EC75149:- TeraHertz (THz) Engineering

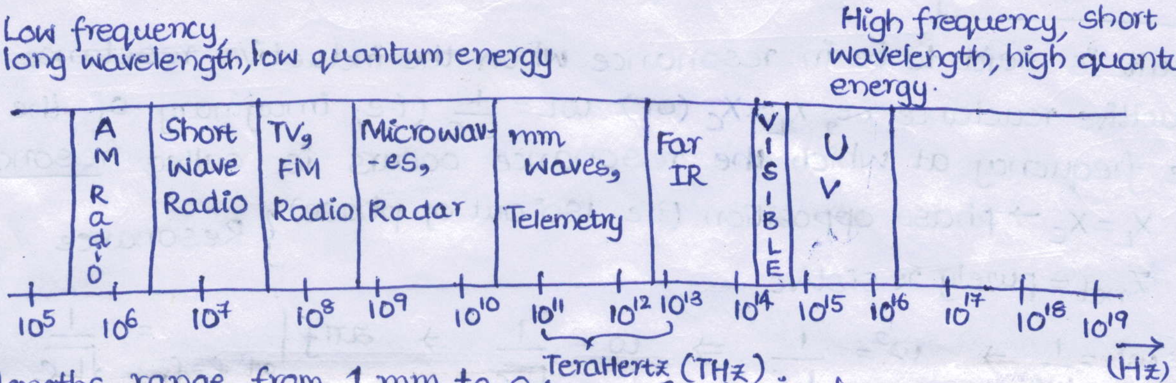
Chapter 1:- TeraHertz Overview and Principles

Topics:- Electromagnetic Radiation and Propagation Fundamentals, TeraHertz Principles, Towards TeraHertz Communication Systems, Key Technological Issues for TeraHertz Technology, Fundamental Limits, TeraHertz Technology, Applications and Opportunities.

- TeraHertz (THz) refers to the region in electromagnetic (EM) Spectrum spanning from 0.1 to 10 THz frequencies. This radiation resides between microwave and infrared (IR) radiation.

- It's an extension of microwave and millimeter-wave frequency bands, promising greater communication bandwidth. Terahertz frequencies exhibit characteristics of both microwave & infrared (IR) radiation.

Like IR and microwaves, THz waves travel in a Line-of-Sight (LOS) manner and are non-ionizing. THz waves can penetrate various non-conducting materials like clothes, wood, paper, plastic, cardboard & ceramics. However, metals highly reflect terahertz radiation.



- TeraHertz wavelengths range from 1 mm to 0.1 mm. So, it is known as Submillimeter band.
- These frequencies are useful in:- Spectroscopy, Pulsed Imaging, Impulse ranging, communication, sensing, security, mine detection, bio-chemical agent detection.

⇒ **Why TeraHertz (THz) frequencies?** (Tera ≈ 10^{12}) → higher frequencies.

Generally, Frequency of radio waves: MHz   Eg:- Frequency range of FM radio for transmission:- 88-108 MHz

Frequency of microwaves: GHz
↳ Wavelengths of microwaves is smaller than radiowaves.

Note:- Frequencies in cell phone:- WiFi (Wireless Fidelity):- Dual frequency → 2.4GHz/5GHz
GPS (Google Positioning System) → L1 (part of L-band)
↓
1575.42 MHz ≈ 1.6 GHz

→ Bluetooth uses 2.4GHz (ISM band)
Range: 2.4 - 2.4835 GHz, FHSS (Frequency Hop Spread Spectrum)
Channels: 79 channels (1 MHz B.W.)

MHz → GHz → THz : 1) To increase the data transfer rate

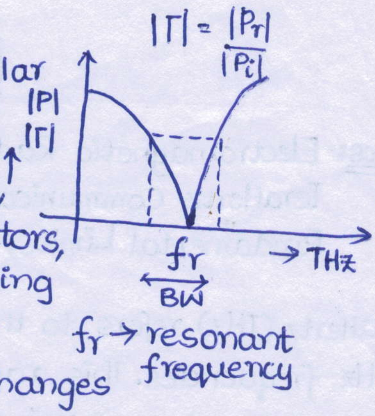
Multiplexing techniques → TDMA (Time division multiplexing access)
→ FDMA (Frequency division multiplexing access)

2) Attains higher bandwidth at THz frequencies.
- As increasing the demand, no. of users ↑es, frequency bands are becoming tiny.
- Provides broader bandwidth, higher frequency usage (i.e; capacity ↑es)

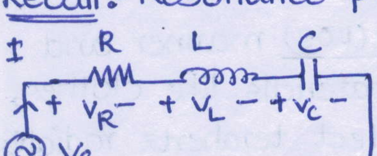
Shannon's channel capacity theorem:- $C = B \log_2 (1 + \frac{S}{N})$ ← SNR

(P.T.O.)

At terahertz (THz) frequencies, resonant frequencies serve as a spectroscopic tool to excite and manipulate fundamental molecular motions, including electron movements, molecular rotations, and lattice vibrations, enabling applications in sensing, spectroscopy, and novel material engineering. In metamaterials and resonators, the geometry dictates the specific resonant frequencies, causing strong EM field confinement and amplified electric fields at these frequencies, which can then be exploited to measure changes in material properties like refractive index through shifts in the resonance frequency



Recall:- Resonance phenomena in series and parallel R-L-C circuits:-



Impedance $Z = R + j\omega L + \frac{1}{j\omega C} = R + j\left(\omega L - \frac{1}{\omega C}\right)$

Current $I = \frac{V_S}{Z}$

The circuit is said to be in resonance when the inductive reactance is equal to the capacitive reactance i.e; $X_L = X_C$ (or) $\omega L = \frac{1}{\omega C}$ (i.e; imaginary of the impedance is zero.) The frequency at which the resonance occurs is called resonant frequency.

$X_L = X_C \rightarrow$ phase opposition (i.e; 180° out of phase) } Resonance

Z_{net} = purely resistive

$$\omega L = \frac{1}{\omega C} \Rightarrow \omega^2 = \frac{1}{LC} \Rightarrow \omega = \frac{1}{\sqrt{LC}} \Rightarrow 2\pi f\Big|_{at\ f=f_r} = \frac{1}{\sqrt{LC}}$$

$$\Rightarrow \boxed{f_r = \frac{1}{2\pi\sqrt{LC}}}$$

① $V = IR$

② $X_L = \omega L$ ⇓ $y = mx$

③ $y = \frac{a}{x} \rightarrow X_C = \frac{1}{\omega C}$ (Reverse quadratic)

At $\omega = 0 \rightarrow$ Capacitor $\rightarrow$ O.C. (open ckt) & Inductor $\rightarrow$ S.C. (Short ckt)

At $\omega = \infty \rightarrow$ Capacitor $\rightarrow$ S.C. (Short ckt) & Inductor $\rightarrow$ O.C. (open ckt)

