
TUES	MWOC(B)		MWOC(C)			**MWOC LAB (B) IST BATCH**	
WED	MWOC(C)	MWOC(B)	MWOC(A)			**MWOC LAB (C) IST BATCH**	
THUR	MWOC(A)	MWOC(C)		COOS(B)		**MWOC LAB (A) IIND BATCH**	
FRI		COOS(A)		COOS(C)		**MWOC LAB (A) IIND BATCH**	
SAT		COOS(B)		COOS(A)		**MWOC LAB (A) IIND BATCH**	

4.Students Roll List ECE-A

SNo	H.T.NO	NAME OF THE STUDENT	SNo	H.T.NO	NAME OF THE STUDENT
1	19S11A04C3	AKHIL K	30	19S11A04F5	SATHVIK V
2	19S11A04C4	AKSHAYA NADENDLA	31	19S11A04F6	SHIRISHA GAJAM
3	19S11A04C5	APOORVA DEEKONDA	32	19S11A04F7	SRIDHAR G
4	19S11A04C6	ASHISH M	33	19S11A04F8	SRILATHA DESHAVENI
5	19S11A04C7	BALAJI M	34	19S11A04F9	SRINIVAS C B S
6	19S11A04C8	CHANDANA PRIYA KANDHAROJU	35	19S11A04G3	TRISHIKA B
7	19S11A04C9	DIVYA VUNIYALA	36	19S11A04G4	VIDHYA A
8	19S11A04D0	GANESH CHETKURI	37	19S11A04G5	VINAY KUMAR BONALA
9	19S11A04D1	HEMANTH URUTURU	38	19S11A04G7	SHAIK MOHAMMAD AKRAM
10	19S11A04D2	HITESH K R	39	19S11A04G8	SHIVA KUMAR REDDY PALLE
11	19S11A04D3	JAGADISH YERROLU	40	20S15A0401	ANIL AITIPAMULA
12	19S11A04D4	JASWANTH SAI YADAV PAMIDI	41	20S15A0402	ANUSHA MANCHIKATLA
13	19S11A04D5	MADHU N	42	20S15A0403	ARCHANA SURABOYINA
14	19S11A04D6	MANOHAR VADLA	43	20S15A0404	ARUN PIDUGU
15	19S11A04D8	MANSI SAINI	44	20S15A0405	AVIKSHITH YEDLA
16	19S11A04D9	NAGA VENKATA SATYANARAYANA V	45	20S15A0406	BHARATH KALYAN ALLARAM
17	19S11A04E0	NAVEEN CH	46	20S15A0407	BHASKAR D B V S
18	19S11A04E1	NIKHIL KUMAR THALLAPALLY	47	20S15A0408	GANAPATHI NAGAVATH
19	19S11A04E2	PADMAHARI M	48	20S15A0409	GOWTHAMI MATTIPALLI
20	19S11A04E3	PRAVEEN KUMAR A	49	20S15A0410	KRISHNAVENI
21	19S11A04E4	RAGHAVENDRA REDDY C	50	20S15A0412	LEELA VINODINI GORLI
22	19S11A04E6	RAJA KIRAN NYALAKANTI	51	20S15A0413	MANOJ KUMAR KALYANAPU
23	19S11A04E7	RAMYA ADEPU	52	20S15A0414	NITHISH MARELLA
24	19S11A04E8	RAMYA K	53	20S15A0415	PRABHAS NERELLA
25	19S11A04E9	SABITHA NALLAGANTI	54	20S15A0416	PRANADEEP POTHUNURI
26	19S11A04F0	SAI GYANESHWAR N	55	20S15A0417	PRANAYA BHUPALA
27	19S11A04F2	SAI PRASAD R	56	20S15A0418	PRASHANTH KUMAR POTTAVARTHI
28	19S11A04F3	SAI ROHITH M	57	20S15A0419	PRAVALIKA K
29	19S11A04F4	SATHISH NALAPARAJU	58	20S15A0420	RAJA SHEKER REDDY BOKKA

ECE-B

SNo	H.T.NO	NAME OF THE STUDENT	SNo	H.T.NO	NAME OF THE STUDENT
1	19S11A0461	ABHHINANDU K G	34	19S11A0497	SAI SANGAMESH GUPTA VATTAMVAR
2	19S11A0462	AKHIL MARYADA	35	19S11A0498	SAI SUMANTH CHARY VADLA
3	19S11A0463	AKHIL VIKKURTHI	36	19S11A0499	SAMAD REDDY GADILA
4	19S11A0464	AMULYA K	37	19S11A04A0	SANMAPRIYA SURAKASULA
5	19S11A0465	ARAVIND REDDY SINGIDI	38	19S11A04A1	SHAIK ABUTALHA
6	19S11A0466	BHARGAV REDDY M	39	19S11A04A2	SHAILESH PALA
7	19S11A0467	BHASKAR NAGA SAI N	40	19S11A04A3	SHEKAR BAGANNAGARI
8	19S11A0468	DHEERAJ KUMAR S	41	19S11A04A4	SHIVA SAI KUMAR B
9	19S11A0469	ESHWAR TEJA VALABOJU	42	19S11A04A5	SOWMYA NALLAGORLA
10	19S11A0470	HARIKRISHNA ANUMULA	43	19S11A04A6	SRAVAN KUMAR JAJAM
11	19S11A0471	HEMA SRI YERRA	44	19S11A04A7	SRISHNA GONE
12	19S11A0472	KARTHIK KUMAR KASULAVADHA	45	19S11A04A8	SRIVIDHYA MAMIDI
13	19S11A0473	KARTHIK MUMMADI	46	19S11A04A9	TARUN CHANDRA T
14	19S11A0474	KETHAN PATEL	47	19S11A04B0	TARUN KUMAR GUMMALA
15	19S11A0475	KOWSHIK C	48	19S11A04B1	THARUN MIDDE
16	19S11A0476	KRISHNA MUSTIPALLY	49	19S11A04B3	UTHAM KUMAR REDDY BADDAM
17	19S11A0477	LIKHITH REDDY UPPELA	50	19S11A04B4	UTTEJ KYATHAM
18	19S11A0478	MADHURYA AKKINAGUNTA	51	19S11A04B5	VAMSHIKRISHNA KOTHI
19	19S11A0479	MANIDEEP THATIPELLY	52	19S11A04B6	VARSHINI PAPANKA
20	19S11A0480	MANVITH REDDY NAREDLA	53	19S11A04B7	VASAVI MANDEPUDI
21	19S11A0481	MD RAASHID ALI	54	19S11A04B8	VIJAYA BADETI
22	19S11A0482	NARASIMHA RAJU B	55	19S11A04B9	VIVEK THALLA
23	19S11A0483	NARENDRA DIKONDA	56	19S11A04C0	YASHWANTH KOTLA
24	19S11A0484	NAVYASRI RAYUDU	57	20S15A0421	RAMYA MADUPU
25	19S11A0486	NIREEKSHAN H	58	20S15A0422	SAI ADITHYA CHATLA
26	19S11A0487	NITHIN CHOWDARY	59	20S15A0423	SAI DHANUSH GUGULOTHU
27	19S11A0488	PAVAN S	60	20S15A0424	SAI PRAKASH GAJULA
28	19S11A0489	PRAVEEN KOLAGANI	61	20S15A0425	SAI TEJA KARNE
29	19S11A0491	RAMYA PATLOLLA	62	20S15A0426	SARA SUSHANK
30	19S11A0492	REDDY PAVAN KALYAN CH	63	20S15A0427	SHIVA KUMAR KALPAGURI
31	19S11A0493	RUCHITHA ASKANI	64	20S15A0428	SRI RAM MANIKANTA PALLA
32	19S11A0494	RUCHITHA THALLA	65	20S15A0429	SUJITH YAMSANI
33	19S11A0495	SAHITHI KURA	66	20S15A0430	VAMSHI GOPAGANI

MICROWAVE AND OPTICAL COMMUNICATIONS

SNo	H.T.NO	NAME OF THE STUDENT	SNo	H.T.NO	NAME OF THE STUDENT
1	19S11A0401	ABHILASH POLAM	36	19S11A0436	RISHIKETHAN REDDY MAMIDI
2	19S11A0402	ABHISHEK REDDY KAITHI	37	19S11A0437	RUCHITHA SHANAGONDA
3	19S11A0403	AJENDER REDDY BADDAM	38	19S11A0438	SAI KUMAR REDDY GURRALA
4	19S11A0404	AKSHITHA PITTALA	39	19S11A0439	SAI NIKHIL KOTHA
5	19S11A0405	ANKAL REDDY PATHAKOTTU	40	19S11A0440	SAI PRASAD RAJA BAI
6	19S11A0406	ANUSHA YERVA	41	19S11A0441	SAI PRIYA KONNERU
7	19S11A0407	ANVESH REDDY GADDAM	42	19S11A0442	SAI SUMANTH PEDDAGOLLA
8	19S11A0408	AVINASH KOLLI	43	19S11A0443	SAI TEJA GANDHAM
9	19S11A0409	BHARGAVA KRISHNA CHENNUPALLY	44	19S11A0444	SAIRAM KURA
10	19S11A0410	BHARGAVI PAILA	45	19S11A0445	SANDHYA RANI DONGALA
11	19S11A0411	BHARGAVI TEKMAL	46	19S11A0446	SANGEETHA KUMBAM
12	19S11A0412	BHAVIKA MANNEKUNTA	47	19S11A0447	SANJEEVINI SOMAYAJI CHEEPALLI
13	19S11A0413	DEEPTHI RAYALA	48	19S11A0448	SATHISH KUMAR BATTA
14	19S11A0414	DIVYATEJA BONGANI	49	19S11A0449	SATYANARAYANA KAVITI
15	19S11A0415	DURGA PRASAD MADDALA	50	19S11A0450	SHARATH KUMAR NARSINGA
16	19S11A0416	GOPI RAVULA	51	19S11A0451	SHIVA KUMAR K
17	19S11A0417	HANUMAN DUKHIYA	52	19S11A0452	SHREEYA CHEERLA
18	19S11A0418	KEERTHANA THONUPUNURI	53	19S11A0453	SOUMYA PATHI
19	19S11A0419	LAHARI MOTHE	54	19S11A0454	SRICHARAN REDDY PONDUGULA
20	19S11A0420	MANASA GUNDRA	55	19S11A0455	SWAPNA GAJJALA
21	19S11A0421	MANASA JANGALA	56	19S11A0456	UMA NAGALLA
22	19S11A0422	MANIKANTA YARA	57	19S11A0457	VAMSHI PANJALA
23	19S11A0423	MOHAN REDDY PININTI	58	19S11A0458	VENU KUMAR GOUD EDIGA
24	19S11A0424	NAGA VENKATA SAI KUMAR BONU	59	19S11A0459	VISHNU SAI P
25	19S11A0425	NAGU GOUD AITAGONI	60	19S11A0460	YASHWANTH GADE
26	19S11A0426	NANDINI KITIKE	61	17S11A04B2	THARUNDEEP RAKAM
27	19S11A0427	NARESH REDDY NAGIREDDY	62	18S11A0404	ANIL BADAVATH
28	19S11A0428	NIKHIL REDDY ETIKYALA	63	18S11A0421	GURUNATH AMGOTH
29	19S11A0429	NIRANJAN REDDY MANNE	64	18S11A0429	NAGARJUNA DEVA
30	19S11A0430	POOJITHA MUCHARLA	65	18S11A0434	RAJKUMAR BADE
31	19S11A0431	PRANITHA PALADUGU	66	18S11A0436	RAVITEJA GANJI
32	19S11A0432	RAKESH GUDI	67	18S11A0457	VIJAY TEJA KANDU
33	19S11A0433	RASHMITHA ALIMI	68	18S11A0459	VYSHNAV KUMAR REDDY KUMMETHA
34	19S11A0434	RAVI KUMAR GUNDEBOINA	69	18S11A04A2	SAI KRISHNA THALLAPELLI

35	19S11A0435	RENUSRI SREERAM			

LESSON PLAN:

Course Code	CourseTitle	Year	Branches	Contact Periods /Week	Academic Year	Date of commencement of Semester
16EC7L 01	MICROWAVE AND OPTICAL COMMUNICATIONS	IV	ECE	5	2022-23	Le g

COURSE OUTCOMES

After completion of the course students are able to

1	Summarize about different types of modes in wave guides and how to decrease the transmission and power losses, different types of microwave solid state devices and their applications (K2)
2	scribe the knowledge about how these microwaves are generated transmitted, amplified and finally measured using Passive devices.(K1,K2)
3	plain the fundamentals, advantages ,Ray theory transmission in Optical Communication and effect of dispersion of the signal, types of fiber materials, different losses in fibers 2,K3,K4)
4	**serve the knowledge about Optical transmitters, receivers and estimation of link and power budget analysis. .(K1,K2)**

UNIT	Out Comes / Bloom's Level	Topics No.	Topics/Activity	Text Book / Reference	Contact Hour	Delivery Method
I	CO1: Summarize about different types of modes in wave guides and how to decrease the transmission and power losses, different types of microwave solid state devices and their applications (K2)		**UNIT-1: WAVEGUIDES**			
		1.1	Microwave Spectrum, Bands and Applications of Microwaves	T1, T2	1	Chalk & Talk,Smart Class, PPT Tutorial
		1.2	Rectangular Waveguides – TE/TM mode analysis	T1, T3	1	
		1.3	Expressions for Fields	T1, T3	1	
		1.4	Characteristic Equation and Cut-off Frequencies	T1, T3	1	
		1.5	Dominant and Degenerate Modes	T1, T3	1	
		1.6	Sketches of TE and TM mode fields in the cross-section	T1, T3	1	
		1.7	Mode Characteristics – Phase and Group Velocities	T1,T3, R1,R2	1	
		1.8	Wavelengths and Impedance Relations	T1,T3, R1,R2	1	
		1.9	Power Transmission and Power Losses in Rectangular wave guide	T1,T3, R1,R2	1	
		1.10	Impossibility of TEM mode.	T1, T3, T3 ,R2	1	
Total					10	
II			**UNIT-2: MICROWAVE ACTIVE DEVICES**			
		2.1	**Transferred Electron Devices**: Gunn Diode-	T1, T2	2	Chalk &

	2: Describe the knowledge about how these microwaves are generated transmitted, amplified and finally measured using Passive devices. (K1,K2)		Principle, Two Valley Model Theory/RWH Theory,			Talk, Smart Class, PPT Tutorial, & Case Study
		2.2	Characteristics and Modes of operation.	T1, T2	1	
		2.3	**Avalanche Transit Time Devices:** IMPATT Diode-Principle of Operation and Characteristics, related expressions	T1, T2	1	
		2.4	TRAPATT Diode- Principle of Operation and Characteristics, related expressions	T1, T2,R1	1	
		2.5	IMPATT Diode , TRAPATT Diode -Problems	T1, T2,R1	1	
		2.6	Two Cavity Klystron Amplifier – Power and Efficiency considerations	T1, T2, R1, R2	1	
		2.7	Reflex Klystron Oscillators – Modes and Efficiency considerations	T1, T2, R1, R2	1	
		2.8	Magnetrons	T1, T2, R1, R2	1	
		2.9	TWT	T1,T2	1	
	Total				10	
III	2: Describe the knowledge about how these microwaves are generated transmitted, amplified and finally measured using Passive devices.(K1,K2) ,	**UNIT – 3: MICROWAVE PASSIVE DEVICES**				
		3.1	Waveguide Corners, Bends, Twists,	T1, T3,R2	1	Chalk & Talk, PPT Tutorial, Smart Class
		3.2	Scattering Parameters and Matrix,	T1, T3		
		3.3	Scattering parameters of Wave Guide Tees: E-Plane	T1,T3, R2	1	
		3.4	H-Plane	T1,T2, R1,R2	1	
		3.5	E & H Plane	T1,T2, R1,R2	1	
		3.6	Hybrid Rings (Rat-Race)	T1, T2, R1,R2	1	
		3.7	Directional Coupler: Single hole	T1,T3, R2	2	
		3.8	Directional Coupler:Multi hole	T1,T3, R1,R2	2	
		3.9	Fixed and Variable Attenuators	T1,T3, R2,R3	1	
		3.10	Ferrite Devices: Gyrator,	T1,T3, R2,R3	1	
		3.11	Isolator	T1,T3, R2,R3	1	

		3.12	Circulator	T1,T3, R1,R2	1	
Total					13	
IV	2: Describe the knowledge about how these microwaves are generated transmitted, amplified and finally measured using Passive devices. (K1,K2)	**UNIT - 4 MICROWAVE MEASUREMENTS**				
		4.1	Description Microwave Bench, Different Blocks and their Features, Precautions,	T1, T2.R1, R2	1	Chalk & Talk, PPT, Smart Class Tutorial, Active Learning & Case Study
		4.2	Frequency Meter	T2.R1	1	
		4.3	Slotted line section,	T2.R1	1	
		4.4	Measurement of Attenuation,	T2.R1	1	
		4.5	Measurement of Frequency	T1, T3.R1,	1	
		4.6	Measurement of Power,	T1, T3.R1, R2	1	
		4.7	Measurement of VSWR,	T1, T3.R1, R2	1	
		4.8	Measurement of Cavity Q	T1, T3.R1, R2	1	
		4.9	Measurement of Impedance.	T1, T3.R1, R2	1	
Total					9	
V	3: Explain the fundamentals, advantages ,Ray theory transmission in Optical Communication and effect of dispersion of the signal, types of fiber materials, different losses in fibers (K2,K3,K4)	**UNIT – 5: OPTICAL FIBERS AND DEVICES**				
		5.1	Propagation of light - Optical fiber structures,	T1, T3.R1, R2	1	Chalk & Talk, Smart Class, PPT Tutorial
		5.2	Acceptance angle, Numerical aperture, Attenuation,	T1, T2.R1, R2	1	
		5.3	Absorption losses	T1, T3.R1, R2	1	
		5.4	Scattering losses	T1, T3.R1, R2	1	
		5.5	Dispersion – Radiation losses	T1, T3.R1, R2	1	
		5.6	Splicing Technique	T1, T3.R1, R2	1	
		5.7	Optical Fiber connector,	T1,	1	

				T3.R1, R2		
		5.8	Connector types	T1, T3.R1, R2	1	
		5.9	single mode fiber connector	T1, T3.R1, R2	1	
				Total	9	
V	4: **Observe knowledge about Optical transmitters, receivers and estimation of link and power budget analysis.(K1,K2)**	**UNIT – 5 : OPTICAL NETWORKS**				
		6.1	Optical Source - LED, ILD characteristics.	T1, T3.R1, R2	1	Chalk & Talk, PPT Tutorial, Smart Class, Active Learning & Case Study
		6.2	Optical detectors – PIN and APD characteristics.	T1, T3, T3,R1	1	
		6.3	Optical transmitters and receivers,	T1, T3, T3,R1, R2	1	
		6.4	System block diagram	T1, T3, T3,R1, R2	1	
		6.5	point to point link	T1, T2.R1, R2	1	
		6.6	link design	T1, T2.R1, R2	1	
		6.7	power budget analysis	T1, T2.R1, R2	1	
		6.8	WDM- DWDM	T2	2	
Content beyond Syllabus (if needed)	Applications of Microwave-Microwave Oven, Fundamentals of RF Engineering					
				Total	9	
				CUMULATIVE PROPOSED PERIODS	**60**	

Text Books:

S.No.	**AUTHORS, BOOK TITLE, EDITION, PUBLISHER, YEAR OF PUBLICATION**
1.	Samuel Y. Liao, Microwave Devices and Circuits –PHI, 3rd Edition, 1994.
2.	M.Kulkarni, Microwave and Radar Engineering- Umesh Publications 4th Edition, 2010.
3.	Gerd Keiser, “Optical Fiber Communications”, the McGraw Hill Companies, 4th Edition, 2008.

Reference Books:

S.No.	**AUTHORS, BOOK TITLE, EDITION, PUBLISHER, YEAR OF PUBLICATION**

1.	Annapurna Das, Sisir K Das, “Microwave Engineering”, 2nd edition, 2006, Tata McGraw Hill.
2.	John. M. Senior, “Optical Fiber Communications Principles and Practice”, Second Edition, PHI, 1992.
Web Details	
1.	https://www.microwaves101.com/encyclopedias/waveguide-primer
2.	http://www.tallguide.com/Waveguidelinearity.html
3.	https://www.tutorialspoint.com/microwave_engineering

6.UNIT WISE LECTURE NOTES

a) Notes of Units

MICROWAVE AND OPTICAL COMMUNICATIONS

IV B. Tech I semester (JNTUH-R18)

ELECTRONICS & COMMUNICATION ENGINEERING

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

IV Year B. Tech ECE – I Sem **L T/P/D C 5 -/-/- 4**

(R15A0421) MICROWAVE ENGINEERINGOBJECTIVES

1. To analyze micro-wave circuits incorporating hollow, dielectric and planar waveguides, transmissionlines, filters and other passive components, active devices.
2. To Use S-parameter terminology to describe circuits.
3. To explain how microwave devices and circuits are characterized in terms of their “S” Parameters.
4. To give students an understanding of microwave transmission lines.
5. To Use microwave components such as isolators, Couplers, Circulators, Tees, Gyrators etc..
6. To give students an understanding of basic microwave devices (both amplifiers and oscillators).
7. To expose the students to the basic methods of microwave measurements.

UNIT I:

Waveguides & Resonators: Introduction, Microwave spectrum and bands, applications of Microwaves, Rectangular Waveguides-Solution of Wave Equation in Rectangular Coordinates, TE/TM mode analysis, Expressions for fields, Cutoff frequencies, filter characteristics, dominant and degenerate modes, sketchesof TE and TM mode fields in the cross-section, Mode characteristics - Phase and Group velocities, wavelengths and impedance relations, Rectangular Waveguides – Power Transmission and Power Losses, Impossibility of TEM Modes ,Micro strip Lines-Introduction,Z0 Relations, losses, Q-factor, Cavity resonators-introduction, Rectangular and cylindrical cavities, dominant modes and resonant frequencies, Q-factor and coupling coefficients, Illustrative Problems.

UNIT II:

Waveguide Components-I: Scattering Matrix - Significance, Formulation and properties, Wave guide multiport junctions - E plane and H plane Tees, Magic Tee,2-hole Directional coupler, S Matrix calculations for E plane and H plane Tees, Magic Tee, Directional coupler, Coupling mechanisms -Probe, Loop, Aperture types, Wave guide discontinuities - Waveguide Windows, tuning screws and posts,Irises,Transitions,Twists,Bends,Corners and matched loads, Illustrative Problems.

Waveguide Components-II: Ferrites composition and characteristics, Faraday rotation, Ferrite components - Gyrator, Isolator, Circulator.

UNIT III:

Linear beam Tubes: Limitations and losses of conventional tubes at microwave frequencies, Classification of Microwave tubes, **O type tubes** - 2 cavity klystrons-structure, Reentrant cavities,velocity modulation process and Applegate diagram, bunching process and small signal theory Expressions for o/p power and efficiency, Reflex Klystrons-structure, Velocity Modulation, Applegate diagram, mathematical theory of bunching, power output, efficiency, oscillating modes and o/p characteristics, Effect of Repeller Voltage on Power o/p, Significance, types and characteristics of slow wave structures, structure of TWT and amplification process (qualitative treatment), Suppression of oscillations, Gain considerations.

UNIT IV:

Cross-field Tubes: Introduction, Cross field effects, Magnetrons-different types, cylindrical travellingwave magnetron-Hull cutoff and Hartree conditions, modes of resonance and PI-mode operation, separation of PI-mode, O/P characteristics.

Microwave Semiconductor Devices: Introduction to Microwave semiconductor devices, classification, applications, Transfer Electronic Devices, Gunn diode - principles, RWH theory, Characteristics, Basic modes of operation - Gunn oscillation modes, LSA Mode, Introduction to Avalanche Transit time devices (brief treatment only), Illustrative Problems.

UNIT V:

Microwave Measurements: Description of Microwave Bench – Different Blocks and their Features, Precautions; Waveguide Attenuators – Resistive Card, Rotary Vane types; Waveguide Phase Shifters – Dielectric, Rotary Vane types. Microwave Power Measurement – Bolometer Method. Measurement of Attenuation, Frequency, VSWR, Cavity Q. Impedance Measurements.

TEXT BOOKS:

8. Microwave Devices and Circuits – Samuel Y. Liao, PHI, 3rd Edition,1994.
9. Microwave and Radar Engineering- M.Kulkarni, Umesh Publications,1998.

REFERENCES :

1. Foundations for Microwave Engineering – R.E. Collin, IEEE Press, John Wiley, 2nd Edition, 2002.
10. Microwave Circuits and Passive Devices – M.L. Sisodia and G.S.Raghuvanshi, Wiley Eastern Ltd., New Age InternationalPublishers Ltd., 1995.
11. Microwave Engineering Passive Circuits – Peter A. Rizzi, PHI, 1999.
12. Electronic and Radio Engineering – F.E. Terman, McGraw-Hill, 4th ed., 1955.
13. Elements of Microwave Engineering – R. Chatterjee, Affiliated East-West Press Pvt. Ltd., New Delhi,1988.

OUTCOMES

14. Understand the significance of microwaves and microwave transmission lines
15. Analyze the characteristics of microwave tubes and compare them
16. Be able to list and explain the various microwave solid state devices
17. Can set up a microwave bench for measuring microwave parameters

UNIT- I

MICROWAVE TRANSMISSION LINES-I

INTRODUCITON

Microwaves are electromagnetic waves with frequencies between 300MHz (0.3GHz) and 300GHz in the electromagneticspectrum.

Radio waves are electromagnetic waves within the frequencies 30KHz - 300GHz, and include microwaves. Microwaves are atthe higher frequency end of the radio wave band and low frequency radio waves are at the lower frequency end.

Mobile phones, phone mast antennas (base stations), DECT cordless phones, Wi-Fi,WLAN, WiMAX and Bluetooth have carrierwave frequencies within the microwave band of the electromagnetic spectrum, and are pulsed/modulated. Most Wi-Fi computersin schools use 2.45GHz (carrier wave), the same frequency as microwave ovens. Information about the frequencies can be foundin Wi-Fi exposures and guidelines.

It is worth noting that the electromagnetic spectrum is divided into different bands based on frequency. But the biological effectsof electromagnetic radiation do not necessarily fit into these artificial divisions.

A waveguide consists of a hollow metallic tube of either rectangular or circular cross section used to guide electromagnetic wave. Rectangular waveguide is most commonly used as waveguide. waveguides are used at frequencies in the microwave range.

At microwave frequencies (above 1GHz to 100 GHz) the losses in the two line transmission system will be very high and hence it cannot be used at those frequencies . hence microwave signals are propagated throughthe waveguides in order to minimize the losses.

Properties and characteristics of waveguide:

1. The conducting walls of the guide confine the electromagnetic fields and thereby guide the electromagnetic wave through multiple reflections .
2. when the waves travel longitudinally down the guide, the plane waves are reflected from wall to wall .the process results in a component of either electric ormagnetic fields in the direction of propagation of the resultant wave.
3. TEM waves cannot propagate through the waveguide since it requires an axial conductor for axial current flow .
4. when the wavelength inside the waveguide differs from that outside the guide, the

velocity of wave propagation inside the waveguide must also be different fromthat through free space.

5. if one end of the waveguide is closed using a shorting plate and allowed a wave to propagate from other end, then there will be complete reflection of the waves

resulting in standing waves.

APPLICATION OF MAXWELLS EQUATIONS TO THE RECTANGULAR WAVEGUIDE:

Let us consider waves propagating along O*z* but with restrictions in the *x* and/or *y* directions. The wave is now no longer necessarily transverse. The wave

equation canbe written as

$$\nabla^2\vec{H} + k^2\vec{H} = 0 \quad \text{where} \quad k = \frac{\omega}{c}$$

In the present case this becomes

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} - k_z^2 + k^2\right)\vec{H} = 0$$

and similarly for .electric field.

There are three kinds of solution possible

TEM	$H_z = E_z = 0,$	i.e. the familiar transverse EM waves
TE	$E_z = 0$	
TM	$H_z = 0$	

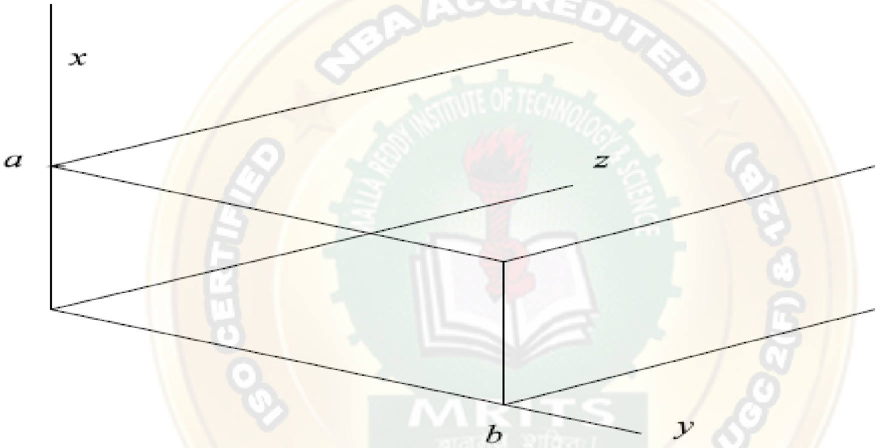
Boundary conditions:

We assume the guides to be perfect conductors so = 0 inside the guides. Hence, thecontinuity of *Et* at a boundary implies that *Et* = 0 in the wave guide at the boundary.

En is not necessarily zero in the wave guide at the boundary as there may be surface charges onthe conducting walls (the solution given below implies that there are such charges)

It follows from Maxwell's equation that because = 0, is also zero inside the conductor (the timedependence of is exp(-iT*t*)). The continuity of *Hn* implies that *Hn* = 0 at the boundary.

There are currents induced in the guides but for perfect conductors these can be only surface currents. Hence, there is no continuity for *Ht*. This is to be contrasted with the boundary conditionused for waves reflecting off conducting surfaces with finite conductivity.



The standard geometry for a rectangular wave guide is given fig 1. A wave can be guided by two parallel planes for which case we let the planes at *x* = 0, *a* extend to *y* = ±4.

TE Modes: By definition, *Ez* = 0 and we start from

$$H_z = H_0 X(x)\, Y(y)\, e^{ik_z z}$$

as the wave equation in Cartesian coordinates permits the use of the separation of variables.

TM Modes: By definition, *Hz* = 0 and we start from

$$E_z = E_0 X(x)\, Y(y)\, e^{ik_z z}$$

It is customary in wave guides to use the longitudinal field strength as the reference. For theparallel plate wave guide there is no y dependence so just set Y

=

TE modes

Using the above form for the solution of the wave equation, the wave equation can be rewritten as

$$\frac{X''}{X} + \frac{Y''}{Y} = k_z^2 - k^2$$

$$\text{Let} \quad \frac{X''}{X} = -k_x^2 \quad \text{and} \quad \frac{Y''}{Y} = -k_y^2 , \quad k_x^2 + k_y^2 + k_z^2 = k^2$$

the minus signs being chosen so that we get the oscillatory solutions needed to fit the boundaryconditions.

Now apply the boundary conditions to determine the restrictions on *Hz*. At *x* = 0, *a*:*Ey* = 0 and *H x* = 0 (*Ez* is zero everywhere)

For the following Griffith's writes down all the Maxwell equations specialized to propagationalong 0*z*. I will write just those needed for the specific task and motivate the choice.

We need to relate *Ey*, *Hx* to the reference *Hz*. Hence, we use the *y* component of ME2 (which has2 *H* fields and 1 *E* field)

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = -i\omega \epsilon_0 E_y$$

The first term is *ikzHx* which is zero at the boundary.

$$\text{Consequently,} \ \frac{\partial H_z}{\partial x} = \mathbf{0} \text{ at } x = 0, \ a \text{ and } \ X = \cos k_x x \ \text{ with}$$

$$k_x = \frac{m\pi}{a}$$

The absence of an arbitrary constant upon integration is justified below. At *y* = 0, *b*:*Ex* = 0 and *Hy* = 0 and we now use the *x* component of ME2

$$\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} = -i\omega \epsilon_0 E_x$$

As the second term is proportional *Hy* we get

The general solution is thus

$$\frac{n\pi}{b}$$

$$H_x = H_0 \cos(k_x x)\cos(k_y y)\, e^{ik_z z}$$

$$= H_0 \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) e^{ik_z z}$$

However, *m* = *n* = 0 is not allowed for the following reason. When *m* = *n* = 0, *Hz* is constant across the waveguide for any *xy* plane. Consider the integral version of Faraday's law for a path that lies in such a plane and encircles the wave guide but in the metal walls.

$$\int \vec{E}\cdot d\vec{\ell} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{a}$$

As *E* = 0 in the conducting walls and the time dependence of is given by exp(-*i*T*t*) this equation requires that . We need only evaluate the integral over the guide as = 0 in the walls. For constant *Bz* this gives *Bzab* = 0. So *Bz* = 0 as is *Hz*. However, as we have chosen *Ez* = 0 this implies a TEM wave which cannot occur inside a hollow waveguide. Adding an arbitrary constant would give a solution like

$$H_x = H_0\left[\cos\left(\frac{m\pi x}{a}\right) + \text{Const}\right]\cos\left(\frac{n\pi y}{b}\right) e^{ik_z z}$$

which is not a solution to the wave equation ... try it. It also equivalent to adding a solution with either *m* = 0 or *n* = 0 which is a solution with a different

Cut off frequency

This restriction leads to a minimum value for *k*. In order to get propagation *kz*2 > 0. Consequently

$$k^2 > k_x^2 + k_y^2$$

i.e. $$\omega^2 > c^2\pi^2\left[\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2\right]$$

Suppose *a* > *b* then the minimum frequency is *c*B/*a* and for a limited range of T (dependent on *a* and *b*) this solution (*m* = 1, *n* = 0, or TE10) is the only one possible.

Away from the boundaries

$$ik_zH_x + k_xH_z^x = -i\omega\epsilon_0E_y$$

where *Hzx* means that cos *k xx* has been replaced by sin *kxx*.

We need another relation between *Ey* and either *Hx* or *Hz*, which must come from the other Maxwell equation (ME1). We have to decide which component of ME1 to use. If we choose the *z* component, the equation involves *Ex* and *Ey*, introducing another unknown field (*Ex*). However, the *x* component involves *Ey* and *Ez*. As *Ez* = 0, this gives the required relation.

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = i\mu_0\omega H_x$$

$$i.e. \qquad -ik_zE_y = i\mu_0\omega H_x\,, \quad \text{or} \quad k_zE_y = -\mu_0\omega H_x$$

Substituting in the above gives

$$-\frac{ik_z^2E_y}{\mu_0\omega} + i\omega\epsilon_0E_y = -k_xH_z^x\,, \qquad E_y = \frac{i\mu_0\omega k_x}{k_x^2 + k_y^2}H_z^x\,, \text{ etc}$$

$$-k_yH_z^y - ik_zH_y = -i\omega\epsilon_0E_x$$

and the *y* component of ME1

$$ik_zE_x = i\mu_0\omega H_y$$

we get

$$-\frac{ik_z^2E_x}{\mu_0\omega} + i\omega\epsilon_0E_x = k_yH_z^y\,, \qquad E_x = -\frac{i\mu_0\omega k_y}{k_x^2 + k_y^2}H_z^y$$

Velocity

The phase velocity v_p is given by

$$v_p = \frac{\omega}{k_z} = \frac{ck}{k_z} = \frac{ck}{\sqrt{k^2 - k_x^2 - k_y^2}} > c$$

However the group velocity is given by

$$v_g = \frac{\partial\omega}{\partial k_z} = c\frac{\partial k}{\partial k_z} = c\frac{k_z}{k} < c \quad \text{and} \quad v_p v_g = c^2$$

TM modes

The boundary conditions are easier to apply as it is *Ez* itself that is zero at the boundaries.

Consequently, the solution is readily found to be

$$E_z = E_0 \sin(k_x x)\sin(k_y y)e^{ik_z z}$$

Note that the lowest TM mode is due to the fact that *Ez* . 0. Otherwise, along with *Hz* = 0, the solution is a TEM mode which is forbidden. The details are not given here as the TM wave between parallel plates is an assignment problem.

It can be shown that for ohmic losses in the conducting walls the TM modes are more attenuated than the TE modes.

