OPTICS AND PHOTONICS (LASER)

(1) LASER → light amplification by stimulated emission of radiation. (1960 – T.H. Maiman, ruby laser)
- unidirectional • monochromatic • coherent
- bright source (high intensity)
- small divergence (in milliradians)

(2)

Laser source	Ordinary source
- process of stimulated or triggered emission	- spontaneous or natural emission
- single value of λ (less than an Angstrom)	- wide λ range (few Angstrom – mono.) (thousands of Angstrom – poly)
- highly coherent (in phase) (few m to km)	- waves with no definite phase relation (few mm to cm for all sources)
- small angular spread, 10^6 times smaller than ordinary	- highly divergent (high angular speed)
- unidirectional	- all directions
- highly intense	- intensity decreases rapidly
- eg. He-Ne laser, Ruby laser, Nd: YAG laser, CO_2, diode laser	- eg. CFL, halogen lamp, Na-vapour lamp, LED, incandescent bulb.

(3) Laser Beam parameters:

(i) Beam Intensity → measure of optical power output from a laser source per unit area
- W/m^2 (unit)
- optical power (few mW) while gas and solid state lasers (power output upto kilowatts)
- Intensity → $I = \frac{P}{A}$ (P: optical power, A: cross sec area of beam)

(ii) monochromaticity → measure of linewidth of radiation emitted from source of light.
- ordinary sources (linewidth of upto 10^{10} Hz)
laser sources (100 Hz only)

(iii) coherence → measure of coherence length.
- refers to time and dist. upto which light waves emitted from a laser source are in phase or bear a fixed phase difference with each other.
- ordinary sources (coh. length from few mm to cm)
laser sources (c.l. from a few m to km)
- $l_{coh} = \frac{\lambda^2}{\Delta\lambda}$ (λ: central λ, Δλ: spread in λ of rad. emitted by laser source)

(iv) directionality → property of laser source.
- ordinary light (all directions)
laser (only along axis of laser source in form of cylindrical cavity)

(v) divergence → measure of angular spread of laser beam as it travels away from laser source.

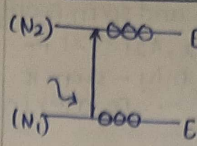
$$\phi = \frac{d_1 - d_2}{z_1 - z_2}$$

(z_1, z_2 → axial/lar dist of detector from laser source)
(d_1, d_2 → diameters of laser beam at distance z_1, z_2)

(4) Interaction of radiation with matter:
- most active constituents of any atom are e^- (moderate energies upto a few electron-volts)

$$h\nu = E_2 - E_1$$

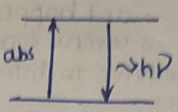
(a) Absorption: (stimulated ab / induced ab)



$$N_{Ab} = B_{12} \cdot N_1 \rho(\nu)$$

(N_{Ab}: no of atoms in level 1; B_{12}: Einstein's coeff. for absorption. (level 1 to 2))

(b) Spontaneous emission:

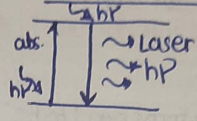


($\tau = 10^{-9}$ s)

$$N_{spem} = A_{21} \cdot N_2 \quad \left\{ A_{21} = \frac{1}{\tau} \right\}$$

(A_{21}: Ein coeff. for spem.)

(c) stimulated emission:



$$N_{stem} = B_{21} \cdot N_2 \cdot \rho(\nu)$$

($\rho(\nu)$: energy density of incident radiation.)

EP

points:

(a) no. of ab. events taking place at any instant is prop. to no. of atoms present in lower energy states (most photons are absorbed as radiation penetrates the matter i.e. attenuated)

(b) uncontrolled, all directions, random phase factors. ∴ light is incoherent, divergent, diffused, undirected may or may not be monochromatic
eg. (ordinary source eg.)

(c) (at room temp.) monoch, coh, directional, focused, intense
no. of st. em. events taking place at any instant is prop. to no. of atoms in higher energy state.

adv. of stem:
- controllable (intensity, energy density)
- induced rad is identical to incident radiation (energy, ν, λ, phase, dirn of prop.)
- with proper active medium, resonance condn, multiplication of photons is achieved, leading to oscillations of radiation within a specially prepared region called → optical resonance cavity.

(5) Components / requirements for laser production:

(a) Population inversion / Inverted state → (c)
no. of active atoms occupying a particular energy state is called population of energy state

N_2 — E_2: $N_1 = g_1 e^{-E_1/kT}$
N_1 — E_1: $\frac{N_1}{N_2} = e^{h\nu/kT}$ (Normal state) ($N_1 \gg N_2$)

$g_1 = g_2$

N_2 — E_2: $N_2 = g_2 e^{-E_2/kT}$
N_1 — E_1: $\frac{N_2}{N_1} = e^{-h\nu/kT}$ (inverted state) ($N_2 >>>> N_1$) → [do in (c)]

(b) Eq. condn and Einstein's coeff:

(Derivation)

$$\frac{B_{21}}{A_{21}} = \frac{c^3}{8\pi h \nu^3 \mu^3}$$

for laser, stem has to dominate spem. ∴ $\frac{B_{21}}{A_{21}}$ stud be more, ∴ A_{21} should be less.

ratio of rates of spem and stem:

$$R = e^{h\nu/kT} - 1$$

stem & spem: $R = \frac{1}{[e^{h\nu/kT} - 1]}$

cont.

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• Laser emission in a non-eq. process:

at room temp & at thermal eq, ab. and spem nearly balance each other — at eq, $N_1 \gg N_2$, $A_{21} > B_{21}$ — rhs of both terms are less than unity — stem is negligible with other two processes. ∴ no laser in normal condn.

(lasers are non-eq. processes)

as for stem, Q must be large so that product on RHS of 1st term becomes greater than unity.

further, we need to make $N_2 > N_1$ — can't happen naturally — supply energy, $N_2 > N_1$ is reverse condn of what is obs. at eq. condn, ∴ we have to disturb eq. condn, lasers are non-eq. processes.

(c) Population inversion:

$N_2 > N_1$ (refer (a) and (b) last part for exp)

(refer diagram of (a))

(d) Pumping Mechanism:

to maintain population inversion, atoms need to be raised to excited state continuously — req. energy to be supplied to system from outside — this process to maintain pop. inv. thru external energy supply is pumping.

(1) Optical pumping → source of light (photons) are used to supply energy.

eg. Krypton lamps or xenon lamps ($\lambda \approx 6000$ Å – 3000 Å)

eg. solid state lasers → Ruby laser → Ruby crystal surrounded by xenon flash lamp

→ The material absorbs incident radiation and a no. of Cr^{3+} ions are excited to higher state

→ Nd-YAG laser

(2) Electrical pumping → electric field is setup by pair of oppositely charged electrodes (cath. & anodes)

eg. CO_2 laser (gas laser)

He-Ne (gas laser) → molecules of He are ionized & accelerated by electric field → they gain K.E. making many molecules to get transf. to excited state.

(3) Direct conversion → semiconductor lasers — diode lasers — energy levels used are CB & VB.

- forward bias enhances diffusion current of holes & e^- to flow into either sides getting many e^- in CB & holes in VB. — 2 level system

→ electrical energy (supplied) → light energy (produced)

(e) Active medium:

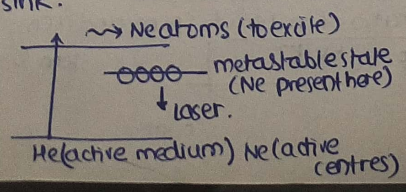
region in which state of pop inv. is achieved is called as active medium / system. — actual laser light is emitted in this region

- system can be solid, liq or gas — further, whole system may not take part in pop. inv, only a fraction is responsible

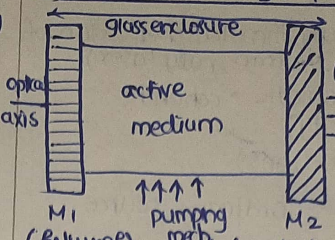
eg. semicond. diode laser — only depletion region undergoes pop. inv.

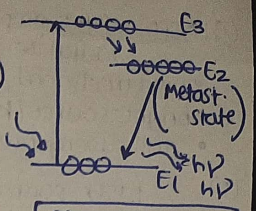
ruby laser — lattice sites occ. by Cr^{3+} ions act as active centres, and ruby (Al_2O_3 crystal) acts as host and heat sink.

eg. He-Ne laser.



(f) Resonant cavity / Optical resonator:





$2L = n\lambda$, $n = 1, 2, 3$

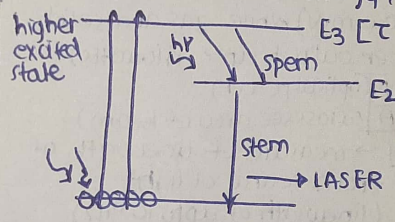
- light emitted in active med consists of spem photons — these do trigger stem but since inducing photons are randomly directed, stem are scattered.
- may have random phase & be incoherent.
- to tune all or most of stem radiation, res cav is used. (only atoms on optical axis are utilised for reflecting photons)

(g) Metastable state:

- excited atoms have natural tendency to deexcite to ground state — process occurs within 10^{-8} sec.
- certain energy states, excited atoms can reside for 10^{-3} sec (it is long compared to normal de-ex. of atoms) these states are metastable states.
- meta stable state are imp as they assist to maintain condn for pop. inv. ($N_2 > N_1$)
- eg. Ne^+ ions → 2s and 3s states → 18.7 eV & 20.66 eV (energies) (He-Ne laser)

eg. argon laser → 4p energy state of Ar^+ ions

eg. Ruby laser → 1.4 eV energy level of Cr^{3+} ions.



(h) Threshold condn for lasing:

$$\gamma \geq \alpha_s + \frac{1}{2L} \ln \frac{1}{r_1 r_2}$$

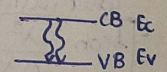
α_s → losses in active med due to scattering — absorption, diff, etc.

r → reflectivity of mirror.

γ → amplification factor.

(i) Pumping schemes:

(A) Two level pumping → diode laser.



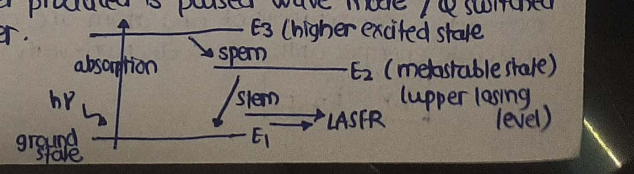
- e^- transferred from VB to CB and come back to VB giving green laser.
- some input energy is lost, but max output efficiency is even better than 70% at times.

(B) Three level pumping → lower level — ground

- atoms raised from ground to excited E_3
- these atoms deexite to intermediate E_2 energy state by some non-radiative process like emission of heat.
- E_2 metastable state → lasing transition to ground state → green laser

* - high energy is required for pumping

* - Laser produced is pulsed wave mode / Q switched laser.



