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ИСПОЛЬЗОВАНИЕ ЭНДОСКОПИИ И РЕФРАКТОМЕТРИИ В МЕДИЦИНЕ

ENDOSCOPY AND REFRACTOMETRY USE IN MEDICINE

Учебно-методическое пособие

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В доступной для студентов форме изложены физические принципы работы и конструктивные особенности классического рефрактометра, а также рассмотрены физические принципы эндоскопии.

Предназначено для студентов всех медицинских специальностей, изучающих медицинскую и биологическую физику на английском языке.

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INTRODUCTION

Refractometry as the method of measuring substances refractive index in order to assess their composition or purity is based on the reflection and refraction of light. Using the principles of light refraction, clinical refractometers are used for clinical purposes such as specific gravity of urine, and total protein in serum or plasma. It is known that refractive index of a solution varies according to its concentration. Hence, its concentration can be obtained from its refractive index. The refractive index of blood serum or plasma depends mainly upon its protein concentration, as proteins are one of the major constituents. The clinical refractometer uses the refractive index method for measuring total protein in serum.

Endoscopy is widely used for various forms of medical examination and treatment. Advancements in “minimally invasive therapy” are continuously being made within the field of medicine. Surgeries that in the past were operated by opening the abdomen can now be performed using an endoscope inserted through a small incision, in most cases leaving minimal scarring only. As a result, the patient’s pain and suffering is reduced and quality of life is significantly improved.

In fact, endoscopy is quite ancient thanks in part to the minimally invasive philosophy that Hippocrates advocated in his lifetime. With his philosophy in mind, surgical pioneers went on to develop lenses, lighting, and cameras to aid in their search for visualization of the interior body cavity, along with trocars, insufflating machines, and tubing to help access it. It is with this understanding that the medical community is humbled by modern endoscopy. In the textbook the physical principles of the endoscopy based on the reflection and refraction of light are considered. Special attention is paid to the total internal reflection and how endoscopes rely on this phenomenon.

This textbook provides a clear and comprehensive introduction to the field, describing in detail the physical principles of refractometer work. The index of refraction, reflection and refraction of light and phenomenon of total internal reflection are considered in the textbook.

REFRACTION AS PHYSICAL PHENOMENON. LIGHT SPEED AND INDEX OF REFRACTION

It is known the speed of light in vacuum is $\boldsymbol{c} = 2.99792458 \cdot 10^8$ m/s, which is usually rounded off to $3.00 \cdot 10^8$ m/s when extremely precise results are not required. In air, the speed is only slightly less. In other transparent materials such as glass and water, the speed is always less than that in vacuum. The ratio of the speed of light in vacuum $\boldsymbol{c}$ to the speed $\boldsymbol{\upsilon}$ in a given material is called ***the index of refraction or absolute index of refraction, n,*** of that material:

$$n = \frac{c}{\upsilon}, \tag{1}$$

The index of refraction is never less than one. Each medium has a different refractive index. The refractive index of a medium is a measure of how much the speed of light is reduced inside the medium. For example, a refractive index of 1.33 means that the speed of light in a vacuum is 1.33 times faster than in the medium being examined. The index of refraction depends on the wavelength of light used and the temperature of the sample. As the speed of light is reduced in the medium, the wavelength is shortened proportionately.

If light travels from a first medium with speed $\boldsymbol{\upsilon_1}$ to a second medium with $\boldsymbol{\upsilon_2}$, the ratio of light speeds in the first medium vs the second one is called ***the relative refractive index*** of the second medium with respect to the first one $\boldsymbol{n_{21}}$:

$$n_{21} = \frac{n_2}{n_1} = \frac{\frac{c}{\upsilon_2}}{\frac{c}{\upsilon_1}} = \frac{\upsilon_1}{\upsilon_2}. \tag{2}$$

That light travels more slowly in matter than in vacuum can be explained at the atomic level as being due to the absorption and reemission of light by atoms and molecules of the material.

REFLECTION AND REFRACTION OF LIGHT

A great deal of evidence suggests that light travels in straight lines under a wide variety of circumstances. The ray model of light assumes that light travels in straight-line paths called light rays. The direction of a ray at a point in space shows the direction in which the wave's energy is travelling at that place. The ray model has been very successful in describing many aspects of light such as reflection, refraction, and the formation of images by mirrors and lenses. Because these explanations involve straight-line rays at various angles, this subject is referred to as geometric optics.

When light strikes the surface of an object, some of the light is reflected. The rest can be absorbed by the object (and transformed to thermal energy) or, if the object is transparent like glass or water, part can be transmitted through. For a very smooth shiny object such as a silvered mirror, over 95 % of the light may be reflected.

In order to describe the relation between reflected and incident rays it is necessary to look at the point where the incident ray meets the reflecting surface. At that point we imagine a line constructed perpendicular to the surface, in geometrical language called the ***normal*** to the surface. The reflected ray also departs from the same point. The angle between the incident ray and the normal is called the ***angle of incidence*** and the angle between the normal and the reflected ray is called the ***angle of reflection***. The behavior of the rays in specular reflection can be described completely by two laws, illustrated in figure 1:

– the incident ray, the normal at the point of incidence and the reflected ray all lie in the same plane;

– the angle of incidence is equal to the angle of reflection.

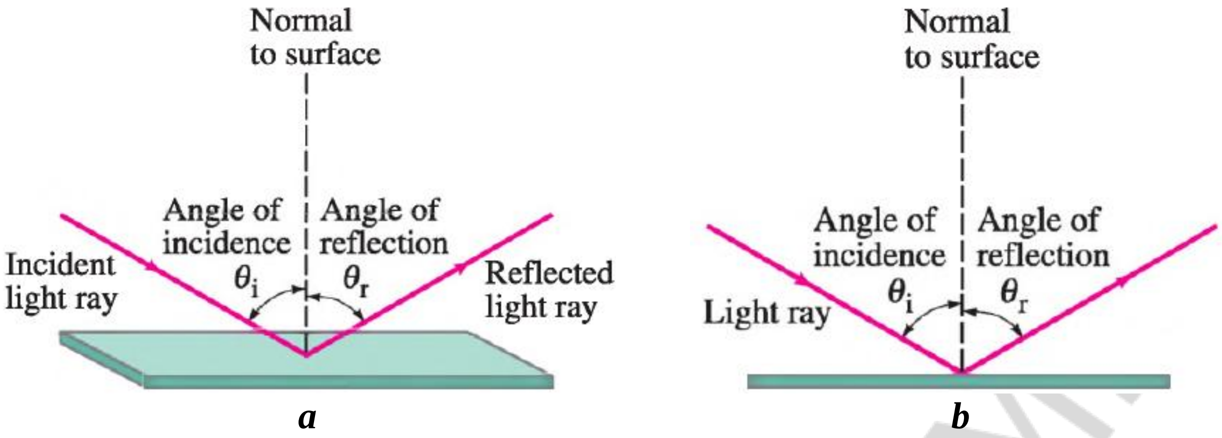


Fig. 1. Law of reflection:
a — shows 3-D view of an incident ray being reflected at the top of a flat surface; *b* — shows side or "end-on" view, which is usually used because of its clarity

When light passes from one transparent medium into another with a different index of refraction, part of the incident light is reflected at the boundary. The remainder passes into the new medium. If a ray of light is incident at an angle to the surface (other than perpendicular), the ray changes direction as it enters the new medium. This change in direction, or bending, is called ***refraction***.

