

METHODIST COLLEGE OF ENGINEERING & TECHNOLOGY

Accredited by NBA & NAAC with “A+” Grade

PC703 EC : MICROWAVE TECHNIQUES

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Professor

**DEPARTMENT OF
ELECTRONICS AND COMMUNICATION ENGINEERING**

Syllabus – Our Approach

➤ Overview of Communication Systems

➤ Pre-requisites :

- Maxwell's equations— EMTL
- Antennas and Wave Propagation

➤ Broadly Our Syllabus is divided into

- Guided Waves
- Waveguides. Cavity Resonators
- Passive Microwave Components
- Microwave Tubes – Amplifiers, Oscillators
- Solid state devices – Amplifiers & Oscillators

Course Objectives

- Understand the concept of Guided waves and its propagation in different modes (TE, TM, and TEM) between parallel planes and to find out applications of different parameters.
- Use of the concept of TE, TM & TEM waves in Waveguides (Rectangular and Circular) and evaluate different parameters & understand the operation of Cavity Resonators.
- Understand the concept of Microwave circuit and evaluate Scattering parameters of microwave components.
- Understand the high frequency limitations of conventional tubes and principle of bunching and velocity modulation analyse the operation of microwave tubes
- Understand principle and operation of Microwave solid state devices & evaluate the characteristics of devices & concept of strip lines, slot lines and fin lines.

OBJECTIVES AND RELEVANCE

- **This course introduces the basic concepts of Microwaves which are the foundation for Microwave communication system design.**
- **This subject is concerned with the theory of systems for the conveyance / transfer/exchange of information at microwave frequencies (high frequencies).**

Course Outcomes

After completing this course, the student will be able to

- Analyse the propagation of Guided waves in different modes between parallel planes.
- Evaluate different parameters (Like impedance, attenuation and quality factor.) for Rectangular & Circular Waveguides & Cavity Resonators.
- Determine Scattering parameters of different microwave components and analyse their properties.
- Integrate the concept of bunching and velocity modulation to summarize the operation of microwave tubes and the high frequency limitations of conventional tubes.
- Analyse the principle, operation and characteristics of different microwave solid state devices

SYLLABUS

UNIT - I

Guided Waves: Propagation of TE, TM and TEM waves between parallel planes. Velocity of propagation, wave impedance, attenuation in parallel plane guides.

UNIT - II

Waveguides: TE and TM waves in rectangular and circular waveguides, Wave Impedance, Characteristic Wave Impedance, Attenuation and Q of waveguides. Cavity resonators, resonant frequency and Q, Applications of cavity resonator.

SYLLABUS

UNIT - III

Microwave Circuits and Components: Concept of Microwave circuit, Normalized voltage and current, Introduction to scattering parameters and their properties, S parameters for reciprocal and Non-reciprocal components- Magic Tee, Directional coupler, E and H Plane Tees and their properties, Attenuators, Phase Shifters, Isolators and circulators.

SYLLABUS

UNIT – IV

Microwave Tubes: High frequency limitations of conventional tubes, Bunching and velocity modulation, mathematical theory of bunching, principles and operation of two cavity, multi cavity and Reflex Klystron.
Theory of crossed field interaction: Principles and operation of magnetrons and crossed field amplifiers, TWT and BWO.

UNIT – V

Microwave Solid State Devices: Principles of operation, characteristics and applications of Varactor, PIN diode, GUNN diode and IMPATT diode. Elements of strip lines, micro strip lines, slot lines and fin-lines.

TEXT BOOKS AND REFERENCES

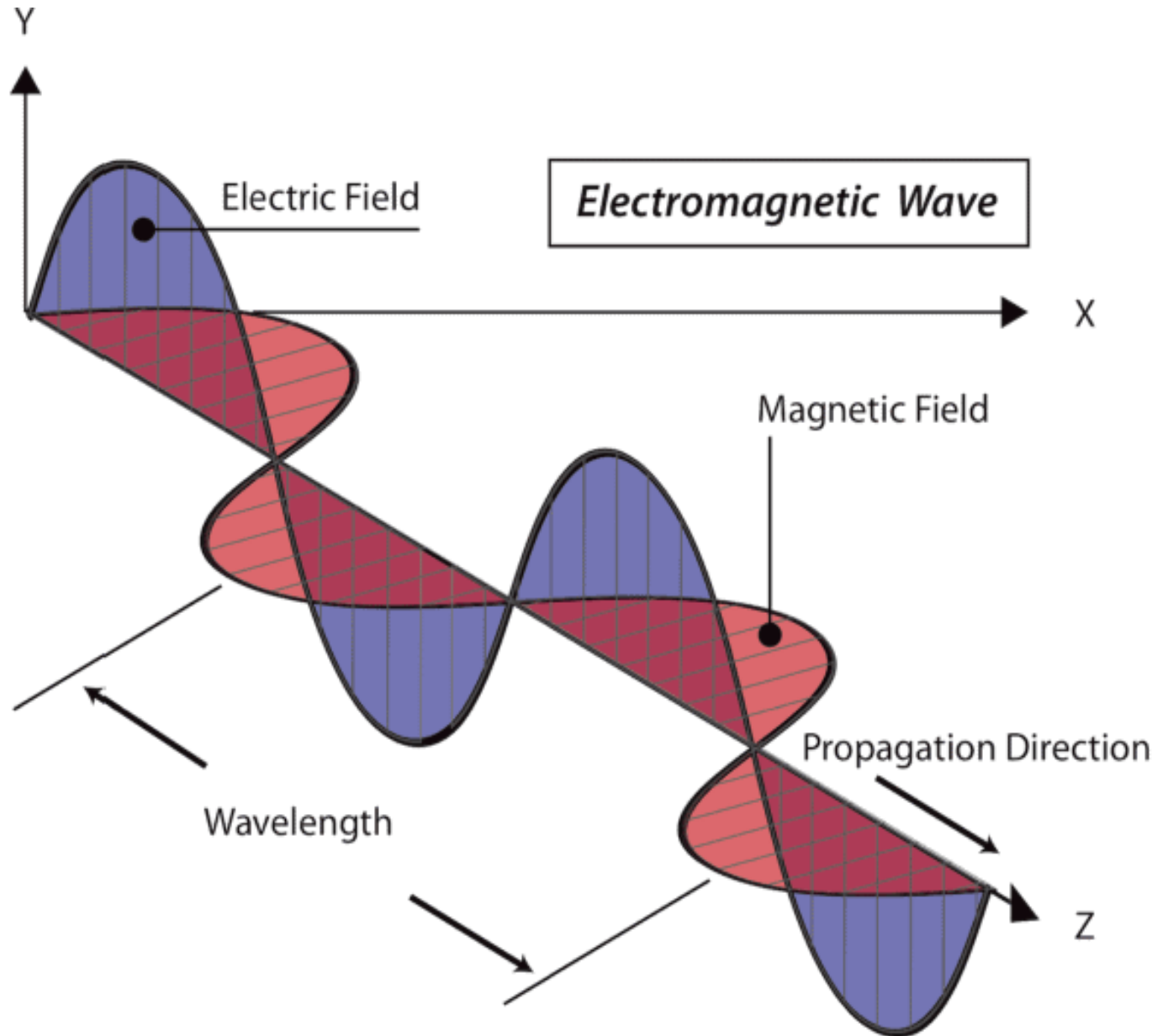
TEXT BOOKS

- 1) Microwave Devices and Circuits – Samuel Y. Liao, Pearson, 3rd Edition, 2003.
- 2) E. C. Jordan & Keith G. Balmain, “Electromagnetic Waves and Radiating Systems”, 2/e, Pearson Education, 2006.
- 3) Microwave Principles – Herbert J. Reich, J.G. Skalnik, P.F. Ordung and H.L. Krauss, CBS Publishers and Distributors, New Delhi, 2004.

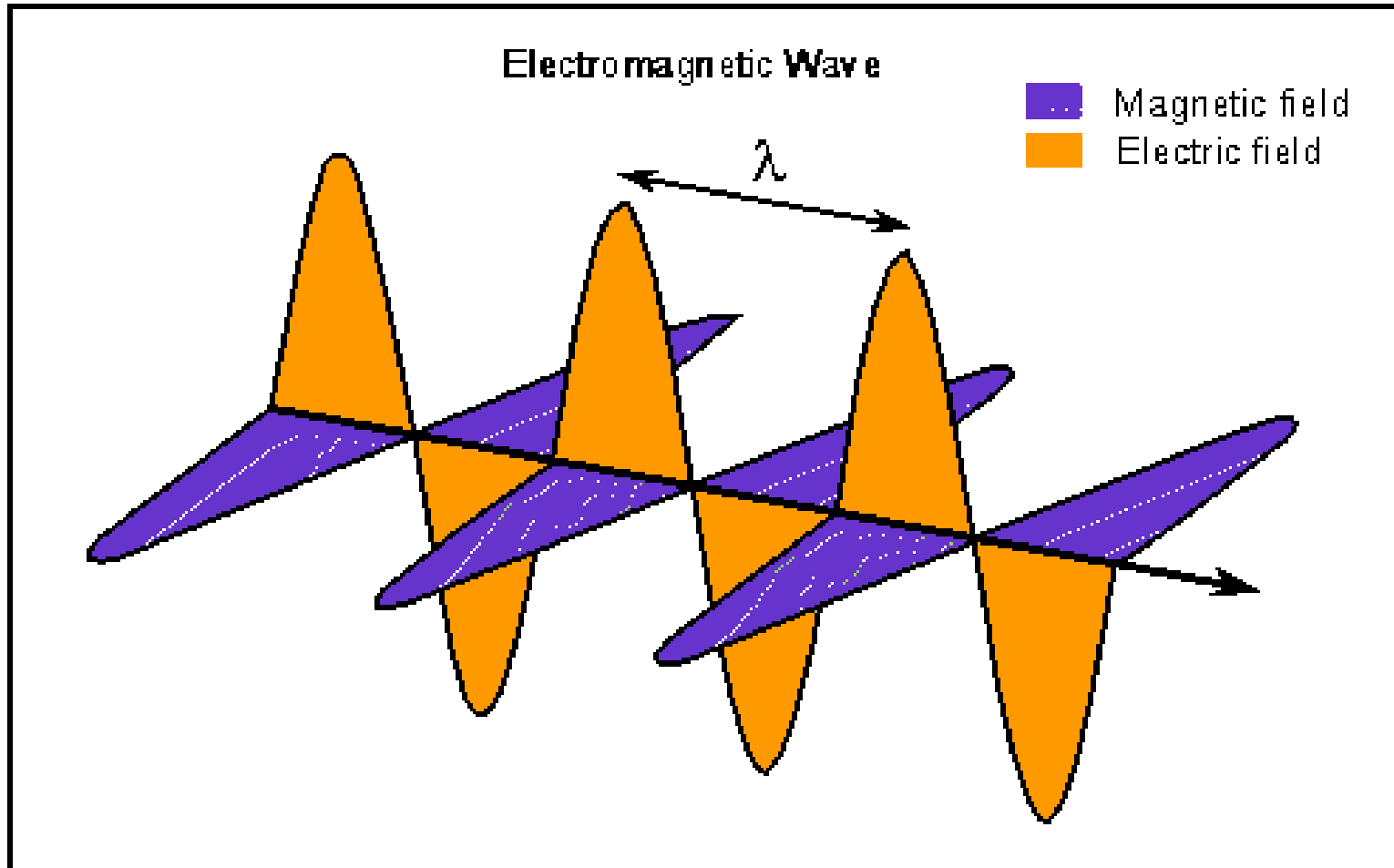
REFERENCES

- a) Foundations for Microwave Engineering – R.E. Collin, IEEE Press, John Wiley, 2nd Edition, 2002.
- b) Microwave Engineering - G.S. Raghuvanshi, Cengage Learning India Pvt. Ltd., 2012.
- c) Annapurna Das and Sisir K., “Microwave Engineering”, McGraw Hill Education, Third edition, 2014.