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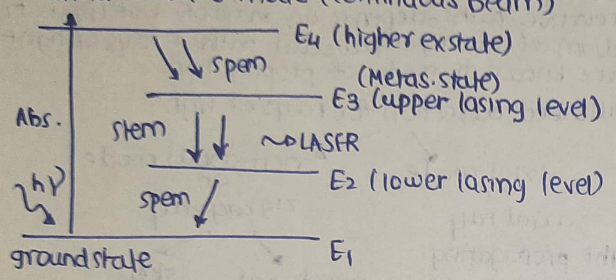
(c) Four level pumping:→ lower, upper energy levels are some intermediate excited energy states.

- atoms are pumped to E_4 – return to E_3 by non-rad. process like heat emission
- E_3 (metastable state) – atoms have lasing transition to state E_2 → green laser
- from E_2, de-excite to ground level by transferring energy during non-rad process like collisions, etc.

• easier to achieve pop. inv. b/w two states, faster
• lesser pumping req. to keep lasing transitions going on

★ – less pumping req.
★ – continuous wave mode (continuous beam)



(OPTICAL FIBRES)

(1) optical fibres: safest, cheapest, fastest, highest capacity data transfer media.

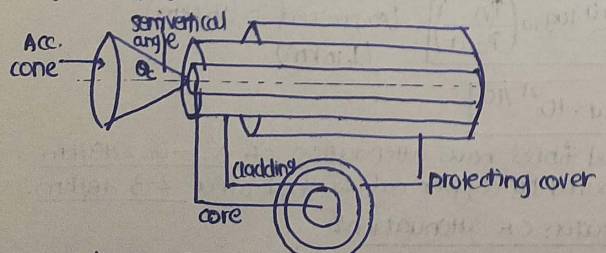
used → communications, surgery, defence, sensors.

- glass or plastic solid threads (not hollow) propagate light in IR, accept & transmit as much light
- work on TIR
- two coaxial regions – core (inner), cladding (outer)

diff. in ref index → very small → 0.01 to 0.1 order.
core diam → 5 to 125 μm
cladding diam → 25 to 500 μm

- acceptance angle: max angle of incidence at end face of optical fibre for which ray can be propagated along core cladding interface.
- acceptance cone: rotating acceptance angle about fibre axis describes a.c. of fibre. → measure of its light gathering capacity.
- two imp. parameters → numerical aperture, normalised freq. / V-number.

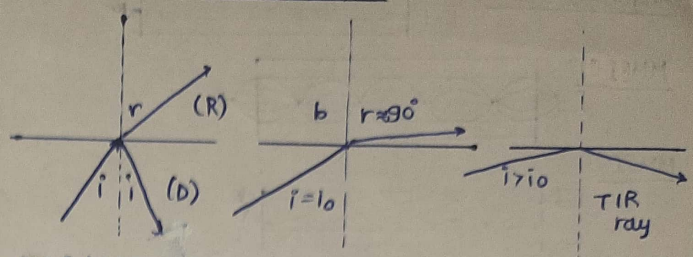
(light beyond acceptance cone, does not contribute to light propagation as no TIR occurs)



advantages of optical fibre:

- cheaper, smaller, lighter, durable, chemically stable, mechanically flexible
- safer, immune to stray EM signals, reduced cross-links, noise-free
- high bandwidth, very high data speeds
- lower losses.

(2) Principle of operation (TIR):



core: denser → n_1, cladding: rarer → n_2

$n_1 > n_2$

$\sin\theta_c = \frac{n_2}{n_1}$ → critical angle (θ_c)

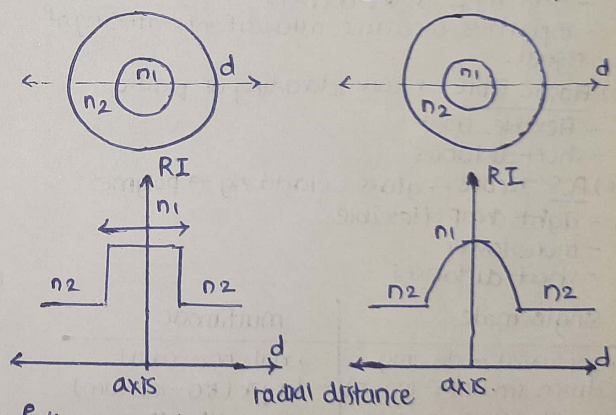
condn for TIR: $i \le i_0$, $\theta \ge \theta_c$

(3) Types of optical fibres:

- Modes of Propagation → single mode, multimode
- Refractive Index Profile → step index, Graded index
- material → all glass (silica), all plastic, PCS (plastic clad fiber) (plastic coated silica)

(A) Ref. index profile: variation of RI with axial dist. from central axis of an optical fibre. ($n_1 > n_2$)

(i) step index (ii) Graded index (parabolic)



- follows meridional rays (zigzag path)
- follows skew rays (helical path)

(B) Modes of Propagation:

- single Mode → SMSI, SMGRIN (rarely used)
- multimode → MMSI, MMGRIN.

MMSI → along with axial dirn, rays can move along diff. dirns going away from axis undergoing multiple internal ref. (zig-zag path) further, rays can traverse their path either within axial plane (meridional rays) or thru non-axial planes (skew rays)

MMGRIN → rays undergo constant deviation in their path as RI continuously changes within core from axis towards cladding boundary.

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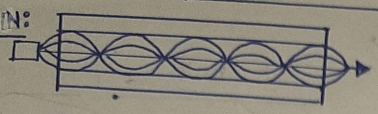
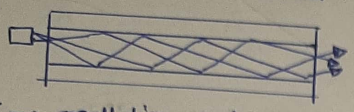
Single mode (SM):

MMGRIN:



MMSI:



★ SMSI → small diam, light travels in straight line, less bending, better output, less losses. long dist comm.

MMSI → greater diam, all signals allowed to pass more loss as diff. signal arrive at diff. time, short dist

MMGRIN → large signal, less losses than MMSI, skew rays or helical rays, angle of incidence in region of high RI to low RI continuously bends

SI → RI core is uniform changes abruptly at core-cladding interface.

GRIN → RI gradually varies with core from axis of fibre to core-cladding interface

GRIN fibre can be graded in linear, parabolic, or staircase manner.

(c) Type of materials:

(i) Silica Fiber → - fused silica / fused Quartz
- add Ge / P in fused silica → RI increases
- add B / F → RI decreases
- impurities can cause attenuation / scattering of signal.

(ii) Plastic Fibre → core, cladding of plastic
- flexible, light
- short distances

(iii) PCS → core → glass ; cladding → polymer
- light, cheap, flexible
- more losses
- short distances.

Single mode	Multimode
- supports axial mode only	- axial, non-axial
- core diam small (5-10 μm)	- larger (50-100 μm)
- works with only laser diode sources	- works with LED as well as laser diode sources
- lowest attenuation losses	- higher
- waveguide dispersion is the limiting parameter	- w.d is insignificant
- long dist.	- short to medium dist
- only SI profile	- SI, GRIN profile
- made from glass	- made from glass or plastic

MMSI	MMGRIN
- RI core is uniform	- RI of core is gradually lowered
- pulse distortion	- pulse distortion is overcome by RI grading
- lower bandwidth	- higher bandwidth
- NA higher	- NA lower
- Reflection losses present	- minimal
- Attenuation higher	- lower
- single mode or multimode	- only multimode
- easier manufacturing process	- complex.

(4) Numerical Aperture (NA):
- measure of amt of light that can be accepted by fibre.
- light gathering capacity of an optical fibre.

$$NA = \sin\theta_{max} = \sqrt{n_1^2 - n_2^2}$$

$$NA = n_1\sqrt{2\Delta} \qquad \Delta = \frac{n_1 - n_2}{n_1}$$

for ray incident

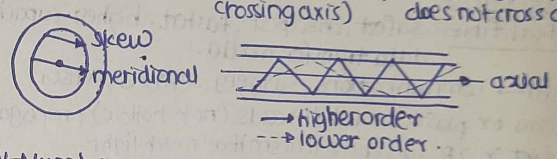
$$\sin\theta_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

for ray incident from air, $n_0 = 1$.

(5) modes of propagation:
- allowed path for a ray of light inside optical fibre
- although TIR is satisfied, fibre does not support all rays falling in cone of acceptance, allows only selective paths, depends on ratio of λ of light to diam. of core region, allowed paths of rays of light are known as modes of propagation
- allowed direction for rays of light

axial mode or axial ray (light propagating along or parallel to axis of fibre)

non-axial mode or zigzag ray → meridional (zigzag path, crossing axis) / skew (zigzag path does not cross axis)



(6) V-Number, No. of allowed modes of propagation:
(V-No. or normalized freq. of fibre)

$$V = \frac{2\pi a}{\lambda} \times NA$$

a → radius of core
λ → wavelength of light

max no. of modes, $N_m = \frac{V^2}{2}$ (MMSI) $N_m = \frac{V^2}{4}$ (MMGRIN)

singlemode (supports axial mode) → $V < 2.405$

(7) Losses: → Attenuation
→ Dispersion / Distortion → Intermodal / Intramodal
Intramodal → waveguide / material / chromatic

(A) Attenuation: (loss of signal while it is propagating in form of light waves thru optical fibre)

$$\alpha = \frac{10}{L}\log_{10}\left(\frac{P_{in}}{P_{out}}\right)$$

(expressed in dB/km) (L in km)

$$P_{in} = P_{out} \cdot 10^{\alpha L/10}$$

- optical fibres have attenuation of 0.1-0.2 dB/km. compared to copper cables that offer 2-3 dB/km.

- contributors of attenuation:

(i) absorption → two types of absorption agents: intrinsic / impurities

intrinsic → absorption of light energy by material of fibre (glass / plastic)

glass → two abs. ranges → 0.1 to 0.3 μm (UV range) / 7 to 12 μm (IR range)

molecular vibrational absorption. / electronic absorption

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- plastic has much higher absorption range - offers higher attenuation.

impurities → chief contributors to absorption.
- can be minimized but cannot be completely removed.
- OH-radicals mix up during manufacturing process.
- Cu, Ni, Cr, V, Mn → also respo. for heavy ab. losses.

(2) Rayleigh scattering → occurs w/z of light passing thru a medium having non-uniform distribution of mass & density.
- amt of scattering $\propto \frac{1}{\lambda^4}$ (λ → wavelength of light)
- glass, plastic → (amorphous) disordered structures & have local microscopic variations in density that causes local variations in RI.

(3) geometric effects → due to manufacturing defects like irregularity in fibre dimensions (core, cladding).
- stress developed due to fibre coating & cabling process, bends, kinks while installation.
- nonuniformity of core cladding interface - results in escape of light, as TIR is unsatisfied.
- bending → causes strain, RI of core cladding gets affected., suffers reflection, refraction at both ends at bending, signal is attenuated due to loss of critical angle for a part of incident light and is known as bending loss.

