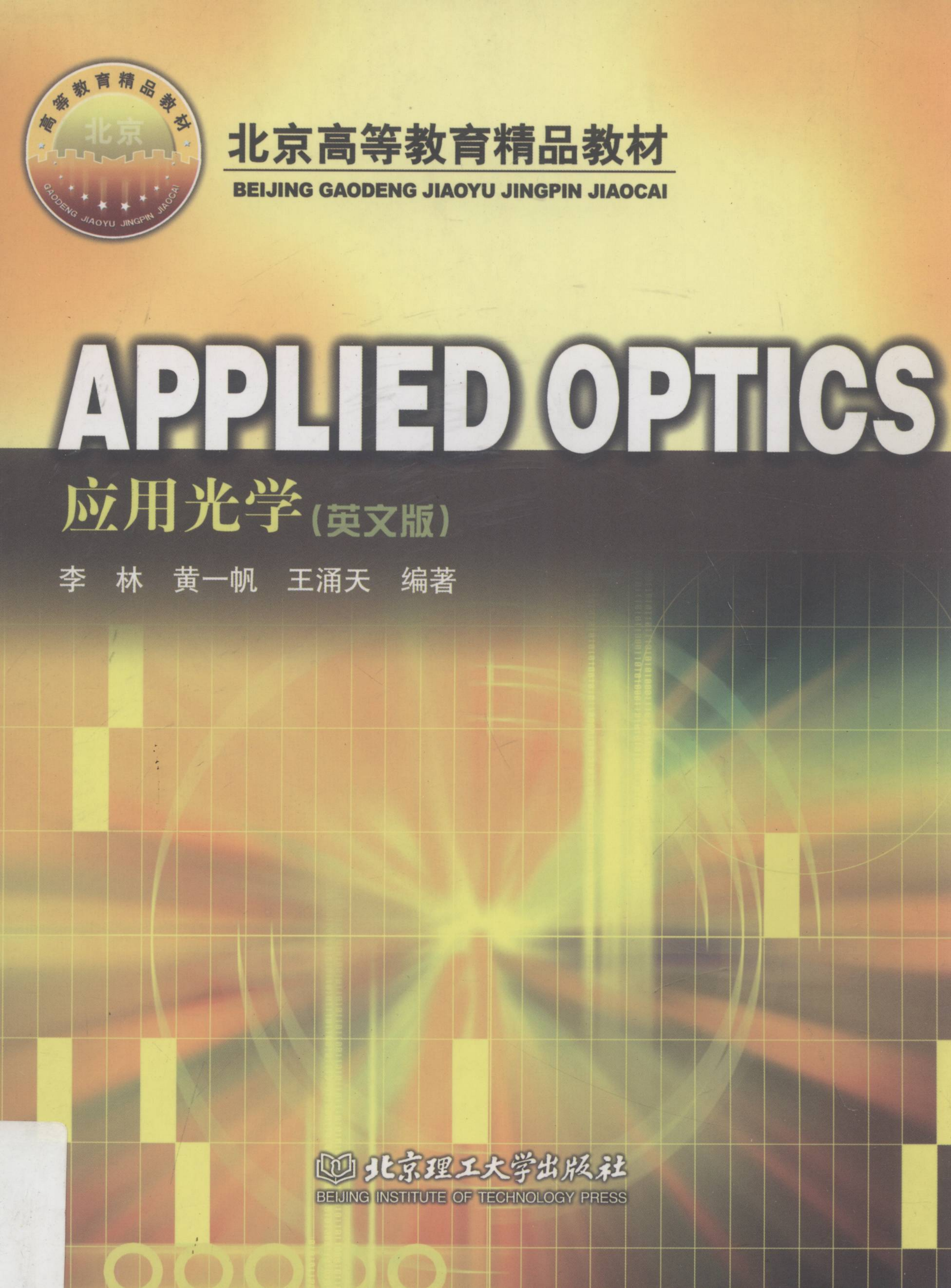


北京高等教育精品教材

BEIJING GAODENG JIAOYU JINGPIN JIAOCAI

APPLIED OPTICS

应用光学（英文版）

李　林　黄一帆　王涌天　编著

北京理工大学出版社
BEIJING INSTITUTE OF TECHNOLOGY PRESS

北京高等教育精品教材

APPLIED OPTICS

应用光学(英文版)