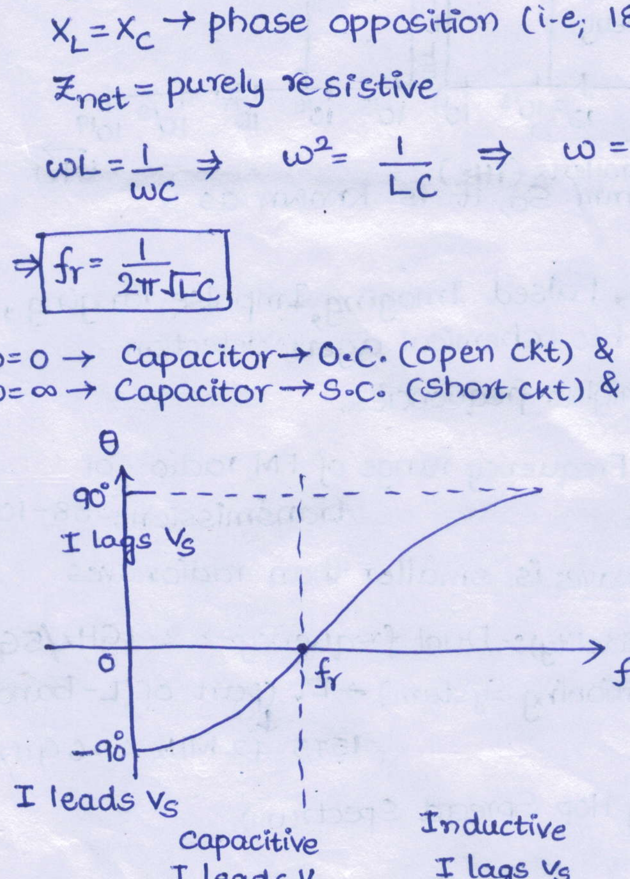


Fig:- Phase plot of Series RLC circuit

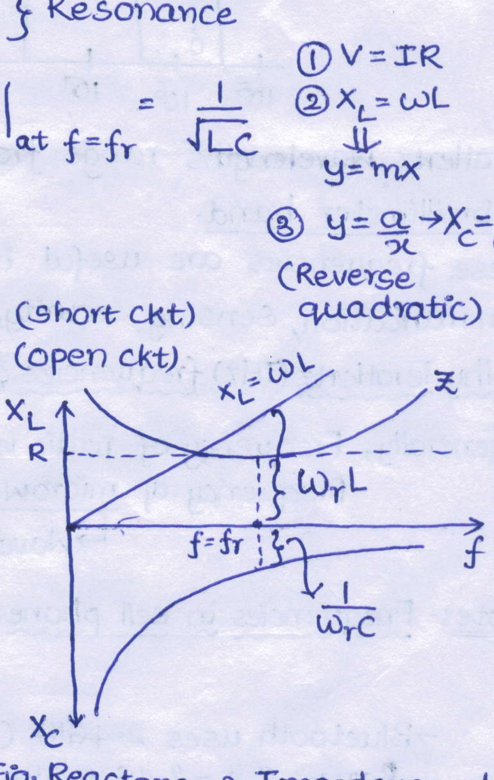
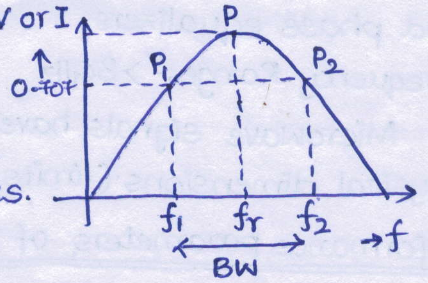


Fig. Reactance & Impedance plots of a Series RLC circuit

- **Observations:-** ① At frequencies below the resonant frequency f_r, capacitive reactance is higher than the inductive reactance and the phase angle of the current leads the voltage. As frequency increases, from zero to f_r, the phase angle changes from -90° to zero.

② At frequencies above the resonant frequency, inductive reactance is higher than the capacitive reactance and hence the phase angle of the current lags the voltage. As frequency increases from f_r and approaches ∞, the phase angle increases from zero and approaches $90°$



We know that $BW = f_2 - f_1$

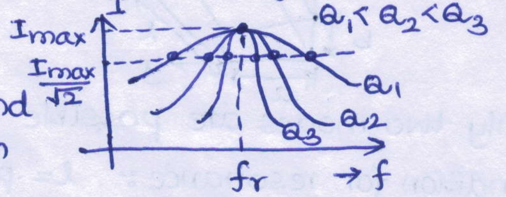
For a series RLC circuit, $(\omega_2-\omega_1) = \frac{R}{L} \Rightarrow (f_2-f_1) = \frac{R}{2\pi L}$

f_r lies in the center of lower and higher cutoff frequencies.

i.e, $f_1 = f_r - \frac{R}{4\pi L}$ and $f_2 = f_r + \frac{R}{4\pi L}$

Q-factor or Figure of merit:- $Q = \frac{f_r}{BW} = \frac{2\pi f_r L}{R}$

Selectivity:- Selectivity of a series RLC circuit indicates how well the given circuit responds to a given resonant frequency and how well it rejects all other frequencies. A circuit with a good selectivity will have maximum gain at resonant frequency and will have minimum gain at other frequencies i.e, it will have very low BW.

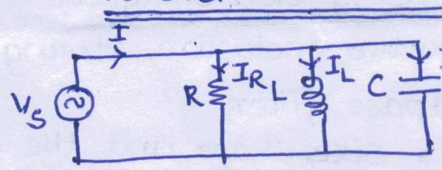


Selectivity $\propto$ Q

At resonance, the voltages across the inductance and capacitance are much larger than the applied voltage in a series RLC circuit and this is called the voltage magnification at resonance, which is equal to Q-factor of the circuit.

Fig:- Effect of quality factor on bandwidth voltage magnification at resonance.

Parallel R-L-C circuit



Admittance $Y = \frac{1}{Z} = \frac{1}{R + j(\omega L - \frac{1}{\omega C})}$

$Im\{Admittance\} = 0 \Rightarrow \omega_r L - \frac{1}{\omega_r C} = 0$

→ Minimum Admittance as impedance is maximum.

$\Rightarrow \omega_r = \frac{1}{\sqrt{LC}} \Rightarrow$ $f_r = \frac{1}{2\pi\sqrt{LC}}$, Same as in series RLC circuit

→ Current becomes minimum in the parallel RLC circuit at resonance.

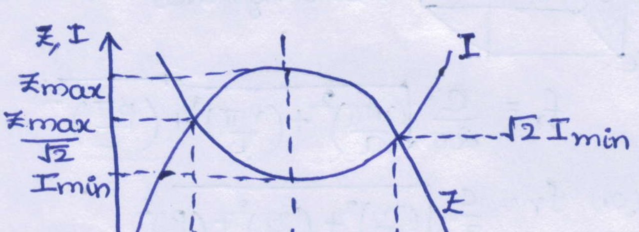
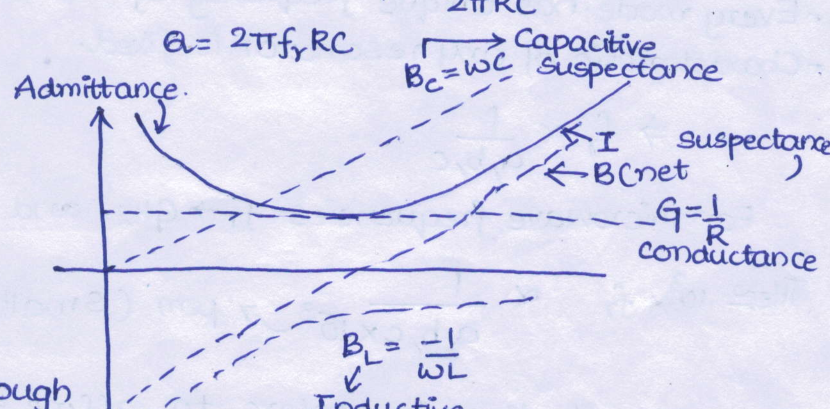


Fig:-Variation of impedance and current with frequency in a parallel RLC circuit

Here, $BW = f_2 - f_1 = \frac{1}{2\pi RC}$

$Q = 2\pi f_r RC$



- Current magnification takes place through the capacitance & inductance at resonant frequency in a parallel RLC circuit

Fig. Conductance, Suspectance & admittance plots of a parallel RLC circuit

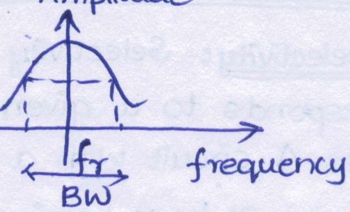
Cavity resonator:- Hollow metallic enclosed tube exhibit resonance behaviour when excited by EM field. It is used mainly in Oscillators, tuned amplifiers, frequency meters and phase equalizers.

-Frequency Range:- >3GHz

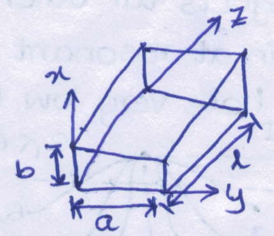
Microwave signals have lumped elements (difficult to obtain high Q) and small - physical dimensions (limits V& I requirements.)