INTRODUCTION



This page was copied from Nick Strobel's Astronomy Notes. Go to his site at www.astronomynotes.com for the updated and corrected version.



What is the speed of EM waves?

- All EM waves travel 300,000 km/sec in space. (speed of light-nature's limit!)
- EM waves usually travel slowest in solids and fastest in gases.

Material	Speed (km/s)
Vacuum	300,000
Air	<300,000
Water	226,000
Glass	200,000
Diamond	124,000

Frequency Spectrum

- The frequency spectrum has to be managed for a particular physical medium
- The spectrum for “over-the-air” communications is allocated by international communications organization
 - International Telecommunications Union (ITU)
 - Federal Communications Commission (FCC) designates and licenses frequency bands in the US.

Frequency Spectrum

- **Frequency Spectrum means a RANGE OF FREQUENCIES – or Representation of Signal Strength as a function of Frequency**
- **Most precious resource in communications is “frequency spectrum”**
- **The “frequency spectrum” has to be shared by a large number of users for various applications:**
 - **AM Radio**
 - **FM Radio**
 - **Television -TV**
 - **Cellular telephony / Mobile Communications**
 - **Wireless local-area-networks**
 - **Satellite and Radar Applications**
 - **Air traffic control**

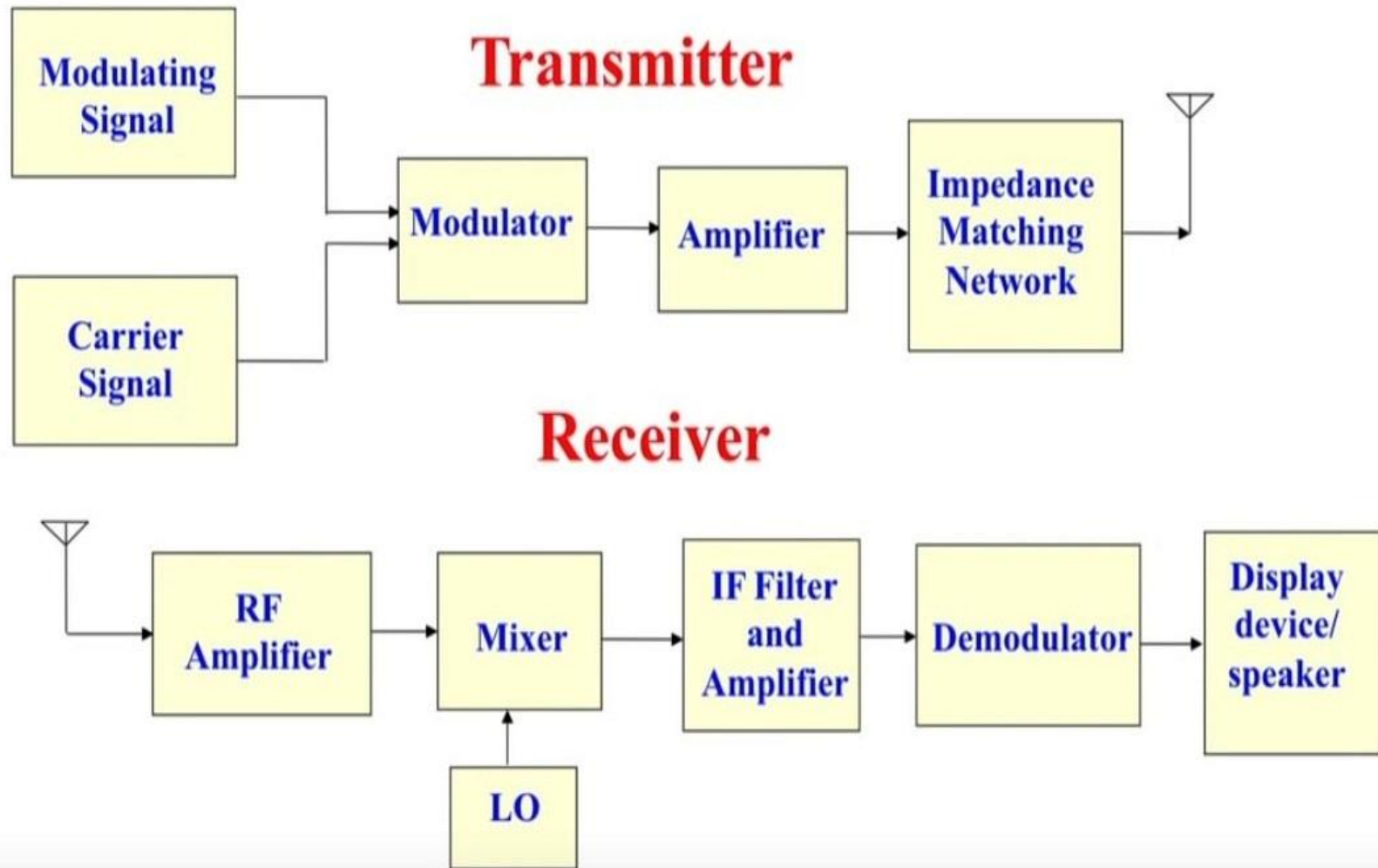
Frequency Spectrum Applications

Application	Frequency Band
AM Radio	0.54-1.6 MHz
TV (Channels 2-6)	54-88 MHz
FM Radio	88-108 MHz
TV (Channels 7-13)	174-216 MHz
Cellular mobile radio	806-901 MHz

Applications and Frequency Bands

- FM Radio – Frequency: 88 to 108 MHz
- CDMA – 824 to 890 MHz
- GSM900 - 890 to 915 and 935 to 960 MHz
- GPS – 1575 ± 10 MHz
- GSM1800 – 1710 to 1780 and 1810 to 1880 MHz
- 3G - 1920 to 1980 and 2110 to 2170 MHz
- 4G – 2300 to 2400 MHz
- Wi-Fi – 2400 to 2483 MHz and 5.2/5.8 GHz Band
- Satellite and Defense Communications (HF to mm wave)

