

OPTICAL MATERIALS

Measurement of Optical Properties of Solids

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Introduction

The interaction of light with solids takes place through different mechanisms, depending on the type of material and the range of wavelength investigated. Insulators or dielectrics are typically transparent to visible light while most semiconductors are opaque to visible light yet transparent to infrared radiations; in contrast metallic solids appear shiny because they reflect all wavelength up to the ultraviolet region. The optical properties of a solid depends on its chemical composition and its structural properties and vary for every material, though, one parameter, the complex refractive index n , is sufficient to characterize entirely the optical properties of a specific material.

In this article we will briefly review the physics underlining the nature of the refractive index n , in order to understand its relationship to the observable quantities such as absorption, reflection, and transmission routinely measured in optics experiments. A description of the experimental techniques, as well as a physical interpretation of the data, will also be presented.

Origin of Light Interaction with Matter

Light is described as a transverse electromagnetic wave consisting of an electric and magnetic field oscillating perpendicular to the direction of propagation at optical frequencies within $10^{13} \rightarrow 10^{17}$ Hz. This range of frequencies comprises the ultraviolet, visible, and infrared domain. On the other hand, solid mediums are composed of charged particles, negative electrons, and positive ions producing electric

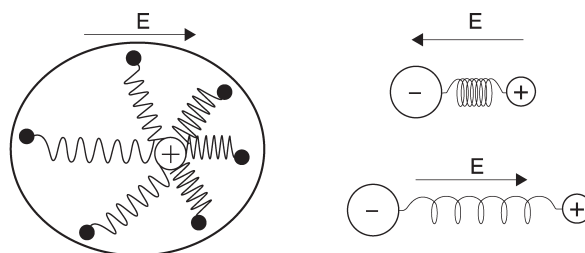
dipoles, which can be polarized under the action of an electric field. Hence, when electromagnetic radiation impinges upon a material it interacts by polarizing the molecular units, producing oscillating dipole moments. This interaction results in several observable optical phenomena such as reflection, transmission, absorption, or scattering, which will be described in more detail in a following section. The classical model of light propagation assumes that the oscillating electric field can interact with several different types of dipole oscillators within the material. Different dipoles are usually accessed by light wave from different frequency range depending on their mass.

Electronic Oscillators

Lorentz originally proposed that the electrons bound to the nucleus of an atom behave as oscillators. In this representation, electrons behave as if they were held by springs and subjected to a linear restoring force, therefore oscillating up and down (Figure 1a). This representation of an atom might seem to contradict the conventional picture of electrons orbiting around the nucleus; however, it is valid as far as light-matter interactions are concerned. The resonant frequency of such an oscillator is proportional to the inverse of its reduced mass μ defined as

$$\frac{1}{\mu} = \frac{1}{m_e} + \frac{1}{m_N} \quad [1]$$

where m_N and m_e are the mass of the nucleus and electrons, respectively. The resonant frequency ω_0 is



(a) Electronic oscillator (b) Vibrational oscillator

Figure 1 (a) Classical oscillator model of a polyelectronic atom. The electrons depicted as black dots are bound to the positive nucleus by springs, which represent the electrostatic restoring forces between the charged particles. The electronic oscillators are distorted under the effect of an electric field. (b) Classical model of a diatomic vibrational oscillator. The chemical bond is represented as a spring and the charged ions vibrate around their equilibrium position under the effect of an oscillating electric field.

then related to μ according to

$$\omega_0 \propto \sqrt{\frac{1}{\mu}} \quad [2]$$

Considering that $m_N \ll m_e$ we can assume that $\mu = m_e$ and show that the smaller mass of the electron determines the resonant frequency of the oscillator. Hence, resonant electronic oscillations are accessed at higher frequencies in the ultraviolet and visible region of the spectrum. In solids, the quantum theory shows that these resonances correspond to excitation of electrons across the gap between a full valence band and an empty conduction band.