李　林　黄一帆　王涌天　编著

北京理工大学出版社
BEIJING INSTITUTE OF TECHNOLOGY PRESS

图书在版编目(CIP)数据

应用光学 . 英文 = Applied Optics/李林，黄一帆，王涌天编著 .—北京：北京理工大学出版社，2008.6 重印

北京高等教育精品教材

ISBN 978-7-5640-0526-9

Ⅰ. 应…　Ⅱ. ①李…②黄…③王…　Ⅲ. 应用光学-高等学校-教材-英文　Ⅳ. O439

中国版本图书馆 CIP 数据核字(2005)第 047883 号

出版发行 / 北京理工大学出版社
社　　址 / 北京市海淀区中关村南大街 5 号
邮　　编 / 100081
电　　话 / (010)68914775(办公室)　68944990(批销中心)　68911084(读者服务部)
网　　址 / http://www.bitpress.com.cn
经　　销 / 全国各地新华书店
印　　刷 / 北京圣瑞伦印刷厂
开　　本 / 787 毫米 × 1092 毫米　1/16
印　　张 / 16
字　　数 / 312 千字
版　　次 / 2008 年 6 月第 1 版第 2 次印刷
印　　数 / 3001 ~ 5000 册
定　　价 / 35.00 元

责任校对 / 陈玉梅
责任印制 / 李绍英

Preface

This book, Applied Optics, is a fundamental technical course for the specialties of optical engineering, optical measurement, control instruments and electronic science and technology. The book mainly includes basic theories and methods of how to solve the problems of geometrical optics, typical optical instruments, optical measurement, color measurement, optical fiber systems, laser systems and infrared optics. The knowledge mentioned above is a must for the opto-electronic students' learning.

The Chinese edition of the book has been acknowledged as the earliest and the best classical text in China. Many Chinese universities have chosen the book as the textbook for the course. However, there is no equivalent English version for applied optics in China, which results in lacking industry wordings for Chinese students. In order to encourage them to keep up with international level and has the ability of referring to global materials during their Master Degree studies, this English version for applied optics is thus pushed forward.

The book starts with the basic theory of geometrical optics, where the imaging properties of the ideal system, the relationship between the object and the image for the symmetrical spherical system, the instruments for the human eyes, the mirror and prism systems and selection of image rays in optical systems are described. Then it discusses the radiometry and photometry, where the calculations of radiometry and photometry for various optical systems are introduced. At last, it incorporates the image quality of an optical system, where geometrical aberrations, wave aberrations and optical transfer function are described. And, the theories of telescope, microscope and camera systems are also included.

The book is co-authored by Li Lin, Huang Yifan and Wang Yongtian, whereas Chapters 2, 4, 6, 7 and 8 are put together by Li Lin; Chapters 3, 5 and 9 are written by Huang Yifan; and Wang Yongtian is responsible for Chapter 1. We would like to express our special gratitude to our friends and colleagues, Professor Yuan Xucang, Professor An Liansheng, Professor Su Datu, Professor Li Shixian and Professor Chen Huangming, who have been constantly giving us advices and suggestions. We would also like to thank many of our students for their assistant work.

In today's ever evolving society, the study of optics has become the forefront of science and technology. New ideas and concepts are emerging every day. We welcome all feedbacks or updates from readers should it be any neglects or mistakes in this book.

Li Lin
Huang Yifan
Wang Yongtian

Contents

Chapter 1 Basic Principles of Geometrical Optics

1.1 Waves and Rays

Light is very closely related to the life and well-being of mankind. The growth of plants relies on light, and human vision relies on light as well. The idiom "seeing is believing" reflects people's recognition of the importance of light. People accumulated abundant perceptual knowledge of light through practical experiences, and started to study light a long time ago.

There are two aspects of people's study of light. One is to study the nature of light in order to explain various optical phenomena, which is called physical optics; the other is to study the laws and phenomena of light propagation, which is called geometrical optics.