Figure 2 shows a ray passing from air into glass. Angle θ_i is the ***angle of incidence*.** Angle θ_r is the ***angle of refraction***, the angle the refracted ray makes with the normal to the surface.

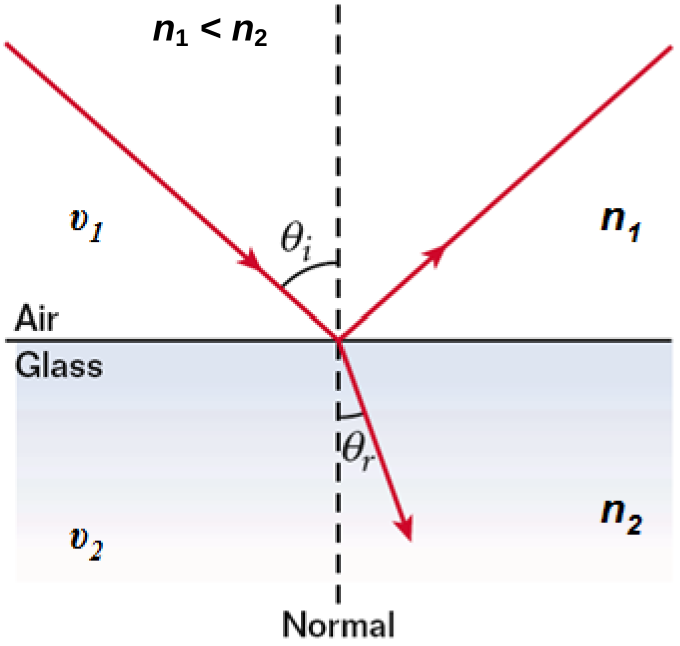


Fig. 2. Law of refraction: when light passes from a medium with a smaller index of refraction n_1 to one with a larger index of refraction n_2 (like from air to glass) ($n_1 < n_2$), the ray bends toward the normal, i. e. $\theta_r < \theta_i$

The ***laws of refraction*** are:

– the incident ray, refracted ray and the normal at the point of incidence all lie in the same plane;

– the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant called the refractive index (Snell’s Law):

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_2}{n_1} = \mathrm{n}_{12} = \frac{\upsilon_1}{\upsilon_2}, \tag{3}$$

where $\boldsymbol{n_1}$ is the absolute index of refraction of the incident medium; $\boldsymbol{n_2}$ is the absolute index of refraction of the second medium; $\boldsymbol{n_{21}}$ is the relative index of refraction of the second medium with respect to the first one; $\boldsymbol{\upsilon_1}$ is the speed of light in incident medium; $\boldsymbol{\upsilon_2}$ is the speed of light in second medium.

PHENOMENON OF TOTAL INTERNAL REFLECTION

When light passes from a medium with a smaller index of refraction $\boldsymbol{n_1}$ to one with a larger index of refraction $\boldsymbol{n_2}$ (like from air to glass) ($\boldsymbol{n_1} < \boldsymbol{n_2}$), the ray bends toward the normal, i. e. $\boldsymbol{\theta_r} < \boldsymbol{\theta_i}$ (fig. 2). If $\boldsymbol{n_1} < \boldsymbol{n_2}$, they say that the second medium has a higher optical density than the first one. In other words, when a ray of light passes obliquely from a medium of lower optical density to one of higher optical density, it is bent toward the normal to the surface. At the greatest angle of incidence $\boldsymbol{\theta_i = 90°}$**,** angle of refraction $\boldsymbol{\theta_{r\,lim}}$ is less than **90°** ($\boldsymbol{\theta_r < 90°}$) and is called **the limit angle of refraction**. In this case the law of refraction states that:

$$\sin\theta_{r\ lim} = \frac{n_1}{n_2}\sin 90^\circ = \frac{n_1}{n_2}. \tag{4}$$

Conversely, when light passes from an optically denser medium to an optically rarer medium (from glass to air $\boldsymbol{n_1} > \boldsymbol{n_2}$) — the ratio $\boldsymbol{n_1/n_2}$ is greater than unity, and **sin** $\boldsymbol{\theta_r}$ is larger than ***sin*** $\boldsymbol{\theta_i}$, and the ray of light is bent away from the normal to the surface (fig. 3).

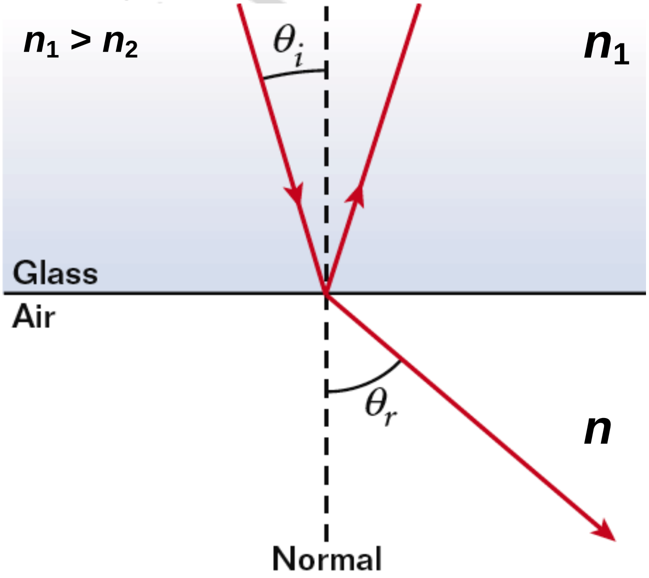


Fig. 3. Law of refraction: when light passes from a medium with a larger index of refraction to one with a smaller index of refraction $\boldsymbol{n_1} > \boldsymbol{n_2}$ (like from glass to air), the ray bends away from the normal, i. e. $\boldsymbol{\theta_r} > \boldsymbol{\theta_i}$.