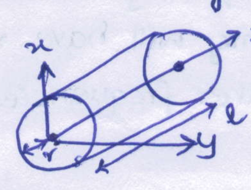
Performance parameters of a cavity resonator:- Resonant frequency f_r = 2a or 2b

Quality factor $Q = \frac{f_r}{(3\,dB\ BW)}$ → Input impedance Z_{in} to match with output



Two types of cavity resonators:- ① Rectangular cavity resonator → More degrees of freedom.
② Cylindrical cavity resonator





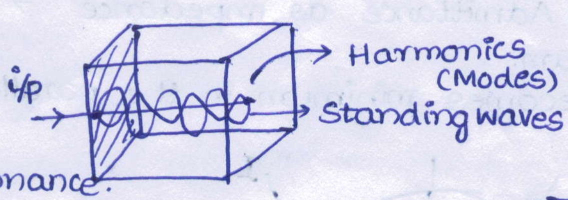
-Only two modes are possible TE_{mnp} and TM_{mnp}

Condition for resonance:- $l = p\left(\frac{\lambda g}{2}\right)$ λg → guided wavelength

• dominant mode happen at $l = \frac{\lambda g}{2}$
↳ lowest cutoff frequency

Resonance in a cavity resonator occurs when an input wave's frequency matches to the cavity's natural resonant frequency, causing electromagnetic waves to form stable standing waves inside the hollow, conductive enclosure, storing energy and allowing the cavity to act as a narrow bandpass filter.

This resonant frequency depends on cavity's size, shape and the dielectric material it contains.



Resonator:- a,b,c → mm

-Every pattern has specific nomenclature.

-Every mode has unique frequency of resonance.

-Characteristic of any resonator is fixed.

$$f_r = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{c}\right)^2}$$

$$\Rightarrow f_r \propto \frac{1}{a,b,c}$$

$$(or)\ f_r = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2}$$

For microwave frequencies f_r → GHz and a,b,c → mm

$THz \simeq 10^3 \times f_r \quad \propto \quad \frac{1}{a,b,c \times 10^{-3}}$ ↗ μm (Small-scale dimensions)

Note:- Affine's linearity refers to affine function characteristic of being a linear function plus constant vector or off set. While affine functions ($y = mx + c$) maintains straight-line graphs and preserve geometric properties like parallelism and ratios of lengths, they are not true linear functions because they donot necessarily pass through the origin.

Need of THz frequencies:- Broader bandwidth, Higher data rates.

Advantages:- ① High Bandwidth:- TeraHertz offers significantly greater BW compared to microwave frequencies, exceeding the capabilities of wireless protocols like 802.11b Wi-Fi (2.4 GHz)

② Penetration of non-conducting materials.

③ Imaging and networking applications over short distances.

④ Safety:- It poses minimal risk to the human body due to its non-ionizing nature.

⑤ Enhanced directionality (Pencil-beamforming) – Confined beam, high directivity

- THz communication exhibits higher frequency and shorter wavelength (hence smaller antenna size.)
- THz allows a comparatively large number of antenna elements to be packed within the same antenna dimension.
- Beams in THz communication are more directional than mmWave communication.
- THz communication reduces the transmit power and interference among the users. The small size of THz antennas leads to miniature chip sizes.

Applications:- ① Biosensing / Sensing

↳ (μm) molecules – Biomolecules (0.1 – 10 THz)

pencil-beam (more -directional)

Sensing:- Captures any information or detecting anything

Eg:- COVID → 35 μm (THz)

Cancer tissues → 1.63 THz

↑ THz freq. systems

② Glucose detection – Non-invasive sensing (in haemoglobin)

↳ enter without permission

↳ absorption & reflection sensors.

- TeraHertz-signal is non-ionising for biomolecules (cannot change the properties of biomolecules)

③ Drug Analysis and Protein Analysis through electromagnetic (EM) wave.

④ Non-destructive testing (NDT) – Through wall-imaging (used in military applications, defense)

⑤ Resonance Spectrum Analysis.

⑥ Metal detection through X-ray (Screening systems)

⑦ XR → Extended Reality, Holographic teleportation, Internet-of-Everything (IoE), non-terrestrial networks, connected robotics & autonomous systems (CRAS)

⑧ Communication ⇝ Radar technology Eg:- 6G → 0.1 – 0.3 THz

↳ Range coverage

Disadvantages:- ① Limited Range:- Not suitable for long-distance communication due to scattering and absorption by elements like clouds, dust, rain.

② Limited penetration:- Offers less penetration depth than microwave radiation and has difficulty in penetrating cloud & fog. It cannot penetrate (water) liquid & metal.

③ Detection challenges:- Detecting THz frequencies is difficult because black body radiation at room temperature is very strong at these frequencies.

④ <u>Cost and Availability</u>:- Sources, detectors & Modulators are not readily available at affordable prices.

<u>TeraHertz (THz) Sources</u>:- Vaccum-electronics based, Semiconductor based, Photoconduction based, Linearity based

An electronic and photonic materials based methods have been built to generate THz sources. These sources are limited to lower average powers, lower peak fields, and lower repitition rates.

Name	Source type
Gas	→ Lasers
Semiconductor	→ Lasers
TeraHertz (THz) parametric oscillator	→ Pulsed lasers
Frequency multiplication	→ Solid-state electronic
Transistors	→ Solid-state electronic
Gyrotrons, Free ē lasers, Synchotrons	} Vaccum-electronics based.
Mercury Lamp	→ Thermal
Mechanical Resonance	→ Continuous pumped lasers.

<u>Recall</u>:-

Microwave Sources
- Linear Beam Devices (O-type)
  - Resonant cavity
    - Klystron Amplifier
    - Reflex klystron amplifier
    - Two-cavity or multi-cavity klystron
  - Slow-wave Structure (non-resonant)
    - Forward wave
      - Helix TWT
      - Coupled Cavity TWT
    - Backward wave
      - BWA
      - BWO
- Cross-Field devices (M-type)
  - Magnetron ← Re-entrant ← Resonant
  - CFA

TUNNEL DIODE → Tunnelling Effect → (quantum mechanical phenomenon)

Cross-field tubes (M-type)
- Resonant
  - Re-entrant
    - Magnetron
- Non-resonant
  - Forward wave
    - Re-entrant → FWCFA
    - Non-reentrant → Dematron
  - Backward wave
    - Re-entrant → Amplitron
    - Non-reentrant → Caricinotron
- Maser effect
  - Gyrotrons

Lorentz-force based systems

$\bar{F} = q\bar{E} + q(\bar{v} \times \bar{B})$

- stationary → electric force
- magnetic force

O-type, M-type

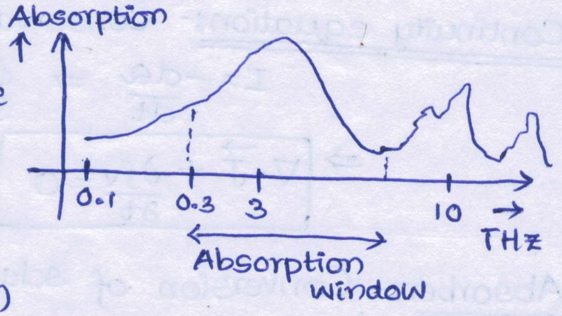
Transit-time devices:- IMPATT diode, BARITT diode, TRAPATT diode

GUNN diode:- Transferred ē devices (TED) → <u>Region of operation</u>:- NDR

↳ High frequency current oscillations occur in certain semiconductor materials when subjected to a strong electric field.

⇒ **Limitations and Issues:-**

① Heavy attenuation in wireless transmission due to high frequency.



② Large absorption windows

③ Restrictive long distance wireless communication due to heavy attenuation at higher frequencies.

④ Scarcity of THz source.

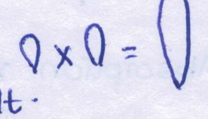
⑤ Small-scale dimension. (High-end machinery and processing for THz frequencies and μm dimensions.)

⑥ Develop antenna technologies. - In wireless system, at THz frequency an antenna is required to provide the radiations like pencil-beam.

To generate pencil beam, ⓐ Attaining massive MIMO (multiple input multiple output)

ⓑ Array: [Works on the principle of superposition/ pattern multiplication]

enhance gain & directivity ← → Signal strength increases.