MAXWELL EQUATIONS

$$ME1 \quad \vec{\nabla} \times \vec{E} = -\mu_0 \frac{\partial \vec{H}}{\partial t} \qquad ME2 \quad \vec{\nabla} \times \vec{H} = \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

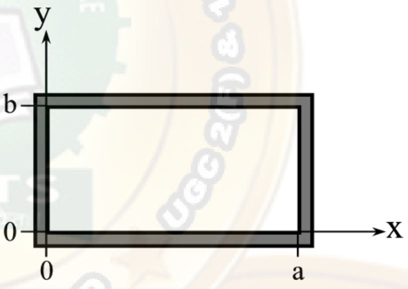
Rectangular Waveguide:

- Let us consider a rectangular waveguide with interior dimensions are a x b,
- Waveguide can support TE and TM modes.

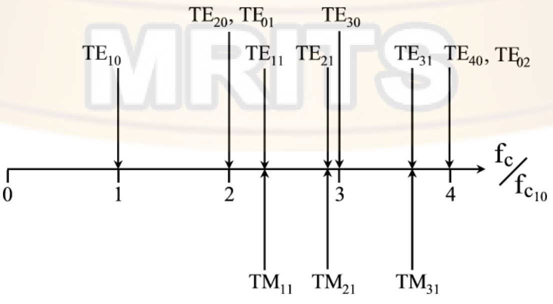
- In TE modes, the electric field is transverse to the direction of propagation.
- In TM modes, the magnetic field that is transverse and an electric field component is in the propagation direction.

- The order of the mode refers to the field configuration in the guide, and is given by m and n integer subscripts, TEmn and TMmn.
  - The m subscript corresponds to the number of half-wave variations of the field in the x direction, and
  - The n subscript is the number of half-wave variations in the y direction.
- A particular mode is only supported above its cutoff frequency. The cutoff frequency is given by

Rectangular Waveguide



e Location of mod



$$f_{c_{mn}} = \frac{1}{2\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m}{a}\right)^2+\left(\frac{n}{b}\right)^2} = \frac{c}{2\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{m}{a}\right)^2+\left(\frac{n}{b}\right)^2}$$

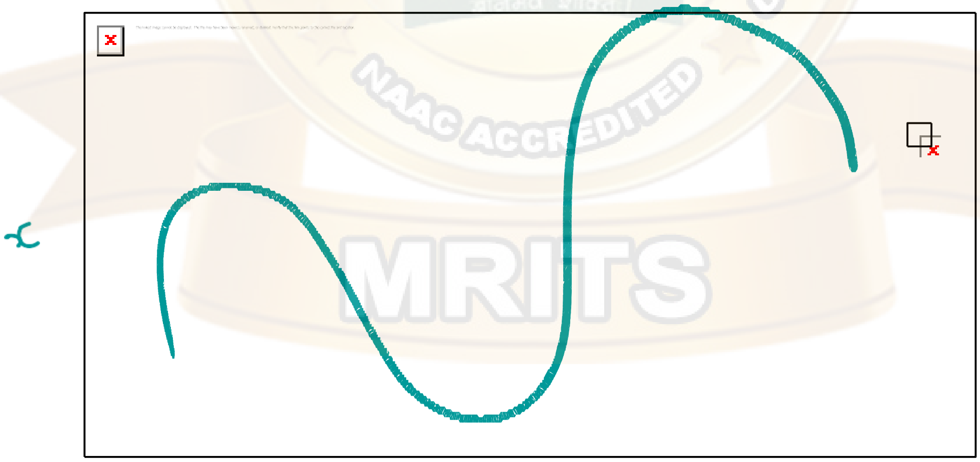
$$\sqrt{\mu_o\varepsilon_o}\ \sqrt{\mu_r\varepsilon_r}\quad \sqrt{\mu_r\varepsilon_r}$$

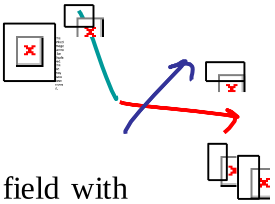
$$u = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\mu_o \mu_r \varepsilon_o \varepsilon_r} = \frac{1 \qquad 1}{\qquad\qquad} = \frac{c}{\qquad}$$

We can achieve a qualitative understanding of wave propagation in waveguide by considering thewave to be a superposition of a pair of TEM waves.

Let us consider a TEM wave propagating in the z direction. Figure shows the wave fronts; bold lines indicating constant phase at the maximum value of the field (+Eo), and lighter linesindicating constant phase at the minimum value (- Eo).

The waves propagate at a velocity uu, where the u subscript indicates media unbounded by guide walls. In air, uu = c.





Since we know **E** = 0 on a perfect conductor, we can replace the horizontal lines of zero field with perfectconducting walls. Now, u+ and u- are reflected off the walls as they propagate along the guide.

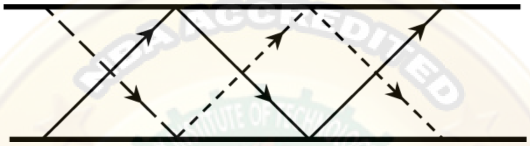
The distance separating adjacent zero-field lines in Figure (b), or separating the conducting walls in

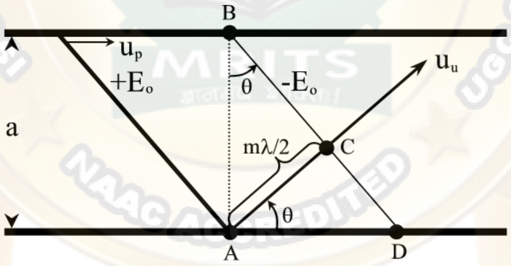
Figure (a),is given as the dimension a in Figure (b).

The distance *a* is determined by the angle q and by the distance between wavefront peaks, or the wavelength l.For a given wave velocity uu, the frequency is f = uu/l.

If we fix the wall separation at a, and change the frequency, we must then also change the angle q if we are tomaintain a propagating wave. Figure (b) shows wave fronts for the u+ wave.

The edge of a +Eo wave front (point A) will line up with the edge of a –Eo front (point B), and the two frontsmust be l/2 apart for the m = 1 mode.





For any value of m, we can write by simple trigonometry

sinq =

m

2

a

u

l =

s

i

n

q

=

$\underline{u}$

a m f

The waveguide can support propagation as long as the wavelength is smaller than a critical value, lc, thatoccurs at q = 90°, or

$$l_c = \frac{2a}{m} = \frac{u_u}{f_c}$$

Where *fc* is the cutoff frequency for the propagating mode.

We can relate the angle θ to the operating frequency and the cutoff frequency by

$$\sin\theta = \frac{\lambda}{\lambda} = \frac{f_c}{f}$$

The time *tAC* it takes for the wavefront to move from A to C (a distance *lAC*) is

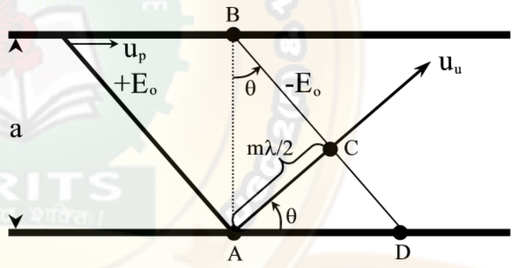
$$tAC = \frac{\text{Distance from A to C}}{\text{Wavefront Velocity}} = \frac{l_{AC}}{u_u} = \frac{m\lambda 2}{u_u}$$

A constant phase point moves along the wall from A to D. Calling this phase velocity *up*, and given the distance *lAD* is

$$l_{AD} = \frac{m\lambda 2}{\cos\theta}$$

Then the time *tAD* to travel from A to D is

$$t_{AD} = \frac{l_{AD}}{u_p} = \frac{m\lambda 2}{\cos\theta \; u_p}$$



Since the times *tAD* and *tAC* must be equal, we have

p

u

u

=

c

o

s

q

The *Wave velocity* is given by

$$u_u = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_o \mu_r \varepsilon_o \varepsilon_r}} =$$

1

1

$= \quad c \qquad \sqrt{\mu_o\varepsilon_o}\ \sqrt{\mu_r\varepsilon_r} \quad \sqrt{\mu_r\varepsilon_r}$

The *Phase velocity* is given by

$$u_p = \frac{u_u}{\cos}$$

$$q$$

$$\sqrt{\ \ }^{2} \quad \sqrt{\ \ }^{2} \quad \sqrt{(\ \ ')}^{2}$$

$$u_G = u_U \cos\theta$$

The *Group velocity* is given byThe phase constant is given by

$\beta \;= \beta_u \;\; 1-$

$\Big(f_c$

$\Big)^2 \quad \sqrt{\qquad f\big|}$

The guide wavelength is given by

$$\lambda = \frac{\lambda_u}{\sqrt{1-\left(f_c \;\; f\right)^2}}$$

The ratio of the transverse electric field to the transverse magnetic field for a propagating mode at a particularfrequency is the *waveguide impedance*.

For a TE mode, the wave impedance is

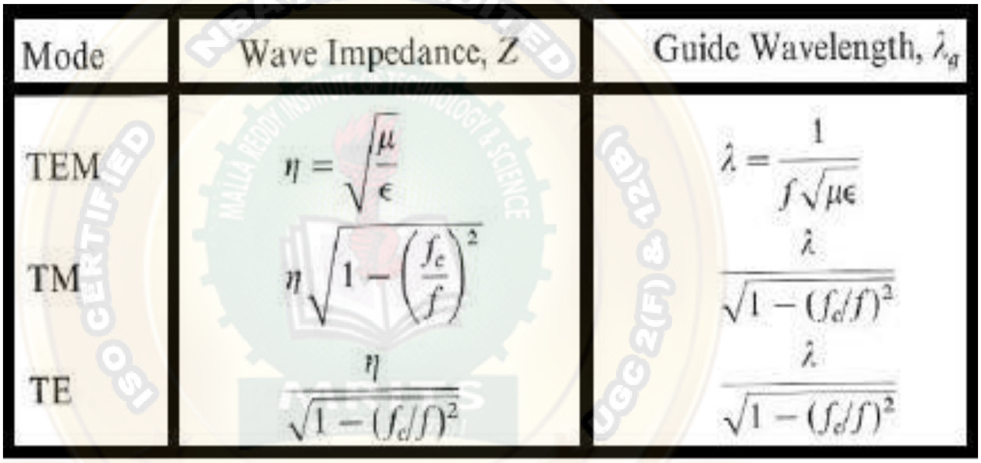
$$\boxed{Z_{mn}^{TE} = \frac{\eta_u}{\sqrt{1-\left(\frac{f_c}{f}\right)^2}}},$$

For a TM mode, the wave impedance is

$$\boxed{Z_{m}^{TM} = \eta_u \sqrt{1-\left(\frac{f_c}{f}\right)^2}}$$

General Wave Behaviors:

The wave behavior in a waveguide can be determined by



Mode	Wave Impedance, Z	Guide Wavelength, λ_g
TEM	$\eta = \sqrt{\frac{\mu}{\epsilon}}$	$\lambda = \frac{1}{f\sqrt{\mu\epsilon}}$
TM	$\eta\sqrt{1 - \left(\frac{f_c}{f}\right)^2}$	$\frac{\lambda}{\sqrt{1-(f_c/f)^2}}$
TE	$\frac{\eta}{\sqrt{1-(f_c/f)^2}}$	$\frac{\lambda}{\sqrt{1-(f_c/f)^2}}$

$$H_x^0 = -\frac{1}{h^2}\left(\gamma\frac{\partial H_z^0}{\partial x} - j\omega\epsilon\frac{\partial E_z^0}{\partial y}\right),$$

$$H_y^0 = -\frac{1}{h^2}\left(\gamma\frac{\partial H_z^0}{\partial y} + j\omega\epsilon\frac{\partial E_z^0}{\partial x}\right),$$

$$E_x^0 = -\frac{1}{h^2}\left(\gamma\frac{\partial E_z^0}{\partial x} + j\omega\mu\frac{\partial H_z^0}{\partial y}\right),$$

$$E_y^0 = -\frac{1}{h^2}\left(\gamma\frac{\partial E_z^0}{\partial y} - j\omega\mu\frac{\partial H_z^0}{\partial x}\right),$$

$$H_x^0 = \frac{j\omega\epsilon}{h^2}\frac{\partial E_z^0}{\partial y},$$

$$H_y^0 = -\frac{j\omega\epsilon}{h^2}\frac{\partial E_z^0}{\partial x},$$

$$E_x^0 = -\frac{\gamma}{h^2}\frac{\partial E_z^0}{\partial x},$$

$$E_y^0 = -\frac{\gamma}{h^2}\frac{\partial E_z^0}{\partial y}.$$

$$\nabla^2 E + k^2 E = 0$$

$$\nabla^2 H + k^2 H = 0$$

where $k^2 = \omega^2 \mu \varepsilon_c$

Then applying on the z-component

$$\nabla^2 E_z + k^2 E_z = 0$$

$$\frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + \frac{\partial^2 E_z}{\partial z^2} + k^2 E_z = 0$$

Solving by methodof Separation of Variables :

$E_Z(x, y, z) = X(x)Y(y)Z(z)$

fromwhere we obtain :

$$\frac{X''}{X} + \frac{Y''}{Y} + \frac{Z''}{Z} = -k^2$$

$$\frac{X''}{X} + \frac{Y''}{Y} + \frac{Z''}{Z} = k$$

$$-k_x^2 - k_y^2 + \gamma^2 = -k^2$$

which resultsin the expressions :

$$X'' + k_x^2 X = 0$$

$$Y'' + k_y^2 Y = 0$$

$$Z'' - \gamma^2 Z = 0$$

From Faraday and Ampere Laws we can find the remaining <u>four</u> components

$$E_x = -\frac{g}{h^2} \qquad \frac{\partial E_z}{\partial x} - \frac{j\omega\mu}{h^2}$$

Modes of propagation:

From the above equations we can conclude:

- TEM (*Ez*=*Hz*=0) can't propagate.

- TE (*Ez*=0) transverse electric
  - In TE mode, the electric lines of flux are perpendicular to the axis of thewaveguide

- TM (*Hz*=0) transverse magnetic, *Ez* exists
  - In TM mode, the magnetic lines of flux are perpendicular to the axis of thewaveguide.
- HE hybrid modes in which all components exists.

TM Mode:

E

$=$

$($

$\underline{m}$

$\underline{\pi}$

$)$

$($

$\underline{n}$

$\underline{\pi}$

$)$

$-j\beta z$

z $E_O \sin|$ x $y|e$

(a |)

si

n

|

)

(

b

$H_z = 0$

$E = -$ $\gamma\left(m\pi\right)$ $\left(m\pi x\right)$ $\left(n\pi y\right)$

γ ∂E $-\gamma z$

z

$E = -$ x $2|$ $|E_0 \cos|$ $|\sin|$ $|e$

- The *m* and *n* represent the mode of propagation and indicates the number ofvariations of the field in the *x* and *y* directions

TM Cutoff:

$$\gamma = \sqrt{\left(k_x^2 + k_y^2\right) - k^2}$$

$$= \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 - \omega^2\mu\varepsilon}$$

- The cutoff frequency occurs when 2 $\left(n\pi\right)$ 2

When $\omega_c^2 \mu\varepsilon = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2$

or $f_c = \frac{1}{2} \frac{1}{\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$

No propagation, everything is attenuated

$\left(m\pi\right)^2$ $\left(n\pi\right)^2$

$\left(n\pi\right)^2$

Propagation:

$\left(m\pi\right)^2$

When $\omega^2 \mu\varepsilon >$

Cutoff

- The cutoff frequency is the frequency below which attenuation occurs and abovewhich propagation takes place. (High Pass)

$$f_{c\,mn} = \frac{u'}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

The phase constant becomes

$$\boxed{\beta = \sqrt{\omega^2 \mu\varepsilon - \left(\frac{m\pi}{a}\right)^2 - \left(\frac{n\pi}{b}\right)^2} = \beta'\sqrt{1-\left(\frac{f_c}{f}\right)^2}}$$

Phase velocity and impedance

- The phase velocity is defined as

$$u_p = \frac{\square}{\beta'} \qquad \lambda = \frac{2\pi}{\square} = \frac{u_p}{f}$$

- intrinsic impedance of the mode is

$$\eta_{TM} = \frac{E_x}{H_y} = -\frac{E_y}{H_x} = \eta'\sqrt{1-\left[\frac{f_c}{f}\right]^2}$$

Microstrip transmission line is a kind of "high grade" printed circuit construction, consisting of a track of copper or other conductor on an insulating substrate. There is a "backplane" on the other side of the insulating substrate, formed from similar conductor.There is a "hot" conductor which is the track on the top, and a "return" conductor which is the backplane on the bottom. Microstrip is therefore a variant of 2-wire transmission line.

If one solves the electromagnetic equations to find the field distributions, one finds very nearly a completely TEM (transverse electromagnetic) pattern. This means that there are only a few regions in which there is a component of electric or magnetic field in the direction of wave propagation.

The field pattern is commonly referred to as a Quasi TEM pattern. Under some conditions one has to take account of the effects due to longitudinal fields. An example is geometrical dispersion, where different wave frequencies travel at different phase velocities, and the group and phase velocities are different.

The quasi TEM pattern arises because of the interface between the dielectric substrate and the surrounding air. The electric field lines have a discontinuity in direction at the interface. The boundary conditions for electric field are that the normal component (ie the component at right angles to the surface) of the electric field times the dielectric constant is continuous across the boundary; thus in the dielectric which may have dielectric constant 10, the electric field suddenly drops to 1/10 of its value in air. On the other hand, the tangential component (parallel to the interface) of the electric field is continuous across the boundary. In general then we observe a sudden change of direction of electric field lines at the interface, which gives rise to a longitudinal magnetic field component from the second Maxwell's equation, curl E = - dB/dt.

Since some of the electric energy is stored in the air and some in the dielectric, the effective dielectric constant for the waves on the transmission line will lie somewhere between that of the air and that of the dielectric. Typically the effective dielectric constant will be 50-85% of the substrate dielectric constant.

SUBSTRATE MATERIALS:

Important qualities of the dielectric substrate include

- The microwave dielectric constant
- The frequency dependence of this dielectric constant which gives rise to "materialdispersion" in which the wave velocity is frequency-dependent
- The surface finish and flatness
- The dielectric loss tangent, or imaginary part of the dielectric constant, which setsthe dielectric loss

- The cost
- The thermal expansion and conductivity
- The dimensional stability with time
- The surface adhesion properties for the conductor coatings
- The manufacturability (ease of cutting, shaping, and drilling)
- The porosity (for high vacuum applications we don't want a substrate whichcontinually "out gasses" when pumped)

Types of substrate include plastics, sintered ceramics, glasses, and single crystal substrates (single crystals may have anisotropic dielectric constants; "anisotropic" means they are different along the different crystal directions with respect to the crystalline axes.)

Common substrate materials

- Plastics are cheap, easily manufacturability, have good surface adhesion, but have poor microwave dielectric properties when compared with other choices.They have poor dimensional stability, large thermal expansion coefficients, and poor thermal conductivity.
    - Dielectric constant: 2.2 (fast substrate) or 10.4 (slow substrate)
    - Loss tangent 1/1000 (fast substrate) 3/1000 (slow substrate)
    - Surface roughness about 6 microns (electroplated)
    - Low thermal conductivity, 3/1000 watts per cm sq per degree
- Ceramics are rigid and hard; they are difficult to shape, cut, and drill; they comein various purity grades and prices each having domains of application; they have low microwave loss and are reasonably non- dispersive; they have excellentthermal properties, including good dimensional stability and high thermal conductivity; they also have very high dielectric strength. They cost more than plastics. In principle the size is not limited.

- Dielectric constant 8-10 (depending on purity) so slow substrate
- Loss tangent 1/10,000 to 1/1,000 depending on purity
- Surface roughness at best 1/20 micron

    - High thermal conductivity, 0.3 watts per sq cm per degree K
- Single crystal sapphire is used for demanding applications; it is very hard, needsorientation for the desired dielectric properties which are anisotropic;

is very expensive, can only be made in small sheets; has high dielectric constant so isused for very compact circuits at high frequencies; has low dielectric loss; has excellent thermal properties and surface polish.

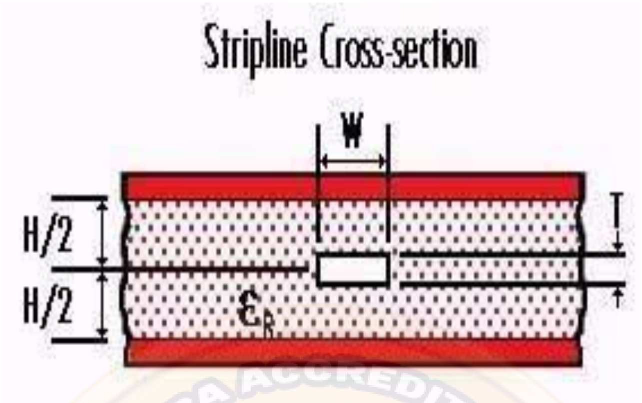
  - Dielectric constant 9.4 to 11.6 depending on crystal orientation (slowsubstrate)
  - Loss tangent 5/100,000
  - Surface roughness 1/100 micron
  - High thermal conductivity 0.4 watts per sq cm per degree K
- Single crystal Gallium Arsenide (GaAs) and Silicon (Si) are both used formonolithic microwave integrated circuits (MMICs).
  - Dealing with GaAs first we have.....
    - Dielectric constant 13 (slow substrate)
    - Loss tangent 6/10,000 (high resistivity GaAs)
    - Surface roughness 1/40 micron
    - Thermal conductivity 0.3 watts per sq cm per degree K (high)

GaAs is expensive and piezoelectric; acoustic modes can propagate in the substrate and can couple to the electromagnetic waves on the conductors.

The dielectric strength of ceramics and of single crystals far exceeds the strength of plastics, and so the power handling abilities are correspondingly higher, and the breakdown of high Q filter structures correspondinglyless of a problem.

It is also a good idea to have a high dielectric constant substrate and a slow wave propagation velocity; this reduces the radiation loss from the circuits. However at the higher frequencies the circuits get impossible small, which restricts the power handling capability.

Stripline is a conductor sandwiched by dielectric between a pair of ground planes, much like a coax cable would look after you ran it over with your small-manhood indicating SUV (let's not go there.) In practice, strip line is usually made by etching circuitry on a substrate that has a ground plane on the opposite face, then addinga second substrate (which is metalized on only one surface) on top to achieve the second ground plane. Strip line is most often a "soft-board" technology, but using low-temperature co-fired ceramics (LTCC), ceramic stripline circuits are also possible.



Transmission lines on either of the interior metal layers behave very nearly like "classic" stripline, the slight asymmetry is not a problem. Excellent "broadside" couplers can be made by running transmission lines parallel to each other on the two surfaces.

Other variants of the stripline are offset strip line and suspended air stripline (SAS).

For stripline and offset stripline, because all of the fields are constrained to the same dielectric, the effective dielectric constant is equal to the relative dielectric constant of the chosen dielectric material. For suspended stripline, you will have to calculate the effective dielectric constant, but if it is "mostly air", the effective dielectric constant will be close to 1.

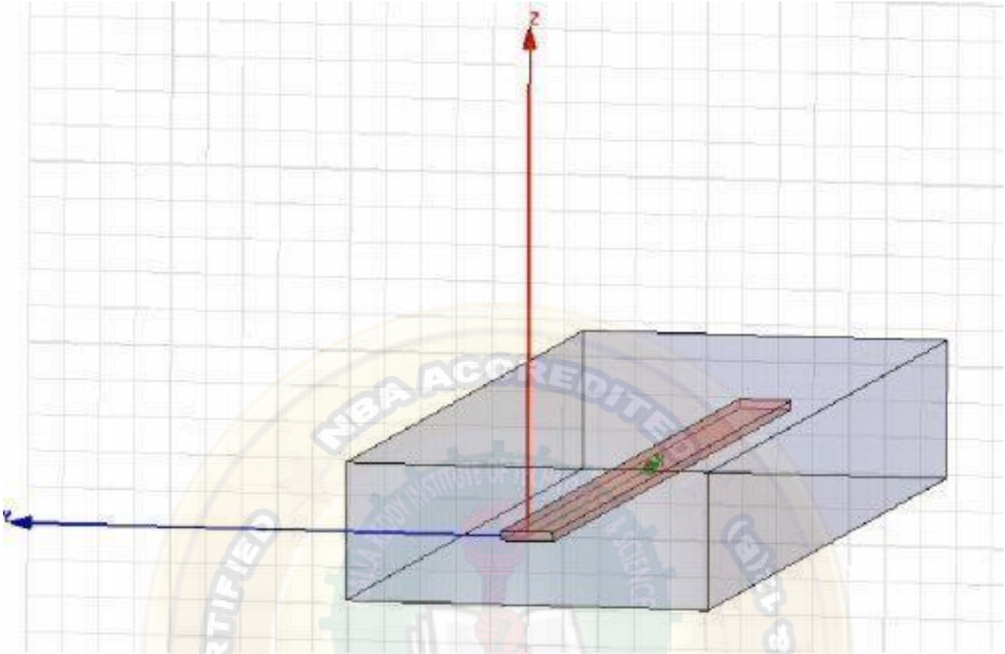
Advantages and disadvantages of stripline:

Stripline is a TEM (transverse electromagnetic) transmission line media, like coax. This means that it is non- dispersive, and has no cutoff frequency. Whatever circuits you can make on microstrip (which is quasi-TEM), you can do better using stripline, unless you run into fabrication or size constraints. Stripline filters and couplers always offer better bandwidth than their counterparts in microstrip.

Another advantage of stripline is that fantastic isolation between adjacent traces can be achieved (as opposed to microstrip). The best isolation results when a picket-fence of vias surrounds each transmission line, spaced at less than 1/4 wavelength. Stripline can be used to route RF signals across each other quite easily when offset stripline is used.

Disadvantages of stripline are two: first, it is much harder (and more expensive) to fabricate than microstrip. Lumped-element and active components either have to be buried between the ground planes (generally a tricky proposition), or transitions to microstrip must be employed as needed to get the components onto the top of the board.

The second disadvantage of stripline is that because of the second ground plane, the strip widths are much narrower for a given impedance (such as 50 ohms) and board thickness than for microstrip. A common reaction to problems with microstrip circuits is to attempt to convert them to stripline. Chances are you'll end up with a board thickness that is four times that of your microstrip board to get equivalent transmission line loss. That means you'll need forty mils thick strip line to replace ten mil thick micro strip! This is one of the reasons that soft-board manufacturers offer so many thicknesses.



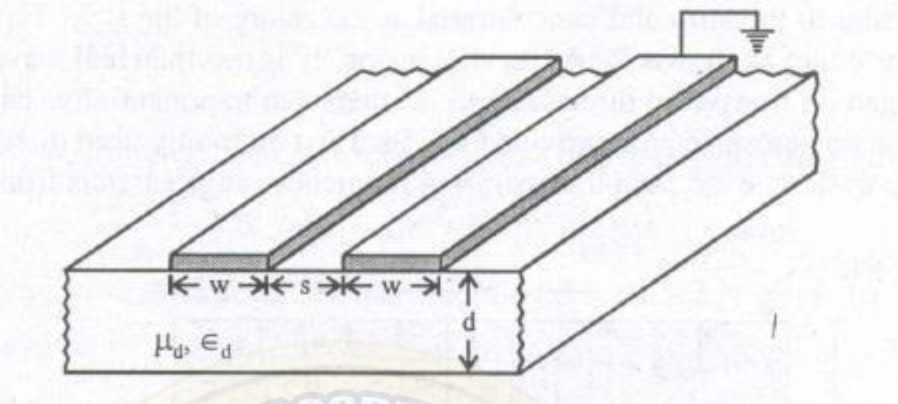
Stripline equations

A simplified equation for characteristic impedance of stripline is given as:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4H}{0.67\pi W\left(0.8 + \frac{t}{D}\right)}\right]$$

COPLANAR STRIP LINES

A coplanar strip line consisting of two strip conductors each of width separated by a distance "s", mounted on a single dielectric substrate, with one conducting strip grounded. Since both the strips are on one side of the substrate unlike the parallel strip lines, connection of shunt elements is very easy. This is an added advantage inthe manufacture of microwave integrated circuits (MICs). Because of this, reliability increases.



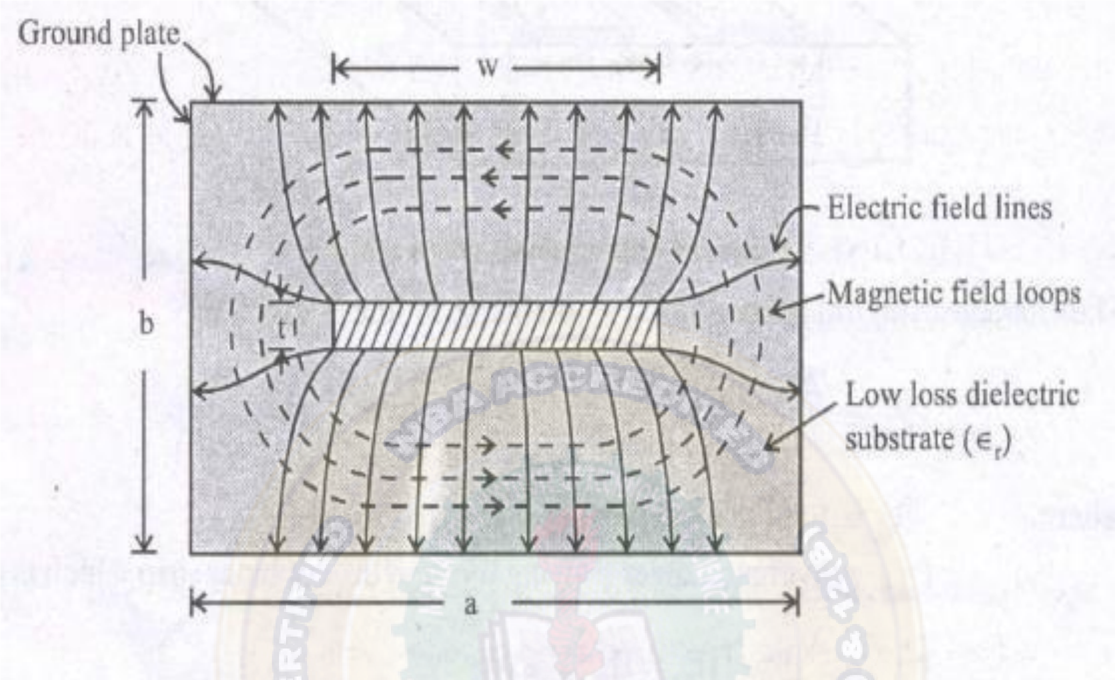
The characteristic impedance of the coplanar strip line is given by

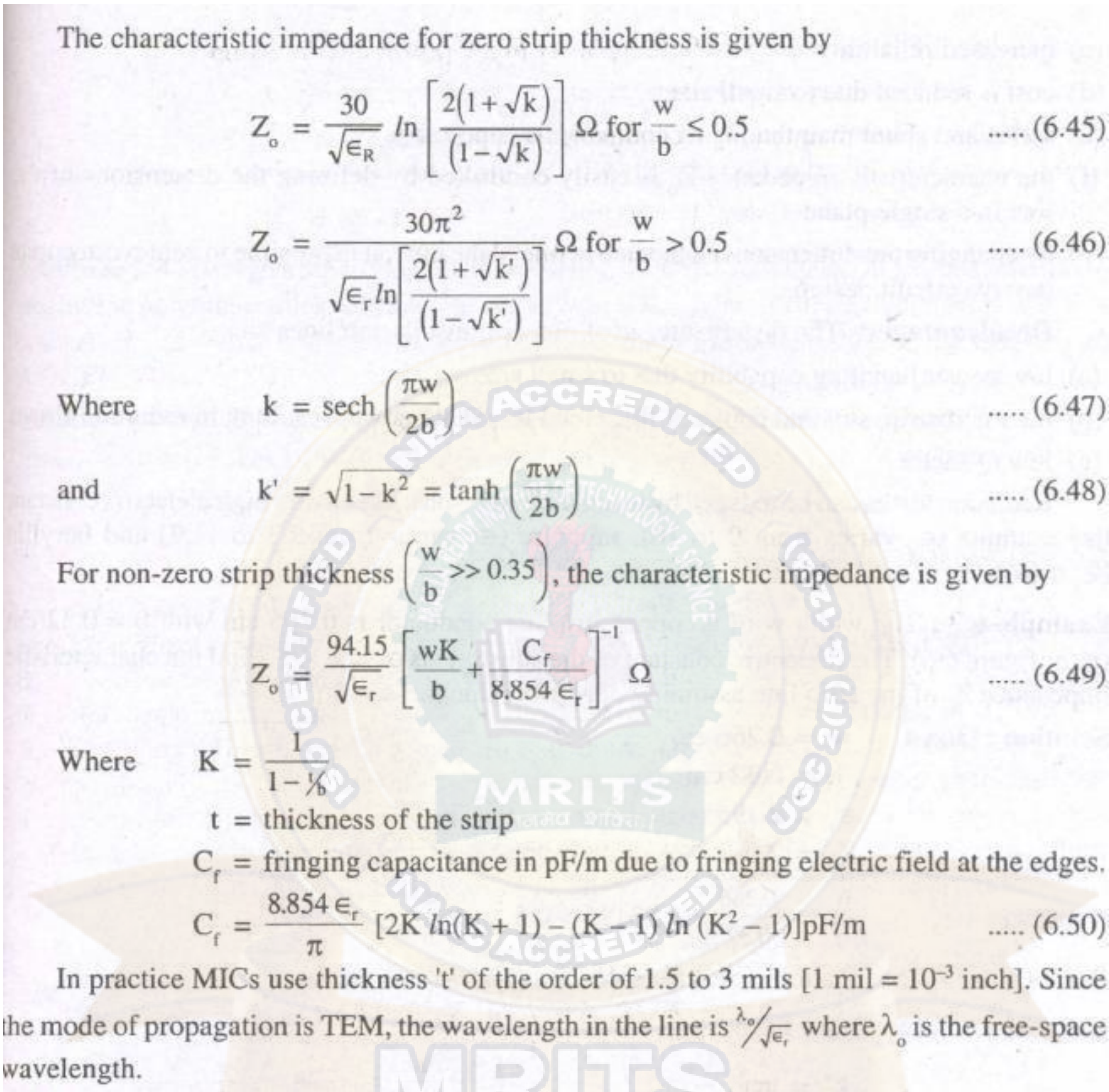
$$Z_0 = \frac{2P_{avg}}{I_0^2}$$

P = average power flowing through the coplanar strip

SHIELDED STRIP LINES

The configuration of strip line consisting of a thin conducting strip of width "w" much greater than its thickness "t". This strip line is placed at the centre surrounded by a low-loss dielectric substrate of thickness "b", between two ground plates as shown. The mode of propagation is TEM (transverse electro-magnetic) wave where the electric field lines are perpendicular to the strip and concentrated at the centre of the strip. Fringing field lines also exist at the edges .When the dimension 'b' is less than half wavelength, the field cannot propagate in transverse direction and is attenuated exponentially. The energy will be confined to the line cross-section provided a> 5b. The commonly used dielectrics are teflon,polyolefine, polystyrene etc., and the operating frequency range extends from 100 MHz to 30 GHz.


Ground plate
w
b
t
a
Electric field lines
Magnetic field loops
Low loss dielectric substrate ($\in_r$)



The characteristic impedance for zero strip thickness is given by

$$Z_o = \frac{30}{\sqrt{\epsilon_R}}\, ln\left[\frac{2(1+\sqrt{k})}{(1-\sqrt{k})}\right] \Omega \text{ for } \frac{w}{b} \le 0.5 \qquad \text{..... (6.45)}$$

$$Z_o = \frac{30\pi^2}{\sqrt{\epsilon_r}\, ln\left[\frac{2(1+\sqrt{k'})}{(1-\sqrt{k'})}\right]} \Omega \text{ for } \frac{w}{b} > 0.5 \qquad \text{..... (6.46)}$$

Where $k = \text{sech}\left(\frac{\pi w}{2b}\right)$ ..... (6.47)

and $k' = \sqrt{1-k^2} = \tanh\left(\frac{\pi w}{2b}\right)$ ..... (6.48)

For non-zero strip thickness $\left(\frac{w}{b} >> 0.35\right)$, the characteristic impedance is given by

$$Z_o = \frac{94.15}{\sqrt{\epsilon_r}}\left[\frac{wK}{b} + \frac{C_f}{8.854\,\epsilon_r}\right]^{-1} \Omega \qquad \text{..... (6.49)}$$

Where $K = \frac{1}{1 - t/b}$

t = thickness of the strip

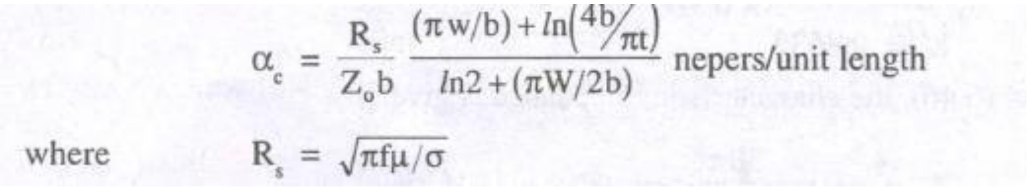
C_f = fringing capacitance in pF/m due to fringing electric field at the edges.

$$C_f = \frac{8.854\,\epsilon_r}{\pi}\,[2K\, ln(K+1) - (K-1)\, ln\,(K^2-1)]\text{pF/m} \qquad \text{..... (6.50)}$$

In practice MICs use thickness 't' of the order of 1.5 to 3 mils [1 mil = 10^{-3} inch]. Since the mode of propagation is TEM, the wavelength in the line is $\lambda_o/\sqrt{\epsilon_r}$ where λ_o is the free-space wavelength.