At a particular incident angle, the angle of refraction will be 90°, and the refracted ray would skim the surface in this case (fig. 4). The incident angle at which this occurs is called the ***critical angle***, $\boldsymbol{\theta_{crit}}$. The relation between critical angle $\boldsymbol{\theta_{crit}}$ and the refractive indices of the two media can be found by inserting the maximum possible value for the angle of refraction, 90°, into Snell's Law which gives

$$\sin\theta_{crit} = \frac{n_2}{n_1}\sin 90^\circ = \frac{n_2}{n_1}. \tag{5}$$

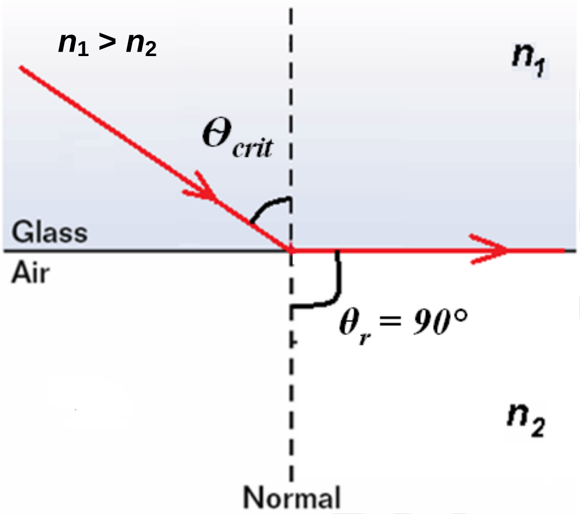


Fig. 4. Since $\boldsymbol{n_1 > n_2}$, there must be a value of incident angle $\boldsymbol{\theta_i}$ less than 90° for which Snell's Law gives $\mathbf{\sin\theta_r = 1}$ and $\boldsymbol{\theta_r = 90°}$. The angle of incidence for which the refracted ray will be grazing the surface at an angle of refraction of 90°, is called the critical angle $\boldsymbol{\theta_{crit}}$

For any incident angle less than $\boldsymbol{\theta_{crit}}$, there will be a refracted ray, although part of the light will also be reflected at the boundary. However, for incident angles greater than $\boldsymbol{\theta_{crit}}$, there is no refracted ray at all, and all of the light is reflected, as for ray in fig. 5.

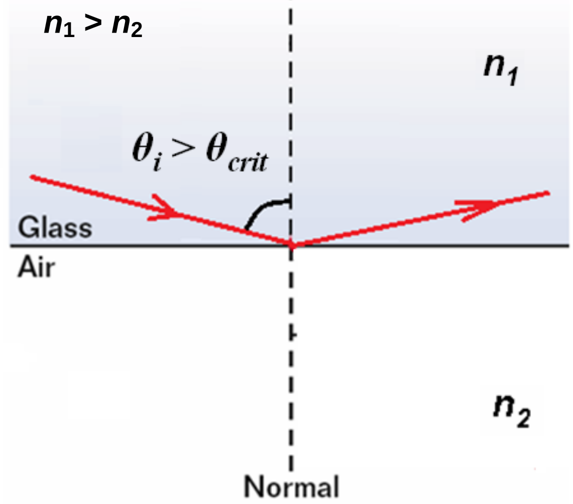


Fig. 5. Total internal reflection can occur when light passes from an optically denser medium to an optically rarer medium (from glass to air $\boldsymbol{n_1 > n_2}$). If the angle of incidence exceeds the critical angle ($\boldsymbol{\theta_i > \theta_{crit}}$), all of the ray reflects from the boundary

This effect is called ***total internal reflection***. Total internal reflection can occur when light passes from an optically denser medium to an optically rarer medium (from a medium of higher refractive index into a medium of lower refractive index) and when the angle of incidence exceeds the critical angle ($\boldsymbol{\theta_i > \theta_{crit}}$).

REFRACTOMETERS AND THEIR APPLICATIONS

A traditional refractometer is an analog instrument for measuring the refractive index (***n***) of a liquid sample, adapted for work in both direct and reflected light (i.e., to investigate transparent and turbid media, respectively). There are several physical principles used in refractometers. Most common are critical angle refractometers, in which the border between a bright and dark is measured.

The original laboratory refractometer is known as the Abbe's refractometer, after the scientist Ernst Abbe who invented the instrument in the late 19th century. This manual device measures the index of refraction of a sample sandwiched between two prisms (fig. 6). The lower prism is called a refracting (or measuring) prism and the upper prism is called an illuminating one. Operation consists of placing 1 or 2 drops of the water sample on the measuring prism, closing an illuminating prism over the sample, then looking through the eyepiece for the reading of the sample refractive index on the scale.

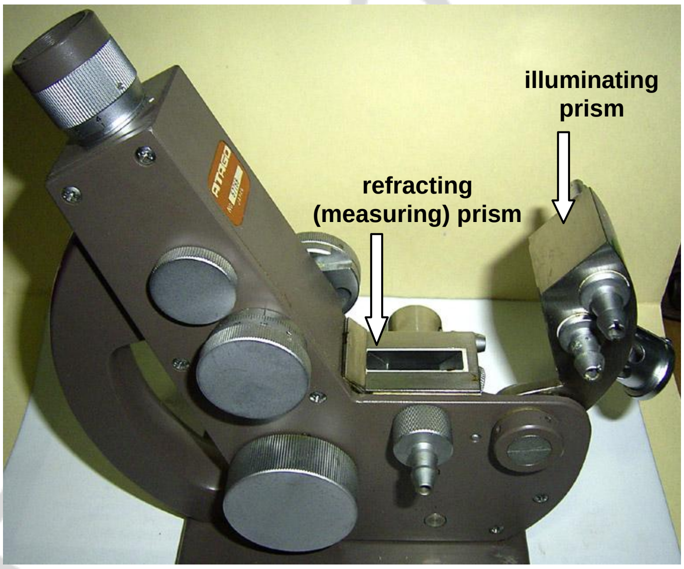


Fig. 6. Refractometer

The refracting prism is made of a glass with a high refractive index and the refractometer is designed to be used with samples having a refractive index smaller than that of the refracting prism. A light source is projected through the illuminating prism, the bottom surface of which is ground (i.e., roughened like a ground-glass joint), so each point on this surface can be thought of as generating light rays traveling in all directions. Light incidents on the boundary between the liquid and the measuring prism at the angle range from 0° to 90°. Therefore light propagates through the measuring prism only in the angle range from **0°** to $\boldsymbol{\theta_{lim}}$.