S0020 **Vibrational Oscillators**

P0025 The second types of dipoles contained in the medium are based on pairs of charged atoms vibrating around their equilibrium position in the solid. Every atoms have a different electronegativity, hence the electronic density on atomic pairs is distorted and result in a charge imbalance, which can couple to the electric field of light. This generates oscillating dipoles, which involves the motion of atomic nucleus (Figures 1b). The nuclear mass being several orders of magnitude larger than the electronic mass, we can show by analogy with eqns [1] and [2] that the resonant vibration will occur at lower frequencies in the infrared region. In solids, the quantum theory shows that the lattice atoms vibrate cooperatively and generate quantized lattice waves called phonons.

S0025 **Free Electron Oscillators**

P0030 In contrast with the bound electrons from the electronic oscillator model, free electrons can move without being subjected to a restoring force. These correspond to the conduction electrons present in metals and to a smaller extent in doped semiconductors. The free electron oscillator model is therefore principally used to describe the optical properties of metals such as reflectivity. The free electrons are well described as conventional oscillator with a natural resonant frequency $\omega_0 = 0$.

P0035 The relationship between the applied electric field E and the resulting polarization of the medium P is expressed through the dielectric susceptibility χ as

$$P = \epsilon_0 \chi E \quad [3]$$

where ϵ_0 is the permittivity of vacuum. We can generally recognize three contributions to the dielectric susceptibility or the polarizability of an optical material (Figure 2). Applied fields in the radio or microwave region oscillate slowly enough that polar molecular units can reorient and align in the direction of the field. The characteristic time for orientational

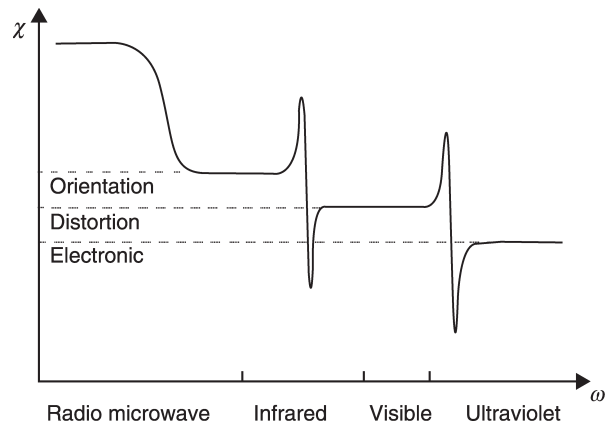


Figure 2 Contributions to the polarizability of a medium as a function of light frequency. At optical frequencies, the molecules cannot re-orient fast enough to follow the reversing electric field and the contribution of dipole orientation is lost.

motion is fairly long and this contribution is quickly lost when the molecules cannot follow the field oscillating at higher frequency. When the field reaches optical frequency, the two remaining contributions are the vibrational and electronic dipoles mentioned above. The vibrational dipoles involve a distortion of the chemical bond and are the slowest process occurring only in the infrared region. This contribution is lost at visible frequencies and leaves only the fast electronic polarization processes.

If we treat it rigorously, the polarization P is actually expressed as a function of higher order terms according to

$$P = \epsilon_0 (\chi E + \chi^{(2)} EE + \chi^{(3)} EEE + \dots) \quad [4]$$

This gives rise to nonlinear effects such as self-focusing and second or third harmonic generation. However, the higher order susceptibilities $\chi^{(n)}$ are very small and these effects are only significant for very high intensity light source such as lasers. In the following text we will only consider linear optical processes.