LOSSES IN STRIP LINES:

For low-loss dielectric substrate, the attenuation factor in the strip line arises from conductor losses and is given by



$$\alpha_c = \frac{R_s}{Z_o b}\,\frac{(\pi w/b) + ln(4b/\pi t)}{ln 2 + (\pi W/2b)} \text{ nepers/unit length}$$

where $R_s = \sqrt{\pi f \mu / \sigma}$

The attenuation constant of a microstrip line depends on frequency of operation, electrical properties ofsubstrate and the conductors and the geometry of mounting of strip on the dielectric.

When the dielectric substrate of dielectric constant is purely non-magnetic then three types of losses occur inmicrostrip lines . they are

1. Dielectric losses in substrate

1.Ohmic losses in strip conductor and ground plane1.Radiation loss

Dielectric losses in substrate:

All dielectric materials possess some conductivity but it will be small , but when it is not negligible, then the displacement current density leads the conduction current density by 90 degrees, introducing loss tangent for a lossy dielectric .

1.Ohmic losses in strip conductor and ground plane

In a microstrip line the major contribution to losses at micro frequencies is from finite conductivity ofmicrostrip conductor placed on a low loss dielectric substrate. Due to current flowing through the strip, there will be ohmic losses and hence attenuation of the microwave signal takes place. The current distribution in the transverse palne is fairly uniform with minimum value at the central axis and shooting up to maximum valuesat the edge of the strip.

2.Radiation losses:

At microwave frequencies , the microstrip line acts as an antenna radiating a small amount of power resulting in radiation losses. This loss depends on the thickness of the substrate, the characteristic impedance Z, effective dielectric constant and the frequency of operation.

For low-loss dielectric substrate, the attenuation factor in the strip line arises from conductor losses and is given by

$$\alpha_c = \frac{R_s}{Z_o b} \frac{(\pi w/b) + \ln\left(4b/\pi t\right)}{\ln 2 + (\pi W/2b)} \text{ nepers/unit length}$$

where $R_s = \sqrt{\pi f \mu / \sigma}$

Advantages and disadvantages of Planar Transmission Lines over Co- axial Lines:

Advantages:-

The advantages of planar transmission lines are

(a) very small size and hence low weight

(b) can be easily mounted on a metallic body including substrate.

(c) increased reliability

(d) cost is reduced due to small size

(e) series and shunt maintaining of components is possible

(f) the characteristic impedance Zo is easily controlled by defining the dimensions of theline in a single plane

(g) by changing the dimensions of the line in one plane only, it is possible to achieveaccurate passive circuit design

Disadvantages:-

The disadvantages of planar transmission lines are

(a) low power handling capability due to small size

(b)The microstrip, slot and coplanar lines tend to radiate power resulting in radiationlosses

(c) low Q-factor

UNIT- II

MICROWAVE WAVEGUIDE COMPONENTS AND APPLICATIONS

INTRODUCITON

WAVE GUIDE CORNERS , BENDS AND TWISTS:

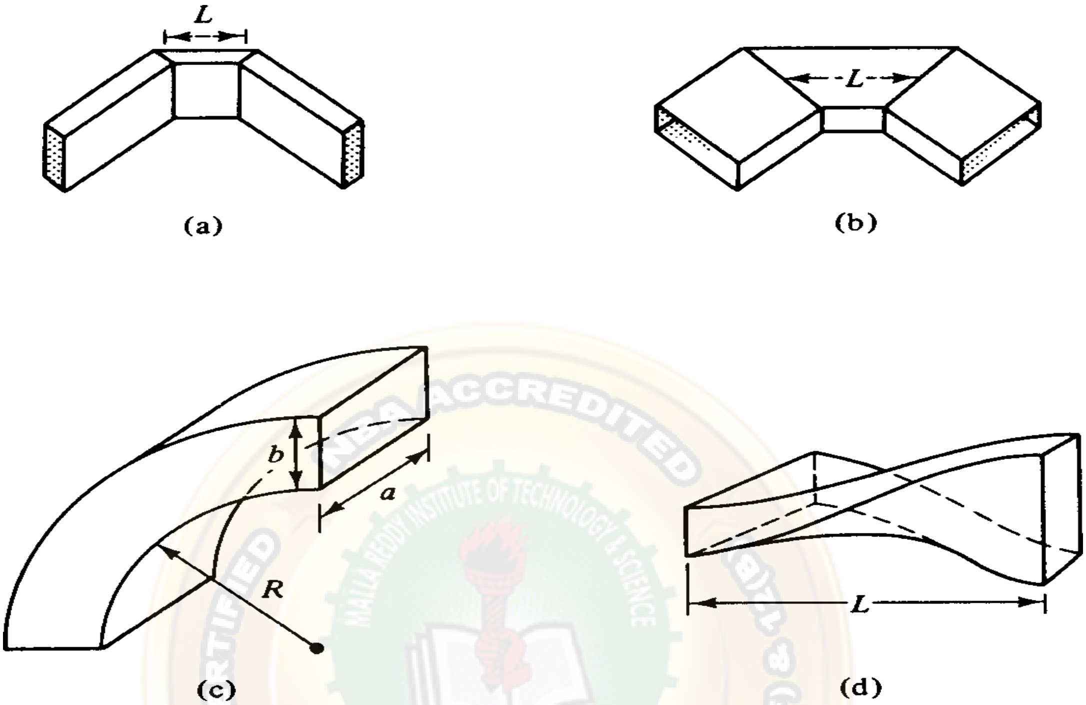
The waveguide corner, bend, and twist are shown in figure below, these waveguide components are normallyused to change the direction of the guide through an arbitrary angle.

In order to minimize reflections from the discontinuities, it is desirable to have the mean length L betweencontinuities equal to an odd number of quarter wave lengths. That is,

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

where n = 0, 1, 2, 3, ... , and Ag is the wavelength in the waveguide. If the mean length L is an odd number of quarter wavelengths, the reflected waves from both ends of the waveguide section are completely canceled. Forthe waveguide bend, the minimum radius of curvature for a small reflection is given by Southworth as

$$R = 1.5b \qquad \text{for an } E \text{ bend} \qquad R = 1.5a \qquad \text{for an } H \text{ bend}$$



(a) (b) (c) (d)

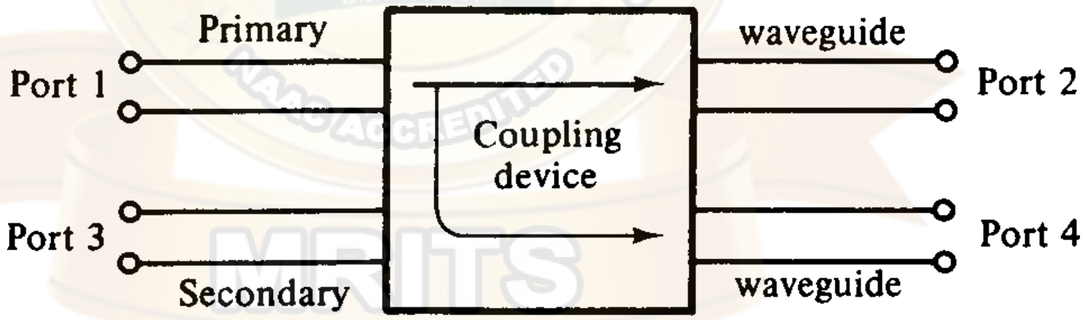
Waveguide corner, bend, and twist. (a) *E*-plane corner. (b) *H*-plane corner. (c) Bend. (d) Continuous twist.

DIRECTIONAL COUPLERS:

A directional coupler is a four-port waveguide junction as shown below. It Consists of a primary waveguide 1-2 and a secondary waveguide 3-4. When all Ports are terminated in their characteristic impedances, there is free transmission of the waves without reflection, between port 1 and port 2, and there is no transmission of power between port I and port 3 or between port 2 and port 4 because no coupling exists between these two pairs of ports. The degree of coupling between port 1 and port4 and between port 2 and port 3 depends on the structure of the coupler.

The characteristics of a directional coupler can be expressed in terms of its Coupling factor and its directivity.

Assuming that the wave is propagating from portto port2 in the primary line, the coupling factor and thedirectivity are defined,



Directional coupler.

where PI = power input to port I

P3 =power output from port 3

P4 = poweroutput from port 4

$$\text{Coupling factor (dB)} = 10\log_{10}\frac{P_1}{P_4}$$

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

It should be noted that port 2, port 3, and port 4 are terminated in their characteristic impedances. The coupling factor is a measure of the ratio of power levels in the primary and secondary lines. Hence if the coupling factor is known, a fraction of power measured at port 4 may be used to determine the power input at port 1 .

This significance is desirable for microwave power measurements because no disturbance, which may be caused by the power measurements, occurs in the primary line. The directivity is a measure of how well the forward traveling wave in the primary waveguide couples only to a specific port of the secondary waveguide ideal directional coupler should have infinite directivity. In other words, the power at port 3 must be zero because port 2 and portA are perfectly matched. Actually well-designed directional couplers have a directivityof only 30 to 35 dB.

Several types of directional couplers exist, such as a two-hole direct couler, four-hole directional coupler, reverse-coupling directional coupler , and Bethe- hole directional coupler the very commonly used two-hole directional coupler is described here.

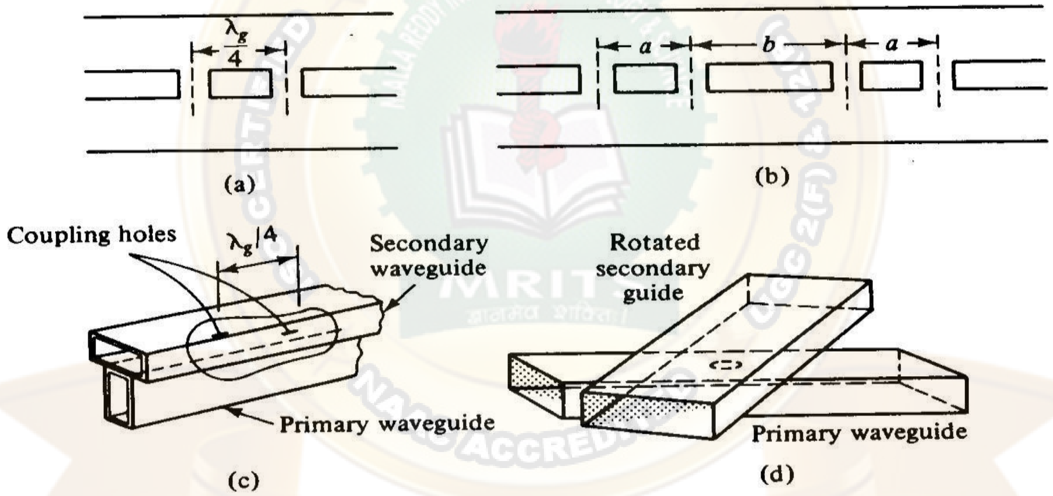


Figure 4-5-2 Different directional couplers. (a) Two-hole directional coupler. (b) Four-hole directional coupler. (c) Schwinger coupler. (d) Bethe-hole directional coupler.

TWO HOLE DIRECTIONAL COUPLERS:

A two hole directional coupler with traveling wave propagating in it is illustrated . the spacing between the centers of two holes is

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

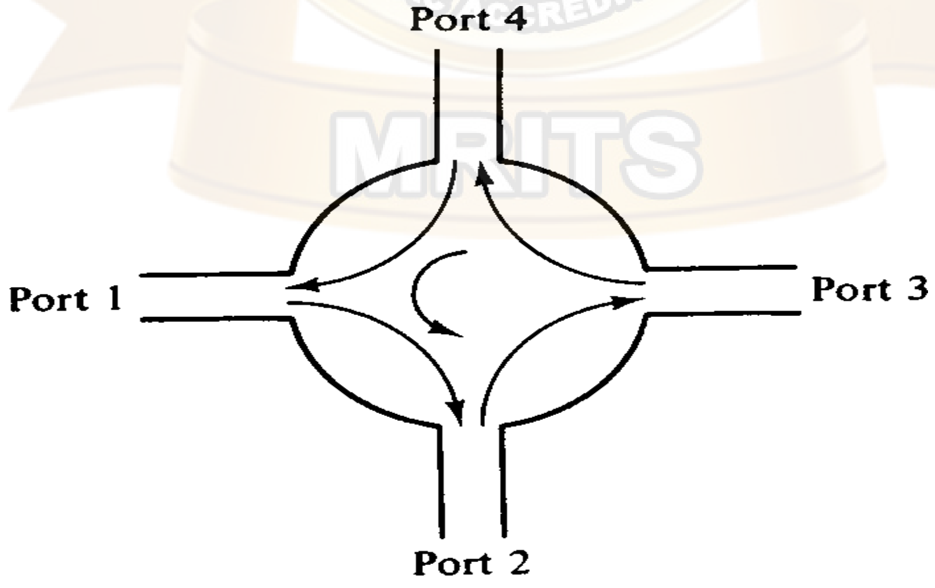
A fraction of the wave energy entered into port 1 passes through the holes and is radiated into the secondary guide as he holes act as slot antennas. The forward waves in the secondary guide are in same phase , regardless of the hole space and are added at port 4. the backward waves in the secondary guide are out of phase and are cancelled in port 3.

CIRCUALTORS AND ISOLATORS:

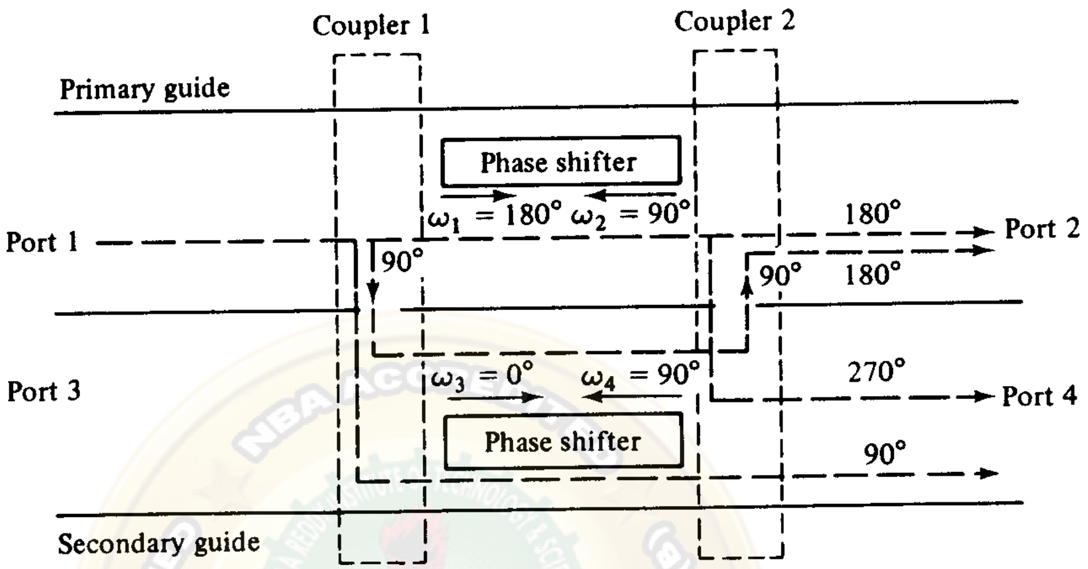
Both microwave circulators and isolators are non reciprocal transmission devices that use the property of Faraday rotation in the ferrite material. A non reciprocal phase shifter consists of thin slab of ferrite placed in a rectangular waveguide at a point where the dc magnetic field of the incident wave mode is circularly polarized. When a piece of ferrite is affected by a dc magnetic field the ferrite exhibits Faraday rotation. It does so because the ferrite is nonlinear material and its permeability is an asymmetric tensor.

MICROWAVE CIRCULATORS:

A *microwave circulator* is a multiport waveguide junction in which the wave can flow only from the *nth* port to the *(n* + I)th port in one direction Although there is no restriction on the number of ports, the four-port microwave circulator is the most common. One type of four-port microwave circulator is a combination of two 3-dB side hole directional couplers and a rectangular waveguide with two non reciprocal phase shifters.



The symbol of a circulator.



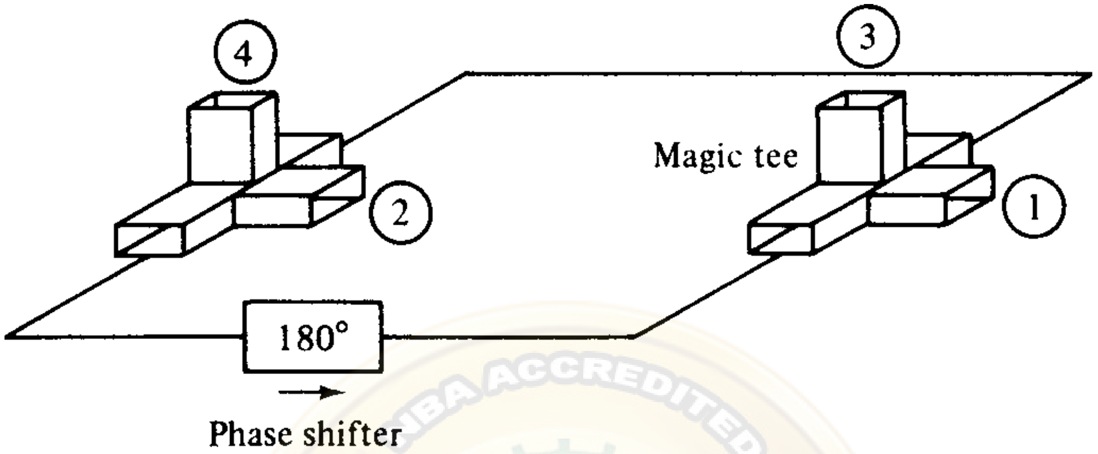
Schematic diagram of four-port circulator.

The operating principle of a typical microwave circulator can be analyzed with the aid of Fig shown above .Each of the two 3-dB couplers in the circulator introduces a phase shift of 90°, and each of the two phase shifters produces a certain amount of phase change in a certain direction as indicated. When a wave is incident to port 1,the wave is split into two components by coupler I. The wave in the primary guide arrives at port 2 with a relative phase' change of 180°. The second wave propagates through the two couplers and the secondary guide and arrives at port 2 with a relative phase shift of 180°. Since the two waves reaching port 2 are in phase, the power transmission is obtained from port 1 to port 2. However, the wave propagates through theprimary guide, phase shifter, and coupler 2 and arrives at port 4 with a phase change of 270°. The wave travels through coupler 1and the secondary guide, and it arrives at port 4 with a phase shift of 90°. Since the two waves reaching port 4 are out of phaseby 180°, the power transmission from port 1 to port 4 is zero. In general, the differential propagation constants in the two directions of propagation in a waveguide containing ferrite phase shifters should be

$$\omega_1 - \omega_3 = (2m + 1)\pi \qquad \text{rad/s}$$

$$\omega_2 - \omega_4 = 2n\pi \qquad \text{rad/s}$$

where *m* and *n* are any integers, including zeros. A similar analysis shows that a wave incident to port 2 emerges at port 3 and so on. As a result, the sequence of power flow is designated as 1 ~ 2 ~ 3 ~ 4 ~ 1. Manytypes of microwave circulators are in use today. However, their principles of operation remain the same. .A four-port circulator is constructed by the use of two magic tees and a phase shifter. The phase shifter produces a phase shift of 180°.



A four-port circulator.

A perfectly matched, lossless, and nonreciprocal four-port circulator has an S matrix of the form

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

Using the properties of S parameters the S-matrix is

$$\mathbf{S} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

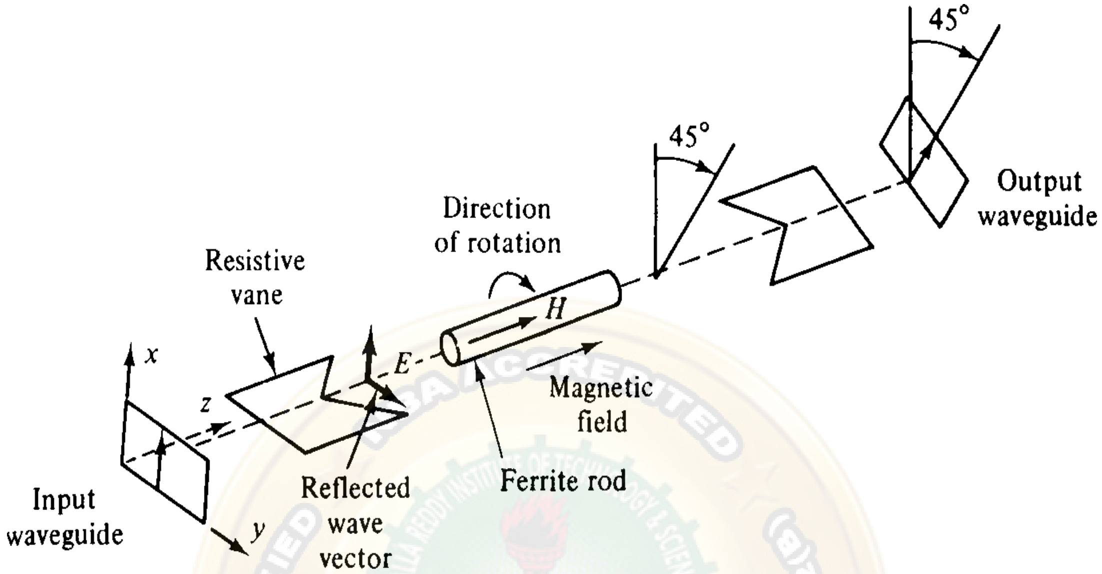
MICROWAVE ISOLATORS:

An *isolator* is a nonreciprocal transmission device that is used to isolate one component from reflections of other components in the transmission line. An ideal isolator completely absorbs the power for propagation in one direction and provides lossless transmission in the opposite direction. Thus the isolator is usually called *uniline.*

Isolators are generally used to improve the frequency stability of microwave generators, such as klystrons and magnetrons, in which the reflection from the load affects the generating frequency. In such cases, the isolator placed between the generator and load prevents the reflected power from the unmatched load from returning to the generator. As a result, the isolator maintains the frequency stability of the generator**.**

Isolators can be constructed in many ways. They can be made by terminating ports 3 and 4 of a four-port circulator with matchedloads. On the other hand, isolators can be made by inserting a ferrite rod along the axis of a rectangular waveguide as shown below.

The isolator here is a Faraday-rotation isolator. Its operating principle can be explained as follows . The input resistive card is in the *y-z* plane, and the output resistive card is displaced 45° with respect to the input card. Thedc magnetic field, which is applied longitudinally to the ferrite rod, rotates the wave plane of polarization by 45°. The degrees of rotation depend on the length and diameter of the rod and on the applied de magnetic field. An input TEIO dominant mode is incident to the left end of the isolator. Since the TEIO mode wave is perpendicular to the input resistive card, the wave passes through the ferrite rod without attenuation. The wave in the ferrite rod section is rotated clockwise by 45° and is normal to the output resistive card. As a result of rotation, the wave arrives at the output.


45°
45°
Output waveguide
Direction of rotation
Resistive vane
H
x
E
z
Magnetic field
Ferrite rod
Input waveguide
Reflected wave vector
y

end without attenuation at all. On the contrary, a reflected wave from the output end is similarly rotated clockwise 45° by the ferrite rod. However, since the reflected wave is parallel to the input resistive card, the wave is thereby absorbed by the input card. The typical performance of these isolators is about 1-dB insertion loss in forward transmission and about 20- to 30-dB isolation in reverse attenuation.

WAVE GUIDE TEE JUNCTIONS:

A waveguide Tee is formed when three waveguides are interconnected in the form of English alphabet T and thus waveguide tee is 3-port junction. The waveguide tees are used to connects a branch or section of waveguide in series or parallel with the main waveguide transmission line either for splitting or combining power in a waveguide system.

There are basically 2 types of tees namely

1.H- plane Tee junction

2.E-plane Tee junction

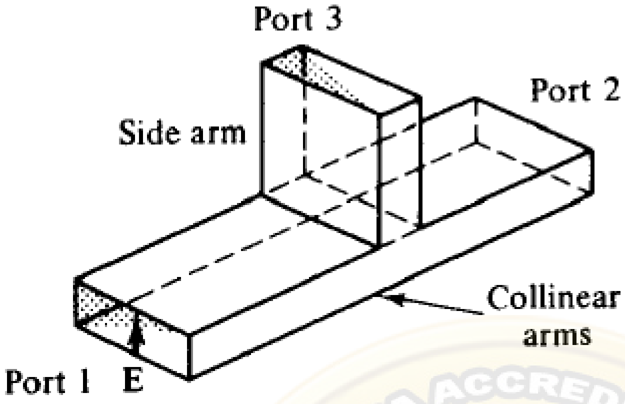
A combination of these two tee junctions is called a hybrid tee or " Magic Tee".

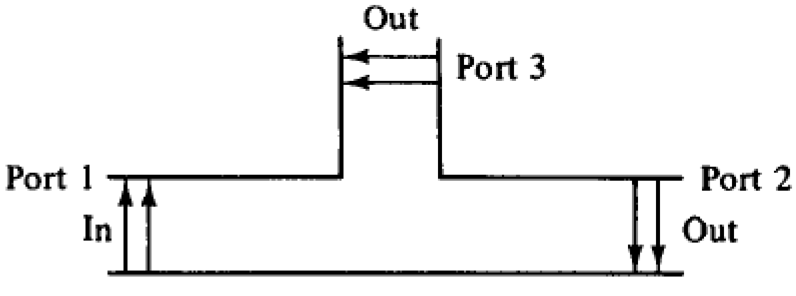
E-plane Tee(series tee):

An E-plane tee is a waveguide tee in which the axis of its side arm is parallel to the E field of themain guide . if the collinear arms are symmetric about the side arm.

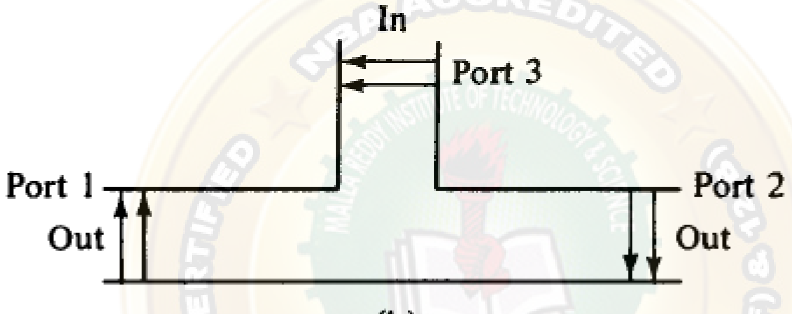
If the E-plane tee is perfectly matched with the aid of screw tuners at the junction , the diagonalcomponents of the scattering matrix are zero because there will be no reflection.

When the waves are fed into side arm, the waves appearing at port 1 and port 2 of the collineararm will be in opposite phase and in same magnitude.


Port 3
Port 2
Side arm
Collinear arms
Port 1
E



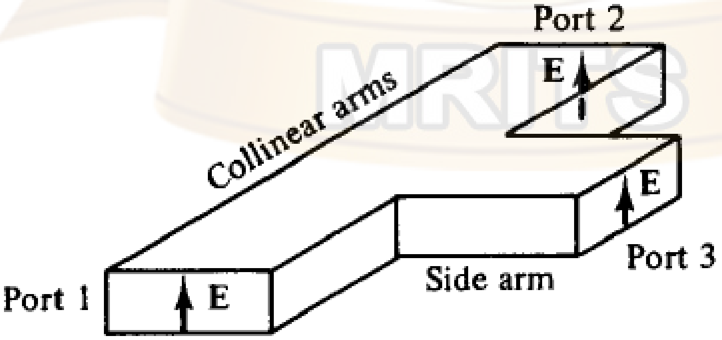
(a)



(b)

H-plane tee: (shunt tee)

An H-plane tee is a waveguide tee in which the axis of its side arm is shunting the E field orparallel to the H-field of the main guide.

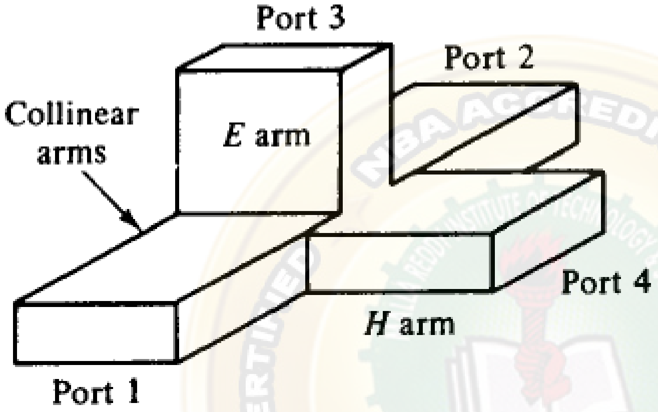


If two input waves are fed into port 1 and port 2 of the collinear arm, the output wave at port 3will be in phase and additive .

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

Magic Tee (Hybrid Tees)

A magic tee is a combination of E-plane and H-plane tee. The characteristics of magic tee are:



1.If two waves of equal magnitude and 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 it will be divided equally between port 1 and port 2 of the collinear arms and will not appear at port 3.

3.If a wave is fed into port 3 , it will produce an output of equal magnitude and opposite phase at port 1 and port 2. the output at port 4 is zero.

4.If a wave is fed into one of the collinear arms at port 1 and port 2, it will not appear in the other collinear arm at port 2 or 1 because the E-arm causes a phase delay while H armcauses a phase advance**.**

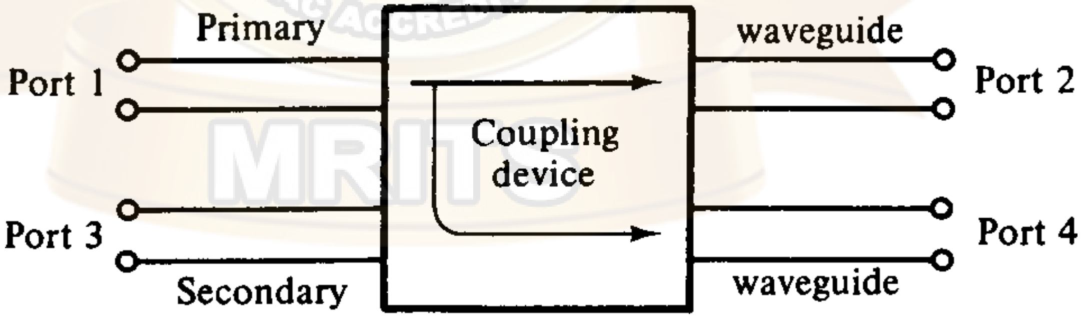
Therefore the **S** matrix of a magic tee can be expressed as

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

DIRECTIONAL COUPLERS:

A directional coupler is a four-port waveguide junction as shown below. It Consists of a primary waveguide 1-2 and a secondary waveguide 3-4. When all Ports are terminated in their characteristic impedances, there is free transmission of the waves without reflection, between port 1 and port 2, andthere is no transmission of power between port I and port 3 or between port 2 and port 4 because no coupling exists between these two pairs of ports. The degree of coupling between port 1 and port4 and between port 2 and port 3 depends on the structure of the coupler.

The characteristics of a directional coupler can be expressed in terms of its Coupling factor and its directivity. Assuming that the wave is propagating from port to port2 in the primary line, the couplingfactor and the directivity are defined,



Directional coupler.

where PI = power input to

port IP3 = power output

$$\text{Coupling factor (dB)} = 10 \log_{10} \frac{P_1}{P_4}$$

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

from port 3 P4 = power

output from port 4

It should be noted that port 2, port 3, and port 4 are terminated in their characteristic impedances.The coupling factor is a measure of the ratio of power levels in the primary and secondary lines. Hence if the coupling factor is known, a fraction of power measured at port 4 may be used to determine the power input at port 1.

This significance is desirable for microwave power measurements because no disturbance, which may be caused by the power measurements, occurs in the primary line. The directivity is a measure of how well the forward traveling wave in the primary waveguide couples only to a specific port of the secondary waveguide ideal directional coupler should have infinite directivity. In other words, the power at port 3 must be zero because port 2 and portA are perfectly matched. Actually well- designed directional couplers have a directivity of only 30 to 35 dB.Several types of directional couplers exist, such as a two-hole direct couler, four-hole directional coupler, reverse-coupling directional coupler , and Bethe-hole directional coupler the very commonly used two-hole directional coupler is described here.

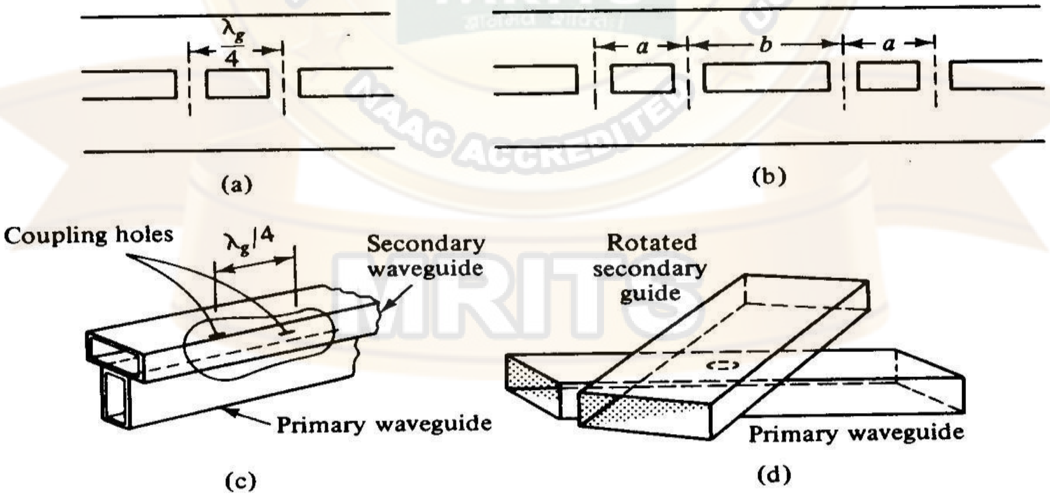


Figure 4-5-2 Different directional couplers. (a) Two-hole directional coupler. (b) Four-hole directional coupler. (c) Schwinger coupler. (d) Bethe-hole directional coupler.

TWO HOLE DIRECTIONAL COUPLERS:

A two hole directional coupler with traveling wave propagating in it is illustrated . the spacing between the centers of two holes is

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

A fraction of the wave energy entered into port 1 passes through the holes and is radiated into the secondary guide as he holes act as slot antennas. The forward waves in the secondary guide are in same phase , regardless of the hole space and are added at port 4. the backward waves in the secondary guide are out of phase and are cancelled in port 3.