The study of the nature of light started very early but progressed relatively slowly. In 1666, Newton first postulated that light is a kind of elastic corpuscles, which is the corpuscular theory. In 1678, Huygens put forward the wave theory, which says that light is a kind of elastic wave propagating in "ether". In 1873, according to the characteristics of the electromagnetic waves, Maxwell showed that light is in fact an electromagnetic disturbance. In 1905, in order to explain the photoelectric effect, Einstein proposed the hypothesis of "photon", which was later confirmed by the discovery of the Compton's effect. Thereafter people began to have a more correct and complete understanding to the nature of light. In modern physics, light is considered to be a kind of matter with wave-particle duality, namely it has the characteristics of both the waves and the corpuscles. Under certain circumstances, one group of characteristics is more apparent than the other. Except for the cases to study the interaction between light and substances when the corpuscular characteristics of the light must be taken into account, light can generally be considered as electromagnetic waves, which are called light waves.

Light waves are different from radio waves in that they have shorter wavelengths. Fig. 1.1 shows the classification of electromagnetic waves according to their wavelengths. Electromagnetic waves with wavelengths between 400 nm and 760 nm ($1\ \text{nm} = 10^{-6}\ \text{mm} = 10\ \text{Å}$) can be sensed by the human eyes, and they are called the visible light. Light waves of different wavelengths produce different color senses. Light of a single wavelength has a specific color, and is called monochromatic light. Fig. 1.2 gives the wavelength ranges that correspond to different colors. Light composed of light waves of different

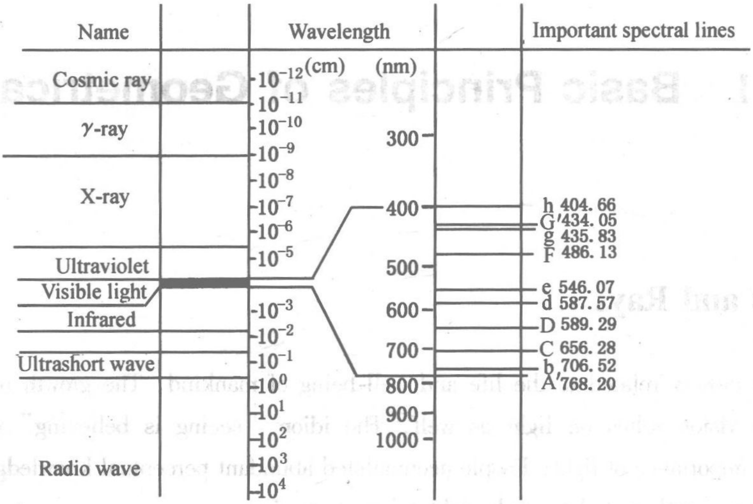


Fig.1.1 Classification of electromagnetic wave

wavelengths is called polychromatic light. White light is a kind of polychromatic light with many different wavelengths.

For electromagnetic waves of different wavelengths, the propagation speed in vacuum is exactly the same, namely $c \approx 3 \times 10^{10}$ cm/s. The relation among the speed of light, the frequency and wavelength of an electromagnetic wave can be expressed as

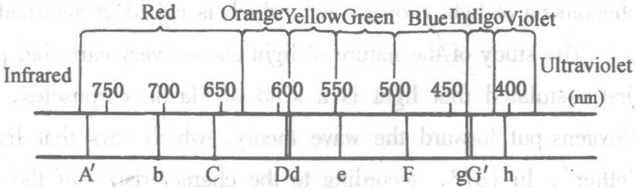


Fig.1.2 Wavelength of visible light

$$v = \frac{c}{\lambda}$$

Therefore electromagnetic waves of different wavelengths have different frequencies. In transparent media such as water and glass, the wavelength and speed of light change, but its frequency is constant.

The surface reached by wave propagation at a moment of time is called the wavefront. In a homogeneous medium, the wave propagates at the same speed in all directions. Thus the wavefronts of the electromagnetic wave emitted by a point light source in a homogeneous medium are concentric spherical surfaces with the source at the center, as seen in Fig.1.3.

Since light is a form of electromagnetic wave, the study of light propagation is fundamentally the problem of wave propagation. However, when studying light propagation with geometric optics, light is presented as geometrical lines that transmit energy rather than as waves. Such a geometrical line is called a ray. A light source emits millions of rays and transmits energy along each of these rays, as drawn in Fig.1.4.