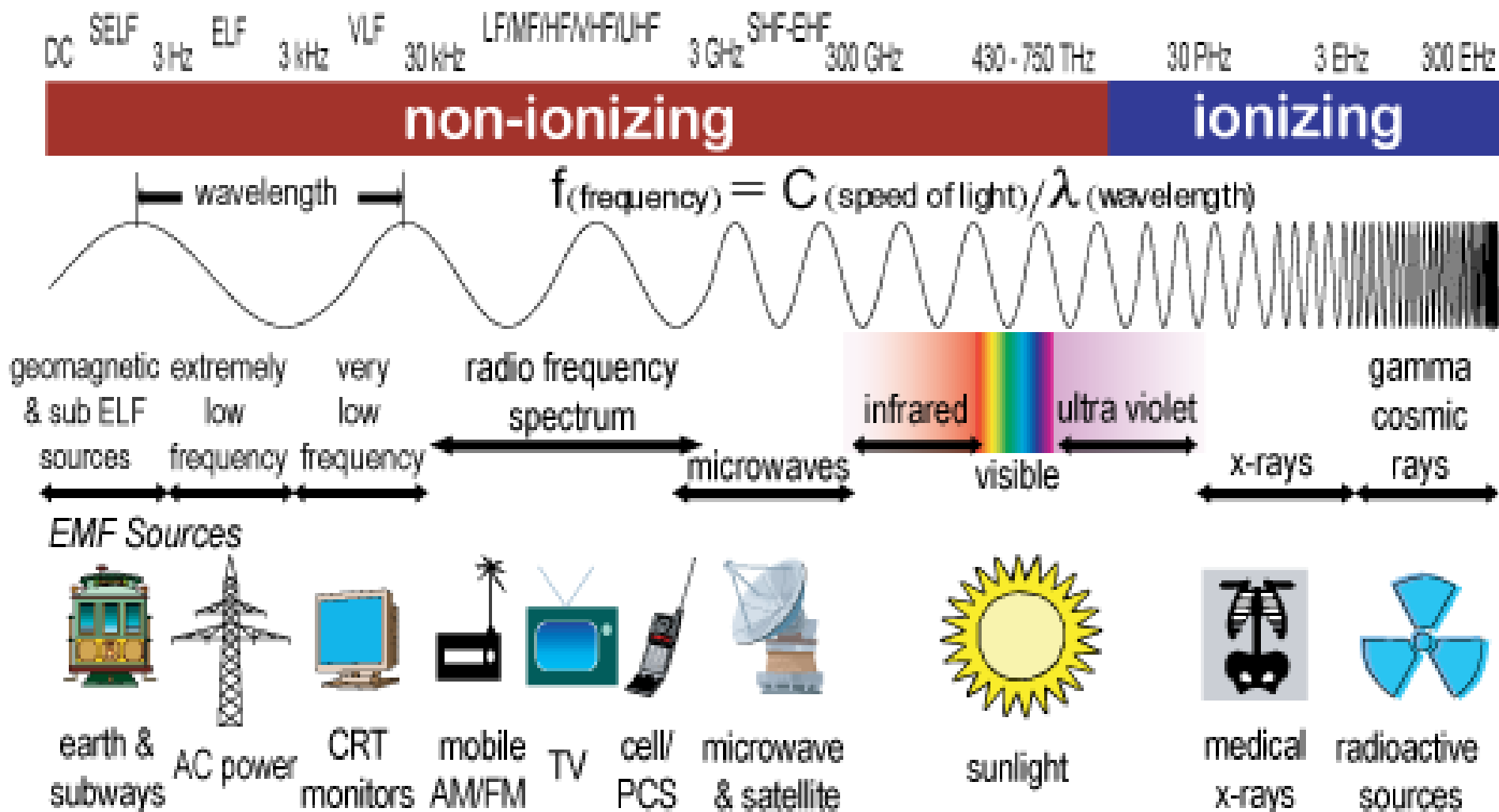
Microwave Communication Systems



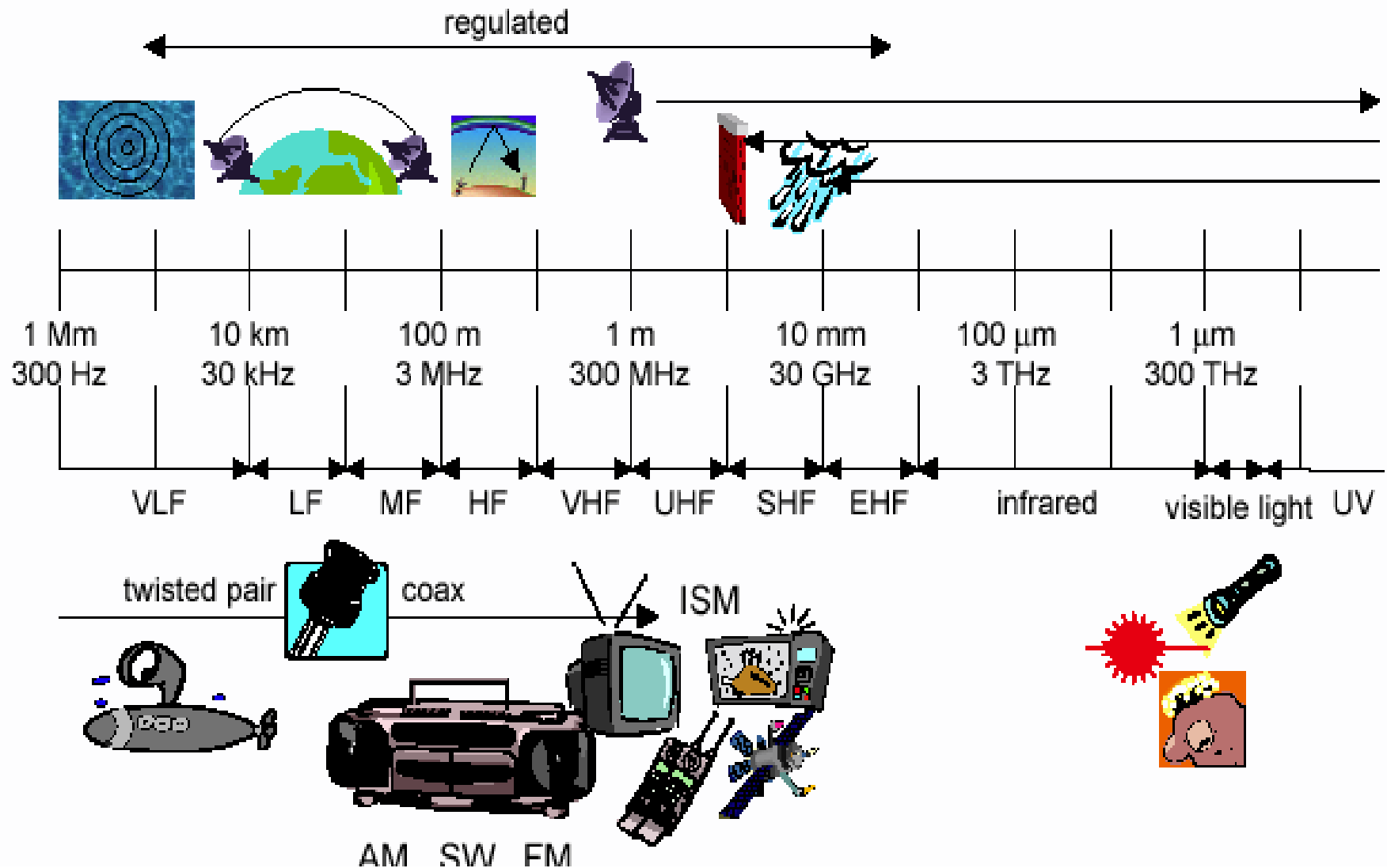
The whole range of EM wave...

- Frequencies is called the *electromagnetic spectrum*.
- Different parts interact with matter in different ways.
- The ones humans can see are called visible light, a small part of the whole spectrum.

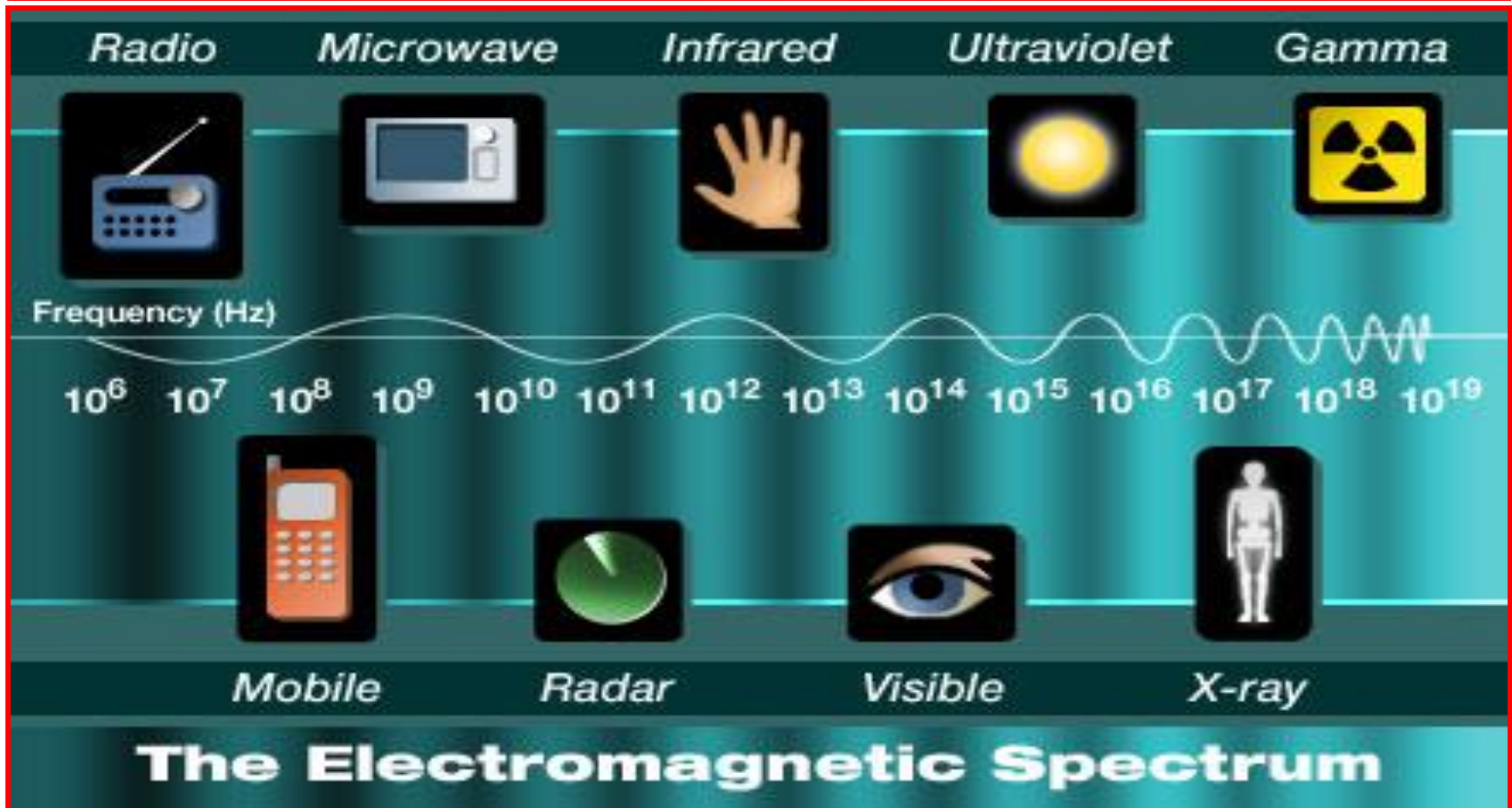
ELECTROMAGNETIC SPECTRUM



Electromagnetic Spectrum

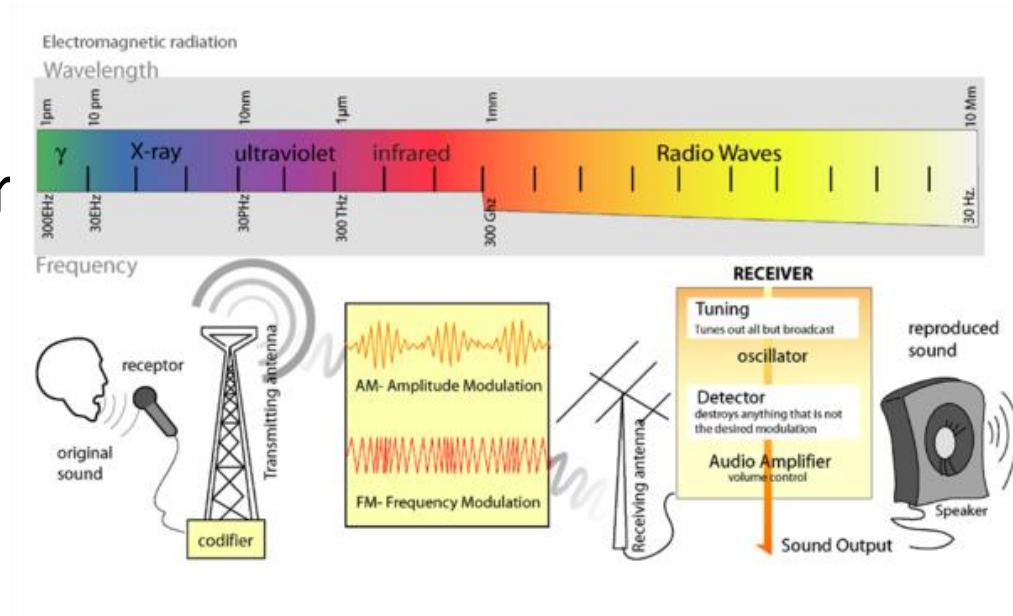


Electro Magnetic Spectrum



Radio Transmission

- Radio stations change sound to EM waves & then your radio receiver changes the EM waves back to sound waves again.