The Dipole Oscillator Model (Lorentz Oscillator)

In the Lorentz model, the bound electrons behave as harmonic oscillators and are constrained to vibrate at their natural resonant frequency ω_0 . These oscillators are also submitted to a damping force corresponding to a resistance to the motion due to collisional processes. The equation of motion is then

$$m \left(\frac{d^2 x}{dt^2} + \gamma \frac{dx}{dt} + \omega_0^2 x \right) = qE \quad [5]$$

where x is the displacement along E , γ is the damping factor, m is the mass of the electron and q its charge. The passage of an electromagnetic wave through a medium exerts an oscillating force on the electrons causing them to vibrate up and down. In other words these electronic dipoles are submitted to a forced oscillation induced by an electric field varying periodically with time. The electric field felt by the atomic dipoles is written as

$$E = E_0 e^{i\omega t} \quad [6]$$

where ω is the frequency of the light.

The electric field of the light wave then drives the dipole oscillations at its own frequency ω and the dipoles displacement oscillates according to

$$x = x_0 e^{i\omega t} \quad [7]$$

Solving eqn [5] for x in terms of E gives the expression for the displacement of the electrons

$$x = \frac{q/m}{\omega_0^2 - \omega^2 + i\gamma\omega} E \quad [8]$$

The atomic dipole moment p induced by the electrons displacement is therefore

$$p = qx = \frac{q^2/m}{\omega_0^2 - \omega^2 + i\gamma\omega} E \quad [9]$$

And for a medium with N atoms per unit volume the total polarization P is

$$P = N \frac{q^2/m}{\omega_0^2 - \omega^2 + i\gamma\omega} E \quad [10]$$

Our result in eqn [10] only contains one natural frequency ω_0 and therefore only accounts for one single type of oscillator in the medium. However, normal optical mediums are composed of different kind of atoms, each with several characteristic resonant frequencies ω_j . In our model, we can simply treat these multiple resonances by considering that each oscillator acts separately and add the contributions of all oscillators.

$$P = \left(\frac{q^2}{m} \sum_j \frac{N_j}{\omega_j^2 - \omega^2 + i\gamma_j\omega} \right) E \quad [11]$$

Comparing eqns [3] and [11] then gives an expression for the polarizability χ of the medium

$$\chi = \frac{q^2}{\epsilon_0 m} \sum_j \frac{N_j}{\omega_j^2 - \omega^2 + i\gamma_j\omega} \quad [12]$$

Additionally, the polarization P is associated with Maxwell's displacement vector, D , through the relationship

$$D = \epsilon_0 E + P \quad \text{and} \quad D = \epsilon E \quad [13]$$

where ϵ is the permittivity of the medium. The permittivity ϵ is normally expressed relative to the permittivity of vacuum ϵ_0 in terms of the dimensionless quantity $\epsilon_r = \epsilon/\epsilon_0$. Where ϵ_r is the familiar dielectric constant of a material, which is related to the refracted index n as $n = \sqrt{\epsilon_r}$.

Combining eqns [3] and [13] we obtain an important relationship linking χ to ϵ_r , and in turn χ to n .

$$\epsilon_r = 1 + \chi \quad \text{or} \quad n^2 = 1 + \chi \quad [14]$$

Finally, combining eqns [12] and [14] we obtain the expression for n in terms of the oscillator model.

$$n^2 = 1 + \frac{q^2}{\epsilon_0 m} \sum_j \frac{N_j}{\omega_j^2 - \omega^2 + i\gamma_j\omega} \quad [15]$$

The Refractive Index

Two important points should be made concerning the result of eqn [15]. The refractive index is a wavelength-dependent quantity and is a complex quantity. The complex refractive index \mathbf{n} is indeed usually expressed as

$$\mathbf{n} = n + i\kappa \quad [16]$$

where n is the real refractive index also defined as the ratio of the wave velocity in vacuum to the velocity in the medium $n = c/v$. And κ is the extinction coefficient, which is directly related to the absorption coefficient α as we shall see in the next section.

As we mentioned in the introductory section, the complex refractive index \mathbf{n} is sufficient to characterize the optical properties of the solid. The real part of the index describes the change in velocity or wavelength of a wave propagating from a vacuum into a medium while the imaginary part is a measure of the dissipation rate of the wave in the medium.

