Experiment # 16

Optics One
Plane Wavefronts & Flat Interfaces

Principles

Nature of Light

Light is *waves*. Light waves are transverse in nature and belong to the family of electro-magnetic waves. These waves are produced by the de-excitation of valence electrons of atoms. Excitation of these electrons occurs when energy (from some external source) is made incident upon them. Visible light is not produced by the de-excitation of electrons of any other orbit.

Waves have no mass. We cannot apply force on a wave! We cannot push it around or punch it (if we are angry). The good thing is that as there is no force, there is no acceleration. This eliminates Dynamics and reduces Kinematics to one simple equation:

$$v = d/t$$

A wave is born with a certain frequency and gets locked on to it. Come rain come shine, the frequency of a wave will not change. We write f for it. The MKS unit of frequency is Hertz or Hz which stands for *cycles per second*. The unit of frequency is s^{-1}. The range of frequencies of light rays to which our eyes are sensitive, is from $4\times10^{14}\,Hz$ (red light) to $7.5\times10^{14}\,Hz$ (violet light). Each frequency is one *color*. There are, therefore, 3.5×10^{14} colors; but our eyes broadly divide them into 7 color groups: red, orange, yellow, green, blue, indigo and violet. If all these colors be present simultaneously (superimposed on one another), the result will be a *white* color. The light coming from the sun is white. A rainbow, however, splits sunlight into the seven color-bands as described above. This group of seven colors is known as *rainbow*.

The time (in seconds) that a wave takes to complete one cycle is defined as its *time period* T. As the unit of f is *1/sec* and that of T is *sec*, we would expect them to be reciprocals of each other. This is quite true. Thus $T = 1/f$ and $f = 1/T$. The time period of the red light is $2.5\times10^{-15}\,\text{sec}$, while that of the violet light is $1.333\times10^{-15}\,\text{sec}$.

The distance a wave travels in one time period is defined as its *wave length*: λ, measured in meters. The range of wavelengths of visible light is from 750 nm (red light) to 400 nm (violet light); where one nanometer is 1×10^{-9} meter.

The product of frequency f and wavelength λ has units of *m/s* or speed. If c be the speed of light in free space (or vacuum), then we may write:

$$f\lambda = c \qquad \text{..........(1)}$$

As electromagnetic waves are the superposition of electric field $\boldsymbol{E}$ and the magnetic field $\boldsymbol{B}$, we may expect to find the value of c from the electric property ε_o and the magnetic property μ_o of free space. Thus:

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}} = \frac{1}{\sqrt{(8.854\times10^{-12})(4\pi)(1\times10^{-7})}} = 3\times10^{8}\ \text{m/s} \qquad \text{..........(2)}$$

Waves exist only in the state of motion. There is no such thing as a wave at rest. Hence waves possess kinetic energy, the energy of the state of motion. The energy carried by a wave is always constant. It can neither be increased nor can it be decreased. It equals amount of energy that was used to excite the valence electron, in the first place. The magnitude of this energy is given by:

$$E = hf \qquad \text{..........(3)}$$

where h is the well known Planck's Constant. Its value is 6.34×10^{-34} Joules-Second (JS). The energy of one unit of red light is $1.885\ \text{eV}$ and that of one unit of violet light is $2.972\ \text{eV}$. ($1\,eV = 1.602\times10^{-19}\ J$). It is this energy which, when incident on the retina of our eye, activates the optic nerves and corresponding information is transmitted to the brain.

Propagation of Light

Light is propagated in accordance with the Huyghen's principle.