(B) Dispersion / Distortion:
- broadening of pulse as light travels thru an op. fib.
- measured in ns/km. (nanosec/km)

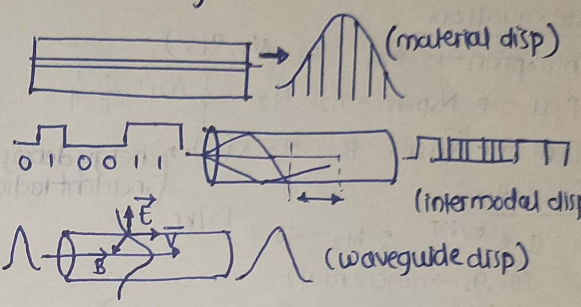
(a) Intermodal Distortion:
- diff modes - diff. velocities
  ∴ time for reaching output end is diff. ∴ pulse broadening occurs.
- axial ray - least time, non axial → longer time.
- occurs in SI (multimode) - as axial ray moves straight, covers longer distance, non-axial cover shorter dist. depending on angle ∴ after some time interval, all modes do not synchronize.
- in GRIN fibres, - overcome by varying RI of core. it is max at axis, dec. towards cladding thus, axial ray has shorter linear dist to cover but travels with lowest speed as it moves thru a region of highest RI.
  non-axial ray has to cover a longer linear dist. but as it moves towards cladding, speed dec. due to reduction in RI, ∴ longer dist. is compensated by higher speed and all modes remain synchronous.

(b) Intramodal Distortion:

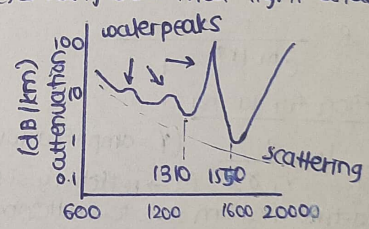
(i) material / chromatic distortion:
- glass or plastic is a dispersive medium, results in diff. λ components moving at diff. speeds, shorter λ travels slower than longer λ and light pulse tends to be broken.
- depends on spectral width of source.
- can be reduced by laser sources. (laser costly than LED circuits ∴ not always desirable)
- incident light separate into colours.

cont.

(ii) waveguide distortion:
- even though light ray is TIR, part of light energy penetrates into cladding.
- happens as travelling wave is an EM wave and medium is dielectric ∴ induced electric field in cladding.
- now, as wave propagates further, part of light penetrated into cladding region travels faster than main part, confined to core region.
- leads to waveguide disp.
- significant in single mode fibre as core diam is extremely small.



(8) Optical Window:
- for better performance, choice of λ is a must to minimize loss and dispersion.
- the band of wavelengths at which attenuation is minimum is called optical / transmission / low loss window
- min. attenuation is in range of 1500 - 1600 nm
- 1.3 μm and around 1.55 μm → net attenuation is lower → small ranges of λ are called op. windows
- most of LEDs or laser diodes are designed to emit in these ranges so that light undergoes min. attenuation



(e) maximum bit rate:
dispersion in fibres is usually expressed in ns/km or ps/km.

intermodal dispersion → $\boxed{\tau_i = \frac{n_1 L \Delta}{c}}$ sec (SI fibre)

$\boxed{\tau_i = \frac{n_2 L}{2c} \Delta^2}$ sec (GRIN - parabolic)

Total disp → $\boxed{\tau = \sqrt{\tau_i^2 + \tau_m^2}}$
↳ material disp.

max bit rate → $\boxed{B \approx \frac{0.7}{\tau}}$ bits/sec

(usually expressed in bits/sec or MBPS)
↓
mega bits per second.

core: glass/plastic, 8 - 100 μm diam.
cladding: glass/plastic, 50 - 200 μm diam.
protective jacket: polyurethane, 100 - 400 μm diam.

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FORMULA LIST:

(1) Intensity: $I = \frac{P}{A}$ (optical power) (cross sec area of beam)

(2) coherence length: $l_{coh} = \frac{\lambda^2}{\Delta\lambda}$ (central λ) (spread in λ of rad. emitted by laser source)

(3) divergence: $\phi = \frac{d_1 - d_2}{z_1 - z_2}$

($z_1, z_2 \rightarrow$ lar/axial dist of detector from laser source)
($d_1, d_2 \rightarrow$ diam. of laser beam at dist z_1, z_2)

(4) rate equations:

absorption $\rightarrow$ $N_{Ab} = B_{12} \cdot N_1 \cdot \rho(\nu)$

spem $\rightarrow$ $N_{spem} = A_{21} \cdot N_2$ $\left\{ A_{21} = \frac{1}{\tau} \right\}$

stem $\rightarrow$ $N_{stem} = B_{21} \cdot N_2 \cdot \rho(\nu) \rightarrow$ (energy density of incident radiation)

(5) population:

$N_1 = g_1 \cdot e^{-E_1/kT}$; $N_2 = g_2 \cdot e^{-E_2/kT}$

($g_1, g_2 \rightarrow$ degeneracy)

$\frac{N_1}{N_2} = e^{h\nu/kT}$ ($N_1 >> N_2$) [Normal state]

$\frac{N_2}{N_1} = e^{-h\nu/kT}$ ($N_2 >>>> N_1$) [Inverted state]

(6) Ratio of population of two energy levels:

$\frac{A_{21}}{B_{21}} = \frac{8\pi h \nu^3 \mu^3}{c^3}$; $\frac{B_{21}}{A_{21}} = \frac{c^3}{8\pi h \nu^3 \mu^3}$

(7) ratio of rates of spem and stem:

spem to stem: $R = e^{h\nu/kT} - 1$

stem to spem: $R = \frac{1}{e^{h\nu/kT} - 1}$

(8) Threshold condition for lasing:

$\gamma \geq \alpha_s + \frac{1}{2L} \ln \frac{1}{r_1 \cdot r_2}$ (γ = amplification factor) ($r \rightarrow$ reflectivity of mirror)

($\alpha_s \rightarrow$ losses in active medium due to scattering, absorption, diffraction, etc.)

(9) no. of photons emitted per sec: $n_t = \frac{P_{optical} \times \lambda}{hc}$

no. of photons emitted: $n = n_t \times \Delta t$

(10) efficiency of laser (electrical pumping/direct conv):

$\eta = \frac{P_{optical}}{V_{operating} \times I_{operating}}$

(11) $E = \frac{hc}{\lambda}$; $\lambda = \frac{hc}{E_2 - E_1}$; $h\nu = E_2 - E_1$

$\frac{N_1}{N_2} = e^{hc/\lambda kT}$; $\frac{N_2}{N_1} = e^{-hc/\lambda kT}$

(1) Numerical aperture: $NA = n_0 \cdot \sin i_{max}$

$NA = \sqrt{n_1^2 - n_2^2}$

$NA = n_1 \sqrt{2\Delta}$

(2) (External) Acceptance angle: $i_{max} = \sin^{-1}(NA)$

(3) (Internal) critical angle: $\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

$\phi_c = \sin^{-1}(1 - \Delta)$

(4) Fractional ref index: $\Delta = \frac{n_1 - n_2}{n_1}$

(5) $NA = \sin\theta_{max} = \sqrt{n_1^2 - n_2^2}$ ($n_0 \rightarrow$ RI of medium)

$\sin\theta_c = \frac{n_2 \text{ (rarer)}}{n_1 \text{ (denser)}}$ ($n_2 \rightarrow$ RI of cladding)

$\sin\theta_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$ ($\theta_{max} \rightarrow$ acceptance angle) ($n_1 \rightarrow$ RI of core)

(6) V-number / normalized freq:

$V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}$ ($a \rightarrow$ radius of core)

(7) Number of modes: (N_{max})

$N_{max} = \frac{V^2}{2}$ (SIF)

$N_{max} = \frac{V^2}{4}$ (GRIN F)

(8) Attenuation: (power of light at output end is always less than power at input end)
(it decreases exponentially with distance)

$\alpha = \frac{10}{L} \log_{10} \frac{P_i}{P_o}$ dB/km ($\alpha \rightarrow$ atte. constant) ($L \rightarrow$ length of fibre in km)

$P_i = P_o \cdot 10^{\alpha L/10}$ ($P_i \rightarrow$ power at input end) ($P_o \rightarrow$ power at output end)

(9) Intermodal dispersion:

$\tau_i = \frac{n_1 L}{c} \Delta$ sec (SI)

$\tau_i = \frac{n_2 L}{2c} \Delta^2$ sec (GRIN)

Total disp: $\tau = \sqrt{\tau_i^2 + \tau_m^2}$ (material disp.)

(conversion: 1 sec/m = 10^{12} ns/km)

(10) max bit rate:

$B = \frac{0.7}{\tau}$ bits/sec.

(11) $\sin i_{max} = n_1 \cdot \cos\phi_c$

(12) $V \leq 2.405$ (single mode)
$V > 2.405$ (multimode)

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ENGINEERING MATERIALS

(LIQUID CRYSTALS)

(1) solid phase → positional and orientational orders are present.
liquid phase → no positional and orientational order
gas phase → no ordering, no intermolecular attraction
liquid crystal → positional order may be lost, but some of orientational order remains
∴ LC phase is reff. to as mesophase

(2) 1988, Friedrich Reinitzer → discovered LC. are soft condensed matters.
found two melting points for cholesteryl benzoate.
145.5°C, 178.5°C

(3) criteria for a molecule being liquid crystalline:
(i) molecule must be elongated in shape - length should be significantly greater than its width.
(ii) molecule must have some rigidity in central region.
(iii) ends of molecule are somewhat flexible.

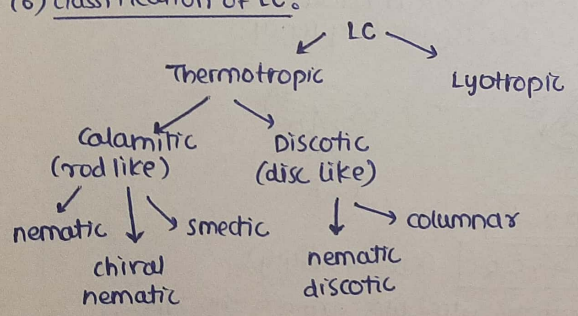
(4) director:
- imaginary vector in preferred direction of liq. crystal molecules is director.
- assuming that direction of preferred orientation in a LC is ↑, this dirn can be represented by an arrow, called the director of LC

(5) order parameter: (S)
- used to measure amount of orientational order present in liquid crystal material.

$$S = \left\langle \frac{3\cos^2\theta - 1}{2} \right\rangle$$

where θ is average angle of molecules with director.
- describes orientational order of liq. crystalline material, allowing for individual orientational deviation of molecules from director, which represents the average over the collection.
- for perfect orientation: θ for all molecules = 0°, S = 1
for completely random orientation: S = 0.

(6) classification of LC:



- nematic LC:
(1) nematic - greek word 'nema' - meaning thread like molecule
(2) axes are oriented parallel to one another resulting in long range orientational order and short range positional order.
(3) molecular long axis points on the average in one favoured direction called director.
(4) anisotropic wrt optical properties, viscosity, electrical and magnetic susceptibility, electrical and thermal conductivity.
(5) used for display applications.

- cholesteric LC:
(1) similar to nematic phase, however, the director in each successive layer is inclined to form angle with direction of axis of molecules in preceding layer.
(2) period of this variation i.e. the distance over which a complete rotation of 360° is completed is known as pitch.
(3) non-polar, optical properties depend on half value of pitch known as period of helix.
(4) due to this, they have ability of selective reflection of light of λ equal to pitch length and show colours when λ is in visible region.
(5) used in sensors, thermometer, display devices, fashion fabrics that change colour with temp.
(6) pitch is affected by → temp, pressure, electric and magnetic fields.