By inspection of eqn [15] we can predict the form of the variation of n with wavelength. At frequencies ω below the resonant frequency ω_j , the terms ω^2 and $i\gamma_j\omega$ are much smaller than ω_j^2 and to a first approximation n is constant. When ω reaches a resonant frequency ω_j , the term $(\omega_j^2 - \omega^2)$ goes to zero and since the term $i\gamma_j\omega$ is very small, the value of n increases very sharply and exhibit a resonance line as depicted in [Figure 3](#).

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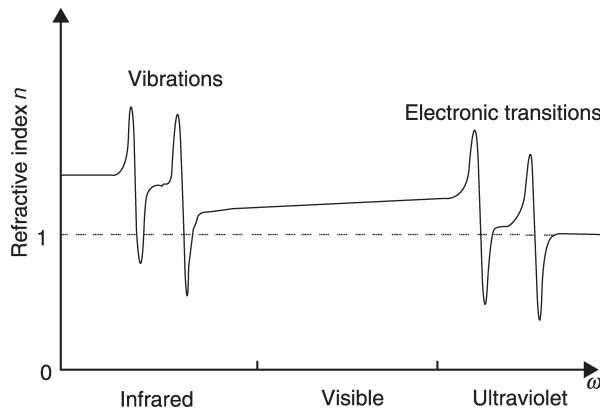


Figure 3 Variation of the refractive index of a hypothetical dielectric solid in the optical frequency range. At high frequency, ω is larger than all resonant frequencies and the refractive index n reaches unity.

On closer inspection of eqn [15] however, we can see that n is not exactly constant in between resonance lines. As ω rises, the denominator slightly decreases and therefore n rises slowly with frequency. The refractive index is then slightly larger for wave of higher frequency. This is why a glass prism bends blue light more strongly than red light. This phenomenon is called dispersion as waves of different frequencies are ‘dispersed’ by the prism.

Another important raised by eqn [15] is that because $(\omega_j^2 - \omega^2)$ goes to zero at a resonant frequency, the damping term $i\gamma_j\omega$ dominates and n becomes almost entirely imaginary. n is then mostly governed by the extinction coefficient κ . The damping associated with the coefficient γ_j corresponds to a friction force causing a loss of energy, which becomes the dominant effect during resonance. The resonance region is then associated with strong attenuation or absorption of the wave. In contrast, between resonant frequencies, the refractive index is almost entirely real as the imaginary part $i\gamma_j\omega$ is negligible in comparison with $(\omega_j^2 - \omega^2)$. Absorption is then very small and that region corresponds to the transparency domain of the material. In fact, we can assume that $n = n$ in the transparent region, that is why tables of optical constants of transparent optical materials only list the real part of the refractive index n . However, at resonant frequencies on either sides of the transparency domain, absorption becomes significant and the imaginary part of the refractive index must be taken into account so that $n = n + i\kappa$.

The refractive index n being a complex quantity it ensues that ϵ_r must also be complex, since $n = \sqrt{\epsilon_r}$. Hence we also define the complex dielectric constant as

$$\epsilon_r = \epsilon_1 + i\epsilon_2 \quad [17]$$

Both parameters describe equivalently the optical properties of a solid so that n or ϵ_r are called the optical constants of the material. Note that it is an unfortunate misnomer since they vary distinctly with wavelength (Figure 3).

Using equation [17] and $n = \sqrt{\epsilon_r}$, we can establish the relationships between the real and imaginary parts of n and ϵ_r .

$$\epsilon_1 = n^2 - \kappa^2 \quad [18]$$

$$\epsilon_2 = 2n\kappa \quad [19]$$

We can see that n and ϵ_r are not independent variables but that the real and imaginary part of ϵ_r can be calculated, knowing the real and imaginary part of n and vice versa.