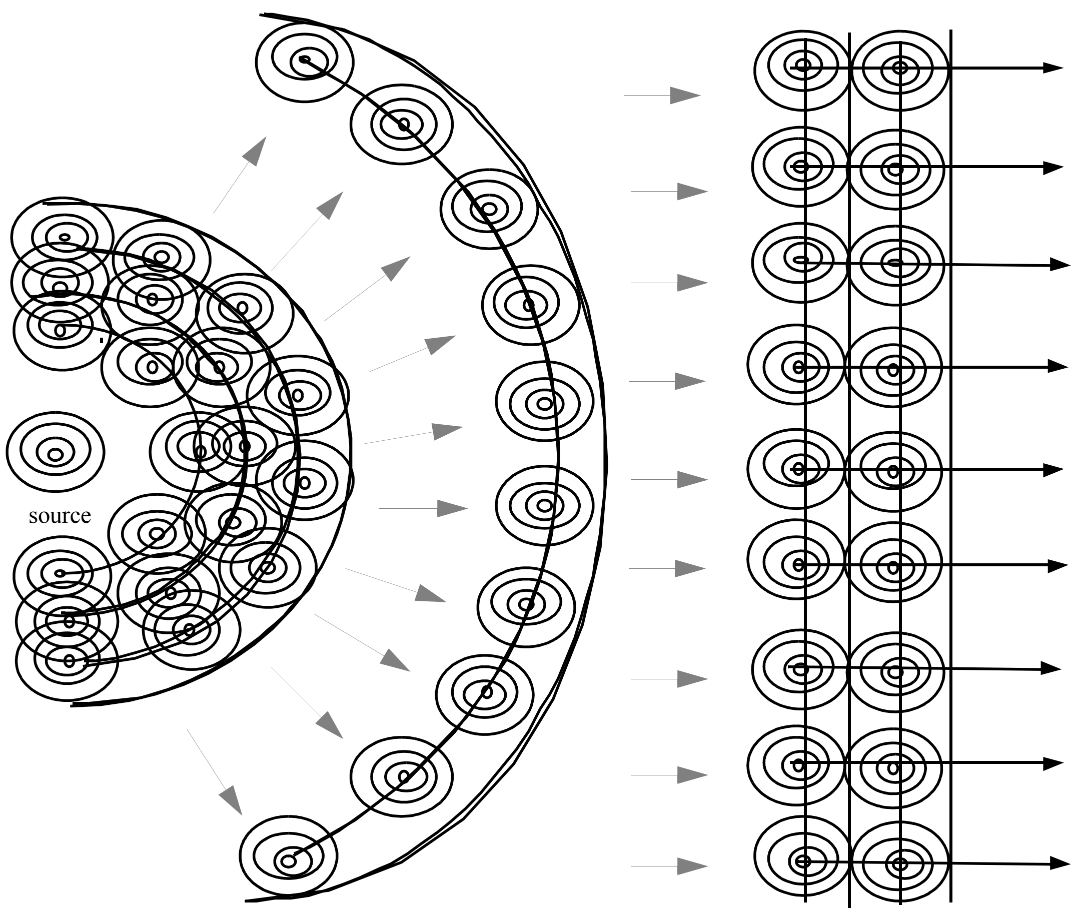

Fig (1) Hughen's Principle

According to the principle, electromagnetic disturbance spreads out from the source, spherically symmetrically, in all directions in the three dimensional space. So it spreads out in concentric spheres. Each point on a sphere acts as a new source and propagates its own concentric spheres. Tangents drawn on all spheres at an instant of time, will form a surface, called the "wave-front" of the wave. In the vicinity of the source, the wavefront is a curved surface but as we move outwards, away from the source, the radius of curvature of the wavefront keeps becoming larger and larger and the surface of the wavefront keep becoming flatter and flatter. At sufficiently large distances from the source, the wavefront becomes a plane surface. A *plane wavefront* is defined mathematically as the wavefront that has an infinitely wide surface and an infinitely long wave-train (the wavefront has travelled an infinite distance from the source). In real life, a plane wave-front is a set of parallel rays that are all in the same phase.

Like all transverse waves, light waves are also sinusoidal. Hence they are represented by the general equation of a transverse wave:

$$A_{inst} = A_{peak} \sin\theta \qquad \theta = 2\pi f \qquad \text{..........(4)}$$

where A_{inst} and A_{peak} are the instantaneous and peak amplitudes of the wave. Intensity of a wave is defined as the square of the peak amplitude.

$$I = A_{peak}^2 \qquad \text{..........(5)}$$

It may also be pointed out that the intensity of light waves decreases inversely as the square of the distance from the source. Thus if the distance of a screen from a source of light be doubled, the intensity will drop down to one-fourth at the new location.

Plane Wavefront

A plane wavefront is popularly known as a *beam of light* or as *a set of parallel rays* or simply *parallel rays*. Furthermore, the rays are said to be *coherent* or in phase with one another i.e. they pass through their nodes and antinodes synchronously.

Media & Interfaces

(a) Medium.