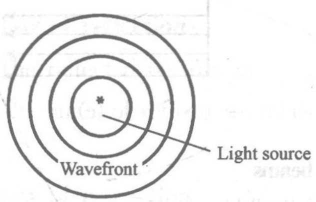


Fig.1.3 Concentric wavefront

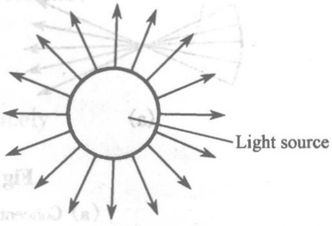


Fig.1.4 Light source and rays

The concept of "ray" was abstracted directly from numerous natural optical phenomena. It can be used to explain many phenomena of light propagation in the nature, such as the casting of shadows, solar and lunar eclipses, pinhole imaging, etc. Most of the optical instruments currently in use were designed using the principles of geometrical optics, which consider light as rays.

With geometrical optics, one studies light propagation by studying the propagation of rays, which are governed by the basic laws of geometrical optics. A ray has the same characteristics as a geometrical line, except that a ray has its direction, which is the direction of energy transmission. Thus a ray is a geometrical line with a specific direction. Now the study of light propagation becomes a problem of geometry, hence the name "geometrical optics".

As mentioned earlier, the wavefronts of a light wave emitted by a point source in a homogeneous medium are concentric spherical surfaces with the source at the center; and according to geometrical optics, a point light source emits millions of rays around from the source point *A*. It can be seen clearly from Fig.1.5 that rays are perpendicular to wavefronts. In other words, a ray is a normal to wavefronts, whereas a wavefront is a surface perpendicular to all the rays. This is the relationship between wavefronts and rays. A bundle of rays converging to or emitted from a single point is called a concentric beam, and the shape of its corresponding wavefront is a sphere, as shown in Fig.1.6(a). A bundle of rays that do not intersect at one point is called an astigmatic beam, and its corresponding wavefront is of an aspheric shape, as shown in Fig.1.6(b). A parallel beam corresponds to a plane wavefront, as shown in Fig.1.6(c).

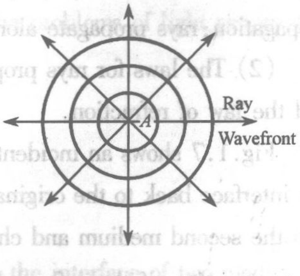


Fig.1.5 Rays and wavefronts

In this book, various phenomena of light propagation are studied according to the principles of geometrical optics, and the principles and phenomena are used to design and manufacture optical instruments. Those optical phenomena that cannot be studied using geometrical optics are studied using

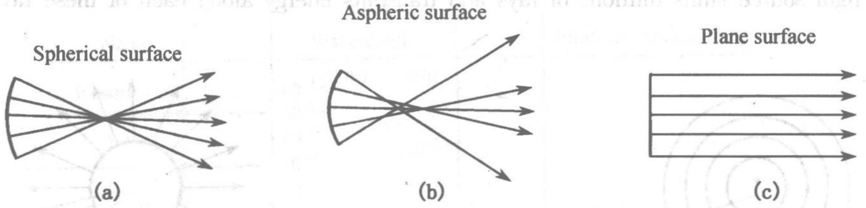


Fig.1.6 Different types of light beams

(a) Concentric beam; (b) Astigmatic beam; (c) Parallel beam

physical optics, which considers light as waves, from a wavefront constructed from rays according to the above-mentioned relationship between rays and wavefronts.

1.2 Basic Laws of Geometrical Optics

In geometrical optics, the problems of light propagation are studied by means of rays, which represent the light as directed geometrical lines. For this purpose, the laws governing the propagation of rays must be established first. Although there are various phenomena of light propagation in the nature, they can be classified into the following two circumstances.

(1) The law for rays propagating in a homogeneous and transparent medium — the law of rectilinear propagation: rays propagate along straight lines in a homogeneous and transparent medium.

(2) The laws for rays propagating at the interface of two homogeneous media — the law of reflection and the law of refraction.

Fig.1.7 shows an incident beam striking an interface of two media. Some of the rays are reflected on the interface back to the original medium, which are called reflected rays; others go through the interface into the second medium and change their directions, which are called refracted rays. The laws governing the propagation of the reflected and refracted rays are called the law of reflection and the law of refraction respectively. In order to explain these laws, the following terms need to be defined.