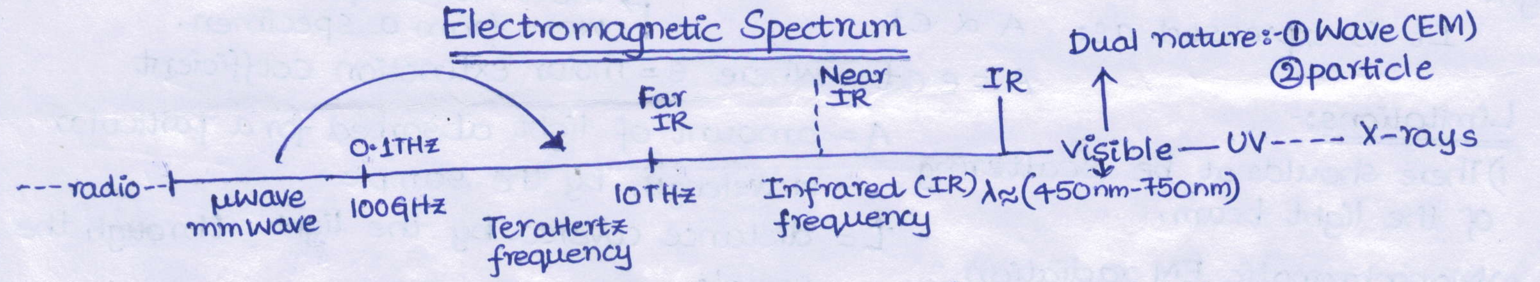


To develop this type of antennas at THz frequencies is difficult.

⑦ For THz fabrication, large permittivity materials are required.

(massive MIMO: used to capture all types of polarised signals.)

Electromagnetic Spectrum



- Transmitted TeraHertz signal can be in a straight line propagation.
- Terahertz (THz) covers the nature of microwave.
- The terahertz radiation can also acquires the properties like microwave i.e, can be obtained by upconversion of frequency using converter and mixer.

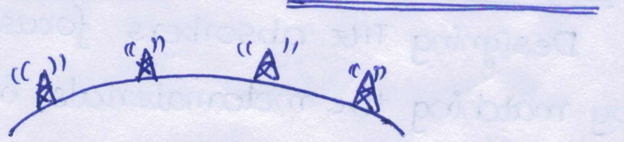
$$f \rightarrow nf$$

n^{th} harmonic

Q. What is Josephson junction?

Note:- For long-distance communication, we use linearly polarised antenna whereas for short-distance communication, a circularly polarised antenna is used.

In generally, vertically polarised waves are used due to "earth's curvature effect"



Material characteristics:- $\epsilon = \epsilon_0 \epsilon_r$: dielectric permittivity

$\mu = \mu_0 \mu_r$: magnetic permeability

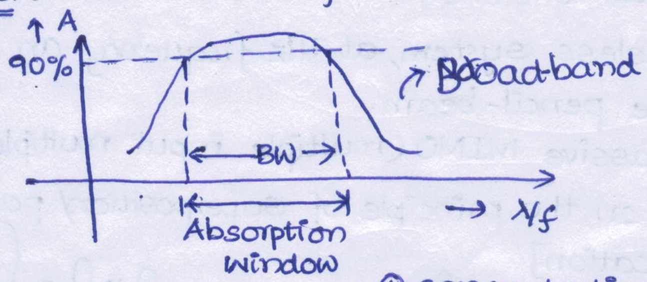
Permittivity defines how much electric field is confined in any dielectric. Similarly, permeability defines how much magnetic field can be confined in any material/ ~~(dielectric)~~ magnetic material.

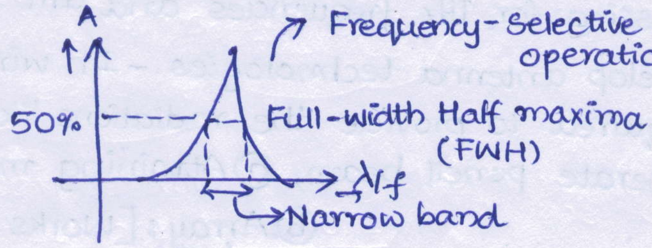
Continuity equation:- Conservation of charge.

$$I = -\frac{dQ}{dt} \Rightarrow \oint_S \vec{J}\cdot\vec{ds} = -\frac{d}{dt}\int_V \rho_v \, dV \Rightarrow \int(\nabla\cdot\vec{J})\, dv = -\frac{d}{dt}\int \rho_v \, dV$$

$$\Rightarrow \boxed{\nabla\cdot\vec{J} + \frac{\partial \rho_v}{\partial t} = 0}$$

Absorber:- Conversion of solar energy to other energies.





% Absorption relies on → ① concentration, ② thickness.

Beer Lambert's law:- It states that, for a given sample path length i.e, thickness and concentration of the sample are directly proportional to the absorbance of the light.

It is expressed as: $A \propto Ct$ → The amount of scattered beam/wave from a specimen.

$A = \epsilon C t$ where ϵ = molar extinction coefficient

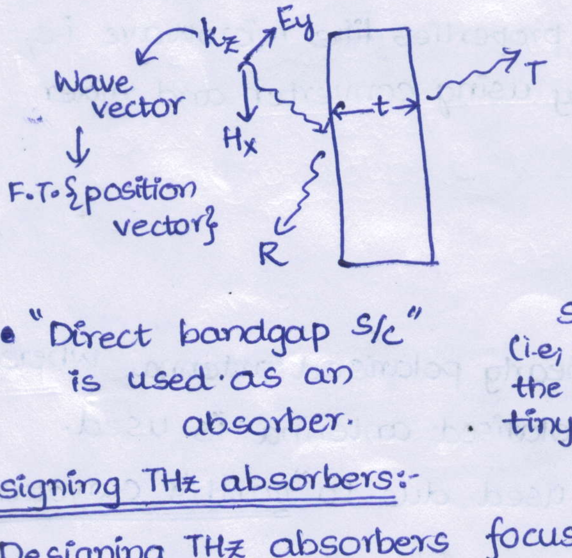
A = amount of light absorbed for a particular wavelength by the sample.

t = distance covered by the light through the sample.

C = concentration of the absorbing species.

Limitations:-

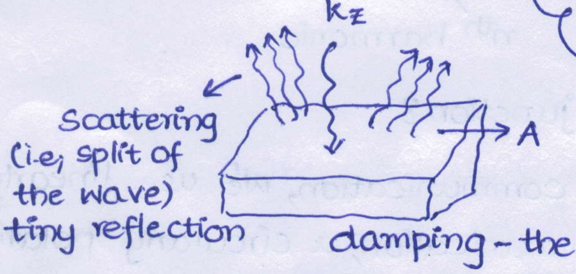
1) There shouldnot be scattering of the light beam.
2) Monochromatic EM radiation should be used.



$A + R + T = 1$

$\boxed{A = 1 - R - T}$

Black body radiation ↓ No reflection & No transmission



damping - the resistance to the oscillations.

• "Direct bandgap S/C" is used as an absorber.

Designing THz absorbers:-

Designing THz absorbers focuses on achieving high, broadband absorption by matching the metamaterials impedance to free space and blocking transmission through a backplane (metallic). Key principles include LC resonances and dipole responses within patterned metallic structures (metamaterials) to generate multiple, distinct absorption peaks. Tunable / reconfigurable properties

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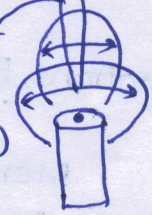
pencil-beam (more -directional)



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  - Backward wave
    - Re-entrant → Amplitron
    - Non-reentrant → Caricinotron
- Maser effect
  - Gyrotrons

Lorentz-force based systems

$\bar{F} = q\bar{E} + q(\bar{v} \times \bar{B})$

- $q\bar{E}$ → stationary → electric force
- $q(\bar{v} \times \bar{B})$ → magnetic force

O-type, M-type

Transit-time devices:- IMPATT diode, BARITT diode, TRAPATT diode

GUNN diode:- Transferred $\bar{e}$ devices (TED) → Region of operation:- NDR

↳ High frequency current oscillations occur in certain semiconductor materials when subjected to a strong electric field.

⇒ Limitations and Issues:-

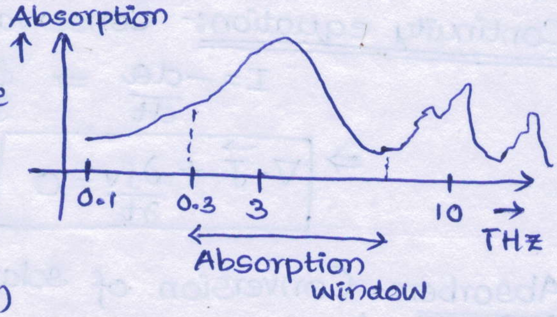
① Heavy attenuation in wireless transmission due to high frequency.