We define a *medium* as the region of space in which light waves travel **or** can travel. Examples of such media are: vacuum, air, water, glass, diamond, plastics, most liquids and most gases. The speed of light is maximum in free space (vacuum) or in air. In a material medium (other than air), the speed of light decreases. For example, a ray of light looses 25% of its free-space speed in water; approximately 42% in glass and no less than 58% in diamond! We have previously used the letter c for the speed of light in free space. Let v be the speed of light in a material medium, then we define a dimensionless quantity *refractive index* n, as the ratio of the speed of light in free space to its speed in a material medium. We get:

$$n = c/v \qquad \text{..........(6)}$$

It should be noted that n is always greater than unity. Its value for water is 1.33; for glass 1.58 and for diamond it is 2.42. As the speed decreases, it is the wavelength λ that gets affected (and will becomes smaller) but not the frequency f. Please recall our earlier statement that frequency can never change. It should further be noted that the color depends on the frequency and *not* on the wavelength!

(b) Interface

We define an *interface* as the surface separating two media. Being a surface, the interface has a direction (please recall that surfaces or areas are vectors). The *official* direction of a surface is perpendicular to the surface and is called *normal*. The word *normal*, in mathematics, stands for being perpendicular. All angles in Optics are measured with respect to the normal to an interface. Depending upon the geometrical shapes and sizes of the medium, an interface may be (i) plane, or (ii) curved. In our experiments, we shall deal with both types of interfaces.

Interactions of Light Rays And Interfaces

As a light wave, travelling in one medium, comes across a different medium, it encounters an interface and interacts with it. The interactions are categorized as: (1) *reflection* (2) *transmission,* and (3) *absorption*. Let the fractions of light intensity reflected, transmitted and absorbed be R, T and A respectively, then the law of conservation of energy requires that:

$$R + T + A = 1 \qquad \text{.........(7)}$$

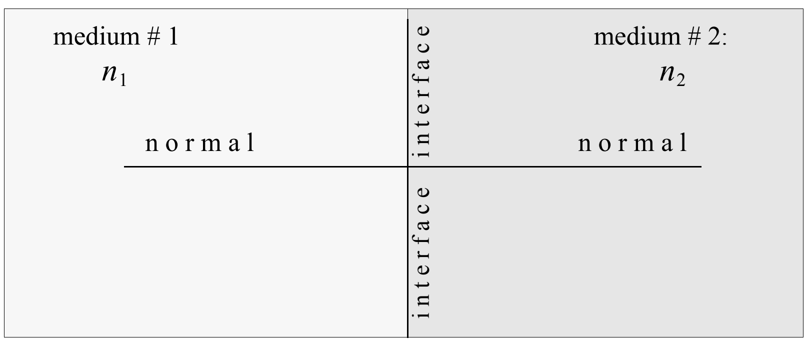

Fig (2) Media, Interface and Normal

For the purposes of the experiments in this course, we shall leave out *absorption*. We shall therefore confine ourselves to *colorless* media only. We shall also, for the sake of simplicity, consider reflection and transmission separately. Thus while considering reflection, transmission will be deemed to be zero (perfect reflection) and likewise for transmission. The study will be in two sections.

(a) $R = 1, \ T = 0, \ A = 0$

(b) $R = 0, \ T = 1, \ A = 0$

An Interesting Characteristic of Transmitting Media

It is an interesting observation that almost all material media are finite in size. The exceptions are free space, air and water. All other transmitting media are usually small in size. Thus, sooner or later light must come out of them. This amounts to saying that light finds two interfaces in a transmitting medium: one when entering the medium and the other when leaving it. Let's write down this very important fact that applies to almost all transmitting media:

TRANSMITTING MEDIA GENERALLY COME WITH TWO INTERFACES

An Inherent Difficulty with Transmitting Media

It is impossible to make measurements *inside* a a solid transmitting medium such as glass or plastics. This is because it is impossible to place an angle measuring device *inside* solids. When a ray of light enters such a medium, we cannot measure the angle of this ray inside that medium. In most cases, however, one may be able to place measuring devices in liquids and gases.

The Laws

Corresponding to the three interactions of light with interfaces, we have three laws. These are empirical in nature but are substantiated by theory and backed by mathematics. The theory was developed by James Clark Maxwell.

In what follows, a medium will be characterized by its refractive index, n . The two media, one on each side of an interface, will be described by their refractive indices: n_1 and n_2 .