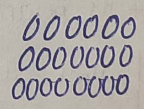
- smectic LC:
(1) smectic - greek word 'smectos' - meaning soap like
(2) molecules are arranged in layers and exhibit some correlations in their positions in addition to the orientational ordering.
(3) long range orientational ordering is always present in all layers of SLC.
(4) interlayer interactions are weaker than lateral forces b/w molecules and hence layers can easily slide over one another.

(7) applications of LC:
LCD, LC thermometer, LC lenses, LC laser, optical images, medicinal uses, helmets, bullet proof jackets, optical memories

(8) advantages of LCD:
brightness, emissions, geometric distortion, power consumption, physical aspects (thin/compact), screen shape (flat), sharpness.

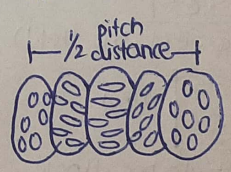
diagrams:

(1) nematic LC:

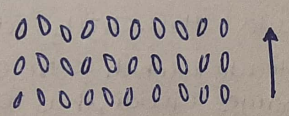


(parallel to each other)

(2) cholesteric LC:



(3) smectic LC:



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(DIELECTRICS)

(1) conductors: substances that contain an unlimited supply of charges that are free to move thru the material. eg. metals.

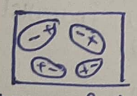
(2) insulators: low free e^-, tightly bound to atom. eg. plastic, paper.

(3) dielectrics: when pot. diff. is applied to certain non-conducting substances, they get polarised. eg. mica, glass, etc.
- no free e^- present
- bound charges
- restoring forces are present
- under the effect of an electric field, get polarized.
- when filled the space b/w two conductors of a capacitor, capacitance increases.
- forbidden gap is large (very)
- excitation of e^- from normally full VB to empty CB is not possible under ordinary conditions. ∴ conduction can't occur.
- even tho it has impurities, extrinsic conduction is not observed.
- resistivity is infinitely high (order $10^{10}-10^{20}\,\Omega m$)
- isotropic → change in behaviour of dielectric is independent of direction of applied field.
- anisotropic → change in behaviour of dielectric depends on dirn of applied field.
- relative displacement of charges give rise to dipole generation ∴ dielectric is said to be polarized. (dielectric polarization) $\boxed{P = \frac{\Sigma d\mu}{V}}$

(4) Dielectrics
↙ polar ↘ non-polar.

(i) polar: molecule in which the centres of gravity of +ve & -ve charges do not coincide. The +ve and -ve charges are centered at a point separated by a distance, ∴ possess a net dipole moment are polar molecules.
- polar nature of Dielectric materials is measured in terms of its permanent dipole moment

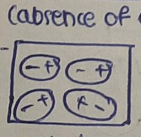
- $\vec{E}=0$



$\mu_{net} = \mu$

(absence of electric field)

$E=\vec{E}$ -



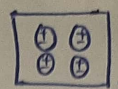
$\mu_{net} = \mu$.

- permanent electric dipole
- polarisation is temperature dependent
- eg. polar molecules: H_2O, CH_3-Cl, C_6H_5Cl, C_2H_5OH

(ii) non-polar: molecule in which centres of gravity of +ve & -ve charges coincide, thus for which the inherent dipole moment is zero, is a non-polar molecule
- induced electric dipole
- polarization is independent of temperature
- eg. H_2, O_2, CH_4, C_6H_6.

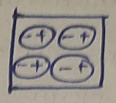
P.T.O.

- $\vec{E}=0$



$\mu = 0$. $\boxed{\mu = qd}$
$(q=0)$
→ net charge = 0, net E field = 0

- $E=\vec{E}$



$\mu_{net} = \mu$.

(5) dipole: measure of polarity of system of electric charges, quantity that describes two opp. charges separated by distance x.
- depends on position of charges, not field lines.
- dipole moment (value): $\boxed{\mu = q.x}$

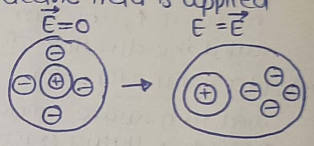
polarization: dielectrics have bound charges.
- these bound charges may be able to move slightly (in opp. dirn) when electric field is applied.
- it is no. of dipole moments induced per unit volume.

$$\boxed{P = \frac{\mu}{V} = \frac{qd}{Ad} = \frac{q}{A}}$$

- numerically equal to surface charge density
- vector qty & its direction is along direction of dipole moment.
- unit: coulomb/m^2. (C/m^2)

polarizability: tendency of a substance to form dipole moment when an electric field is applied across it.

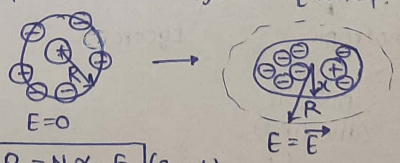
$\boxed{\mu \propto E}$ $\boxed{\mu = \alpha E}$ → polarizability.



if N atoms per unit volume,
$\boxed{P = N\mu = N\alpha E}$

(6) Types of polarization:

(i) Electronic polarisation:
- electric strain produced in an atom by application of electric field.
- results from displacement of nucleus & e^- in opp. dirn in presence of applied field with creation of dipole moment.
- independent of temperature
- fastest one to occur (order of 10^{-14} to 10^{-15}s)
- persists for longer frequency.

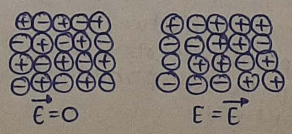


$\boxed{P = N\alpha_e E}$ (ε pol)

$\boxed{\alpha_e = 4\pi\varepsilon_0 R^3}$ (ε polarisability)

- monoatomic molecules exhibit this type.

(ii) space polarisation:
- occurs due to accumulation of electric charges at interface of a multiphased material.
- possible when one of phases present posses much higher resistivity than the other.
- found to occur in ferrites and semiconductors



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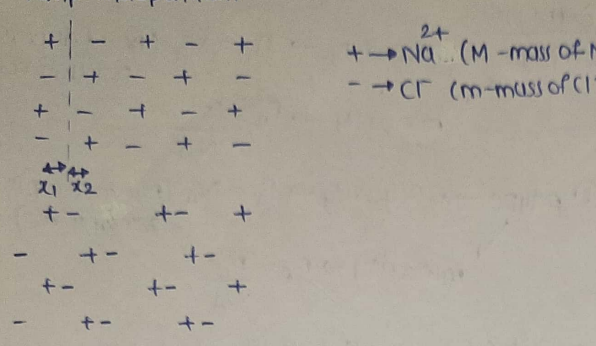
(iii) Ionic polarization:

- occurs in ionic crystals
- occurs due to elastic displacement of +ve and -ve ions from equilibrium positions.
- temp. independent



- restoring force is present.
- dipoles cannot rotate, and the lattice is distorted a little

$\boxed{P_i = N\alpha_i E}$ (I polarization)

$\boxed{\alpha_i = \frac{e^2}{\omega_0^2}\left(\frac{1}{M}+\frac{1}{m}\right)}$ (I polarisability)

ω_0 → natural freq. of solid
N → no. of atoms in material
E → electric field.

(iv) orientation polarization:

- due to presence of polar molecules in dielectric material which have permanent dipole moment.
- when $\vec{E}$ is applied on dielectric material, it tries to align the dipole in its direction that results in existence of dipole moment in material.
- occurs in assymetric molecules
- temp. dependent.
- no restoring force.

(polar dielectrics diagram)

$\boxed{P_o = N\alpha_o E}$ (O polarization)

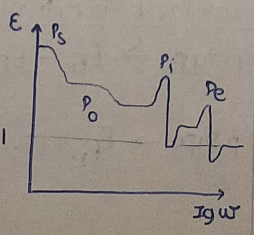
$\boxed{\alpha_o = \frac{\mu_{net}^2}{3KT}}$ (O polarizability)

Total polarization: $\boxed{P = P_e + P_i + P_o + P_s}$ (P_s → neglected)

$$\boxed{\varepsilon_r = 1 + \frac{N}{\varepsilon_0}\left(4\pi\varepsilon_0 R^3 + \frac{e^2}{\omega_0^2}\left[\frac{1}{M}+\frac{1}{m}\right] + \frac{\mu^2}{3KT}\right)}$$

(7) Frequency dependence of polarization:

- when dielectric is placed in an alternating field, dielectric gets polarized, the total polarization depends on ability of dipole to orient themselves in field direction.
- P_e - fastest - $\sim 10^{13}-10^{15}$ Hz
  P_i - sluggish - $\sim 10^{9}-10^{13}$ Hz
  P_o - below 10^9 Hz.
  P_s - below 10 Hz.



- average time taken by dipole to orient in field direction is → relaxation time (τ_d)
- reciprocal of relaxation time → relaxation freq (ν)
- if freq. of applied E field >> relaxation freq. of dipole (ν)
  ↓
  dipoles can't orient themselves.
  if relaxation time of dipole (τ_d) < half of time period of electric field ($\frac{T_{EF}}{2}$)
  ↓
  dipole easily follows field direction.
- at low freq (audio freq) → all types of pol. exists.
  $P = P_e + P_i + P_o$
- in rf freq or microwave freq → P_o absent as it can't follow field reversal
  $P = P_i + P_e$
- in infrared and optical freq → P_i fails to follow field reversal.
  $P = P_e$
- relative permittivity in optical region (ε_r) = n^2 (sq. of RI of the dielectric)
- in UV region: electron cloud fails to follow field reversal ∴ Total Pol = 0. but $\varepsilon_r = 1$.

(8) application of dielectric materials:

capacitors, insulation, semiconductors (improve performance), transformers, sensor devices, radio freq transmission lines, LCD, power cables.