② Large absorption windows

③ Restrictive long distance wireless communication due to heavy attenuation at higher frequencies.

④ Scarcity of THz source.

⑤ Small-scale dimension. (High-end machinery and processing for THz frequencies and μm dimensions.)

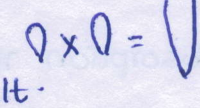


⑥ Develop antenna technologies. - In wireless system, at THz frequency an antenna is required to provide the radiations like pencil-beam.

To generate pencil beam, ⓐ Attaining massive MIMO (multiple input multiple output)

ⓑ Array: [Works on the principle of superposition/ pattern multiplication.]

enhance gain & directivity ⟵ ⟶ Signal strength increases.

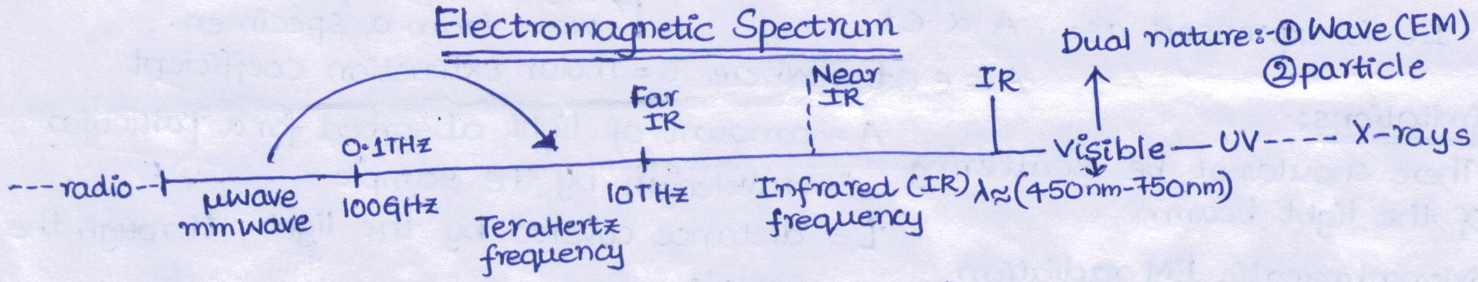


To develop this type of antennas at THz frequencies is difficult.

⑦ For THz fabrication, large permittivity materials are required.

(massive MIMO: used to capture all types of polarised signals.)

Electromagnetic Spectrum



- Transmitted TeraHertz signal can be in a straight line propagation.
- Terahertz (THz) covers the nature of microwave.
- The terahertz radiation can also acquires the properties like microwave i.e, Can be obtained by upconversion of frequency using converter and mixer.

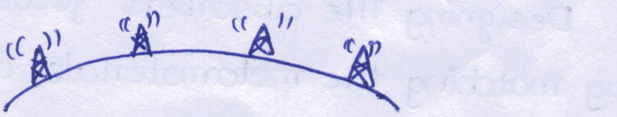
$$f \rightarrow nf$$

n^{th} harmonic

Q. What is Josephson junction?

Note:- For long-distance communication, we use linearly polarised antenna whereas for short-distance communication, a circularly polarised antenna is used.

In generally, vertically polarised waves are used due to "earth's curvature effect"



Material characteristics:- $\epsilon = \epsilon_0 \epsilon_r$: dielectric permittivity

$\mu = \mu_0 \mu_r$: magnetic permeability

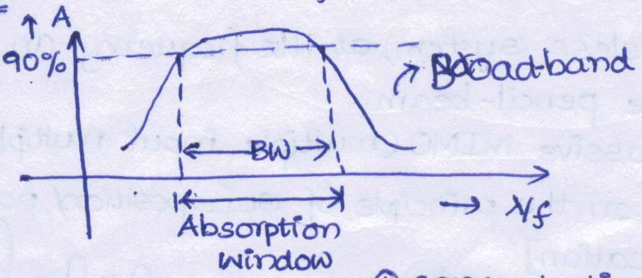
Permittivity defines how much electric field is confined in any dielectric. Similarly, permeability defines how much magnetic field can be confined in any material/ (dielectric) magnetic material.

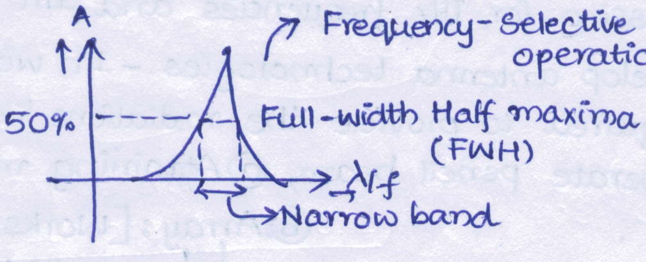
<u>Continuity equation</u>:- Conservation of charge.

$$I = -\frac{dQ}{dt} \Rightarrow \oint_S \vec{J}\cdot\vec{ds} = -\frac{d}{dt}\int_V \rho_V \, dV \Rightarrow \int(\nabla\cdot\vec{J})\, dV = -\frac{d}{dt}\int \rho_V \, dV$$

$$\Rightarrow \boxed{\nabla\cdot\vec{J} + \frac{\partial \rho_V}{\partial t} = 0}$$

<u>Absorber</u>:- Conversion of solar energy to other energies.





% Absorption relies on → ① concentration, ② thickness.

<u>Beer Lambert's law</u>:- It states that, for a given sample path length i.e, thickness and concentration of the sample are directly proportional to the absorbance of the light.

It is expressed as: $A \propto Ct$ ↱ The amount of scattered beam/ wave from a specimen.

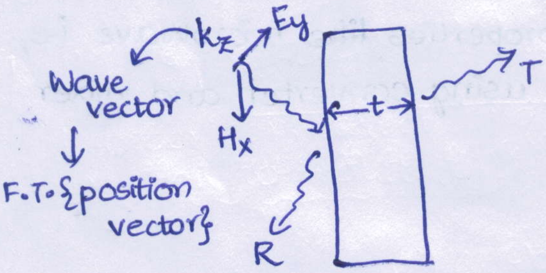
$A = \epsilon C t$ where ϵ = molar extinction coefficient

A = amount of light absorbed for a particular wavelength by the sample.

t = distance covered by the light through the sample.

C = concentration of the absorbing species.

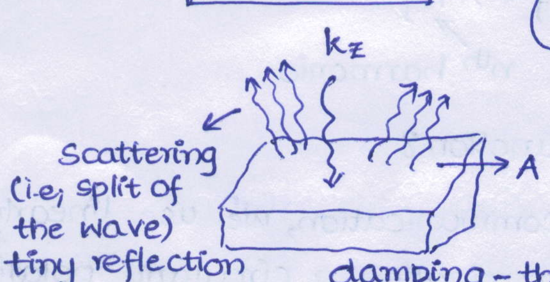
<u>Limitations</u>:-
1) There shouldnot be scattering of the light beam.
2) Monochromatic EM radiation should be used.



$$A + R + T = 1$$

$$\boxed{A = 1 - R - T}$$

Black body radiation
↓
No reflection &
No transmission



damping - the resistance to the oscillations.

• "Direct bandgap S/C" is used as an absorber.

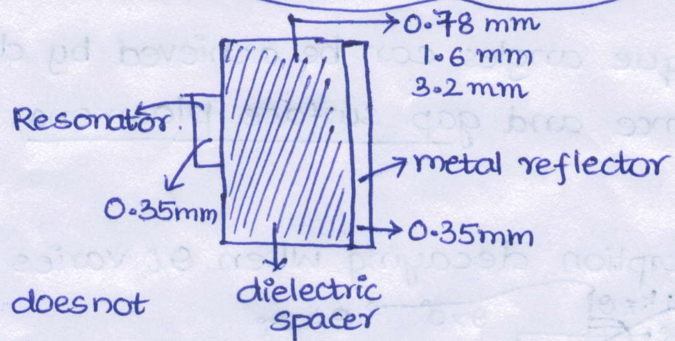
<u>Designing THz absorbers</u>:-

Designing THz absorbers focuses on achieving high, broadband absorption by matching the metamaterials impedance to free space and blocking transmission through a backplane (metallic). Key principles include <u>LC resonances</u> and dipole responses within patterned metallic structures (metamaterials) to generate multiple, distinct absorption peaks. Tunable / reconfigurable properties are achieved by incorporating graphene or VO_2, where structural designs, such as H-shaped microstructures, are used to increase bandwidth & achieve wide-angle absorption. allows for electrical / thermal tuning.