S-matrix for Directional coupler:

The following characteristics arc observed in an ideal Directional Coupler:

1. Since the directional coupler is a 4-portjunction, the order or (S I matrix is 4 x 4 givcnby

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

2. Microwave power fed into port (I) cannot comc out of port (3) as port (3) is the backport. Therefore the scattering co-efficient S13 is zero...'

$$S_{13} = 0$$

3. Because of the symmetry of the junction, an input power at port (2) cannot couple toport (4) as port (4) is the back-port for port (2)

$$S_{24} = 0$$

4. Let us assume that port (3) and (4) are perfectly matched to the junction so that

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

Then, the remaining two ports will be "automatically" matched to the junction

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

From the symmetric property of ISI matrix, we have

$$S_{ij} = S_{ji}$$

With the above characteristic values for S-parameters, the matrix of (5.125) becomes

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

From unitary property of equation we have

$$[\text{Since } S_{21} = S_{12}, S_{31} = S_{13} = 0, S_{32} = S_{23}, S_{41} = S_{14}, S_{42} = S_{24} = 0 \text{ and } S_{43} = S_{34}]$$

$$[S]\,[S]^* = [U]$$

$$\begin{bmatrix} 0 & S_{12} & 0 & S_{14} \\ S_{12} & 0 & S_{23} & 0 \\ 0 & S_{23} & 0 & S_{34} \\ S_{14} & 0 & S_{34} & 0 \end{bmatrix} \begin{bmatrix} 0 & S_{12}^* & 0 & S_{14}^* \\ S_{12}^* & 0 & S_{23}^* & 0 \\ 0 & S_{23}^* & 0 & S_{34}^* \\ S_{14}^* & 0 & S_{34}^* & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Considering 1st row and 1st column,

$$|S_{12}|^2 + |S_{14}|^2 = 1$$

Considering 2st row and 2nd column,

$$|S_{12}|^2 + |S_{23}|^2 = 1$$

Considering 3rd row and 3rd column,

$$|S_{23}|^2 + |S_{34}|^2 = 1$$

Considering 1st row and 3rd column,

$$S_{12} S_{23}^* + S_{14} S_{34}^* = 0$$

Comparison of equations (5.133) and (5.134) yields

$$S_{14} = S_{23}$$

Comparing equations (5.134) and (5.135), we get

$$S_{12} = S_{34}$$

Let S_{12} be ***"real and positive "equal*** to p

Then $S_{34} = p = S_{34}^* = S_{12}$

Using equations (5.137) and (5.139) in (5.136), we get

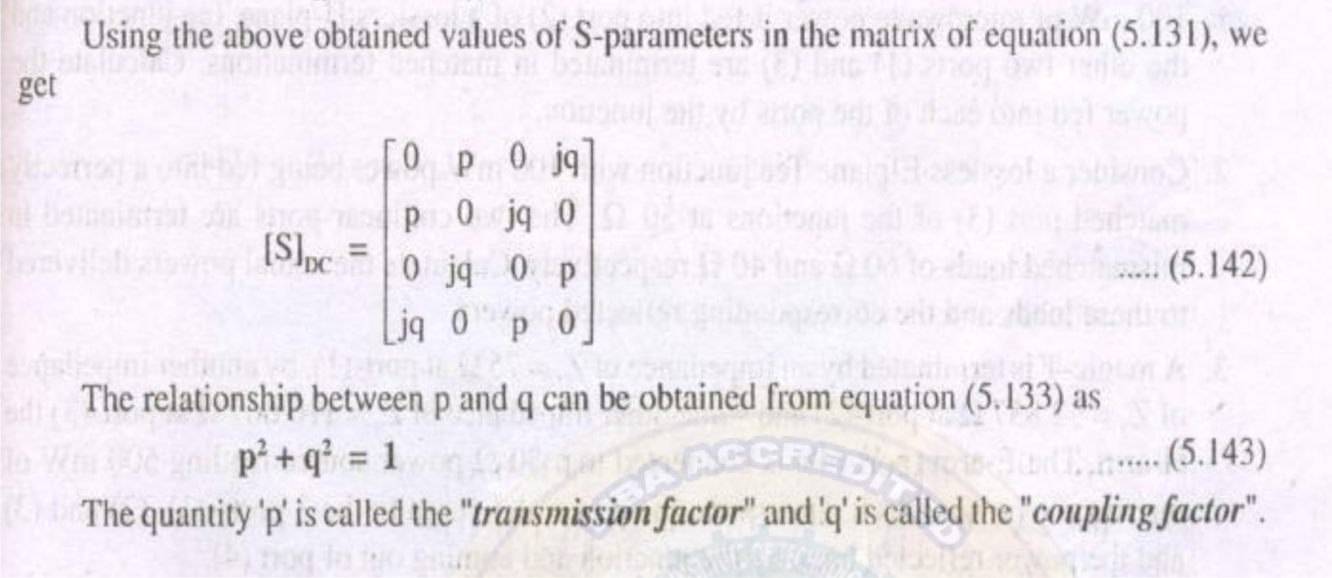
$$S_{12} S_{23}^* + S_{23} S_{12} = 0$$

$$\therefore \quad S_{12} (S_{23} + S_{23}^*) = 0$$

Since $S_{12} \neq 0$, we must have $S_{23} + S^*_{23} = 0$

Equation (5.140) will be satisfied only when S_{23} is purely imaginary.

Let $S_{23} = jq = S_{14}$



Using the above obtained values of S-parameters in the matrix of equation (5.131), we get

$$[S]_{DC} = \begin{bmatrix} 0 & p & 0 & jq \\ p & 0 & jq & 0 \\ 0 & jq & 0 & p \\ jq & 0 & p & 0 \end{bmatrix} \qquad \text{..... (5.142)}$$

The relationship between p and q can be obtained from equation (5.133) as

$$p^2 + q^2 = 1 \qquad \text{..... (5.143)}$$

The quantity 'p' is called the "***transmission factor***" and 'q' is called the "***coupling factor***".

UNIT-3 MICROWAVE TUBES

Limitations and Losses of conventional tubes at microwave frequencies

Following are the limitations of conventional active devices like transistors or tubes at microwave frequencies

1) Interelectrode capacitance.

What is interelectrode capacitance?

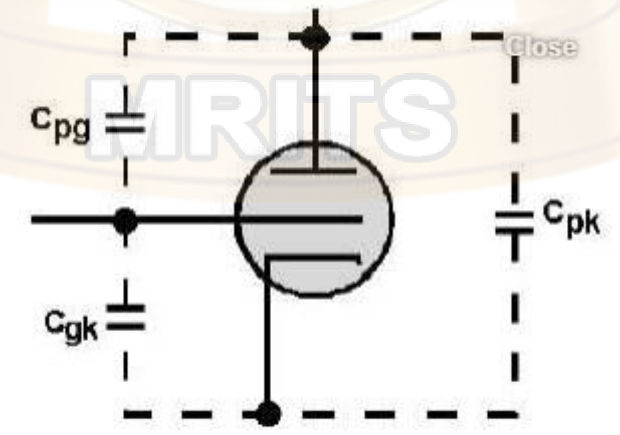
Vacuum has a dielectric constant of 1. As the elements of the triodes are made of metal and are separated by adielectric, capacitance exists between them. This capacitance is interelectrode capacitance.

The capacitance between the plate and grid is Cpg. The grid-to-cathode capacitance is Cgk. The total capacitanceacross the tube is Cpk.

Now, we know that the capacitive reactance is given by

So as the input frequency increases, the effective grid to cathode impedance decreases due to decrease in reactance ofinterelectrode capacitance. At higher frequencies (greater than 100MHz) it becomes so small that signal is short circuited with the tube. Also, gain of the device reduces significantly.

This effect can be minimized by taking smaller (reducing the area) electrodes and by increasing distance betweenthem (i.e. reducing capacitance because C=epsilon*A/d) therefore by increasing reactance.

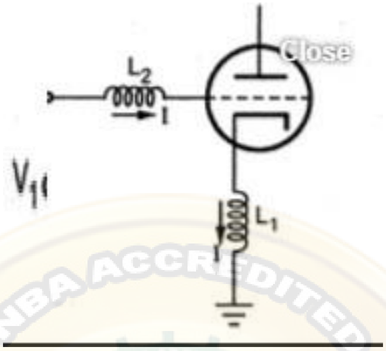


2) Lead inductance.

Lead or stray inductance are effectively in parallel within the device with the interelectrode capacitance. Inductivereactance is given by:

$X_L = 2 \pi f L$

As the frequency increases, the effective reactance of the circuit also increases. This effect raise the frequency limit tothe device. The inductance of cathode lead is common to both grid and plate circuits. This provides a path for degenerative feedback which reduces the overall efficiency of the circuit.



3) Transit time

Transit time is the time required for electrons to travel from the cathode to the plate. At low frequency, the transit time is very negligible. But, however at higher frequencies, transit time becomes an appreciable portion of a signalcycle which results in decrease in efficiency of device.

4) Gain bandwidth product

Gain bandwidth product is independent of frequency. So for a given tube higher gain can be only obtained at theexpense of narrower bandwidth.

5) Skin effect

This effect is introduced at higher frequencies. Due to it, the current flows from the small sectional area to the surfaceof the device. Also at higher frequencies, resistance of conductor increases due to which the there are losses.

$R=\rho l(\sqrt{f})$

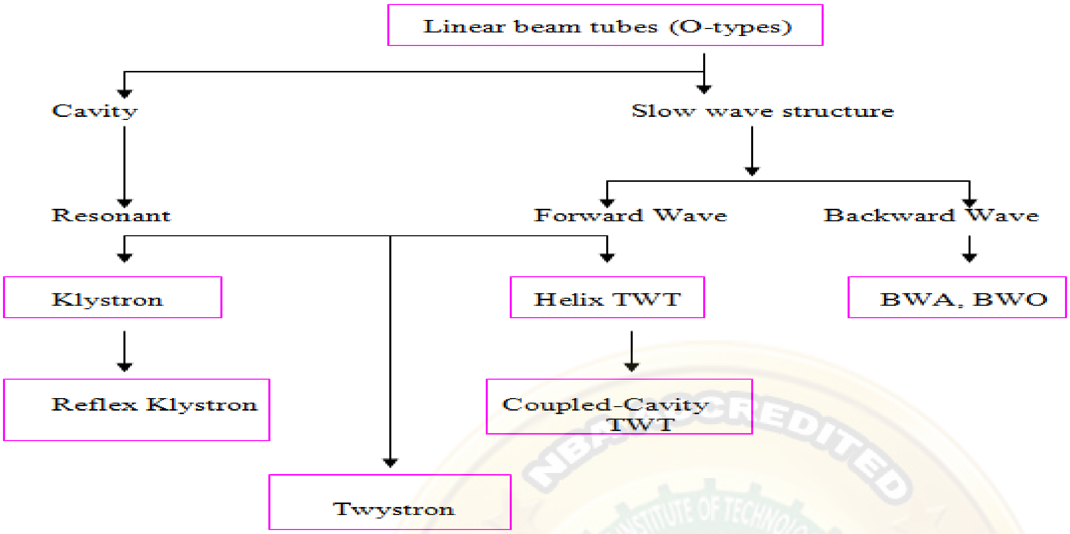
6) Dielectric loss

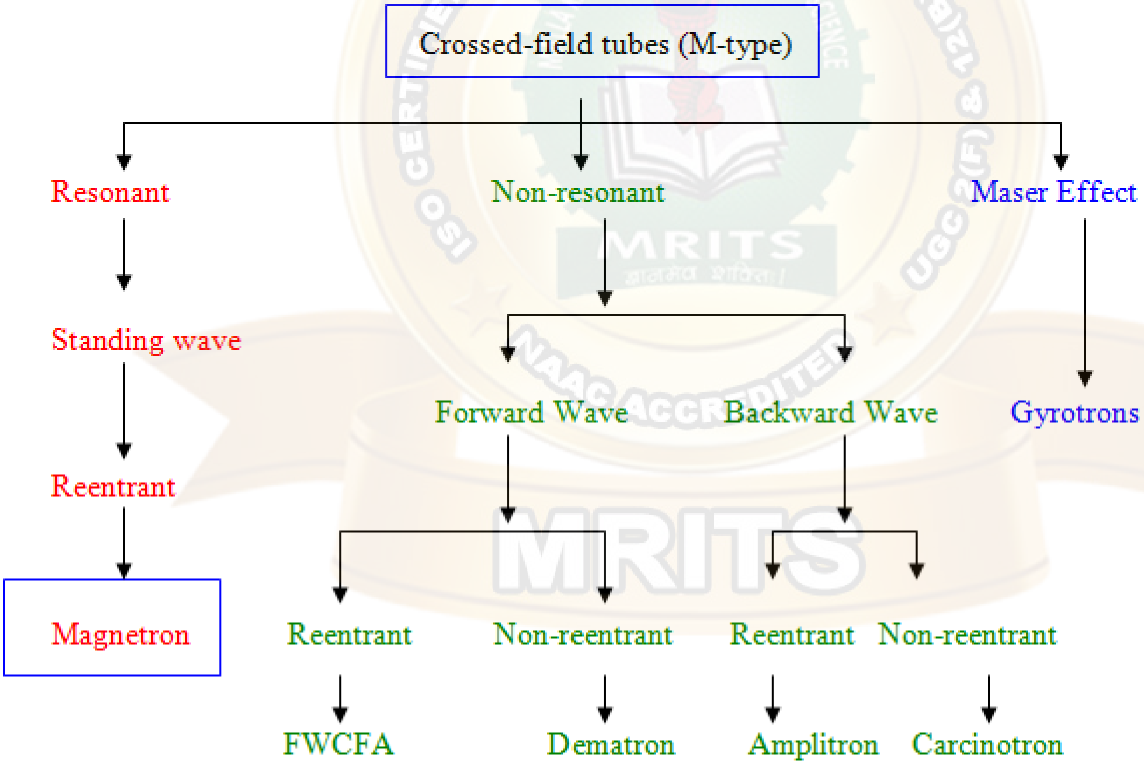
Dielectric material is generally different silicon plastic encapsulation materials used in microwave devices. At higherfrequencies the losses due to these materials are also prominent.

Microwave Tubes:

1.Linear beam tubes (O-type)-Dc magnetic field is in parallel with the dcelectric field.

2.Crossed-field tubes (M-type)-Dc electric field and the dc magnetic fieldare perpendicular to each other.





Cavity Klystrons

In microwave region, performs the functions of generates, receives and amplifies signals

Configurations:

1.Reflex – low power microwave oscillator
2.Multicavity – low power microwave amplifier

a) Reflex Klystron

-Has a reflector and one cavity as a resonator
-Reflex action of electron beam

Performance:

- Frequency range: 2-200 GHz
- BW: ± 30 MHz for _VR: ±10 V
- Power o/p: 10mW – 2.5W
- used as microwave source in lab,microwave transmitter
- frequency modulation and amplitude modulation

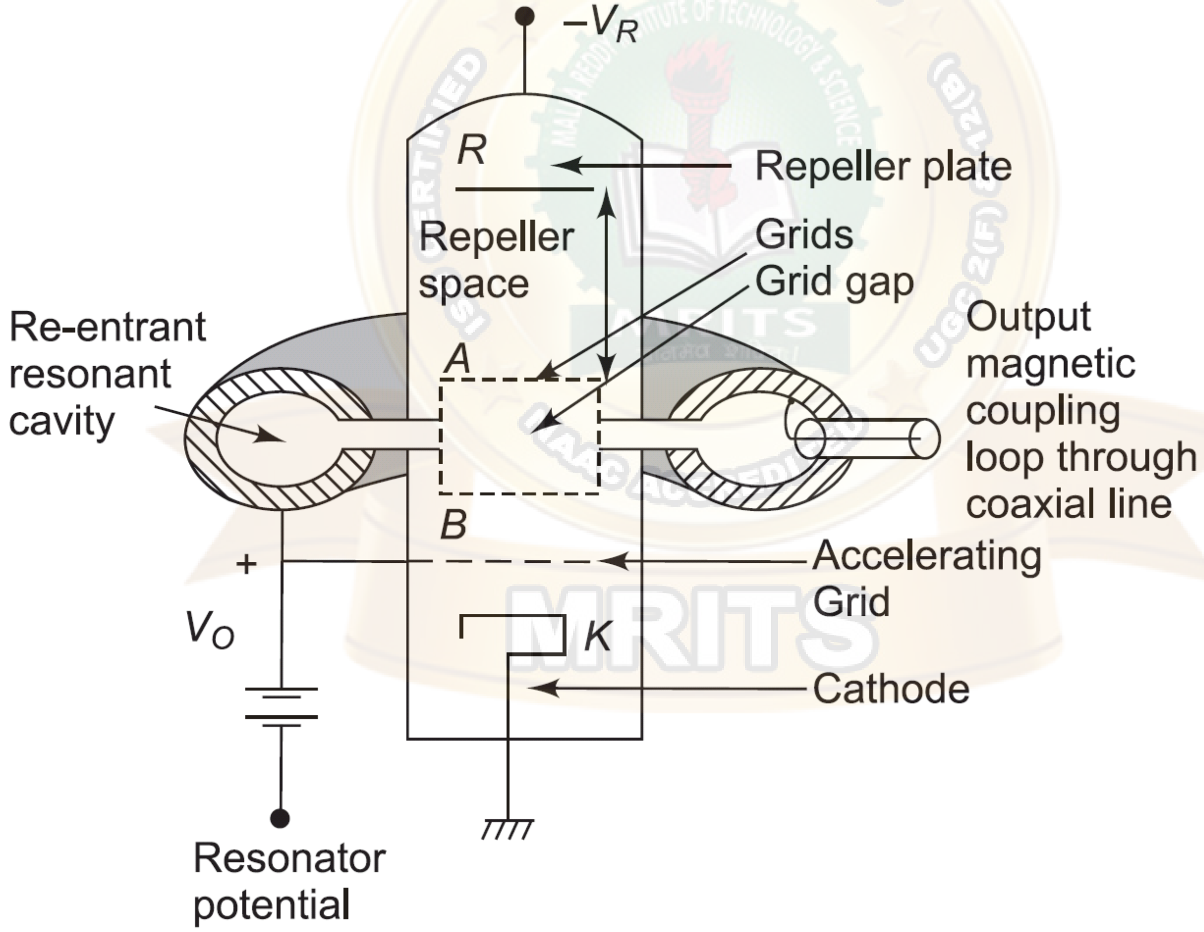


Fig. 9.3 *Functional diagram of a reflex klystron*

Mechanism of oscillation

_ The electron passing through the cavity gap
–experience the RF field

_ velocity modulated

a: Electrons which encountered the positive half cycle of the RF field in the cavity gap will be

acceleratedb: Electrons which encountered zero RF field will pass with unchanged original velocity

c: Electrons which encountered the negative half cycle will be retarded and entering the repellerspace.

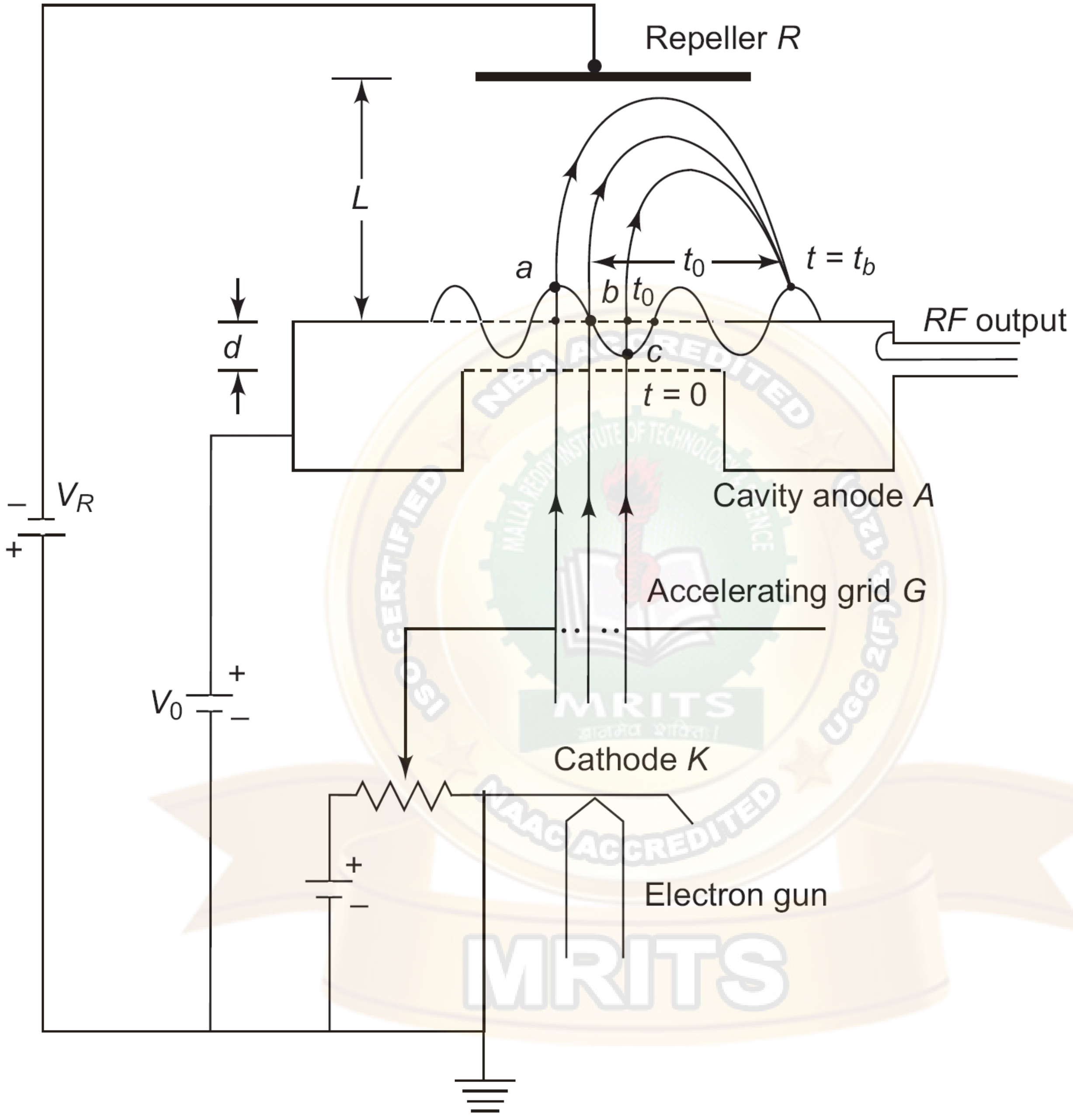


Fig. 9.4 *Reflex klystron operation*

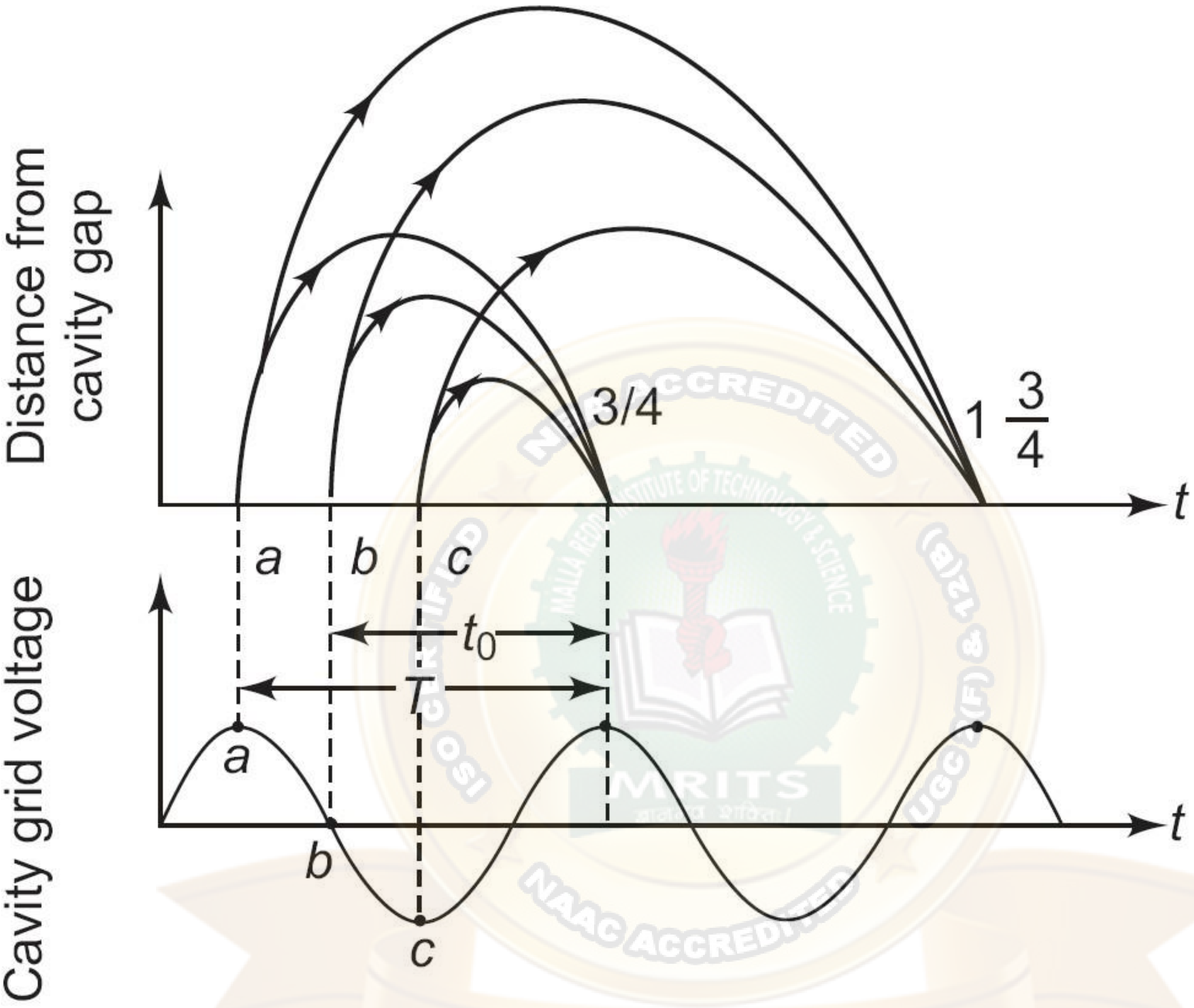


Fig. 9.5 *Reflex klystron modes*

Multicavity Klystron

Two cavity Klystron Amplifier

_ Assumption for RF amplification

_ Transit time in the cavity gap is very small compared to the period of the input RF signal cycle

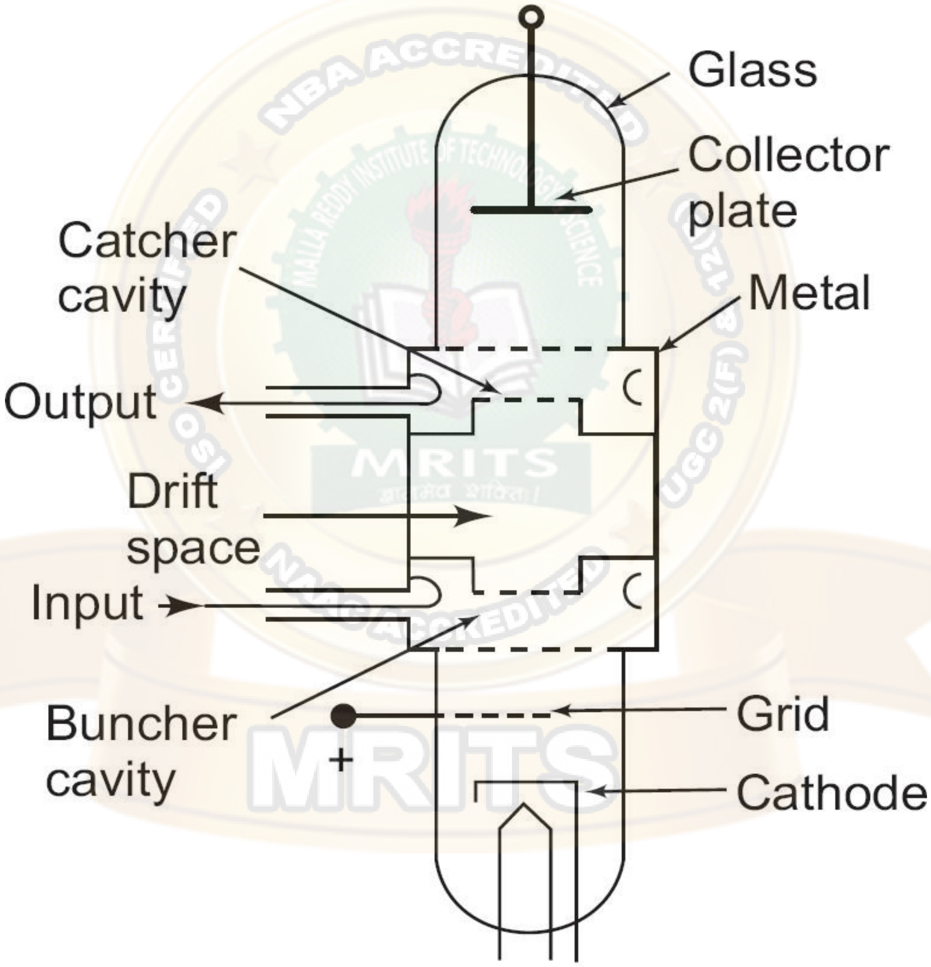
_ Input RF signal amplitude is very small compared to the dc beam voltage

_ The cathode, anode, cavity grids and collectors are all parallel

_ No space charge or debunching take place at the bunch point

_ The RF fields are totally confined in the cavity gaps, zero in the drift space

_ Electrons leave the cathode with zero initial velocity



(a)

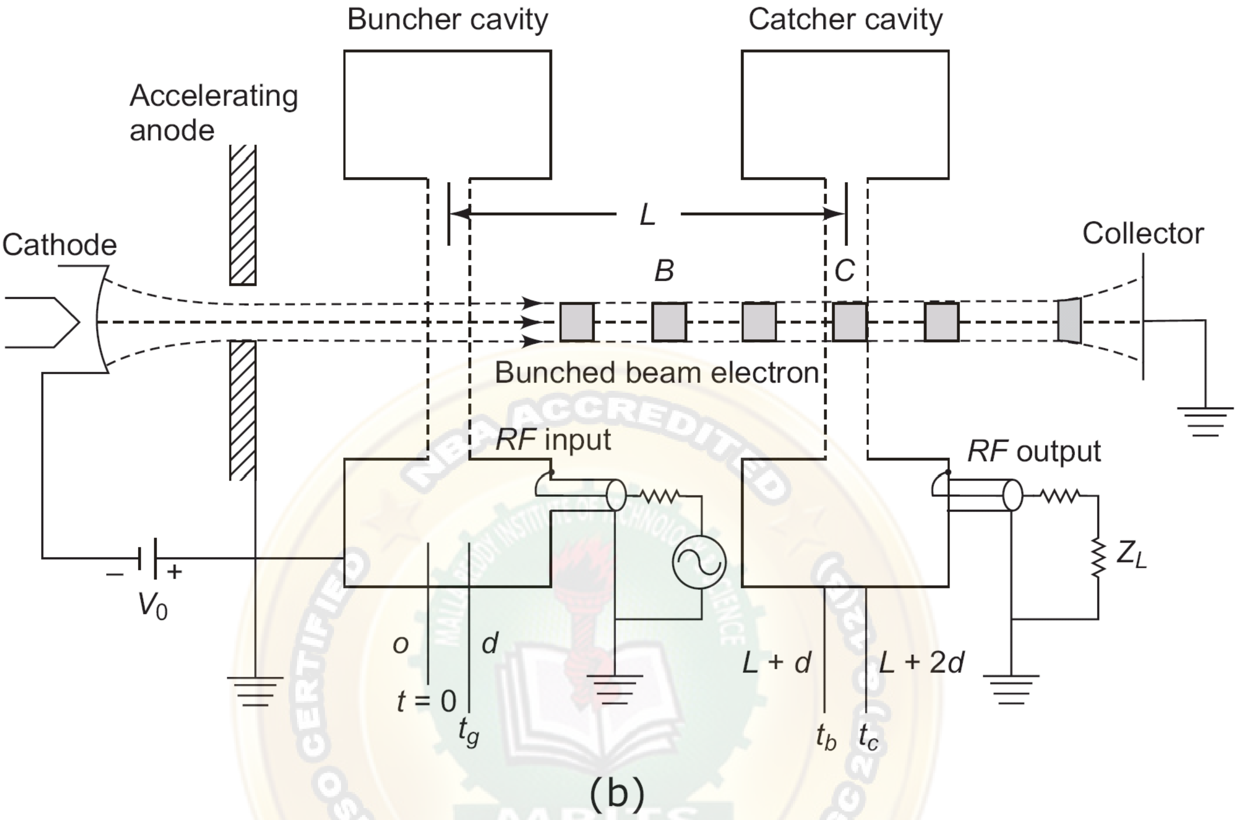


Fig. 9.12 *Two-cavity klystron amplifier: (a) Schematic diagram (b) Functional diagram*

Traveling wave tube (TWT)

Travelling Wave Tube Amplifier:

_ High gain > 40 dB
_ Low NF < 10 dB
_ Wide Band > Octave

_ Frequency range:0.3 – 50 GHz

_ Contains electron gun, RF interaction circuit, electron beam focusing magnet, collector
_ Amplify a weak RF input signal many thousands of times

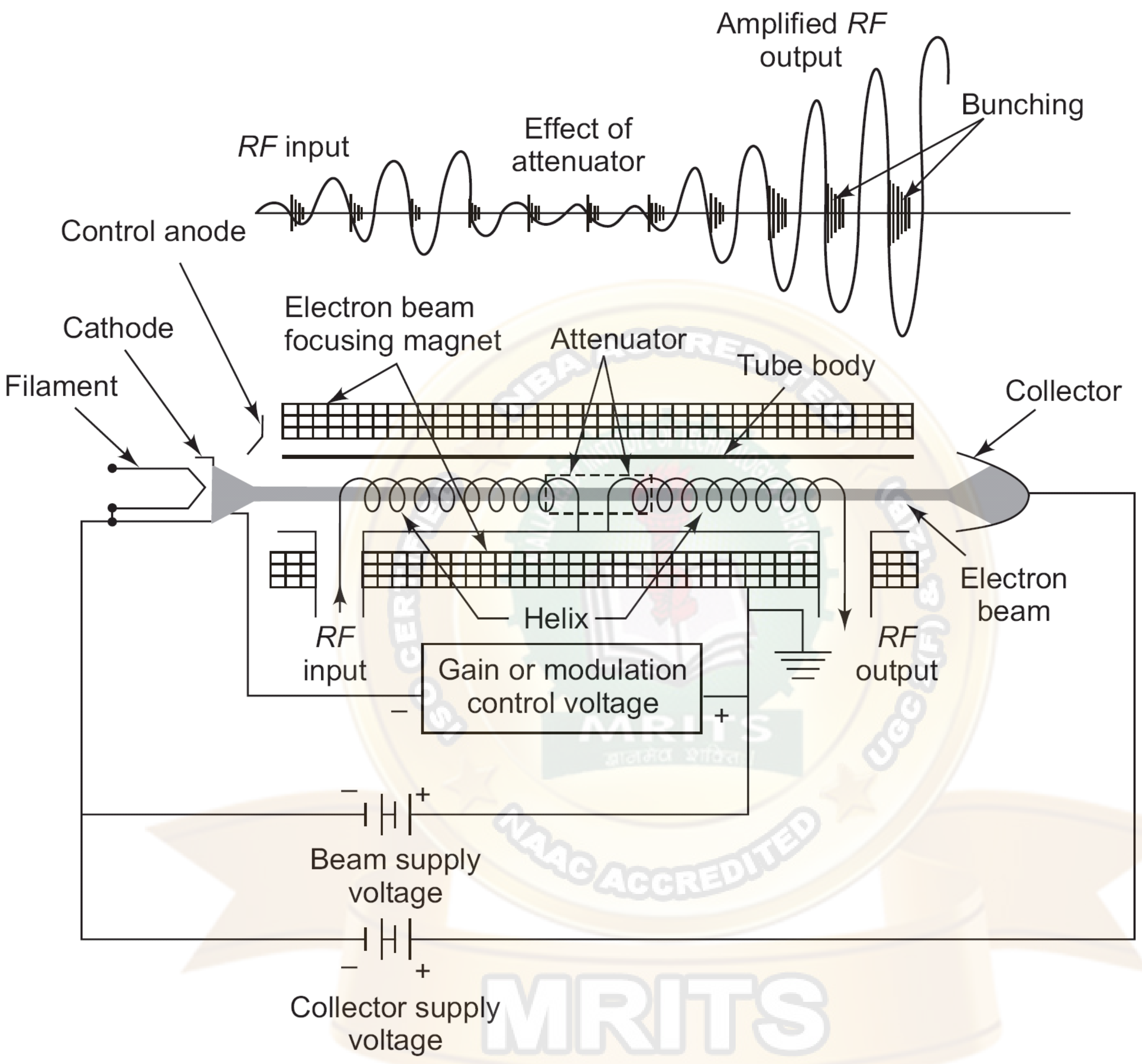


Fig. 9.18 *TWT amplifier tube and circuit*

a) Electron gun

_ To get as much electron current flowing into as small a region as possible without distortion or fuzzy edges

Sources of electrons for the beam- 6 elements:

- gun shells
- heater
- cathode
- control grid

- focus electrode
- anode

b) RF interaction circuit
_ Interaction structures : helix, ring bar, ringloop, coupled cavity
_ RF circuit – complex trade off analysis, based on many interlocking parameters
_ Low power level : helix
_ Medium power level : ring loop, ring bar
_ Power level & frequency increased: RF losses on the circuit become more appreciate able.

c) Electron beam focusing
_ A magnetic field – to hold the electron beam together as it travels through the interactionstructure of the tube
_ The beam tends to disperse or spread out as a result of the natural repulsive forcesbetween electrons.
_ Methods of magnetic focusing
_ Solenoid magnetic structure
_ Permanent magnet
_ Periodic permanent magnet (PPM)
_ Radial magnet PPM

d) The collector
_ To dissipate the electrons in the form of heat as they emerge from the slow wave structure
_ Accomplished by thermal conduction to a colder outside surface – the heat is absorbed by circulated air or a liquid

1. Gain compression
_ the amount of gain decrease from the small signal condition (normally 6dB)

2. Beam Voltage
_ the voltage between the cathode and the RF structure

3. Synchronous Voltage
_ the beam voltage necessary to obtain the greatest interaction between the electrons in the electron beam and the RFwave on the circuit

4. Gain
_ the ratio of RF output power to RF input power (dB)

5. Phase Characteristic
_ Phase shift – the phase of output signal relative to the input signal
_ Phase sensitivity – the rate of phase change with a specific operating parameter.

