Introduction

This article describes some complex devices which are commonly used in the laboratory for analysis of condensed matter, instruments which measure the fundamental quantity of light, and use the interaction between light radiation and matter. It is assumed, that the reader is confident with simple optical instruments such as lenses, mirrors, prisms, and diffraction gratings. A complete description of the fundamental optical phenomena is given elsewhere in this encyclopedia and can be easily found in literature on fundamental optics. Before describing optical instruments in detail, a brief overview of light behavior is given. Among the instruments commonly used in the laboratory, the spectrometer or devices based on scattering, absorption, and reflection are widely described in other sections of this encyclopedia. Also interferometric methods used in microscopy are illustrated elsewhere. Here, the focus is on the following instruments: refractometer, interferometer, polarimeter, ellipsometer, and radiometer.

Optical Terminology and Fundamental Optical Phenomena

Light is an electromagnetic wave with wavelengths between 0.1 nm and 100 μm. Visible light corresponds to wavelength in the range of 400–700 nm, vacuum ultraviolet light is in the range 0.1 μm to 10 nm; at the other end of the wavelength scale between 100 and 1000 μm is the microwave region. Figure 1 shows electromagnetic wavelength regions and Table 1 shows important parameters that are used to characterize light and the media through which it passes. At this point, a few comments are necessary. First of all in free space, light behaves like a transverse wave which means that the variations of the electric vector \( \mathbf{E} \), are perpendicular to the propagation direction. In electromagnetic waves, the electric field \( \mathbf{E} \) and magnetic field \( \mathbf{B} \) are perpendicular to each other and to the propagation vector \( \mathbf{k} \) (Figure 2). The simplest case of a three-dimensional wave is the plane wave in which all the surfaces upon which a disturbance has a constant phase form a set of planes, each generally perpendicular to the propagation direction. There are quite practical reasons for studying this sort of wave, one of which is that by using optical devices, one can readily produce light resembling plane waves, and this case is taken up in detail in the following.

The mathematical expression for a plane wave that is perpendicular to a given vector \( \mathbf{k} \) in complex representation is

\[
E = E_0 e^{i(\mathbf{k} \cdot \mathbf{r} + \omega t)}
\]

The vector \( \mathbf{k} \) whose magnitude is the propagation number \( k \) is called the propagation vector, and it is linked to the wave quantity by the following useful relations:

\[
k = \frac{2\pi}{\lambda} = \frac{2\pi n}{\lambda_0}
\]

where \( \lambda \) is the wavelength, and \( n \) is the refractive index of light. The speed of light is

\[
\nu = \lambda \nu = n \lambda_0 \nu = nc
\]

where \( c \) is the velocity of light in vacuum

\[
c = 2.997 \ 924 \ 58 \times 10^8 \ \text{m s}^{-1}
\]
ray direction. The time-averaged value of the magnitude of the Poynting vector is the irradiance and is given by

\[ I = \langle S \rangle = \varepsilon_0 c \langle E^2 \rangle \]  

where \( \varepsilon_0 \) is the permittivity of free space, \( 8.8542 \times 10^{-12} \text{Fm}^{-1} \).

Since light in vacuum is a transverse wave, an appreciation of its vectorial nature is of great importance, which means that all phenomena of optical polarization should be treated in terms of a vector wave picture. Before going into details of optical devices, two things should be noted. One is that electromagnetic waves propagating in real material media are generally not transverse. Another is that for unpolarized light, in which the wave vector changes direction randomly and rapidly, or in some other cases, scalar approximation becomes useful, as in the theory of interference and hence the simpler scalar representation of the light wave is considered wherever possible.

The parameter used to describe the interaction of light with the material is the complex index of refraction \( \tilde{n} \), which is a combination of a real part and an imaginary part and is given by

\[ \tilde{n} = n + i \kappa \]  

The real part is called the index of refraction and the imaginary part the extinction coefficient. For a dielectric material such as glass, none of the light is absorbed and \( \kappa = 0 \); in this case the concern is only \( n \), as previously defined. In an absorbing medium, \( \kappa \) describes the attenuation of the wave field in the

[Table 1 Fundamental parameters of electromagnetic radiation and optical media]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity of light in vacuo</td>
<td>( c_0 = \sqrt{\mu_0 \varepsilon_0} )</td>
<td>( 2.997 , 924 , 58 \times 10^8 )</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>Permeability of free space</td>
<td>( \mu_0 )</td>
<td>( 4\pi \times 10^{-7} )</td>
<td>H m(^{-1})</td>
</tr>
<tr>
<td>Permittivity of free space</td>
<td>( \varepsilon_0 )</td>
<td>( 8.854 , 16 \times 10^{-12} )</td>
<td>F m(^{-1})</td>
</tr>
<tr>
<td>Velocity of light in a medium</td>
<td>( c = \sqrt{\mu_0 \varepsilon_0} )</td>
<td>( \frac{c}{n} )</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>Refractive index</td>
<td>( n = \sqrt{\frac{\varepsilon_r}{\mu_r}} )</td>
<td>usually 1</td>
<td>dimensionless</td>
</tr>
<tr>
<td>Relative permeability of a medium</td>
<td>( \mu_r )</td>
<td></td>
<td>dimensionless</td>
</tr>
<tr>
<td>Dielectric constant of a medium</td>
<td>( \varepsilon_r )</td>
<td></td>
<td>dimensionless</td>
</tr>
<tr>
<td>Frequency</td>
<td>( \nu = \frac{c}{\lambda} )</td>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>Wavelength in vacuo</td>
<td>( \lambda_0 = \frac{c}{\nu} )</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Wavelength in a medium</td>
<td>( \lambda = \frac{c}{\nu} = \frac{\lambda_0}{n} )</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Wave number</td>
<td>( \tilde{\nu} = \frac{1}{\lambda} )</td>
<td></td>
<td>cm(^{-1})</td>
</tr>
<tr>
<td>Wave vector</td>
<td>( k = \frac{2\pi}{\lambda} )</td>
<td></td>
<td>m(^{-1})</td>
</tr>
<tr>
<td>Photon energy</td>
<td>( E = \hbar \nu )</td>
<td></td>
<td>J (1.6 \times 10^{-19} J = 1 \text{eV})</td>
</tr>
<tr>
<td>Electric field of wave</td>
<td>( E )</td>
<td></td>
<td>V m(^{-1})</td>
</tr>
<tr>
<td>Magnetic field of wave</td>
<td>( B )</td>
<td></td>
<td>A m(^{-1})</td>
</tr>
<tr>
<td>Poynting field of wave</td>
<td>( S = E \times B )</td>
<td></td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>Intensity</td>
<td>( I = \langle S \rangle )</td>
<td></td>
<td>W m(^{-2})</td>
</tr>
</tbody>
</table>

[Figure 2 Picture of a plane polarized light. For plane polarized light, the \( E \) and \( B \) vector remain in perpendicular planes to the propagation vector \( k \).]

and where the wave frequency

\[ \nu = \frac{\omega}{2\pi} \]  

[5]

It is to be noticed that at any given time the surfaces joining all points of equal phase are known as wave fronts.