- Absorbers are built from unit cells consisting of a patterned top metallic layer and a ground metallic plane separated by a dielectric layer.

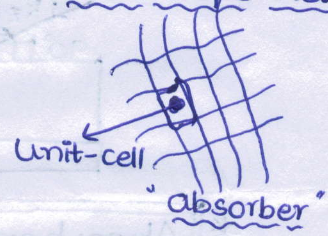
Polarization and Angle Insensitivity:- Symmetrical designs are used to make the absorber insensitive to the polarization and incident angle of the THz waves.

Designing of absorbers for μwave & THz frequencies other than optical frequencies



- Frequency response doesnot depend on the no. of unit cells & arrangement.
- Each unit-cell absorbs 250 - 750 nm
- The thickness of the metals must be considered greater than few skin depths.

Microscopic view of cloth



- The thickness of the dielectric must be considered atleast $\lambda/4$.
- Resonator must provide frequency-selective operation.
- The planar geometry of absorber must be arranged in the form of periodic distribution of unit-cells where response of each unit-cell is independent of dimensions of window and application each other.
- In a single unit-cell arrangement in a material, it requires very large thickness to absorb the whole incident wave. So, we have to reduce the thickness.

How to reduce thickness? To reduce the thickness of THz absorbers, you can design meta-materials with complex, 3D or vertically stacked structures to achieve broadband absorption in a thin layer, use advanced two-dimensional materials like graphene for tunable, ultra-broadband absorption, or incorporate parasitic capacitors or tuned dielectric resonators within a simple meta-surface to achieve significant miniaturization. Alternatively, for films, spin-coating thinner layers or reducing spin speed can result in thinner films.

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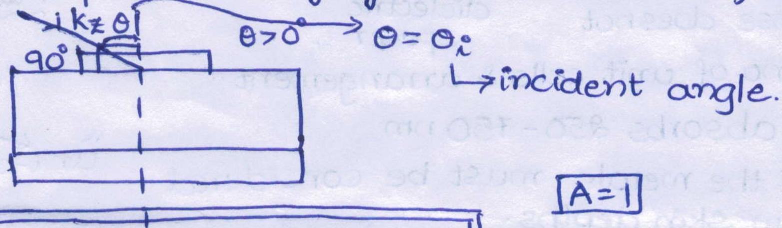
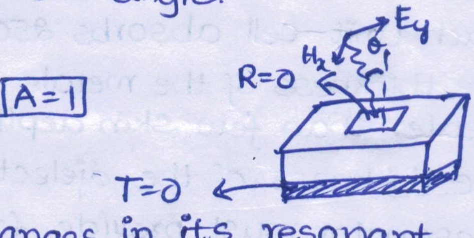
Role of Incidence Angle in THz absorbers

The angle of incidence critically affects THz absorbers by influencing wave propagation, interference, critical angles & the resonant behaviour of the absorber structure. While some of these absorbers are designed for wide-angle insensitivity due to rotational symmetry or specific resonance mechanisms, many THz absorbers show a shift in their absorption band or changes in absorptivity as the angle of incidence increases. This effect occurs because the increasing angle alters the effective electrical size of the absorber's resonant units, leading to shifts in the resonance frequency and potentially affecting absorptivity.

- High absorption at oblique angles can be achieved by designing for fundamental dipole resonance and gap surface plasmons, which are less sensitive to angle.

In case of solar cell, absorption decaying when θ_i varies from 0° to 90°

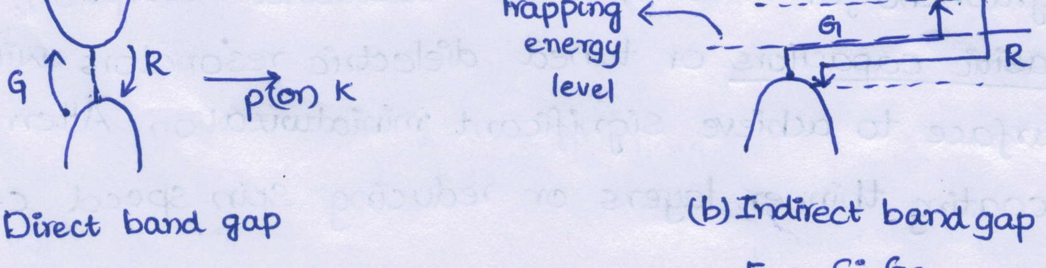




* Absorber as a sensor

An absorber acts as a sensor by exploiting changes in its resonant frequency or absorption spectrum that are triggered by external factors like the presence of an analyte or a change in its physical properties. By monitoring shifts in the resonant wavelength or other characteristics of the absorption, the absorber can detect and measure properties such as the refractive index of a substance, making it a sensitive tool for biosensing & environmental monitoring.

Recall:- Direct bandgap & Indirect bandgap semiconductors.



(a) Direct band gap

Eg:- GaAs

(b) Indirect band gap

Eg:- Si, Ge

Material Selection for THz Components:-

Complex permittivity and complex conductivity:-

$$\nabla \times H = \sigma E + \frac{\partial D}{\partial t}$$

$$\nabla \times H = \sigma E + j\omega\varepsilon E$$

$$\nabla \times H = (\sigma + j\omega\varepsilon) E$$

$$\nabla \times H = \underbrace{\sigma\left(1 + \frac{j\omega\varepsilon}{\sigma}\right)}_{\text{modified conductivity}} E = \sigma^c E = J^c$$

Similarly, $\nabla \times H = j\omega\varepsilon\left(\frac{\sigma}{j\omega\varepsilon} + 1\right) E$

$\nabla \times H = j\omega\varepsilon^c E$ ← ε^c: complex permittivity

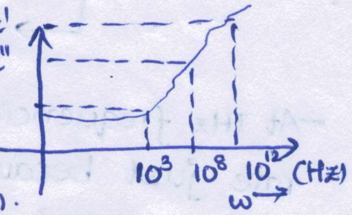
Here, $\nabla \times H = \sigma^c E$ → conduction current in terms of complex conductivity

$\nabla \times H = j\omega\varepsilon^c E$ → displacement current in terms of complex permittivity

Conclusion:- Conductivity & permittivity → both are complex number and frequency dependent.

$$\varepsilon^c = \varepsilon\left\{\frac{\sigma}{j\omega\varepsilon} + 1\right\} = \frac{\sigma}{j\omega} + \varepsilon = \varepsilon - \frac{j\sigma}{\omega} \Rightarrow \varepsilon^c = \varepsilon' - j\varepsilon''$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon} \rightarrow \text{Loss tangent}$$



ε' depicts stored energy whereas ε'' defines loss/dissipation.

- For terahertz frequencies, materials offer high permittivity. Low cost metals like Cu, Al offers a large value of permittivities at high frequencies in THz. and optical range.
- ε' is independent of conductivity that represents the stored energy. whereas ε'' $\left(= \frac{\sigma}{\omega}\right)$ is dependent on σ (conductivity) in proportionality which creates the loss or dissipation in dielectrics.
- The value of existing σ in any dielectric lowers the value of stored electric field following the Ohm's law ($J = \sigma E$) which decrease the potential across the terminal of a capacitor.

$$J = \sigma E \Rightarrow \downarrow E = \frac{J}{\sigma \uparrow}$$

$$\downarrow E = \frac{V \downarrow}{d}$$

- At high frequencies, noble metals (like Au, Ag) can work as perfect dielectric conductors but they offer high development for system development.
- Based on this material selection, the terahertz design and system (components) at terahertz (THz) frequencies can be developed using ① Metals, ② Dielectrics, ③ Semi-conductors and ④ others.

a. The usage of dielectric materials utilises a cavity resonator of high permittivity dielectric material (>10 – 1000).

Note:- These materials have η (>90%) i.e, higher gain than metals i.e, high directivity

Utilizing dielectric resonator can be complex task due to it offers a large thickness of the developed elements/components.

b. The processing of semiconductor materials is a complex task that

(P.T.O.)

adds complexity to the system development.