Moreover, it can be shown that the real and imaginary parts of each individual parameter are not independent either but can be computed from one another with use of the following Kramers–Kronig relations.

$$\epsilon_1(\omega) = 1 + \frac{2}{\pi} \int_0^\infty \frac{\omega' \epsilon_2(\omega')}{\omega'^2 + \omega^2} d\omega' \quad [20]$$

$$\epsilon_2(\omega) = -\frac{2\omega}{\pi} \int_0^\infty \frac{\epsilon_1(\omega')}{\omega'^2 + \omega^2} d\omega' \quad [21]$$

In these equations, only the principal value of the integral is calculated so that ϵ_1 can be computed if ϵ_2 is known over all frequencies and vice versa. The same equation connect n and κ together.

This analysis shows that it is only necessary to know one real or one imaginary part over a wide frequency range to determine all others. The interaction of light with matter is in fact characterized by a single independent real quantity.

Absorption

All electromagnetic phenomena are governed by Maxwell’s equations. The form of an electromagnetic wave propagating through a medium is obtained by solving Maxwell’s equation. For a wave propagating along z through a homogeneous, optically isotropic medium the form of the oscillating electric field is given by:

$$E = E_0 e^{i(kz - \omega t)} \quad [22]$$

where k is the wave vector and ω the angular frequency of the light. For a wave traveling into a transparent medium of refractive index n , the

relationship between k and ω is

$$k = \frac{n\omega}{c} \quad [23]$$

However, for an ordinary optical material there are regions of absorption and the refractive index is therefore complex. We should then rewrite eqn [23] as

$$k = (n + i\kappa) \frac{\omega}{c} \quad [24]$$

By substituting this value of k in eqn [22] we obtain an expression with two exponential terms

$$E = E_0 e^{-\frac{\omega\kappa z}{c}} e^{i(\frac{\omega n z}{c} - \omega t)} \quad [25]$$

The term $e^{i(\frac{\omega n z}{c} - \omega t)}$ represents a wave traveling at a speed $v = c/n$, while the term $E_0 e^{-\frac{\omega\kappa z}{c}}$ represent the amplitude of this wave which decays exponentially with distance z . The intensity I of the wave is proportional to the square of the amplitude so that

$$I \propto e^{-\frac{2\omega\kappa z}{c}} \quad \text{or} \quad I \propto e^{-\alpha z} \quad [26]$$

where α is the familiar absorption coefficient routinely measured by absorption spectroscopy. Hence we obtain an important relationship relating the observable quantity α to the imaginary part of the refractive index κ according to

$$\alpha = \frac{2\kappa\omega}{c} \quad [27]$$

Local Field Correction

It should be pointed out that the derivation of our refractive index expression eqn [15] assumes that only the electric field of the light affects the polarization of the dipole oscillators. However, this assumption is not correct in dense materials because of the contribution from the electric field of neighboring atomic dipoles. The field generated by each dipole will affect all other dipoles in the vicinity. It is possible to approximate this contribution by accounting for the effect of dipoles within a local sphere. The result of this approximation is known as the Clausius–Mossotti equation, which is accurate for isotropic medium such as glasses and cubic crystals

$$\frac{n^2 - 1}{n^2 + 2} = \frac{\chi}{3} \quad [28]$$

Measurable Optical Parameters

Four things can happen to a beam of light propagating through a thick slab of optical material (Figure 4).

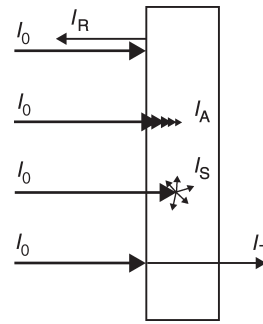


Figure 4 Representation of the four main optical processes happening to a beam as it propagates through a slab of transparent material. P0020

Some of the light can be reflected at the surface of the solid, some can be absorbed by the sample, some can be scattered in different directions, and some of the light can be transmitted through the sample. The effect on the light beam, resulting from these phenomena, can be quantified by a number of optical coefficients, which characterize the macroscopic properties of the material.