The velocity of light in vacuum is \( c = \sqrt{\mu_0 \varepsilon_0} \); in a medium, it depends both on the relative magnetic permeability \( \mu_r \) and dielectric constant \( \varepsilon_r \) of the medium, \( \mu_r = 1 \) for all practical optical materials so that the refractive index and the dielectric constant are related by \( n = \sqrt{\varepsilon_r} \). When light propagates in a non-isotropic medium, such as a crystal, \( n \) and \( \varepsilon_r \) will generally depend on the direction of the wave propagation and its polarization state.

The Poynting vector

\[ S = c^2 \varepsilon_0 E \times B \]  

[6]
medium and it is related to the absorption linear coefficient. A complex index of refraction is a characteristic of an absorbing medium.

Real and imaginary parts of the index of refraction are, in fact, functions of the wavelength \( \lambda \); this is why when white light enters a prism, it emerges with the various colors separated. This phenomenon is called dispersion and is described by the Kramers–Kronig equations for both the real and imaginary part of the complex index of refraction or by an approximated expression by power series of 1 = \( \lambda \) using Cauchy coefficient. For optical materials, the change of index with wavelength is very gradual, and often negligible, unless the wavelength approaches a region where the material is not transparent. For this reason, in this article the description of optical systems is simplified assuming that the light is monochromatic. When light is reflected by a plane boundary between two media of different refractive index, the three rays, that is, incident, reflected, and refracted lie in the same plane and the angle of incidence is always equal to the angle of reflection as shown in Figure 3. When a light ray crosses the boundary, the angle of refraction \( \theta_2 \) is related to the angle of incidence accordingly to Snell’s law

\[
\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1} \quad [9]
\]

If \( n_2 < n_1 \), there is a maximum angle of incidence for which there can be a refracted wave because \( \sin \theta_2 \) cannot be greater than unity for a real angle. This is called the critical angle \( \theta_c \) and is given by \( \sin \theta_c = n_2/n_1 \). Total internal reflection is illustrated in Figure 3 when \( \theta_1 \) exceeds \( \theta_c \) and the boundary acts as a very good mirror.

One or both the media in Figure 3 may be anisotropic. The incident wave will then generally split into two components, and assist a double-refraction phenomenon. One of the components obeys Snell’s law directly (the ordinary wave) while for the other component, Snell’s law is modified (the extraordinary wave).

Looking at the wave field at a boundary between two media, it can be seen that there is still an interdependence sheared by the amplitudes which can be evaluated and which depends on polarization as in a case in which \( E \) is perpendicular as well as parallel to the plane of incidence. There are two expressions that are general statements that apply to all linear, isotropic, and homogeneous media; they are called Fresnel equations. For electric field of the wave field perpendicular to the plane of incidence (S polarization)

\[
r_s = \frac{E_{0s}}{E_{0t}} = \frac{n_2 \cos \theta_1 - n_1 \cos \theta_t}{n_2 \cos \theta_1 + n_1 \cos \theta_t} \quad [10]
\]

Figure 3 (a) Reflection and refraction of a light ray at the boundary between two different isotropic media of refractive index \( n_1 \) and \( n_2 \). The case shown is for \( n_2 > n_1 \). (b) Critical angle and (c) total internal reflection for \( n_1 > n_2 \).

Here \( r_s \) denotes the amplitude reflection coefficient and \( t_s \) is the amplitude transmission coefficient.

For electric field of the wave field parallel to the plane of incidence (P polarization)

\[
\frac{E_{0s}}{E_{0t}} = \frac{n_2 \cos \theta_1 - n_1 \cos \theta_t}{n_2 \cos \theta_1 + n_1 \cos \theta_t} \quad [12]
\]

\[
t_p = \frac{E_{0p}}{E_{0t}} = \frac{2n_2 \cos \theta_1}{n_1 \cos \theta_t - n_2 \cos \theta_t} \quad [13]
\]

When the reflecting surface is not a dielectric and \( k \) is nonzero, the index of refraction in the Fresnel equations is the complex index of refraction and the Fresnel equations are in general complex number.
Refractometer

The index of refraction is a topical parameter for isotropic material. Most of the refractive index measurements are based on “prism refraction.” Since the angle of deviation between the incident beam and the refracted beam from a prism varies with the angle of the prism, with the angle of incidence of the ray on the prism, and with the refractive index of the prism, measuring angles involved in the process gives the value of the refractive index of the prism. The deviation of a ray of light passing through a simple prism can be described with the aid of Figure 4. The various angles $z$, $i$, $r$, and $\theta$ satisfy Snell’s law irrespective of the polarization state of the input beam, provided the prism is made of an isotropic material. The deviation $\theta$ of a ray depends on the incidence angle $i$ and increases as the angle of incidence is increased. From the symmetry of the system, it follows that the deviation is minimum for the ray that passes through the prism symmetrically. When the prism is used in the position of minimum deviation

$$i = \frac{1}{2} z + \frac{1}{2} \theta$$

Hence, in the minimum deviation condition, the prism index of refraction is

$$n = \frac{\sin (z + \theta)/2}{\sin z/2}$$

When $\theta$ and $z$ have been measured, the refractive index of the prism material can be calculated. If the angles are measured to about one second, $n$ can be found to $\pm 0.0001$.

The configuration can be used to determine the refractive index of a liquid by employing a hollow prism whose faces are parallel-sided plates of glass. The walls of such a vessel have no effect on the angle of deviation, and the angle of the liquid prism is the same as that of the vessel. Hence, $z$ and $\theta$ can be measured in the usual way. It is important to point out that the refractive index of liquid varies rapidly with temperature, and there is usually no point in attempting an accuracy better than 0.0001 in the refractive index unless special care is given to temperature control.

Widely used is the “critical angle prism refractometer” which uses a critical angle configuration: the idea is to look at the light totally reflected by the internal prism wall. An alternative method is to position the incident beam so that rays fall on the prism at grazing or near-grazing incidence. The rays falling on the face BA of Figure 4b at grazing incidence emerge from face AC at angle $\phi$, and those rays incident on BA at angles less than 90° emerge from AC at an angle greater than $\phi$. No light emerges at angles less than $\phi$. When a detector is placed in front of the AC plane, with the arrangement shown in the figure, the right-hand side of the field view is dark and the left-hand side of the field view is bright; the edge between the bright and dark zones is used to measure $\phi$. In this configuration

$$n^2 = 1 + \left(\frac{\sin \phi + \cos z}{\sin z}\right)^2$$

gives the refractive index of the prism material.

The same method may be employed to determine the refractive index of a liquid of which only a small
quantity is available, provided the index of the prism is greater than that of the liquid. A drop of the liquid is placed on the face BA and a thin glass plate is placed over it. If necessary, it is possible to have a wedge form of the liquid to be examined, and the glass is held in position by a capillary action. In this case, the refraction index of the liquid is

\[ n_0 = \sin \alpha \sqrt{n^2 - \sin^2 \phi} - \cos \alpha \sin \phi \]  

It should be noted that the maximum possible value of \( r \) is the critical angle, and that there is a grazing incidence and a grazing emergence. Hence, the angle of a prism used in the upper configuration must not be greater than twice the critical angle, otherwise it is impossible for rays to be transmitted through the prism.