The law of reflection:

The angle at which a ray of light is reflected at an interface is necessarily equal to the angle at which it is incident on the interface. Mathematically speaking:

$$\theta_r = \theta_i \qquad \text{..........(8)}$$

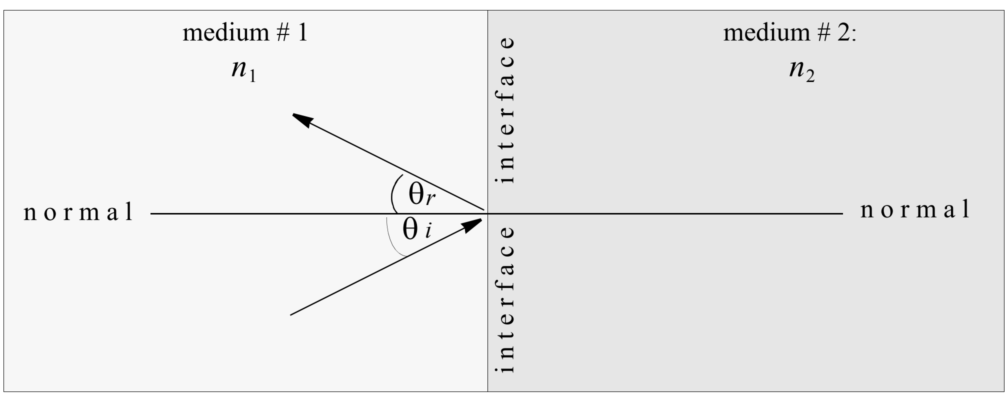

Fig (3) The Law of Reflection

The Law of Transmission

The angle at which a ray of light is transmitted in a second medium, is given by Snell's Law. The law states that for two media with refractive indices n_1 and n_2, the relation between the incident light and the transmitted light is given by the expression:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \text{..........(9)}$$

This is known as *Snell's Law.* It is illustrated in Fig (4). Please note that θ_1 is the same as θ_i .

As $n_1 = c / v_1$ and $n_2 = c / v_2$

we may rewrite Eqn (9) as

$$\sin\theta_1 / v_1 = \sin\theta_2 / v_2 \qquad \text{..........(10)}$$

where we divided both sides by c . Again, as:

$$v_1 = f \lambda_1 \text{ and } v_2 = f \lambda_2$$

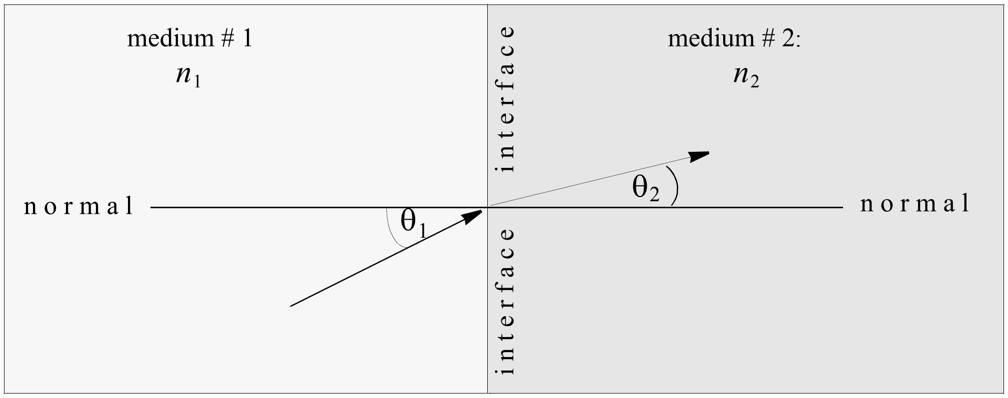

Fig (4) The Law of Transmission

we may rewrite Eqn (10) as

$$\sin\theta_1/\lambda_1 = \sin\theta_2/\lambda_2 \qquad \text{..........(11)}$$

where we divided both sides by f. From Eqns (9), (10) and (11), we get a *master* formula for the law of reflection:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} \qquad \text{..........(12)}$$

Some Intriguing Consequences of Transmission

Consider the transmission of light at an interface, separating medium #1 from medium #2. As each medium is characterized by its refractive index, let us assume that light is travelling from medium n_1 to medium n_2. We have two possibilities: (a) $n_2 > n_1$ (b) $n_1 > n_2$. These are shown respectively in Figs (5) & (6)

