Passive Optical Properties of Glass
Lecture 1:

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Glassy Optical Materials: Motivation

- Good optical properties
- Hard to synthesize

- Easy to synthesize
- Bad optical properties

- Good optical properties
- Easy to synthesize
Optical properties of materials

- Four things can happen when light proceeds into a solid.

\[ I_o = I_R + I_T + I_A + I_S \]

- Part of the light can be reflected by the surface of the solid. **Reflection**
- Part of the light can be absorbed by coupling into the solid. **Absorption**
- Part of the light can be scattered by the atoms and defects in the solid. **Scattering**
- Part of the light can be transmitted through the solid. **Transmission**

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Optical properties of materials:

- Light is an electromagnetic wave. An electric and magnetic field oscillating perpendicular to the direction of propagation.

- When light penetrates a solid, the oscillating electric field couples with dipoles created by charged particles (nucleus, electrons, ions) composing the solid.

- The mechanism and magnitude of this interaction varies for every materials and depends on its:
  - chemical composition
  - structural properties

- One parameter is sufficient to characterize entirely the optical properties: the complex refractive index $n = n + ik$
Origin of light-matter interaction

- Light can couple with **electronic oscillators**: electrons bound to nucleus

\[
\begin{align*}
    m_e & : \text{mass of an electron} \\
    m_N & : \text{mass of a nucleus} \\
    \frac{1}{\mu} & = \frac{1}{m_e} + \frac{1}{m_N} \\
    \text{Reduced mass:} & \\
    \omega_0 & \propto \sqrt{\frac{1}{\mu}} \\
\end{align*}
\]

\(m_N >> m_e\) and \(\mu \approx m_e\), hence the small electronic mass of electrons determine the resonant frequency of electronic oscillator which is very high in the UV and visible region of the spectrum.
Origin of light-matter interaction

- Light can couple with vibrational oscillators: ionic bonds and some covalent bonds.

\[ \mu = \frac{m_1 m_2}{m_1 + m_2} \]

Resonant frequency:

\[ \nu = \frac{1}{2\pi} \sqrt{\frac{k}{\mu}} \]

Atomic mass are orders of magnitude larger than the mass of electrons hence the resonant frequency of vibrational oscillator is low, typically in the infrared region of the spectrum.
Polarization

• Hence a material gets polarized under the action of the electric field of an electromagnetic wave (light).

The ability of the material to polarize is expressed as the dielectric susceptibility: $\chi$

$$P = \varepsilon_0 \chi E$$

It is the proportionality constant between the disturbing field $E$ and the materials response, the polarization $P$.

In a solid glass, there is no rotational degree of freedom, hence no contribution from dipole orientation. But there is distortion (vibrations) in the IR and electronic oscillations in the UV-Vis. Note that in between there is no strong coupling: This will define the optical transparency window of the glass.
Lorentz Oscillator:

In the transparency window, the electrons oscillate in response to the E field of light but its motion is damped by collision with other electrons.

Newton’s law of dynamic ($\Sigma F = ma$) for a forced oscillator with damping:

$$m\left(\frac{d^2x}{dt^2} + \gamma \frac{dx}{dt} + \omega_0^2 x\right) = qE$$

where $x$ is the displacement along $E$, $\gamma$ is the damping factor, $m$ is the mass of the electron and $q$ its charge.
Lorentz Oscillator:

Oscillating E field: \[ E = E_0 e^{i\omega t} \]

Resulting dipole oscillation: \[ x = x_0 e^{i\omega t} \]

Combine \[ m \left( \frac{d^2x}{dt^2} + \gamma \frac{dx}{dt} + \omega_0^2 x \right) = qE \]
and \[ x = x_0 e^{i\omega t} \]
and solve for \( x \).

This gives
\[ x = \frac{q/m}{\omega_0^2 - \omega^2 + i\gamma\omega} E \]
the displacement or distortion of the electronic dipole.

And the resulting dipole polarization
\[ p = qx = \frac{q^2/m}{\omega_0^2 - \omega^2 + i\gamma\omega} E \]
Lorentz Oscillator:

For $N$ electrons of charge $q$ the total polarization $P$ is:

$$P = N \frac{q^2/m}{\omega_0^2 - \omega^2 + i\gamma\omega} E$$

And for various oscillators $N_j$ with resonant frequency $\omega_j$:

$$P = \left( \frac{q^2}{m} \sum_j \frac{N_j}{\omega_j^2 - \omega^2 + i\gamma_j\omega} \right) E$$

We now have an expression for the polarizability or dielectric susceptibility of the material: $\chi$

$$\chi = \frac{q^2}{\varepsilon_0 m} \sum_j \frac{N_j}{\omega_j^2 - \omega^2 + i\gamma_j\omega}$$
The Refractive Index:

χ is directly related to the refractive index n through the dielectric constant of the materials ε_r according to:

\[ n = \sqrt{\varepsilon_r} \quad \text{and} \quad \varepsilon_r = 1 + \chi \quad \text{or} \quad n^2 = 1 + \chi \]

We now have an expression for the refractive index of the material as a function of the light frequency ω:

\[ n^2 = 1 + \frac{q^2}{\varepsilon_0 m} \sum_i \frac{N_i}{\omega_i^2 - \omega^2 + i \gamma_i \omega} \]

Note that the refractive index is a complex quantity: \( n = n + i \kappa \)
Variation of Refractive Index with frequency:

For $\omega < \omega_j$, the term $(-\omega^2 - i\gamma\omega)$ is negligible in comparison to $\omega_j^2$ and $n$ is almost constant between resonances.

However it should be noticed that for increasing $\omega$ the denominator slightly decreases and $n$ therefore increases with $\omega$. This is the reason for light dispersion (prism).