A two-prism configuration with the critical-angle method is used in the Abbe refractometer, shown in Figure 5a. The liquid under test is placed between two prisms of high refractive index. The prism P corresponds to the prism to be used in the total reflection configuration. Light that strikes P in grazing incidence emerges at the angle \( \phi \) to be measured. The measurement of the emerging angle would enable one to determine the refractive index of the liquid, if \( \alpha \) and the refractive index \( n \) of P are known.

Critical-angle based refractometers have three main disadvantages: (1) they measure light rays coming from the prism on a field view where bright and dark areas have to be separated and measured, which is a basically asymmetric system, (2) the refractive index of the glass prism must be greater than that of the specimen under test, and (3) the measured index corresponds to a surface layer and may differ from that of the main bulk of the specimen. The Hilger-Chance instrument (Figure 5b) was developed to overcome these difficulties. The composite glass block is made by combining two prisms as indicated. Monochromatic collimated light passes through the V-block and specimen. The direction of the emergent light depends upon the refractive index of the specimen. It will be seen that two perpendicular plane surfaces must be produced on the specimen, but it is not necessary for these to be of the highest quality since a film of liquid can be placed between the faces of the specimen and the V-block. Since the method is not a critical-angle method, the refractive index of the specimen can be greater than or less than that of the V-block. The accuracy found with this instrument is 0.000 01. The instrument can be used for liquids if the V-block is provided with side plates to form a trough, but 2–3 cc of liquid are required.

Finally, accurate measurements of the index of refraction up to 0.000 001 can be done using interferometry which measures the optical path difference (geometrical difference per index of refraction), and hence provides the index of refraction of the sample under test if the geometric path (usually thickness of the sample) is well known. The interferometric technique is widely used for several samples, isotropic or not, also for polarizing active material. Ellipsometry remains at the moment the most powerful method for investigating complex systems, such as nonisotropic multilayered samples or gradient varying samples.

**Interferometers**

Interferometers are complex optical devices based on interference phenomenon. Optical interference occurs when two or more light waves interact yielding a resultant irradiance that deviates from the sum of the component irradiances.

A few of the more important interferometric systems will be examined here. Interferometric devices are divided into two groups: wave front splitting and amplitude splitting. In the first case, portions of the primary wave front are used as sources to emit secondary waves, or in conjunction with optical devices to produce virtual sources of secondary waves. These secondary waves are then brought together to interfere. In the case of amplitude splitting, the primary wave itself is divided into two segments, which travel different paths before recombining and interfering.

In accordance with the principle of superposition, the light field or the electric field intensity \( E \), at a
point in space, arising from the separate field \( E_1, E_2, \ldots \) of various contributing sources is given by

\[
E = E_1 + E_2 + \cdots \tag{18}
\]

Taking the time average of both sides, one finds that the irradiance in the case of two superposed fields becomes \( I = I_1 + I_2 + I_{12} \) provided that \( I_1 = \langle E_1^2 \rangle \), \( I_2 = \langle E_2^2 \rangle \), and \( I_{12} = 2 \langle E_1 \cdot E_2 \rangle \), where \( \langle \rangle \) is the time average over a time interval \( T \) much greater than the period of the harmonic function. The latter expression is known as the interference term and is \( I_{12} = \langle E_{01} \cdot E_{02} \cos \delta \rangle \), and \( \delta = (k_1 \cdot r - k_2 \cdot r + \phi_1 - \phi_2) \) is the phase difference arising from a combined path length and initial phase-angle difference.

The most common situations correspond to \( E_{01} \) parallel to \( E_{02} \). In that case, the irradiance reduces to the value found in the scalar case: \( I_{12} = E_{01} E_{02} \cos \delta \) and the total irradiance is

\[
I = I_1 + I_2 + 2 \sqrt{I_1 I_2} \cos \delta \tag{19}
\]

If a screen is placed in the region of interference, bright and dark zones would be visible, which are known as interference fringe patterns.

At various points in space, the resultant irradiance can be greater, less than, or equal to \( I_1 + I_2 \), depending on \( \delta \). When \( \delta = 0, \pm 2\pi, \pm 4\pi, \ldots \) \( \cos \delta = 1 \) and maximum of irradiance is obtained. The waves are said to be in phase and one speaks of this as total constructive interference. When \( 0 < \cos \delta < 1 \), the waves are out of phase. As \( \delta = \pi/2 \), \( \cos \delta = 0 \) the optical disturbance is said to be 90° out of phase, and \( I = I_1 + I_2 \). For \( -1 < \cos \delta < 0 \), one has the condition of destructive interference. The minimum in the irradiance results when the waves are 180° out of phase, \( \cos \delta = -1 \). This occurs when \( \delta = \pm \pi, \pm 3\pi, \pm 5\pi, \ldots \), and it is referred to as total destructive interference.

A special case arises when \( I_1 = I_2 = I_0 \), the two sources have equal irradiance and

\[
I = 2I_0(1 + \cos \delta) = 4I_0 \cos^2 \frac{\delta}{2} \tag{20}
\]

for which it follows that \( I_{\text{min}} = 0 \) and \( I_{\text{max}} = 4I_0 \).

When two beams interfere to produce a stable pattern, they must have very nearly the same frequency. A significant frequency difference would result in a rapidly varying, time-dependent phase difference, which in turn would cause \( I_{12} \) to average to zero during the detection interval. The most common means of overcoming this problem is to make one source serve to produce two coherent secondary sources.

It is to be remembered that because of the granular nature of the emission process, conventional monochromatic sources produce light that is a mix of photon wave trains. At each illuminated point in space, there is a net field that oscillates for less than 10 ns or so before it randomly changes phase. This interval over which the lightwave resembles a sinusoid is a measure of what is called its temporal coherence time. The average time interval during which the lightwave oscillates in a predictable way is designated as the coherence time of the radiation. The longer the coherence time, the greater the temporal coherence of the source. The corresponding spatial extent over which the lightwave oscillates in a regular, predictable way is called the coherence length \( l_c = c \times t_c \), where \( c \) is the velocity of light. The most common means to produce interference, as will be seen, is to make one source serve to produce two coherent secondary sources that will interfere. An interference fringe pattern will be seen as long as the difference between the optical paths of the two secondary sources is no longer than the coherence length of the lightwave. Nowadays, laser sources are quite cheap and easier to use than lightwave sources with a temporal coherence ranging up to at least 1 ms, corresponding to Km of coherence length.