Inspection of fig. 7 shows that light traveling from point ***A*** to point ***B*** will have the largest angle of incidence ($\boldsymbol{\theta_i \approx 90°}$) and hence the largest possible angle of refraction $\boldsymbol{\theta_{lim}}$ (so called a limit angle of refraction $\boldsymbol{\theta_{lim}}$) for that sample. All other rays of light entering the refracting prism will have smaller $\boldsymbol{\theta_{lim}}$ and hence lie to the left of point ***C***. Thus, a detector placed on the back side of the refracting prism would show a light region to the left and a dark region to the right.

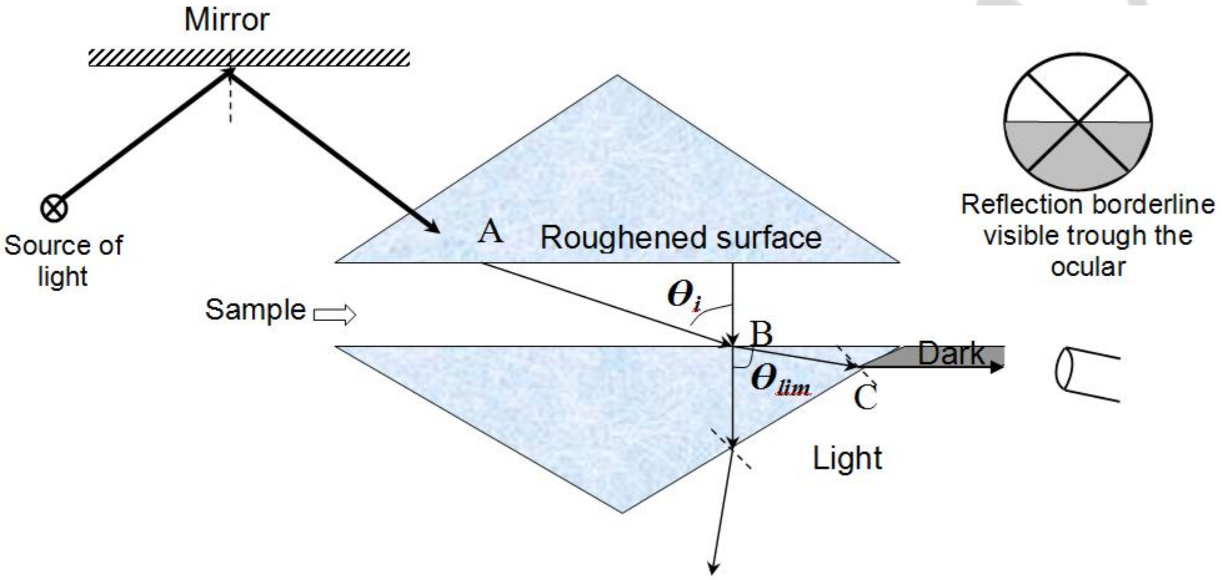


Fig. 7. Cross section of part of the optical path of a refractometer. The sample thickness has been exaggerated for clarity

The reflective borderline position is determined by the limit angle of refraction $\boldsymbol{\theta_{lim}}$ which in turn depends on the refractive index $\boldsymbol{n_{liquid}}$ of a liquid under investigation. The refractive index of the liquid $\boldsymbol{n_{liquid}}$ is given by the equation:

$$n_{liquid} = n_{glass} \cdot \sin \theta_{lim}. \qquad (6)$$

The reflection borderline can be colored in colors ranging from red to blue due to the phenomenon of dispersion i.e. the variation of the index of refraction of a transparent substance with the wavelength (frequency) of light. Compensator dial is adjusted to give a sharp reflection borderline. When the compensator dial is properly set, the reflection borderline will not have any color at the crosshairs, and will be faintly red at one end and faintly blue at the other.

It is well known that refractive index of a solution varies according to its concentration. Hence, a measurement of refractive index can be used to measure concentration. Samples with different concentration have different refractive indexes and will produce different angles of refraction and this will be reflected in a change in the position of the borderline between the light and dark regions. By appropriately calibrating the scale, the position of the borderline can be used to determine the refractive index of any sample.

Clinical refractometers are used for medical purposes such as determination of protein in urine, urine density, blood serum (the refractive index of blood serum or plasma depends mainly upon its protein concentration, as proteins are one of the major constituents), the analysis of the cerebral and synovial fluid, the density of subretinal and other fluids of the eye.

Refractometers are also widely used in pharmacy for the study of aqueous solutions of various drugs, calcium chloride (0 % and 20 %); novocaine (0.5 %, 1 %, 2 %, 10 %, 20 %, 40 %); ephedrine (5 %); glucose (5 %, 25 %, 40 %); of magnesium sulfate (25 %); sodium chloride (10 %); kordiamin, etc., and in food industry — in sugar and bread factories, confectionery factories for determining the following parameters, such as humidity of honey (up to 20 %), fraction of solids in different musts, mass fraction of soluble solids by sucrose (BRIX) in products of fruit and vegetable processing, percentage of fat in solid foods, concentration of salts.

FIBER OPTICS PRINCIPLES

Total internal reflection is the principle behind fiber optics. Glass and plastic fibers as thin as a few micrometers in diameter are common. A bundle of such tiny fibers is called a light pipe or cable, and light can be transmitted along it with almost no loss because of total internal reflection. Here a light ray enters one end of a transparent rod or fiber and is totally reflected many times, bouncing from side to side until it reaches the other end (fig. 8). This alone is not very useful, but what is important is that when the pipe is bent, the light path can be bent with it, staying within the pipe. The light pipe still works provided that each angle of incidence remains greater than the critical angle, so the light cannot get out until it reaches the flat end of the light pipe.