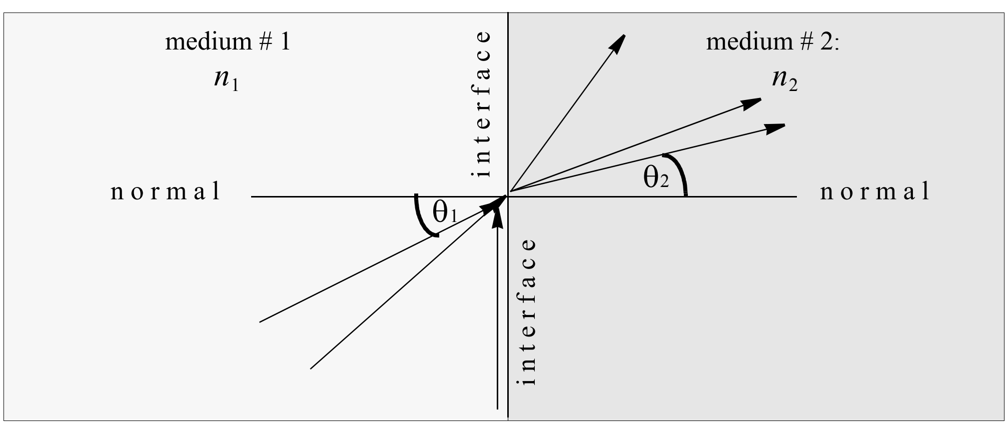

Fig (5) Transmission from (optically) rarer to (optically) denser medium

(a) $n_2 > n_1$. We say that light is travelling from an optically rarer medium to an optically denser medium. From Eqn (9) we expect that $\sin\theta_2 < \sin\theta_1$; or $\theta_2 < \theta_1$. This means that the angle of transmission is smaller than the angle of incidence. Remember that both angles are measured with respect to the normal. We further observe that a change in the angle of incidence θ_1 will result in a smaller change in the angle of transmission θ_2. Thus we may say that θ_1 approaches 90° faster than θ_2. When θ_1 has reached 90°, θ_2 is still less than 90°. One would expect to get transmitted light in medium #2 for *every* incident light in medium #1.

(b) $n_1 > n_2$. As light travels from an optically denser medium to an optically rarer medium, Eqn (9) indicates an opposite behavior. The angle of transmission is now larger and approaches 90° faster than angle of incidence and we may not get a transmitted light for *every* incident light ray! This is what we call an *intriguing* result. Light incident in the denser medium cannot always be seen in the rarer medium. As the angle of incidence increases beyond the *critical* angle (to be defined soon), the light returns to the first medium! It simply *doesn't show up* in the second medium! The light gets totally internally reflected and the phenomenon is known as Total Internal Reflection. The angle of incidence at which the angle of transmission is 90°, is called the *critical angle*, θ_c. When $\theta_1 = \theta_c$, then $\theta_2 = 90°$. As $\sin 90 = 1$, we find from Eqn (9) that, for $n_1 > n_2$:

$$\sin\theta_c = n_2 / n_1 \qquad \text{.........(13)}$$

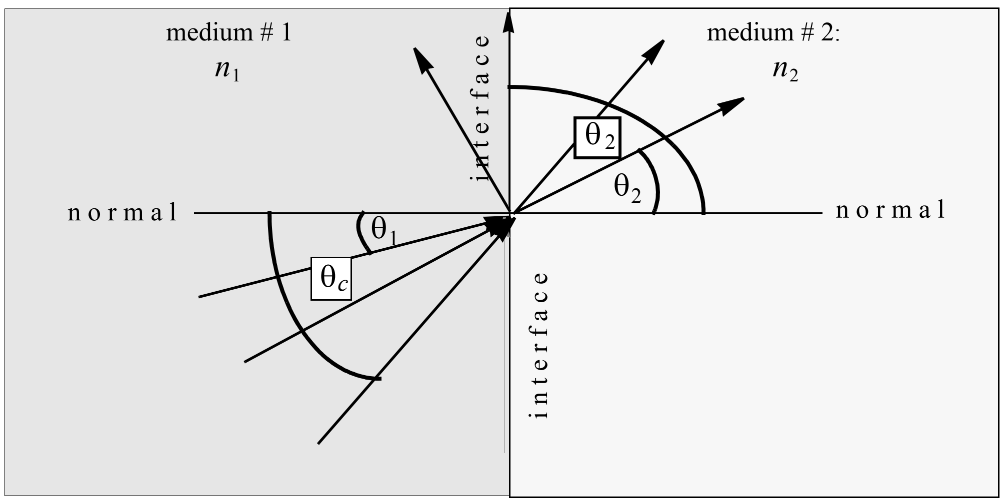

Fig (6) Transmission from Optically Denser to Optically rarer medium

Normal Incidence

When a ray of light, travelling ***along*** the normal $\theta_i = \theta_1 = 0$, encounters an interface, it is said to be incident normally. Normal incidence of a ray of light is also intriguing. We find that such a ray does not bend at all and keeps travelling along the normal line. In case of reflection, the ray will retrace its bath backward i.e. $\theta_r = 0$. In case of transmission, it can be easily shown that the ray will keep on travelling in the forward direction *along* the normal, without bending i.e. $\theta_2 = 0$. This result stems from the fact that $\sin 0° = 0$.

Applications

For each of the two types of interactions of plane wavefronts with interfaces, namely (1) $R = 1,\ T = 0$, and (2) $R = 0,\ T = 1$, we may have either a plane interface or a curved interface. Examples of plane interfaces are plane mirrors, rectangular blocks of transparent materials, prisms etc. Examples of curved interfaces are very many. For the sake of simplicity, we consider only the regularly curved surfaces; for example: slices of surfaces of spheres. The optical devices made of such surfaces are spherical mirrors and lenses. In the present experiment, we shall study the interaction of light with a plane interface resulting in reflection and transmission. In the ensuing experiment, we shall study the same interactions at a curved interface.

Objectives of the Experiment.

To study the interactions of a plane wavefront of light with a plane interface:

(a) to verify the law of reflection

(b) to verify the law of transmission and hence find the refractive index of glass

(c) to find the critical angle for a glass-air system.

Setting Up

(a) Setting up a plane wavefront

The optical bench holds all components magnetically. Our source of light is enclosed in a black box, called the *light box*. There is an on/off switch and a knob to control the direction of the light beam. A *parallel ray* lens and a *slits plate* are mounted on one component holder (on the two sides of it). The combination is placed in front of the light box (with the parallel rays lens facing the light box), few centimeters away from it. The slits plate has seven slits. Seven distinct rays emerge from the arrangement. Our job is to make these seven rays parallel to one another. This can be done by moving the *lens-slits plate* combination back and forth on the optical bench till the seven rays are literally parallel to one another. The rays will remain parallel, no matter where we see it on a screen. There are several ways of doing so that the instructor can show you. But one can also use the optical bench itself (no screens). Standing some distance away from the bench, along its length, and looking obliquely along the length of the bench, one can see all the rays on the bench itself. The student can direct the partner to move the component holder (with lens and slits plate) back or forth till the rays are parallel and can also have the rays centered on the bench, by asking for the control knob to be rotated clockwise or counterclockwise.

Once this is done, we have a plane wavefront. We may mount a second plate, called the *slit mask* (with one slit) on another component holder and place it right next to the (*lens + slits plate)* holder to obtain a single beam of light, centered on the optical bench.

(b) Setting up an interface

Place the circular table on the bench next to the slit. mask. Align the beam very carefully along the line marked *normal*. Next place the plane mirror or the cylindrical lens on the line, marked *component*. Please note that the component line is perpendicular to the normal line. The mirror (or the lens) should be centered at the intersection of the component and the normal lines.

(c) Setting up angles of incidence

The circular table has been engraved with angles from zero degree to 180 degrees, on each side of the *normal line*. By rotating the table, it is possible to set up an angle of incidence between the (single) ray of light and the *normal*. Thus it is possible to set up any angle of incidence.

(d) Measuring angles of reflection

The reflected ray is visible clearly on the table. Angles of reflection can be read on the scale provided. The angles recorded are directly the required angles of reflection, as predicted by the law of reflection.

(e) Measuring angles of transmission

As stated earlier, we cannot put any angle measuring device (such as a protractor,), inside a solid transmitting medium, such as a glass block. Any light that we see around the glass block, has already emerged from glass! To see it inside glass, we must place our eyes inside the glass. This is, obviously, quite impossible. We are, here, *inherently incapable* of making a measurement!