**Wave Front Splitting Interferometer**

A hypothetical monochromatic plane wave illuminating two parallel narrow closely spaced slits, \( S_1 \) and \( S_2 \), is to be considered. This is shown in a two-dimensional view in Figure 6. When symmetry exists, the segments of the primary wave front arriving at the two slits will be exactly in phase, and the slits will constitute two coherent secondary sources. One expects that the two waves coming from \( S_1 \) and \( S_2 \) overlap, interference will occur (provided the optical path difference is less than the coherence length, \( c \cdot t_c \)). In a realistic physical situation, the distance between the screen and the slits will be very large in comparison with the distance \( a \) between the two slits, and all the fringes would be fairly close to the center \( O \) of the screen. One can express the path difference as

\[
r_1 - r_2 = a \theta \tag{21}
\]

since \( \theta \sim \sin \theta \).

Following this approximation \( \theta = y/s, r_1 - r_2 = ay/s \). Constructive interference will occur when \( r_1 - r_2 = m\lambda \); thus from the last two relations, one obtains

\[
y_m = \frac{s}{a} m\lambda \tag{22}
\]
This gives the position of the \( m \)th bright fringe on the screen, if the maximum at 0 is counted as the zeroth fringe.

The interferometric configuration discussed above is known as Young’s experiment. The same physical and mathematical considerations apply directly to a number of other wavefront splitting interferometers. Most common among these are Fresnel double mirror, Fresnel double prism, diffraction grating, and mirror configuration.

### Amplitude Splitting Interferometer

Suppose that a light wave was incident on a semi-transparent mirror, or simply a sheet of glass. Part of the wave is transmitted and another part is reflected. Both the transmitted and the reflected waves will have lower amplitudes than the original one. When the two separate waves are brought together again at the detector, interference results as long as the original coherence between the two are not destroyed and if the path length differs by a distance lower than the coherence length.

#### Dielectric films

The simpler amplitude splitting interference effects are observable in sheet transparent materials. Consider the simple case of a transparent parallel plate of dielectric material having a thickness \( d \) (Figure 7). Suppose that the film is nonabsorbing and that the amplitude–reflection coefficients at the interfaces are so low that only the first two reflected beams \( E_{1r} \) and \( E_{2r} \) need be considered. One may consider \( S \) to be a monochromatic point source. The film serves as an amplitude-splitting device, so that \( E_{1r} \) and \( E_{2r} \) are parallel on leaving the film and can be brought together at a point \( P \) on the focal plane of a lens. From Figure 7, the optical path length difference for the two reflected beams is given by

\[
\Lambda = 2n_d \cos \theta_1 \tag{23}
\]

The corresponding phase difference associated with the optical path-length difference is then just the product \( k_0 \Lambda \), where \( k_0 = 2\pi/\lambda_0 \). If the film is immersed in a single medium \( n_1 = n_2 = n \) and there...
is an additional phase shift arising from the reflections between the two light beams themselves, one internally and one externally reflected, there will be a relative phase shift of $\pi$ radians. Accordingly, $\delta = k_0 \Lambda \pm \pi$. In the reflected light, an interference maximum, a bright spot appears at $P$ when $\delta$ is an even multiple of $\pi$. In that case

$$d \cos \theta = (2m + 1) \frac{\lambda_0}{4n_s}$$

[24]

This also corresponds to a minima in the transmitted light. Interference minima in reflected light (maxima in transmitted light) result when $\delta$ is an odd multiple of $\pi$. For such cases

$$d \cos \theta = 2m \frac{\lambda_0}{4n_s}$$

[25]

The thickness of sheet transparent materials commonly used in optics, varies from films less than the length of a light wave, to plates several centimeters thick. A layer of material is referred to as a thin film for a given wavelength of electromagnetic radiation when its thickness is of the order of that wavelength. The applications of thin dielectric films are manifold, as are their structures which extend from the simplest single coatings to intricate arrangements of hundreds of layers. Coatings for high reflecting mirrors, to eliminate unwanted reflections, nonabsorbing beamsplitters, dichroic mirrors, multilayer broad, and narrow bandpass filters are examples of the thin film optical devices.

**Mirrored interferometer** Among the amplitude-splitting interferometers that utilize mirrors and beam splitters, the best known and historically most important is the Michelson interferometer. Its configuration is illustrated in Figure 8: a quasimonochromatic source emits a wave, part of which travels to the right. The beam splitter $O$ divides the wave into two, one segment traveling to the right and one up into the background. The two waves are reflected by mirrors $M_1$ and $M_2$ and return to the beam splitter. Part of the wave coming from $M_2$ passes through the beam splitter going downward, and part of the wave coming from $M_1$ is deflected by the beam splitter toward the detector. Thus the two waves are united, and interference can be expected. The optical path difference for these rays is $2d$, where $d$ is the difference length between the two interferometer arms ($OM_1$ and $OM_2$), which represents a phase difference of $k_0 2d$. There is an additional phase term arising from the fact that the wave traversing the arm $OM_2$ is internally reflected in the beam splitter, whereas the $OM_1$ wave is internally reflected at $O$. If the beam splitter is simply uncoated, the relative phase shift resulting from the two reflections will be $\pi$ radians. Destructive rather than constructive interference will occur when $2d = m \lambda_0$, where $m$ is an integer. If the light source is slightly divergent, an observer will see a circular fringe system. When the mirrors of the interferometer are inclined with respect to each other, making a small angle (i.e., when $M_1$ and $M_2$ are not quite perpendicular), a pattern of straight parallel fringes is visible.

It is apparent that the Michelson interferometer can be used to make extremely accurate length measurements. As the movable mirror is displaced by $\lambda_0/2$, each fringe will move to the position previously occupied by an adjacent fringe. One need only count the number of fringes $N$, or a portion of a fringe, that has moved past a reference point to determine the distance traveled by the mirror $\Delta d = N(\lambda_0/2)$.  

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**Figure 7** Thin layer interference.

**Figure 8** Michelson interferometer.
Very accurate measurements of wavelengths are also performed using the Michelson interferometer. The beam of a reference light source, usually a very stable and well-known wavelength $\lambda_r$, and the beam within the unknown wavelength $\lambda_x$ are aligned into the interferometer with identical paths but opposite directions. This produces two different fringe systems to be revealed by two different detectors. While the movable mirror is displaced, sinusoidal signals are visible by the detectors: the rates of the interference maxima are counted by the detectors for both the known and unknown wavelengths. From the ratio of both counting rates, the unknown wavelength $\lambda_x$ can be obtained by $\frac{\lambda_x}{\lambda_r} = \frac{N_r}{N_x}$.

The Twyman–Green interferometer is essentially a variation of the Michelson interferometer. It is an instrument of great importance in the domain of modern optical testing. Illustrated in Figure 9, the setup has a lens $L_1$, used to provide a source of incoming plane waves, and a lens $L_2$, which permits all the light, from the aperture to enter the detector so that the entire field can be seen.

Twyman–Green interferometers are used to test the quality of a surface or of a lens with respect to a reference wave front. For instance, if a reference flat high-quality surface is used for mirror $M_1$, the mirror $M_2$ can be tested and any wave front distortions produced by the surface of $M_2$ will appear in the final interferogram, provided that high-quality low-deformation lenses $L_1$ and $L_2$ have been used.

