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BEEE102L- Basic Electrical and Electronics Engineering

Module-5 : Optical Properties of Materials

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CONTENT

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- Light scattering (903), attenuation in optical fibers (904);
- Luminescence, phosphors (907), Light Emitting Diode (LED) (912).
- Liquid Colour Display(LCD) (924)
- Electro optic effects (928).

Introduction:

- "Light" as the electromagnetic radiation.
- Wavelengths in the visible range, typically 400 to 700 nm.
- EM waves that can have somewhat shorter or longer wavelengths such as ultraviolet (UV) and infrared (IR) light.
- Today's light wave communications use EM waves with wavelengths of 1300 and 1550 nm; in the infrared.

Optical properties of materials are those characteristic properties that determine the interaction of light with matter; the best example being the refractive index n that determines the speed of light in a medium through $\boldsymbol{v = c/n}$, where v is the speed of light in the medium and c is the speed of light in free space.

The **refractive index *n***, for example, depends on the dielectric polarization mechanisms as well as the wavelength λ. The material's *n*–λ behavior is called the **dispersion relation** and is one of the most important characteristics in many optical device applications.

LIGHT WAVES IN A HOMOGENEOUS MEDIUM

We can treat light as an EM wave with time-varying electric and magnetic fields $\boldsymbol{E_x}$ and $\boldsymbol{B_y}$, respectively, which propagate through space in such a way that they are always perpendicular to each other and the direction of propagation 'z' is as depicted in Figure 9.1.

The simplest traveling wave is a sinusoidal wave, which, for propagation along z, has the general mathematical form

$$E_x = E_0 \cos(\omega t - kz + \phi_0) \ldots\ldots\ldots \text{Eq. 9.1}$$

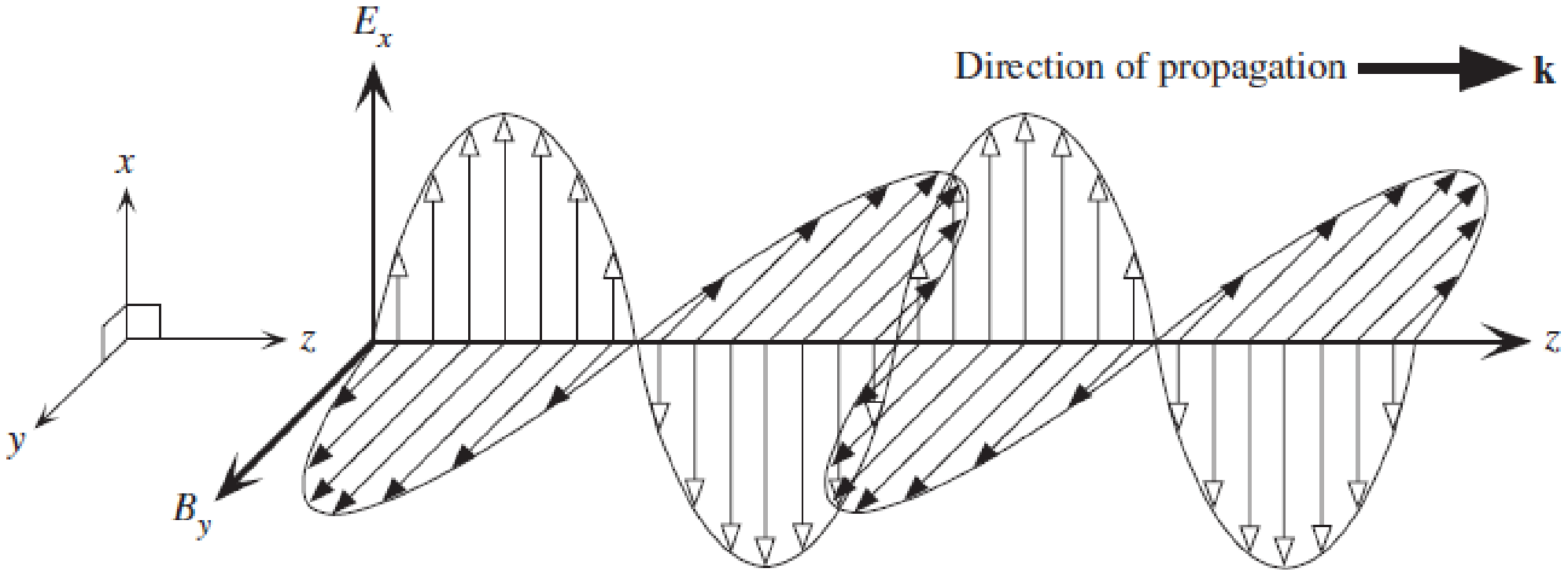


Figure 9.1 An electromagnetic wave is a traveling wave that has time-varying electric and magnetic fields that are perpendicular to each other and the direction of propagation *z*.

In any plane perpendicular to the direction of propagation (along *z*), the phase of the wave, according to Equation 9.1, is constant which means that the field in this plane is also constant. A surface over which the phase of a wave is constant is referred to as a **wavefront.** A wavefront of a plane wave is obviously a plane perpendicular to the direction of propagation as shown in Figure 9.2.

$$E_x = E_0 \cos(\omega t - kz + \phi_0)$$

where E_x is the electric field at position z at time t;

k is the **propagation constant,** or **wavenumber,** given by $2\pi/\lambda$, where λ is the wavelength;

ω is the angular frequency;

E_0 is the amplitude of the wave;

ϕ_0 is a phase constant which accounts for the fact that at $t = 0$ and $z = 0$, E_x may or may not necessarily be zero depending on the choice of origin.

The argument $(\omega t - kz + \phi_o)$ is called the **phase** of the wave and denoted by ϕ.

Equation 9.1 describes a **monochromatic plane wave** of infinite extent traveling in the positive z direction as depicted in Figure 9.2.

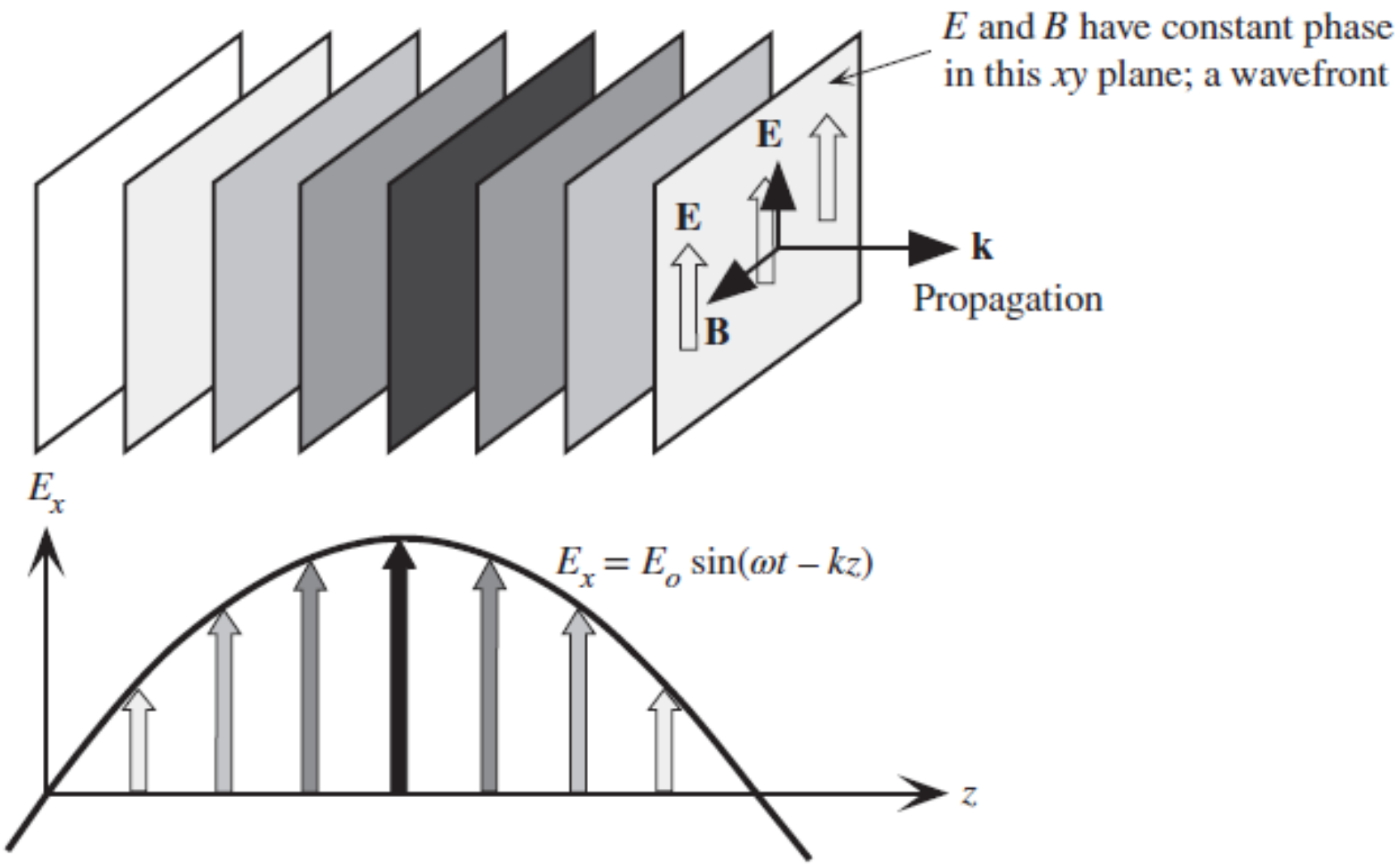


Figure 9.2 A plane EM wave traveling along z, has the same E_x (or B_y) at any point in a given xy plane.

All electric field vectors in a given xy plane are therefore in phase. The xy planes are of infinite extent in the x and y directions.

$$E_x = E_0 \cos(\omega t - kz + \phi_0)$$

Traveling wave along 'z'

In general

$$exp(j\phi) = \cos(\phi) + j\sin(\phi)$$

$$\cos(\phi) = Re[exp(j\phi)]$$

$$E_x(z, t) = \text{Re}[E_o \exp(j\phi_o) \exp j(\omega t - kz)]$$

$$E_x(z, t) = \text{Re}[E_c \exp j(\omega t - kz)]$$

where $E_c = E_0\, exp(j\phi_0)$ is a complex number that represents the amplitude of the wave and includes the constant phase information ϕ_0.

We indicate the direction of propagation with a vector **k**, called the **wavevector,** whose magnitude is the propagation constant $k = 2\pi/\lambda$. It is clear that **k** is perpendicular to constant phase planes as indicated in Figure 9.2.

During a time interval δt, this constant phase (and hence the maximum field) moves a distance δz. The phase velocity of this wave is therefore $\delta z/\delta t$. Thus the **phase velocity** 'v' is

$$v = \frac{dz}{dt} = \frac{w}{k} = f\lambda$$

REFRACTIVE INDEX

When an EM wave is traveling in a dielectric medium, the oscillating electric field polarizes the molecules of the medium at the frequency of the wave. The EM wave propagation can be considered to be the propagation of this polarization in the medium. The field and the induced molecular dipoles become coupled. The net effect is that the polarization mechanism delays the propagation of the EM wave. The stronger the interaction between the field and the dipoles, the slower is the propagation of the wave.

$$Refractive\ index\ (n) = \frac{c}{v} \quad \rightarrow v = \frac{c}{n}$$

$$Phase\ velocity\ in\ any\ medium, \qquad v = \frac{1}{\sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r}}$$

For an EM wave traveling in free space

$$v = \frac{1}{\sqrt{4\pi \times 10^{-7} \times 1 \times 8.854 \times 10^{-12} \times 1}} = 3 \times 10^8\ m/s$$

For an EM wave traveling in a nonmagnetic dielectric medium of relative permittivity ε_r, the phase velocity 'v' is given by

$$v = \frac{1}{\sqrt{\mu_0 \varepsilon_0 \varepsilon_r}}$$

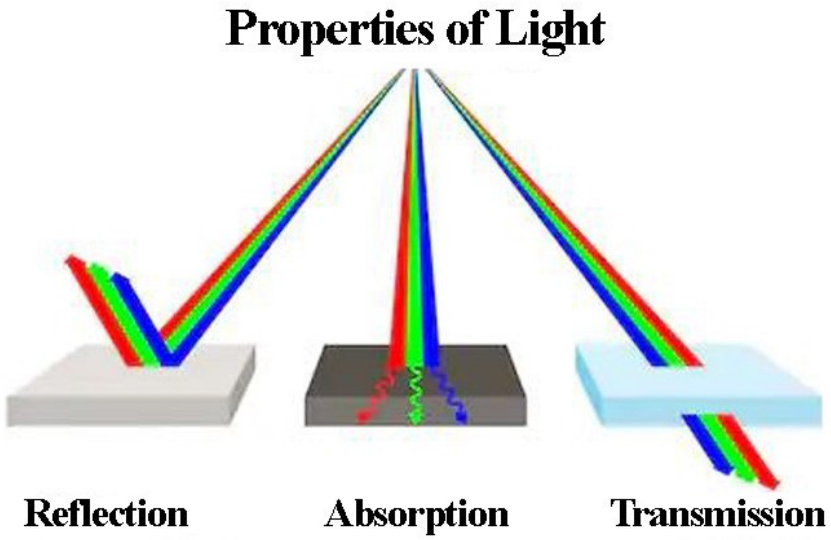
The ratio of the speed of light in free space to its speed in a medium is called the **refractive index** *n* of the medium,