(9) $\boxed{C = \frac{K\varepsilon_0 A}{d}}$ (k or ε_r) $\boxed{V = \frac{Q}{C}}$ $\boxed{E = \frac{Q}{K\varepsilon_0 A}}$ $\boxed{V = \frac{Qd}{K\varepsilon_0 A}}$ $\boxed{E = \frac{V}{d}}$

displacement of charge (D):

$\boxed{D = \varepsilon_0 E}$ (free space)

$\boxed{D = \varepsilon E = \varepsilon_0 \varepsilon_r E}$ (in medium) $\boxed{\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}}$

$\boxed{P = \varepsilon_0 E(\varepsilon_r - 1)}$

$\boxed{P = \varepsilon_0 E \chi_r}$

$\boxed{\chi_r = \varepsilon_r - 1}$

$\boxed{\mu \propto E}$

$\boxed{P = N\mu}$

Clausius Mossotti Equation: (strictly for solids)

$$\boxed{\alpha_e = \frac{3\varepsilon_0(\varepsilon_r - 1)}{N(\varepsilon_r + 2)}}$$

for other cases,

$$\boxed{\alpha_e = \frac{\varepsilon_0(\varepsilon_r - 1)}{N}}$$

Internal field in solids:

$$\boxed{E_i = \frac{\gamma \vec{P}}{\varepsilon_0}}$$

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(SEMICONDUCTORS)

(Numerical formulae):

(1) $\rho_i = \dfrac{1}{n_i e(\mu_e + \mu_h)}$

(2) $n_h = \dfrac{n_i^2}{N_D}$

(3) $\rho_n = \dfrac{1}{n_e \mu_e e}$

(4) $\dfrac{n}{V} = \dfrac{\rho N}{M}$

(5) $n_i = \sqrt{N_c N_v} \cdot \exp\left[-\dfrac{E_g}{2kT}\right]$

(6) $V_d = \mu_e E$

(7) $J_{drift} = neV_d$

(8) $J_{drift} = P \cdot D_p \cdot \dfrac{dp}{dx}$

(9) $f(E) = \dfrac{1}{1+\exp\left[\dfrac{E-E_F}{kT}\right]}$

$f(E_c) = \dfrac{1}{1+\exp\left[\dfrac{E_c-E_F}{kT}\right]}$

for room temp, $T = 300K$, $kT = 0.025eV$

(10) $E_c - E_F = \dfrac{E_g}{2}$

(11) $E_{F_p} - E_{F_i} = -kT \ln\left[\dfrac{n_p}{n_i}\right]$

(12) $f(E_v) = \dfrac{1}{1+\exp\left[\dfrac{E_v-E_F}{kT}\right]}$

Fermi-Dirac function of energy and temp:

$F(E) = \dfrac{1}{1+e^{(E-E_F)/kT}}$

Extrinsic:

① n type → majority → $n_n = N_D$ (no. of donors per unit vol)
→ minority → $P_n = \dfrac{n_i^2}{N_D}$

② p type → majority → $P_p = N_A$ (no. of acceptors per unit vol)
→ minority → $n_p = \dfrac{n_i^2}{N_A}$

mobility: $V_d = \mu E$ ($m^2/V sec$)
E → electric field intensity

microscopic ohm's law: $J = \sigma E$
J → current density, σ → conductivity

drift current density:

① n type → $J_n = q_n \mu_n E$

② p type → $J_p = q_p \mu_p \cdot E$

③ intrinsic → $J = qE(n\mu_n + p\mu_p)$

diffusion and diffusion coeff:

① n type → $J_n = q \cdot D_n \cdot \dfrac{dn}{dx}$

② p type → $J_n = -q \cdot D_p \cdot \dfrac{dp}{dx}$

③ intrinsic → $J = q\left(D_n \dfrac{dn}{dx} - D_p \dfrac{dp}{dx}\right)$

Einstein's relations:

$\dfrac{D_n}{\mu_n} = \dfrac{D_p}{\mu_p} = \dfrac{kT}{q}$ = constant at given temp.

total current density:

$J_{total} = q\left[\left(D_n \cdot \dfrac{dn}{dx} - D_p \cdot \dfrac{dp}{dx}\right) + (n\mu_n + p\mu_p) \cdot E\right]$

conductivity and resistivity:

① n type → $\sigma = q \cdot n \mu_n$
② p type → $\sigma = qp\mu_p$
③ intrinsic → $\sigma = q n_i (\mu_n + \mu_p)$
} (s/m)

④ $\rho = \dfrac{1}{\sigma}$ Ω-m

fermi level in extrinsic sc:

① n type → $E_{F_n} - E_{F_i} = k_B \cdot T \cdot \ln \dfrac{n}{n_i}$

② p type → $E_{F_p} - E_{F_i} = -k_B \cdot T \cdot \ln \dfrac{p}{n_i}$

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QUANTUM MECHANICS

① de Broglie's hypothesis:

— experimental finding summed up into set of logical arguments based on symmetry.

energy → radiation / waves, matter / particles

- radiation / waves → wave properties → Interference, Diffraction; particle properties → Photoelectric effect, Compton effect
- matter / particles → particle properties → Rectilinear, circulary, Projectile, oscillations, scattering, Gravitation; wave particles (wave mech?) → new experiments?

during that time, there was no experimental basis to his hypothesis but many took it seriously and soon wave nature of e^- was demonstrated by 2 exp: (a) Davison and Germer
(b) G P Thomson

(similar to X-ray diffraction & based on diff of e^- using crystals as three dimensional diff. gratings)

De Broglie's eqn: $\lambda = \frac{h}{mv}$ ($v < c$ always)

② The two experiments above confirmed de Broglie's hypothesis and thus wave nature of material particles.

D.-G exp. stood as pioneering exp in confirmation of Q.M., even though exp were performed using beams of protons, neutrons, α particles. similar exp. were done using heavier atoms, ions, molecules (bucky balls (C_{60})) to prove wave nature of matter.

③ matter waves: waves associated with all material particles moving with certain speed.

phase velocity: rate at which plane containing waves having same phase (viz. the wave front) advances in a certain direction.

wave packet: large no. of waves added and resulting a repetitive pattern. It carries the energy associated with the system.

the collection of these waves is a wave group and the speed at which the entire group moves is diff than vel of individual waves.

'k' → wave vector function.

* particle can be represented by a wave packet.

④ matter waves: (refer defn)

* The exact value of a physical quantity is somehow a representation of pure particle picture used in classical mechanics

* the probabilistic value with some spread (often taken as uncertainty) is a kind of wave picture used in quantum mechanics.

In QM, this prob. nature is carried by an abstract mathematical qty. called 'wave function'

* properties (of matter waves)

(1) associated with all moving particles
(2) $\lambda \propto \frac{1}{p}$ (wavelength $\propto \frac{1}{\text{momentum}}$)
(3) independent of charge of particle
(4) neither mechanical nor electromagnetic
(5) a particle cannot be rep. by a single wave, it is asso. with large no. of waves forming a wave packet
(6) qty that varies with space & time periodically is taken as wave function
(7) square of wave function gives probability of locating the particle.

EM Waves	Matter waves
(1) asso. with photons, zero rest mass	(1) asso. with all moving particles, non-zero rest mass
(2) a single de Broglie wave can be asso. with photon	(2) cannot be asso. with material particle
(3) qtys that vary periodically with space & time are electric & mag fields	(3) qty here is wave function
(4) elec & mag fare real physical qtys & can be measured experimentally	(4) abstract math. qty., no direct physical interpretation
(5) sq. of field amplitude gives intensity of EM waves	(5) sq. of w.f gives prob. of locating particle in a given interval.

⑤ wave-particle duality:

(1) In QM, all material particles — rep by wave packet of finite extent. mathematically, it is formed by coupling large no. of waves by means of Fourier analysis.
(2) spread of wave packet linked with uncertainty in exact location of particle.
(3) to get exact location, wave packet shud be restricted in its extent. but then, wave nature becomes indeterministic. when wave packet shrinks to a point giving exact particle picture, wave nature collapses.
(4) if we try to have a perfect wave picture, wave packet shud be extended further but doing so, posn of particle & particle nature become highly uncertain. when wave packet extends to infinity, giving exact wave picture, particle nature collapses.

{ since all materials show wavelike properties such as interf, diff, we asso. wave nature to particle or matter in general }

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⑥ Heisenberg's uncertainty principle:

It is impossible to exactly determine the position and momentum of an object simultaneously such that product of their uncertainties is never better than the factor $h/2\pi$.

$$\Delta x \cdot \Delta p \simeq \hbar$$

$$\hbar = \frac{h}{2\pi}$$

$h = 6.63 \times 10^{-34}$ JS

$\hbar = 1.05 \times 10^{-34}$ JS

Other forms:

(1) Energy-time uncertainty product: $\Delta E \cdot \Delta t \geq \frac{h}{2\pi}$

(2) Angular posn - angular mom un. pr.: $\Delta\theta \Delta L \geq \frac{h}{2\pi}$

Implications:

(1) non-existence of e^- in nucleus (refer derivation)

(2) minimum energy possessed by an e^- in atom: (refer derivation)

(3) finite width of spectral lines
- wavelength (or freq.) of radiation emitted from any monochromatic source are never sharp at a particular value but always have some spread.
(refer derivation)

(4) virtual particle / vacuum fluctuations
- spontaneous generation of virtual particles, which take energy from vacuum within the limits of energy-time uncertainty at short range and time.
These virtual particles play a crucial role in high energy particle physics.

(5) zero-point energy
In Quantum electrodynamics, zero-point energy is lowest possible energy level or ground state in a quantized EM field. It is also a consequence of uncertainty principle

⑦ Wave function:

wave - doubly periodic phenomenon, meaning, we can asso. atleast one physical qty. which is a periodic function of space (posn) and time.

(wave - disturbance in medium)

Sound waves — pressure variations

Light waves - electric / magnetic fields

(water waves - ripples)

The square of wave function $|\psi|^2$ or $\psi^*\psi$ is called probability of finding the particle and it is a real no. b/w 0 and 1 (0 to 0% and 100%). thus, matter waves are somewhat related to probabilistic outcome for any kind of measurement performed on particles. sometimes, matter waves are called 'waves of probability'.

Conditions on wave function:

wave function shud satisfy foll. requirements:

① finite, single valued, continuous (and hence differentiable) everywhere

② Its derivatives $\left(\frac{\partial\psi}{\partial x}, \frac{\partial\psi}{\partial t}, \text{etc}\right)$ must also be finite, single valued and continuous.

③ It must be normalised meaning as $x \to \pm\infty$, $\psi(x,t) \to 0$

④ must have atleast one physically acceptable solution.

⑤ must obey the principle of superposition of waves,
i.e. if ψ_1 and ψ_2 are solutions of wave eqn then $A\psi_1 + B\psi_2$ is also a solution.

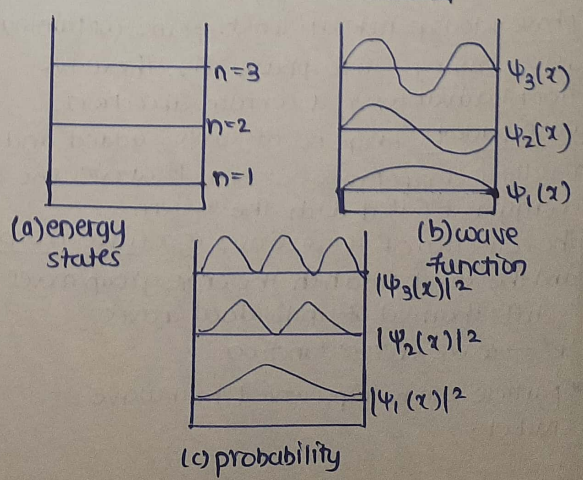
Schrodinger eqn	Newton's eqn (2nd law of motion)
(1) central eqn. of QM (non-relativistic)	(2) central eqn of classical mech.
(2) general time independent form $i\hbar\frac{\partial\psi}{\partial t} = \hat{H}\psi$	(2) general form $\vec{F} = \frac{d\vec{p}}{dt}$
(3) describes wave & particle prop. of matter	(3) only particle properties
(4) obeys principle of linear superposition	(4) does not fit into that context
(5) energy eqn	(5) force eqn
(6) scalar eqn	(6) vector eqn
(7) applies to micro and macroscopic scales	(7) only macroscopic
(8) Newton's second law of motion can be derived from Schrodinger's eqn	(8) vice versa not possible

⑧ Application of schrodinger's eqn:

(1) free particle

(2) Infinite potential well / particle in a box

⑨ schematic rep. for E, ψ and $|\psi|^2$:



(a) energy states

(b) wave function

(c) probability

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⑩ Quantum Computing:

- Richard Feynman, a Nobel Laureate suggested the use of QM concepts for computer algo.
- a quantum computer is that machine which utilizes quantum mechanical effects such as superposition or quantum entanglement to improve computational power.
- advantages:
  1. encode more information
  2. powerful
  3. massively parallel
  4. can easily crack secret codes
  5. fast in searching databases
  6. hard computational problems become tractable
- Qubit: Basic unit in a quantum computer (the same way bit is to classical computers) rep. by multiple ways:
  eg. ground state (0), excited state (1) [of an ion.]
  [e^- or nucleon] → spin state up(1), down(0)
  [photon] → left polarized (1), right pol. (0)

In QM, these base states are rep. by vectors in 2^n dimensional space where n is size of the computer word.