How does a radio receive different stations?

- Each station broadcasts at a certain frequency which you tune in by choosing their frequency.
- ***Carrier wave***- the frequency of the EM wave that a station uses
- Microphones convert sound waves to a changing electric current or electronic signal containing the words & music.

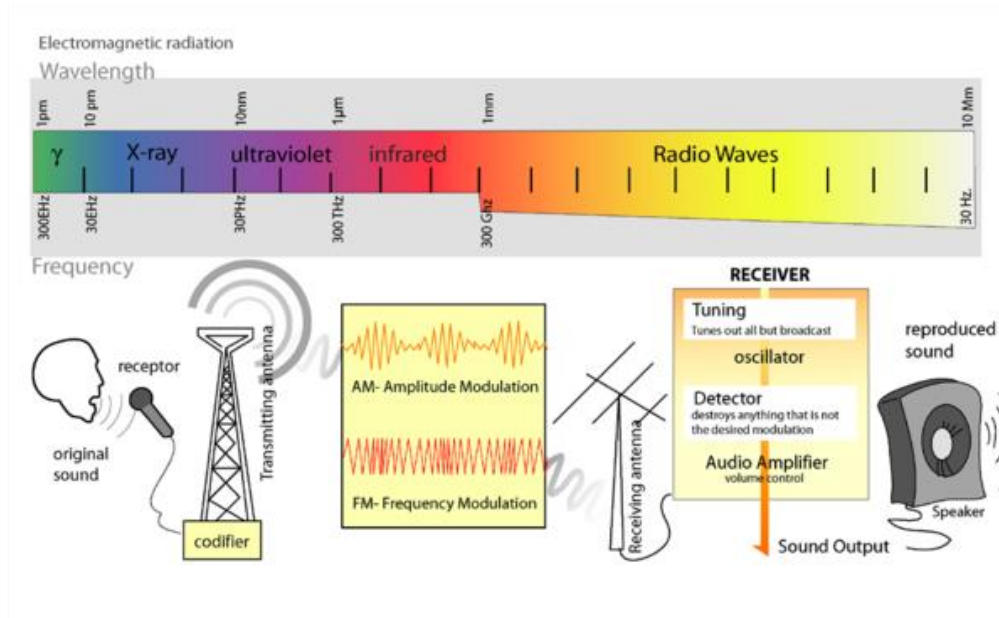
How does a radio receive different stations?

- Microphones convert sound waves to a changing electric current or electronic signal containing the words & music.
- The modified carrier wave vibrates electrons in the station's antennae creating a radio wave that travels out in all directions at the speed of light to your radio antennae.

How does a radio receive different stations?

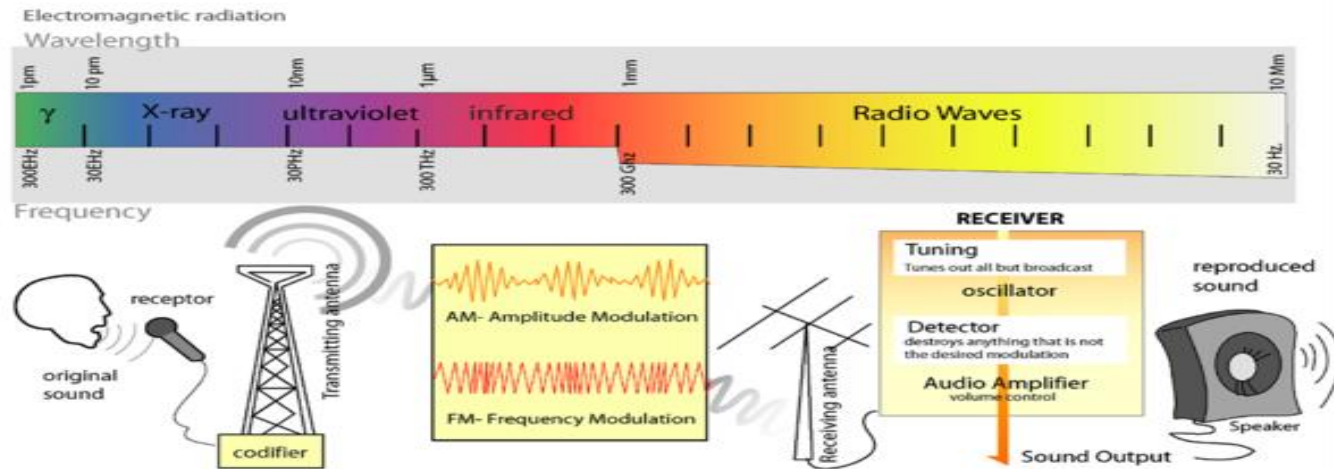
- The modified carrier wave vibrates electrons in the station's antennae creating a radio wave that travels out in all directions at the speed of light to your radio antennae.
- The vibrating electrons produce a changing electric current which your radio separates the carrier wave from the signal to make the speakers vibrate creating sound waves....

What is AM radio?



In AM amplitude changes but frequency does not. AM frequencies range from 540,000 Hz to 1,6000,000 Hz usually listed in kHz.

What is FM radio?



- In FM radio stations transmit broadcast information by changing the frequency of the carrier wave. The strength of FM waves is always the same and is in megahertz. Mega=million

Television

- Uses radio waves to send electronic signals in a carrier wave.
- Sound is sent by FM; color and brightness is sent at the same time by AM signals.

What is a cathode-ray tube?

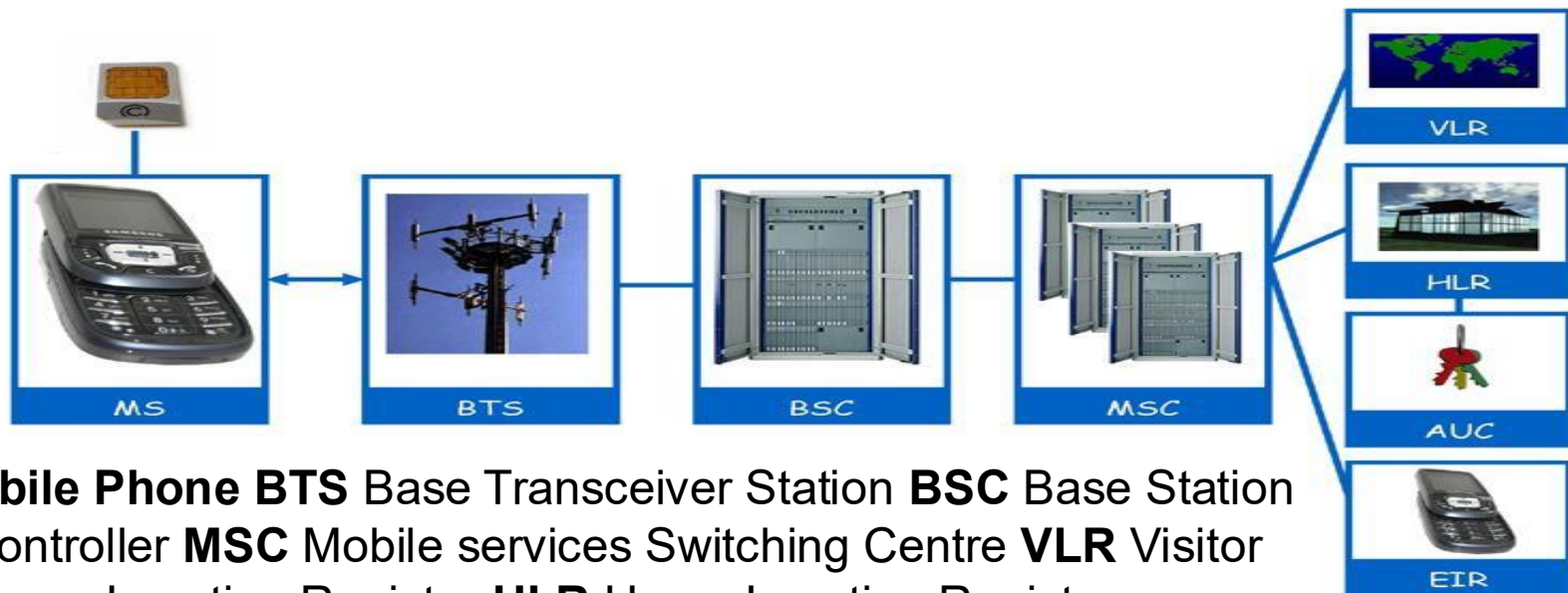
- Many TVs and computer monitors display images on a CRT, a sealed vacuum tube in which beams of electrons are produced.
- Color TV produces 3 electron beams inside the CRT which strike the inside of the screen that is covered with more than 100,000 rectangular spots.

What is a cathode-ray tube?

- There are 3 types of spots, red, green and blue. The electron beams move back and forth across the screen.
- The signal from the TV station controls how bright each spot is. Three spots together can form any color.
- You see a full color image on the TV.

Telephones

- Sound waves → microphone → electric signal → radio waves → transmitted to and from microwave tower → receiver → electric signal → speaker → sound wave



Mobile Phone **BTS** Base Transceiver Station **BSC** Base Station
Controller **MSC** Mobile services Switching Centre **VLR** Visitor
Location Register **HLR** Home Location Register

Communications Satellites



- Thousands of satellites orbit Earth. A radio or TV station sends microwave signals to the satellite which amplifies the signal and sends it back to a different place on Earth. Satellite uses dif freq to send & receive.

Global Positioning System

- GPS is a system of 24 satellites, ground monitoring stations and portable receivers that determine your exact location on Earth. GPS receiver measures the time it takes for radio waves to travel from 4 different satellites to the receiver. The system is owned and operated by the US Dept of Defense, but the microwaves can be used by anyone.

Microwaves

- Microwaves are electromagnetic waves whose frequencies ranges from 300 MHz – 300 GHz or wavelengths in air ranging from 100 cm – 1 mm.
- The word *Microwave* means very short wave, which is the shortest wavelength region of the radio spectrum and a part of the electromagnetic spectrum.