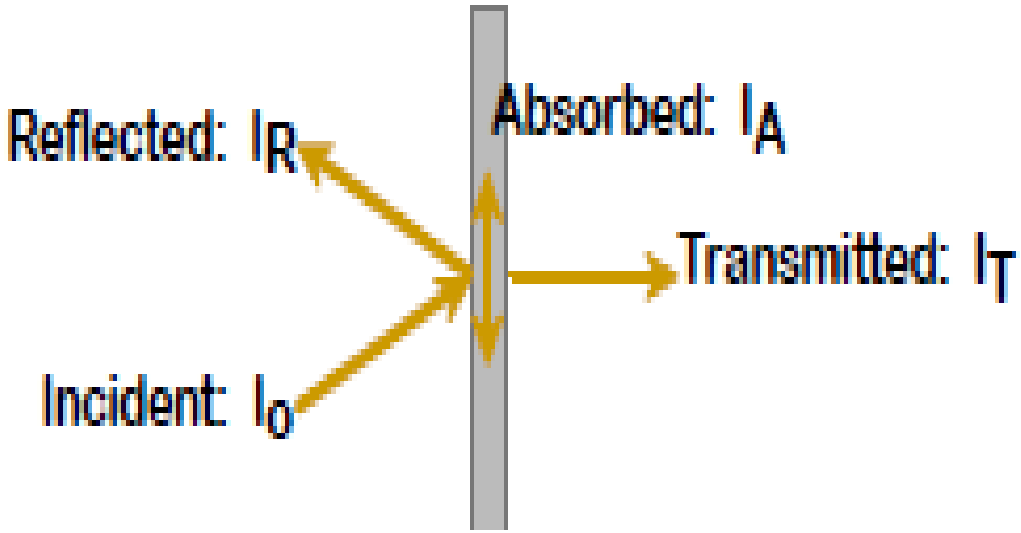
$$n = \frac{c}{v} = \sqrt{\varepsilon_r}$$

Suppose that in free space k_0 is the wavevector ($k_0 = 2\pi / \lambda_0$) and λ_0 is the wavelength,
then the wavevector *k* in the medium will be $\boldsymbol{nk_0}$ and the wavelength $\boldsymbol{\lambda}$ will be λ_0/n.
Indeed, we can also define the refractive index in terms of the wavevector *k* in the medium with respect to that in a vacuum k_0,

$$n = \frac{k}{k_0}$$ **Refractive index**

In free space, the Refractive index is one (1)


Properties of Light
Reflection
Absorption
Transmission


Reflected: I_R
Absorbed: I_A
Transmitted: I_T
Incident: I_0

EXAMPLE 9.2

GaAs DISPERSION RELATION For GaAs, from $\lambda = 0.89$ to 4.1 μm, the refractive index is given by the following dispersion relation,

GaAs dispersion relation

$$n^2 = 7.10 + \frac{3.78\lambda^2}{\lambda^2 - 0.2767} \qquad [9.18]$$

where λ is in microns (μm). What is the refractive index of GaAs for light with a photon energy of 1 eV?

SOLUTION

At $hf = 1$ eV,

$$\lambda = \frac{hc}{hf} = \frac{(6.62 \times 10^{-34}\ \text{J s})(3 \times 10^{8}\ \text{m s}^{-1})}{(1\ \text{eV} \times 1.6 \times 10^{-19}\ \text{J eV}^{-1})} = 1.24\ \mu\text{m}$$

Thus,

$$n^2 = 7.10 + \frac{3.78\lambda^2}{\lambda^2 - 0.2767} = 7.10 + \frac{3.78(1.24)^2}{(1.24)^2 - 0.2767} = 11.71$$

so that $n = 3.42$

Note that the n versus λ expression for GaAs is actually a Sellmeier-type formula because when $\lambda^2 \gg \lambda_1^2$, then A_1 can be simply lumped with 1 to give $1 + A_1 = 7.10$.

Go through EXAMPLE 9.3 and EXAMPLE 9.4 in Kasap Text book

GROUP VELOCITY AND GROUP INDEX

Since there are no perfect monochromatic waves in practice, we have to consider the way in which a group of waves differing slightly in wavelength will travel along the '*z*' direction as depicted in Figure 9.5.

When two perfectly harmonic waves of frequencies $\omega-\delta\omega$ and $\omega+\delta\omega$ and wavevectors $k-\delta k$ and $k+\delta k$ interfere, as shown in Figure 9.5.

They generate a **wavepacket** which contains an oscillating field at the mean frequency ω that is amplitude modulated by a slowly varying field of frequency $\delta\omega$.

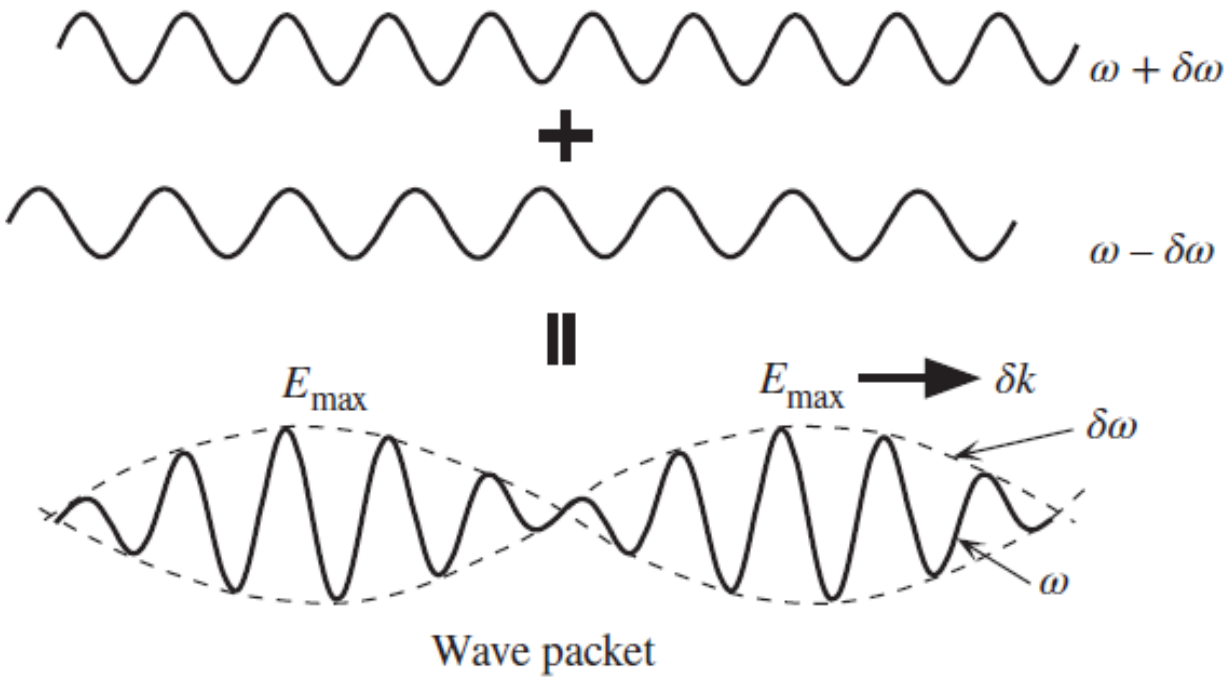


Figure 9.5 Two slightly different wavelength waves traveling in the same direction result in a wave packet that has an amplitude variation that travels at the group velocity.

The maximum amplitude moves with a wavevector δk and thus with a **group velocity** that is given by $\delta\omega / \delta k$, that is,

Group velocity in a vacuum

$$v_g(\text{vacuum}) = \frac{d\omega}{dk} = c = \text{Phase velocity}$$

Group velocity in a medium

$$v_g(\text{medium}) = \frac{d\omega}{dk} = \frac{c}{n - \lambda \dfrac{dn}{d\lambda}}$$

$$v_g(\text{medium}) = \frac{c}{N_g}$$

Group index

$$N_g = n - \lambda \frac{dn}{d\lambda}$$

EXAMPLE 9.6 **GROUP AND PHASE VELOCITIES** Consider a light wave traveling in a pure SiO_2 (silica) glass medium. If the wavelength of light is 1300 nm and the refractive index at this wavelength is 1.447, what is the phase velocity, group index (N_g), and group velocity (v_g)?

SOLUTION

The phase velocity is given by

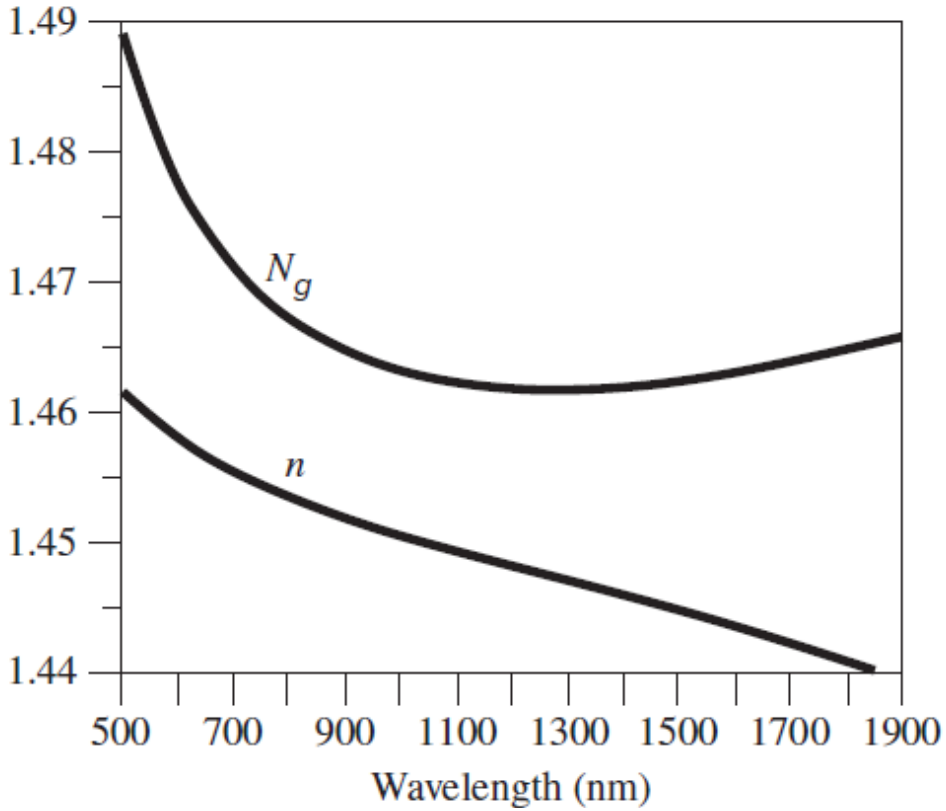


Figure 9.6 Refractive index n and the group index N_g of pure SiO_2 (silica) glass as a function of wavelength.

$$v = \frac{c}{n} = \frac{3 \times 10^8 \text{ m s}^{-1}}{1.447} = 2.073 \times 10^8 \text{ m s}^{-1}$$

From Figure 9.6, at $\lambda = 1300$ nm, $N_g = 1.462$, so

$$v_g = \frac{c}{N_g} = \frac{3 \times 10^8 \text{ m s}^{-1}}{1.462} = 2.052 \times 10^8 \text{ m s}^{-1}$$

The group velocity is ~0.7 percent smaller than the phase velocity.

COMPLEX REFRACTIVE INDEX AND LIGHT ABSORPTION

Generally when light propagates through a material, it becomes *attenuated* in the direction of propagation as illustrated in Figure 9.17.

We distinguish between ***absorption*** and ***scattering*** both of which give rise to a loss of intensity in the regular direction of propagation.

In absorption, the **loss in the power in the propagating EM wave is due to the conversion of light energy to other forms of energy, e.g., lattice vibrations (heat) during the polarization of the molecules of the medium**, local vibrations of impurity ions, and excitation of electrons from the valence band to the conduction band.

Scattering is a process by which the energy from a propagating EM wave is redirected as secondary EM waves in various directions away from the original direction of propagation.

Lossless propagation $E = E_0 \exp j(\omega t - kz)$

- when a monochromatic light wave (E) is propagating in a dielectric medium. As the wave travels through the medium, the molecules become polarized. This polarization effect is represented by the relative permittivity ε_r of the medium.
- If there were no losses in the polarization process, then the relative permittivity ε_r would be a real number and the corresponding refractive index $n = \sqrt{\varepsilon_r}$ would also be a real number.