The Mach–Zehnder interferometer shown in Figure 10 consists of two beamsplitters and two totally reflecting mirrors. The two waves within the apparatus travel along separated paths. A difference between the optical paths can be introduced by a slight tilt of one of the mirrors. Since the two paths are separated, the interferometer finds myriad applications. An object interposed in one beam will alter the optical path-length difference, thereby changing the fringe pattern. This results in a very accurate determination of the index of refraction of the sample and its local variations. For these reasons, a common application of the device is to observe the density variations in liquid or gas flow patterns.

Another amplitude-splitting device is the Sagnac interferometer shown in Figure 11. It is to be noticed that the main feature of the device is that there are two identical but oppositely directed paths taken by the beams that form closed loops before they are united to produce interference. A slight shift in the orientation of one of the mirrors will produce a path-length difference and a resulting fringe pattern changing. When the entire interferometer (mirrors, source, and detector) rotates about a perpendicular axis passing through its center, the rotation effectively shortens the path taken by one beam in comparison to that of the other. In the interferometer, the result is a fringe shift proportional to the angular

---

**Figure 9** Twyman–Green interferometer and arrangement for a mirror test.

**Figure 10** Mach–Zehnder interferometer.

**Figure 11** Sagnac interferometer.
speed of rotation $\Omega : \Delta N = 4A\Omega/c\lambda$, where $A$ is the area formed by the beams of light.

Shearing interferometer The method of lateral shearing interferometry consists of displacing the light beam wave front laterally by a small amount and obtaining the interference pattern between the original and the displaced wave fronts. **Figure 12** schematically illustrates the principle in one of the simpler experimental configurations, based on a plane parallel plate. There are many physical arrangements to obtain lateral shear. The most popular arrangements derive from the use of beam dividers, that means, of amplitude splitting interferometers. In this way, the amplitude of the incident wave front is divided, but the shape of the wave front does not change. If the wave front is considered nearly planar, it can be expressed as $W(x, y)$, where $(x, y)$ are the coordinates of point $P$. When this wave front is sheared in the $x$ direction by an amount $s$, the sheared wave front is expressed by $W(x - s, y)$. The resultant path difference at $P$ between the original and the sheared wave front is:

$$\Delta W = W(x - s, y) - W(x, y)$$

The path difference $\Delta W$ may be obtained at various points on the wave front from the relation: $\Delta W = m\lambda$, where $m$ is an integer indicating the order of the interference fringe. It is expected that for a perfect, plane wave $\Delta W = 0$ a null fringe will occur, but as soon as the wave front is distorted and $\Delta W$ is not zero, a fringe system, sometimes rather complicated, is visible. When the wave front is laterally sheared, normally it is assumed that the new wave front is not tilted with respect to the original one. It is possible to obtain a known amount of tilt between the two wave fronts by using a wedge with a small angle instead of a parallel plate in **Figure 12** setup. In such a case, the optical path difference associated with this tilt may be presented as a linear function of the coordinate along the tilt, and a system of straight fringes is generated. A deviation from the straight fringe system is a measure of the wave front deformation.

Lateral shearing interferometers are commonly used for checking the collimation of a lens, or measuring lens parameters such as focal length or the refractive index, for studying of homogeneity of transparent solid samples, and for flow studies. Another application involves the measurement of surface imperfections of concave or convex surfaces.

Here, it is important to note that Mach–Zehnder, Twyman–Green, and shearing interferometers are widely used in noncontact measurement of surface height profiles. They can be used to determine surface roughness or geometries of small features. All these interferometric profile measurements are noncontact and therefore do not harm the surface under test. They are very sensitive and can measure heights with a precision of up to 0.1 Å RMS (root mean square). Quantitative phase-measurement techniques are generally used to determine the phase difference between an object point and a reference. This phase is then converted into height information. Because of

![Figure 12](https://example.com/figure12.png)

**Figure 12** Schematic diagram of a lateral shearing interferometer using a plane parallel plate of glass. Diagram also illustrates the original and the sheared wave front, and lateral shearing interferogram of a wave front distorted by spherical aberration.
the precision in measurement and noncontact configuration, interferometric optical profilometers are appropriate for on-line process control. All these instruments measure heights relative to a reference surface rather than absolute distance. All profiling instruments can be calibrated relative to an existing, traceable standard; however, most of these instruments are better than existing standards, so it is hard to determine their absolute accuracy.

The main limitation of interferometric optical profilers is due to the phase shift induced by reflection of the object beam from the test surface. Every material induces a phase shift depending on its complex index of refraction. As long as a surface comprises of a single material and does not have a transparent coating on it, the phase shift does not cause a problem. When two dissimilar materials are next to each other on the surface, they will have different phase shifts upon reflection and the height difference at the boundary will be incorrect. This problem can be overcome using a coating with an opaque material, or by knowing the optical constants of the different materials.

**Multiple beam interferometer** The multiple beam interferometer (also known as Fabry–Perot interferometer after its inventors) consists of two plane parallel highly reflecting surfaces or mirrors separated by some distance \(d\) (Figure 13). Light coming in the volume between the mirrors can be partly reflected and transmitted by the surfaces. The distance \(d\) generally ranges from several millimeters to several centimeters when the apparatus is used interferometrically, and to few tens of centimeters or more when it serves as a laser resonant cavity. Consider a point source \(S_1\) and one ray emitted, entering by way of the partially reflecting plate, it is multiply reflected within the gap. The transmitted rays are collected by a lens and brought to a screen. The multiple waves generated in the cavity, arriving at \(P\) from \(S_1\) are coherent among themselves. All the rays incident on the parallel plates at a given angle will result in a circular fringe of uniform irradiance. The interference bands will be narrow concentric rings, corresponding to multiple-beam transmission pattern. The phase difference between two successively transmitted waves is

\[
\delta = \frac{4\pi n}{\lambda_0} d \cos \theta_t + 2\phi
\]

where \(\phi\) is an additional phase shift introduced by metallic films at the surfaces, if present. \(\phi\) can be considered constant and, in general, \(d\) is so large and \(\lambda_0\) so small that \(\phi\) can be neglected. One can consider that reflectance \(R\) is the fraction of the flux density reflected at each incidence and \(T\) the transmittance. One can neglect absorption from the metal films that are used to increase the reflectance, and consider \(R + T = 1\). The irradiance of the transmitted beam is

\[
I_t = I_0 \left( \frac{1 - R^2}{1 - R^2 + 4R^2 \sin^2(\delta/2)} \right)
\]

and the irradiance of the reflected beam is

\[
I_t = I_0 R \left( \frac{4 \sin^2(\delta/2)}{1 - R^2 + 4R \sin^2(\delta/2)} \right)
\]
Multiple-beam interference has resulted in a redistribution of the energy density in comparison to the sinusoidal two-beam pattern. Peaks in the transmission occur at specific values of the phase difference $\delta = 2\pi n$. The frequency range $\delta \nu$ between two maxima is the free spectral range of the interferometer. For normal incidence, the free spectral range becomes $\delta \nu = c/(2nd)$. Accordingly, the irradiance will drop to half of its maximum value whenever $\delta$ shifts from $\delta_{\text{max}}$ of $2(1 - R)/\sqrt{R}$. In frequency units, the halfwidth becomes $\Delta \nu = (c/(2nd))((1 - R)/(\pi \sqrt{R}))$.