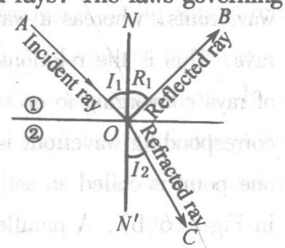


Fig.1.7 Incident, reflected and refracted rays

The angle between the incident ray AO and the normal of the media interface $ON(\angle AON = I_1)$ is called the angle of incidence. The angle between the reflected ray OB and the normal $ON(\angle BON = R_1)$ is called the angle of reflection. The angle between the refracted ray OC and the normal $ON(\angle CON' = R_1)$ is called the angle of refraction. The plane containing the incident ray and the normal is called the plane of incidence.

Now the laws of reflection and refraction can be described as follows.

The law of reflection:

(1) The reflected ray lies in the plane of incidence.

(2) The angle of reflection equals the angle of incidence, namely

$$I_1 = R_1 \tag{1.1}$$

The law of refraction:

(1) The refracted ray lies in the plane of incidence.

(2) For a certain pair of media, the ratio between the sine of the angle of incidence and that of the angle of refraction is a constant regardless of the value of the incident angle, namely

$$\frac{\sin I_1}{\sin I_2} = n_{1,2} \tag{1.2}$$

where $n_{1,2}$ is the relative refractive index of the second medium with respect to the first medium.

In order to study light propagation in an inhomogeneous medium, the inhomogeneous medium can be considered as being composed of an infinite number of homogeneous media, and a ray traveling through it is refracted continuously. Media with different gradient functions and coefficients can generate different curved ray paths, but they all follow the law of refraction. It is clear that the laws of rectilinear propagation, reflection and refraction can be used to explain various phenomena of ray propagation in the nature. They are the important laws of physics in geometrical optics; hence they are known as the basic laws of geometrical optics. The essence of geometrical optics is to study the problems of light propagation with mathematical methods on the basis of the three basic laws.

1.3 Refractive Index and Speed of Light

Fig.1.8 shows a beam of parallel rays incident upon the surface P, the interface of two media. As all the rays are of the same angle of incidence I_1, all the refracted rays should have the same angle of refraction I_2 according to the law of refraction. Thus the refracted beam is still a parallel beam. The incident wavefront and the refracted wavefront, which are perpendicular to the rays, are two planes.

In Fig.1.8, the position of the wavefront is at OQ at a specific moment. After a period of time t, it moves to $O'Q'$ due to wave propagation. Denoting the speeds of light propagation in the two media as v_1 and v_2 respectively, the following equations can be obtained from Fig.1.8.

$$QQ' = v_1 \cdot t; \quad OO' = v_2 \cdot t \tag{1.3a}$$

As the wavefront OQ is perpendicular to the ray AO and the interface surface P is perpendicular to

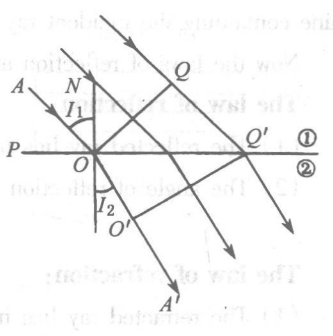


Fig.1.8 Refractive index and speed of light

its normal ON, obviously $\angle QOQ' = \angle AON = I_1$. Similarly, $\angle O'Q'O = \angle A'ON' = I_2$. Also, from the triangles $\triangle OQQ'$ and $\triangle OQ'O'$, we have

$$\sin I_1 = \frac{QQ'}{OQ'};\quad \sin I_2 = \frac{OO'}{OQ'} \tag{1.3b}$$

Substituting Eq. (1.3a) into Eq. (1.3b) leads to

$$\frac{\sin I_1}{\sin I_2} = \frac{v_1}{v_2} = n_{1,2} \tag{1.3}$$

It can be seen that $n_{1,2}$, the relative refractive index of the second medium with respect to the first medium, is equal to the ratio of the speed of light in the first medium v_1 and that in the second medium v_2. This is the relation between the refractive index and the speed of light. The speed of light is a constant for a specific type of medium. Therefore, the relative refractive index between any two designated media is a constant. This is one way to verify the validity of the law of refraction.