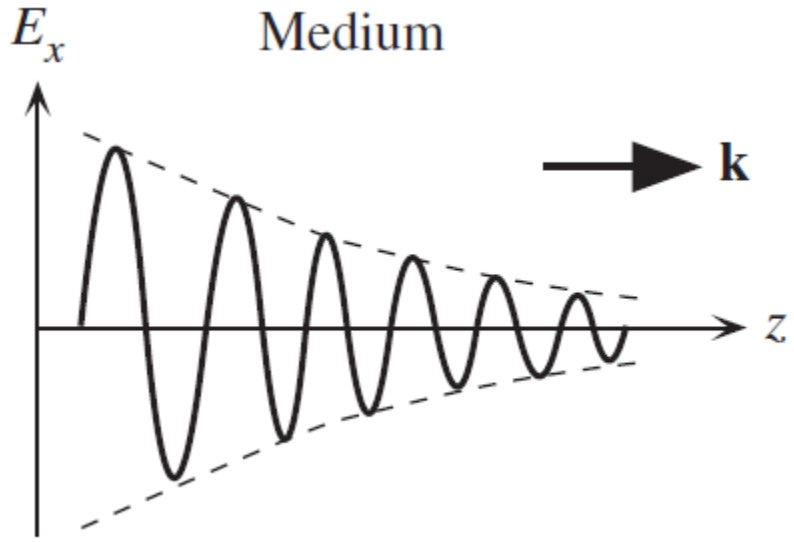


Figure 9.17 Attenuation of light in the direction of propagation.

However, we know that there are always some losses in all polarization processes due to displaced from their equilibrium positions by an alternating electric field and made to oscillate, some of the energy from the electric field is coupled and converted to lattice vibrations ("sound" and heat).

Complex relative permittivity/Dielectric constant $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$

where the real part determines the polarization of the medium with losses ignored and the imaginary part describes the losses in the medium. For a lossless medium, obviously $\varepsilon_r = \varepsilon_r'$.

The loss ε_r'' depends on the frequency of the wave and usually peaks at certain natural (resonant) frequencies. If the medium has a finite conductivity (*e.g.*, due to a small number of conduction electrons), then there will be a Joule loss due to the electric field in the wave driving these conduction electrons. This type of light attenuation is called **free carrier absorption.**

An EM wave that is traveling in a medium and experiencing attenuation due to absorption can be generally described by a **complex propagation constant** k, that is,

$$k = k' - jk''$$

$$E = E_0\, exp(-k''z) \exp j(wt - k'z) \qquad E = E_0 \exp j(\omega t - kz)$$

- The amplitude decays exponentially while the wave propagates along z.
- The **real** k' part of the complex propagation constant (wavevector) describes the propagation characteristics, *e.g.*, phase velocity $v = w/k'$.
- The **imaginary** k'' part describes the rate of attenuation along z.

Suppose that k_o is the propagation constant in a vacuum. This is a real quantity as a plane wave suffers no loss in free space. The **complex refractive index** N with real part n and imaginary part K is defined as the ratio of the complex propagation constant in a medium to propagation constant in free space,

Complex refractive index

$$\mathrm{N} = n - jK = \frac{k}{k_o} = \left(\frac{1}{k_o}\right)[k' - jk'']$$

Refractive index and Extinction coefficient

$$n = \frac{k'}{k_o} \quad \text{and} \quad K = \frac{k''}{k_o}$$

In the absence of attenuation

$$k'' = 0 \qquad k = k' \qquad \text{and} \qquad \mathrm{N} = n = \frac{k}{k_o} = \frac{k'}{k_o}$$

$$\mathrm{N} = n - jK = \sqrt{\varepsilon_r} = \sqrt{\varepsilon_r' - j\varepsilon_r''}$$

By squaring both sides

$$n^2 - K^2 = \varepsilon_r' \qquad \text{and} \qquad 2n\,K = \varepsilon_r''$$

Reflection coefficient

$$r = -\frac{\mathrm{N} - 1}{\mathrm{N} + 1} = -\frac{n - jK - 1}{n - jK + 1}$$

The reflectance is then

Reflectance

$$R = \left|\frac{n - jK - 1}{n - jK + 1}\right|^2 = \frac{(n-1)^2 + K^2}{(n+1)^2 + K^2}$$

which reduce to the usual forms when the extinction coefficient $K = 0$.

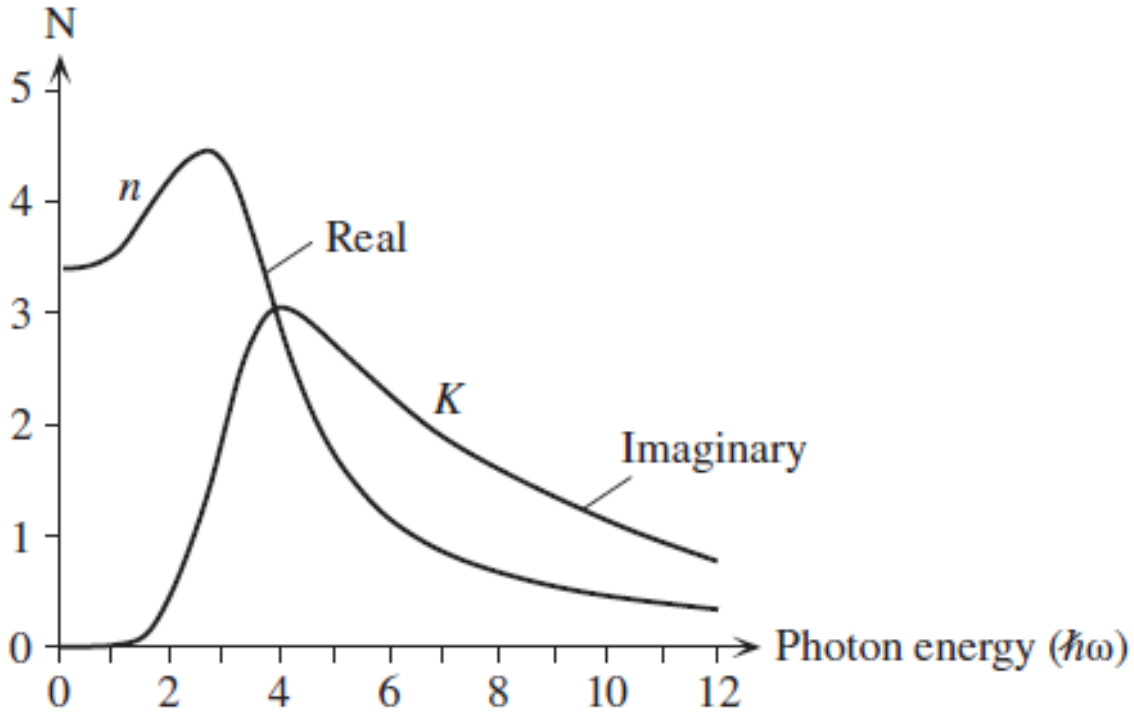


Figure 9.18 Optical properties of an amorphous silicon film in terms of real (n) and imaginary (K) parts of the complex refractive index.

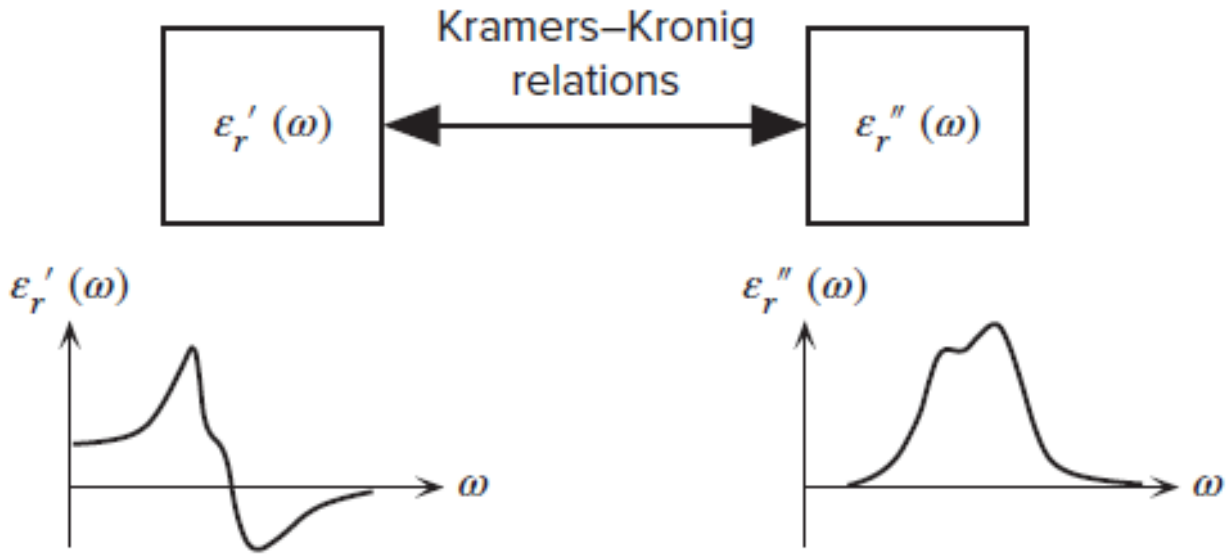


Figure 9.19 Kramers–Kronig relations allow frequency dependences of the real and imaginary parts of the relative permittivity to be related to each other. The material must be a linear system.

LIGHT SCATTERING

Scattering of an EM wave implies that a portion of the energy in a light beam is directed away from the original direction of propagation as illustrated for a small dielectric particle scattering a light beam in Figure 9.25. There are various types of scattering processes.

When a propagating wave encounters a molecule, or a small dielectric particle (or region), which is smaller than the wavelength.

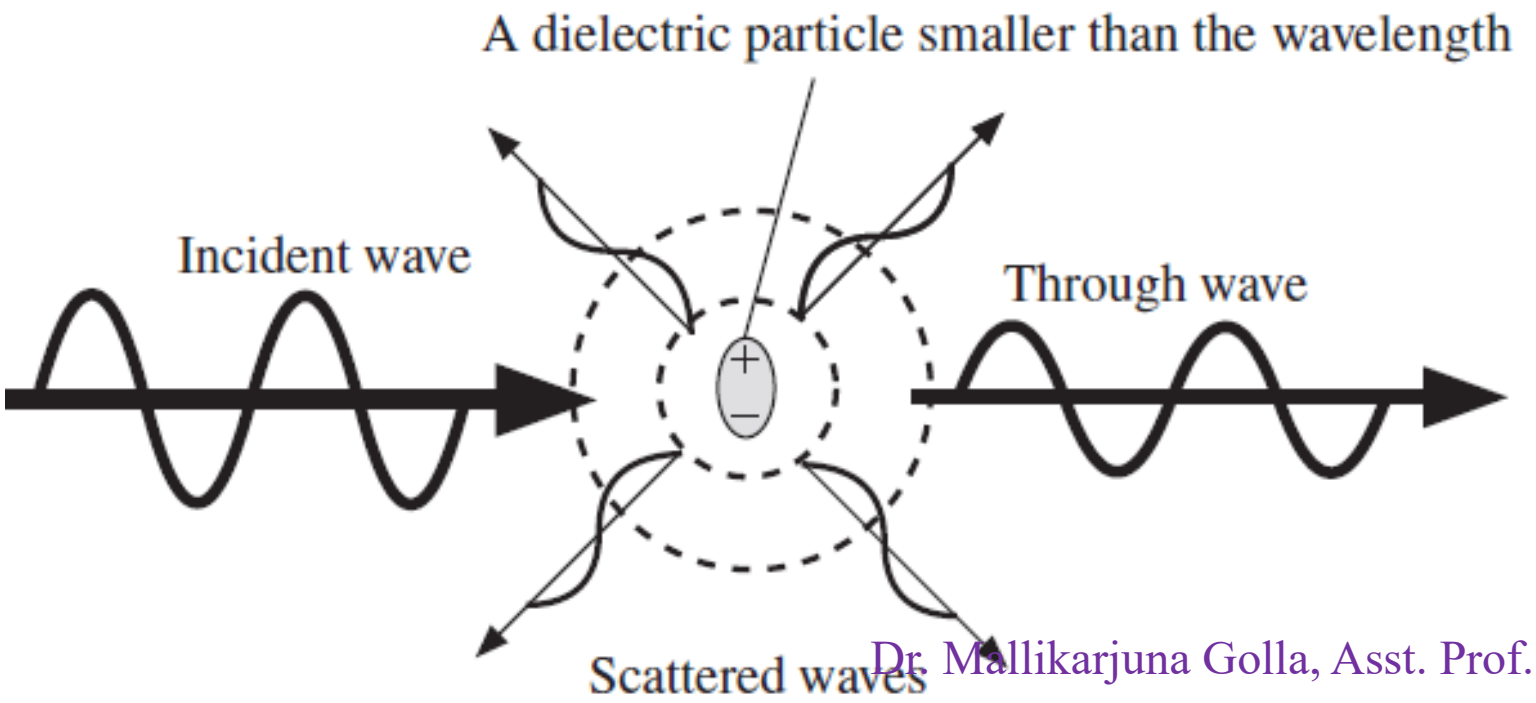


Figure 9.25 Rayleigh scattering involves the polarization of a small dielectric particle or a region that is much smaller than the light wavelength.