UNIT- IV

TRANSFER ELECTRON 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 *(12 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 *(-I!R)* is generated by the power supply associated with the negative resistance. In 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 1tDs are fabricated from compound semiconductors, such as gallium arsenide (r.As),indium phosphide (lnP), or cadmium telluride (CdTe). Transistors operate As "warm" electrons whose energy is not much greater than the thermal energy 0.026eVat room temperature) of electrons in the semiconductors.

GUNN EFFECT DIODES – GaAs diode

Gunn effect are named after J. B. Gunn who is 1963 discovered a periodic fluctuation of current passing through the n- type gallium arsenide . when the applied voltage exceeded a certain critical value.

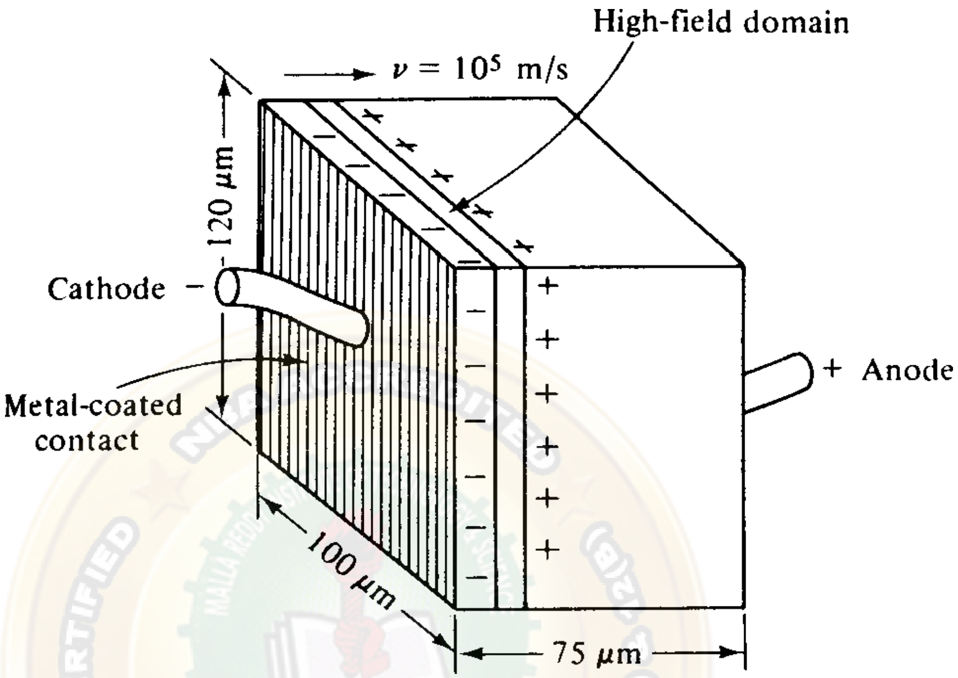
Shockley in 1954 suggested that the two terminal negative resistance devices using semiconductors hadadvantages over transistors at high frequencies.

In 1961 , Ridley and Watkins described a new method for obtaining negative differential mobility in semiconductors. The principle involved is to heat carriers in a light mass , low mobility , higher energy sub band when they have a high temperature.

Finally Kroemer stated that the origin of the negative differential mobility is Ridley Watkins Hilsum’s mechanism of electron transfer into the valleys that occur in conduction bands.

Gunn effect:

The below figure shows the diagram of a uniform n-type GaAs diode with ohmic contacts at the end surfaces. Gunn stated that “ Above some critical voltage , corresponding to an electric field of 2000 to 4000 Volts/cm, the current in every specimen became a fluctuating function of time.


High-field domain
$\nu = 10^5$ m/s
120 μm
Cathode
Metal-coated contact
100 μm
75 μm
Anode

Gunn Diodes

Single piece of GaAs or Inp and contains no junctions Exhibits

negativedifferential resistance

Applications:

low-noise local oscillators for mixers (2 to 140 GHz). Low-power

transmitters andwide band tunable sources

Continuous-wave (CW) power levels of up to several hundred mill watts can be obtained in the X-, Ku-, andKa-bands. A power output of 30 mW can be achieved from commercially available devices at 94 GHz.

Higher power can be achieved by combining several devices in a power combiner.

Gunn oscillators exhibit very low dc-to-RF efficiency of 1 to 4%.

Gunn also discovered that the threshold electric field Eili varied with the length and type of material. He developed an elaborate capacitive probe for plotting the electric field distribution within a specimen of n-typeGaAs of length *L* = 210 JLIll and cross-sectional area 3.5 x 10-3 cm2 with a low-field resistance of 16 n.

Current instabilities occurred at specimen voltages above 59 V, which means that the threshold field is

$$E_{th} = \frac{V}{L} = \frac{59}{210 \times 10^{-6} \times 10^{2}} = 2810 \text{ volts/cm}$$

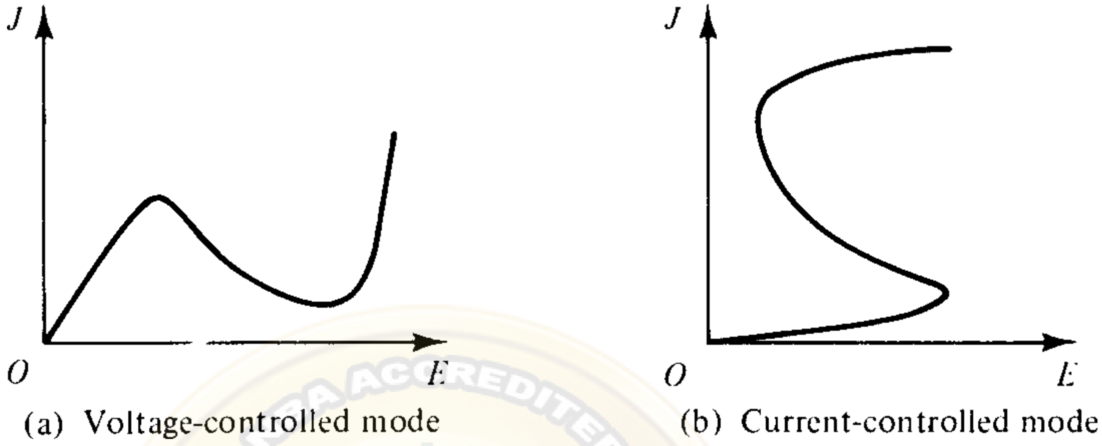
RIDLEY WATKINS AND HILSUM THEORY:

Many explanations have been offered for the Gunn effect. In 1964 Kroemer [6] suggested that

Gunn' sobservations were in complete agreement with the Ridley- Watkins-Hilsum (RWH) theory.

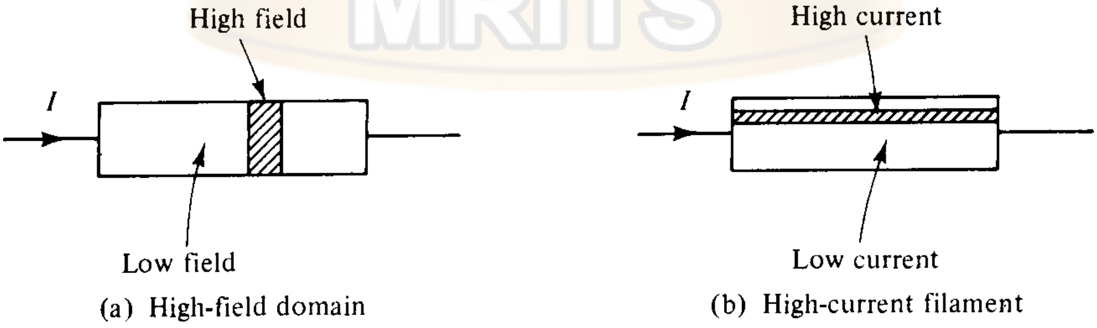
Differential Negative Resistance:

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 tothe terminals of the sample. There are two modes of negative-resistance devices: voltage- controlled and current controlled Modes.



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

In the voltage-controlled mode the current density can be multivalued, whereas in the current-controlled mode the voltage can be mu1tivalued. 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 low and high-field domains lie along equi potentials; thus they are in planes perpendicularto the current direction.

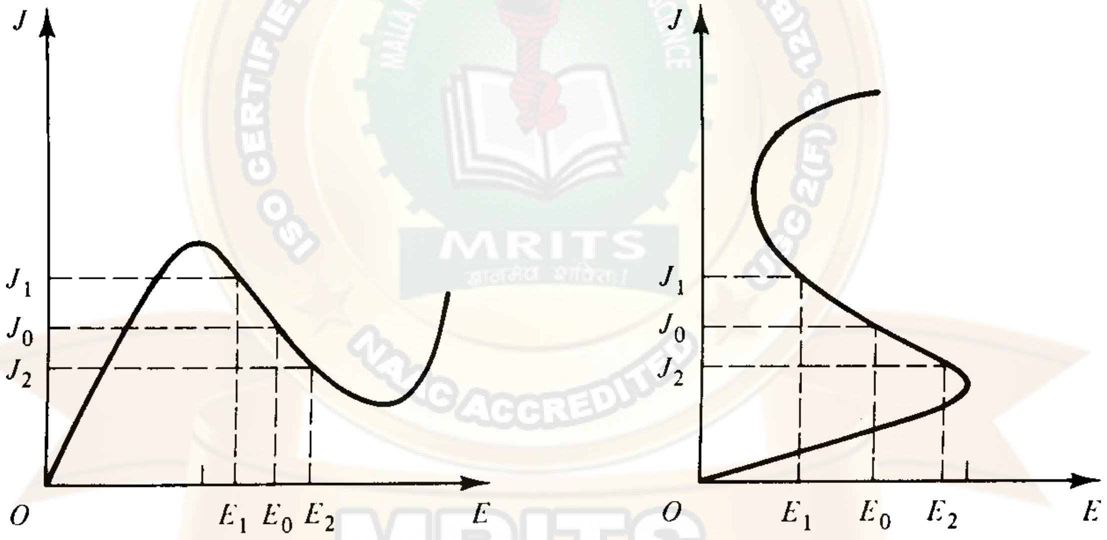


(a) High-field domain (b) High-current filament

Expressed mathematically, the negative resistance of the sample at a particular region is

$$\frac{dI}{dV} = \frac{dJ}{dE} = \text{negative resistance}$$

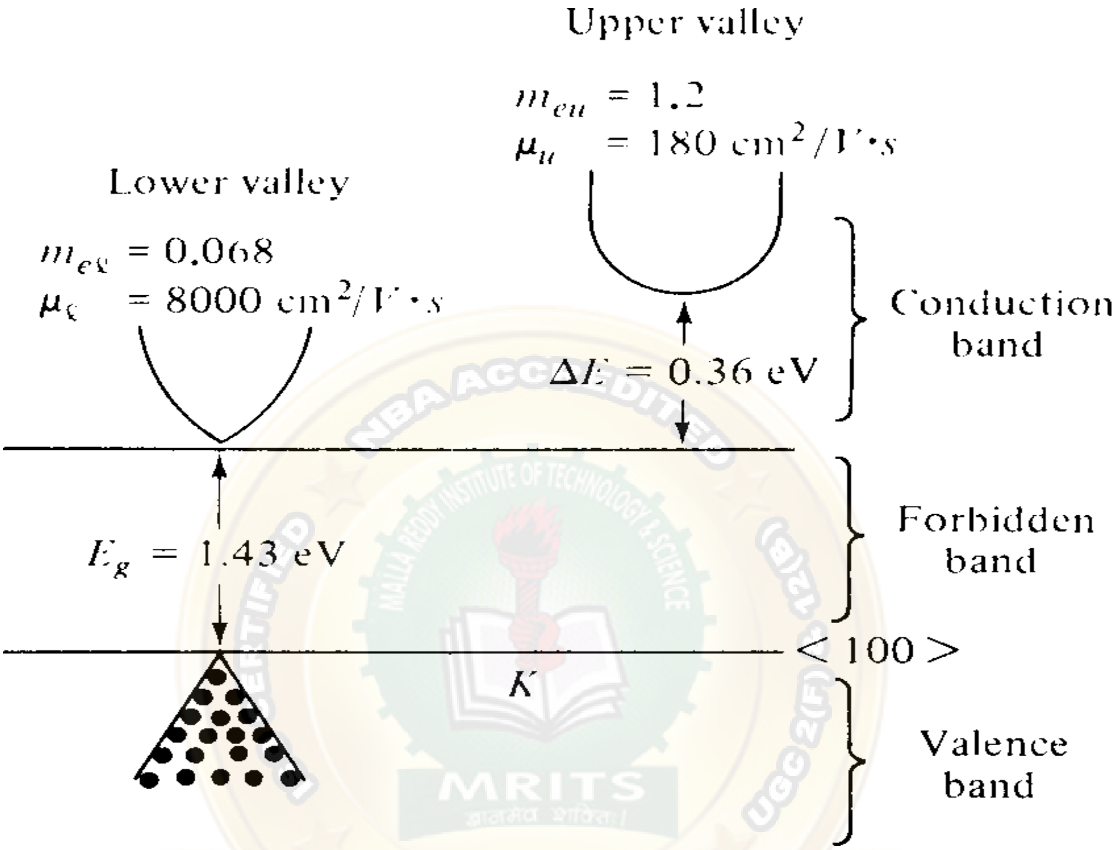
If an electric field *Eo* (or voltage *Vo)* is applied to the sample, for example, the current density 10is generated.As the applied field (or voltage) is increased to *E1* (or *V2),* the current density is decreased to 12. When the field (or voltage) is decr~ to £. (or *VI),* the current density is increased to 1, . These phenomena of the voltage controlled negative resistance are shown in Fig. 7-2-3(a). Similarly, for the current controlled mode, the negative-resistance profile is as shown below.



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

TWO VALLEY MODEL THEORY:

Kroemer proposed a negative mass microwave amplifier in 1958 [lO] and 1959 [II]. According *to* the energy band theory of the *n* -type GaAs, a high-mobility lower valley is separated by an energy of 0.36 eV from a low-mobility upper valley

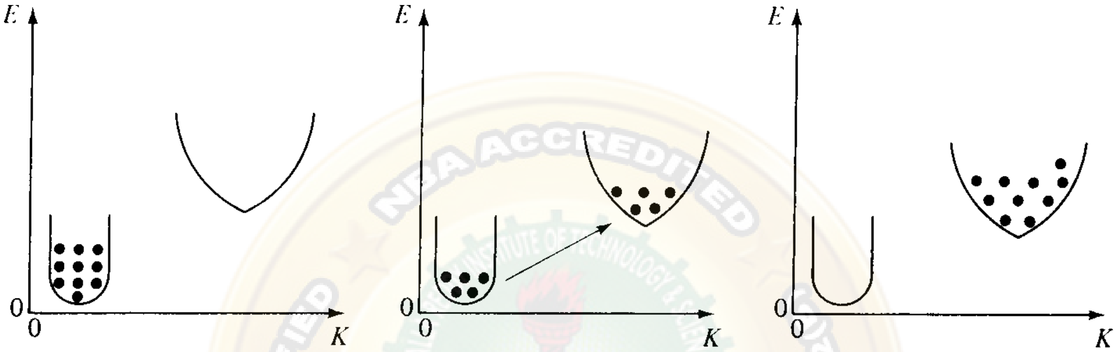


Electron densities in the lower and upper valleys remain the same under an Equilibrium condition. When the applied electric field is lower than the electric field of the lower valley *(E < Ee),* no electrons will transfer to theupper valley.

When the applied electric field is higher than that of the lower valley and lower than that of the uppervalley *(Ee < E < Eu)),* electrons will begin to transfer to the upper valley.

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

When a sufficiently high field *E* is applied to the specimen, electrons are accelerated and their effective temperature rises above the lattice temperature also increases. Thus electron density/I and are both functions of electric field *E*.



(a) $E < E_\ell$ (b) $E_\ell < E < E_u$ (c) $E_u < E$

Transfer of electron densities.

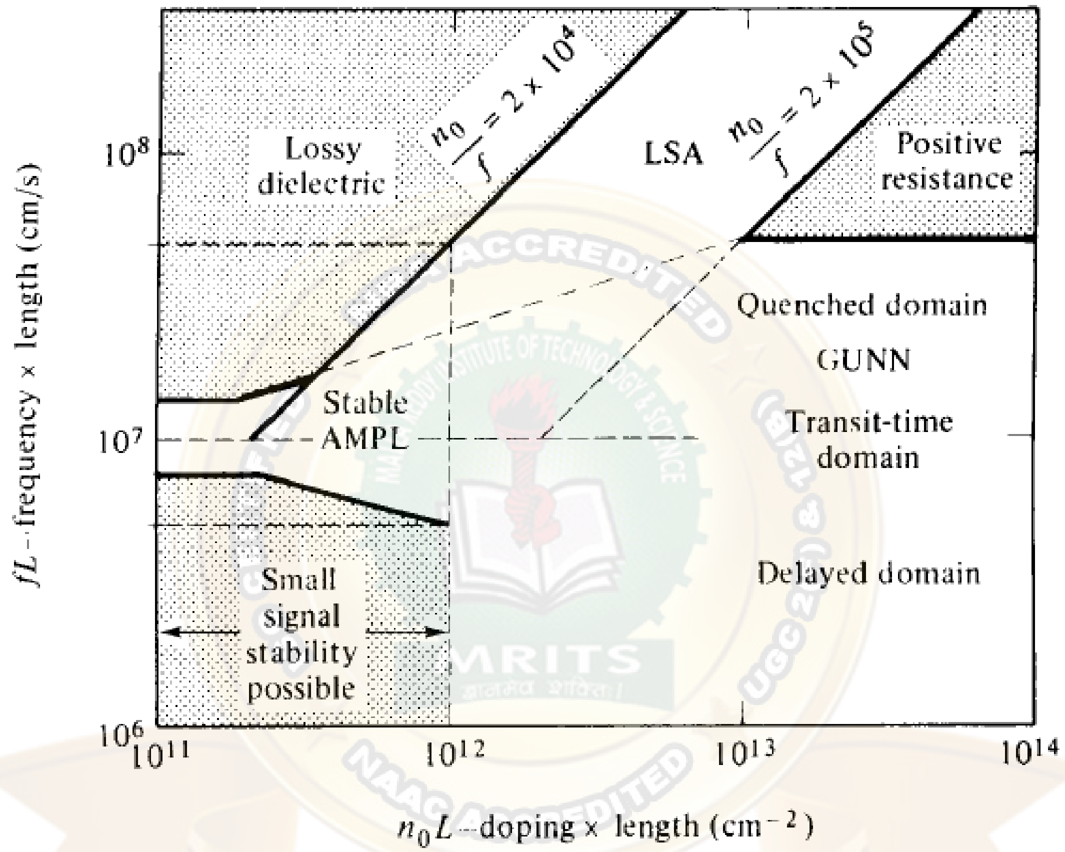
MODES OF OPERATION OF GUNN DIODE:

A gunn diode can operate in four modes:

1. Gunn oscillation mode
2. stable amplification mode
3. LSA oscillation mode
4. Bias circuit oscillation mode

Gunn oscillation mode: This mode is defined in the region where the product of frequency multiplied bylength is about 107 cm/s and the product of doping multiplied by length is greater than 1012/cm2.In this region the device is unstable because of the cyclic formation of either the accumulation layer or the high field domain.

When the device is operated is a relatively high Q cavity and coupled properly to the load, the domain Iquenched or delayed before nucleating.

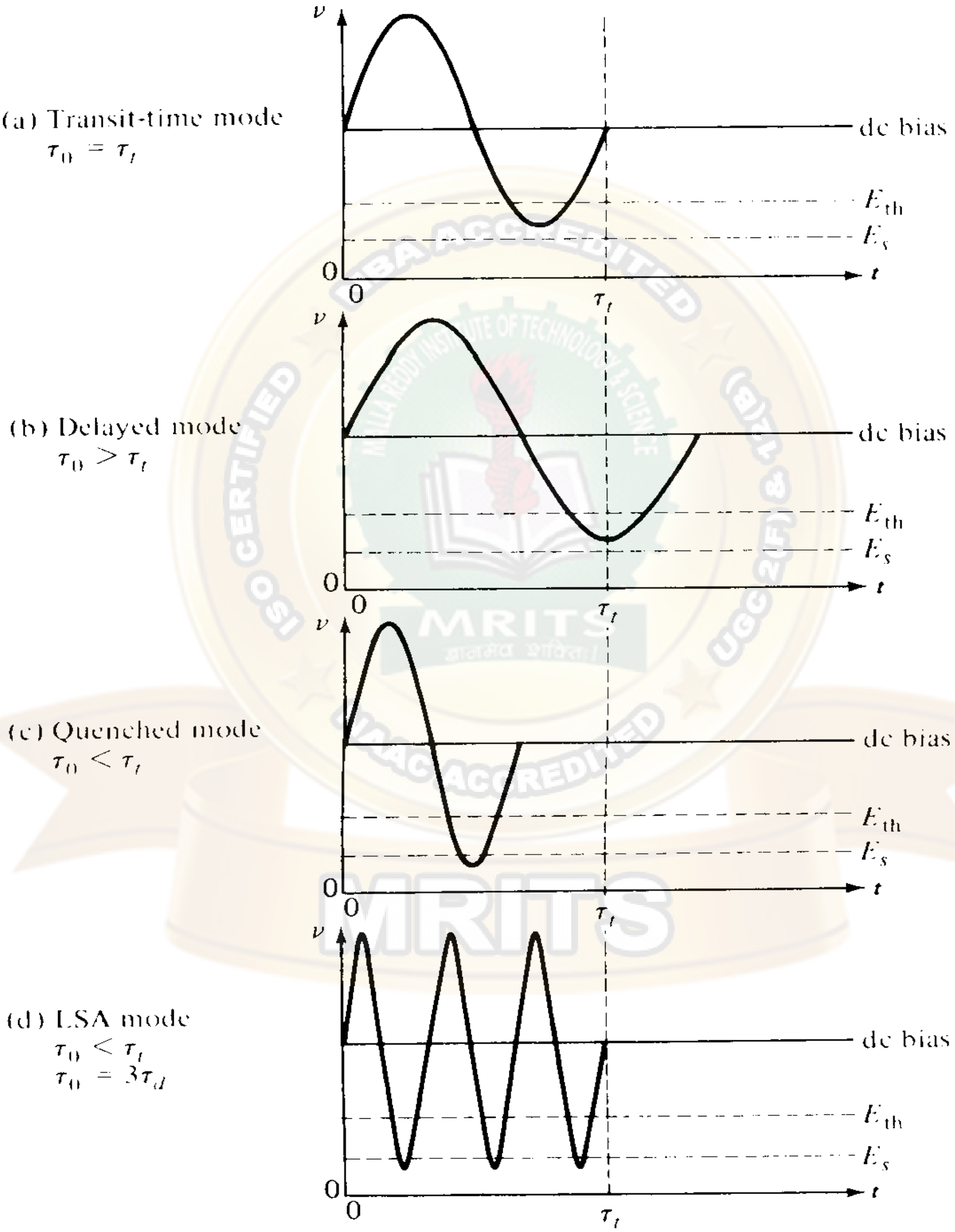


***2.*Stable amplification mode**: This mode is defined in the region where the product of frequencytimes length is about 107 *cmls* and the product of doping times length is between l0^{11}and *10^{12}/cm2*

3. LSA oscillation mode: This mode is defined in the region where the product of frequency times length is above 10^7 *cmls* and the quotient of doping divided by frequency is between 2×10^4 and 2×10^5.

4. Bias-circuit oscillation mode: This mode occurs only when there is either Gunn or LSA oscillation. and it isusually 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 100MHz .



Delayed domain mode (106 cm/s < *fL* < 107 cm/s). When the transit time is Chosen so that the domain iscollected while E < Eth as shown in Fig. 7-3-4(b), a new domain cannot form until the field rises above threshold again. In this case, the oscillation period is greater than the transit time-that is, $T_o > T_t$. This

delayed mode is also called *inhibited mode.* The efficiency of this mode is about 20%.

Quenched domain mode (fL > 2 X 107 cm/s).

If the bias field drops below the sustaining field *Es* during the negative half-cycle as shown ,the domain collapses before it reaches the anode. When the bias field swings back above threshold ,a new domain is nucleated and the process repeats. Therefore the oscillations occur at the frequency of the resonant circuit ratherthan at the transit-time frequency, It has been found that the resonant frequency of the circuit is several timesthe transit-time frequency, since one dipole does not have enough time to readjust and absorb the voltage of the other dipoles . Theoretically, the efficiency of quenched domain oscillators can reach 13%

LSA MODE

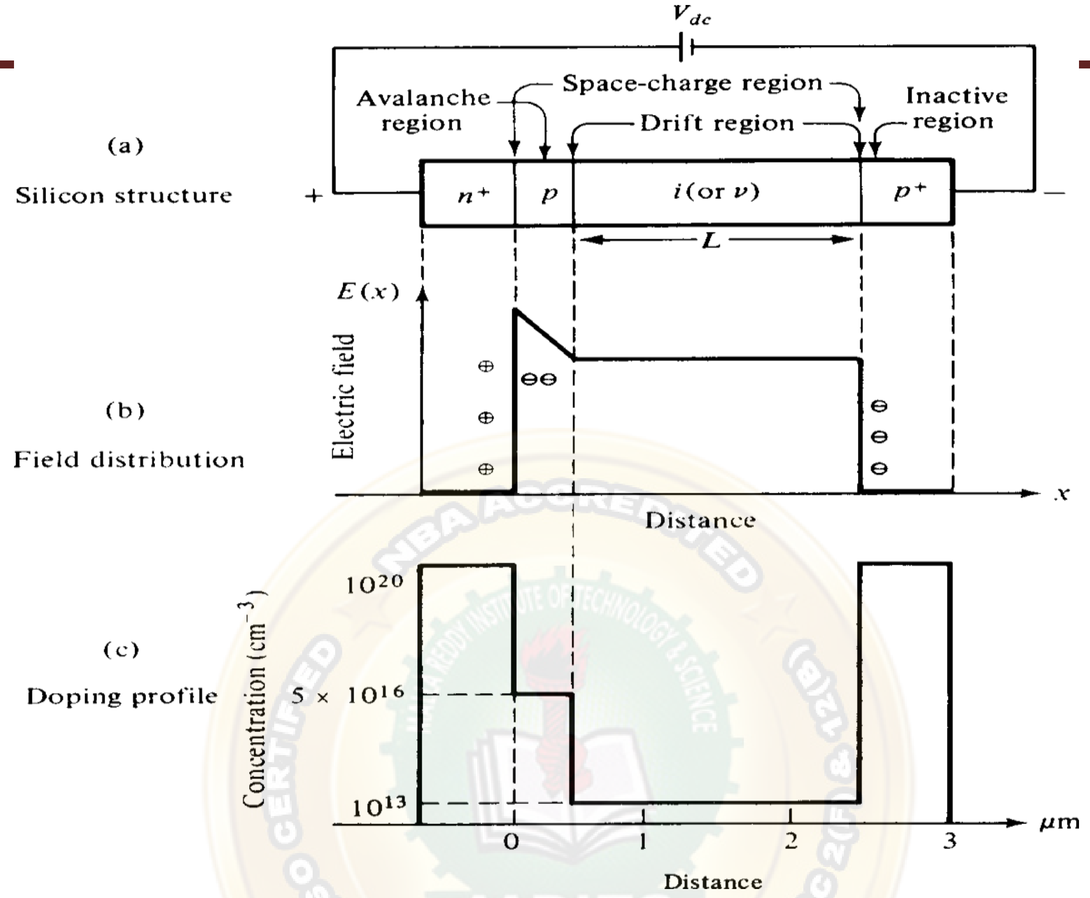
When the frequency is very high, the domains do not have sufficient time to form While the field is above threshold. As a result, most of the domains are maintained In the negative conductance state during a large fraction of the voltage cycle. Any Accumulation of electrons near the cathode has time to collapse while the signal is Below threshold. Thus the LSA mode *is* .the simplest mode of operation.

AVALANCHE TRANSIT TIEM DEVICES:

READ DIODE:

Read diode was the first proposed avalanche diode. The basic operating principles of IMPATT diode can be easily understood by first understanding the operation of read diode.

The basic read diode consists of four layers namely n+ p I p+ layers. The plus superscript refers to very high doping levels and 'i' denotes intrinsic layer. A large reverse bias is applied across diode . the avalanche multiplication occurs in the thin "p" region which is also called the high field region or avalanche region.



The holes generated during the avalanche process drift through the intrinsic region while moving towards p+ contact. The region between n+ p junction and the i-p+ junction is known as space charge region.

When this diode is reverse biased and placed inside an inductive microwave cavity microwave oscillations are produced due to the resonant action of the capacitive impedance of the diode and cavity inductance. The dc biaspower is converted into microwave power by that read diode oscillator.

Avalanche multiplication occurs when the applied reverse bias voltage is greater then the breakdown voltage sothat the space charge region extends from n+p junction through the p and I regions, to the i to p+ junction.

IMPATT DIODE:

lmpatt diodes are manufactured having different forms such as n+pip+, p+nin+, p+nn+ abrupt junction and p+ i n+ diode configuration. The material used for manufacture of these modes are either Germanium, Silicon, Gallium Arsenide (GaAs) or Indium Phosphide (In P).

Out of these materials, highest efficiency, higher operating frequency and lower noise is obtained with GaAs. But the disadvantage with GaAs is complex fabrication process and hence higher cost. The figure below showsa reverse biased n+ pi p+ diode with electric field variation, doping concentration versus distance plot, the microwave voltage swing and the current variation.

PRINICPLE OF OPERATION:

When a reverse bias voltage exceeding the breakdown voltage is applied, a high electric field appears across then+ p junction. This high field intensity imparts sufficient energy to the valence electrons to raise themselves into the conduction band. This results avalanche multiplication of hole-electron pairs. With suitable doping profile design, it is possible to make electric field to have a very sharp peak in the close vicinity of the junction resulting in "impact avalanche multiplication". This is a cumulative process resulting in rapid increase of carrier density. To prevent the diode from burning, a constant bias source is used to maintain average current at safe limit 10, The diode current is contributed by the conduction electrons which move to the n+ region and the associated holes which drift through the steady field and a.c. field.· The diode ~wings into and out of avalanche conditions under the influence of that reverse bias steady field and the a.c. field.

Due to the drift *time* of holes being' small, carriers drift to the end contacts before the a.c. voltage swings the diode out of the avalanche Due to building up of oscillations, the a.c. field takes energy from the applied bias lid the oscillations at microwave frequencies are sustained across the diode. Due to this a.c. field, the hole current grows exponentially to a maximum and again decays exponentially to Zero.

During this hole drifting process, a constant electron current is induced in the external Circuit which starts flowing when hole current reaches its peak and continues for half cycle Corresponding to negative swing of the

a.c. voltage as shown in figure Thus a 180 degrees Phase shift between the external current and a.c. microwave voltage provides a negative Resistance for sustained oscillations.

The resonator is usually tuned to this frequency so that the IMPATI diodes provide a High power continuous wave (CW) and pulsed microwave signals.

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

$$\omega_r \equiv \left(\frac{2\alpha' v_d I_0}{\epsilon_s A}\right)^{1/2}$$

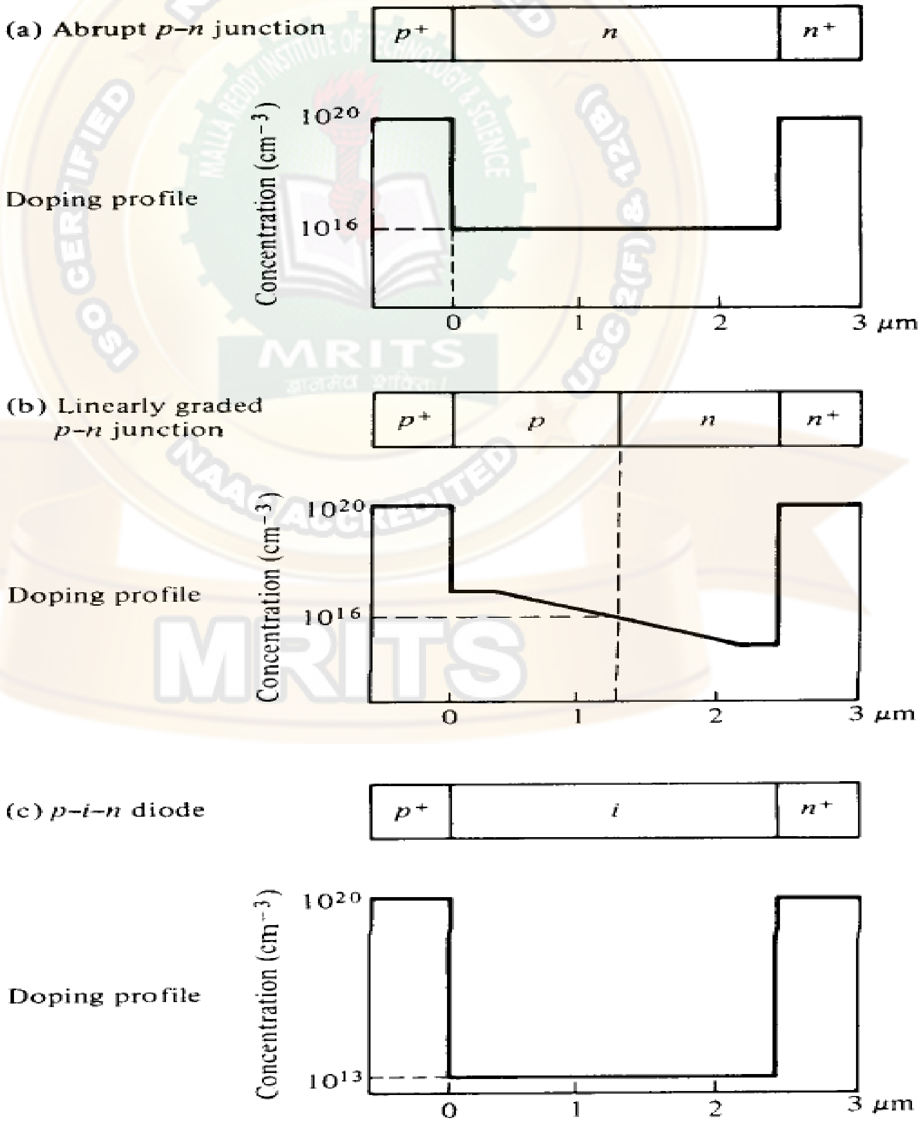
Applications of IMPATT Diodes

(i) Used in the final power stage of solid state microwave transmitters forcommunication purpose.

(ii) Used in the transmitter of TV system.

(iii) Used in FDM/TDM systems.

(iv) Used as a microwave source in laboratory for measurement purposes.