MICROWAVE FREQUENCY BANDS(IEEE)

Designation	Frequency Range	Applications
HF	0.003 to 0.03 GHz	Overseas radio broadcasting, Point to Point Radio Telegraphy and Telephony , RFID.
VHF	0.03 to 0.3 GHz	FM, television broadcasts, line-of-sight ground-to-aircraft and aircraft-to-aircraft communications, land mobile and maritime mobile communications, amateur radio, weather radio.
UHF	0.3 to 1 GHz	Land Mobile radio system, Digital television , Remote control Systems.

Designation	Frequency Range	Applications
L	1 to 2 GHz	Military telemetry, GPS, mobile phones (GSM), amateur radio
S	2 to 4 GHz	Weather radar, surface ship radar, some communications satellites, microwave ovens, microwave devices/communications, radio astronomy, mobile phones, wireless LAN, Bluetooth, ZigBee, GPS, amateur radio
C	4 to 8 GHz	Long-distance radio telecommunications
X	8 to 12 GHz	Satellite communications, radar, terrestrial broadband, space communications, amateur radio, molecular rotational spectroscopy

MICROWAVE FREQUENCY BANDS(IEEE)

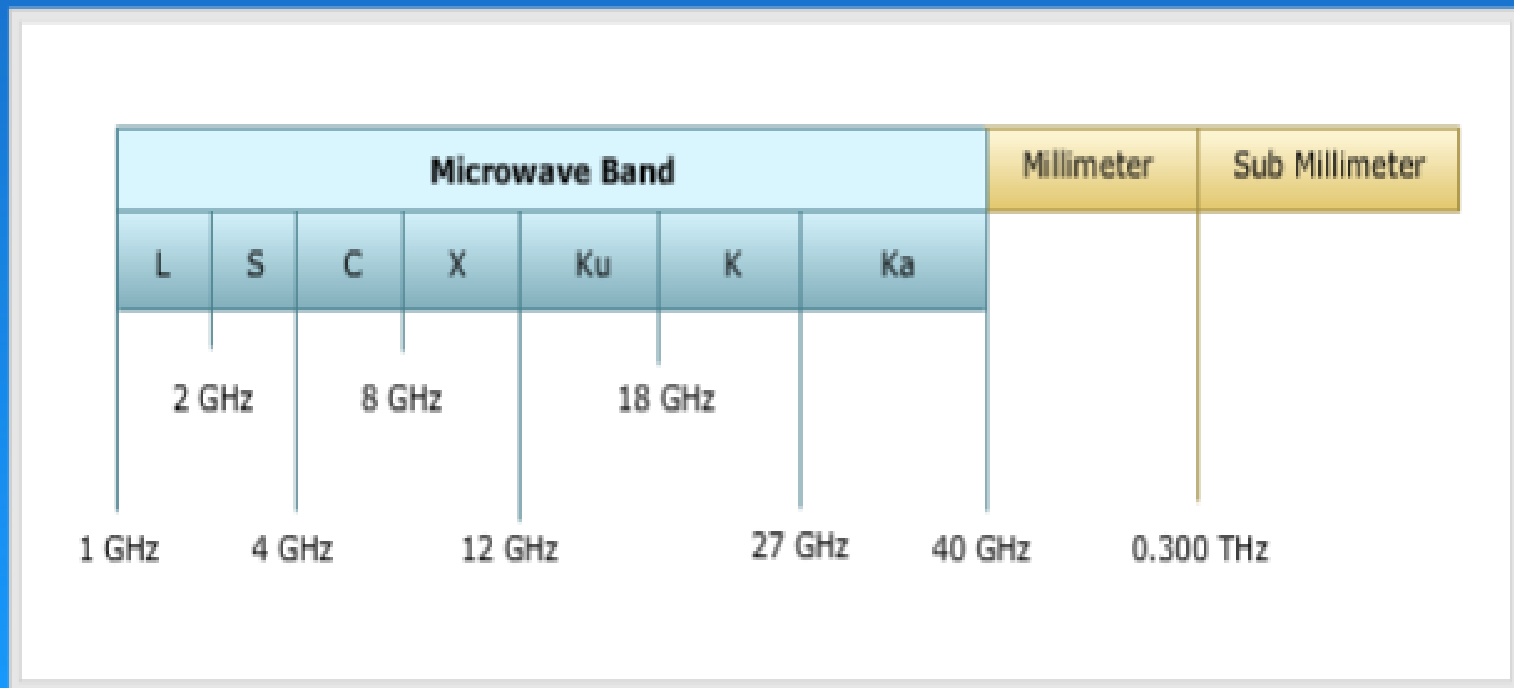
Designation	Frequency Range	Applications
K_u	12 to 18 GHz	Satellite communications, molecular rotational spectroscopy
K	18 to 27 GHz	Radar, satellite communications, astronomical observations, automotive radar, molecular rotational spectroscopy
K_a	27 to 40 GHz	Satellite communications, molecular rotational spectroscopy
V	40 to 75 GHz	Millimeter wave radar research, molecular rotational spectroscopy and other kinds of scientific research

Designation	Frequency Range	Applications
W	75 to 110 GHz	Satellite communications, millimeter-wave radar research, military radar targeting and tracking applications, and some non-military applications, automotive radar
mm	30 to 300 GHz	Radio astronomy, remote sensing, automotive radars, military applications, imaging, security screening, and telecommunications, smart driving, Virtual Reality Headsets
Sub mm	300 to 3000 GHz	Astronomy , Medical Imaging , Security, Communication.

Microwave Spectrum and Bands

- The term microwave frequency is generally used for the wavelengths measured in centimeters ranging from 30 cm to 1 mm
- Microwave indicates the wavelengths in the micron ranges

Microwave Spectrum



Microwave Components and Systems

Passive Microwave Components

- T-line
- Antenna
- Power Divider / Combiner
- Coupler
- Filter
- Attenuator

Active Microwave Components

- Amplifier
- Oscillator
- Mixer
- RF Switch
- Phase Shifter

Microwave Systems

- Mobile Phone
- Mobile Phone Jammer
- Repeater / Signal Enhancer
- RFID
- RF Transceiver
- GPS and GSM Modules
- Radar
- RF Energy Harvesting
- Microwave Equipment
- High Power Microwave System

Wave length	Frequency Designations	Transmission Media	Propagation Modes	Representative Applications	Frequency
1 cm	Extra High Frequency (EHF)	Wave guide	Line-of-sight radio	Satellite, Microwave relay, Earth-satellite radar.	100 GHz
10 cm	Super High Frequency (SHF)				10 GHz
1 m	Ultra High Frequency (UHF)			Wireless comm. service, Cellular, pagers, UHF TV	1 GHz
10m	Very High Frequency (VHF)	Coaxial Cable	Sky wave radio	Mobile, Aeronautical, VHF TV and FM, mobile radio	100 MHz
100m	High Frequency (HF)			Amateur radio, Civil Defense	10 MHz
1 km	Medium High Frequency (MF)			AM broadcasting	1 MHz
10 km	Low Frequency (LF)	Wire pairs		Aeronautical, Submarine cable, Navigation,	100 kHz
100km	Very Low Frequency (VLF)			Transoceanic radio	10 kHz

BAND	FREQUENCY	WAVE-LENGTH	PROPAGATION CHARECTERISTICS	APPLICATION
ELF	30-300Hz	10-1Mm	Penetration into earth and sea. Very low	Communication with submarines
VLF	3-31kHz	100-01km	Surface wave upto 1000km. Sky wave in the night extends range. Low attenuation both during day and night. Very reliable.	Long distance point to-point communication.
LF	30-3000kHz	10-1km	Surface wave and sky wave at night. Surface wave attenuation greater than VHF.	Point-to-point marine communication, time standard frequency broadcast.
MF	300-3000kHz	1000-100m	Ground wave during day in addition sky wave at night. Attenuation high in daytime and low at night time.	Broadcasting and marine communications.
HF	3-30MHz	100-10m	Reflection from ionosphere and varies as per time of day. Season frequency. Quality generally poor.	Moderate and long distance communication of all types.
VHF	30-300MHz	10-1m	Space wave line of sight.	Television FM service, aviation and police.
UHF	300-3000MHz	100-10cm	Same as VHF. Affected by tall objects like hills skyscrapers.	Short distance communication including Radar.
SHF	3-30GHz	10-1cm	Same as VHG, UHF suffers atmosphere attenuation above 10GHz.	Radar, microwave and space communication.

Introduction of Microwave

- Microwaves are electromagnetic waves whose frequencies range from 1 GHz to 300 GHz
- In the term microwave, "micro" indicates that these are very small compared to the waves that are used in typical radio broadcasting, having shorter wavelengths
- In general, the wavelength varies from a few tens of 'cm' to a fraction of 'mm' as indicated in equation(a)
- Distributed circuit elements and transmission line theory are the most useful methods for design and analysis of microwave devices
- The same equations of electromagnetic theory are also applicable to microwaves

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{3 \times 10^9} = 0.1 \text{ metre } [f = 3\text{GHz}]$$

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{300 \times 10^9} = 0.001 \text{ metre } [f = 300\text{GHz}]$$

$$= 10^{-3} \text{ metre} = 1\text{mm} \quad \text{.....(a)}$$

CHARACTERISTICS OF MICROWAVES

Microwave possesses certain useful characteristics:

- 1.Microwave wavelengths are very small.**
- 2.Microwave pulses are very short so that they can be used for distance or time measurement.**
- 3.High frequency of microwaves means very large bandwidth is available for communication.**

CHARACTERISTICS OF MICROWAVES

4. Microwave radiation penetrates fog and clouds, travels in straight lines and gives reflections hence can be used for distance and direction measurements.

5. Microwaves are necessary for communications through the ionosphere which reflects lower frequency radio waves.

6. Microwave power is absorbed by water or any other material containing water so that Microwaves can be used for heating and drying.

Properties of Microwaves

1. Microwave is an electromagnetic radiation of short wavelength.
2. They can be reflected by conducting surfaces just like optical waves since they travel in straight line.
3. Microwave current flows through a thin outer layer of an ordinary cable. (Skin Effect)
4. Microwaves are easily attenuated within short distances.
5. They are not reflected by ionosphere

Properties of Microwaves

Contd...