The field forces dipole oscillations in the particle (by polarizing it), which leads to the emission of EM waves in "many" directions so that a portion of the light energy is directed away from the incident beam.

- The electric field in the wave polarizes the particle by displacing the lighter electrons with respect to the heavier positive nuclei.
- The electrons in the molecule couple and oscillate with the electric field in the wave (AC electronic polarization). The oscillation of charge "up" and "down," or the oscillation of the induced dipole, radiates EM waves all around the molecule as depicted in Figure 9.25.
- We should remember that an oscillating charge is like an alternating current which always radiates EM waves (like an antenna).
- The net effect is that the incident wave becomes partially reradiated in different directions and hence loses intensity in its original direction of propagation.
- We may think of the process as the particle absorbing some of the energy via electronic polarization and reradiating it in different directions.
- It may be thought that the scattered waves constitute a spherical wave emanating from the scattering molecule, but this is not generally the case as the reemitted radiation depends on the shape and polarizability of the molecule in different directions.

The scattering process involves electronic polarization of the molecule or the dielectric particle.

This process couples most of the energy at ultraviolet frequencies where the dielectric loss due to electronic polarization is maximum and the loss is due to EM wave radiation.

Therefore, as the **frequency of light increases, the scattering becomes more severe**.

In other words, **scattering decreases with increasing wavelength**.

For example, **blue light which has a shorter wavelength than red light** is scattered more strongly by air molecules.

When we look at the sun directly, it appears yellow because the blue light has been scattered in the direct light more than the red light.

When we look at the sky in any direction but the sun, our eyes receive scattered light which appears blue; hence the sky is blue.

At sunrise and sunset, the rays from the sun have to traverse the longest distance through the atmosphere and have the most blue light scattered which gives the sun its red color at these times.

ATTENUATION IN OPTICAL FIBERS

Attenuation=Absorption + Scattering

- An optical fiber is a cylindrical dielectric waveguide (nonconducting waveguide) that transmits light along its axis through the process of total internal reflection.
- As light propagates through an optical fiber, it becomes attenuated by a number of processes that depend on the wavelength of light.
- Figure 9.26 shows the **attenuation coefficient, as dB per km**, of a typical silica-glass-based optical fiber as a function of wavelength.
- The sharp increase in the attenuation at wavelengths beyond 1.6 μm in the infrared region is due to energy absorption by "lattice vibrations" of the constituent ions of the glass material.

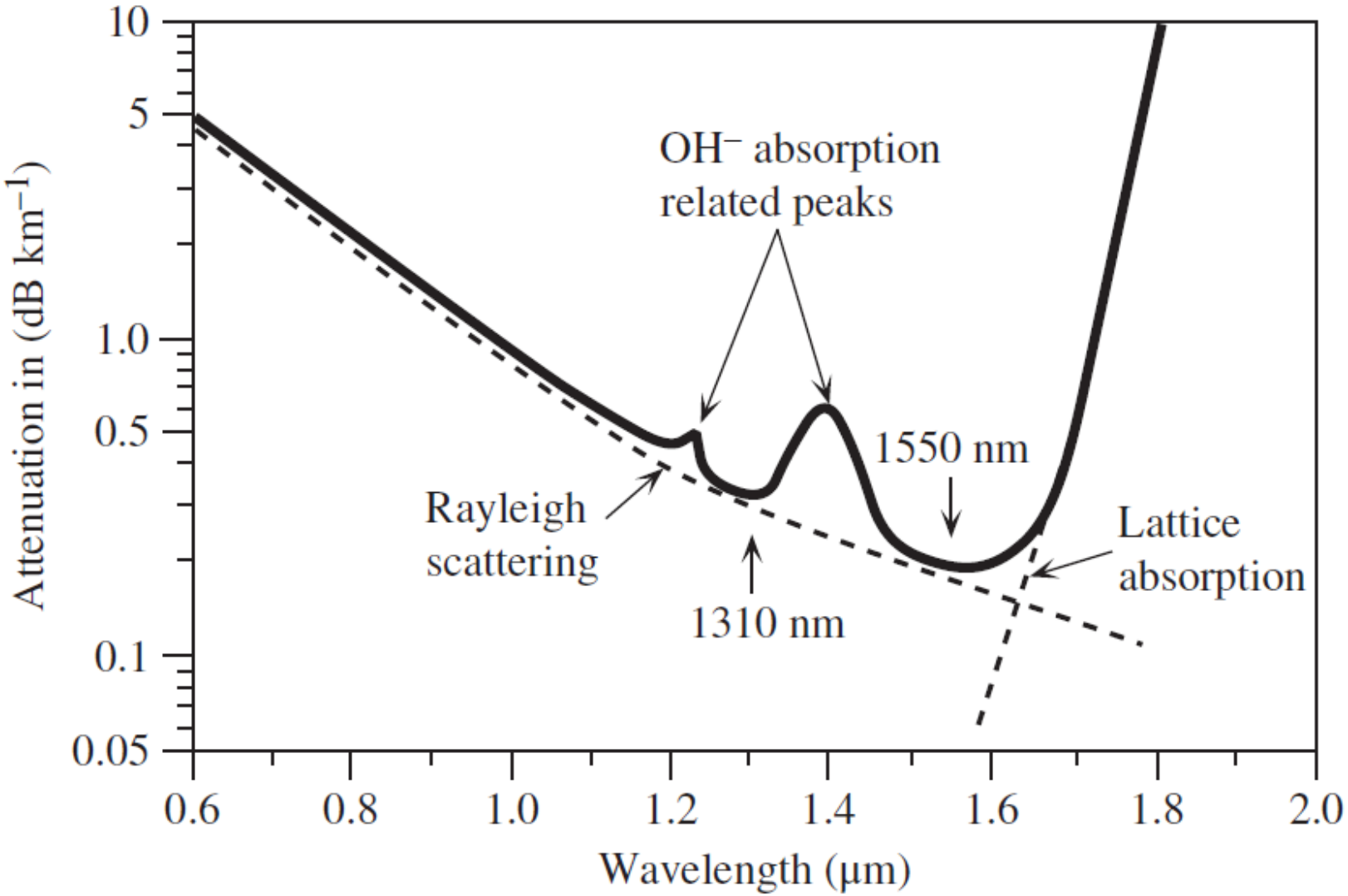


Figure 9.26 Illustration of typical attenuation versus wavelength characteristics of a silica-based optical fiber.

There are two communications channels at 1310 and 1550 nm.

There is a marked attenuation peak centered at 1.4 μm, and minor peak at about 1.24 μm. These **attenuation regions arise from the presence of hydroxyl ions(OH) as impurities in the glass structure** inasmuch as it is difficult to remove all traces of hydroxyl (water) products during fiber production.

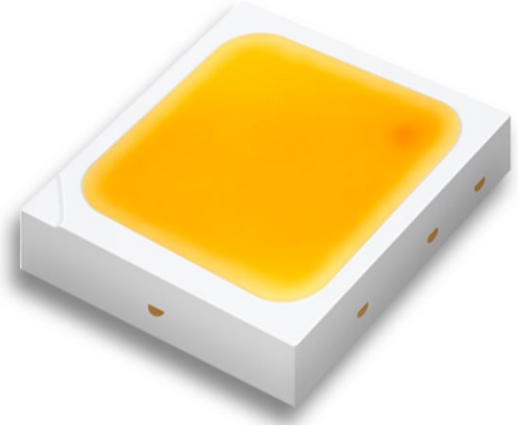
Further, **hydrogen atoms can easily diffuse into the glass structure at high temperatures during production** which leads to the formation of hydrogen bonds in the silica structure and OH ions.

Energy is absorbed mainly by the stretching vibrations of the OH bonds within the silica structure which has a fundamental resonance in the infrared region (beyond 2.7 μm) but overtones or harmonics at lower wavelengths (or higher frequencies).

The first overtone at around 1.4 μm is the most significant as can be seen in Figure 9.26. The second overtone is around 1 μm, and in high-quality fibers this is negligible.

LUMINESCENCE, PHOSPHORS, AND WHITE LEDS

- **Luminescence:** the emission of light produced by means other than heat.
- **Phosphors** can absorb light and then reemit light even after the excitation light source has been turned off; this is an example of luminescence.
- Luminescence is the emission of light by a material, called a phosphor, due to the absorption and conversion of energy into electromagnetic radiation as illustrated in Figure 9.27a and b.



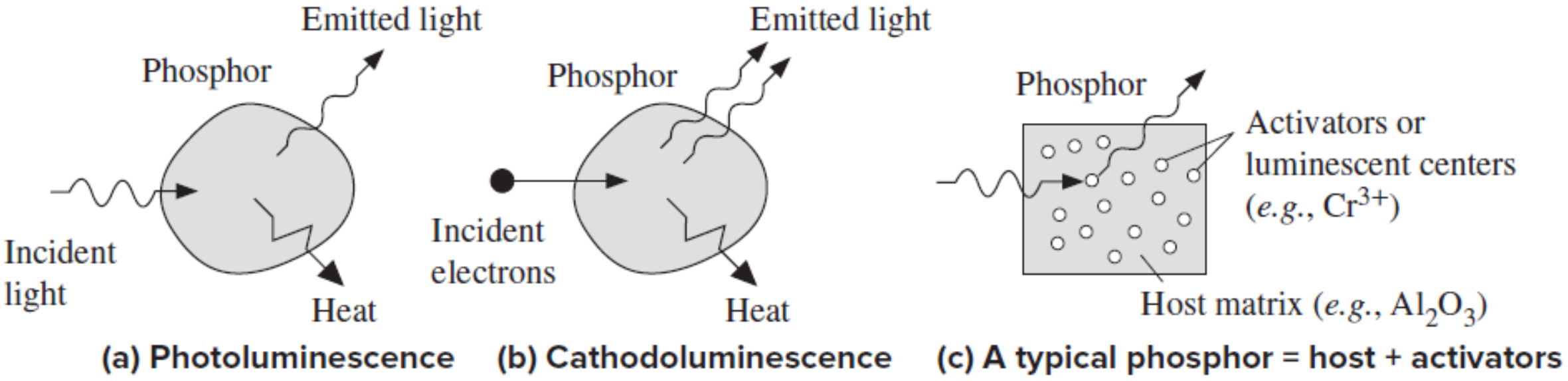


Figure 9.27 Photoluminescence, cathodoluminescence, and a typical phosphor.

- The luminescent radiation emitted by the phosphor material is considered to be quite separate from the thermal radiation emitted by virtue of its temperature.
- Luminescence is light emitted by a **nonthermal source when it is excited**, in contrast to the emission of radiation from a heated object such as the tungsten filament of a light bulb; the latter is called incandescence.

- Typically the emission of light occurs from certain dopants, impurities, or even defects, called luminescent or luminescence centers, purposefully introduced into a **host matrix**, which may be a crystal or glass as shown in Figure 9.27c. The luminescent center is also called an **activator**.
- There are many examples of phosphors. For example, in ruby, the Cr^{3+} ions are the luminescent centers in the sapphire (Al_2O_3) crystal host. Cr^{3+} ions can absorb UV or violet light and then emit red light. This phosphor system is written as $Al_2O_3 : Cr^{3+}$. The excitation and emission involves only the Cr^{3+} ion.

Luminescence is normally categorized according to the source of excitation energy.

Photoluminescence involves excitation by photons (light) as in Figure 9.27a.

X-ray luminescence involves incident X-rays exciting a phosphor to emit light.

Cathodoluminescence, as shown in Figure 9.27b, is light emission when the excitation is the bombardment of the phosphor with energetic electrons as in TV cathode ray tubes.

Electroluminescence is light emission due to the passage of an electric current.