Reflection of light at the surface of a solid is described by the reflectance R defined as the ratio of the reflected intensity I to the incident intensity I_0 . For a beam falling perpendicularly on a flat surface, the reflection is called specular and is governed by the complex refractive index according to the Fresnel equation P0120

$$R = \frac{I}{I_0} = \frac{(n - 1)^2 + \kappa^2}{(n + 1)^2 + \kappa^2} \quad [29]$$

This provides us with a second important formula relating a measurable quantity (R) to the optical constant of the material. For measurements performed within the transparency region of a solid, the value of κ is much less than n and eqn [29] reduces to the more familiar form

$$R = \frac{(n - 1)^2}{(n + 1)^2} \quad [30]$$

Absorption occurs when the light frequency reaches the natural resonance of some dipole oscillators in the medium. The energy of the electromagnetic wave is partly transferred to the material and generally dissipated in the form of heat. The light intensity is therefore attenuated as it propagates through the material and the attenuation efficiency is quantified by the absorption coefficient α . The intensity decreases exponentially with pathlength z according to Beer's law

$$I(z) = I_0 e^{-\alpha z} \quad [31]$$

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where I_0 is the incident intensity. The imaginary part κ of the optical constant can then be directly obtained from measurements of α using eqn [27].

P0125 Scattering is the process whereby light is redirected in different directions due to microscopic density fluctuation in the sample produced by defects, impurities, or structural inhomogeneities. The intensity of light propagating in the forward direction is attenuated by the scattering event and it can be quantified in a way equivalent to absorption. The intensity has an exponential dependence on pathlength z analogous to Beer's law

$$I(z) = I_0 e^{-Sz} \quad [32]$$

where S is the scattering coefficient. When the scattering center is smaller than the wavelength of light this phenomenon is called Rayleigh scattering and the scattering coefficient S vary with the inverse fourth power of the wavelength

$$S(\lambda) \propto \frac{1}{\lambda^4} \quad [33]$$

By measuring light attenuation we cannot tell the difference between absorption and scattering and the total attenuation is $\alpha_{\text{Tot}} = \alpha + S$. However, the scattering contribution is generally much weaker than the absorption and can be neglected so that $\alpha_{\text{Tot}} = \alpha$.

P0130 Transmission occurs when the light is neither reflected, absorbed, or scattered. The beam is then transmitted through the sample and the fraction of light exiting the back surface is quantified as the transmittance T . If we disregard scattering in comparison to absorption then conservation of energy require that

$$R + T + A = 1 \quad [34]$$

where A is the fraction of light absorbed. The transmittance can then be compiled from R and α for an incident beam I_0 traveling across a sample of thickness l . In this case we must consider the reflection of the light on the front surface as well as on the back surface when it exits the transparent medium. The expression for the transmittance accounting for dual reflection is

$$T = (1 - R)^2 e^{-\alpha l} \quad [35]$$

It should be noted that a rigorous treatment of eqn [35] should account for multiple reflections between the front and back surface in the interior of the sample. In this case, interference effects complicate the determination of n and a modified version of eqn [35] can be computed by summing up the

intensities due to the contribution of the multiple reflections.

P0135 Transmission and reflection measurement are readily obtained using conventional spectrometers. Two types of spectrometers must be used to cover the entire optical spectral region. FTIR (Fourier Transform Infra Red) spectrometers use a glow bar as the light source, which enable to cover the infrared and near infrared domain. The UV-VIS (ultraviolet visible) double beam spectrometers use a tungsten and deuterium lamp and cover the spectrum from the ultraviolet down to the near infrared. Using eqns [27], [29] and [35], the reflection and transmission measurements thus obtained are used to calculate the real and imaginary component of the optical constant over the entire optical frequency range.

P0140 An example of transmission measurement is shown in Figure 5, for a dielectric and a semiconductor.