For $\omega = \omega_j$, the term $(\omega_j^2 - \omega^2) \to 0$, the denominator decreases and $n$ shows a resonance peak.
At the resonance $\omega = \omega_j$, the term $(\omega_j^2 - \omega^2) \to 0$, and the index therefore becomes imaginary. $n$ is therefore controlled by the extinction coefficient $\kappa$.

The damping factor $i\gamma \omega$ dominate and results in large loss of energy. The resonance is therefore associated with strong attenuation or absorption of the wave.

Indeed: $\alpha = \frac{2\kappa \omega}{c}$ where $\alpha$ is the absorption coefficient.
In the transparent region, the term \((\omega_j^2 - \omega^2) \gg i\gamma\omega\), and the index becomes mostly real.

The damping factor \(i\gamma\omega\) is negligible, there is no significant absorption and the material is transparent.

We normally approximate that \(n = n\) in the transparency region. That is why refractive indices are listed as real quantities in optics tables.
BIBLIOGRAPHY:

For a detailed recap of these topics, see:


The pdf of this chapter is posted on the Glass Course web site (available for download).
Measurement of optical parameters

- Four things can happen when light proceeds into a solid.

- Part of the light can be reflected by the surface of the solid. **Reflection**

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- Part of the light can be scattered by the atoms and defects in the solid. **Scattering**

- Part of the light can be transmitted through the solid. **Transmission**

- Therefore, for an incident beam of intensity $I_o$ entering the solid:

  $$I_o = I_R + I_T + I_A + I_S$$
The intensity reflected at the surface of a glass is determined by the reflectance \( R \) defined for a incident beam normal to the surface according to the Fresnel equation:

\[
R = \frac{I}{I_0} = \frac{(n - 1)^2 + \kappa^2}{(n + 1)^2 + \kappa^2}
\]

For measurements performed in the transparency region \( \kappa = 0 \) and

\[
R = \left( \frac{n - 1}{n + 1} \right)^2
\]

This provides us with a formula relating a measurable quantity (\( R \)) to the optical constant of the material \( n \).
Measurement of optical parameters: Absorption

In the resonant regions the phenomenon of absorption correspond to transfer of energy from the light wave into the material.

\[ \frac{I}{I_0} = e^{-\alpha z} \]

The intensity of the wave decays exponentially with path length \( z \) according to Beer’s law:

\[ I \propto e^{-\frac{2\kappa \omega z}{c}} \quad \text{or} \quad I \propto e^{-\alpha z} \]

where \( \alpha \) is the absorption coefficient.

This provides us with another formula relating a measurable quantity (\( \alpha \)) to the imaginary part \( \kappa \) of the optical constant of the material.

\[ \alpha = \frac{2\kappa \omega}{c} \]
Measurement of optical parameters: Scattering

Rayleigh Scattering results from microscopic density fluctuations and corresponds to redirecting light in multiple directions. No energy is transferred to the material during Rayleigh scattering. (**Elastic scattering** unlike Raman scattering)

The intensity of the wave decays exponentially with path length \( z \) in a way analogous to Beer’s law:

\[
I(z) = I_0 e^{-sz}
\]

and

\[
S(\lambda) \propto \frac{1}{\lambda^4}
\]
Measurement of optical parameters: Scattering

- The shorter the wavelength, the higher the scattering efficiency.

\[ I_S = \frac{a}{\lambda^4} I_o \]

- The scattering intensity decreases with \( \lambda^4 \).

- For example, blue light is scattered much more efficiently than red light.
Measurement of optical parameters: Transmission

Glasses are homogeneous material and scattering is usually negligible. If we disregard scattering then $R+T+A=1$.

The transmission through a slab of glass must then account for absorption as well as reflection on front and back surface.

\[ I_o \rightarrow I_{R1} \rightarrow I_{R2} \rightarrow I_T \]

\[ z \]

The expression for the transmittance is then:

\[ T = \frac{I_T}{I_o} = (1 - R)^2 e^{-\alpha z} \]
Optical window

Reflection

Electronic transitions

Multiphonon vibrations

Transmission

Wavelength (microns)

Dielectric: SiO₂ glass

Semiconductor: GeSe₃ glass

Optical window
Spectrometers:

- No spectrometer has light sources and detectors that cover the entire range of wavelength, we need two types of spectrometers to fully characterize a glass optical window.

**UV-visible spectrometer**

![UV-visible spectrometer](image1)

![Dielectric: SiO₂ glass](image2)

**Infrared spectrometer**

![Infrared spectrometer](image3)
Spectrometers:

- Most spectrometers consist of three parts:
  - A light source covering the range of interest (infrared, UV etc.)
  - A monochromator to discriminate wavelengths
  - A detector to measure the transmitted intensity through the sample
UV- Vis - NIR Spectrometers:

- Typically covers a range of wavelength from 180 nm to 3000 nm which include UV, visible and near infrared.

**LIGHT SOURCE**
- **Deuterium lamp** are used as light source for the UV range.
- **Tungsten or halogen lamps** are used for the visible region.

**MONOCHROMATOR**
- **Gratings** are more efficient, smaller and cheaper than prism.

**DETECTOR**
- **Photomultipliers tube (PMT):**
- **Charge Coupled Device (CCD):**
  - Silicon semiconductor
FTIR Spectrometers:

• Typically covers the wavelength range from 2 μm (2000 nm) to 30 μm which includes all molecular vibrations

LIGHT SOURCE

Glow bar: Black body Radiations (heated coil of silicon carbide)

INTERFEROMETER

(Not technically a MONOCHROMATOR)

DETECTOR

Pyroelectric Detectors

MCT (HgCdTe) highly sensitive for low intensity