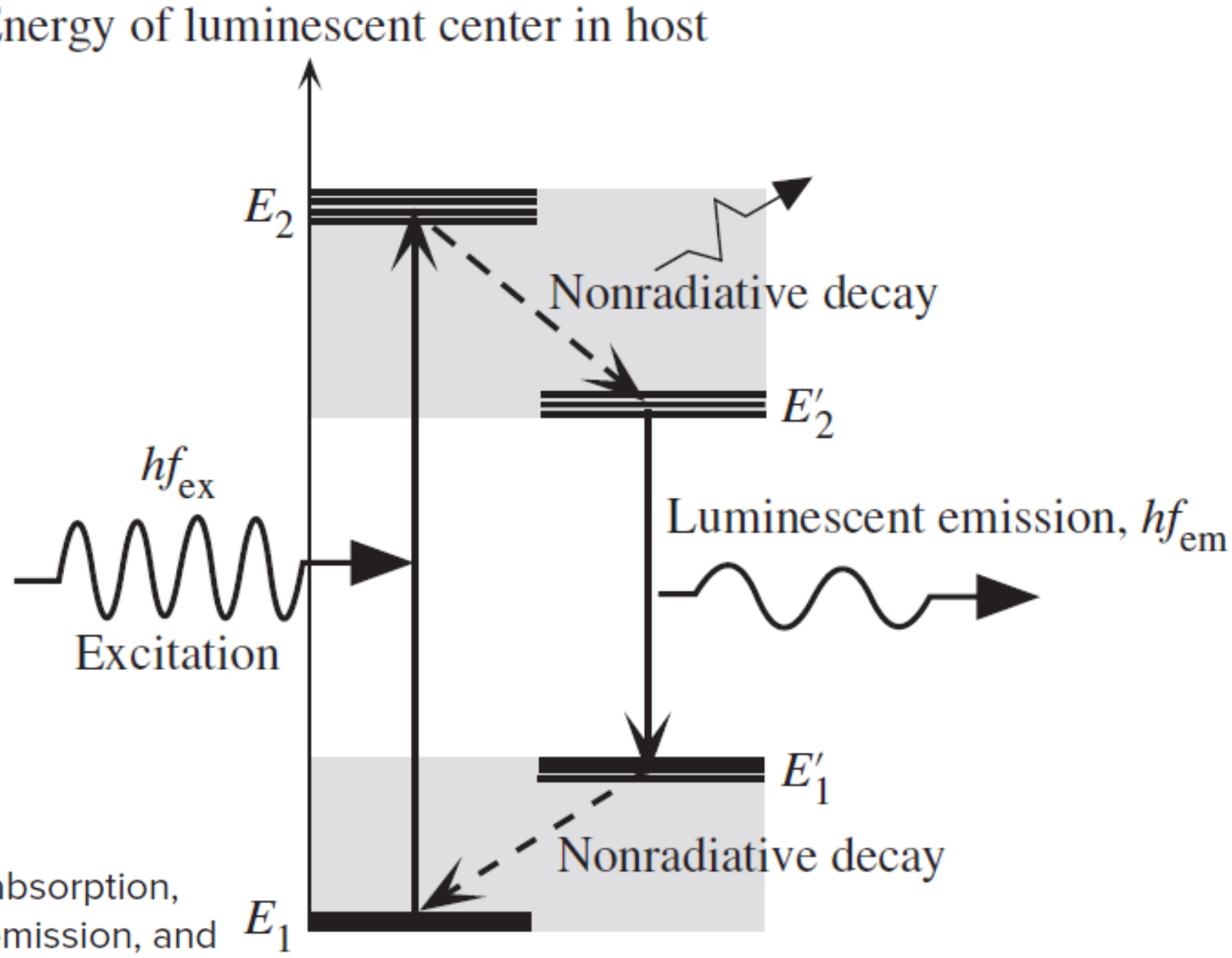


Figure 9.28 Photoluminescence: light absorption, excitation, nonradiative decay and light emission, and return to the ground state E_1.

The energy levels have been displaced horizontally for clarity.

- In very general terms, we can represent the energy of an **activator** in a host matrix by the highly simplified energy diagram in Figure 9.28.
- The ground state of the **activator** is E_1. Upon excitation by an incident radiation of suitable energy hf_{ex} the activator becomes excited to E_2.
- From this energy level, it **decays, or *relaxes***, down relatively quickly (on a time scale of the order of picoseconds) to an energy level E'_2 by **emitting phonons or lattice vibrations**.
- This type of decay is called ***radiationless* or *nonradiative decay***. From E'_2, the activator decays down to E'_1 by emitting a photon (spontaneous emission), **which is the emitted luminescent radiation**.
- The emitted photon energy is hf_{em}, which is less than the excitation photon energy hf_{ex}. The return from E'_1 to the ground state E_1 involves phonon emissions. Further, for some activators, E'_1 is either very close to E_1, or it is E_1. The energy levels such as E_2, E'_2, E'_1, etc., are not well-defined single levels but involve finely spaced multilevels.

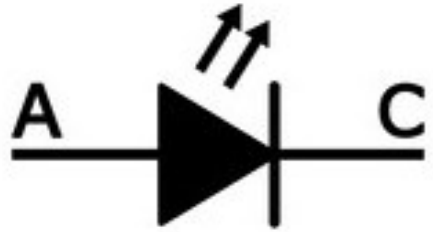
In this example, the activator absorbed the incident radiation and was directly excited, which is known as **activator excitation.** The Cr^{3+} ions in $Al_2O_3 : Cr^{3+}$ can be excited directly by blue light and would then emit in the red.

There are many phosphors in which the excitation involves the host. In **host excitation,** the host matrix absorbs the incident radiation and transfers the energy to the activator, which then becomes excited to E_2 in Figure 9.28, and so on.

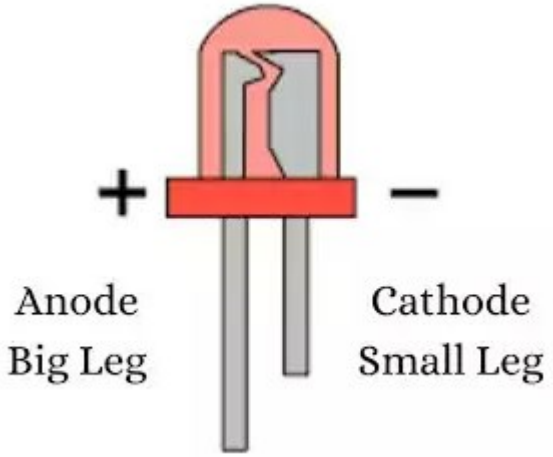
Table 9.4 Selected phosphor examples

Phosphor	Activator	Useful Emission	Example Excitation	Comment or Application
Y_2O_3:Eu^{3+}	Eu^{3+}	Red	UV	Fluorescent lamp, color TV
$BaMgAl_{10}O_{17}$:Eu^{2+}	Eu^{2+}	Blue	UV	Fluorescent lamp
$CeMgAl_{11}O_{19}$:Tb^{3+}	Tb^{3+}	Green	UV	Fluorescent lamp
$Y_3Al_5O_{12}$:Ce^{3+}	Ce^{3+}	Yellow	Blue, violet	White LED
Sr_2SiO_4:Eu^{3+}	Eu^{3+}	Yellow	Violet	White LED (experimental)
ZnS:Ag^+	Ag^+	Blue	Electron beam	Color TV blue phosphor
$Zn_{0.68}Cd_{0.32}S$:Ag^+	Ag^+	Green	Electron beam	Color TV green phosphor
ZnS:Cu^+	Cu^+	Green	Electron beam	Color TV green phosphor

WHITE LED:



- LED is a diode which emits visible light when forward bias.
- LED works on the basic principle called “recombination” of electron-hole pair.
- The electrons fall down from high energy level of conduction band to low energy level of valance band is called recombination process.

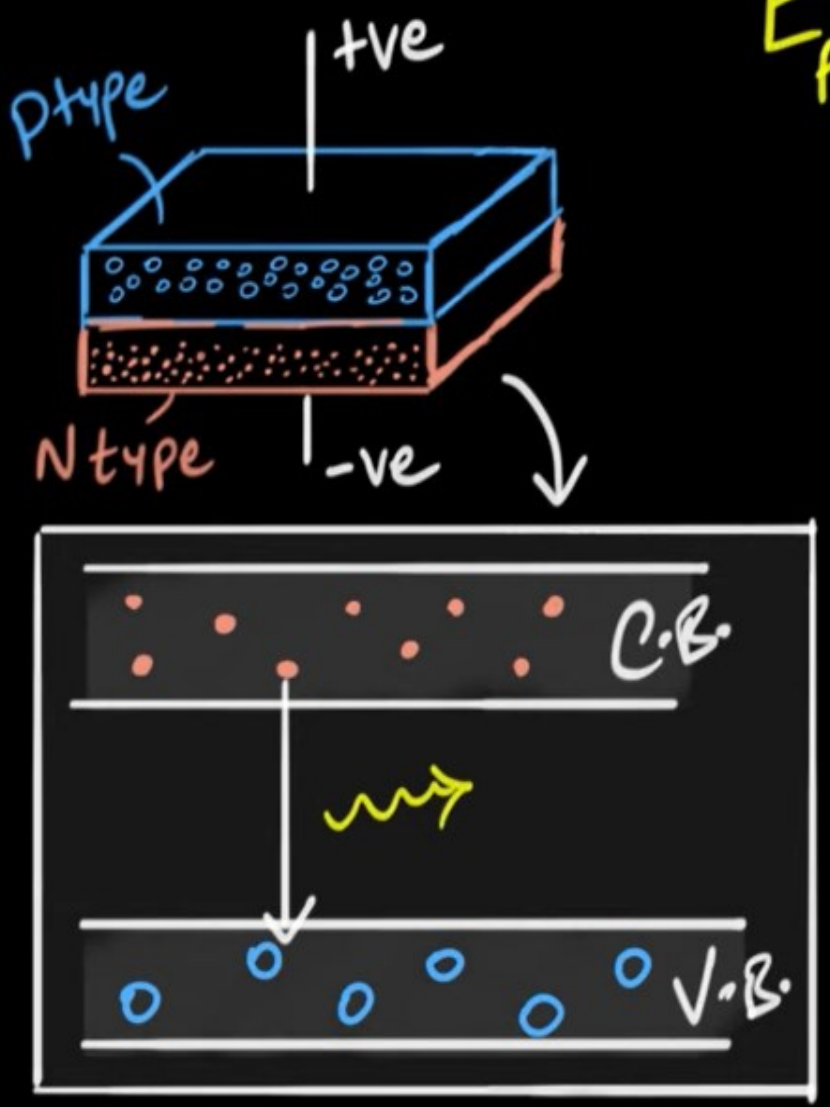


- In this transition, the excess energy is released in the form of photon energy. i.e $E_g = E_c - E_v = hv = \frac{hc}{\lambda}$.
- The emitted photon energy in the form of light and it has monochromatic color depends on band gap energy of frequency.

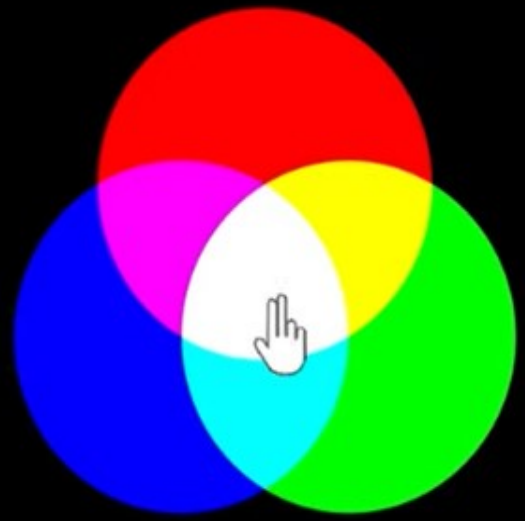
https://www.youtube.com/watch?v=8pBaM-LdO1E&list=WL&index=16&t=471s

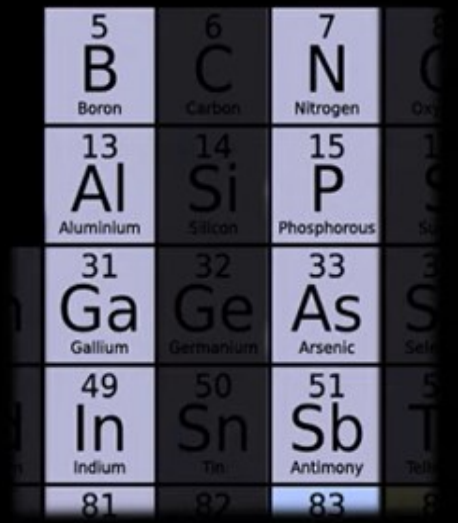
$$E_{photon} = E_{band\ gap} = hf$$

$$2eV \sim 3eV$$

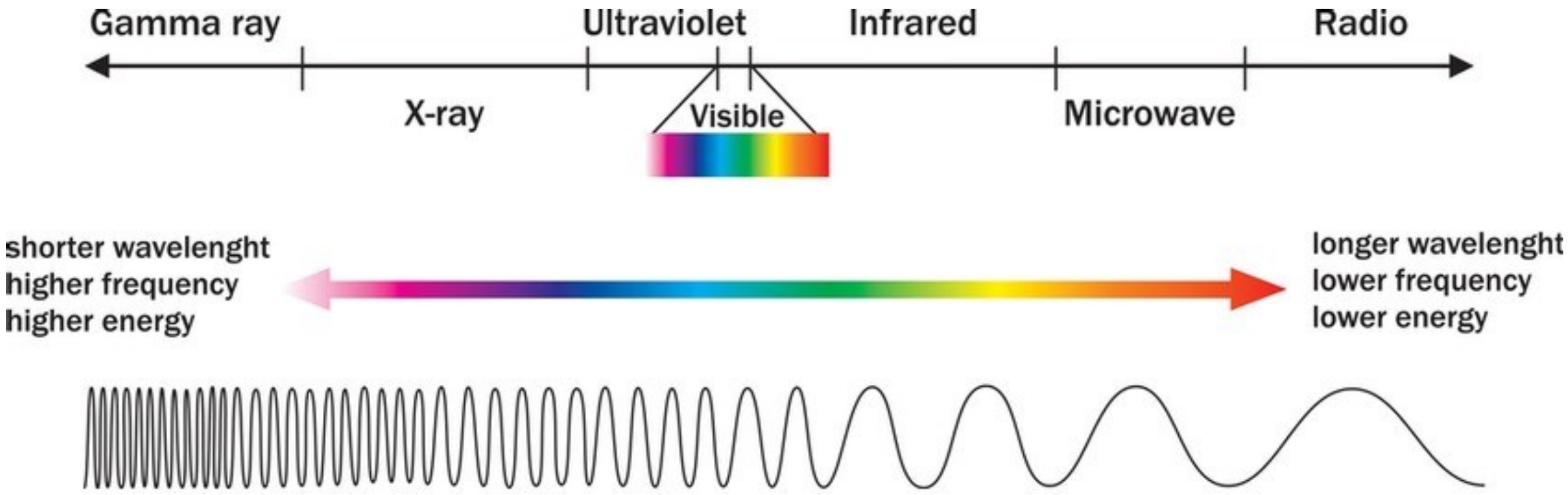


GaAsPh





Silicon	1.1
Germanium	0.7
Gallium arsenide	1.4
Gallium phosphide	2.3
Gallium nitride	3.4



- The Silicon and Germanium diodes can not used for LED. These are **indirect gap semiconductors**. The energy gap for Si=1.1ev and Ge=0.7ev, and corresponding values of wavelength **do not fall in visible region**.
- On the other hand, GaAs, GaAsP, GaP etc. which are obtained by mixing group 3 with group 5 elements. These are **direct band gap semiconductors**, and energy gap such that corresponding **wavelength falls in the visible region**.