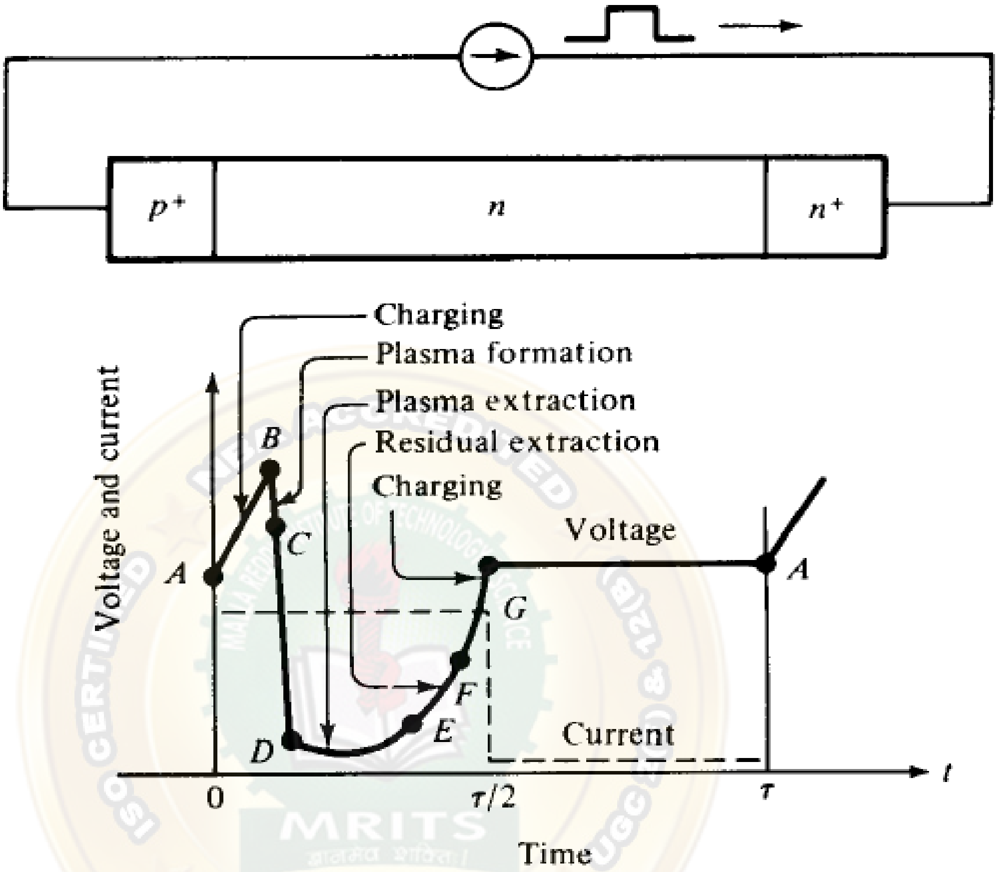
TRAPATT DIODE:

Silicon is usually used for the manufacture of TRAPATT diodes and have a configuration of p+ n n+ as shown .The p-N junction is reverse biased beyond the breakdown region, so that the current density is larger. This decreases the electric field in the space charge region and increases the carrier transit time. Due to this, the frequency of operation gets lowered to less than 10 GHz. But the efficiency gets increased due to low power dissipation.

Inside a co-axial resonator, the TRAPATT diode is normally mounted at a point where maximum RF voltage swing is obtained. When the combined dc bias and RF voltage exceeds breakdown voltage, avalanche occurs and a plasma of holes and electrons are generated which gets trapped. When the external circuit current flows, the voltage rises and the trapped plasma gets released producing current pulse across the drift space. The total transit time is the sum of the drift time and the delay introduced by the release of the trapped plasma. Due to this longer transit time, the operating frequency is limited to 10 GHz. Because the current pulse is associated with low voltage, the power dissipation is low resulting in higher efficiency.

The disadvantages of TRAPATT are high noise figure and generation of strong harmonics due to short durationof the current pulse.

TRAPATT diode finds application in S-band pulsed transmitters for pulsed array radar systems.



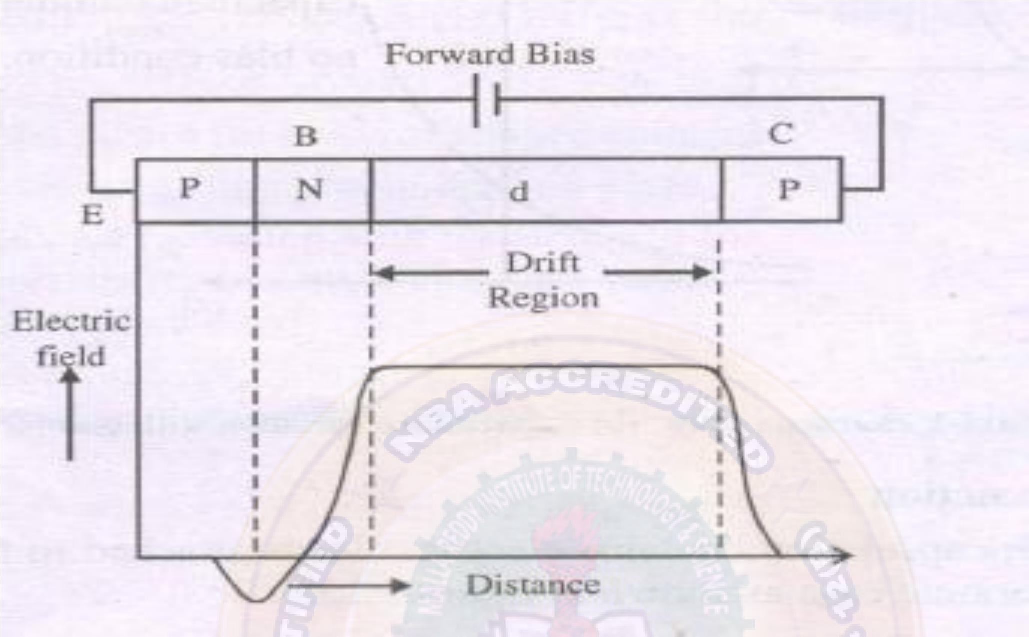
The electric field is expressed as

$$E(x,\ t) = E_m - \frac{qN_A}{\epsilon_s}x + \frac{Jt}{\epsilon_s}$$

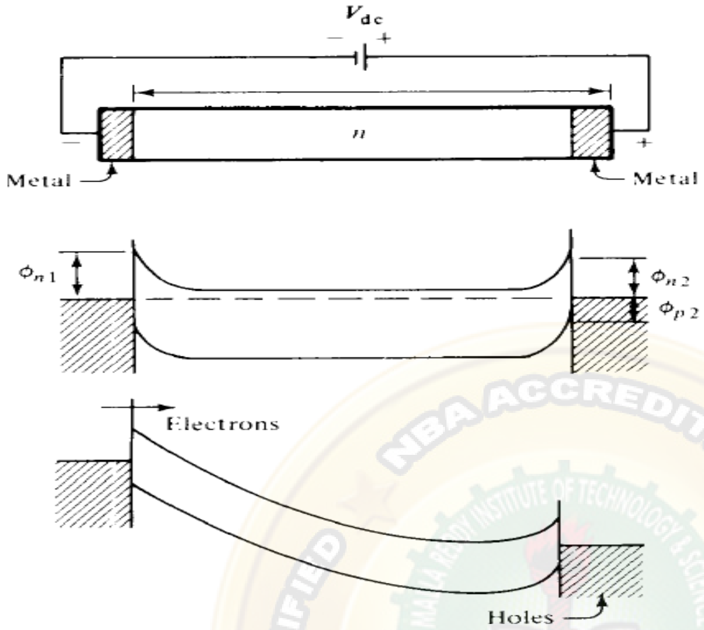
BARITT DIODE (Barrier injection transmit time devices):

BARITT devices are an improved version of IMPATT devices. IMPATT devices employ impact ionization techniques which is too noisy. Hence in order to achieve low noise figures, impact ionization is avoided in BARRITT devices. The minority injection is provided by punch-through of the intermediate region (depletion region). The process is basically of lower noise than impact ionization responsible for current injection in an IMPATT. The negative resistance is obtained on account of the drift of the injected holes to the collector end ofthe aterial.

The construction of a BARITT device consisting of emitter, base, intermediate or drift or depleted region and collector. An essential requirement for the BARITT device is therefore that the intermediate drift region be entirely depleted to cause punch through to the emitter-base junction without causing avalanche breakdown of the base-collector junction.



The parasitic should be kept as low as possible. The equivalent circuit depends on the type of encapsulation andmounting make. For many applications, there should be a large capacitance variation, small value of minimum capacitance and series resistance Rs' Operation is normally limited to f/l0 [25 GHz for *Si* and 90 GHz for GaAs]. Frequency of operation beyond (f /10) leads to increase in R, decrease in efficiency and increase in noise.



(a) M–n–M diode

(b) Energy band diagram in thermal equilibrium

(c) Energy band under bias condition

UNIT- IV

ATTENUATORS:

In order to control power levels in a microwave system by partially absorbing the transmitted microwave signal, attenuators are employed. Resistive films (dielectric glass slab coated with aquadag) are used in the design of both fixed and variable attenuators. A co-axial fixed attenuator uses the dielectric lossy material inside the centre conductor of the co-axial line to absorb some of the centre conductor microwave power propagating through it dielectric rod decides the amount of attenuation introduced. The microwave power absorbed by the lossy material is dissipated as heat.

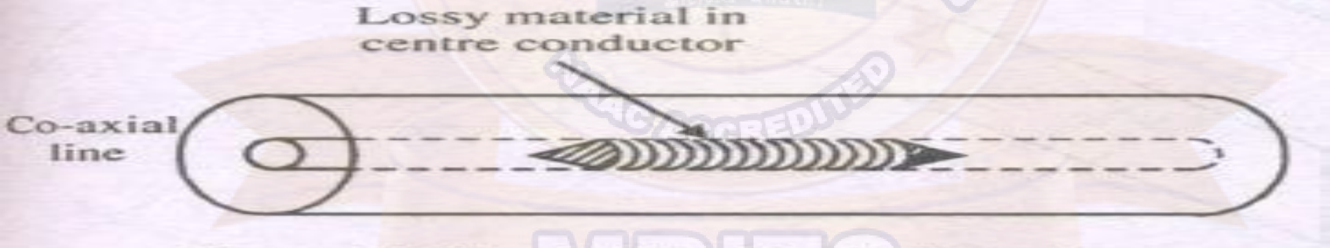


Figure 5.6 Co-axial line fixed attenuator

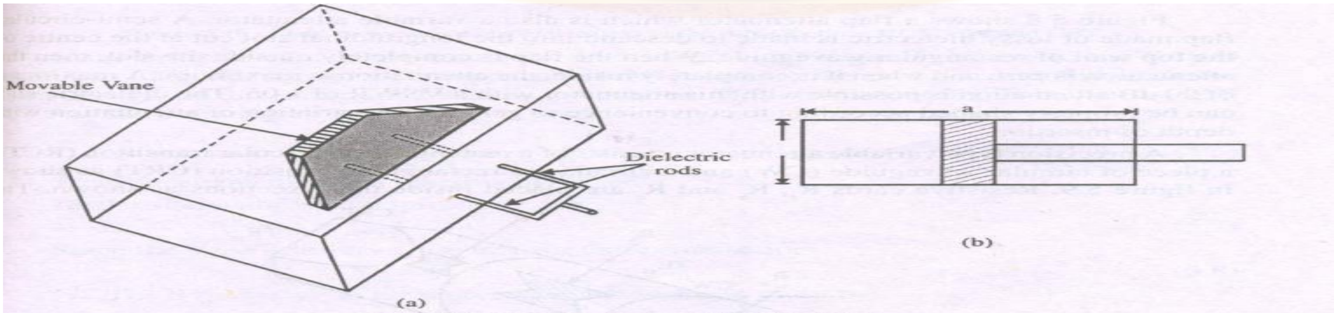


Figure 5.7 : Movable vane variable attenuator

Figure 5.8 shows a flap attenuator which is also a variable attenuator. A semi- circular flap made of lossy dielectric is made to descend into the longitudinal slot cut at the centre of the top wall of rectangular waveguide. When the flap is completely outside the slot, then the attenuation is zero and when it is completely inside, the attenuation is maximum. A maximum direction of 90 dB attenuation is possible with this attenuator with a VSWR of 1.05. The dielectric slab can be properly shaped according to convenience to get a linear variation of attenuation within the depth of insertion.

A precision type variable attenuator consists of a rectangular to circular transition (ReT), a piece of circular waveguide (CW) and a circular-to-rectangular transition

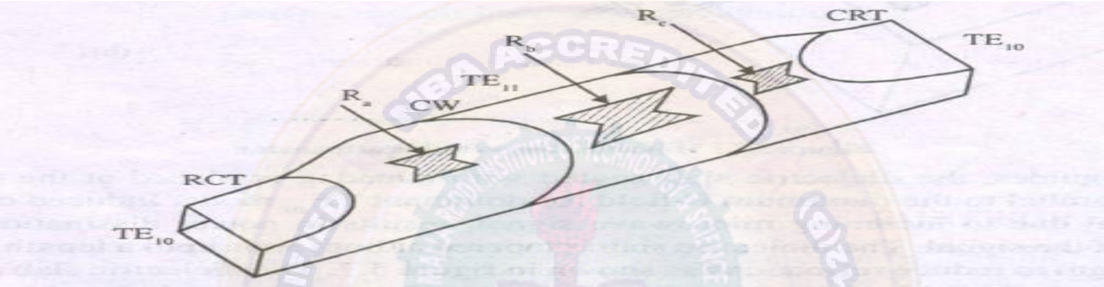


Figure 5.9 : Precision type variable attenuator

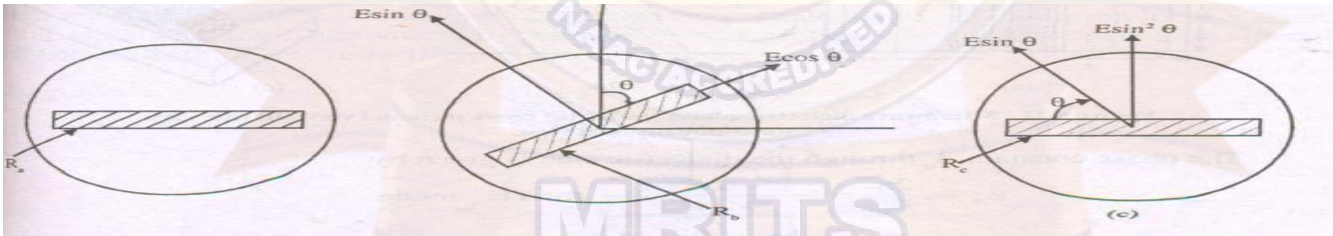


Figure 5.10 : Field components of electric field in the three sections RCT, CW and CRT

PHASE SHIFTERS:

A microwave phase shifter is a two port device which produces a variable shift in phase of the incoming microwave signal. A lossless dielectric slab when placed inside the rectangular waveguide produces a phase shift.

PRECISION PHASE SHIFTER

The rotary type of precision phase shifter is shown in figure 5.12 which consists of a circular waveguide containing a lossless dielectric plate of length 2l called "half- wave section", a section of rectangular-to-circular transition containing a lossless dielectric plate of length l, called "quarter-wave section", oriented at an angle of 45° to the broader wall of the rectangular waveguide and a circular-to-rectangular transition again containing a lossless dielectric plate of same length 1 (quarter wave section) oriented at an angle 45°. The incident TEIO mode becomes TEll mode in circular waveguide section. The half-wave section produces a phase shift equal to twice that produced by the quarter wave section. The dielectric plates are tapered at both ends to reduce reflections due to discontinuity.

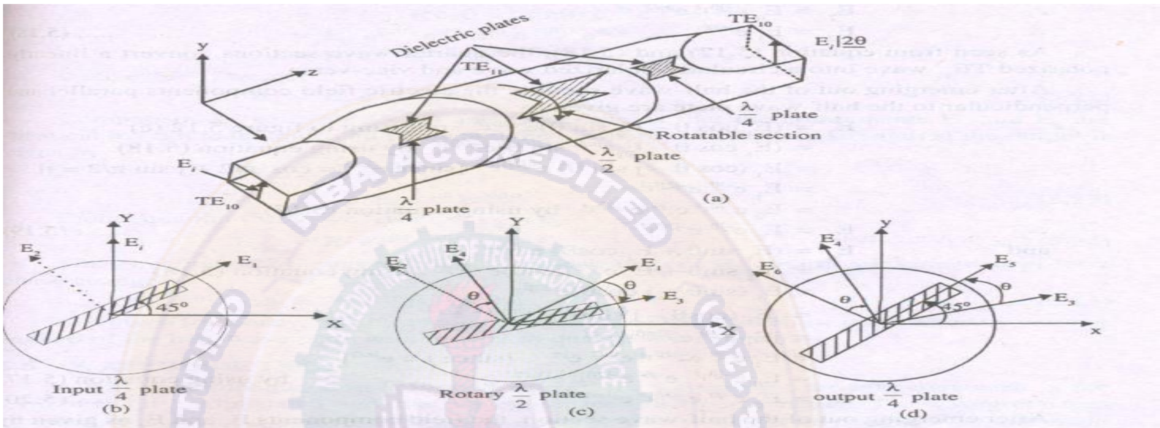


Figure 5.12 : Illustrating precision rotary phase shifter

When TEIO mode is propagated through the input rectangular waveguide of the rectangular to circular transition, then it is converted into TEll in the circular waveguide section. Let E; be the maximum electric field strength of this mode which is resolved into components, EI parallel to the plate and E2 perpendicular to El as shown in figure 5.12 (b). After propagation through the plate these components are given by

$$E_1 = (E_i \cos 45^0)\, e^{-j\beta_1 l} = E_0\, e^{-j\beta_1 l}$$

and $$E_2 = (E_i \sin 45^0)\, e^{-j\beta_2 l} = E_0\, e^{-j\beta_2 l}$$

Where $$E_0 = \frac{E_i}{\sqrt{2}}$$

The length I is adjusted such that these two components E1 and Ez have equal amplitude but differing in phase by = 90°.

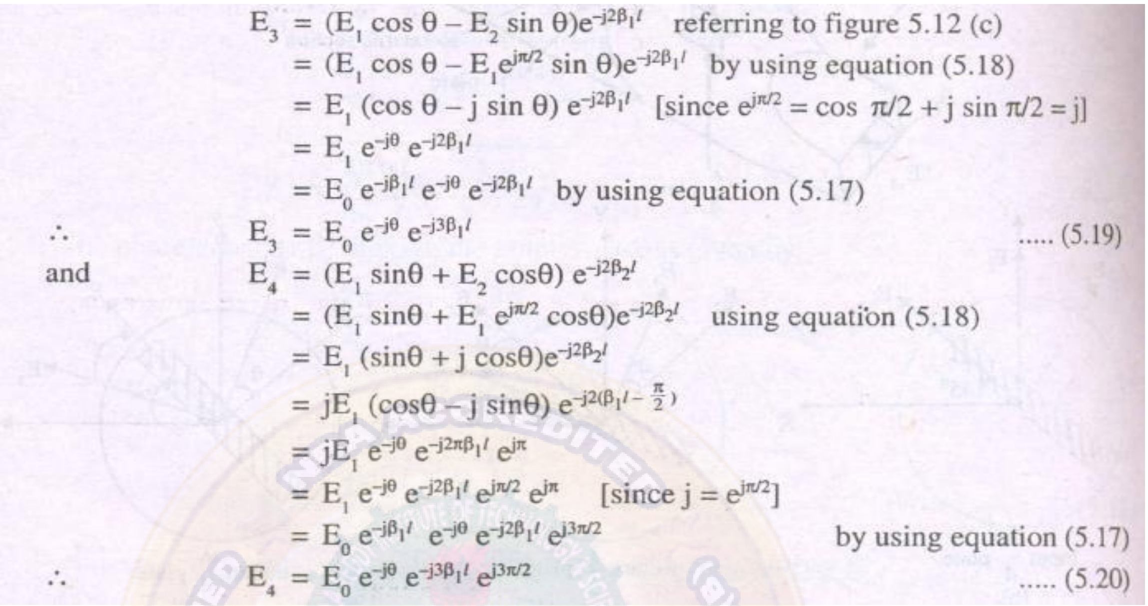
$$E_1 = E_0\, e^{-j\beta_1 l}$$

$$E_2 = E_0\, e^{-j(\beta_1 l - 90^0)} = E_0\, e^{-j(\beta_1 l - \frac{\pi}{2})}$$

$$\therefore \quad E_2 = E_0\, e^{-j\beta_1 l}\, e^{j\pi/2}$$

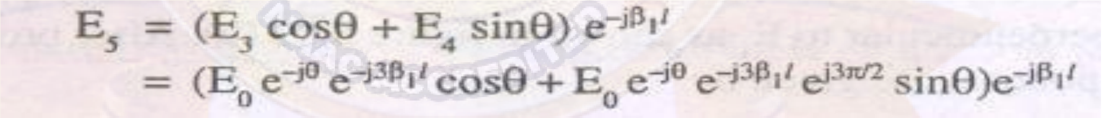
$$\therefore \quad E_2 = E_1\, e^{j\pi/2}$$

The quarter wave sections convert a linearly polarized TEll wave into a circularly polarized wave and vice- versa. After emerging out of the half-wave section, the electric field components parallel and perpendicular to the half-wave plate are given by

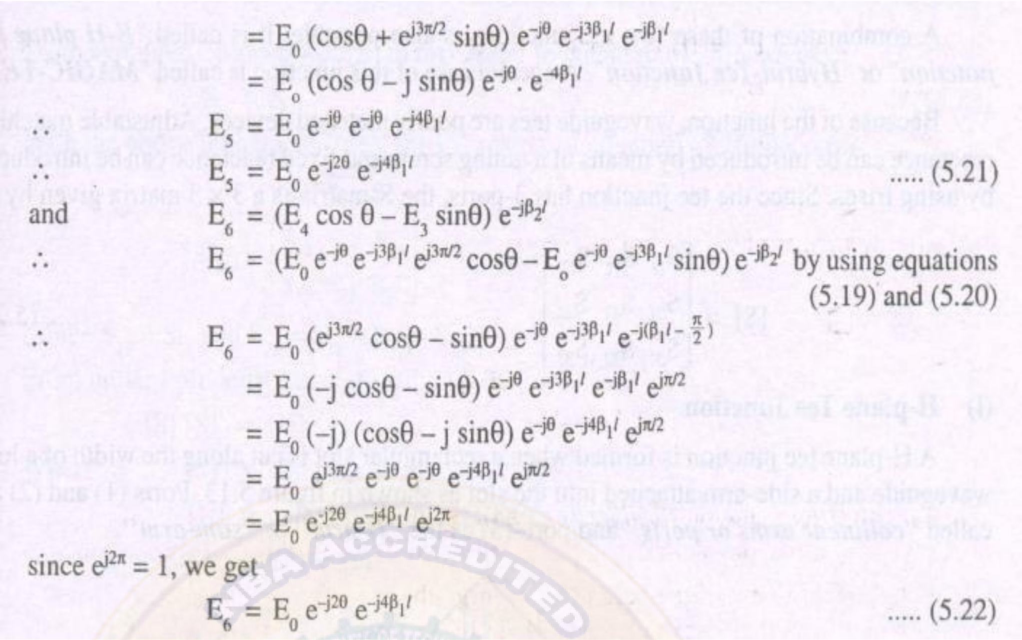


$$
\begin{aligned}
E_3 &= (E_1 \cos\theta - E_2 \sin\theta)e^{-j2\beta_1 l} && \text{referring to figure 5.12 (c)}\\
&= (E_1 \cos\theta - E_1 e^{j\pi/2} \sin\theta)e^{-j2\beta_1 l} && \text{by using equation (5.18)}\\
&= E_1 (\cos\theta - j\sin\theta)\, e^{-j2\beta_1 l} && [\text{since } e^{j\pi/2} = \cos\ \pi/2 + j\sin\pi/2 = j]\\
&= E_1\, e^{-j\theta}\, e^{-j2\beta_1 l}\\
&= E_0\, e^{-j\beta_1 l}\, e^{-j\theta}\, e^{-j2\beta_1 l} && \text{by using equation (5.17)}\\
\therefore \quad E_3 &= E_0\, e^{-j\theta}\, e^{-j3\beta_1 l} && \text{..... (5.19)}\\
\text{and} \quad E_4 &= (E_1 \sin\theta + E_2 \cos\theta)\, e^{-j2\beta_2 l}\\
&= (E_1 \sin\theta + E_1\, e^{j\pi/2} \cos\theta)e^{-j2\beta_2 l} && \text{using equation (5.18)}\\
&= E_1 (\sin\theta + j\cos\theta)e^{-j2\beta_2 l}\\
&= jE_1 (\cos\theta - j\sin\theta)\, e^{-j2(\beta_1 l - \frac{\pi}{2})}\\
&= jE_1\, e^{-j\theta}\, e^{-j2\pi\beta_1 l}\, e^{j\pi}\\
&= E_1\, e^{-j\theta}\, e^{-j2\beta_1 l}\, e^{j\pi/2}\, e^{j\pi} && [\text{since } j = e^{j\pi/2}]\\
&= E_0\, e^{-j\beta_1 l}\ e^{-j\theta}\, e^{-j2\beta_1 l}\, e^{j3\pi/2} && \text{by using equation (5.17)}\\
\therefore \quad E_4 &= E_0\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{j3\pi/2} && \text{..... (5.20)}
\end{aligned}
$$

After emerging out of the half-wave section, the field components E3 and E4 as given by equations (5.19) and (5.20), may again be resolved into two TEll mQdes, polarized parallel and perpendicular to the output quarterwave plate. At the output end of this quarterwave plate, the field components parallel and perpendicular to the quarter wave plate, by referring to figure 5.12 (d), can be expressed as



$$
\begin{aligned}
E_5 &= (E_3 \cos\theta + E_4 \sin\theta)\, e^{-j\beta_1 l}\\
&= (E_0\, e^{-j\theta}\, e^{-j3\beta_1 l} \cos\theta + E_0\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{j3\pi/2} \sin\theta)e^{-j\beta_1 l}
\end{aligned}
$$



$$= E_0 (\cos\theta + e^{j3\pi/2} \sin\theta)\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{-j\beta_1 l}$$

$$= E_o (\cos\theta - j \sin\theta)\, e^{-j\theta} .\, e^{-4\beta_1 l}$$

$$\therefore \quad E_5 = E_0\, e^{-j\theta}\, e^{-j\theta}\, e^{-j4\beta_1 l}$$

$$\therefore \quad E_5 = E_0\, e^{-j2\theta}\, e^{-j4\beta_1 l} \qquad ..... (5.21)$$

$$\text{and} \quad E_6 = (E_4 \cos\theta - E_3 \sin\theta)\, e^{-j\beta_2 l}$$

$$\therefore \quad E_6 = (E_0\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{j3\pi/2} \cos\theta - E_o\, e^{-j\theta}\, e^{-j3\beta_1 l} \sin\theta)\, e^{-j\beta_2 l} \text{ by using equations (5.19) and (5.20)}$$

$$\therefore \quad E_6 = E_0 (e^{j3\pi/2} \cos\theta - \sin\theta)\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{-j(\beta_1 l - \frac{\pi}{2})}$$

$$= E_0 (-j \cos\theta - \sin\theta)\, e^{-j\theta}\, e^{-j3\beta_1 l}\, e^{-j\beta_1 l}\, e^{j\pi/2}$$

$$= E_0 (-j) (\cos\theta - j \sin\theta)\, e^{-j\theta}\, e^{-j4\beta_1 l}\, e^{j\pi/2}$$

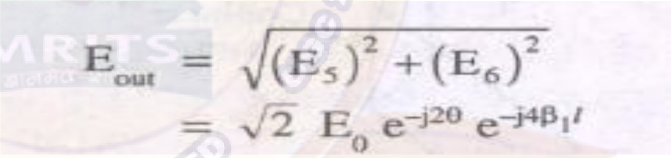
$$= E_0\, e^{j3\pi/2}\, e^{-j\theta}\, e^{-j\theta}\, e^{-j4\beta_1 l}\, e^{j\pi/2}$$

$$= E_0\, e^{-j2\theta}\, e^{-j4\beta_1 l}\, e^{j2\pi}$$

since $e^{j2\pi} = 1$, we get

$$E_6 = E_0\, e^{-j2\theta}\, e^{-j4\beta_1 l} \qquad ..... (5.22)$$

Comparison of equation (5.21) and (5.22) yields that the components Es and E6 are identical in both magnitude and phase and the resultant electric field strength at the output is given by



$$E_{out} = \sqrt{(E_5)^2 + (E_6)^2}$$

$$= \sqrt{2}\ E_0\, e^{-j2\theta}\, e^{-j4\beta_1 l}$$

UNIT-V

OPTICAL FIBER

Introduction

Fiber-optic communication is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. Fiber is preferred over electrical cabling when high bandwidth, long distance, or immunity to electromagnetic interference are required. This type of communication can transmit voice, video, and telemetry through local area networks, computer networks, or across long distances.

Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals. Researchers at Bell Labs have reached internet speeds of over 100 peta bit ×kilometer per second using fiber-optic communication. The process of communicating using fiber-optics involves the following basic steps:

1. Creating the optical signal involving the use of a transmitter, usually from an electricalsignal

2. Relaying the signal along the fiber, ensuring that the signal does not become too distortedor weak

3. Receiving the optical signal

4. Converting it into an electrical signal

Historical Development

First developed in the 1970s, fiber-optics have revolutionized the telecommunications industry and have played a major role in the advent of the Information Age. Because of its advantages over electrical transmission, optical fibers have largely replaced copper wire communications in core networks in the developed world.

In 1880 Alexander Graham Bell and his assistant Charles Sumner Tainter created a very early precursor to fiber-optic communications, the Photophone, at Bell's newly established Volta Laboratory in Washington, D.C. Bell considered it his most important invention. The device allowed for the transmission of sound on a beam of light.On June 3, 1880, Bell conducted the world's first wireless telephone transmission between two buildings, some 213 meters apart. Due to its use of an atmospheric transmission medium, the Photophone would not prove practical until advances in laser and optical fiber technologies permitted the secure transport of light. The Photophone's first practical use came in military communication systems many decades later.

In 1954 Harold Hopkins and Narinder Singh Kapany showed that rolled fiber glass allowed light to be transmitted. Initially it was considered that the light can traverse in only straight medium. Jun-ichi Nishizawa, a Japanese scientist at Tohoku University, proposed the use of optical fibers for communications in 1963. Nishizawa invented the PIN diode and the static induction transistor, both of which contributed to the

development of optical fiber communications.

In 1966 Charles K. Kao and George Hockham at STC Laboratories (STL) showed that the losses of 1,000 dB/km in existing glass (compared to 5–10 dB/km in coaxial cable) were due to contaminants which could potentially be removed.

Optical fiber was successfully developed in 1970 by Corning Glass Works, with attenuation low enough for communication purposes (about 20 dB/km) and at the same time GaAs semiconductor lasers were developed that were compact and therefore suitable for transmitting light through fiber optic cables for long distances. In 1973, Optelecom, Inc., co-founded by the inventor of the laser, Gordon Gould, received a contract from APA for the first optical communication systems. Developed for Army Missile Command in Huntsville, Alabama, it was a laser on the ground and a spout of optical fiber played out by missile to transmit a modulated signal over five kilometers.

After a period of research starting from 1975, the first commercial fiber-optic communications system was developed which operated at a wavelength around 0.8 μm and used GaAs semiconductor lasers. This first-generation system operated at a bit rate of 45 Mbit/s with repeater spacing of up to 10 km. Soon on 22 April 1977, General Telephone and Electronics sent the first live telephone traffic through fiber optics at a 6 Mbit/s throughput in Long Beach, California.

In October 1973, Corning Glass signed a development contract with CSELT and Pirelli aimed to test fiber optics in an urban environment: in September 1977, the second cable in this test series, named COS-2, was experimentally deployed in two lines (9 km) in Turin,for the first time in a big city, at a speed of 140 Mbit/s.

The second generation of fiber-optic communication was developed for commercial use inthe early 1980s, operated at 1.3 μm and used InGaAsP semiconductor lasers. These early systems were initially limited by multi mode fiber dispersion, and in 1981 the single-mode fiber was revealed to greatly improve system performance, however practical connectors capable of working with single mode fiber proved difficult to develop. Canadian service provider SaskTel had completed construction of what was then the world's longest commercial fiber optic network, which covered 3,268 km (2,031 mi) and linked 52 communities. By 1987, these systems were operating at bit rates of up to 1.7 Gb/s with repeater spacing up to 50 km (31 mi). The first transatlantic telephone cable to use optical fiber was TAT-8, based on Desurvire optimised laser amplification technology. It went into operation in 1988.

Third-generation fiber-optic systems operated at 1.55 μm and had losses of about 0.2 dB/km. This development was spurred by the discovery of Indium gallium arsenide and the development of the Indium Gallium Arsenide photodiode by Pearsall. Engineers overcame earlier difficulties with pulse- spreading at that wavelength using conventional InGaAsP semiconductor lasers. Scientists overcame this difficulty by using dispersion-shifted fibers designed to have minimal dispersion at 1.55 μm or by limiting the laser spectrum to a single longitudinal mode. These developments eventually allowed third-generation systems to operate commercially at 2.5 Gbit/s with repeater spacing in excess of 100 km (62 mi).

The fourth generation of fiber-optic communication systems used optical amplification to reduce the need for repeaters and wavelength-division multiplexing to increase data capacity. These two improvements caused a revolution that resulted in the doubling of system capacity every six months starting in 1992 until a bit rate of 10 Tb/s was reached by 2001. In 2006 a bit-rate of 14 Tbit/s was reached over a single 160 km (99 mi) line using optical amplifiers.

The focus of development for the fifth generation of fiber-optic communications is on extending the wavelength range over which a WDM system can operate. The conventional wavelength window, known as the C band, covers the wavelength range 1.53–1.57 μm, and dry fiber has a low-loss window promising an extension of that range to 1.30–1.65 μm. Other developments include the concept of "optical solutions", pulses that preserve their shape by counteracting the effects of dispersion with the nonlinear effects of the fiber by using pulses of a specific shape.

In the late 1990s through 2000, industry promoters, and research companies such as KMI, andRHK predicted massive increases in demand for communications bandwidth due to increased use of the Internet, and commercialization of various bandwidth-intensive consumer services, such as video on demand. Internet protocol data traffic was increasing exponentially, at a faster rate than integrated circuit complexity had increased under Moore's Law. From the bust of the dot-com bubble through 2006, however, the main trend in the industry has been consolidation of firms and off shoring of manufacturing to reduce costs.

Advantages of Fiber Optic Transmission

Optical fibers have largely replaced copper wire communications in core networks in the developed world, because of its advantages over electrical transmission. Here are the main advantages of fiber optic transmission.

Extremely High Bandwidth: No other cable-based data transmission medium offers the bandwidth that fiber does. The volume of data that fiber optic cables transmit per unit time is far great than copper cables.

Longer Distance: in fiber optic transmission, optical cables are capable of providing low power loss, which enables signals can be transmitted to a longer distance than copper cables.

Resistance to Electromagnetic Interference: in practical cable deployment, it’s inevitableto meet environments like power substations, heating, ventilating and other industrial sources of interference. However, fiber has a very low rate of bit error (10 EXP- 13), as a result of fiber being so resistant to electromagnetic interference. Fiber optic transmission is virtually noise free.

Low Security Risk: the growth of the fiber optic communication market is mainly driven by increasing awareness about data security concerns and use of the alternative raw

material. Data or signals are transmitted via light in fiber optic transmission. Therefore there is no way to detect the data being transmitted by "listening in" to the electromagnetic energy "leaking" through the cable, which ensures the absolute security of information.

Small Size: fiber optic cable has a very small diameter. For instance, the cable diameter of a single OM3 multimode fiber is about 2mm, which is smaller than that of coaxial copper cable. Small size saves mere space in fiber optic transmission.

Light Weight: fiber optic cables are made of glass or plastic, and they are thinner thancopper cables. These make them lighter and easy to install.

Easy to Accommodate Increasing Bandwidth: with the use of fiber optic cable, new equipment can be added to existing cable infrastructure. Because optical cable can provide vastly expanded capacity over the originally laid cable and WDM (wavelength division multiplexing) technology, including CWDM and DWDM, enables fiber cables the ability to accommodate more bandwidth.

Disadvantages of Fiber Optic Transmission

Though fiber optic transmission brings lots of convenience, its disadvantages also cannot be ignored.

Fragility: usually optical fiber cables are made of glass, which lends to they are more fragile than electrical wires. In addition, glass can be affected by various chemicals includinghydrogen gas (a problem in underwater cables), making them need more cares when deployed underground.

Difficult to Install: it's not easy to splice fiber optic cable. And if you bend them too much, they will break. And fiber cable is highly susceptible to becoming cut or damaged during installation or construction activities. All these make it difficult to install.

Attenuation & Dispersion: as transmission distance getting longer, light will be attenuated and dispersed, which requires extra optical components like EDFA to be added.

Cost is Higher Than Copper Cable: despite the fact that fiber optic installation costs are dropping by as much as 60% a year, installing fiber optic cabling is still relatively higher than copper cables. Because copper cable installation does not need extra care like fiber cables. However, optical fiber is still moving into the local loop, and through technologies such as FTTx (fiber to the home, premises, etc.) and PONs (passive optical networks), enabling subscriber and end user broadband access.

Special Equipment Is Often Required: to ensure the quality of fiber optic transmission, some special equipment is needed. For example, equipment such as OTDR (optical time-domain reflectometry) is required and expensive, specialized optical test equipment such as optical probes and power meter are needed at most fiber endpoints to properly provide testing of optical fiber.