The refractive index of one medium with respect to another is called relative refractive index, and that of the medium with respect to vacuum is called absolute refractive index. Since the difference between the speed of light propagation in air and that in vacuum is very small, usually the absolute refractive index of air is set to 1, and the relative refractive index of a medium with respect to air is used as its absolute refractive index.

The speed of light in vacuum is c. From Eq. (1.3), the absolute refractive indices of the first and second media are given by

$$n_1 = \frac{c}{v_1};\quad n_2 = \frac{c}{v_2}$$

Dividing the second equation above by the first yields

$$\frac{n_2}{n_1} = \frac{c/v_2}{c/v_1} = \frac{v_1}{v_2}$$

Substituting the above equation into Eq. (1.3), we obtain

$$n_{1,2} = \frac{n_2}{n_1} \tag{1.4}$$

which means that the relative refractive index of the second medium with respect to the first medium equals to the ratio of the absolute refractive index of the second medium to that of the first.

The law of refraction can now be expressed as

$$\frac{\sin I_1}{\sin I_2} = n_{1,2} = \frac{n_2}{n_1}$$

which can be rewritten in a symmetrical form as

$$n_1\sin I_1 = n_2\sin I_2 \tag{1.5}$$

This is the law of refraction expressed in terms of the absolute refractive indices. Because of its symmetrical form, one can take either I_1 as the angle of incidence and I_2 as the angle of refraction, or I_2 as the angle of incidence and I_1 as the angle of refraction. Thus Eq. (1.5) can be used both for the case when a ray enters the second medium from the first medium, and for the case when a ray enters the first medium from the second. This is much more convenient than Eq. (1.2) that expresses the law of refraction with the relative refractive index. For this reason, the absolute refractive indices will be used in the expression of the law of refraction hereafter.

1.4 Reversibility of Ray Paths and Total Internal Reflection

In this section, the basic laws of geometrical optics are used to study two important phenomena of light propagation — reversibility of ray paths and total internal reflection.

1.4.1 Reversibility of Ray Paths

Suppose a ray propagates from A to B along a certain path. If a ray is emitted from the point B along the outgoing ray but with its direction reversed, the reversed ray will propagate from B to A along the same path. This is called the law of ray path reversibility for light propagation. According to the law, the path of light propagation can be studied along the actual traveling direction of the ray or along its reversed direction, and the results are exactly the same.

The correctness of the law can be verified using the three basic laws.

According to the law of rectilinear propagation, in a homogeneous and transparent medium, a ray propagates along a straight line. As there is only one straight line between any two points, the ray must travel along this line whether it is from A to B or B to A, hence the verification of the law of ray path reversibility for this case.

As for the cases of reflection and refraction, according to the equations for the laws of reflection and refraction, Eqs. (1.1) and (1.5), we have

$$I_1 = R_1; \quad n_1\sin I_1 = n_2\sin I_2$$

The left and right sides of these two equations represent respectively the geometrical positions of the incident ray and the reflected or refracted ray, and the two sides are completely symmetrical. Exchanging the two sides of the equations, they become

$$R_1 = I_1; \quad n_2\sin I_2 = n_1\sin I_1$$

If R_1 is considered as the angle of incidence, I_1 becomes the angle of reflection. If I_2 is taken as the angle of incidence, I_1 is now the angle of refraction. According to the above equations, if the incident ray is placed on the position of the original reflected or refracted ray, the position of the new reflected or refracted ray coincides with the original incident ray, as seen in Fig. 1.9 and Fig. 1.10.

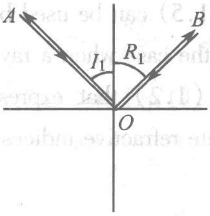


Fig. 1.9 Reversibility of ray paths in reflection

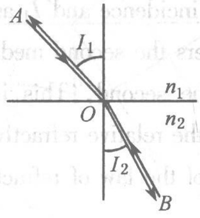


Fig. 1.10 Reversibility of ray paths in refraction

Whether a ray propagates in a homogeneous medium, or gets reflected or refracted on the interface of two media, the law of ray path reversibility remains valid. Therefore, the law is always true regardless how many times the ray is reflected and refracted and what kinds of media it propagates through.