- Antenna gain is proportional to the electrical size of the antenna. At higher frequencies, more antenna gain is therefore possible for a given physical antenna size, which has important consequences for implementing miniaturized microwave systems.
- More bandwidth can be realized at higher frequencies. Bandwidth is critically important because available frequency bands in the electromagnetic spectrum are being rapidly depleted.
- Microwave signals travel by line of sight are not bent by the ionosphere as are lower frequency signals and thus satellite and terrestrial communication links with very high capacities are possible.
- Effective reflection area (radar cross section) of a radar target is proportional to the target's electrical size. Thus generally microwave frequencies are preferred for radar systems.

Advantages and Limitations

1. Increased bandwidth availability:

Microwaves have large bandwidths compared to the common bands like short waves (SW), ultrahigh frequency (UHF) waves.

For example, when the microwave signal extending from $\lambda = 1 \text{ cm}$ to $\lambda = 10 \text{ cm}$ (i.e) from 30,000 MHz – 3000 MHz, this region has a bandwidth of 27,000 MHz.

2. Improved directive properties:

- The second advantage of microwaves is their ability to use high gain directive antennas, any EM wave can be focused in a specified direction (Just as the focusing of light rays with lenses or reflectors)

3. Fading effect and reliability:

- Fading effect due to the variation in the transmission medium is more effective at low frequency.
- Due to the Line of Sight (LOS) propagation and high frequencies, there is less fading effect and hence microwave communication is more reliable.

4. Power requirements:

- Transmitter / receiver power requirements are pretty low at microwave frequencies compared to that at short wave band.

5.Transparency property of microwaves:

- Microwave frequency band ranging from 300 MHz – 10 GHz are capable of freely propagating through the atmosphere.
- The presence of such a transparent window in a microwave band facilitates the study of microwave radiation from the sun and stars in radio astronomical research of space.

ADVANTAGES OF MICROWAVES

1. Microwave communication does not require a dedicated path between stations.
2. Microwave can carry large quantities of information.
3. Requires relatively small antennas.
4. Microwaves can easily propagate through ionized layers hence most suited for satellite communications.

ADVANTAGES OF MICROWAVES

- 5. Transmission distance is large hence less number of repeaters are required for amplification.
- 6. Propagation delay is negligible or minimum.
- 7. Signal cross talk is eliminated.
- 8. Highly reliable systems.
- 9. Least maintenance is required.

DISADVANTAGES OF MICROWAVES

1. At microwave frequencies, circuit design is complex.
2. Measurements at microwave frequencies are difficult.
3. Line of Sight (LOS) propagation limits the use of Microwaves.

APPLICATIONS

Microwave Applications: Overview

Civil

Wireless Communication

Vehicle Collision Avoidance

Remote Sensing

Military

Aircraft Safety and Navigation

RADAR

Missile Guidance and Control

Applications

Medical

Cancer/Tumor Detection

Medical Diagnostics and Therapy

APPLICATIONS

- Microwaves have a wide range of applications in modern technology, which are listed below
- 1. **Telecommunication:** Intercontinental Telephone and TV, space communication (Earth – to – space and space – to – Earth), telemetry communication link for railways etc.
- 2. **Radars:** detect aircraft, track / guide supersonic missiles, observe and track weather patterns, air traffic control (ATC), burglar alarms, garage door openers, police speed detectors etc.

APPLICATIONS

3.Commercial and industrial applications

- Microwave oven
- Drying machines – textile, food and paper industry for drying clothes, potato chips, printed matters etc.
- Food process industry – Precooling / cooking, pasteurization / sterility, hat frozen / refrigerated precooled meats, roasting of food grains / beans.
- Rubber industry / plastics / chemical / forest product industries
- Mining / public works, breaking rocks, tunnel boring, drying / breaking up concrete, breaking up coal seams, curing of cement.
- Drying inks / drying textiles, drying / sterilizing grains, drying / sterilizing pharmaceuticals, leather, tobacco, power transmission.
- Biomedical Applications (diagnostic / therapeutic) – diathermy for localized superficial heating, deep electromagnetic heating for treatment of cancer, hyperthermia (local, regional or whole body for cancer therapy).

APPLICATIONS

4. Identifying objects or personnel by non – contact method.
5. Light generated charge carriers in a microwave semiconductor make it possible to create a whole new world of microwave devices, fast jitter free switches, phase shifters, HF generators, etc.

APPLICATIONS

- Various molecular, atomic, and nuclear resonances occur at microwave frequencies, creating a variety of unique applications in the areas of basic science, remote sensing, medical diagnostics and treatment, and heating methods.

Today, the majority of applications of microwaves are related to radar and communication systems. Radar systems are used for detecting and locating targets and for air traffic control systems, missile tracking radars, automobile collision avoidance systems, weather prediction, motion detectors, and a wide variety of remote sensing systems.

APPLICATIONS

Microwave communication systems handle a large fraction of the world's international and other long haul telephone, data and television transmissions.

Most of the currently developing wireless telecommunications systems, such as direct broadcast satellite (DBS) television, personal communication systems (PCSs), wireless local area networks (WLANS), cellular video (CV) systems, and global positioning satellite (GPS) systems rely heavily on microwave technology.

APPLICATIONS OF MICROWAVES

1. Telecom: Mobile Communications , Satellite Communications.
2. Point-to-Point Communications: Satellite, Cellular access technologies.
3. Space and remote sensing technology.
4. Sensing/Spectroscopy, radio astronomy.
5. Medical diagnostics ,imaging and treatment applications.
6. Defence equipments.

APPLICATIONS OF MICROWAVES

7. Radar communication and target tracking.

8. Security and Surveillances.

9. Car avoidance radar , Traffic surveillance, Air traffic security.

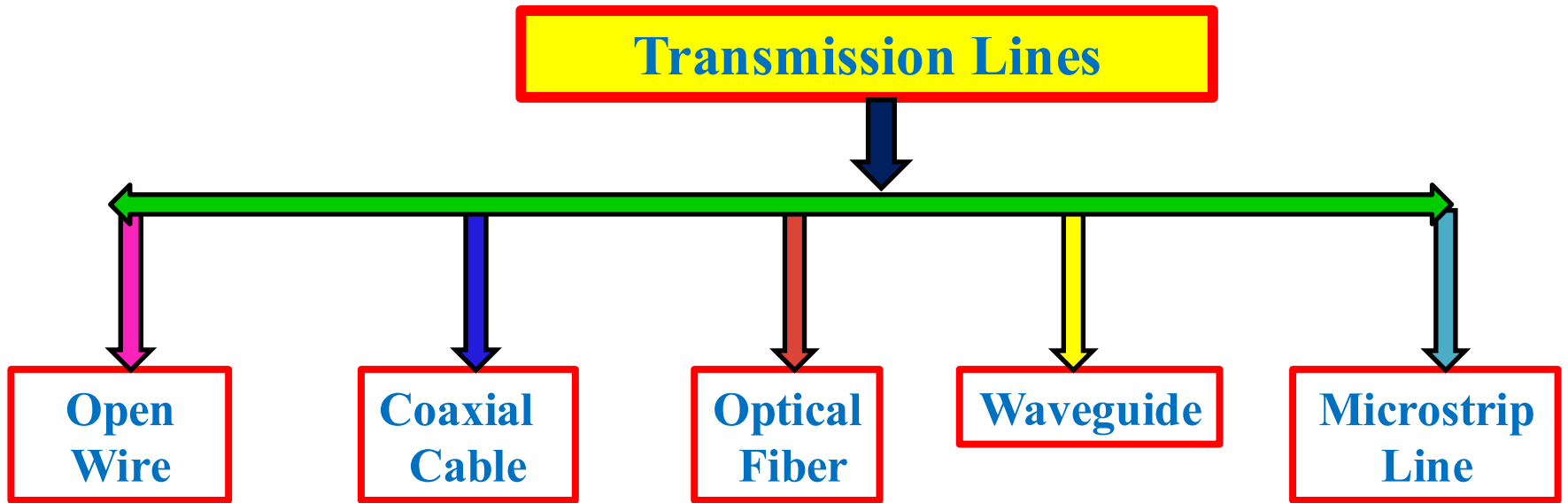
10. Navigation, positioning and measurement.

11. GPS

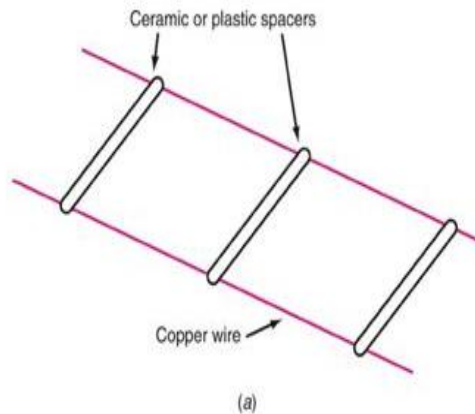
12. Food processing.