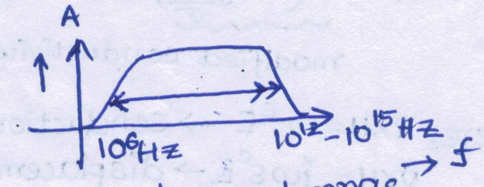
Note:- Generally, these materials are composite semiconductors.

Eg:- GaAs (Gallium Arsenide), Indium Antimonide (InSb), TiO_2

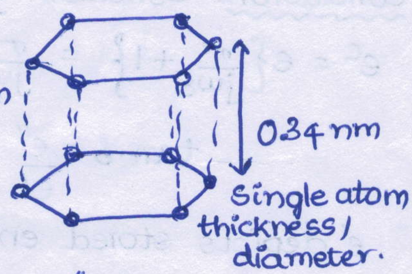
c. In metals, generally used THz absorbers and reflectors can be developed at these frequencies.

d. Others:

Utilizing non-metallic materials with very high conductivity.



Eg:- 1) Graphite → availability is more
- → Non-metallic in nature
- → High conductivity: No I^2R losses
- → Lossy antennas can be replaced by some loop antennas.
- → $\epsilon \approx 12$, $\sigma = 10^7$ S/m → high loss (high)



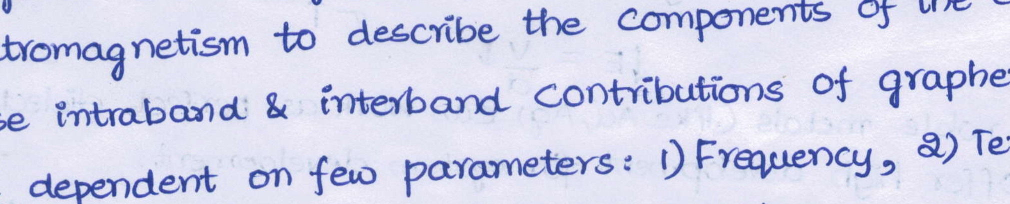
- At THz frequencies, graphite provides very high absorption rate just because of its high conductivity (σ)
- It can provide a broad absorption spectra.
- Single layer of graphite is known as "graphene".

2) Graphene → Single layer of graphite
- → Very high conductivity i.e; $\sigma_{graphene} \approx 1000$ times $\sigma_{graphite}$
- → Mechanical strength is greater than ordinary metals

- Graphene provides absorption which is 2-3 times higher than metals.
- Graphene's surface conductivity (σ) refers to its ability to conduct electric current across its 2D-surface. This is described by Kubo's formulation. It breaks down graphene's conductivity into intraband and interband
- Diagonal conductivity is often used in quantum mechanics or electromagnetism to describe the components of the conductivity tensor.
- These intraband & interband contributions of graphene's conductivity are dependent on few parameters: 1) Frequency, 2) Temperature, 3) Fermi Energy (chemical potential) and 4) Scattering rate (Γ)

Note:- Scattering rate:- Defines no. of collisions $|\Gamma| = \frac{1}{\tau}$ → Relaxation time.
Time difference between successive collisions

→ For a good quality material, $\tau \to \infty$ (No collisions)



→ Metals provide small-scale systems integrate these in microchips for the design of antennas having high gain & efficiency.

$\sigma \in f(\mu_c)$ ⇝ ① DC field, ② Magnetic field
↳ Fermi Energy & ③ Doping (At the time of manufacturing)

Limitations:- Electronic reconfigurability / tunability
↳ for active components and device miniaturization at TeraHertz (THz) frequencies
- due to the restricted cutoff frequencies & high losses of conventional electronic devices like varactors and diodes.

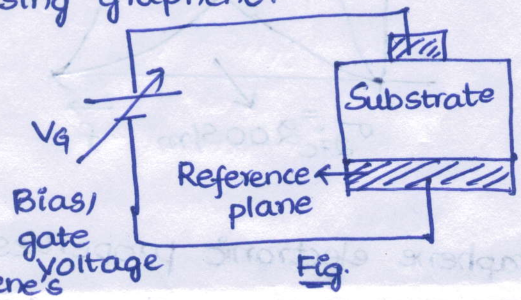
Solution:- To overcome this, ① Integrating CMOS with meta-atoms,
② Using "graphene" in layered structures
③ Developing MEMS-based metamaterials or functional material tunability to enable reconfigurable THz devices for sensing and high-speed communication.

Reconfigurability / Tunability:- Refers to the ability of THz devices to dynamically alter their operational characteristics such as, frequency, amplitude, or polarisation in response to external stimuli like voltage or light.

A. Electrically / Magnetically tunable device using graphene.

Eg:- Metamaterials, Absorbers

- These exploits graphene's unique electrical properties to alter TeraHertz (THz) wave interactions.



- Devices are often tuned by changing graphene's chemical potential with an electrical voltage or by applying a magnetostatic field to modulate resonant currents and phase.

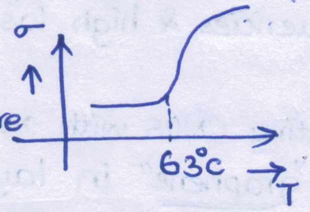
	Electrical Tuning	Magnetic Tuning
Method	An electrical voltage is applied across the graphene layer to change its Fermi level or chemical potential.	An external static or magnetostatic bias magnetic field is applied to the graphene-based structure.
Mechanism	The electrical gating dynamically adjusts graphene's conductivity, influencing its interaction with THz waves and tuning resonant frequencies.	The magnetic field generates a Lorentz force that affects the movement of e^-s within the graphene, altering the resonant currents & shifting the metasurface's response.
Applications	Filters, Absorbers, and modulators (dynamically adjusted by electrical potential)	Graphene-based absorbers & modulators. - Providing new ways to control THz wave properties like absorption & phase.

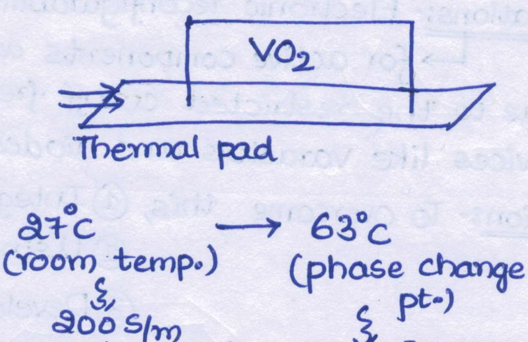
B. Thermally tunable devices (Photonic crystals, Vortex Beam Generators)

Temperature Sensitive materials / Phase change Materials (PCMs)

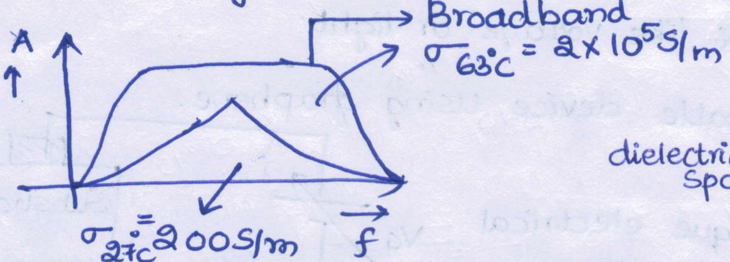
Eg:- VO_2, V_2O_5, V_2O_3

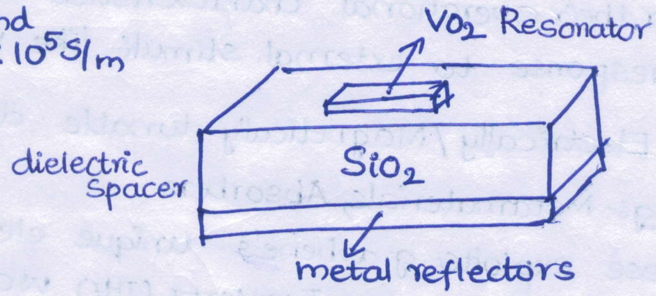
Thermally tunable terahertz (THz) devices utilize materials whose properties change with temperature such as InSb, VO_2 to alter their optical or electromagnetic characteristics.





- These devices include metamaterials, photonic crystals and absorbers that can modulate resonance frequency, absorption & frequency (phase) shifts by controlling temperature, enabling applications like tunable filters, sensors & vortex beam generators.





Note:- Graphene electronic properties are also temperature-dependent. In some THz absorber designs, graphene can act as a reflector, with temperature variations modulating its properties and thus the device's absorption.