Applications of Optical Fiber Communications

Fiber optic cables find many uses in a wide variety of industries and applications. Someuses of fiber optic cables include:

Medical -Used as light guides, imaging tools and also as lasers for surgeries

Defense/Government-Used as hydrophones for seismic waves and SONAR , as wiring inaircraft, submarines and other vehicles and also for field networking

Data Storage- Used for data transmission

Telecommunications- Fiber is laid and used for transmitting and receiving purposes

Networking- Used to connect users and servers in a variety of network settings and helpincrease the speed and accuracy of data transmission

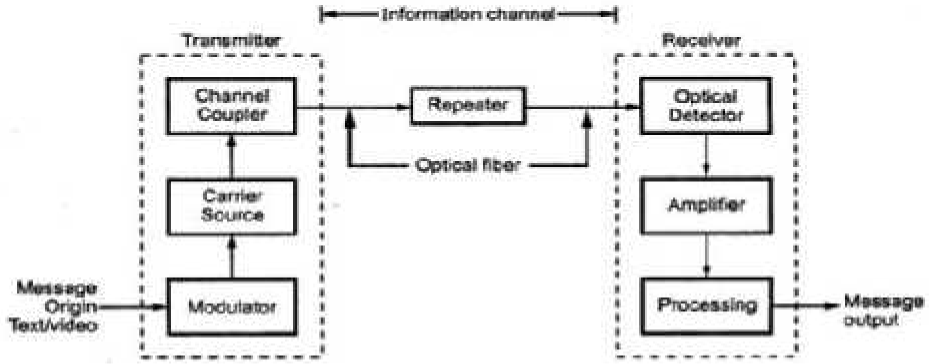
Industrial/Commercial- Used for imaging in hard to reach areas, as wiring where EMI is anissue, as sensory devices to make temperature, pressure and other measurements, and as wiring in automobiles and in industrial settings.

Broadcast/CATV-Broadcast/cable companies are using fiber optic cables for wiring CATV, HDTV, internet, video on- demand and other applications. Fiber optic cables are used for lighting and imaging and as sensors to measure and monitor a vast array of variables. Fiber optic cables are also used in research and development and testing across all the above mentioned industries

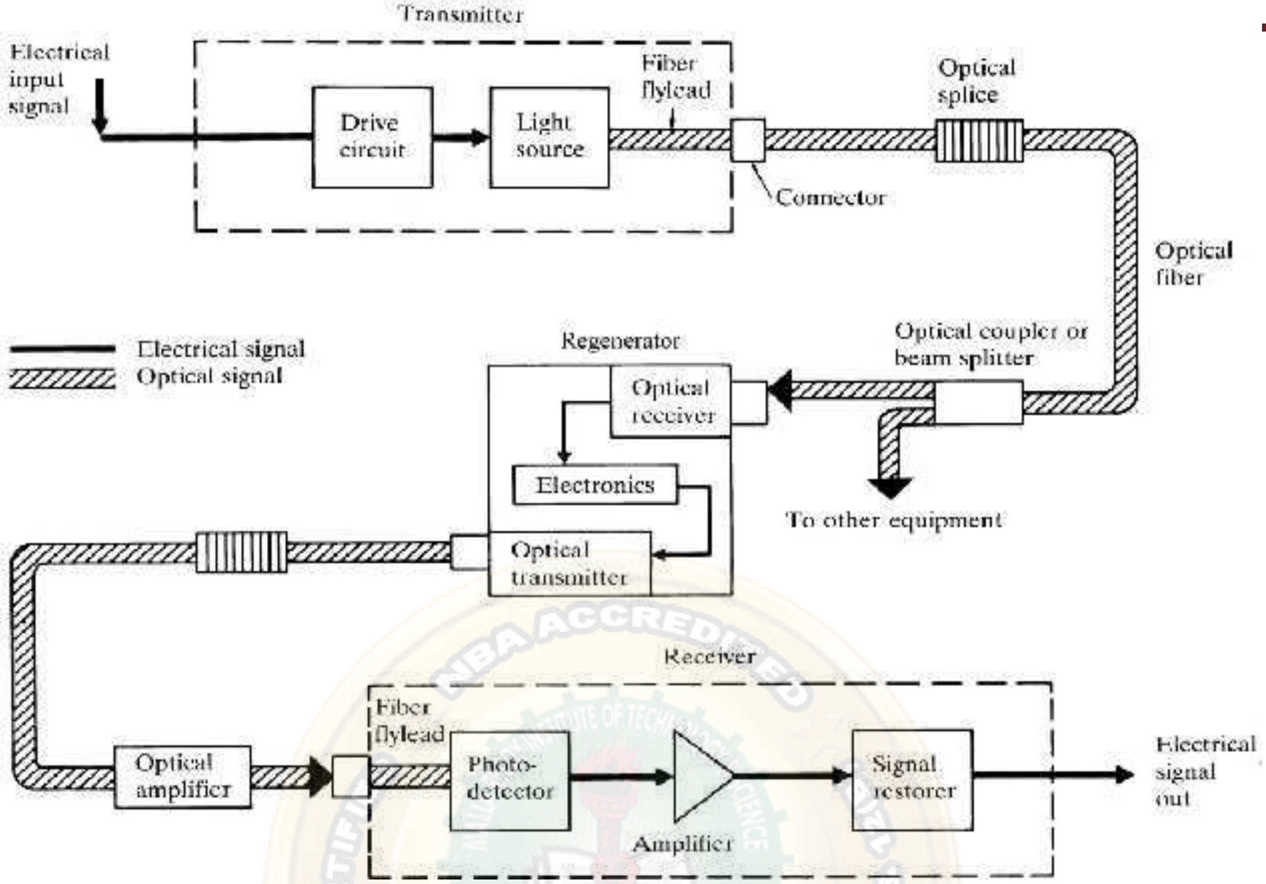
The optical fibers have many applications. Some of them are as follows

- Used in telephone systems
- Used in sub-marine cable networks
- Used in data link for computer networks, CATV Systems
- Used in CCTV surveillance cameras
- Used for connecting fire, police, and other emergency services.
- Used in hospitals, schools, and traffic management systems.
- They have many industrial uses and also used for in heavy duty constructions.

Block Diagram of Optical Fiber Communication System



Block Diagram of Optical Fiber Communication System



Message origin:

Generally message origin is from a transducer that converts a non-electrical message into an electrical signal. Common examples include microphones for converting sound wavesinto currents and video (TV) cameras for converting images into current. For data transfer between computers, the message is already in electrical form.

Modulator:

The modulator has two main functions.

1) It converts the electrical message into proper format.

2) It impresses this signal onto the wave generated by the carrier source.

Two distinct categories of modulation are used i.e. analog modulation and digital modulation.

Carrier source:

Carrier source generates the wave on which the information is transmitted. This wave is called the carrier. For fiber optic system, a laser diode (LD) or a light emitting diode (LED) isused. They can be called as optic oscillators, they provide stable, single frequency waves withsufficient power for long distance propagation.

Channel coupler:

Coupler feeds the power into information channel. For an atmospheric optic system, the channel coupler is a lens used for collimating the light emitted by the source and directing thislight towards the receiver. The coupler must efficiently transfer the modulated light beamfrom the source to the optic fiber. The channel coupler design is an important part of fiber system because of possibility of high losses.

Information channel:

The information channel is the path between the transmitter and receiver. In fiber optic communications, a glass or plastic fiber is the channel. Desirable characteristics of the information channel include low attenuation and large light acceptance cone angle. Optical amplifiers boost the power levels of weak signals. Amplifiers are needed in very long links to provide sufficient power to the receiver. Repeaters can be used only for digital systems. They convert weak and distorted optical signals to electrical ones and then regenerate the original digital pulse trains for further transmission.

Another important property of the information channel is the propagation time of the waves travelling along it. A signal propagating along a fiber normally contains a range of fiber optic frequencies and divides its power along several ray paths. This results in a distortion of the propagation signal. In a digital system, this distortion appears as a spreading and deforming of the pulses. The spreading is so great that adjacent pulses begin to overlap and become unrecognizable as separate bits of information.

Optical detector:

The information begin transmitted is detected by detector. In the fiber system the optic wave is converted into an electric current by a photodetector. The current developed by the detector is proportional to the power in the incident optic wave. Detector output current contains the transmitted information. This detector output is then filtered to remove the constant bias and then amplified. The important properties of photodetectors are small size, economy, long life, low power consumption, high sensitivity to optic signals and fast response to quick variations in the optic power. Signal processing includes filtering, amplification. Properfiltering maximizes the ratio of signal to unwanted power. For a digital system decisioncircuit is an additional block. The bit error rate (BER) should be very small for quality communications.

Signal processing:

Signal processing includes filtering, amplification. Proper filtering maximizes the ratio of signal to unwanted power. For a digital syst5em decision circuit is an additional block. The bit error rate (BER) should be very small for quality communications.

Message output:

The electrical form of the message emerging from the signal processor is transformed into a sound wave or visual image. Sometimes these signals are directly usable when computers or other machines are connected through a fiber system.

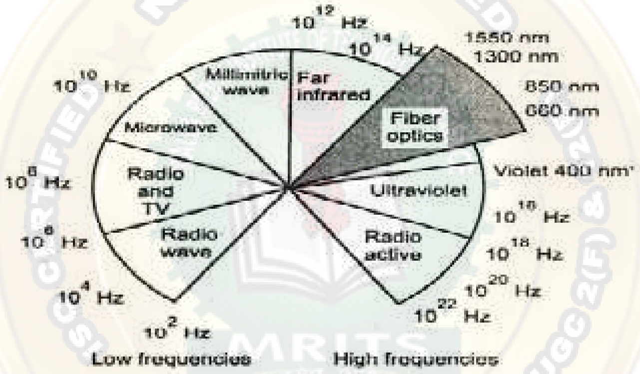
Electromagnetic Spectrum

The radio waves and light are electromagnetic waves. The rate at which they alternate in polarity is called their frequency (f) measured in hertz (Hz). The speed of electromagnetic wave (c) in free space is approximately 3 x 10^8 m/sec. The distance travelled during each cycle is called as wavelength (λ)

In fiber optics, it is more convenient to use the wavelength of light instead of the frequency with light frequencies; wavelength is often stated in microns or nanometers.

1 micron (μ) = 1 Micrometre (1 x 10^{-6}) ;1 nano (n) = 10^{-9} meter

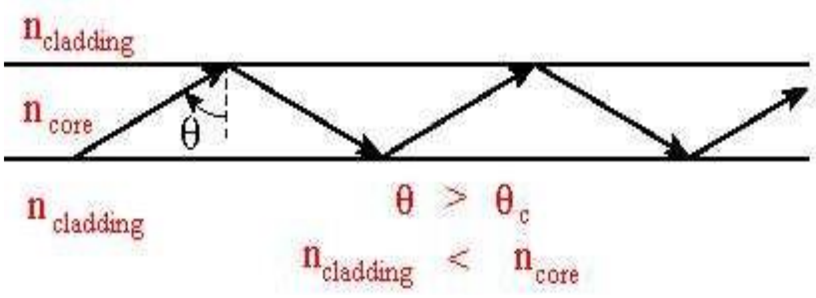
Fiber optics uses visible and infrared light. Infrared light covers a fairly wide range of wavelengths and is generally used for all fiber optic communications. Visible light is normally used for very short range transmission using a plastic fiber



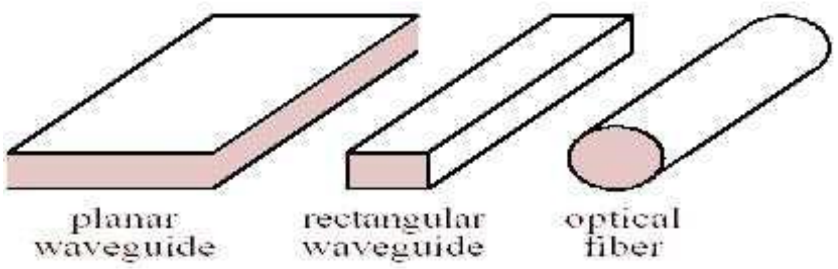
Electromagnetic Spectrum

Optical Fiber Waveguides

In free space light ravels as its maximum possible speed i.e. 3 x 10^8 m/s or 186 x 10^3 miles/sec. When light travels through a material it exhibits certain behavior explained by laws of reflection, refraction. An optical wave guide is a structure that "guides" a light wave by constraining it to travel along a certain desired path. If the transverse dimensions of the guide are much larger than the wavelength of the guided light, that explain how the optical waveguide works using geometrical optics and total internal reflection.



A wave guide traps light by surrounding a guiding region, called the core, made from a material with index of refraction n_{core}, with a material called the cladding, made from a material with index of refraction $n_{cladding} < n_{core}$. Light entering is trapped as long as $\sin\theta > n_{cladding}/n_{core}$.

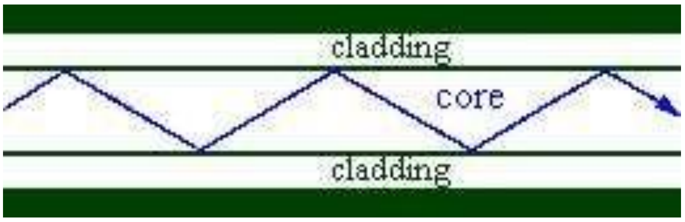


Light can be guided by planar or rectangular wave guides, or by optical fibers. An optical fiber consists of three concentric elements, the core, the cladding and the outer coating, often called the buffer. The core is usually made of glass or plastic. The core is the light-carrying portion of the fiber. The cladding surrounds the core. The cladding is made of a material with a slightly lower index of refraction than the core. This difference in the indices causes total internal reflection to occur at the core-cladding boundary along the length of the fiber. Light is transmitted down the fiber and does not escape through the sides of the fiber.

Fiber Optic Core: the inner light-carrying member with a high index of refraction.

Cladding: the middle layer, which serves to confine the light to the core. It has a lower indexof refraction.

Buffer: The outer layer, which serves as a "shock absorber" to protect the core and claddingfrom damage. The coating usually comprises one or more coats of a plastic material to protect the fiber from the physical environment.



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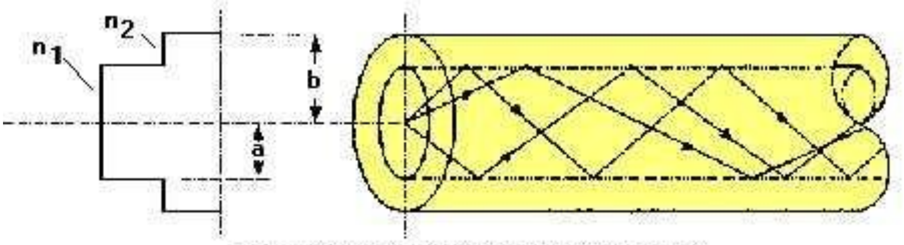
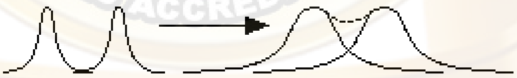
Light injected into the fiber optic core and striking the core-to-cladding interface at an angle greater than the critical angle is reflected back into the core. Since the angles of incidence and reflection are equal, the light ray continues to zigzag down the length of the fiber. The light is trapped within the core. Light striking the interface at less than the critical angle passes into the cladding and is lost.



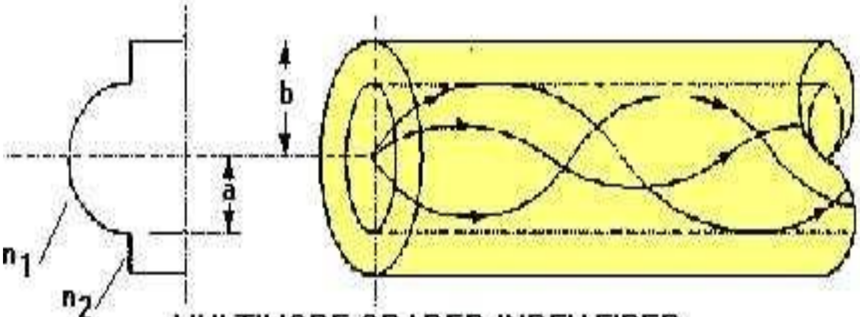
MULTIMODE STEP-INDEX FIBER

Fibers for which the refractive index of the core is a constant and the index changes abruptlyat the core-cladding interface are called step-index fibers.Step-index fibers are available with core diameters of 100 mm to 1000 mm. They are well suited to applications requiring high-power densities, such as delivering laser power for medical and industrial applications.

Multimode step-index fibers trap light with many different entrance angles, each mode in a step-index multimode fiber is associated with a different entrance angle. Each mode therefore travels along a different path through the fiber. Different propagating modes have different velocities. As an optical pulse travels down a multimode fiber, the pulse begins to spread. Pulses that enter well separated from each other will eventually overlap each other. This limits the distance over which the fiber can transport data. Multimode step-index fibers are not well suited for data transport and communications.

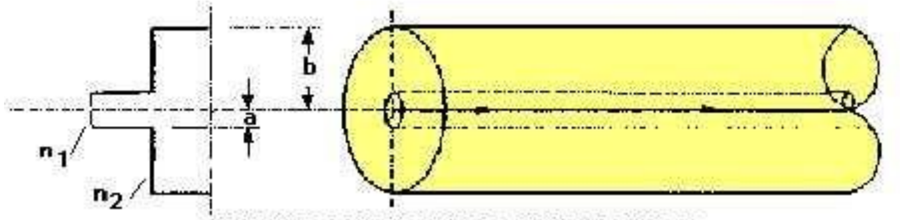


In a multimode graded-index fiber the core has an index of refraction that decreases as the radial distance from the center of the core increases. As a result, the light travels faster near the edge of the core than near the center. Different modes therefore travel in curved pathswith nearly equal travel times. This greatly reduces the spreading of optical pulses.



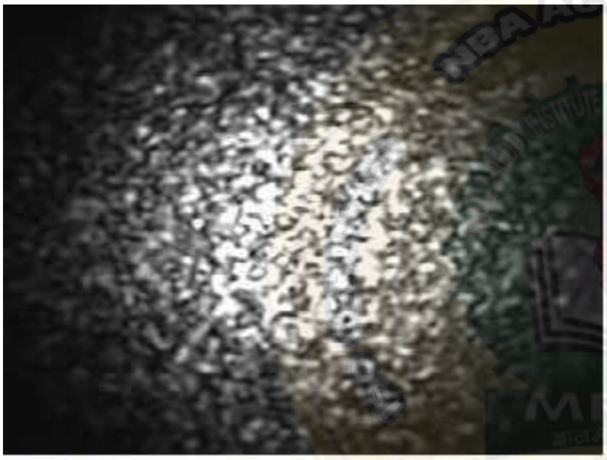
MULTIMODE GRADED-INDEX FIBER

A single mode fiber only allows light to propagate down its center and there are no longer different velocities for different modes. A single mode fiber is much thinner than a multimode fiber and can no longer be analyzed using geometrical optics. Typical core diameters are between 5 mm and 10 mm.



SINGLE MODE STEP-INDEX FIBER

When laser light is coupled into a fiber, the distribution of the light emerging from the other end reveals if the fiber is a multimode or single mode fiber.

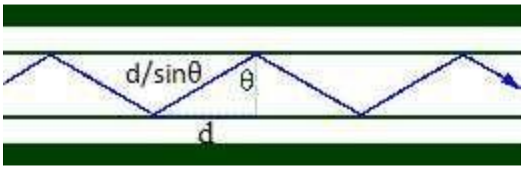


Light emerging from a multi-mode fiber

Light emerging from a single mode fiber

Optical fibers are used widely in the medical field for diagnoses and treatment. Optical fibers can be bundled into flexible strands, which can be inserted into blood vessels, lungs and other parts of the body. An Endoscope is a medical tool carrying two bundles of optic fibers inside one long tube. One bundle directs light at the tissue being tested, while the other bundle carries light reflected from the tissue, producing a detailed image. Endoscopes can be designed to look at regions of the human body, such as the knees, or other joints in the body

In a step-index fiber in the ray approximation, the ray propagating along the axis of the fiber has the shortest route, while the ray incident at the critical angle has the longest route. Determine the difference in travel time (in ns/km) for the modes defined by those two rays fora fiber with n_{core} = 1.5 and $n_{cladding}$ = 1.485.



Solution:

If a ray propagating along the axis of the fiber travels a distance d, then a ray incident at thecritical angle θ_c travels a distance $L = d/\sin\theta_c$.

The respective travel times are $t_d = d_n\text{core}/c$ and t_L =

$d_n\text{core}/(\sin\theta_c\, c)$.$\sin\theta_c = n\text{cladding}/n\text{core}$.

$\theta_C = 81.9$ deg.

For d = 1000 m , t_d = 5000 ns and t_L =5050.51 ns.

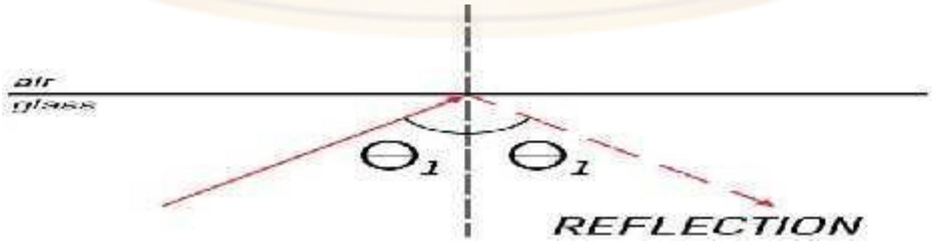
The difference in travel time is therefore 50.51

ns/km.**Ray theory**

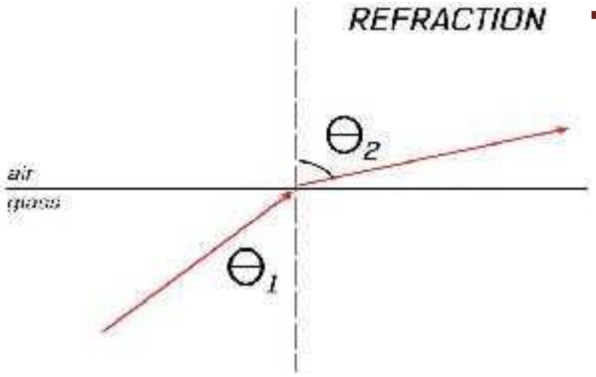
The phenomenon of splitting of white light into its constituents is known as dispersion. The concepts of reflection and refraction of light are based on a theory known as Ray theory or geometric optics, where light waves are considered as waves and represented with simple geometric lines or rays.

The basic laws of ray theory/geometric optics

- In a homogeneous medium, light rays are straight lines.
- Light may be absorbed or reflected.
- Reflected ray lies in the plane of incidence and angle of incidence will be equal to theangle of reflection.
- At the boundary between two media of different refractive indices, the refracted ray will liein the plane of incidence. Snell's Law will give the relationship between the angles of incidence and refraction.



Reflection depends on the type of surface on which light is incident. An essential condition for reflection to occur with glossy surfaces is that the angle made by the incident ray of light with the normal at the point of contact should be equal to the angle of reflection with that normal. The images produced from this reflection have different properties according to the shape of the surface. For example, for a flat mirror, the image produced is upright, has the same size as that of the object and is equally distanced from the surface ofthe mirror as the real object. However, the properties of a parabolic mirror are different and so on.



Refraction is the bending of light in a particular medium due to the speed of light in thatmedium. The speed of light in any medium can be given by

$$v = \frac{c}{n}$$

$$\boxed{\text{Refractive index } n = \frac{\text{Speed of light in air}}{\text{Speed of light in medium}} = \frac{c}{v}}$$

The refractive index for vacuum and air is 1.0 for water it is 1.3 and for glass refractive indexis 1.5. Here n is the refractive index of that medium. When a ray of light is incident at the interface of two media with different refractive indices, it will bend either towards or away from the normal depending on the refractive indices of the media. According to Snell’s law, refraction can be represented as

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

n_1= refractive index of first medium

n_2 θ_1 = angle of incidence, n_2= refractive index of second medium

θ_2 = angle of refraction

For $n_1 > n_2$, θ_2 is always greater than θ_1. Or to put it in different words, light moving from a medium of high refractive index (glass) to a medium of lower refractive index (air) will move away from the normal.

Total internal reflection

To consider the propagation of light within an optical fiber utilizing the ray theory model it is necessary to take account of the refractive index of the dielectric medium. Optical materials are characterized by their index of refraction, referred to as n. The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium.

When a beam of light passes from one material to another with a different index of refraction,the beam is bent (or refracted) at the interface.

$$n_I \sin I = n_R \sin R$$

where *nI* and *nR* are the indices of refraction of the materials through which the beam is refracted and *I* and *R* are the angles of incidence and refraction of the beam. If the angle of incidence is greater than the critical angle for the interface (typically about 82° for optical fibers), the light is reflected back into the incident medium without loss by a process knownas total internal reflection .

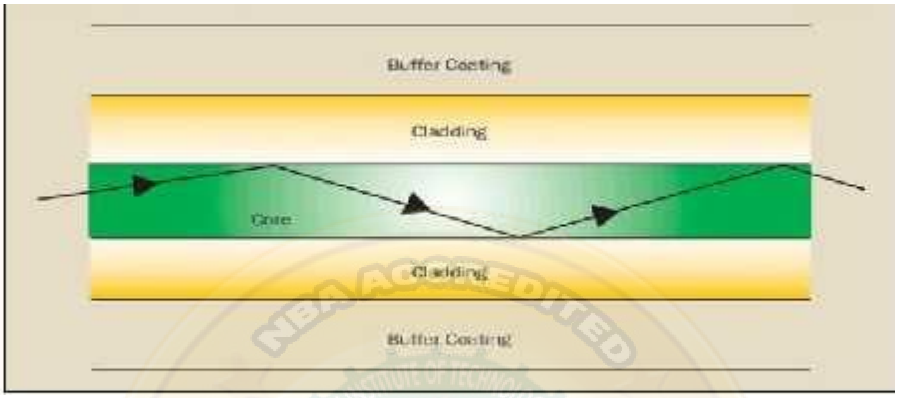


Figure Total Internal Reflection allows light to remain inside the core of the fiber

Refraction is described by Snell's law:

A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs, as illustrated in Figure . It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index *n* and is at an angle φ to the normal at the surface of the interface.

If the dielectric on the other side of the interface has a refractive index *n* which is less than *n*1, then the refraction is such that the ray path in this lower index medium is at an angle to the normal, where is greater than . The angles of incidence and refraction are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction, which states that:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

Or

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1}$$

It may also be observed in Figure that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection). As *n* is greater than *n*, the angle of refraction is always greater than the angle of incidence. Thus when the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics, the angle of incidence must be less than 90°.

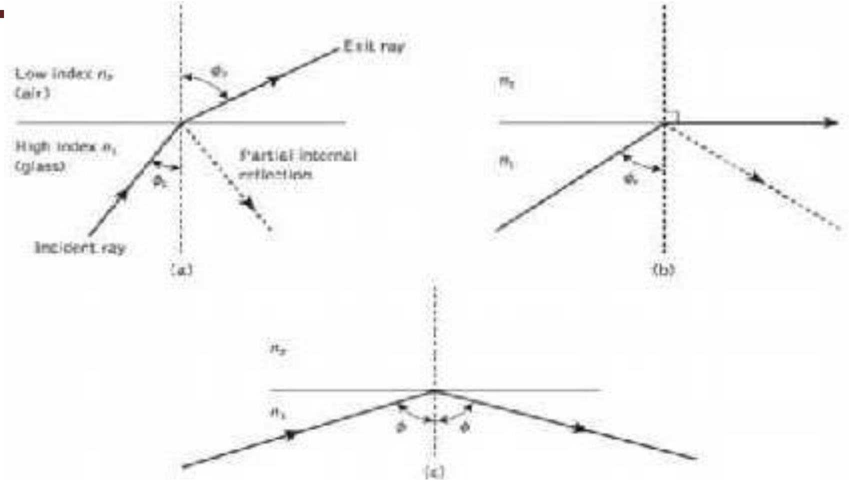


Figure Light rays incident on a high to low refractive index

This is the limiting case of refraction and the angle of incidence is now known as the critical angle φ_c, as shown in Figure. The value of the critical angle is given by

$$\sin \phi_c = \frac{n_2}{n_1}$$

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency (around 99.9%). Hence, it may be observed in Figure that total internal reflection occurs at the interface between two dielectrics of differing refractive indices when light is incident on the dielectric oflower index from the dielectric of higher index, and the angle of incidence of the ray exceeds the critical value. This is the mechanism by which light at a sufficiently shallow angle (less than90°) may be considered to propagate down an optical fiber with low loss.

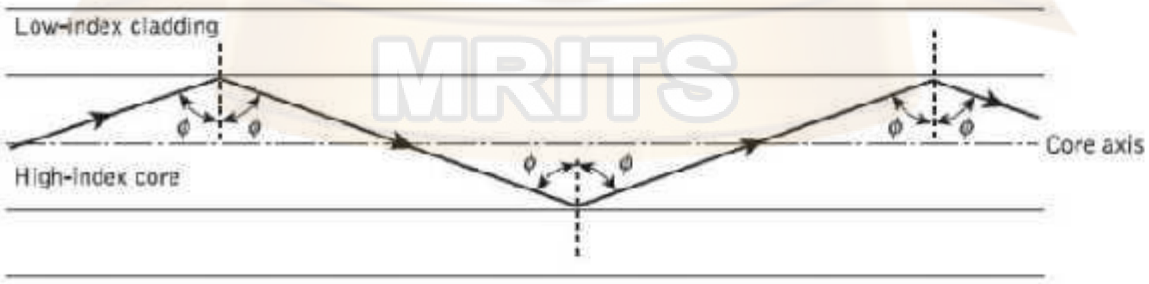


Figure Transmission of a light ray in a perfect optical fiber

The above figure illustrates the transmission of a light ray in an optical fiber via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding. The ray has an angle of incidence φ at the interface which is greater than the critical angle and is reflected at the same angle to the normal. The light ray shown in Figure is known as a meridional ray as it passes through the axis of the fiber core. This type ofray is the simplest to describe and is generally used when illustrating the fundamental transmission properties of optical fibers.

It must also be noted that the light transmission illustrated in Figure assumes a perfect fiber, and that any discontinuities or imperfections at the core–cladding interface would probably result in refraction rather than total internal reflection, with the subsequent loss of the light ray into the cladding.

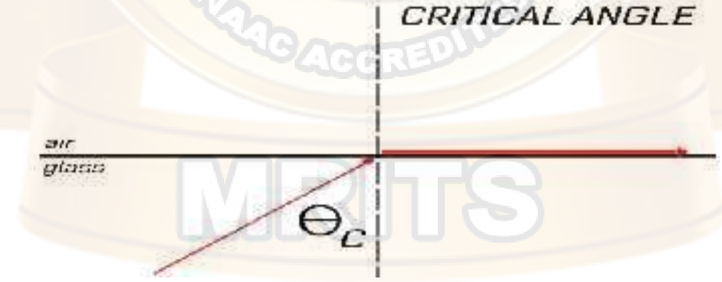
Critical Angle

When the angle of incidence is progressively increased, there will be progressive increase of refractive angle. At some condition the refractive angle becomes 90^{o} to the normal. When this happens the refracted light ray travels along the interface. The angle of incidence at the point at which the refractive angle becomes 90^{o} is called the critical angle. The critical angle is defined as the minimum angle of incidence at which the ray strikes the interface of two media and causes an angle of refraction equal to 90^{o}. Figure shows critical angle refraction. When the angle of refraction is 90 degree to the normal the refracted ray is parallel to the interface between the two media. Using Snell’s law

$$\sin \phi_c = \frac{n_2}{n_1} \sin 90^\circ$$

$$\because \qquad \sin 90^\circ = 1$$

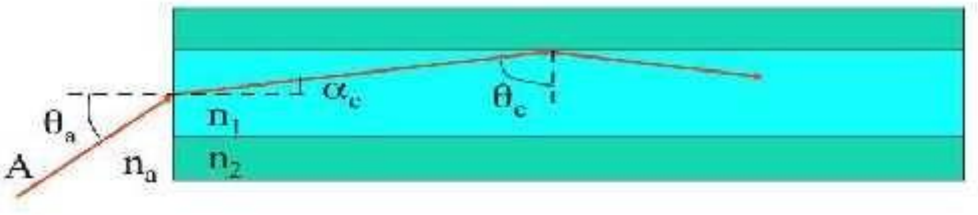
$$\boxed{\text{Critical angle } \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)}$$



It is important to know about this property because reflection is also possible even if the surfaces are not reflective. If the angle of incidence is greater than the critical angle for a given setting, the resulting type of reflection is called Total Internal Reflection, and it is the basis of Optical Fiber Communication.

Acceptance angle

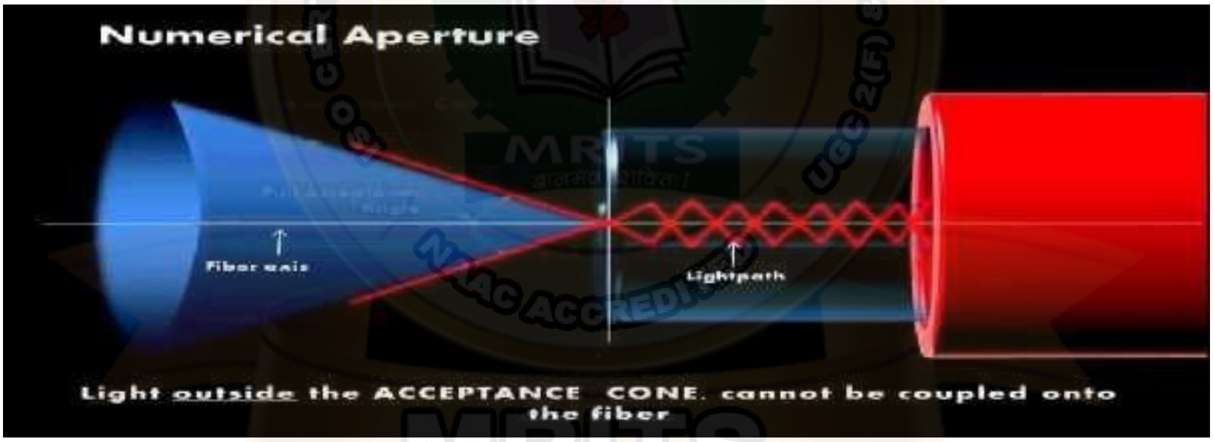
In an optical fiber, a light ray undergoes its first refraction at the air-core interface. The angle at which this refraction occurs is crucial because this particular angle will dictate whether the subsequent internal reflections will follow the principle of Total Internal Reflection. This angle, at which the light ray first encounters the core of an optical fiber is called Acceptance angle.

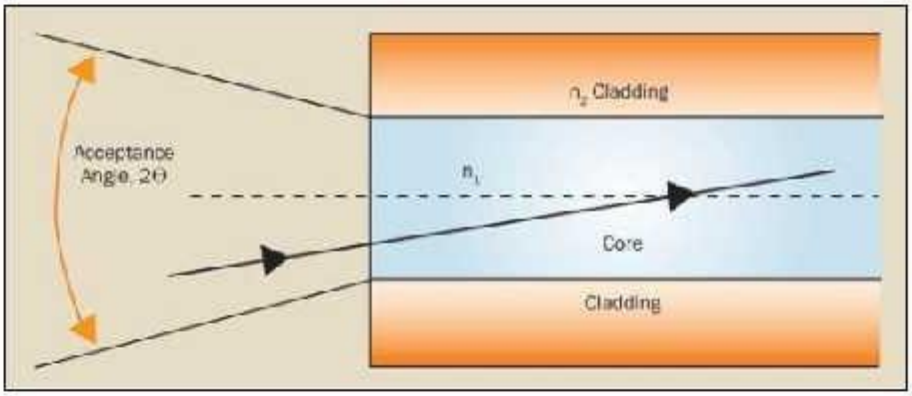


The objective is to have θ_c greater than the critical angle for this particular setting. As you can notice, θ_c depends on the orientation of the refracted ray at the input of the optical fiber. This in turn depends on θ_α, the acceptance angle. The acceptance angle can be calculatedwith the help of the formula below.

Numerical Aperture

Numerical Aperture is a characteristic of any optical system. For example, photo-detector, optical fiber, lenses etc. are all optical systems. Numerical aperture is the ability of the optical system to collect the entire light incident on it, in one area. The blue cone is known as the cone of acceptance. As you can see it is dependent on the Acceptance Angle of the optical fiber. Light waves within the acceptance cone can be collected in a small area which can then be sent into the optical fiber (Source).