1.4.2 Total Internal Reflection

Generally, a ray falling upon an interface of two media is split into two rays: one is reflected at the interface back to the original medium, and the other is refracted through the interface into the other medium. Along with the increase of the angle of incidence, the intensity of the reflected ray increases whereas the intensity of the refracted ray decreases.

Fig. 1.11 shows a point light source A in the medium n_1 emitting rays to different directions and casting them onto the interface between n_1 and n_2. Each ray is split into a refracted ray and a reflected ray. According to the law of refraction, i.e., $n_1 \sin I_1 = n_2 \sin I_2$, when $n_1 > n_2$, $I_2 > I_1$.

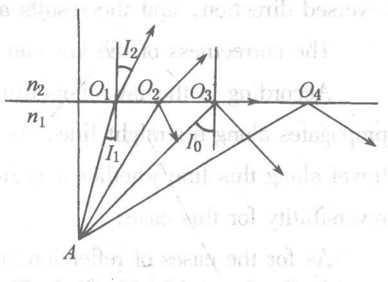


Fig. 1.11 Total internal reflection

When the angle of incidence I_1 increases, the corresponding angle of refraction I_2 will increase. At the same time, the intensity of the reflected ray increases, and that of the refracted ray decreases. There is an angle of incidence I_0 that will make the angle of refraction I_2 equals 90°, when the refracted ray sweeps over the interface of the two media with its intensity close to zero. When $I_1 > I_0$, the refracted ray no longer exists, and the incident ray is totally reflected. This phenomenon is known as total internal reflection, and the angle of incidence I_0 that corresponds to an angle of refraction $I_2 = 90°$ is called the critical angle, or the angle of total internal reflection. From the law of refraction

$$n_1 \sin I_0 = n_2 \sin 90° = n_2$$

we have

$$\sin I_0 = \frac{n_2}{n_1} \tag{1.6}$$

Total internal reflection can possibly occur only when the ray is cast from a medium of higher refractive index to a medium of lower refractive medium, such as from glass to air or from water to air. When the ray is cast from a medium of lower refractive index to a medium of higher refractive medium, there will be no total internal reflection because the angle of refraction is smaller than the angle of incidence.

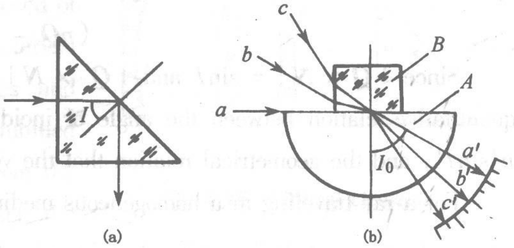
The phenomenon of total internal reflection is widely used in optical instruments. Fig.1.12(a) illustrates a reflecting prism based on total internal reflection. Using such a prism to replace a mirror with a reflective coating can reduce energy loss, because a mirror with an ordinary reflective coating may absorb about 10% of the incident light power, and the coating may easily get deteriorated or scratched. To use a prism of total internal reflection, the incident angles of all the rays on the reflecting surface must be greater than the critical angle I_0, otherwise a reflective coating is still required on the reflecting surface.

For glasses with different refractive indices, the critical angles for the glass-air interface are different. The values of the critical angles for different refractive indices are listed in Table 1.1.

Table 1.1 Critical angles for different refractive indices

n	1.5	1.52	1.54	1.56	1.58	1.60	1.62	1.64	1.66
I_0	41°48′	41°8′	40°30′	39°52′	39°16′	38°41′	38°7′	37°34′	37°3′

Another important application of the total-internal-reflection phenomenon is in the measurement of the refractive index of a medium. In Fig.1.12(b), A is made of a medium of known refractive index of the value n_A, and B is made of the medium to be measured, whose refractive index is denoted as n_B. Rays from different directions such as a, b, c... are refracted through the interface. When $n_A > n_B$, the largest refractive angle corresponds to the ray a that sweeps over the interface, and its value equals the angle of total internal reflection I_0. As the angles of refraction of all the rays are smaller than I_0 and there are no refracted rays beyond I_0, a line dividing the illuminated area and the dark area can be located at the



(a) (b)

Fig.1.12 Total internal reflection in right angle prism and in refractive index measurement