13. Cooking, drying, heating.

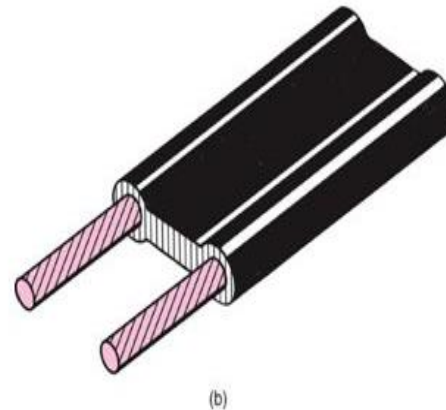
TYPES OF TRANSMISSION LINES



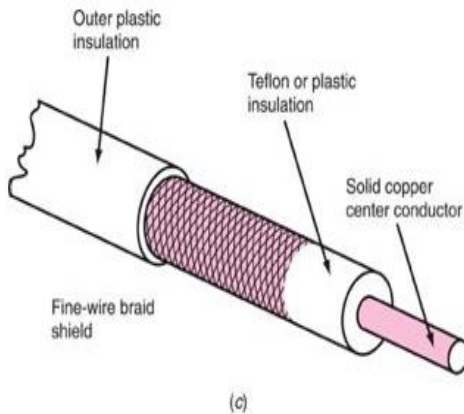
TYPES OF TRANSMISSION LINES



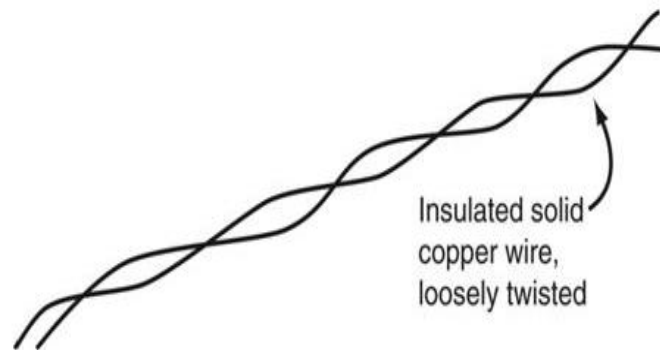
Open Wire Line



Twin Lead

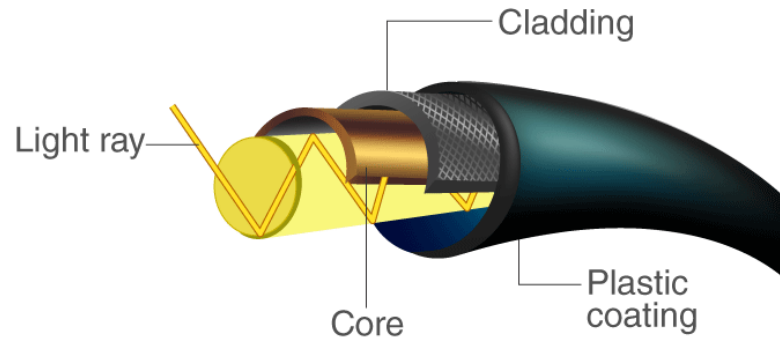


Coaxial Cable



(d) Twisted-pair Cable

TYPES OF TRANSMISSION LINES



Optical Fiber

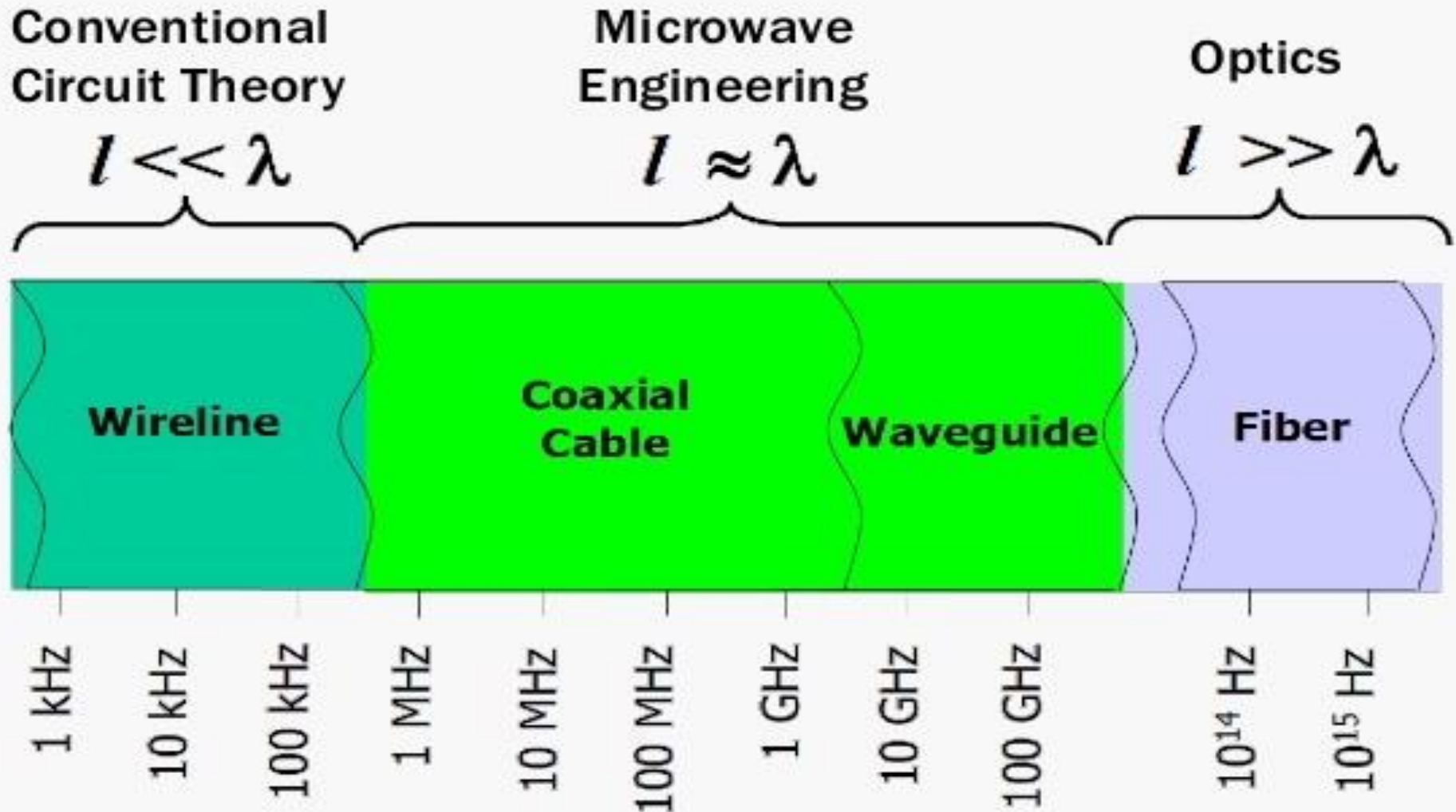


Waveguide

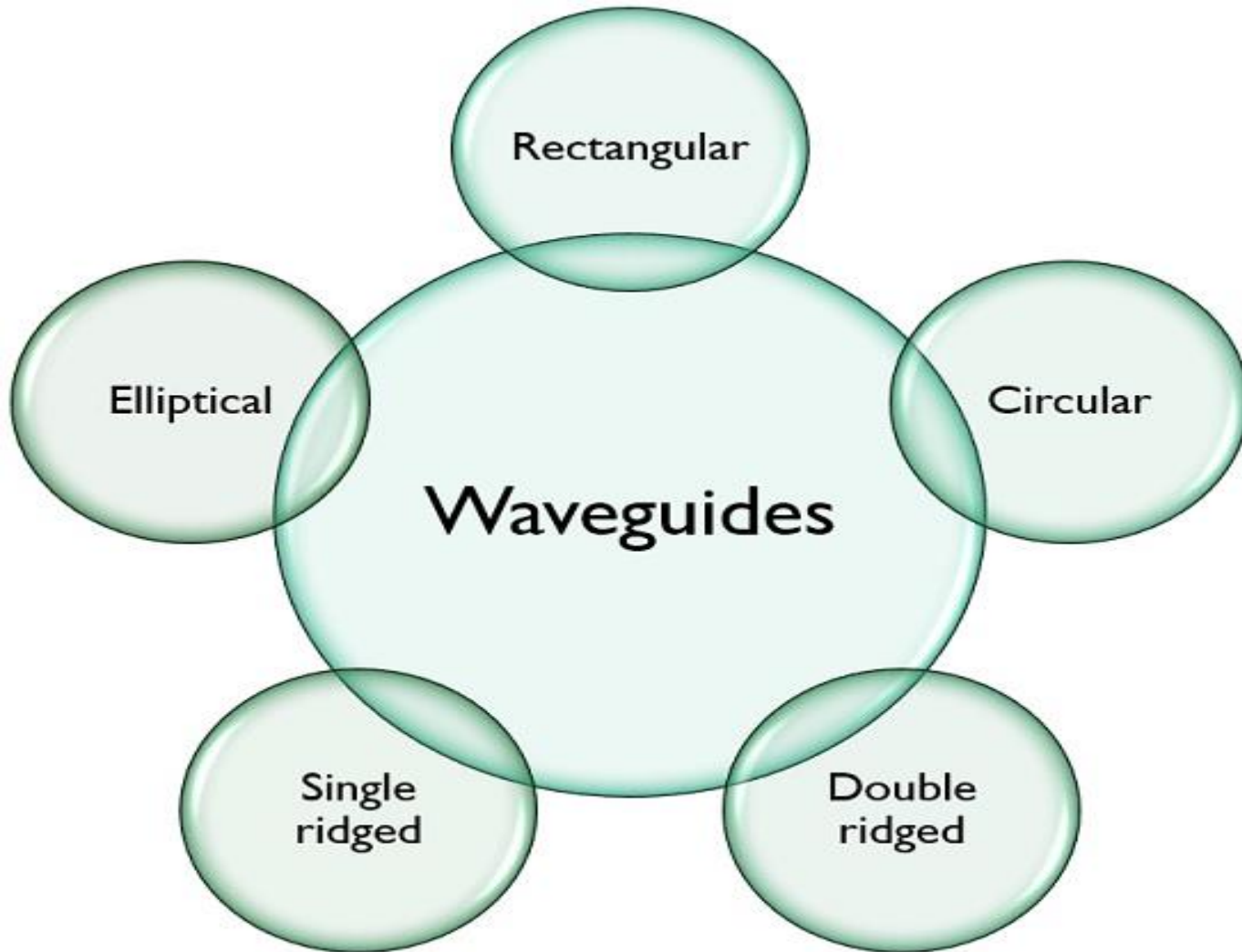


Micro strip Line

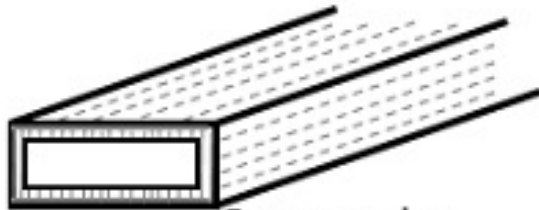
OPERATING FREQUENCIES OF DIFFERENT TRANSMISSION LINES



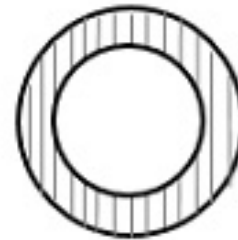
TYPES OF WAVEGUIDES



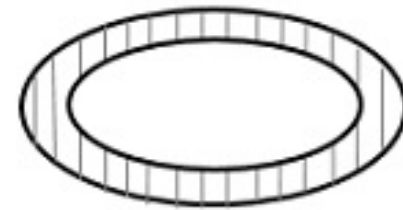
TYPES OF WAVEGUIDES



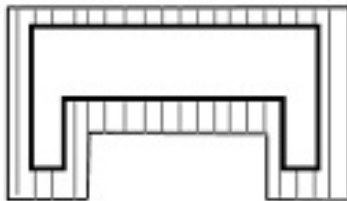
Rectangular
waveguide



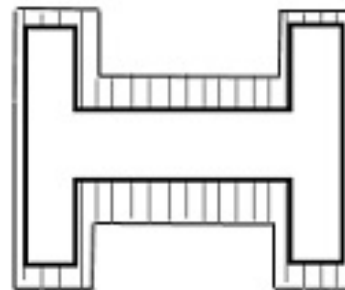
Circular
waveguide



Elliptical waveguide

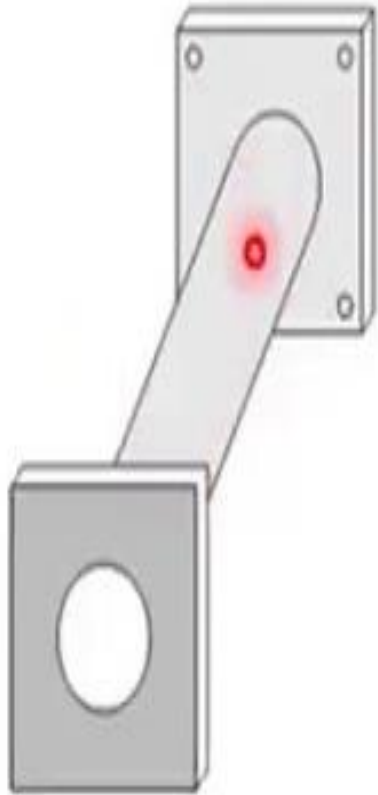


Single ridged
waveguide

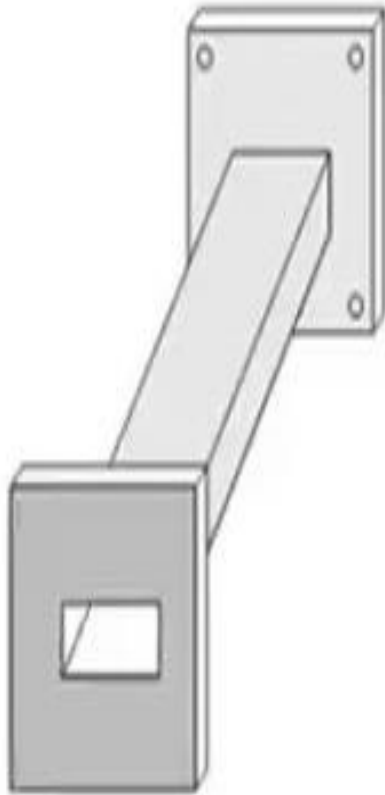


Double ridged
waveguide

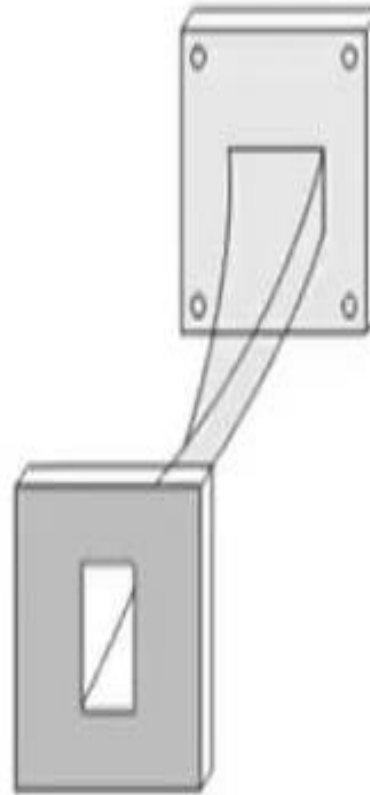
TYPES OF WAVEGUIDES



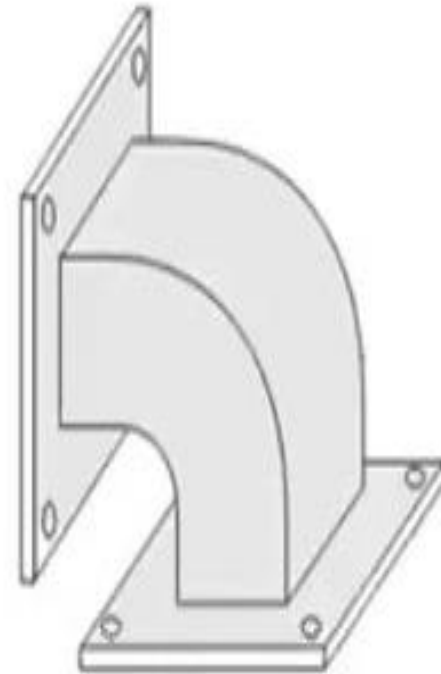
Circular



Rectangular



Twist



90° elbow

WAVEGUIDE COMPONENTS



Rectangular waveguide



Waveguide to coax adapter

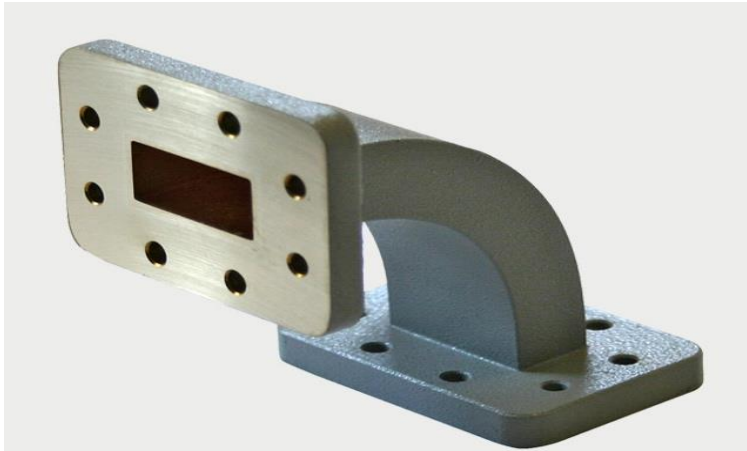


Waveguide bends



E-tee

WAVEGUIDE COMPONENTS



90° Elbow

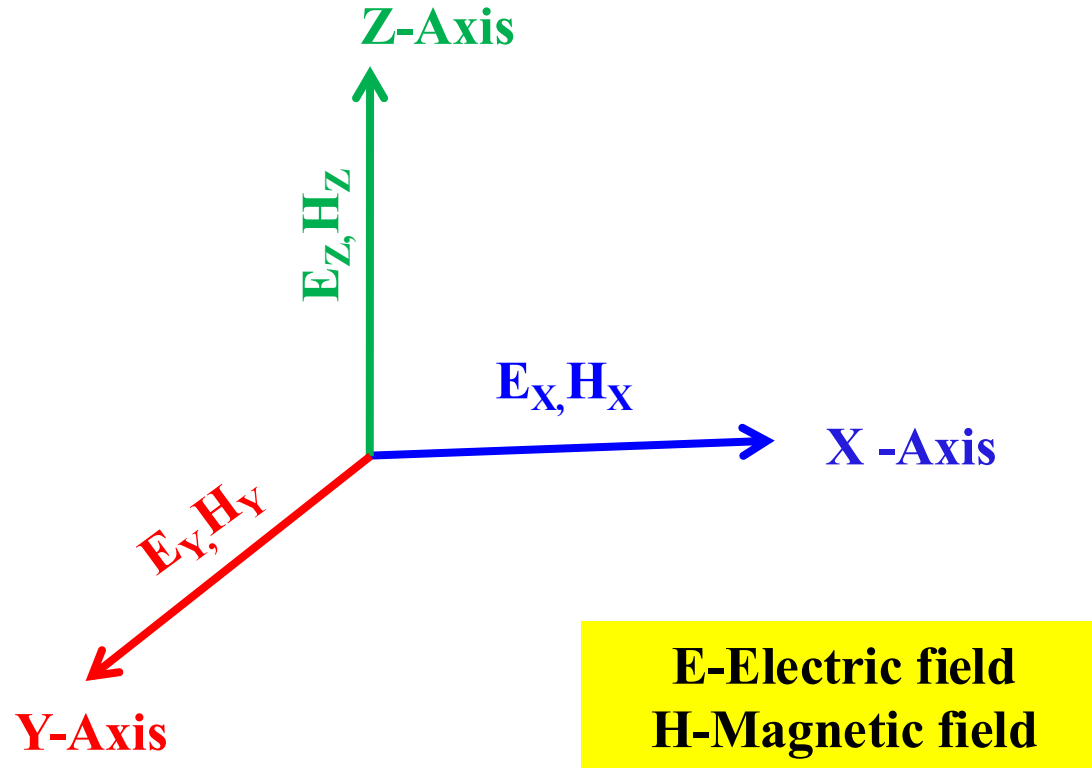


E-Plane Tee



H-Plane Tee

COMPONENTS OF ELECTRIC AND MAGNETIC FIELD INTENSITIES IN AN EM WAVE



POSSIBLE TYPES OF MODES

1. Transverse Electro Magnetic (TEM) Wave : Here both electric and magnetic fields are directed components.