- Recent inexpensive white LEDs that have appeared on the market seem to emit white light by emitting a mixture of blue and yellow light which are registered visually by the eye as appearing white. (Yellow consists of red and green mixed together, so mixing blue and yellow generates "white.")
- The production of white LEDs became possible due to development of bright blue-emitting LEDs based on gallium-indium-nitride (GaInN).
- The white LED uses a semiconductor chip emitting at a short wavelength (blue, violet, or ultraviolet) and a *phosphor* to convert some of the blue light to yellow light as depicted in Figure 9.30a.
- The phosphor absorbs light from the diode and undergoes luminescent emission at a longer wavelength.

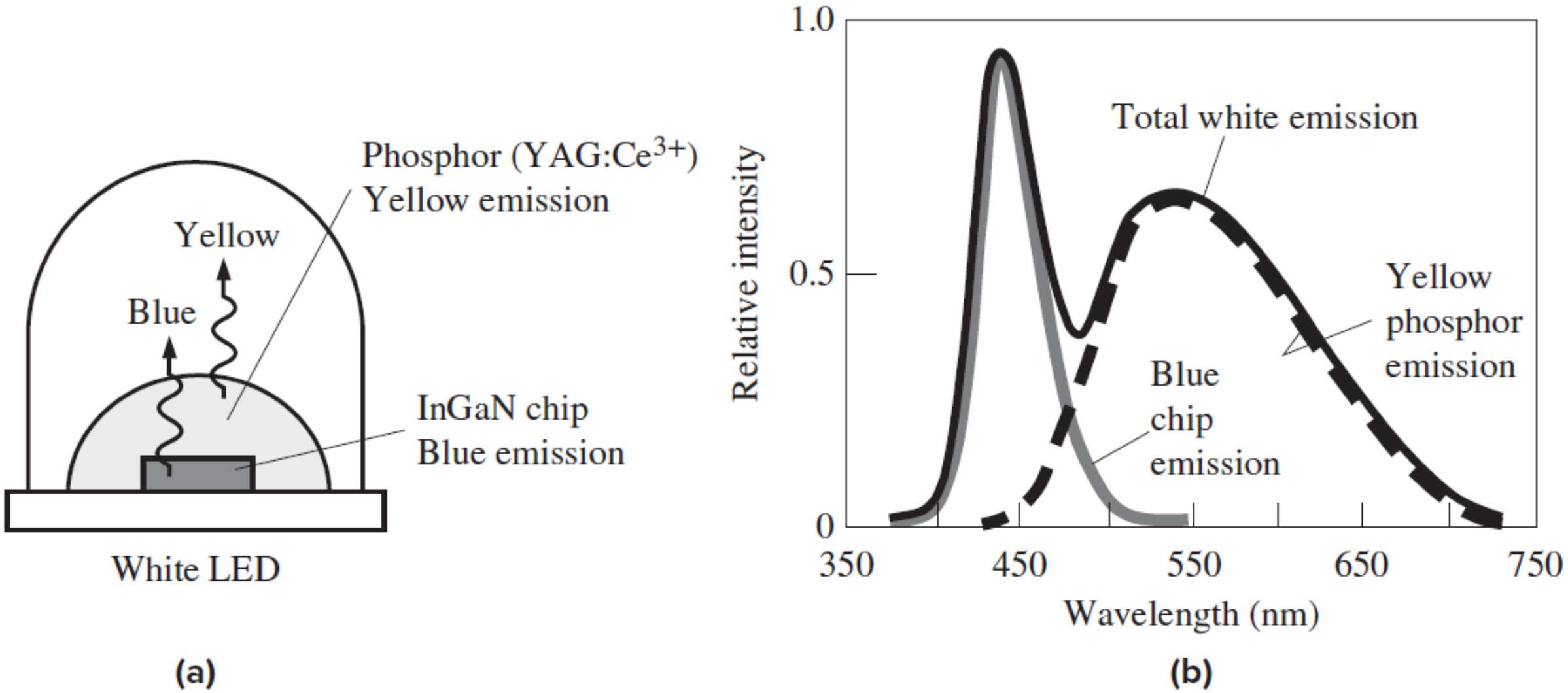
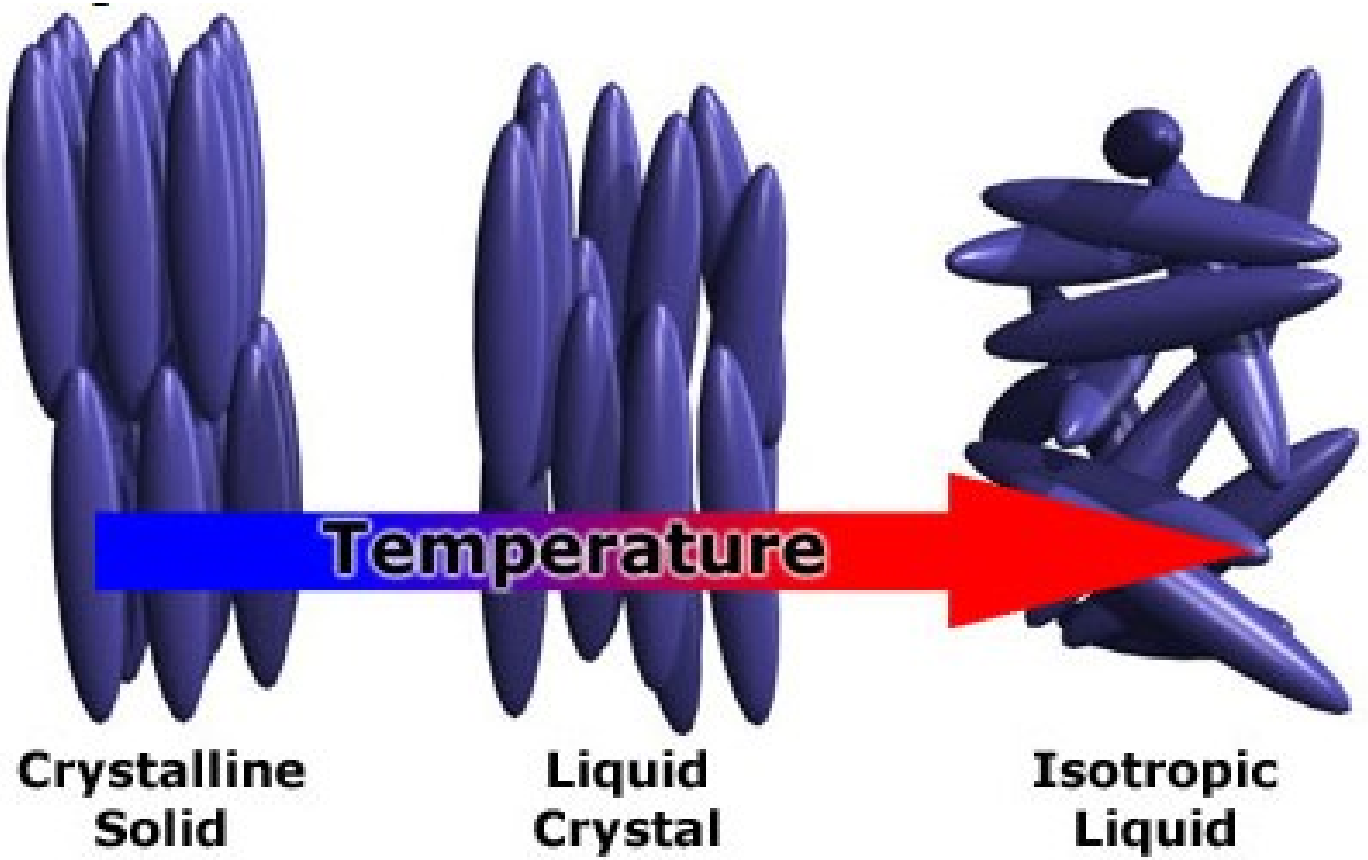


Figure 9.30 (a) A typical "white" LED structure. (b) The spectral distribution of light emitted by a white LED. Blue luminescence is emitted by the GainN chip and "yellow" phosphorescence or luminescence is produced by a phosphor. The combined spectrum looks "white."

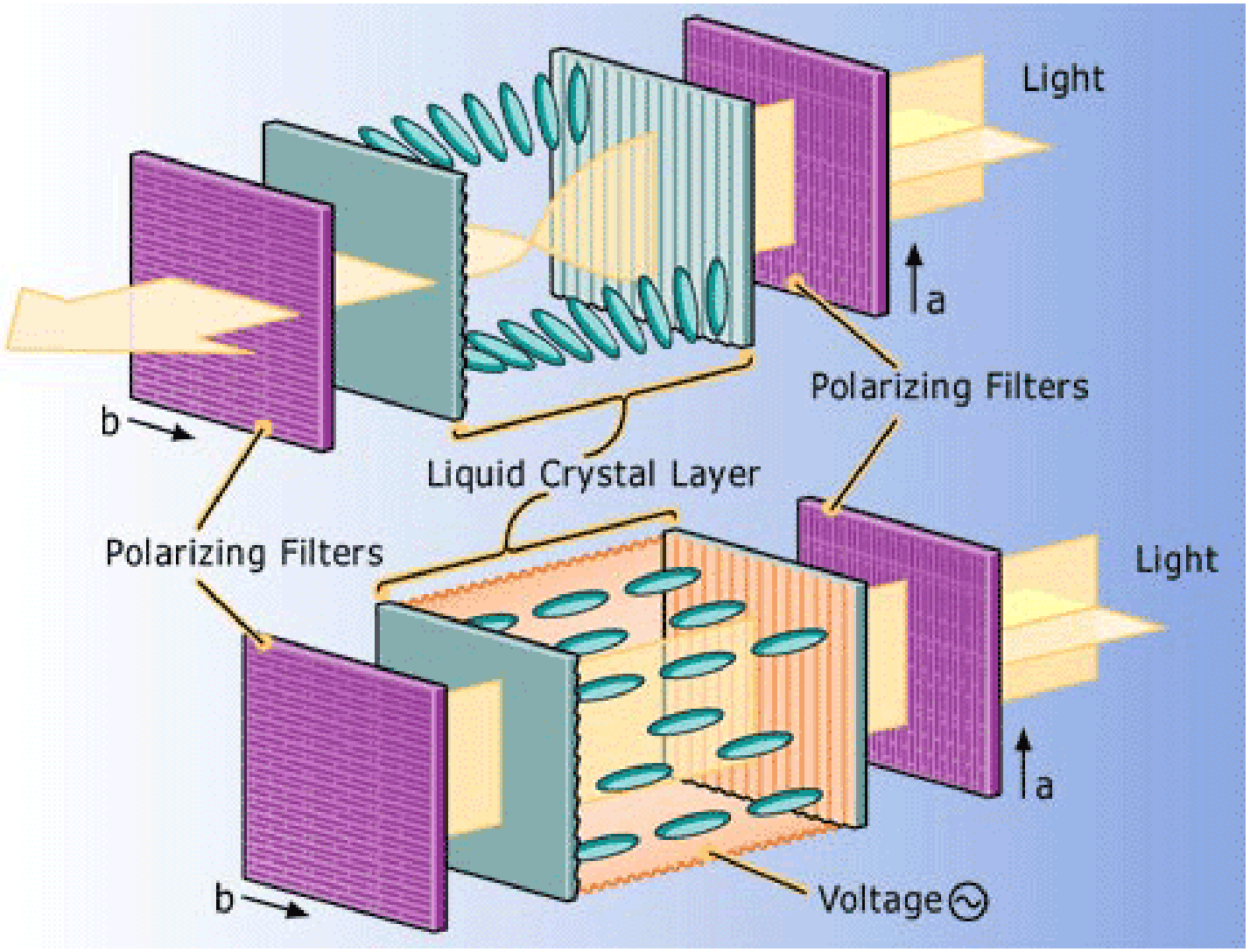
- Obviously, the quality and spectral characteristics of the combined emission vary with different designs;
- Figure 9.30b shows example spectra involved in the blue and yellow emissions and the overall “white” emission from a white LED.
- Typical phosphors have been based on yttrium aluminum garnets ($Y_3Al_5O_{12}$, YAG) as the host material. This host is doped with one of the rare earth elements for the activator.
- Cerium is a common dopant element in YAG phosphors; that is, the phosphor is $Y_3Al_5O_{12}:Ce^{3+}$, which is able to efficiently absorb the blue and emit the yellow.
- White LEDs are now replacing most incandescent sources for general lighting.