The ratio $\delta \nu/\Delta \nu$ to the free spectral range $\delta \nu$ and the halfwidth $\Delta \nu$ is called the finesse $F$ of the interferometer:

$$F = \frac{\Delta \nu}{\delta \nu} = \frac{\pi \sqrt{R}}{1 - R} \quad [30]$$

The finesse is determined only by the reflectivity $R$ of the surfaces.

The Fabry–Perot interferometer is frequently used to examine the detailed structure of spectral lines. Two incident waves with frequencies $v_1$ and $v_2 = v_1 + \Delta \nu$ produce two systems of fringes partly superimposed. This will introduce into two transmitted irradiiances corresponding to the two different wavelengths. The spectral resolution $\nu/\Delta \nu$ of the interferometer is determined by the free spectral range $\delta \nu$ and by the finesse $F$. A Fabry–Perot interferometer with $d = 1$ cm, $R = 0.98$ for a wavelength light in the visible range, that is, $\lambda = 500$ nm, having negligible wedge and high-quality surfaces, so that the finesse is mainly determined by the reflectivity, achieves $F = 155$, a resolving power $\Delta \lambda/\lambda = 10^{-7}$. This means that the line width of the instrument is $\delta \lambda = 5 \times 10^{-5}$ nm and in frequency unit, $\delta \nu = 60$ MHz.

Both the applications and configurations of the Fabry–Perot interferometer are numerous indeed. Solid etalon, or air-spaced plane parallel reflecting surfaces are used as transmission filters. Using spherical mirrors where the demand for parallelism is imposed. This will trade into two transmitted irradiances corresponding to the two different wavelengths. The spectral resolution $\nu/\Delta \nu$ of the interferometer is determined by the free spectral range $\delta \nu$ and by the finesse $F$. A Fabry–Perot interferometer with $d = 1$ cm, $R = 0.98$ for a wavelength light in the visible range, that is, $\lambda = 500$ nm, having negligible wedge and high-quality surfaces, so that the finesse is mainly determined by the reflectivity, achieves $F = 155$, a resolving power $\Delta \lambda/\lambda = 10^{-7}$. This means that the line width of the instrument is $\delta \lambda = 5 \times 10^{-5}$ nm and in frequency unit, $\delta \nu = 60$ MHz.

Both the applications and configurations of the Fabry–Perot interferometer are numerous indeed. Solid etalon, or air-spaced plane parallel reflecting surfaces are used as transmission filters. Using spherical mirrors where the demand for parallelism is dropped, with high-reflectivity dielectric coating can achieve high large finesse $F > 10$ 000. Spherical mirror Fabry–Perot configurations are also used for laser cavities.

As a final comment on interferometers, it needs to be pointed out that nowadays much of the progress in the field of interferometry has come not from inventing new forms of interferometers, but from powerful fringe analysis methods, such as phase-shift interferometer analysis in optical testing, mostly helped by computer data treatment, and from making user-friendly instruments. Interferometry has the great advantage of a high-precision and noncontact capability in measurement. Commercial interferometric systems can achieve a resolution in the direction of propagation of the light beams of 2 nm and in the transversal plane ten times larger. This corresponds also to a resolution in the index of refraction measurement resolution of 10–6 and in highly controlled laboratory experiments in a 10–8 resolution. The major impediment of interferometry is its sensitivity: because of this, instruments tend to measure the whole surrounding environment, which can adversely affect accuracy.

**Polarimeter and Ellipsometer**

As discussed above, light may be treated as transverse electromagnetic waves. Thus far, only linear polarized light has been considered, that is, light for which the orientation of the electric field is constant, although its magnitude and sign vary in time. The electric field, therefore, resides in a fixed plane that contains both $E$ and $k$, the electric field vector and the propagation vector in the direction of motion, and is known as the plane of vibration.

One can resolve any plane polarized wave into two orthogonal components with the appropriate relative phase difference. For a wave propagation along the $z$ axis, the two orthogonal electric field components can be represented in the form

$$E_x(z, t) = i \cos(kz - \omega t) \quad [31]$$

$$E_y(z, t) = j \cos(kz - \omega t + \epsilon) \quad [32]$$

If $\epsilon$ is equal to zero or an integral of $\pm 2\pi$, the resultant electric field becomes

$$E = (iE_{0x} + jE_{0y}) \cos(kz - \omega t) \quad [33]$$

and has a fixed amplitude. If $\epsilon$ is an odd integer multiple of $\pm \pi$, the electric field is again linearly polarized but the plane of vibration has been rotated. Circular polarization occurs when both constituent waves have equal amplitudes and their relative phase difference $\epsilon = \pm \pi/2 + 2m\pi$, where $m = 0, \pm 1, \pm 2, \ldots$ the consequent wave is given by

$$E = E_0[i \cos(kz - \omega t) \pm j \cos(kz - \omega t)] \quad [34]$$

The amplitude is constant but the electric field $E$ is time varying and it rotates clockwise (right-circularly polarized light) or counterclockwise (left-circularly polarized) at an angular frequency $\omega$.

Both linear and circular polarized light may be considered to be special cases of elliptically polarized light. This means that, in general, the resultant electric field vector will rotate and change its magnitude as well. In such cases, the endpoint of
E. will trace out an ellipse in a fixed space perpendicular to k.

Instruments employed to measure polarization of a light beam after its interaction with a sample are commonly known as polarimeters or ellipsometers. A polarimeter is used when a light beam is transmitted through the sample whereas an ellipsometer is commonly used when a light beam is reflected by the sample. Both, the polarimeter and ellipsometer, use polarizers and retarders.

An optical device with an input of nonpolarized light and an output of some form of polarized light is known as a polarizer. For instance, an instrument that separates the two linear orthogonal components of electric field, discarding one and passing on the other, is a linear polarizer. Depending on the output it could also be classified as circular or elliptical polarizer. Polarizers come in many different configurations, but they are all based on one of the four fundamental physical mechanisms: dichroism or selective absorption, reflection, scattering, and birefringence or double refraction.

Polarizers are used in two different ways. If the polarizer is used to convert unpolarized light to polarized light, it is called the “polarizer.” If it is used to determine the state of polarized light (usually by locating the null), it is called the “analyzer.”

The next optical element to be considered is called the “retarder” or “quarter-wave-plate.” The wave plate, in general, is an anisotropic optical element with a fast axis and a slow axis, both of which are perpendicular to each other and to the direction of propagation of light. The component of the wave which is aligned with the fast axis passes through the optical element faster than the component aligned with the slow axis. The thickness of the wave plate can be chosen such that the phase difference is exactly 90°.