$$E_z = 0, H_z = 0$$

2. Transverse Electric (TE) Wave : Here only the electric field is purely transverse to the direction of propagation and the magnetic field is not purely transverse .

$$E_z = 0, H_z \neq 0$$

3. Transverse Magnetic (TM) Wave : Here only the magnetic field is purely transverse to the direction of propagation and the electric field is not purely transverse.

$$E_z \neq 0, H_z = 0$$

4. Hybrid (HE) Wave : Here neither electric nor magnetic fields are purely transverse to the direction of propagation.

$$E_z \neq 0, H_z \neq 0$$

Maxwell's Equations

Differential Form

(1) $\vec{\nabla} \cdot \vec{D} = \rho$ or $\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}$ Gauss's law

(2) $\vec{\nabla} \cdot \vec{B} = 0$ Gauss's law for magnetism

(3) $\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$ Faraday's law of induction

(4) $\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$ or $\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$ Ampère's law

- Together with the Lorentz force these equations form the basic of the classic electromagnetism $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$ Lorentz Force

$$\vec{D} = \epsilon_0 \vec{E}$$

ϵ_0 =permittivity of free space

$$\vec{B} = \mu_0 \vec{H}$$

μ_0 =permeability of free space

ρ = electric charge density (As/m³)

J = electric current density (A/m²)

D = electric flux density/displacement field (Unit: As/m²)

E = electric field intensity (Unit: V/m)

H = magnetic field intensity (Unit: A/m)

B = magnetic flux density (Unit: Tesla=Vs/m²)

Thank you!

Questions?