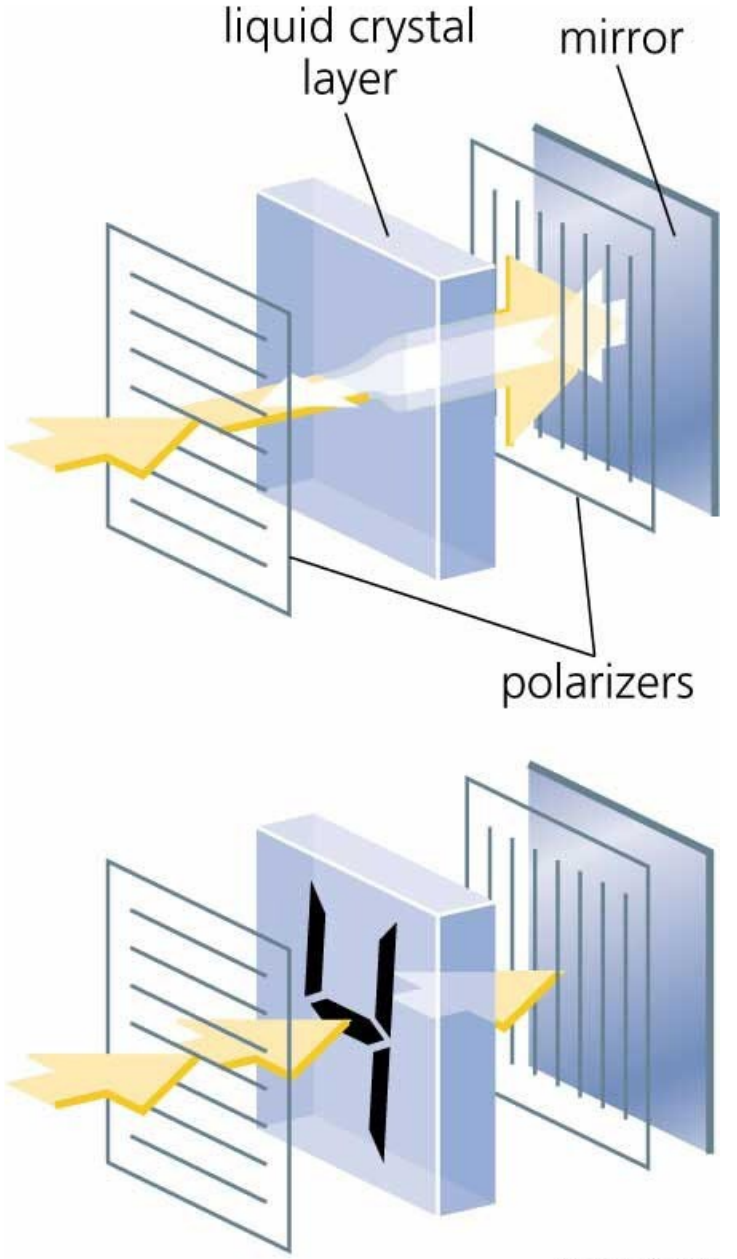

Temperature
Crystalline Solid
Liquid Crystal
Isotropic Liquid

NEMATIC PHASE

Smectic A

Smectic C





Precision Graphics

Liquid Crystal Display (LCD):

- Liquid crystal displays (LCDs) are widely used in many flat panel televisions and computer displays.
- LCDs contain **liquid crystals** that change the polarization of a passing beam of light.
- Liquid crystals (LCs) are **materials that possess rod-like molecules as shown** in 9.42a. These molecules, called **mesogens**, **have strong dipoles**, which means that the whole LC structure can be easily polarized.
- LCs is that they have properties that are between **those of a liquid phase and those of a crystalline solid phase**; e.g., **they can flow like a liquid but, at the same time, have crystalline domains that lead to anisotropic optical properties**.
- A distinct characteristic of the liquid crystal state is the **tendency of the mesogens to point along a common axis called the director**.

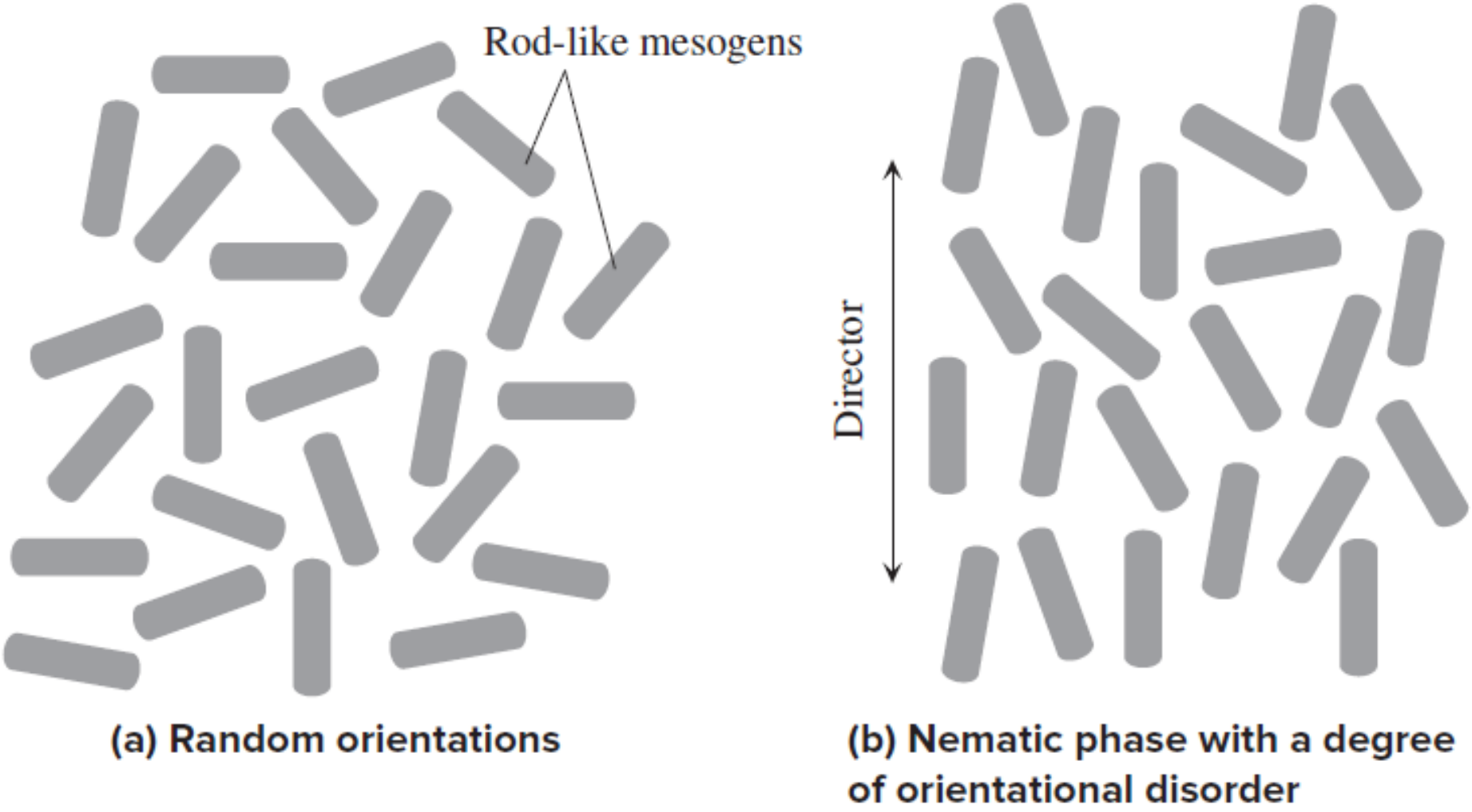


Figure 9.42 Schematic illustration of orientational disorder in a liquid with rod-like mesogens. (a) No order, and rods are randomly oriented. (b) There is a tendency for the rods to align with the *director*, the vertical axis, in this example.

- This is a preferred common axis in the liquid crystal along which the mesogens try to align themselves, which results in an orientationally ordered state as depicted in Figure 9.42b.
- The orientational order in the liquid crystal state lies between that of a normal crystalline solid, i.e., fully ordered periodic structure **and** that of a normal liquid, i.e., nearly fully disordered; and hence is given the name mesogenic state.
- The degree of alignment of mesogens along the director, that is, the degree of anisotropy, depends on the temperature because thermally induced random motions of the mesogens act against dipole alignment.
- The degree of alignment will be a maximum at low temperatures and decreases with increasing temperature, until at some critical temperature the random thermal motions destroy the order.
- The liquid crystals are known to have a number of phases. We will consider the **nematic phase**, which is characterized by mesogens that have no positional order, but tend to point along the same direction, i.e., along the director.

- The physical properties of the nematic phase depend sensitively on the degree of alignment, and can be highly anisotropic for well-aligned materials. A distinct advantage is that an applied field can control the molecular orientation and hence the optical properties.
- **The optical properties of LCs can be controlled by an applied field**. The LCD behaves as a light modulator or a light valve. The **display has a thin film of liquid crystal (*μm*), placed between two semitransparent electrically conducting electrodes to form a cell**.
- **Most of LCDs are consisting twisted nematic (TN) crystal cell** as shown in Fig. 9.43a, the two electrodes have surfaces that have been treated, i.e., have an orientational layer, to act as directors for the molecules and the directors are at **right angles to each other**.
- Its molecules arranged in a **helical structure**, and is able to "twist" or rotate the electric field in light that passes through it.
- **Two polarizers A and B** have been placed at the entrance and the exit ends of the cell respectively. Thus, polarized light enters the cell and has its polarization rotated by 90° as it passes through the cell, and arrives at the exit polarizer.

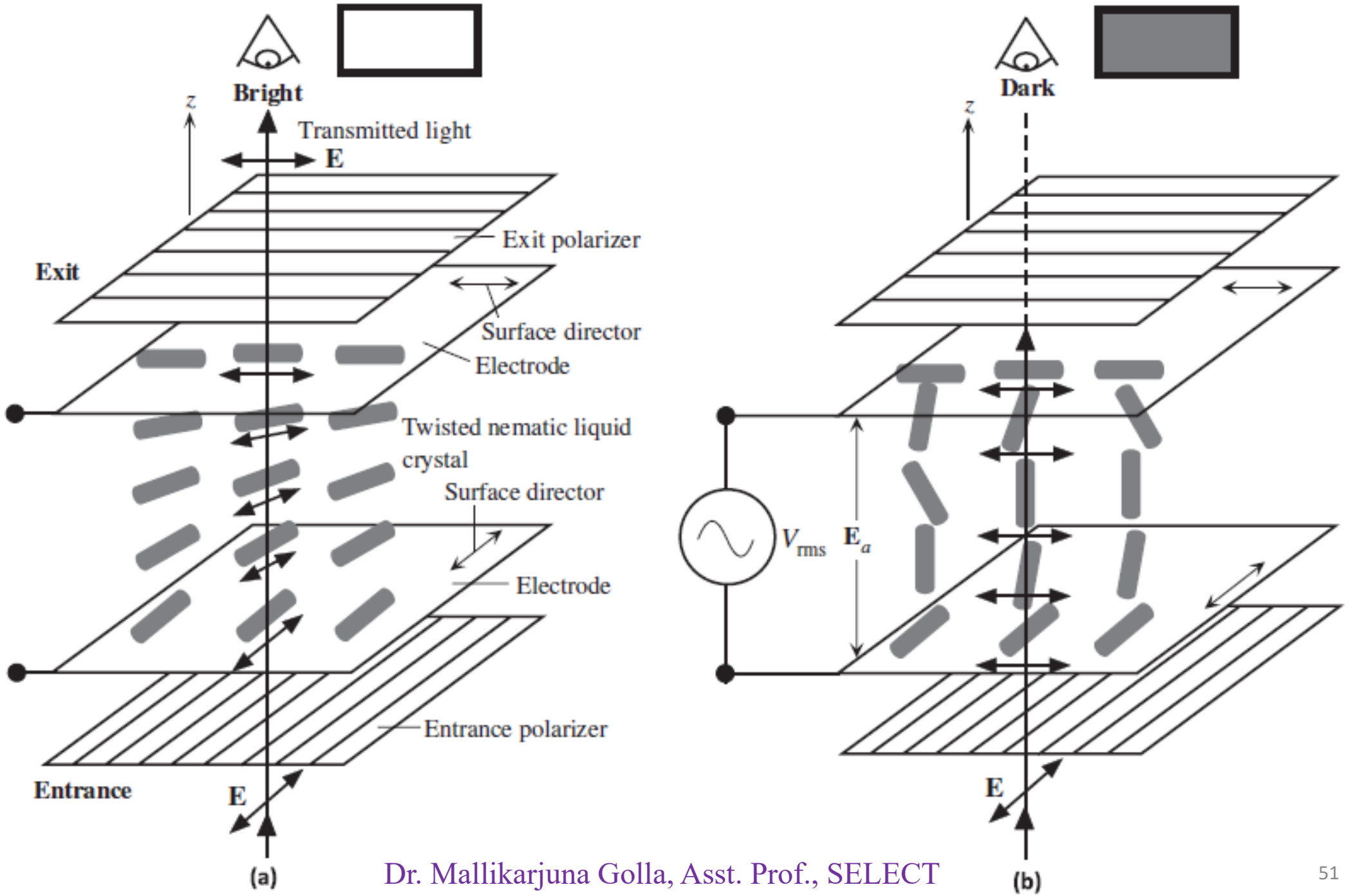

Bright
z
Transmitted light
E
Exit
Exit polarizer
Surface director
Electrode
Twisted nematic liquid crystal
Surface director
Electrode
Entrance polarizer
Entrance
E
(a)
Dark
z
V_{rms}
E_a
E
(b)

Figure 9.43 Transmission based LCD. (a) In the absence of a field, the liquid crystal has the twisted nematic phase and the light passing through it has its polarization rotated by 90°. The light is transmitted through both polarizers. The viewer sees a bright image. (b) When a voltage, and hence a field $\mathbf{E}_a$, is applied, the molecules in the liquid crystal align with the field $\mathbf{E}_a$ and are unable to rotate the polarization of the light passing through it; light therefore cannot pass through the exit polarizer. The light is extinguished, and the viewer sees dark image.