**Polarimeter**

Polarimeters are optical instruments used for determining the polarization properties of light beams and samples. Light-measuring polarimeters determine the polarization state of a beam of light and give its polarization characteristics. Sample-measuring polarimeters are used in light–matter interaction in which an incident beam can be transmitted, reflected, diffracted, or scattered by the sample. Polarimeters are used to determine the relationship between the polarization states of incident beams and output beam. Polarimeters are composed of a polarization generator consisting of all elements needed to produce a beam of a known polarization state, and a polarization analyzer to perform a particular polarization component in the output light beam.

A common polarimetric configuration is shown in Figure 14a. Light from the source passes through a linear polarizer whose orientation 21 is adjustable. The generated linearly polarized light interacts with the sample and is analyzed by a second linear polarizer whose orientation 22 is also adjustable. This polarimeter is sufficient only when linear polarization effects are dominant. Whenever circular polarization effects are present in the sample, elliptical properties of the output light must be considered and a more complete polarimeter is needed as shown in Figure 14b.

Typical applications of polarimeters include calibration of polarization elements for optical systems, but they are also widely used to analyze any optically active substances. There is a large number of organic and inorganic substances that are optically active in their crystalline, liquid, or dissolved state. Being optically active means that these substances are able to rotate the direction of oscillation of polarized light around a determined angle. A well-known optical substance is sugar: if it is dissolved in an optically inactive liquid like water, the degrees of angle of rotation depend – amongst other factors – on the concentration of the solution. This angle of rotation can be determined by a polarimeter with the highest possible precision. Analysis of active sugar solutions, and of any active solutions, is the most important application of polarimeters in the quality control, determination of concentration, and purity control in food, chemical, and pharmaceutical industries.
Ellipsometer

In ellipsometry, a collimated beam of a well-known polarized and monochromatic light is incident on a sample surface and the state of polarization of the reflected light is analyzed. In a typical scheme shown in Figure 15a, light is linearly polarized at a known but arbitrary plane of vibration identified by angle \( \theta_i \) with the plane of incidence. The two components of polarization being \( S \) and \( P \), are taken respectively parallel and perpendicular to the plane of incidence. For optically isotropic structures, ellipsometry is carried out at oblique incidence and reflected light results to be elliptically polarized. For incident electric field components \( E_i \) and \( E_{ip} \), the corresponding field components of the reflected light are given by

\[
E_{rs} = r_s E_{is}, \quad E_{rp} = r_p E_{ip} \tag{35}
\]

where \( r_p \) and \( r_s \) are the complex Fresnel reflection coefficients of the sample for \( P \) and \( S \) polarized light.

By taking the ratio of the respective sides of the two equations, one gets

\[
\rho = \frac{r_p}{r_s} = \frac{E_{is}/E_{ip}}{E_{rs}/E_{rp}} \tag{36}
\]

The second term in the equation describes the incident and reflected polarization states of light. Therefore, pure polarization measurements determine the ratio of the complex reflection coefficient for the \( S \) and \( P \) polarizations. These ratios are subsequently related to the structural and optical properties of the ambient–sample interface region by invoking an appropriate model and the electromagnetic theory of reflection.

The ellipsometric measurement is normally expressed in terms of \( \Psi \) and \( \Delta \):

\[
\tan \Psi e^{i\Delta} = \rho = \frac{r_p}{r_s} \tag{37}
\]

Referring to Figure 15, the phase difference between the parallel component and the perpendicular component of the incoming wave is denoted as \( \delta_1 \), and the phase difference between the parallel and the perpendicular component of the outgoing wave as \( \delta_2 \). It results that the parameter \( \Delta = \delta_1 - \delta_2 \) is the change in phase difference that occurs upon reflection and its value can be from 0° to 360°. Without regard to phase, the amplitude of both perpendicular and parallel components may change upon reflection, their ratio represented by the \( \tan \Psi \).

As ellipsometry measures a ratio quantity, the measurement is potentially more precise and accurate than a traditional intensity reflectance or transmission measurement. On the other hand, since ellipsometry is a polarization-based measurement, relatively complex optical instrumentation is required. Spectroscopic ellipsometry measures the complex ratio \( \rho \) as a function of wavelength, whereas variable angle spectroscopic ellipsometry performs the above measurement as a function of both wavelength and angle of incidence.

In case multiple interfaces have to be analyzed, it is possible to derive the ratio of the amplitude of the resultant reflected wave to the amplitude of the incident wave as a function of the Fresnel reflection coefficients for the single interfaces, wavelength of light, and thickness of layers.

For many instruments used today, the intensity measurement of the reflected light is related to...
rotation of the analyzer of polarization on the reflected beam. This instrument is shown schematically in Figure 15b. In this case the polarizer on the incident beam is set at a fixed angle, usually 45°. The quarter wave plate (QWP) is fixed with the fast axis perpendicular to the plane of incidence and can be placed in the beam or removed from it. Only one of the polarizing elements (the analyzer) is rotated. The intensity $I$ measured as a function of time $t$ by the light detector can be expressed as

$$I(t) = I_0[1 + z \cos 2A(t) + \beta \sin 2A(t)] \quad [38]$$

where $A(t) = 2\pi ft + A_c$ with $f$ being the angular frequency of the rotation and $A_c$ being a constant phase offset. $I_0$ is the average intensity, and $z$ and $\beta$ are the Fourier coefficients. For a rotating analyzer instrument, the optimum precision is obtained when the light incident on the rotating analyzer is circularly polarized. If the phase shift induced by the reflection is $\sim 90°$, the optimum precision would be realized by using linearly polarized light (no QWP). The light starts out linearly polarized (components in phase) and the reflection changes it into near-circularly polarized light. If, on the other hand, the phase shift due to the reflection is either none or $\sim 180°$ without the QWP, the light incident on the analyzer would be almost linearly polarized. In this case the QWP is used. Typically, $\Psi$ is measured without the QWP in place and $\Delta$ is measured both with and without the QWP. Depending on the value obtained, one or the other of the measurements is used.

The Fourier coefficients $z$ and $\beta$ are given by

$$z = -\cos 2\Psi \quad \text{and} \quad \beta = \sin 2\Psi \cos \Delta_m \quad [39]$$

where $\Delta_m$ is the measured phase difference between the parallel and the perpendicular components of the light at the analyzer. These equations can be inverted to give

$$\cos \Delta_m = \pm \sqrt{\frac{\beta^2}{1 - z^2}} \quad [40]$$

and

$$\tan \Psi = \frac{\sqrt{1 + z}}{1 - z} \quad [41]$$

If the QWP is not used, the phase shift induced by the reflection is given by $\Delta = \Delta_m$. If the QWP is in place and the light incident on the sample is circularly polarized, then it is necessary to add the retardation of the QWP to the measured value. If the QWP is perfect, then $\Delta = \Delta_m + 90°$.