The qubit with two possible states is rep. as.

$$|\psi\rangle = a|0\rangle + b|1\rangle \quad -①$$

(a combination of such qubits in superposed state will also be in a superposed state).

$|\ \rangle$ → (notation) → 'ket' vector. (column matrix)
popularly called as 'Dirac's notation'.

The output is probabilistic and probability amplitude in the example ① will be $a^2 + b^2$ for a particular output.

- Quantum Hardware:
  1. Quantum dot: consists of an e^- trapped in a cage of atoms. such e^- possess discrete energy levels. ground state (0), excited state (logic 1) laser source is used as gate (control)
  2. Ion trap: uses some ions such as Ca. Ca ion (atom in ground state (logic 0), metastable state (logic 1)
  3. NMR: qubits are rep. by nuclear spin states using nuclei of certain elements. A magnetic field is used as gate.

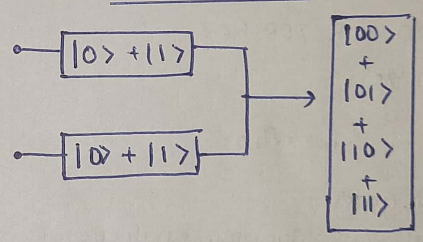
→

- Classical vs Quantum computers

Classical	Quantum
(1) uses semiconductor based CMOS logic gates	(1) may use atomic, electronic, nuclear or photonic properties
(2) ON/OFF state of CMOS transistor determines logic 1/0	(2) logic 1/0 rep. by spin up/down, ground state/excited state, right/left pol, etc.
(3) Bit can be 1 or 0 at specific time	(3) Bit (qubit) can be both 1 and 0 at a specific time
(4) processor executes bit by bit operation	(4) processor operates on all bits simultaneously.

- major sectors: (adv.)
  1. cryptography
  2. big data analysis
  3. astronomical computations
  4. weather models
  5. finance
  6. e-commerce

- Quantum Register.



(single computational step)

- Quantum logic gates: basic building blocks of Quantum computers
- Quantum circuit: model of quantum computation in which a computation is sequence of quantum gates, measurements, initialization of qubits, etc.

OR

a combination of diff. logic gates to perform a computational task.

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Qubit operations:

state $0 \equiv |0\rangle$, state $1 \equiv |1\rangle$

$|0\rangle \equiv \begin{bmatrix} 1 \\ 0 \end{bmatrix}$, $|1\rangle \equiv \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

$|0\rangle \rightarrow$ transforms to $\rightarrow \langle 0|$ (conjugate)

$|q\rangle \rightarrow |q\rangle^{*T}$ $T \rightarrow$ transpose.

$*$ complex conjugate

$|q\rangle^{+} = \langle q|$

Qubit addition / sub; qubit multiplication

Conjuge state $+ = *T$

$|q\rangle$ $|p\rangle \rightarrow$ state vector.

conjugate state $\langle q|$ $\langle p|$

non-commutative property (vector product)

$AB \neq BA$

$\langle p|q\rangle \neq |q\rangle\langle p|$

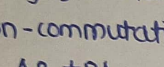
Superposed state: $|\psi\rangle$

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

$\alpha, \beta \rightarrow$ arbitrary constants

Logic gates:

AND, OR, NAND, NOR, XOR, NOT.



b = 1	0
0	1

} bit-flip

Quantum Logic gates:

① Pauli X gate (σ_x : quantum analogue of NOT gate)

$$\sigma_x = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

② Pauli Z gate (σ_z)

$$\sigma_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

③ Hadamard gate (H)

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

④ CNOT gate: $|q_1, q_2\rangle$

$q_1 \rightarrow$ control bit, $q_2 \rightarrow$ data bit

Operation: if $q_1 = 1$, flip data bit q_2

$q_1 = 0$, don't change data bit q_2

* special superposed states:

$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) = |+\rangle$

$\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = |-\rangle$

Formulae (for numericals).

(1) $\lambda = \frac{h}{mv} = \frac{h}{p}$

(2) $\lambda = \frac{h}{\sqrt{2mE}}$

(3) $\lambda = \frac{h}{\sqrt{2mqV}}$

(4) $\lambda = \frac{h}{\sqrt{2meV}}$ (for e^-)

(5) $E = \frac{hc}{\lambda}$, $KE = \frac{p^2}{2m}$

(6) % uncertainty in momentum $= \frac{\Delta p}{p}$

$\Delta p = \frac{\hbar}{\Delta x}$ ($\hbar = 1.05 \times 10^{-34}$)

$p = mv$.

$\Delta x . \Delta p = \hbar$

$\Delta E . \Delta t = \hbar$

(7) $\Delta E . \Delta t = \hbar$

$\hbar \Delta \nu . \Delta t = \hbar$

$\hbar = \frac{h}{2\pi}$

(8) $P = \int_{L_1}^{L_2} |\psi(x)|^2 . dx$

(9) $\psi(x) = \sqrt{\frac{2}{L}} . \sin \frac{n\pi x}{L}$

ground state $n = 1$.

(10) normalization condition:

$P = \int_{L_1}^{L_2} |\psi(x)|^2 . dx = 1$

(11) Energy $= \frac{h^2 n^2}{8mL^2}$ (one D Quantum well)

(12) momentum $p = \sqrt{2mE}$

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ELECTROMAGNETISM AND PLASMA THEORY

(I) PLASMA:

- fourth state of matter, greek word - 'plasma' meaning 'jelly' or 'moldable substance' - Sir William Crookes (1879) - named as 'radiant matter' - Irving Langmuir (1927) studied ionized gas and gave new state of matter 'plasma' - more than 99% of mass of universe is plama state - it is a hot ionized gas consists approx. equal nos. of +ve ions and free - e⁻s resulting in more or less no. overall charge
- when a gas is heated enough ($T > 100{,}000°C$), that the atoms collide with each other and knock their e⁻s off and in this process a mixture of ions, e⁻'s and neutral atoms is formed - plasma.
- when solid heated sufficiently that thermal motion of atoms break crystal lattice apart - liquid
- liq. crystal heated enough that atoms vaporize off the surface faster than they recondense - gas
- solid: - tightly packed, regular pattern, vibrate, do not move from place to place

  liquid: close together, no regular arrangement, vibrate, move about and slide past each other

  gas: separated, no regular arrangement, vibrate, move freely at high speeds.

  plasma: no definite vol. or shape, composed of electrical charged particles

- characterization of plasma:

(i) electron temperature:

- a classical plasma in thermal equilibrium has particles of all velocities and vel. distribution of these particles is known to be Maxwellian. maxwell's distribution is given by, (one-d)

$$f(u) = A \cdot \exp\left(\underbrace{-\frac{1}{2}mu^2}_{KE} / k_B T\right) \quad -①$$

$f(u)$ → no. of particles per unit volume with velocity b/w u and $u+du$

k_B → 1.38×10^{-23} J/K

$$n \text{ (no. of particles per unit volume)} = \int_{-\infty}^{\infty} f(u).du$$

$$A = n\left(\frac{m}{2\pi k_B T}\right)^{1/2} \quad -②$$

$$E_{av} = \frac{\int_{-\infty}^{\infty} \frac{1}{2} mu^2 f(u).du}{\int_{-\infty}^{+\infty} f(u).du} \quad -③$$

$$E_{av} = \frac{1}{2}k_B T. \quad -④$$

$$A = n\left(\frac{m}{2\pi k_B T}\right)^{3/2} \text{ and } E_{av} = \frac{3}{2}k_B T. \quad -⑤$$

→

absolute temp. of 1eV plasma

$k_B T = 1eV = 1.6 \times 10^{-19}$ J

or $T = 11600K$.

$\therefore 1eV = 11600K$.

each component of plasma can have temp. of its own that maybe diff. from each other - it is cuz of fact that collission rate among e⁻ or ions themselves is larger than rate of collision b/w an e⁻ & an ion. as a result, e⁻ and ions can have separate Maxwellian dist. with diff. temp. T_e and T_i. Plasma may not last long for two temp. to equalize. In presence of magnetic field, even a single species, say e⁻s, can have two diff. temp, cuz force acting on e⁻ along mag. field is diff than that acting normal to mag. field. as a result, the components of vel. ∥ & ⊥ to mag. field may belong to diff. Maxwellian distributions with temp. $T_{\parallel}$ and $T_{\perp}$.

(ii) charge particle number density / degree of ionization:

- plasma contains e⁻, ions, neutral particles
- plasma behaviour is determined by density of charge particles relative to neutral particles. this relative density of charged particles in plasma is desc. by parameter called d.o.i.
- the fractional ionization to be expected in a gas in thermal eq. is given by Saha eqn:

$$\frac{n_i}{n_n} \approx 2.4 \times 10^{21} \cdot \frac{T^{3/2}}{n_i} \exp\left(-\frac{u_i}{k_B T}\right) \quad -①$$

n_i, n_n → densities (number per m^3) of ion & neutral

T → temp (in K)

u_i → ionization energy of gas.

- rate of ionization increases with temp T, an ionized atom may recombine with an e⁻ to become neutral again, recombination rate will increase & ion density will decrease with increase in density of e⁻s, which we can take equal to n_i. it explains appearance of factor n_i^{-1} on rhs of ①.
- ∴ d.o.i depends on temp as well as density of gas
- for ordinary air at room temp., $k_B T << u_i$ - fractional ionization given by ① is extremely low.
- fractional ionization becomes significant only when $k_B T$ becomes comparable to u_i, then n_i/n_n rises abruptly and gas is in plasma state. thus, plasma exists in astronomical bodies with very high temp. the interstellar plasma medium owes its origin to low value of n_i and hence low recombination rate

→

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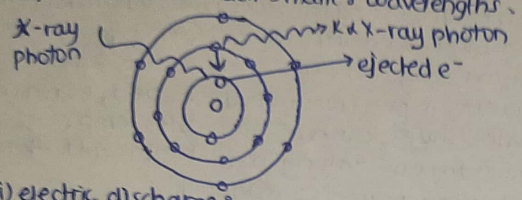
- how to create plasma: (in lab)

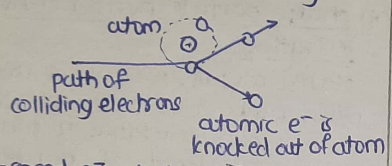
(i) photoionization:

- occurs by absorption of incident photons whose energy is equal to or greater that ionization potential of absorbing atom.
- excess energy of photon is transformed into K.E. of e^--ion pair formed.
- it can also be produced by X-rays or (γ) gamma rays, that have much smaller wavelengths.