Three things help us out of this impasse. (1) The transmitting media usually have two interfaces. (2) Normal Incidence. (3) Tangents on the circumference of a circle are always perpendicular to radii.

(1) Of the two interfaces one interface admits the light into the transmitting medium while the other lets it out. The light ray changes its direction at *both* interfaces. The first change of direction is of course, what we wish to measure. The second change of direction (and hence the second interface) is a nuisance. It makes it impossible for us to measure the angle at the first interface. Now, if somehow we could make the second interface a *non-interface,* the ray of light will not change direction a second time and will come out at the same angle at which it entered the transmitting medium!

(2) One way of making an interface, a non-interface is to invoke *normal incidence*. Supposing we cut the glass block in such a way that the second interface is perpendicular to the path of the ray of light inside glass, then this path of the ray will become the *normal* to the second interface. The ray, then, will not bend at the second interface and will keep on moving along the same straight path *outside* the glass block at which it was travelling inside the glass block! We shall have no problem measuring the angle outside the glass block, which will be the same as inside the glass block!

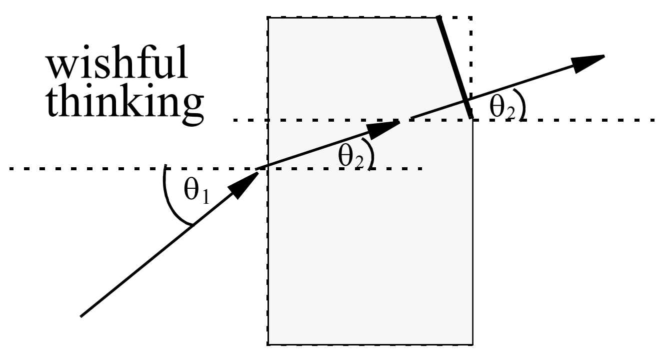

Fig (7) Invoking "Normal Incidence"

The above situation, however, is simply a *wishful thinking*. This is because we don't know θ_2 and so we don't know where to cut!

Why not cut the glass for *all possible* $\theta_2's$? Then we will not have to know θ_2 in advance.

(3) Let us make the path of the ray, a *radius* of some circle. As the radius of a circle is always perpendicular to the tangent, the ray will be incident normally on the second interface. The second interface will behave as a non-interface, thereby allowing us to measure angles inside the glass block, outside the glass block!

The outcome of all of the above is shown in Fig (8). Here we have a semi-circular block of glass that has two interfaces: (i) a flat surface, and (ii) a semi-circular surface. The flat surface will serve as the *active* interface. A ray of light travelling across this interface (in either direction) will undergo a change of direction, as per the Snell's law. The semi-circular surface will serve as the *inactive* interface, or a *non-interface* if, *and only if*, the ray travel **along** the radius of the cylindrical glass lens. A ray of light travelling radially to this interface (in either direction) will not undergo a change of direction! **And** angles measured *outside* glass will be the angles *inside* glass.

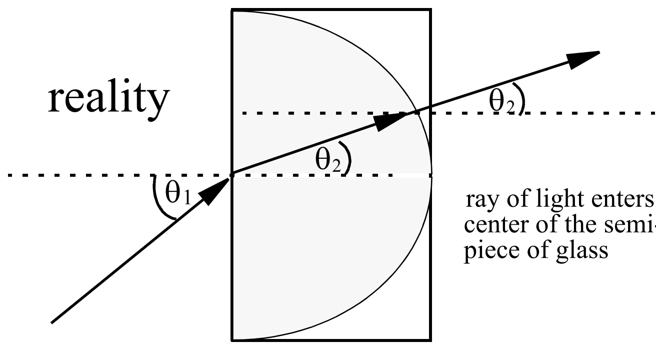

Fig (8) A glass Block with Only One Interface

Thus we find that it is possible to measure angles *inside*-the-glass-block, *outside*-the-glass-block by choosing the block to be in the form of a semi-circle and letting the rays of light be incident **at its center**. Any deviation from the center, on account of careless positioning or otherwise, will lead one to erroneous results. The arrangement can be used both for the study of transmission of light from rarer to denser medium, and from denser to rarer medium.

(f) Plan of work

The three objectives of the experiment will be carried out as follows.

(a) To verify the law of reflection, we shall use a plane mirror.