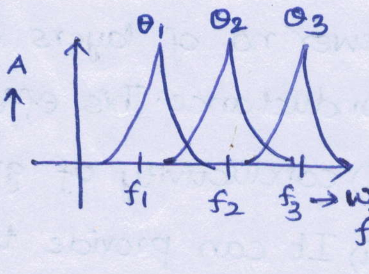
C. Incident Angle - Multiplexed devices: (No biasing i-e, no temperature biasing, no voltage biasing)

Terahertz (THz) devices designed to operate with multiple signals or functions, where the angle of the incident THz wave influences which signal or function is selected.

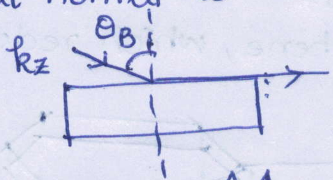
- It refers to a specialized device, often a metasurface or antenna, designed to interact with THz waves and allow for the manipulation or detection of multiple functionalities or signals, by varying the angle of incidence of the incoming THz beam. These devices exploit the interaction of THz radiation with patterned structures to achieve tunable filtering, enhanced sensing, or multi-functional operation, providing benefits like increased sensitivity and improved light-matter interaction for applications such as chemical sensing and imaging.

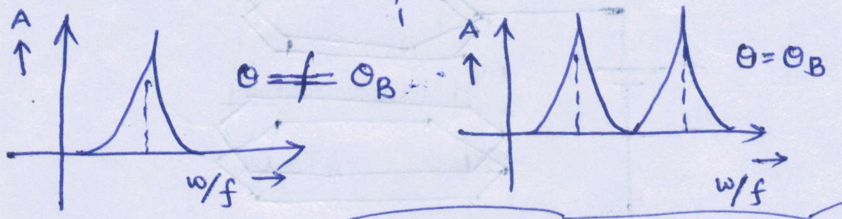
- **Multiplexing:** By changing the incident angle, the device can selectively filter certain frequencies, enhance sensing capabilities for different analytes, or even switch between different imaging modes.

→ **Advantages:-** ① Label-free detection, ② Non-invasive Inspection & ③ High Sensitivity



Note:- Brewster effect: The specific incident angle where no reflection occurs (R=0) and all the wave is transmitted at normal to the axis of incident.





• How the incident angle interacts with Brewster's effect in Multiplexed devices?

→ Incident angles on multiplexed devices can leverage Brewster's effect to achieve polarization-sensitive optical responses, leading to multiple resonance peaks in graphene-based devices or optical switches. By varying the angle of incidence, the spectral position of these peaks can be tuned, providing independent tunability and enabling applications like refractive index sensing or creating perfect light absorbers.

a. Brewster's angle or polarization:- All the Brewster angle, light polarized parallel to the plane of incidence (p-polarized) is perfectly transmitted through a dielectric interface, while the reflected light is completely polarized ⊥r to the plane of incidence (s-polarized.)

b. Anisotropic Structures and Multiple Resonances:- When structures are designed to be anisotropic (like graphene resonators / nanopillar arrays), their optical properties vary with oerientation. An incident light beam at a specific angle can interact with these anisotropic structures to trigger multiple resonance peaks, following a generalized Brewster effect.

c. Angle tunable spectra:- In such multiplexed devices, the incident angle can be varied to tune the spectral position of these resonance peaks independently. This allows for the modulation of frequencies and creates tunable spectral bands.

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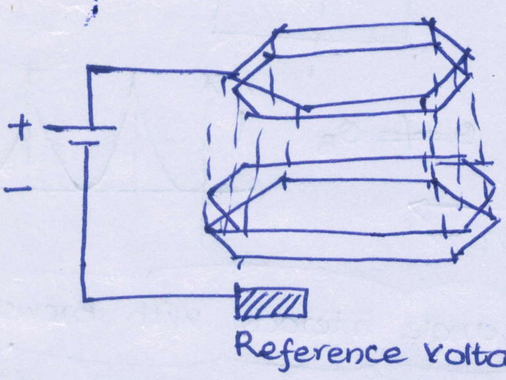
* Dependence of conductivity of graphene on no. of layers:-

- Fewer no. of layers of graphene can provide higher value of kinetic conductance. This effects the characteristics in the following ways:-
  - i) conductivity of graphene reduces with the increment in no. of layers
  - ii) It can provide the large sensitivity for the applied DC voltage for fewer no. of layers (stack of layers) in graphene, which reduces with the increment in no. of layers.



:- Plasma → Fourth states of matter

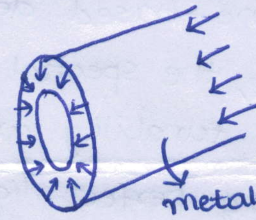
Work function:- Minimum energy to break the covalent bonds.
(hν)

$\vec{J} = \sigma \vec{E}$

$\sigma = \frac{J}{E}$

We know that,

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \Rightarrow \delta \propto \frac{1}{\sqrt{f}}$$

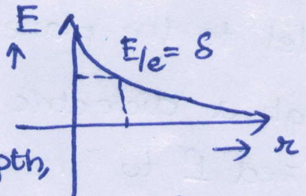


$$\delta \propto \frac{1}{\sqrt{\sigma}}$$

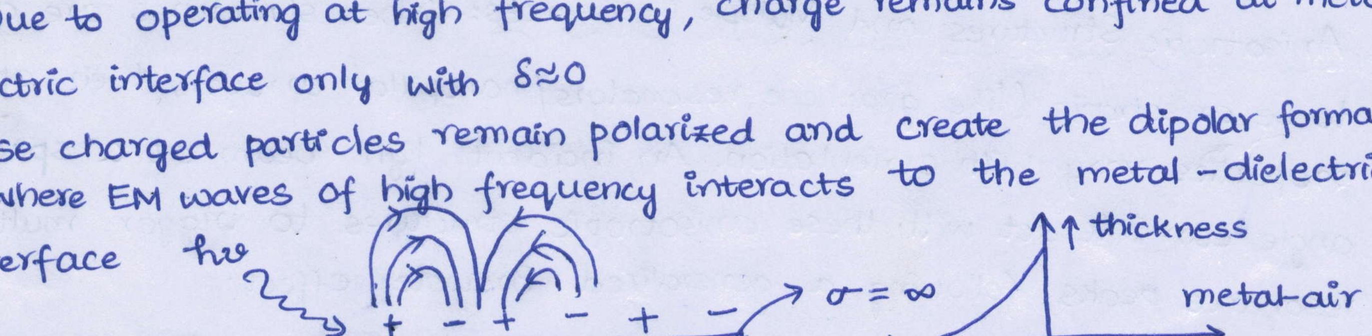
$\sigma \uparrow\uparrow, \delta \downarrow$

$\sigma >> 0$ in case of metallic conductor

$E = 0$ inside.



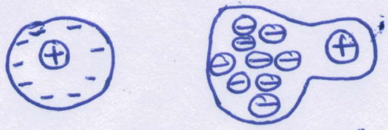
- Because of very small depth of penetration (skin depth, δ). Due to operating at high frequency, charge remains confined at metal-dielectric interface only with $\delta \simeq 0$
- These charged particles remain polarized and create the dipolar formation where EM waves of high frequency interacts to the metal-dielectric interface

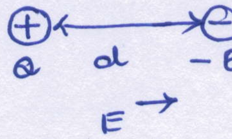


- The creation of electronic dipole at metal - air interface because of interaction of wave to this, is known as "surface plasmons" (polarized electrons/ polarized charged particles/plasmonic arrangement)

– The bunch of electrons is sufficiently getting energy from the wave. So, they can move freely at metal–air interface. So, this is known as plasma or 2D-charge/$\bar{e}$ gas.

Note:- 1. Dipole moment :- Tendency of $\bar{e}$s moving towards the hole in a dipole is known as dipole moment.





$I \propto \vec{E}$

2. Types of dipole antennas:-
1) Infinitesimal dipole/ Hertzian dipole ($\lambda/50$)
2) Short dipole ($\lambda/10$)
3) Half-wave dipole ($\lambda/2$)
4) Finite-length dipole (λ)

Furthermore, ① What is "Surface plasmonic resonance"?
② What do you understand by plasma frequency?

——— X ———

All notes were prepared by
S. Tharakeswara Reddy
following the class discussions.