Many desired material parameters can be extracted by this technique, including layer thickness, surface and/or interfacial roughness, and optical constants.

$$n = n_0 + \imath n_1 \quad [42]$$

where $n_0 = c/v$ is the index of refraction and $n_1$ is the extinction coefficient and takes care of absorption phenomena. The ellipsometric data measured on a bulk sample can be directly inverted into the optical constants of the material, assuming that surface oxide or roughness effects are negligible:

$$\tilde{n} = n_0 + \imath \kappa = \sin \phi^2 \left[1 + \tan \phi^2 \left(\frac{1 - \rho}{1 + \rho}\right)^2\right] \quad [43]$$

where $\phi$ is the angle of incidence and $\rho$ is measured by an ellipsometer.

This equation gives the averaged and a first appreciation of physical parameters under test. A full optical and microstructure analysis of real materials including multilayer structures, requires use of an appropriate model and regression analysis. It should be noted that $\rho$ is the quantity measured by an ellipsometer and, assuming the instrument is operating properly, it is correct. The calculated sample parameters, such as thickness and index of refraction and the extinction coefficient, can be corrected, depending on whether the model assumed is correct. Typical examples of applications are determination of thickness and index of refraction of thin-film stacks up to five layers, material, optical constant of photoresist which is critical for industrial lithography, measurement of thickness and composition of complex compound semiconductor structures, optical multilayer coatings, and variation in optical coating index.

**Radiometer**

Radiometry deals with the measurement of amounts of light. Photometry takes into account the response of the human eye which rises to a nonlinear and wavelength-dependent subjective impression of radiometric quantities.

Radiant power $W$, measured in watts, is the total amount of energy emitted by a light source per second. The spectral variation of radiant power can be specified in terms of the radiant power density per unit wavelength interval $W_\lambda$

$$W = \int_{0}^{\infty} W_\lambda \, d\lambda \quad [44]$$
If the light source emits radiation only for some specific duration, it is more useful to specify the source in terms of its radiant energy output \( Q_e \), measured in joules. If the source emits radiation for a time \( T \), one can write

\[
Q_e = \int_0^T W(t) \, dt
\]  

[45]

The amount of power emitted by a source in a particular direction per unit solid angle is called radiant intensity \( I_e \), and is measured in watts per steradian. In general,

\[
W = \int I_e(\Omega) \, d\Omega
\]  

[46]

where the integral is taken over a closed surface surrounding the source. If \( I_e \) is the same in all directions, the source is said to be an isotropic radiator. At distance \( r \) from such a source, if \( r \) is much greater than the dimension of the source, the radiant flux crossing a small area \( \Delta S \) is

\[
\phi_e = \frac{I_e \Delta S}{r^2}
\]  

[47]

The irradiance at this point, measured in W m\(^{-2} \), is

\[
E_e = \frac{I_e}{r^2}
\]  

[48]

which is equal to the average value of the Poynting vector measured at that point. The radiant flux emitted or reflected or scattered per unit area of a surface is called the radiance \( L_e \), and it is measured in W m\(^{-2} \). For an extended source, the radiant flux emitted per unit solid angle per unit area of the source is called its radiance or brightness \( L_e \):

\[
L_e = \frac{\delta I_e}{\delta S_n}
\]  

[49]

where the area \( \delta S_n \) is the projection of the surface element of the source in the direction being considered. When the light emitted from a source or scattered from a surface has a radiance that is independent of the viewing angle, the source or surface is called a perfectly diffuse or Lambertian radiator. For such a source, the radiant intensity at an angle \( \theta \) to the normal to the surface is clearly

\[
I_e(\theta) = I_e(0) \cos \theta
\]  

[50]

The total flux emitted per unit area of such a surface is its radiant emittance, which, in this case, is \( M_e = \pi L_e(0) \).

For plane waves, since all the energy in the wave is transported in the same direction, it is customary to specify the radiant flux crossing unit area normal to the direction of propagation, and call this the intensity \( I \) of the plane wave. Because lasers emit radiation into an extremely small solid angle, they have very high radiant intensity, and it is once again more usual to refer simply to the intensity of the laser beam at a point as the energy flux per second per unit area. Presently, radiometry involves the measurement of the energy content of electromagnetic radiation fields and the determination of how this energy is transferred from a source, through a medium, and to a detector, independently of its effect on a particular detector. The measurement of the effect of the transfer of radiation, such as absorption, reflection, or scatter is usually called spectrophotometry.

In common practice, radiometry is divided according to regions of the spectrum in which the same experimental technique can be used. Thus, vacuum ultraviolet, visible and near visible, intermediate-infrared, far infrared, and microwave regions are considered separate fields in radiometry.

Photometry concerns radiometry related to human vision, and measurement of the ability of electromagnetic radiation to produce a visual sensation in a physically realizable manner. The response of the human eye gives rise to a nonlinear and wavelength-dependent subjective impression of radiometric quantities. The response function of the human eye extends roughly from 400 to 700 nm with a peak at 555 nm. In photometry, radiometric quantities are used with different names and units. The luminous intensity, for instance, is the equivalent of the radiometric quantity, radiant intensity, and in photometry is measured as candela where 1 candela = 1 lumen str\(^{-1} \).

Today, measurement of the energy content of electromagnetic radiation is performed with an electrically calibrated detector, which is a device for measuring absolute radiant power in comparison to electrical power. It consists of a thermal detector that has a radiation-heater within the surface, or the heater is in good thermal contact with the surface. When the device is irradiated, the detector senses the temperature of the radiantly heated surface. The radiation source is then blocked and the power to the electrical heater adjusted to reproduce the temperature of the radiantly heated surface. The electrical power to the heater is measured and equated to the radiant power on the surface. As the measurement has to be accurate, differences between the radiant and the electrical heating modes must be evaluated.

Detectors are distinguished by two types of radiant power absorber configurations: a flat surface coated
with a highly absorbing material or a cavity-shaped, light-trapping detector. Cavity-shaped radiometers are usually more accurate over a greater spectral range than flat-surface radiometers. However, a flat-surface receiver can be fabricated with less thermal mass than a cavity-shaped receiver, and, therefore, may have greater sensitivity and a faster response time.

Electrically calibrated detectors are in widespread use today; they are commercially available and are calibrated in the factory with a calibration lamp. They use either a thermocouple, a thermopile, or a bolometer. They operate at ambient temperature and are commonly used for solar/artificial lighting and for laser power measurements.

See also: Crystal Optics; Holography; Optical Properties of Materials.

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**Further Reading**


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**Optical Microscopy**

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Metallurgical microscopes differ from biological microscopes primarily in the manner by which the specimen is illuminated due to the opacity of metals. Unlike biological microscopes, metallurgical microscopes must use reflected light, rather than transmitted light. **Figure 1** is a simplified ray diagram of a metallurgical microscope. The prepared specimen is placed on the stage with the surface perpendicular to the optical axis of the microscope and is illuminated through the objective lens by light from a lamp or arc source. This light is focused by the condenser lens into a beam that is made approximately parallel to the optical axis of the microscope by a half-silvered mirror. The light then passes through the objective onto the specimen. It is then reflected from the surface of the specimen, back through the objective, the half-silvered mirror, and then to the eyepiece to the observer's eye, or to a camera port or a film plane.

![Figure 1](image-url)