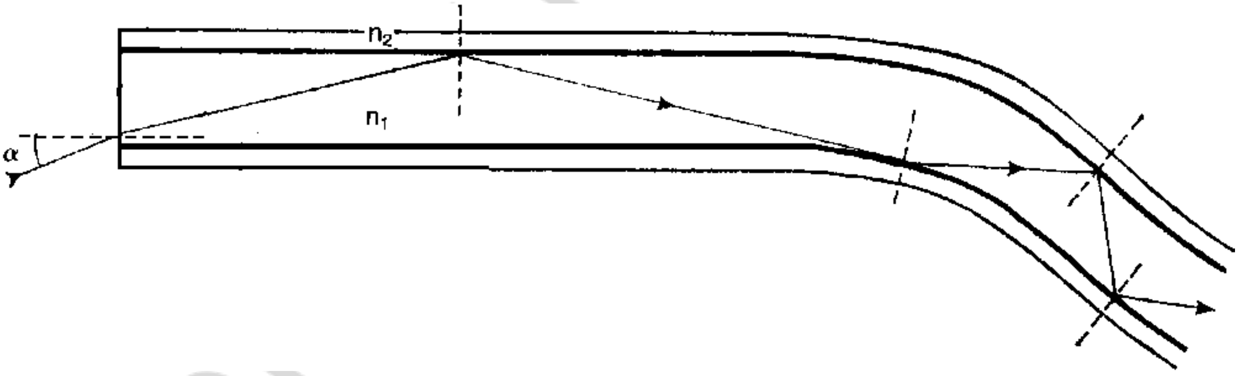


Fig. 8. Light reflected totally at the interior surface of a glass or transparent plastic fiber

Although there is a high contrast in refractive index between the material of the fiber and air, fibers often need to be coated with a protective medium which reduces the ratio of refractive indices and hence, also, the value of the critical angle. In order to make sure that the angles of incidence remain large enough, the fiber should not be bent too severely.

In endoscope flexible cable light cannot be transmitted by individual fibers since they are too weak on their own. Therefore, thousands of small fibers are combined to intensify the light being transmitted. This bundle of fibers combines the two most basic necessities of visualization: illumination of the interior body and transmission of the lighted image to the user's eye or camera. To clarify, there is one bundled unit of fibers that have been separately insulated into those two units for lighting and reflecting the image. The illumination bundle is just that, a non-specific arrangement of fibers called an "incoherent" blend. However, the fibers in the image bundle must be organized in such a way that the pattern found at the distal tip is the same at the proximal end. Each fiber transmits one piece of information like one pixel on a computer screen. Those 'pixel' images must line up in the exact manner they accepted the image inside the patient so that the image the viewer sees is the same coherent image. This arrangement of the image bundle is called "coherent".

Modern endoscopes that use fiber-optic technology can be made of flexible tubing rather than the rigid scopes of past designs. Fiber optics replaced the "standard relay assembly". The resolution of the image reflected back to the user is higher than were classical endoscopes. It should not be forgotten that this resolution still depends on the physical structure of the fibers. When the fibers are regularly spaced, with an even density, they transmit the highest quality image. More fibers translate to more "pixels" in the analogy above, but when the fibers are much smaller than 5μm their physical strength and structural integrity are lost and fracturing becomes a concern. It is for this reason the range of 5–25 μm has become standard. Another advantage of many small fibers are their ability to allow the reflected image to be transmitted with high precision and clarity even when the bundle is curved.

ENDOSCOPY IMAGING SYSTEMS

The word endoscopy is derived from the Greek words "*endo*" meaning "inside" and "*skopeein*" meaning "to see". Endoscopy is a medical procedure that uses a specialized instrument called an endoscope. Endoscopes are devices for the visual examination of body cavities, and are sometimes used for certain kinds of surgery. From the physical point of view they are based on the reflection and refraction of light. Endoscopes are inserted into the body cavity to be examined either through natural body openings (nasal and pharyngeal cavity, larynx, airways, urethra, uterus, rectum) or surgical incisions (abdomen, thorax, joints).

Endoscopes can be categorized according to three aspects: complexity, method of illumination and method of observation. There are four groups of endoscopes with different complexity (fig. 9).

Endoscopic mirrors. Examples: Laryngoscope is spoon-like mirror used for the examination of the larynx and posterior part of the nasal cavity. Ophtalmoscopic mirror is planar or concave mirror with a central orifice. It serves for induction of so called red reflex — reflection of light from the retina.

Fig. 9. Different types of endoscopes:
a — endoscopic mirror — laryngoscope; *b* — endoscopes with rigid tubes — rectoscope and cystoscope; *c* — fibroscope; d — capsule endoscopy

Endoscopes with rigid tubes. In the ear, nose and throat field, slim rigid endoscopes are used for the observation of ear drums, nasal cavities, vocal chords and other structures. They are also used in urology for procedures such as transurethral prostatectomies and renalectomies, and in obstetrics and gynecology procedures for the removal of uterine myomas.

Fibroscopes and videoendoscopes. Example: Gastrointestinal endoscope is used for examining the esophagus, stomach, and large & small intestines.

Capsule endoscopy. Capsule endoscopy is a less burden form of examination able to capture images of the entire small intestine by having the patient swallow a capsule the size of a large pill that contains a small camera and light source. Images from the capsule are sent wirelessly to an antenna unit attached to the patient’s body and are recorded by a receiver. When finished, the recorded image data is downloaded to a personal computer for viewing by the doctor performing the diagnosis.

There are two approaches to endoscopic surgery: a medical approach and a surgical approach. The medical approach involves inserting the endoscope into a natural opening of the body, such as the mouth, nose, urethra, or anus, and performing a therapeutic procedure, e.g. resecting a tumor. The surgical approach involves substituting endoscopic surgery in place of an open surgical procedure such as laparatomy or thoracotomy. However, these procedures still require small incisions in order to insert the endoscope itself.

Endoscopy done through existing body openings can usually be done under local anaesthesia, but other types that require a small puncture to see an “internal cavity” may need hospital admission and a general anaesthetic. In each type small pieces of tissue can be removed for tests and some other procedures can be done.

There is a list of the major types of endoscopy:

– ***gastroscopy***: to see the gullet, stomach and upper small intestine;

– ***colonoscopy***: to see the large intestine;

– ***laparoscopy***: to see the “stomach cavity” and the organs therein;

– ***proctoscopy:*** this is used to check for piles and other conditions of the anus and rectum;

– ***cystoscopy***: to see the urinary bladder;

– ***bronchoscopy:*** to see the air passages to the lungs;

– ***laryngoscopy:*** to see the larynx or voice box;

– ***nasopharyngoscopy***: to see the nose and related cavities;

– ***arthroscopy***: to see inside joints such as the knee joint;

– ***thoracoscopy***: to see inside the chest cavity.

Historically, it was known that it is possible to insert tubes into body orifices, but to see clearly a method was needed to illuminate the inside of the organ to be seen. The earliest crude attempts used oil lamps, which were later replaced by small electric filament bulbs. These were not very bright and tended to produce a lot of heat. Medical endoscopy really came into its own after the invention and application of fibre-optic technology to endoscopy. Fibre-optic endoscopes use bundles of thin glass fibres to transmit light to and from the organ being viewed. These fibres use the principle of total internal reflection to transmit almost 100 % of the light entering one end to the other end.

Structure and components of endoscope system are illustrated in fig. 10. When examining a cross section of an endoscope flexible cable one can see four main components: two illumination bundles; one observation bundle; working (instrument) channel for insertion of surgical tools; tubes for air and water.