(ii) electric discharge:

- an electric field is applied across the ionized gas, that accelerates free e^-s to energies sufficiently high to ionize other atoms by collisions.



- when a high-speed e^- collides with an e^- bound to nucleus, it can give both e^- enough energy to escape. Thus, ionization is occurred.

- waves in plasma:

- interconnected set of particles and fields which propagate in a periodically repeating fashion.
- due to its electrical conductivity, a plasma couples to electric and magnetic fields. this complex of particles & fields supports a wide range of wave phenomena.
- electromagnetic fields in a plasma are assumed to have two parts, one static/equilibrium part and one oscillating / perturbation part.
- depending on oscillation of magnetic field, plasma waves can be classified into electromagnetic or electrostatic.
- when Faraday's law of EMI is applied then it's found that electrostatic waves are purely longitudinal whereas electromagnetic waves may be longitudinal and transverse both.

- how to contain plasma:

- due to extreme heat of most plasmas, conventional materials cannot be used to contain it.
- plasma is an excellent conductor and hence magnetic fields are used to contain high-density, high-temp. plasmas cuz such fields exert pressures and tensile forces on plasma

→

- classification of plasmas:

- The D.O.I. of plasma is the proportion of charged particles to the total no. of particles including neutrals and ions.

$$D.O.I.(\alpha) = \frac{n_i}{n_i + n_n}$$

n_i → no. density of ions
n_n → no. density of neutral atoms

depending on D.O.I. it is classified as:

(1) fully ionized plasma: D.O.I. approaching 1 (i.e. 100%)

eg. solar wind (interplanetary medium), stellar interiors (sun's core), fusion plasmas

(2) partially ionized plasma: D.O.I. < 1

eg. ionosphere, gas discharge tubes

- plasmas in nature:

① space: stars, coronas, solar wind, star nurseries, interstellar nebulae.

② terrestrial: fire (hotter than 1500°C), lightning, ionosphere, magnetosphere, plasmasphere, polar wind, sprites.

③ artificial: TV screen, neon signs, fluorescent lamps, rocket exhaust, ion thrusters, plasma ball, fusion test reactor, laser produced plasma, arcs produced by tesla coils.

- future of plasma:

- challenge is to create high temp. in controlled manner to harness energy of nuclear fusion.
- practical goal is to produce nuclear fusion on earth.
- Fusion Test Reactor (FTR) - charged gas to confine it with magnetic fields & to heat it to temp. hotter than core of sun.
- other researchers persue plasmas for making computer chips, rocket propulsion, cleaning environment, destroying biological hazards, healing wounds and other applications.

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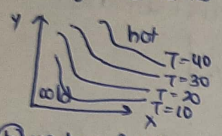
(2) ELECTROMAGNETISM:

① Fields:

- a region of space where some physical qty takes diff. values at diff. points in the region.
- at each pt. of region, there exists a corr. value of physical qty.
- it is a mathematical function of posn and time
- ⓐ scalar field: if value of a physical qty at each pt. is scalar qty.

  eg. temp.

  (a temp of body changes pt. to pt. in complex way and varies with time 't', function of x, y, z)



ⓑ vector field: physical qty at each point is a vector qty. it has mag & dirn.

- associated with each pt. in region varies from pt. to pt.

eg. flow of liq in constricted pipe

② operator Del ($\vec{\nabla}$):

$$\vec{\nabla} = \hat{i}\frac{\partial}{\partial x} + \hat{j}\frac{\partial}{\partial y} + \hat{k}\frac{\partial}{\partial z}$$

↓

vector operator, possesses all properties of an ordinary vector.

can be operated on scalar and vector.

- operated on scalar field → Gradient → vector (gives)

  vector via dot product → divergence → scalar

  vector via cross product → curl → vector

③ Gradient of a scalar field: (directional derivative)

it gives the direction of max. change in ϕ.

- meaning: if a surface $\phi(x,y,z) = c$ passes through point P, then value of function at each point on surface is same as P. such a surface is called level surface through P. Two level surfaces cannot intersect.

(refer the derivations)

④ Fundamental theorems and continuity equation:

(a) Gradient: $\int_a^b (\vec{\nabla}\phi)\, d\vec{l} = \phi(b) - \phi(a)$

(b) Divergence: $\int_V (\vec{\nabla}\vec{v})\, dv = \int_{surface} \vec{v}\cdot d\vec{s}$

(c) curl: $\int_{surface} (\vec{\nabla}\times\vec{v})\cdot d\vec{s} = \int_{line} \vec{v}\cdot d\vec{l}$ (stoke's theorem)

(d) continuity equation: $\vec{\nabla}\cdot\vec{J} + \frac{\partial \rho}{\partial t} = 0.$

⑤ Electric field:

- a region of space around a charge in which any other charge experiences force of attraction or repulsion.

it is measured in terms of vector qty. called electric field Intensity ($\vec{E}$)

- the electric f. intensity of a charge at any point (P) is defined as force acting on unit +ve charge at that point.

$$\vec{E} = \frac{\vec{F}}{q_0} \quad \text{unit: N/C}$$

for a point charge q, $\vec{I}$ at distance 'r'

$$\vec{E} = \left(\frac{1}{4\pi\varepsilon_0\varepsilon_r}\right)\frac{q}{r^2}\cdot\hat{r}$$

↳ unit vector

in magnitude;

$$E = \left(\frac{1}{4\pi\varepsilon_0\varepsilon_r}\right)\left(\frac{q}{r^2}\right)$$

⑥ Electric field due to continuous charge distribution:

ⓐ for line charge: $\lambda = \frac{dq}{dl} \rightarrow dq = (\lambda)dl$

$$q = \int_{line} \lambda\, dl \qquad (\lambda \rightarrow \text{linear charge density})$$

$$\vec{E} = \left(\frac{1}{4\pi\varepsilon_0\varepsilon_r}\right)\int_{line} \frac{\hat{r}}{r^2}\lambda\, dl$$

ⓑ for surface charge: $\sigma = \frac{dq}{ds} \rightarrow dq = \sigma\, ds$

$$q = \int_{surface} \sigma\, ds \qquad (\sigma \rightarrow \text{surface charge density})$$

$$\vec{E} = \left(\frac{1}{4\pi\varepsilon_0\varepsilon_r}\right)\int_{surface} \frac{\hat{r}}{r^2}\sigma\, ds$$

ⓒ for volume charge: $\rho = \frac{dq}{dv} \rightarrow dq = \rho\, dv$

$$q = \int_{vol} \rho\, dv$$

$$\vec{E} = \left(\frac{1}{4\pi\varepsilon_0\varepsilon_r}\right)\int_{vol} \frac{\hat{r}}{r^2}\rho\, dv.$$

⑦ gradient properties:

if A and B are two scalars,

1) $\nabla(A \pm B) = \nabla A \pm \nabla B$
2) $\nabla(AB) = A(\nabla B) + B(\nabla A)$

⑧ directional derivative:

DD of ϕ in direction of a is $\frac{d\phi}{ds} = \hat{a}\cdot \text{grad}\,\phi$

where $\hat{a} = \frac{dr}{|dr|}$

↳ unit vector in direction of dr.

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⑨ Gradient of a scalar field:

- a unique vector field whose dot product with any vector v at each point x is directional derivative of f along v.

$$(\nabla f(x)) \cdot v = D_v \cdot f(x)$$

⑩ divergence:

- vector operator that measures magnitude of a vector field's source or sink at given point, in terms of signed scalar.
- it represents vol. density of outward flux of a vector field from an infinitesimal volume around a given point.

$$\text{div } A = \nabla \cdot A.$$

⑪ curl of a vector:

- vector operator that describes infinitesimal rotation of a 3D vector field, at every pt. in field, curl of that pt. is rep. by a vector, the attributes of vector (length & direction) characterize rotation at that point)
- the dirn of curl is axis of rotation, determined by right hand rule. and mag. of curl is mag. of rotation.

⑫ - field with null div → solenoidal field
field with null curl → irrotational field.

- div. of curl of any vector A must be zero.

$$\nabla(\nabla \times A) = 0.$$

(a curly field must be a solenoidal field)

- curl F = 0, F is irrotational vector.
if F is irr., then there exists a scalar point function ϕ such that $F = \nabla\phi$ (ϕ is scalar pot of F)

work done in moving object from P to Q in irr. field

$$[\phi]_P^Q = \phi(Q) - \phi(P)$$

curl signifies angular vel. or rotation of body

⑬ for irr. or conservative field

$$\bar{\nabla} \times \bar{F} = 0$$

for solenoidal field

$$\bar{\nabla} \cdot \bar{F} = 0$$

⑭ electric potential: scalar qty. used to measure strength of charge at a given point.

- defined as work done to bring unit +ve charge from ∞ to given point.
- defined as qty whose rate of change in any dirn is electric intensity in that direction.

⑮ magnetic field:

- space in which a moving charge experiences a velocity dependent force
- science of time-independent magnetic fields caused by steady currents is magnetostatics
- in 1819, Oersted observed that a current carrying wire produces magnetic field around it. this phenomenon is called Magnetic Effect of electric current.

⑯ Gauss's law in differential form: $\bar{\nabla} \cdot \bar{E} = \frac{1}{\varepsilon_0} \rho$.

⑰ For an electrostatic field, curl vanishes

$$\bar{\nabla} \times \bar{E} = 0 \text{ ie. } \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \partial/\partial x & \partial/\partial y & \partial/\partial z \end{vmatrix}$$

For a magnetic field, divergence is zero

$$\bar{\nabla} \cdot \bar{V} = 0$$

⑱ Electric field is related to electric potential through eqn: $\bar{E} = -\bar{\nabla} V$

⑲ irrotational or conservative field: $\bar{\nabla} \times \bar{F} = 0$
solenoidal field: $\bar{\nabla} \cdot \bar{F} = 0$

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SENSORS

① **measurement:** an imp subsystem (mechanical or electronic) consists of actuators, sensors, signal processing devices, transducers. - used in systems that perform specific tasks, communicate with real world

② **sensors:** device that receives and responds to a signal. once sensor detects one or more input signals, it converts it into analog or digital rep. of input signal.
Devices that perform 'input' function are called sensors.