- Since this light has its polarization aligned with the optical axis of the exit polarizer (B), it passes through the polarizer. Therefore, without an applied field, the light is transmitted through the LCD, which appears bright.
- When an electric field 'Ea' is applied by connecting an AC voltage (typically a few volts) to the two electrodes on the opposite the faces of the cell as shown in Figure 9.43b. The applied field now disturbs the alignment of the molecules in the nematic liquid crystal.
- The field 'Ea' acts as an externally imposed director and the molecules align with the field, which results in the twisted molecular arrangement being destroyed.
- The polarization of the light entering the cell is unaffected and therefore the light cannot pass through the exit polarizer (B).The LCD cell therefore appears dark. In fact, the light transmission can be completely extinguished by applying a sufficiently large field.

- If a **mirror** is placed behind the second polarizer, the display operates under reflection instead of transmission.
- How can we reverse the switching behavior, that is, switch the LCD from dark (without an applied voltage) to bright (with applied voltage)?
- This can be **easily achieved by using parallel polarizers**, that is A and B in Figure 9.43a have the same polarization direction.
- In this case, there would be no transmitted light in Figure 9.43a and transmitted light in b.
- **By varying the applied voltage between the threshold** for reorientation and the saturation field for unwinding the twisted nematic structure, we can obtain grey scale modulation.
- The transparent electrodes are typically indium-tin-oxide, and can be patterned by lithographic techniques into various desirable shapes. More than 50 percent of TV screens use the LCD technology.

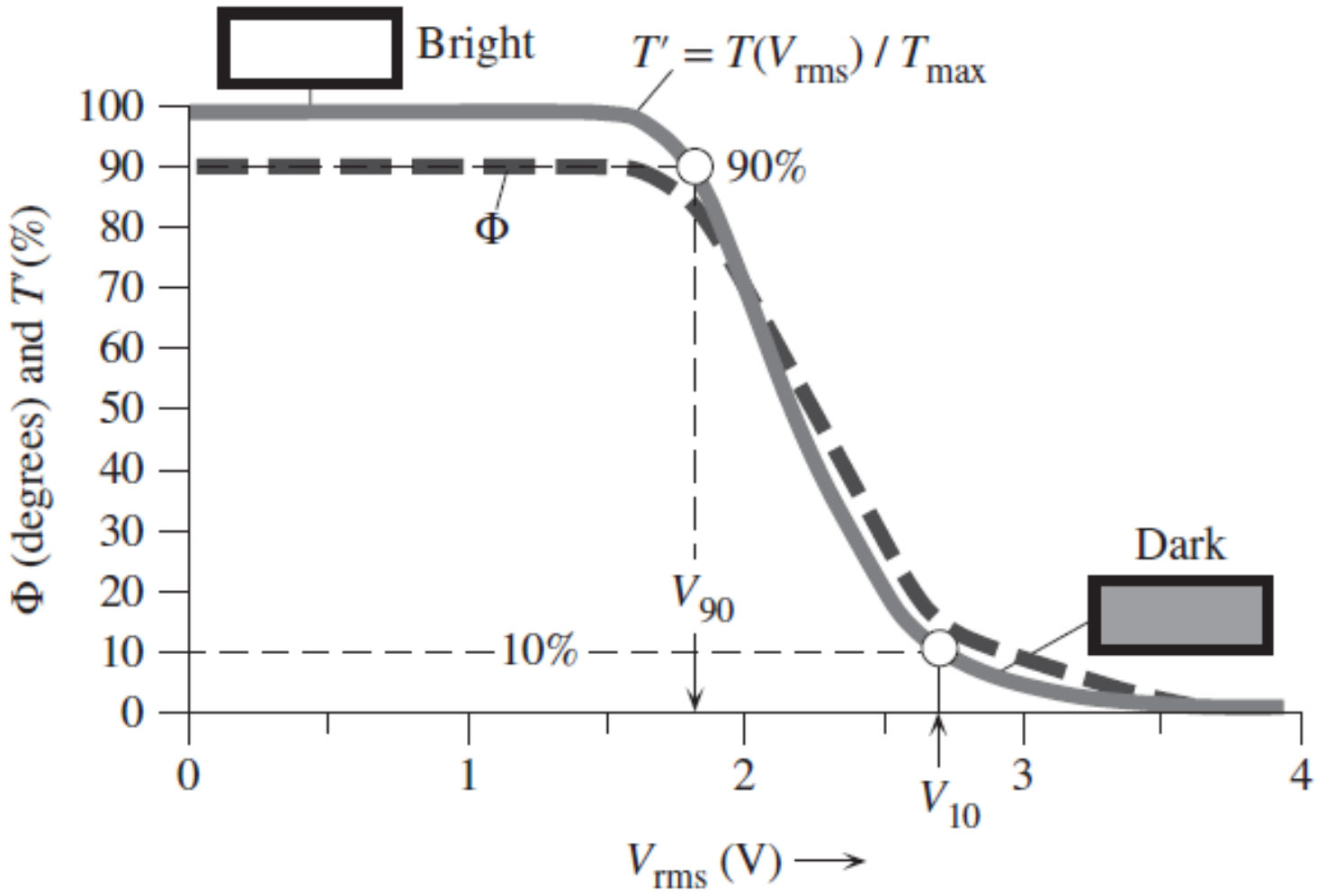
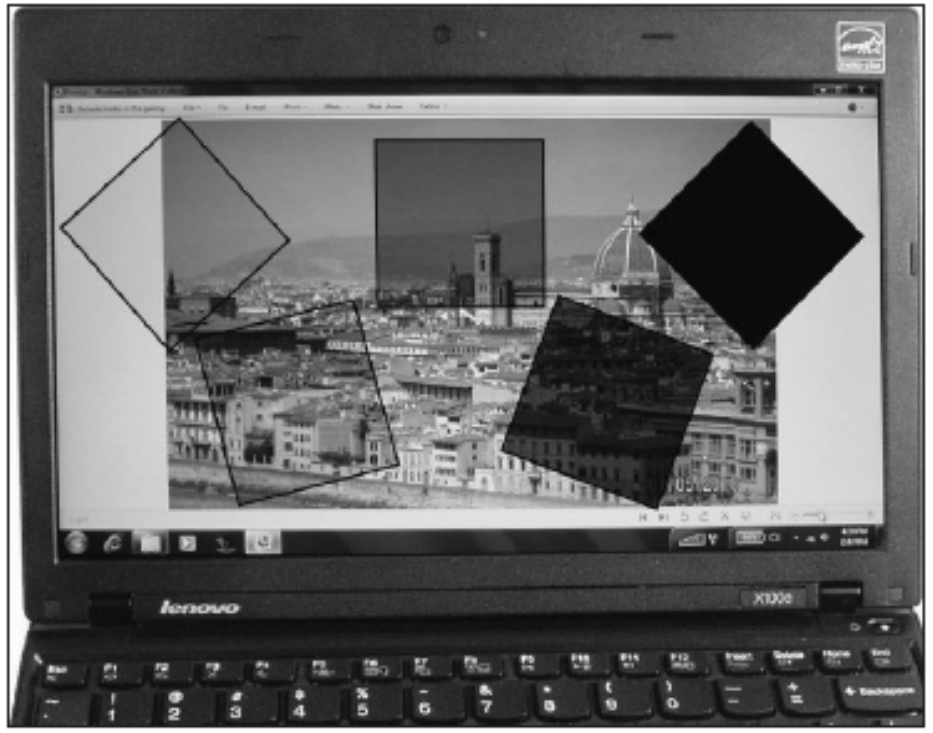


Figure 9.44 Plots of the rotation angle Φ of the linearly polarized light versus the rms voltage V_{rms} across an LCD cell, and the normalized transmittance defined by $T' = T(V_{rms})/T_{max}$ (%) versus V_{rms} for a typical twisted nematic liquid crystal cell.



The light from an LCD display is linearly polarized. A number of square polarizers have been placed on the screen of this laptop computer at different angles until the light is totally extinguished. There are five polarizers placed on the screen at different angles.

Photo by S. Kasap.

- The electric field in Figure 9.43b has been applied by connecting an AC voltage to the LCD electrodes. LCDs are always operated with an AC voltage; typical operating frequencies for LCDs are ~1 kHz.
- The reversal of the field does not change the principle of operation because molecules always try to align parallel to the field, which is along either +z or −z.
- In both cases, the field 'E' in the light beam is not rotated and the light through the LCD is extinguished at the second polarizer (B).
- The amount of transmission through an LCD depends on the rms value of the AC voltage. Manufacturers typically provide the transmittance versus rms voltage characteristics of their LCDs.
- The rotation angle 'Φ' of the linearly polarized light through the liquid crystal medium depends on the rms voltage *Vrms* across an LCD cell, which is shown in Figure 9.44.

- It is clear from Figure 9.44 that the rms voltage V_{rms} must reach a certain **threshold** value before any effect is seen. We need to apply a certain threshold voltage to start untwisting the alignment of the mesogens.
- The rms voltage V_{90} corresponding to 90 percent normalized transmission T' is generally defined as the **threshold voltage.**
- The voltage at which T' has dropped to 10 percent defines the **saturation voltage,** V_{10}. LCD response times for turning on (alignment with the applied field) and off (alignment with the surface directors) depend on the properties of the LC, the thickness of the cell, and temperature.
- At room temperature, these turn on and off times are typically in the millisecond time range with the turn off time usually being longer than the on time. It is faster to align the molecules with the applied field, than the time it takes for them to naturally align with the surface directors when the applied field is turned off.

https://www.youtube.com/watch?v=Gx-JVoOFYhs&t=341s

ELECTRO-OPTIC EFFECTS:

- Electro-optic effects refer to changes in the refractive index of a material induced by the application of an external electric field, which therefore "**modulates**" the optical properties.
- We can apply such an external field by placing electrodes on opposite faces of a crystal and connecting these electrodes to a battery.
- The presence of such a field distorts the electron motions in the atoms or molecules of the substance or distorts the crystal structure resulting in changes in the optical properties.
- For example, an applied external field can cause an optically isotropic crystal such as GaAs to become birefringent.

- The frequency of the applied field has to be such that the field **appears static over the time scale** it takes for the medium to change its properties, that is, respond, as well as for any light to cross the substance.
- The electro-optic effects are classified according to first- and second-order effects.

If we were to take the refractive index n to be a function of the applied electric field E, that is, $n = n(E)$, we can of course expand this as a Taylor series in E. The new refractive index n' is

$$n' = n + a_1 E + a_2 E^2 + \cdots$$

where the coefficients a_1 and a_2 are called the linear electro-optic effect and second-order electro-optic effect coefficients, respectively.

- Although we would expect even higher terms in the expansion in Equation 9.83, these are generally very small and their effects negligible within the highest practical fields.
- The change in n due to the first E term is called the Pockels effect.
- The change in n due to the second E_2 term is called the Kerr effect, and the coefficient a_2 is generally written as λK where K is called the Kerr coefficient.

$$\Delta n = a_1 E \qquad [9.84] \qquad \textit{Pockels effect}$$

$$\Delta n = a_2 E^2 = (\lambda K) E^2 \qquad [9.85] \qquad \textit{Kerr effect}$$


Thank You!