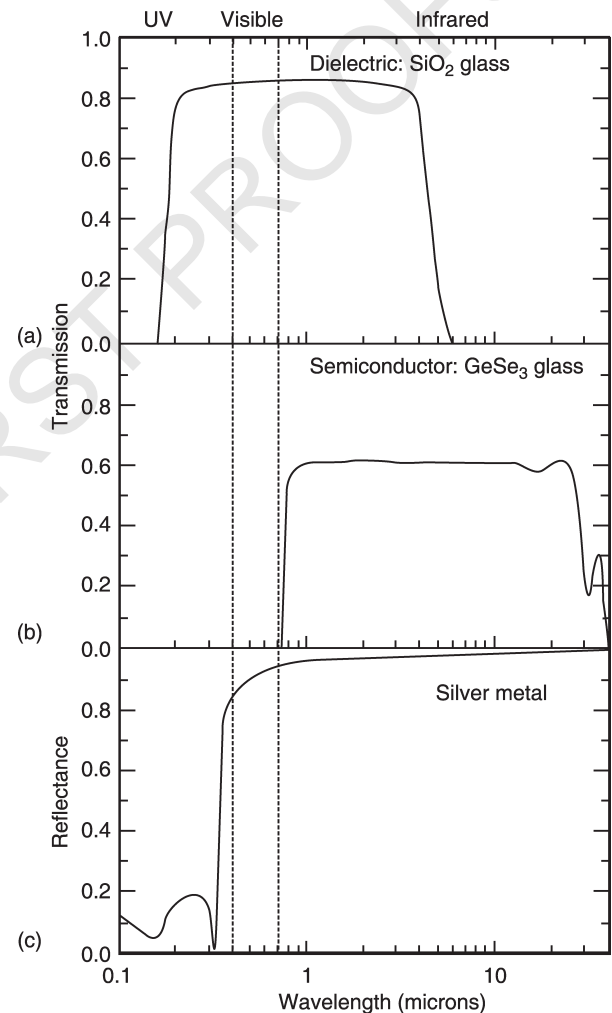


Figure 5 (a) Transmission spectrum of SiO₂ glass, a standard dielectric solid. (b) Transmission spectrum of GeSe₃ glass, a semiconductor ($E_g = 1.6$ eV). (c) Reflectance spectrum of silver metal. P0025

The two spectra have the same principal features. At short wavelength the edge of the transparency window is due to absorption of energy by the valence electrons. In classical terms this corresponds to the resonance of electronic oscillators, and in quantum mechanical terms to the excitation of electrons from the valence to the conduction band. This edge is due to a sharp increase of κ , which extends over a significant range of frequency corresponding to the domain of opacity or high absorption. The wavelength at the edge determines the minimum energy of the photon necessary to promote an electron across the bandgap Eg. Insulators have a large bandgap and appear transparent to the human eye because visible light is not energetic enough to promote an electron across Eg. In contrast, semiconductors have a smaller bandgap and appear black (opaque) because all the visible light is absorbed to induce electronic transitions. On the low frequency side the transparency window is limited by atomic vibrations in the solid structure. The wavelength of the vibrations increases with the mass of the atomic oscillators. Semiconductor compounds have higher atomic masses and therefore transmit at longer wavelength in the infrared while insulator have lower atomic mass and exhibit their vibrational absorption edge at shorter wavelength.

In between the two absorption regions, κ is very small and the material is transparent. The refractive index is almost entirely governed by the real part n . Eqn [15] shows that n is proportional to the number N of electronic oscillators. The refractive index will then be higher for heavy atoms with a high electronic density. Consequently, semiconductors exhibit a maximum transmission of only 60% because of significant surface reflectivity (eqn [35]) resulting from their higher refractive index n (eqn [30]).