③ **actuators:** device that converts energy into motion or mechanical energy
it is a specific type of transducer
Devices that perform 'output' func are called actuators

④ **Transducer:** a device which converts one form of energy to another.
input - physical, output - electrical → sensor
input - electrical, output - physical → actuator.
eg. microphone converts sound waves to electrical signals.
loudspeaker converts electrical signals to sound waves

⑤ **selection criteria:**
① range → diff b/w max & min value of sensed parameter
② resolution → smallest change sensor can diff.
③ accuracy → diff b/w measured & true value
④ precision → reproduce repeatedly with accuracy
⑤ sensitivity → ratio of change in output to a unit change in input
⑥ resonance → freq. at which output magnitude peak occurs.
⑦ operating temp → range in which sensor performs as specified.
⑧ deadband → range of input for which there is no output
⑨ signal to noise ratio → ratio b/w mag. of signals and noise at output
⑩ response time → speed of change in output on a step-wise change of measurand. it is always specified with an indication of input step and output range for which resp. time is defined.

→

⑥ **characterization of sensors:**
① Thermal (temp, heat)
② electrical (res, current, vol, inductance)
③ magnetic (mag. flux density, mag moment)
④ optical (wavelength, pol, intensity of light)
⑤ chemical (pH, concn., composition)
⑥ pressure (pressure, force)
⑦ vibration (disp, accln, vel)
⑧ rain/moisture (water, moisture)
⑨ tilt (angle of inclination)
⑩ speed (vel, distance)

⑦ **Two main types of sensors in IOT applications:**
(1) passive → detect change in env. without any dedicated power supply (eg. temp)
(2) active → require some power to function (eg. battery)

passive	active
- no external power req	- req.
- used to detect energy when naturally occurring energy is available	- own energy source for illumination
- no interference prb.	- less interference prb
- operate in same env. condn	- diff env. condn
- sensitive	- not sensitive
- not suited for darkness	- suited
- difficulties in interpreting output signals	- easy to interpret
- less control of noise	- better control
- low price	- high price
- eg. camera, sonar, etc.	- eg. LASER, radar, etc.

⑧ **popular IOT sensors:**
Temp, humidity, fire detection, light, gas detection, proximity, soil moisture, smart packing, flood detection, health monitoring, IR, chemical sensors.

⑨ **mechanical sensors:**
sensitive to changes in mechanical properties.
① **Pressure sensors:** measures a physical change that happens, as a rn to pressure differences. these physical changes are converted to electric signals.
ⓐ **Piezoelectric pressure sensors:**
- piezoelectric effect.
- piezoelectric materials used include quartz, potassium sodium tartrate, dihydrogen phosphate
- measurement of accln and pressure, force.
- mea. of vibration and shock in airplanes, ships, bridges, buildings, aviation esp.

→

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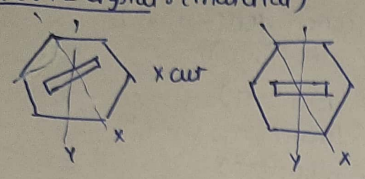
Piezoelectric effect: ability of certain materials to generate an electric charge in response to applied mech. stress.

Inverse P.E: electrical energy is applied to make a crystal expand. the main function of this effect is to convert electrical energy to mechanical energy

Quartz crystal: (material)



X-axis: electrical axis
Y-axis: mechanical axis
Z-axis: optical axis

Xcut crystal: → face ⊥ar to X-axis. produces longitudinal waves of few kHz.

Ycut crystal: → face ⊥ar to X-axis. produces transverse waves of order of MHz.

(b) **magnetostriction effect**:
- property of a ferromagnetic material causes them to expand or contract in response to mag. field.
- allows magnetostrictive materials to convert electromagnetic energy to mechanical energy.
- as mag. field is applied to material, its molecular dipoles and mag. field boundaries rotate to align with field. this causes material to strain and elongate.

• **strain gauge pressure sensors**:
- working principle of metal res. strain gauge is that resistance of strain res. adsorbed on base material changes with mechanical deformation. effect is known as resistance strain effect.
- res. strain gauge is a sensitive device that converts strain change on test piece to an electrical signal.

(2) **Motion sensors**:

(a) **PIR (Passive Infrared)**: include thin pyroelectric film material that responds to IR radiation by emitting electricity. , indoor alarms.

(b) **ultrasonic sensor**: emit ultrasonic sound waves above range of human hearing, waves bounce off and return to motion sensor.

(c) **microwave sensor**: emit microwave pulses. waves bounce off and return to sensor, cover larger area than PIR sensors, but more susceptible to electronic interference.

(d) **tomographic sensor**: sense disturbances to radio waves as they pass from node to node of a mesh network. detect over large areas as they sense through obstructions.

• **producing ultrasonic waves**:

US waves (properties):
- high energy content
- reflects, refracts and gets absorbed
- large dist. transmission with no appreciable loss of energy.
- produce intense heating effect when passed thru. a substance.

Production of US waves:
(1) magnetostriction generator / oscillator
(2) piezo-electric generator / oscillator

(10) **Environmental sensors**:

(1) **Temp. sensors**: measure amt. of energy in form of heat and cold produced by object & system.

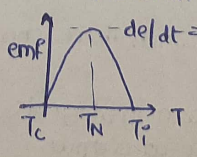
Types:

(a) **Thermostat**: kind of contact temp. sensor employing an electro-mechanical component
- using two diff kinds of metals, copper, nickel, tungsten, aluminium, etc. stuck together to form a Bi metallic strip.
- when cold, one strip contracts and contacts closed, current passes.
- when hot, one metal strip expands, opens, stop flow of current.

(b) **Thermistor**: electrical res. changes as object temp. changes.
- combination of thermal resistors.
- semiconductors materials or metallic oxides pressed into bead / disk / cylinder and encapsulated with an impermeable material like epoxy or glass
- temp ↑↓, resistance ↑↓
- used for precise temp. measurement, control and compensation.

(c) **Thermocouple**: used for measurement of temp. variation in measurement of sensors.
- two metals joined together to form a junction. (hot junction, cold junction)
- based on Thomson, Seebeck, Peltier effect.
- broadest range of temp. sensors (−200°C to 2000°C)

• **Seebeck effect**: if one junction of metal pair is kept hot and other is cold, galvanometer shows deflection - emf generated - thus produced is thermo emf and resulting current is thermoelectric current.
- phenomenon of generation of emf in a thermocouple when two junctions are at diff. temp.



$$E = at + \frac{bt^2}{2}$$

at T_N; $\frac{de}{dt} = 0$

$$\therefore a + bt = 0 \longrightarrow t = -a/b$$

- **seebeck coeff**: performance is determined by S.C. 'a' and 'b' are constants ~~that~~ depend on particular pair.

$a \rightarrow \mu V/°C$, $b \rightarrow \mu V/°C^2$, $de/dt \rightarrow$ thermoelectric power

- **Neutral Temp (t_n)**: temp diff. beyond which thermo emf starts decreasing $t_n = -a/b$
- **temp. of inversion (t_i)**: temp. diff. at which current is zero, temp. beyond which dirn of current changes

$T_n = (T_i + T_c)/2$

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② **Humidity sensor:**

- humidity – amount of water present in surrounding air.
- hygrometer – measures humidity (device)
- non-electrical qty. that is converted to electrical by using resistance, capacitance, impedance properties
- used in agriculture, medical, env. monitoring
- **types:**

① **resistive:** main element is material whose resistance changes with change in humidity or relative humidity.
- wire / electrode coated with hydroscopic salt (LiCl) can be used.

② **crystal hygrometer:** crystals coated with hydroscopic materials.
- crystals are used as freq. determination elements in oscillator, if humidity changes, freq. changes.
- freq. changes due to humidity as mass of crystal changes with amt. of water absorbed by coating

③ **microwave refractometer:** has two cavities, each coupled with klystron, a material that produces microwaves in which one cavity is filled with dry air and other cavity is filled with mixture whose humidity is to be measured.

④ **capacitive hygrometer:** changes are caused by changes in capacitance.
- dielectric material is used.
- hydroscopic material that exhibits change in dielectric constant with change in humidity.
- such hydroscopic material or salt can be used in construction of ch.

⑤ **aluminium oxide hygrometer:** in c.H. type, al. ox. is coated on anodized al. and this al. exhibits change in dielectric constant wrt changes in humidity.
- change can be measured by bridge or electric method.

(11) **Electro-Optic Sensors:**

Types → UV detectors, IR, optical, microwave, radio, radiation and particle detectors

① **IR sensors**

- Thermal sensors
  - Thermistor / Bolometer
  - Thermo-couple / Thermopile
  - Pyroelectric
- Photon sensors
  - photoconductive detectors
    - photodiodes
    - phototransistors
  - photovoltaic detectors → solarcells

Pyroelectric detectors:

alignment / separation of bound charges when temp varies. (depending upon substance)

photon sensors:

① **photoconductive:** change in current due to light
- reverse biased
- types: photodiodes, phototransistors

② **photovoltaic:** generation of voltage due to light
- zero biased mode
- types: solarcells

• **photodiodes:**

PN normal P-n junction diode

PIN broad undoped region b/w P and N sides

APD: Avalanche photodiode

SPD: schotky photodiode or metal-semiconductor diode

- **parameters:**

responsivity → ratio of photocurrent generated to incident optical power, measures sensitivity of photodiode.

$$R_\lambda = \frac{I_p}{P}$$

total current → $I_{total} = I_{SAT}\left[e^{\frac{qV_A}{k_BT}} - 1\right] - I_p$

$$I_p \text{ (photocurrent)} = \frac{q\eta AP}{h\nu}$$

(η → quantum eff → no. of e⁻-hole pairs gen per no. of photons absorbed)

(P → rad. power density)

- **advantages:**

① high sensitivity ② wide spectral response ③ low dark current ④ fast response time ⑤ low noise ⑥ high quantum efficiency.

- **disadvantages:**

① large size ② temp. dependence ③ power consumption (more power)

- **applications:**

① fibre optics communication ② env sensing ③ automatic brightness control ④ imaging and scanning ⑤ automation ⑥ detection of nuclear radiation

- **materials for PIN photodiodes:**

material	wavelength sensitivity
silicon	190 – 1100
germanium	800 – 1700
indium gallium arsenide	800 – 2600
lead sulphide	1000 – 3500

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② Image sensors:

- conv. light from image to an electronic image
- light patterned and its order has to be preserved to reproduce image, pattern is usually 2D ordered matrix of intensity *.
- unit in which conv. of patterned light to electrical signal occurs is pixel.
- pixel – smallest imaging element in image sensor
- pixel density controls quality of image. (HD, 4K, UHD)
- in appl like holograms, 3rd dim. is recorded by capturing phase of light waves

① CCD (charged coupled device)

adv: ① higher sensitivity
② lower noise
③ simple, robust design
④ cost effective

appl: ① security cam.
② cellphone cam (CMOS CCD)
③ Raman spectroscopy (molecular bonding)

② CMOS (complementary metal-oxide semiconductor)

(refer PDF for diagrams)

Formulae (for numericals):

① $f = \frac{1}{2L}\sqrt{\frac{Y}{\rho}} = \frac{1}{2t}\sqrt{\frac{Y}{\rho}}$

② $T_n = \frac{T_i + T_c}{2}$ (at neutral temp)

③ Thermo emf:

$e = at + \frac{1}{2}bt^2$

↓ diff b/w hot & cold temp.

④ Thermoelectric power:

$P = \frac{de}{dt} = a + bt$

⑤ at neutral temp:

$T_n = \frac{-a}{b}$ as $\frac{de}{dt} = 0$

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