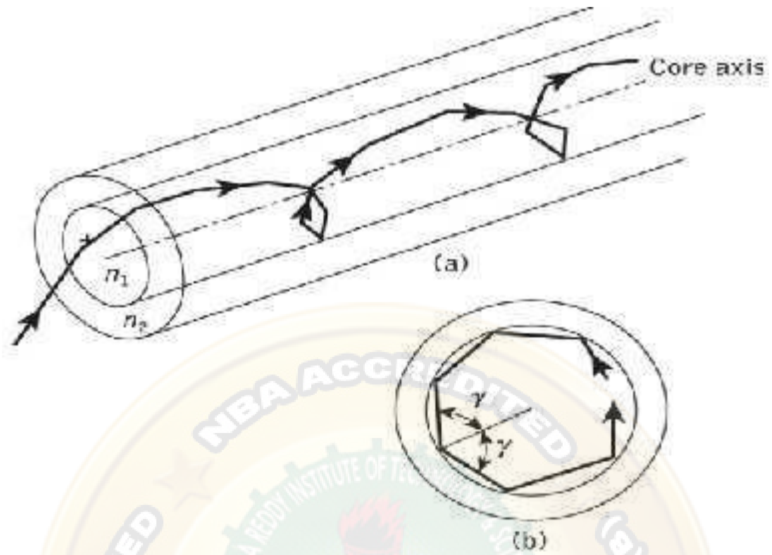




Numerical aperture (NA), shown in above Figure, is the measure of maximum angle at which light rays will enter and be conducted down the fiber. This is represented by the following equation:

$$\mathrm{NA} = \sqrt{(n^2_{core} - n^2_{cladding})} = \sin\theta$$

Skew rays: In a multimode optical fiber, a bound ray that travels in a helical path along the fiber and thus (a) is not parallel to the fiber axis, (b) does not lie in a meridional plane, and (c) does not intersect the fiber axis is known as a Skew Ray.



Figure, view (a), provides an angled view and view (b) provides a front view.

1. Skew rays are rays that travel through an optical fiber without passing through its axis.

2. A possible path of propagation of skew rays is shown in figure.

3. Skew rays are those rays which follow helical path but they are not confined to a single plane. Skew rays are not confined to a particular plane so they cannot be tracked easily. Analyzing the meridional rays is sufficient for the purpose of result, rather than skew rays, because skew rays lead to greater power loss.

4. Skew rays propagate without passing through the center axis of the fiber. The acceptance angle for skew rays is larger than the acceptance angle of meridional rays.

5. Skew rays are often used in the calculation of light acceptance in an optical fiber. The addition of skew rays increases the amount of light capacity of a fiber. In large NA fibers, the increase may be significant.

6. The addition of skew rays also increases the amount of loss in a fiber. Skew rays tend to propagate near the edge of the fiber core. A large portion of the number of skew rays that are trapped in the fiber core are considered to be leaky rays.

7. Leaky rays are predicted to be totally reflected at the core-cladding boundary. However, these rays are partially refracted because of the curved nature of the fiber boundary. Mode theory is also used to describe this type of leaky ray loss.

Cylindrical fiber

1. Modes

When light is guided down a fiber (as microwaves are guided down a waveguide), phase shifts occur at every reflective boundary. There is a finite discrete number of paths down the optical fiber (known as modes) that produce constructive (in phase and therefore additive) phase shifts that reinforce the transmission. Because each mode occurs at a different angle to the fiber axis as the beam travels along the length, each one travels a different length through the fiber from the input to the output. Only one mode, the zero-order mode, travels the length of the fiber without reflections from the sidewalls. This is known as a single-mode fiber. The actual number of modes that can be propagated in a given optical fiber is determined by the wavelength of light and the diameter and index of refraction of the core of the fiber.

The exact solution of Maxwell's equations for a cylindrical homogeneous core dielectric waveguide* involves much algebra and yields a complex result. Although the presentation of this mathematics is beyond the scope of this text, it is useful to consider the resulting modal fields. In common with the planar guide TE (where $E_z = 0$) and TM (where $H_z = 0$) modes are obtained within the dielectric cylinder. The cylindrical waveguide, however, is bounded in two dimensions rather than one. Thus two integers, l and m, are necessary in order to specify the modes, in contrast to the single integer (m) required for the planar guide.

For the cylindrical waveguide, therefore refer to TE_{lm} and TM_{lm} modes. These modes correspond to meridional rays traveling within the fiber. However, hybrid modes where E_z and H_z are nonzero also occur within the cylindrical waveguide.

These modes, which result from skew ray propagation within the fiber, are designated HE_{lm} and EH_{lm} depending upon whether the components of H or E make the larger contribution to the transverse (to the fiber axis) field. Thus an exact description of the modal fields in a step index fiber proves somewhat complicated.

Fortunately, the analysis may be simplified when considering optical fibers for communication purposes. These fibers satisfy the weakly guiding approximation where the relative index difference Δ1. This corresponds to small grazing angles θ. In fact is usually less than 0.03 (3%) for optical communications fibers. For weakly guiding structures with dominant forward propagation, mode theory gives dominant transverse field components. Hence approximate solutions for the full set of HE, EH, TE and TM modes may be given by two linearly polarized components.

These linearly polarized (LP) modes are not exact modes of the fiber except for the fundamental (lowest order) mode. However, as in weakly guiding fibers is very small, then HE– EH mode pairs occur which have almost identical propagation constants. Such modes are said to be degenerate. The superposition of these degenerating modes characterized by a common propagation constant correspond to particular LP modes regardless of their HE, EH, TE or TM field configurations. This linear combination of degenerate modes obtained from the exact solution produces a useful simplification in the analysis of weakly guiding fibers.

The relationship between the traditional HE, EH, TE and TM mode designations and the LPlm mode designations is shown in Table. The mode subscripts l and m are related to the electric field intensity profile for a particular LP mode. There are in general 2l field maxima around the circumference of the fiber core and m field maxima along a radius vector. Furthermore, it may be observed from Table 1.1 that the notation for labeling the HE and EH modes has changed from that specified for the exact solution in the cylindrical waveguide mentioned previously.

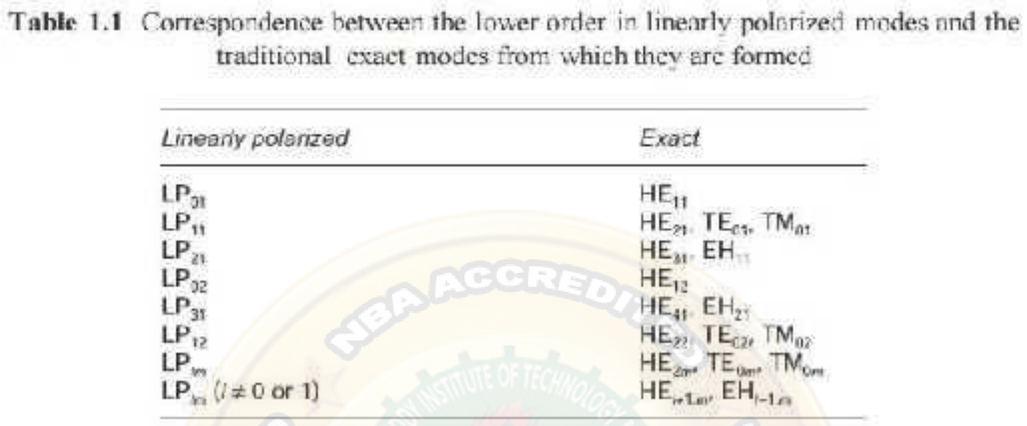


Table 1.1 Correspondence between the lower order in linearly polarized modes and the traditional exact modes from which they are formed

Linearly polarized	*Exact*
LP_{01}	HE_{11}
LP_{11}	HE_{21}, TE_{01}, TM_{01}
LP_{21}	HE_{31}, EH_{11}
LP_{02}	HE_{12}
LP_{31}	HE_{41}, EH_{21}
LP_{12}	HE_{22}, TE_{02}, TM_{02}
LP_{lm}	HE_{2m}, TE_{0m}, TM_{0m}
LP_{lm} ($l \neq 0$ or 1)	$HE_{l+1,m}$, $EH_{l-1,m}$

2. Mode coupling

Thus, so far the propagation aspects of perfect dielectric waveguides were considered. However, waveguide perturbations such as deviations of the fiber axis from straightness, variations in the core diameter, irregularities at the core–cladding interface and refractive index variations may change the propagation characteristics of the fiber. These will have the effect of coupling energy traveling in one mode to another depending on the specific perturbation. Ray theory aids the understanding of this phenomenon, as shown in Figure which illustrates two types of perturbation. It may be observed that in both cases the ray nolonger maintains the same angle with the axis. In electromagnetic wave theory this corresponds to a change in the propagating mode for the light. Thus individual modes do not normally propagate throughout the length of the fiber without large energy transfers toadjacent modes, even when the fiber is exceptionally good quality and is not strained or bent by its surroundings. This mode conversion is known as mode coupling or mixing. It is usuallyanalyzed using coupled mode equations which can be obtained directly from Maxwell’s equations.

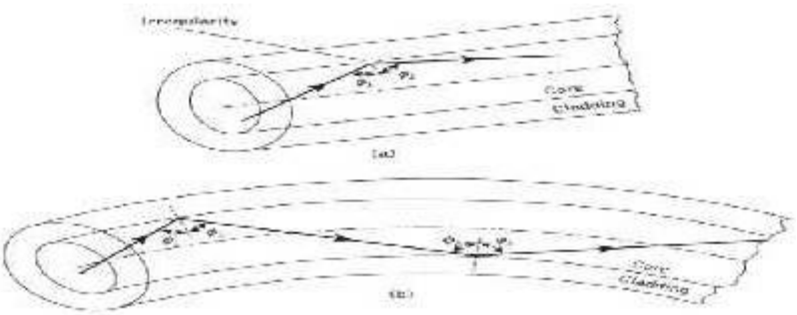


Figure Ray theory illustrations showing two of the possible fiber perturbations which givemode coupling: (a) irregularity at the core–cladding interface; (b) fiber bend

3. Step index fibers

The optical fiber considered in the preceding sections with a core of constant refractive index n_1 and a cladding of a slightly lower refractive index $n_2$is known as step index fiber. This is because the refractive index profile for this type of fiber makes a step change at the core– cladding interface, as indicated in Figure which illustrates the two major types of step index fiber.

Figure shows a multimode step index fiber with a core diameter of around 50μm or greater, which is large enough to allow the propagation of many modes within the fiber core. This is illustrated in Figure by the many different possible ray paths through the fiber. Figure shows a single-mode or monomode step index fiber which allows the propagation of only one transverse electromagnetic mode (typically HE11), and hence the core diameter must be ofthe order of 2 to 10μm. The propagation of a single mode is illustrated in Figure as corresponding to a single ray path only (usually shown as the axial ray) through the fiber. The single-mode step index fiber has the distinct advantage of low intermodal dispersion (broadening of transmitted light pulses), as only one mode is transmitted, whereas with multimode step index fiber considerable dispersion may occur due to the differing group velocities of the propagating modes. This in turn restricts the maximum bandwidth attainable with multimode step index fibers, especially when compared with single-mode fibers.

The refractive index profile may be defined as

$$n(r) = \begin{cases} n_1 & r < a \quad \text{(core)} \\ n_2 & r \geq a \quad \text{(cladding)} \end{cases}$$

in both cases

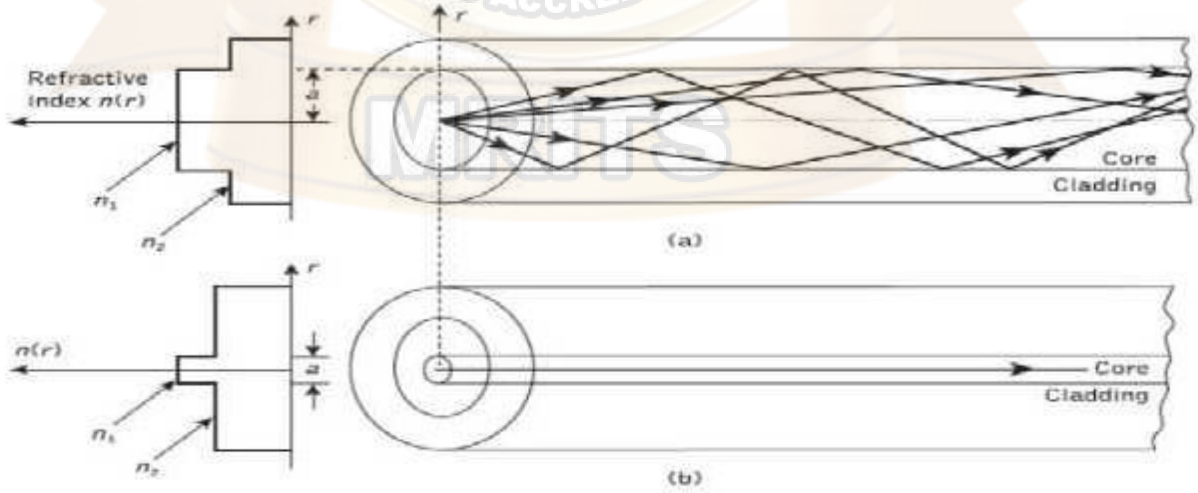


Figure Refractive index profile and ray transmission in step index a) multimode b) singlemode

However, for lower bandwidth applications multimode fibers have several advantages oversingle- mode fibers. These are:

a) The use of spatially incoherent optical sources (e.g. most light-emitting diodes) whichcannot be efficiently coupled to single-mode fibers.

b) Larger numerical apertures, as well as core diameters, facilitating easier coupling to optical sources

c) Lower tolerance requirements on fiber connectors

Multimode step index fibers allow the propagation of a finite number of guided modes along the channel. The number of guided modes is dependent upon the physical parameters (i.e. relative refractive index difference, core radius) of the fiber and the wavelengths of thetransmitted light which are included in the normalized frequency V for the fiber.

Mode propagation does not entirely cease below cutoff. Modes may propagate as unguided or leaky modes which can travel considerable distances along the fiber. Nevertheless, it is the guided modes which are of paramount importance in optical fiber communications as theseare confined to the fiber over its full length. The total number of guided modes or mode volume M_s for a step index fiber is related to the V value for the fiber by the approximate expression that allows an estimate of the number of guided modes propagating in a particular multimode step index fiber.

4. Graded index fibers

Graded index fibers do not have a constant refractive index in the core* but a decreasing core index $n(r)$ with radial distance from a maximum value of$n1$ at the axis to a constant value n_2 beyond the core radius a in the cladding. This index variation may be represented as:

$$n(r) = \begin{cases} n_1\left(1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right) & \text{when } r < a \ (core) \\ n_1(1 - 2\Delta)^{\frac{1}{2}} \approx n_2 & when\ r \geq a \ (\text{cladding}) \end{cases}$$

where is the relative refractive index difference and α is the profile parameter which givesthe characteristic refractive index profile of the fiber core. Equation which is a convenient method of expressing the refractive index profile of the fiber core as a variation of α, allows representation of the step index profile when α = ∞, a parabolic profile when α = 2 and a triangular profile when α = 1. This range of refractive index profiles is illustrated in Figure. The graded index profiles which at present produce the best results for multimode optical propagation have a near parabolic refractive index profile core with ∼∼2. Fibers with such core index profiles are well established and consequently when the term ‘graded index’ is usedwithout qualification it usually refers to a fiber with this profile.

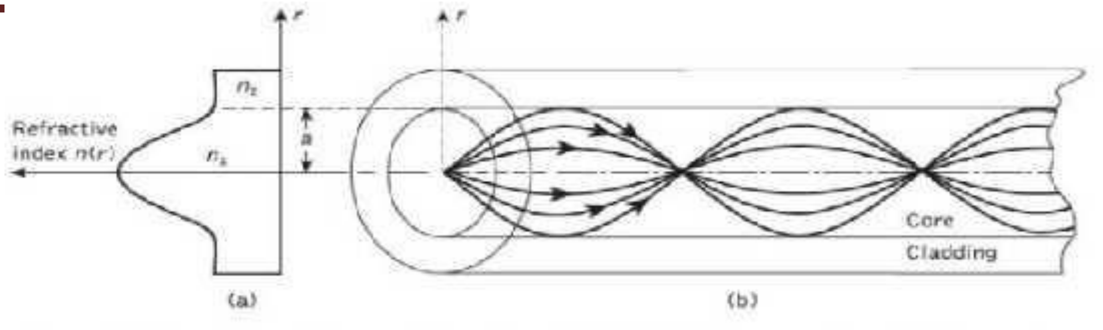


Figure Refractive index profile and ray transmission in multimode graded index

Where, r = Radial distance from fiber axis, a = Core radius, n_1= Refractive index of core, n_2 = Refractive index of cladding, α = Shape of index profile.

Profile parameter α determines the characteristic refractive index profile of fiber core. For this reason in this section, consider the waveguiding properties of graded index fiber with aparabolic refractive index profile core. A multimode graded index fiber with a parabolic index profile core is illustrated in Figure. It may be observed that the meridional rays shown appear to follow curved paths through the fiber core. Using the concepts of geometric optics, the gradual decrease in refractive index from the center of the core creates many refractions of the rays as they are effectively incident on a large number or high to low index interfaces. This mechanism is illustrated in Figure where a ray is shown to be gradually curved, with an ever- increasing angle of incidence, until the conditions for total internal reflection are met, and the ray travels back towards the core axis, again being continuously refracted.

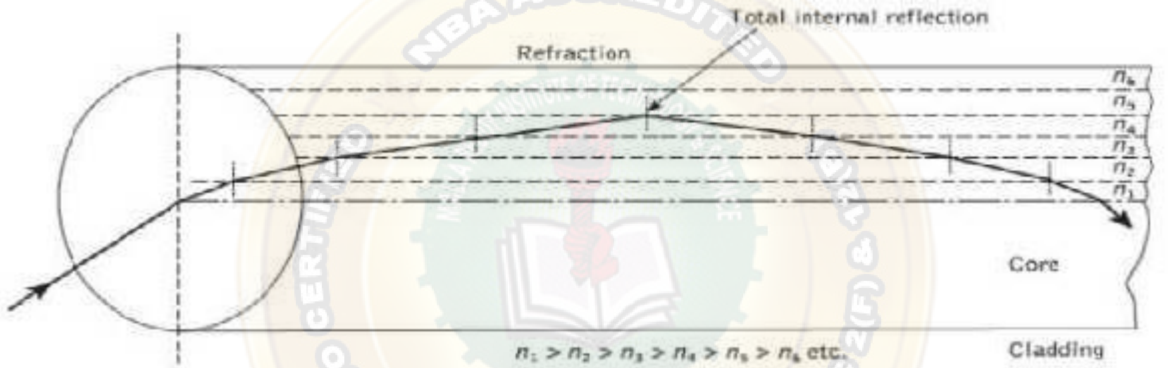


Figure An expanded ray diagram showing refraction

Multimode graded index fibers exhibit far less intermodal dispersion than multimode step index fibers due to their refractive index profile. Although many different modes are excited inthe graded index fiber, the different group velocities of the modes tend to be normalized by theindex grading. Again considering ray theory, the rays traveling close to the fiber axis have shorter paths when compared with rays which travel.

However, the near axial rays are transmitted through a region of higher refractive index and therefore travel with a lower velocity than the more extreme rays. This compensatesfor the shorter path lengths and reduces dispersion in the fiber. A similar situation exists for skew rays which follow longer helical paths, as illustrated in Figure. These travel for the most part in the lower index region at greater speeds, thus giving the same mechanism of mode transit time equalization. Hence, multi- mode graded index fibers with parabolic or near- parabolic index profile cores have trans- mission bandwidths which may be orders of magnitude greater than multimode step index fiber bandwidths.

Consequently, although they are not capable of the bandwidths attain- able with single-mode fibers, such multimode graded index fibers have the advantage of large core diameters (greater than 30 μm) coupled with bandwidths suitable for long- distance communication. The parameters defined for step index fibers (i.e. NA, Δ, V) may be applied to graded index fibers and give a comparison between the two fiber types.

However, it must be noted that for graded index fibers the situation is more complicated since the numerical aperture is a function of the radial distance from the fiber axis. Graded index fibers, therefore, accept less light than corresponding step index fibers with the same relative refractive index difference.

Single-mode fiber

The advantage of the propagation of a single mode within an optical fiber is that the signal dispersion caused by the delay differences between different modes in a multimode fiber may be avoided. Multimode step index fibers do not lend themselves to the propagation of a single mode due to the difficulties of maintaining single-mode operation within the fiber when mode conversion (i.e. coupling) to other guided modes takes place at both input mismatches and fiber imperfections. Hence, for the transmission of a single mode the fiber must be designed to allow propagation of only one mode, while all other modes are attenuated by leakage or absorption. Following the preceding discussion of multimode fibers, this may be achieved through choice of a suitable normalized frequency for the fiber. For single-mode operation, only the fundamental LP01 mode can exist. Hence the limit of single-mode operation depends on the lower limit of guided propagation for the LP11 mode. The cutoff normalized frequency for the LP11 mode in step index fibers occurs at Vc = 2.405. Thussingle-mode propagation of the LP01 mode in step index fibers is possible over the range:

$$0 \leq V < 2.405$$

As there is no cutoff for the fundamental mode. It must be noted that there are in fact two modes with orthogonal polarization over this range, and the term single-mode applies to propagation of light of a particular polarization. Also, it is apparent that the normalized frequency for the fiber may be adjusted to within the range given in Equation by reduction of the core radius.

1. Cutoff wavelength

It may be noted that single-mode operation only occurs above a theoretical cutoff wavelength λ_c given by:

$$\lambda_c = \frac{2\pi a n_1}{V_c}(2\Delta)^{\frac{1}{2}}$$

Where V_c- Cut off normalized frequency.

Dividing above equation by

$$V = \frac{2\pi}{\lambda} a n_1 (2\Delta)^{\frac{1}{2}}$$

$$\frac{\lambda_c}{\lambda} = \frac{V}{V_c}$$

Thus for step index fiber where V_c=2.405, the cut-off wavelength is given by

$$\lambda_c = \frac{V\lambda}{2.405}$$

An effective cutoff wavelength has been defined by the ITU-T which is obtained from a 2 m length of fiber containing a single 14 cm radius loop. This definition was produced becausethe first higher order LP11 mode is strongly affected by fiber length and curvature near cutoff. Recommended cutoff wavelength values for primary coated fiber range from 1.1 to 1.28 μm for single-mode fiber designed for operation in the 1.3μm wavelength region in order to avoid modal noise and dispersion problems. Moreover, practical transmission systems are generally operated close to the effective cutoff wave- length in order to enhance the fundamental mode confinement, but sufficiently distant from cutoff so that no power is transmitted in the second- order LP11 mode.

2. Mode-field diameter and spot size

Many properties of the fundamental mode are determined by the radial extent of its electromagnetic field including losses at launching and jointing, micro bend losses, waveguidedispersion and the width of the radiation pattern. Therefore, the MFD is an important parameter for characterizing single-mode fiber properties which takes into account the wavelength-dependent field penetration into the fiber cladding. In this context it is a better measure of the functional properties of single- mode fiber than the core diameter. For step index and graded (near parabolic profile) single-mode fibers operating near the cutoff wavelength λ_c, the field is well approximated by a Gaussian distribution. In this case the MFD is generally taken as the distance between the opposite 1/e = 0.37 field amplitude points and the power 1/e2 = 0.135 points in relation to the corresponding values on the fiber axis. Another parameter which is directly related to the MFD of a single-mode fiber is the spot size (or mode-field radius) ω0. Hence MFD = $2\omega_0$, where ω_0 is the nominal half width of the input excitation.

The MFD can therefore be regarded as the single- mode analog of the fiber core diameter in multimode fibers. However, for many refractive index profiles and at typical operating wavelengths the MFD is slightly larger than the single-mode fiber core diameter. Often, for real fibers and those with arbitrary refractive index profiles, the radial field distribution is not strictly Gaussian and hence alternative techniques have been proposed. However, the problem of defining the MFD and spot size for non-Gaussian field distributions is difficult one and at least eight definitions exist.

3. Effective refractive index

The rate of change of phase of the fundamental LP01 mode propagating along a straight fiber is determined by the phase propagation constant. It is directly related to the wavelength of the LP01 mode λ_{01} by the factor 2π, since β gives the increase in phase angle per unit length. Hence:

$$\beta\lambda_{01} = 2\pi \quad \text{or} \quad \lambda_{01} = \frac{2\pi}{\beta}$$

Morever, it is convenient to define an effective refractive index for single mode fiber, sometimes referred to as a phase index or normalized phase change coefficient n_{eff} by the ratio of the propagation constant of the fundamental mode to that of the vaccum propagation constant.

$$n_{eff} = \frac{\beta}{k}$$

Hence, the wavelength of the fundamental mode is smaller than the vaccum wave by the factor 1/ n_{eff} ,where

$$\lambda_{01} = \frac{\lambda}{n_{eff}}$$

It should be noted that the fundamental mode propagates in a medium with a refractive index n(r) which is dependent on the distance r from the fiber axis. The effective refractive index cantherefore be considered as an average over the refractive index of this medium. Within a normally clad fiber, not depressed-cladded fibers, at long wavelengths (i.e. small *V* values) theMFD is large compared to the core diameter and hence the electric field extends far into the cladding region. In this case the propagation constant β will be approximately equal to $n2k$ (i.e. the cladding wave number) and the effective index will be similar to the refractive index of the cladding n_2. Physically, most of the power is transmitted in the cladding material. At short wavelengths, however, the field is concentrated in the core region and the propagation constant β approximates to the maximum wave number nlk. Following thisdiscussion, and as indicated previously, then the propagation constant in single-mode fiber varies over the interval $n_2k< \beta <n_1k$. Hence, the effective refractive index will vary over the range $n_2<neff<n_1$.

4. Group delay and mode delay factor

The transit time or group delay τ_g for a light pulse propagating along a unit length of fiber is the inverse of the group velocity, υ_g

$$\tau_g = \frac{1}{\upsilon_g} = \frac{d\beta}{d\omega} = \frac{1}{c}\frac{d\beta}{dk}$$

The group index of a uniform plane wave propagating in a homogenous medium has been identified as

$$N_g = \frac{c}{\upsilon_g}$$

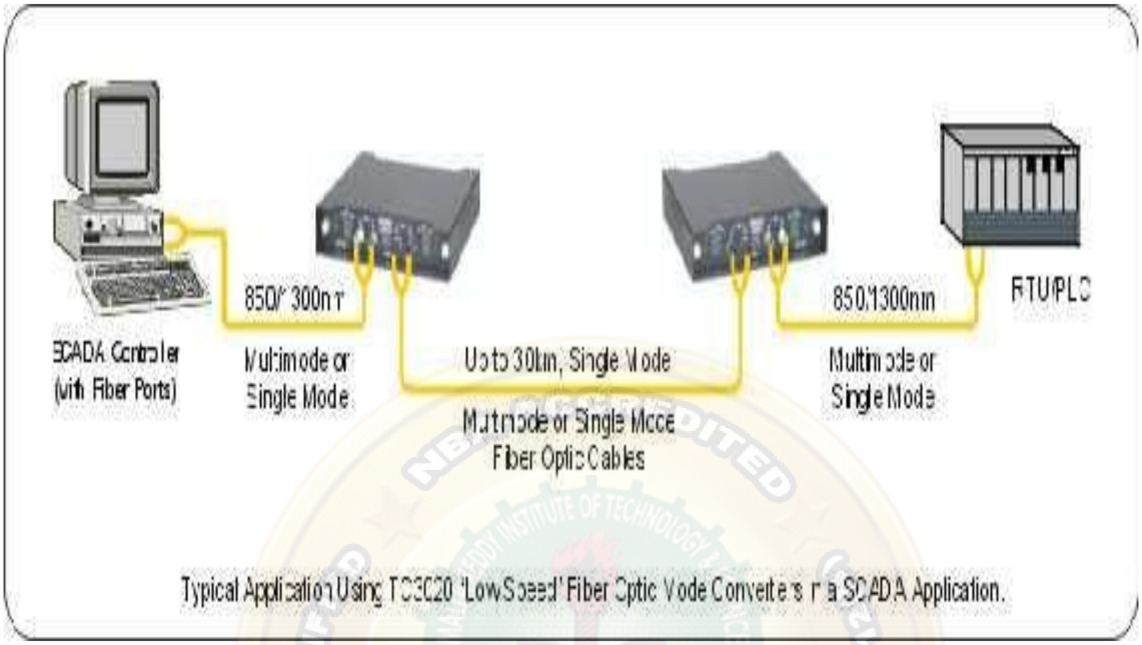
However, for a single mode fiber, it is usual to define an effective group index by

$$N_{ge} = \frac{c}{\upsilon_g}$$

Hence, where υ_g is considered to be the group velocity of the fundamental fiber mode. Hence,the specific group delay of the fundamental fiber mode becomes:

$$\tau_g = \frac{N_{ge}}{c}$$

APPLICATIONS



Examples of Typical Application of Fiber Optic Mode in SCADA application

Examples of Application of optical fiber in Dentistry

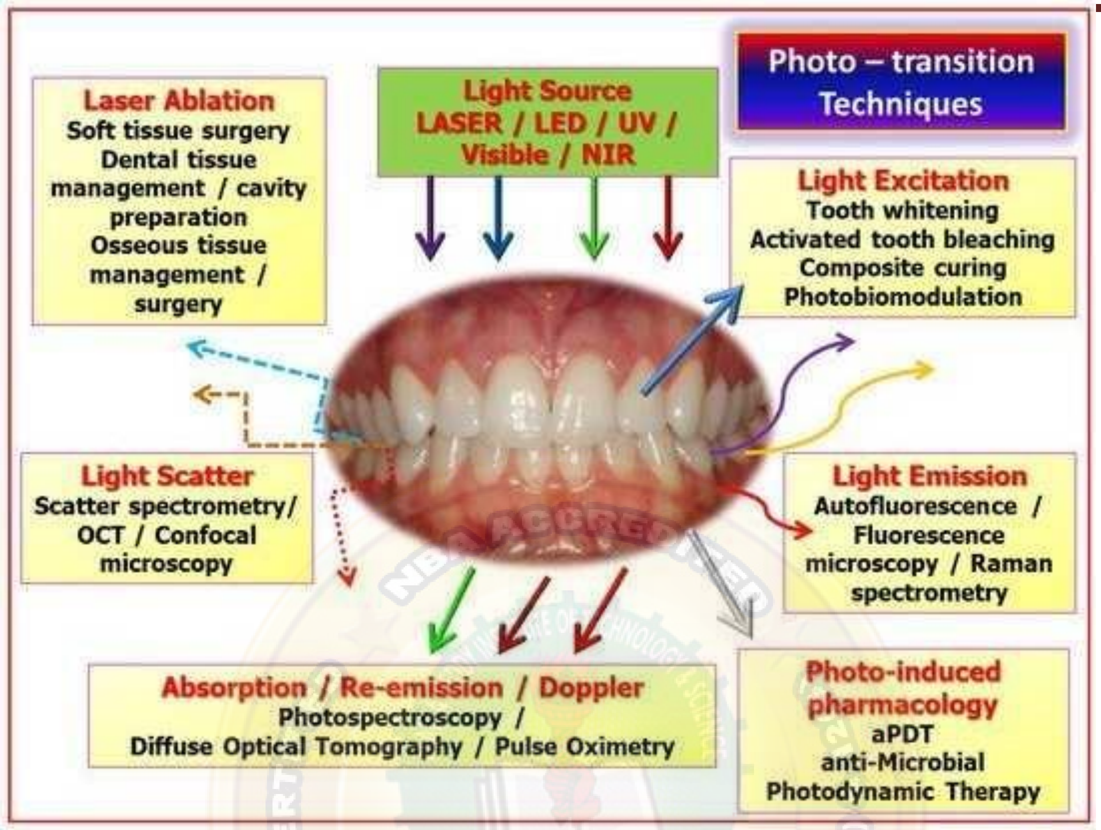


Photo – transition Techniques
Light Source
LASER / LED / UV / Visible / NIR
Laser Ablation
Soft tissue surgery
Dental tissue management / cavity preparation
Osseous tissue management / surgery
Light Excitation
Tooth whitening
Activated tooth bleaching
Composite curing
Photobiomodulation
Light Scatter
Scatter spectrometry/ OCT / Confocal microscopy
Light Emission
Autofluorescence / Fluorescence microscopy / Raman spectrometry
Absorption / Re-emission / Doppler
Photospectroscopy /
Diffuse Optical Tomography / Pulse Oximetry
Photo-induced pharmacology
aPDT
anti-Microbial
Photodynamic Therapy

R15

Code No: 127FE

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY HYDERABAD

B.Tech IV Year I Semester Examinations, May/June - 2019MICROWAVE ENGINEERING

(Electronics and Communication Engineering)

Time: 3 Hours Max. Marks: 75

Note: This question paper contains two parts A and B.
Part A is compulsory which carries 25 marks. Answer all questions in Part A.Part B consists of 5 Units. Answer any one full question from each unit. Each question carries 10 marks and may have a, b, c as sub questions.

PART- A

(25 Marks)

1.a) What modes are the dominant modes in TE and TM waveguides. [2]
b) Define effective permittivity of Microstip line. [3]
c) Define Q factor of Circular waveguides. [2]
d) Compare probe and loop connections. [3]
e) What are the reentrant cavities? [2]
f) How Microwave tubes are classified? [3]
g) What is strapping in Magnetron? [2]
h) How cross-field concept is used to produce oscillations in Magnetron? [3]
i) What type of slot is used in Microwave bench? [2]
j) What are the properties of S-matrix? [3]

PART-B

(50 Marks)

2.a) What are the applications of Microwave frequencies?
b) Derive the equation for impedance of Microstrip line.

c) Prove the cutoff frequency of Rectangular waveguide in TM and TE

d) modes is same. [10]

OR

3.a) Determine the equations of Fields of Rectangular waveguide in TM mode starting fromMaxwell's equations.

b) Explain the power loss in waveguides with suitable equations. [5+5]

4.a) What are the different types of Phase shifters? Explain them with neat diagrams.

b) Draw the structure diagram of H-plane Tee and explain its characteristics. [5+5]

OR

5.a) Explain how Ferrites are used for isolators? Explain any one of such circuit.

b) What are the waveguide windows? How these are used in Microwave circuits? [5+5]

6. Explain the bunching process of two cavity klystron amplifier with Applegate diagramand also derive the equations for power efficiency. [10]

OR

7.a) What are the different oscillating modes in TWT and explain them.

b) Compare the performance of TWT with Klystron amplifier. [6+4]

8. Explain the electron bunching process in Cylindrical Magnetron with neat diagrams andderive the Hartee condition. [10]

OR

9.a) Draw the characteristics of Gunn diode and explain how negative resistance region isobtained?

b) What are the applications of Gunn diode? [6+4]

10. What are the characteristics of two hole direction coupler and derive the S-matrix of it. [10]

OR

11. Explain how to measure the VSWR of a given load at microwave frequencies with neatblock diagram. [10]

Code No: 157CM **R18**

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY HYDERABAD
B. Tech IV Year I Semester Examinations, February/March - 2022MICROWAVE AND
OPTICAL COMMUNICATIONS
(Electronics and Communication Engineering)
Time: 3 Hours Max. Marks: 75

Answer any Five Questions All Questions
Carry Equal Marks

\- - -

1.a) Explain in detail the operation of Reflex Klystron and derive equation for its efficiency.
b) What is Velocity modulation? How is it different from normal modulation? Explain how velocity modulation is utilized in Klystron amplifier. [8+7]

2.a) Explain the operation of TWT and derive its gain. Give its characteristics and applications.
b) What is a Gunn Diode? Explain how it works as a Oscillator and also discuss about the characteristic curve. [8+7]

3.a) Explain the operation of magnetron and derive its Hull Cutoff Voltage equation.
b) Explain the operation of IMPATT Diode and explain its characteristics curve. [7+8]

4.a) Discuss the design of Waveguide terminations.
b) With a neat diagram explain in detail about H-plane tee and determine its S-matrix. [8+7]

5.a) What are ferrites? How they are useful in microwaves? Explain faradays rotation.
b) Explain the design and working principle of a Gyrator. [8+7]

6.a) Explain the operation of Magic Tee. Describe how it can be used in constructing a Circulator and a Duplexer.
b) Discuss in detail the operation of a 2-hole directional coupler, Calculate the coupling factor if the power in the primary waveguide is 65mw and the power delivered to the directional coupler is 7mw. [8+7]

7.a) With a neat block diagram of typical microwave bench, explain the functionality of each block.
b) Define an optical fiber. Explain in detail different types of optical fibers with neatsketches. [8+7]

8.a) Explain P-I-N photo detector with neat sketch.
b) Briefly explain the types of losses occur in optical fiber. [7+8]

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