Most applications of materials in optics are only concerned with the transparency domain so that the useful optical constant is reduced to the real part n . Hence a number of experimental techniques have been developed to obtain n , often by measuring angles of refraction with the use of Snell's law

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad [36]$$

where θ_1 is the angle of the beam incident in the medium of index n_1 , and θ_2 the angle of the beam refracted at the interface with a medium of index n_2 (Figure 6). The basic principle is to compare the sample with a standard glass of known refractive index and measure the refraction angle at their interface. The sample's index can then be obtained following eqn [36]. Since n varies with wavelength, these techniques are normally performed with

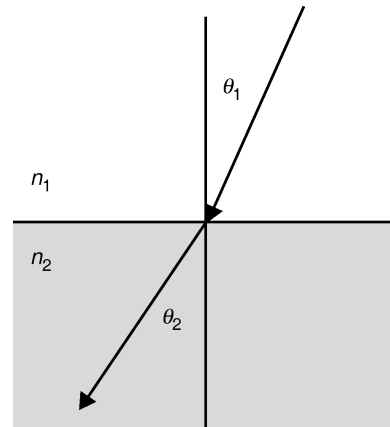


Figure 6 Refraction of a beam propagating across the interface between two mediums of different refractive index. The incident angle and the refraction angle are related to the index of refraction through Snell's Law.

monochromatic light and provide n at a single wavelength. Among these methods are: the *Abbe refractometer*, using a glass hemisphere as a standard, the *V-block refractometer*, using a V shaped prism as a standard, and the *prism goniometer* based on the relative deviation between a known glass prism and a prism shaped sample.

Ellipsometry is another technique widely used to measure the index n . This technique is normally used on thin films deposited on substrate, as it allows to simultaneously measure the thickness and the refractive index. However, the method can also be applied to bulk samples. The principle of ellipsometry is based on measuring the change in polarization of a beam reflected off the sample surface as a function of incidence angle. The reflected light is elliptically polarized to an extent depending on n . This technique is especially useful to measure n at frequency range above the absorption edge where the sample is highly absorbing.

Metals

The optical properties of metals are mainly characterized by their very high reflectivity, which causes their shiny appearance. All metals reflect light in the infrared and visible region up to a cutoff frequency in the ultraviolet. This critical frequency is called the plasma frequency ω_p . The physical significance of the plasma frequency can be understood using the Drude-Lorentz model of the free electron oscillator. As mentioned previously, the free electron can be described accurately as dipole oscillators with a resonant frequency $\omega_0 = 0$. If we consider a system with negligible damping, we can introduce $\gamma = 0$ and by assuming all free electrons to be equivalent we can

consider only one type of oscillators so that eqn [15] reduces to

$$n^2 = 1 - \frac{\omega_p^2}{\omega^2} \quad [37]$$

where

$$\omega_p^2 = \frac{Nq^2}{\epsilon_0 m_e} \quad [38]$$

Equation [37] means that in the low frequency domain $\omega < \omega_p$, the refractive index n must be imaginary ($n^2 < 0$) and in the high frequency domain $\omega > \omega_p$, n is a real positive number. The low frequency region is therefore dominated by the extinction coefficient κ and the reflectance R , given by eqn [29], is essentially unity. In the high frequency limit, R decreases and n is real. These features are shown in Figure 5c. Metals are opaque and highly reflective below the plasma frequency, while they become transparent in the ultraviolet.

v	phase velocity
α	absorption coefficient
ϵ_0	permittivity of vacuum
ϵ_r	relative dielectric constant
κ	extinction coefficient
λ	wavelength
μ	reduced mass
χ	dielectric susceptibility
ω	angular frequency
ω_0	resonant frequency
ω_p	plasma frequency

See also

Optical Instruments: Ellipsometry (00833); Spectrometers (00837). **Optical Materials:** Scattering from Surfaces and Thin Films (00875).

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List of Units and Nomenclature

A	absorbance
c	light velocity in vacuum
D	electric displacement
E	electric field
I	intensity of light (power per unit surface)
k	wave vector
m_e	mass of electron
m_N	mass of nucleus
n	complex refractive index
n	real refractive index
p	dipole moment
P	polarization
q	charge of electron
R	reflectance
S	scattering coefficient
T	transmittance

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