The image is formed by a small lens attached to the end of a collection of thousands of individual fibers. Each fiber carries light from one part of the image, which can be viewed at the other end where the light emerges. In order to get a useful image at the output end, the fibers must be arranged in the same way that they were at the input end. In order to view tumor tissue in a more detailed manner, some endoscopes have an optical zoom feature. Recent models also support high-definition video displays. Light guide fiber bundles conduct light from the external light source through the endoscope to illuminate body cavities. Instruments are pushed in and out of the instrument channel for harvesting tissue (biopsy), removing tumors, cauterizing bleeding lesions, etc. The nozzle on the distal tip is used to clean the lens with water and expand body cavities by insufflating them with air.

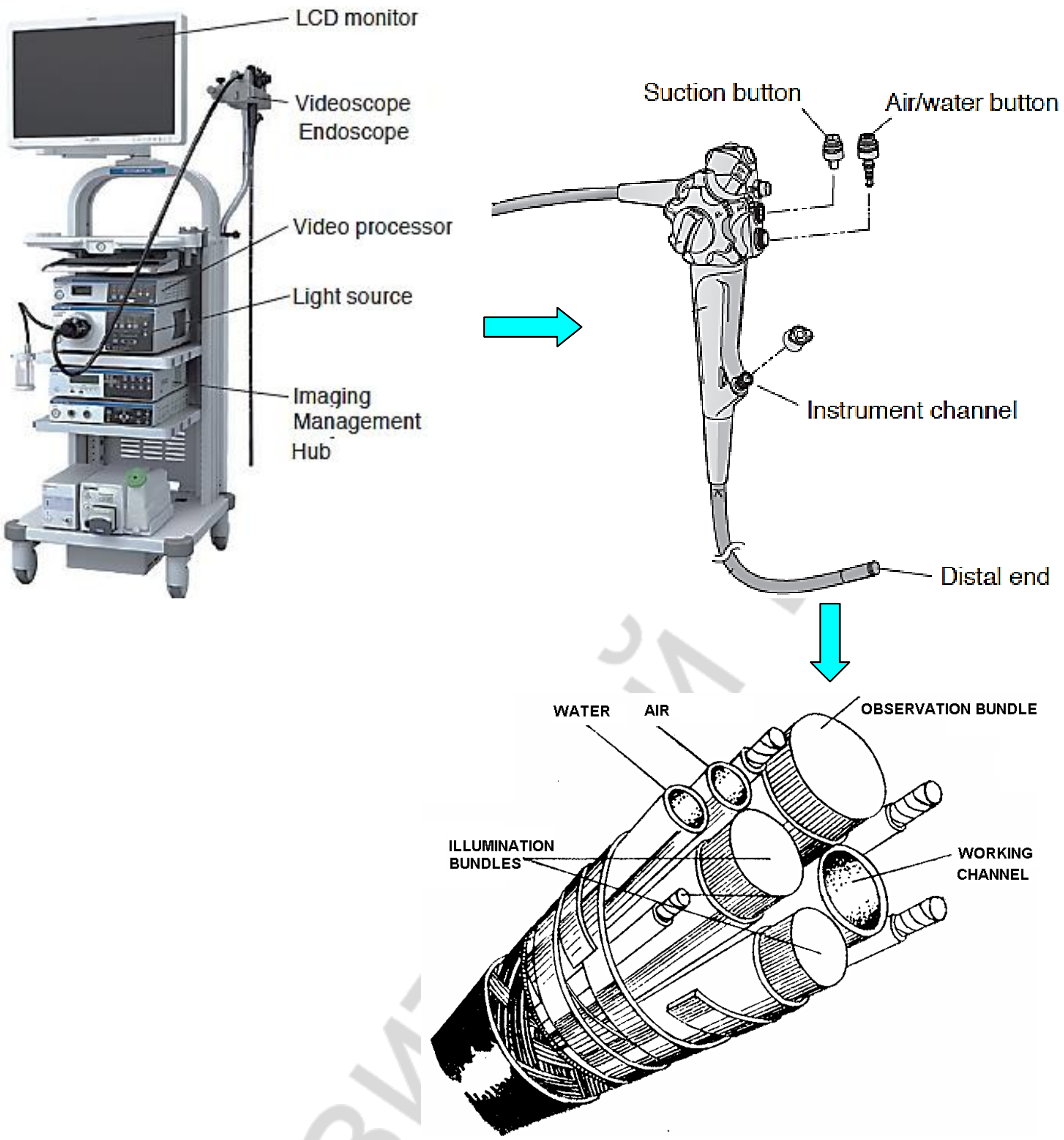


Fig. 10. Structure and components of an endoscope system. On the distal end of endoscope cable there are four main components: two illumination bundles; one observation bundle; working (instrument) channel for insertion of surgical tools; tubes for air and water

Figure 11 represents the examination of patient's stomach by inserting a light pipe known as an endoscope through the mouth and the back of throat, down gullet (esophagus), into stomach and into the first part of small intestine (duodenum).

Light is sent down an outer set of fibers to illuminate the stomach. The reflected light returns up a central core set of fibers. Light directly in front of each fiber travels up that fiber. At the opposite end, a viewer sees a series of bright and dark spots, much like a TV screen — that is, a picture of what lies at the opposite end. Lenses are used at each end. The image may be viewed directly or on a monitor screen or film. The fibers must be optically insulated from one another, usually by a thin coating of material with index of refraction less than that of the fiber. The more fibers there are, and the smaller they are, the more detailed the picture. During the test the endoscopist may take samples (also called biopsies) for analysis or to check for infection in the lining of the stomach with the bacteria Helicobacter pylori. The samples are removed painlessly through the endoscope, using tiny forceps. The endoscope is removed once the procedure has been completed. Such instruments, including bronchoscopes, colonoscopes (for viewing the colon), and endoscopes (stomach or other organs), are extremely useful for examining hard-to-reach places.

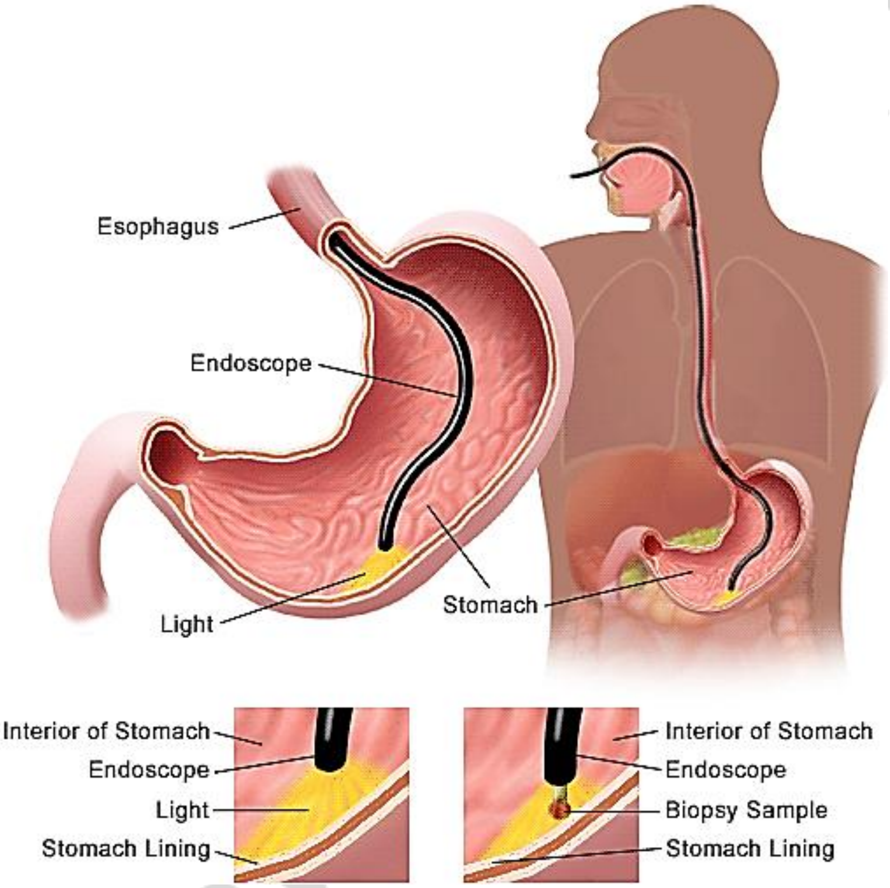


Fig. 11. Esophagogastroduodenoscopy examination. The test allows the endoscopist to look directly at the lining of esophagus (gullet), stomach and duodenum (the first part of the small intestine)

THE ORDER OF THE LABORATORY WORK “REFRACTOMETER USE TO DETERMINE SOLUTIONS CONCENTRATION”

Aim of the study — to determine the refractive index of the solution of unknown concentration by the refractometer.

Practical part. It is required in this lab work to find the dependence of solution refractive index on the solution concentration and to determine the unknown concentration of solution by graphically and analytically.

In order to determine the unknown concentration of solution the refractometer should be at first calibrated, i.e. one have to start with measurements of refractive index of a pure solvent (H_2O) and refractive indexes of known concentration solutions, and then to measure the refractive index of the test solution of unknown concentration. After that the calibration graph (the graph of dependence of the solutions refractive index on the concentration of solution) should be ploted. Using the calibration curve one can find the refractive index of the solution of unknown concentration C_x. And then it is necessary to write the analytical dependence $n = f(C)$ and calculate the C_x.

A laboratory Abbe's refractometer is presented in fig. 12. It allows to measure the wide range of solution refraction indexes — from 1.2 up to 1.7. The measurements are carried out in natural light. Refraction indexes of transparent media are determined in transmitted light.

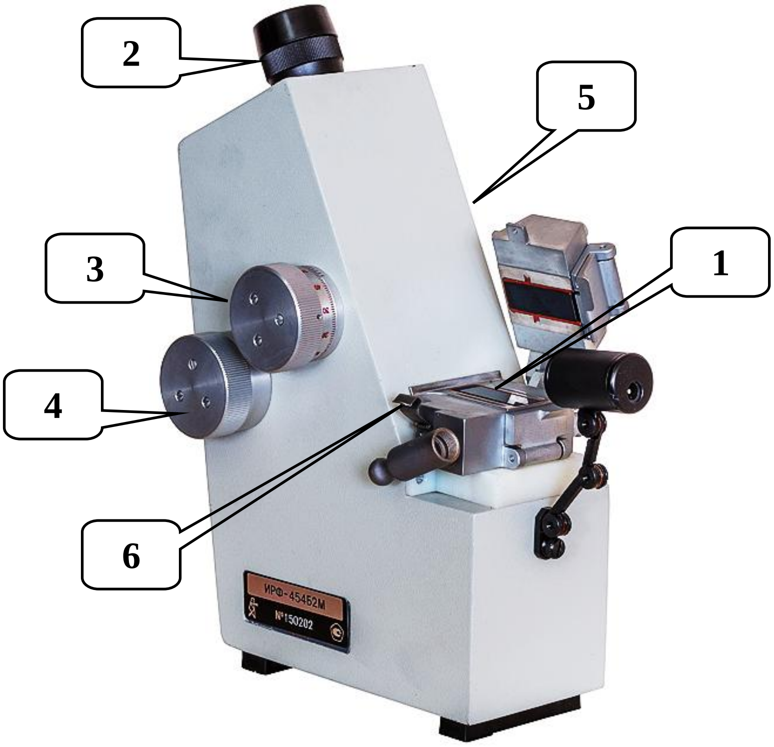


Fig. 12. Main parts of a laboratory Abbe's refractometer

On the body of the refractometer a refractometric unit 1 and an eyepiece 2 are installed. In the left part of the body there is a mirror 5 with a cover (in the figure it cannot be seen). Refractometric unit consists of two parts: upper and lower. The lower fixed part is a measuring prism, and the upper is illuminating prism.

The illuminating prism can be thrown back by an angle of ~100°, after removing the hook 6.

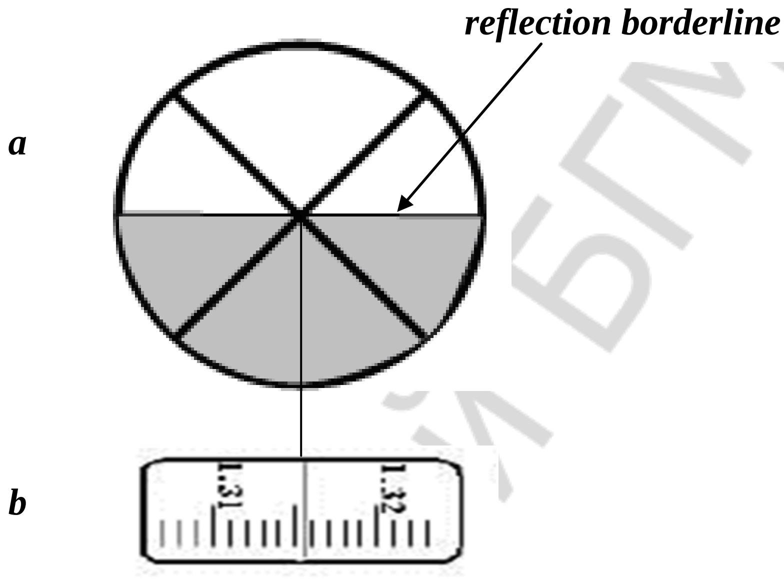
Setup procedure:

1. Open the cover of the mirror 5 and the window of the illuminating prism. Rotate the eyepiece to get a clear image of the scales of the refractometer (fig. 13).
2. Clean polished surface of the measuring prism carefully.
3. Put two or three drops of distilled water using a pipette or a glass rod, without touching the prisms. Close the illuminating prism and lock it by the hook 6. Turn mirror 5 to achieve maximum illumination of the scale.
4. Move the eyepiece to make sharp image of the refractometer scales.

5. Rotate the flywheel 3 (compensator dial) until the color of the borderline will disappear. When the compensator dial is properly set, the borderline will not have any color at the crosshairs.

6. Rotate the flywheel 4 and set the reflection borderline on the upper field of view of the eyepiece exactly on the crosshairs (fig. 13, *a*) and than find the refractive index on lower scale (fig. 13, *b*).

7. Repeat the procedure for all solutions.



8. Fill the table 1 with experimental data.

Fig. 13. Double scale of the eyepiece field of view:
a — reflection borderline visible through the ocular; *b* — the refractive index scale

Table 1

The results of the measurements

***C*, %**	***0***	***C_1* =**	***C_2* =**	***C_3* =**	***C_x***
n					
k	–				***k_{mean}*** =

9. Plot the calibration graph (the graph of dependence of the solution refractive index on the concentration of solution) $n = f(C)$ (fig. 14). Calculate the coefficient $k = \text{tg}\alpha$, where α is an angle between the graph and C-axis. Fill the table with k value for every solution and calculate its mean value.

10. Determine the unknown concentration of solution C_x using the approximation of n_x to the graph $n = f(C)$.

11. Derive the analytical dependence $n = n_0 + k \cdot C$.

12. Calculate the unknown concentration C_x using previously obtained analytical formula. Compare calculated value C_x with the value obtained in the graph.

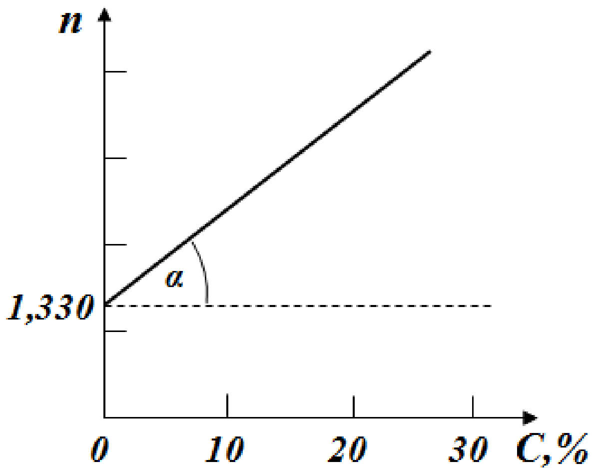


Fig. 14. Dependence of the refractive index on the concentration $n = f(C)$

QUESTIONS

1. What is an absolute refractive index and relative one?
2. What is the law of refraction of light (Snell’s Law)?
3. Under what conditions is the phenomenon of total internal reflection of light observed?
4. What is the critical angle of total reflection?
5. What is the fiber optics? How is it used in endoscopes?
6. What is the angle of refraction when a light ray incident perpendicular to the boundary between two transparent materials?
7. When a wide beam of parallel light enters water at an angle, the beam broadens. Explain why.
8. A ray of light is refracted through three different materials (fig. 15). Rank the materials according to their index of refraction, least to greatest.

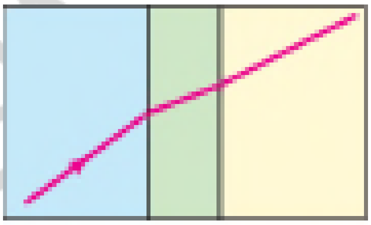


Fig. 15. Question 8

9. When you look up at an object in air from beneath the surface in a swimming pool, does the object appear to be the same size as when you see it directly in air? Explain.
10. What is the critical angle for the interface between water and diamond? To be internally reflected, the light must start in which material?
11. Explain the working principles of refractometer.

PROBLEMS

1. Light beam incidents from the air to camphor at an angle 40º and refracts in this medium at an angle 24° 35'. Determine the critical angle of refraction of the camphor.

2. The speed of light in the medium is $2 \cdot 10^8$ m/s. What is the refractive index of the substance?

3. A diver shines a flashlight upward from beneath the water at a 38.5° angle to the vertical. At what angle does the light leave the water?

4. Rays of the Sun are seen to make a 33.0° angle to the vertical beneath the water. At what angle above the horizon is the Sun?

5. A beam of light in air strikes a slab of glass (n = 1.56) and is partially reflected and partially refracted. Determine the angle of incidence if the angle of reflection is twice the angle of refraction.

6. A light beam strikes a 2.0-cm-thick piece of plastic with a refractive index of 1.62 at a 45° angle. The plastic is on top of a 3.0-cm-thick piece of glass for which n = 1.47. What is the distance D in fig. 16?

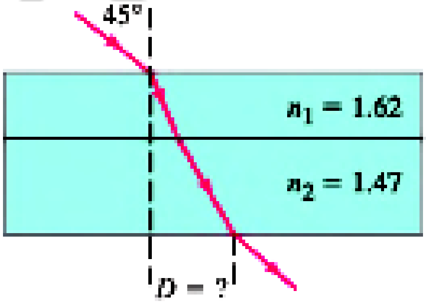


Fig. 16. Problem 6

7. The critical angle for a certain liquid-air surface is 49.6°. What is the index of refraction of the liquid?

8. A ray of light, after entering a light fiber, reflects at an angle of 14.5° with the long axis of the fiber, as in fig. 17.

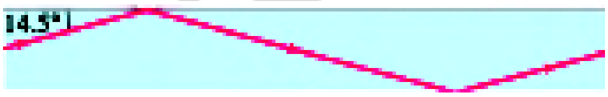


Fig. 17. Problem 8

Calculate the distance along the axis of the fiber that the light ray travels between successive reflections off the sides of the fiber. Assume that the fiber has an index of refraction of 1.55 and is 1.40×10^{-4} m in diameter.

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