(b) To verify the law of transmission, we shall select an air-glass system and use a cylindrical glass lens with its flat surface facing the incident light. Here $n_2 > n_1$. A graph of $\sin\theta_1$ against $\sin\theta_2$ will have a slope of n_2/n_1. But since the refractive index of air is unity, the slope will just be n_2, the refractive index of glass. This is an interesting experimental method of determining the refractive index of glass.

(c) To find the critical angle for the glass-air system, we shall use the same cylindrical glass block but this time the curved surface will face the incident light. Light will enter glass through the curved surface and will emerge from the flat surface. As the curved surface is a non-interface, we shall be measuring the angle of incidence at the glass-air interface (inside the glass block), outside the glass block. Recall Snell's Law (Eqn 9):

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

The left hand side represents glass while the right hand side is for air.

Rearranging and letting $n_2 = 1$ (for air), we get:

$$\sin\theta_1 = \frac{1}{n_1}\sin\theta_2$$

From Eqn.(13), setting $n_2 = 1$, we get $\sin\theta_c = 1/n_1$. Inserting this value of $1/n_1$ in the last equation, we get:

$$\sin\theta_1 = (\sin\theta_c)(\sin\theta_2) \qquad \text{..........(14)}$$

If we plot a graph of $\sin\theta_1$ (glass) against $\sin\theta_2$ (air), as per Eqn (14), the slope will be $\sin\theta_c$. Our graph will provide us with a value of θ_c.

Procedure

(1) Switch on the light source and obtain a set of parallel rays as described briefly in *setting up*. Use the combination of the *slit plate* and the *slit mask* to get a single ray of light.

(2) Place the *rotating table* on the optical bench right next to the slit mask. Place the circular plate on the rotating table with the side showing *component* and *normal* lines, on top. Carefully align the beam along the entire length of the *normal* line.

(a) Law of Reflection

(3) Set the plane mirror along the *component* line, aligning it with the line as best as you can. The mirror should lie symmetrically around the *normal* line.

(4) Select the following values for the angle of incidence θ_i : 5°, 10°, 15°,....80°. For each θ_i, carefully measure and record the value of θ_r, the angle of reflection.

(b) Law of Transmission: (i) Air-Glass System;

Determining the Refractive Index of Glass

(5) Replace the plane mirror by the cylindrical glass lens. The flat side should lie along the *component* line and the curved side should be away from the incident-light side. The lens must be carefully centered at the intersection of the *component* line and the *normal* line. The transmitted ray, in this case, will coincide with the other half of the normal line To accomplish this linearity, you cannot rotate the lens. It must be moved sideways only.

(6) As the angles of transmission are going to be smaller than the angles of incidence, we shall set angles of transmission θ_2 and measure the corresponding angles of incidence θ_1 (on the incident-light side). This may appear to be slightly illogical but we shall do so to maximize accuracy.

Select following angles as θ_2: 4°, 8°, 12°,... 40°. Measure, carefully, the corresponding angles of incidence θ_1. Enter in the data table.

(c) Law of Transmission: (ii) Glass-Air System;

Determining the Critical Angle

(7) Reverse the position of the cylindrical glass lens. The flat side is still on the component line, centered as before; but the curved side is now towards the incident light. Angles of transmission θ_2 will now be larger than the angles of incidence θ_1. For reasons of maximizing accuracy, we shall select smaller angles, θ_1 and measure the larger ones.

Select following angles as θ_1 : 4°, 8°, 12°,... 40° Measure the corresponding angles of transmission θ_2 carefully and precisely. Enter in the data table.

(8) After completing step (7), increase θ_1 slowly until the transmitted beam just about disappears on the emergent side. Read and record θ_1 as θ_c. This is the classical experimental method for finding the critical angle.

(9) The experiment ends. Disassemble all components and place everything neatly in the basket. Only those things should be placed in the basket that came in the basket. Do not just *dump* everything in the basket. Make sure glass surfaces do not get scratched.

Calculations and Graphs

(1) Calculate the sine values of all angles of incidence and reflection. Plot $\sin\theta_r$ on y-axis and $\sin\theta_i$ on the x-axis. Find the slope. Compare it with its expected value. This value has not been written down explicitly; but you should find it from Eqn (9) by setting $n_1 = n_2$ and then determining the ratio of the two angles. Please also note that by setting $n_1 = n_2$ the two angles will be deemed to be in the same medium. Find percent error.

(2) Calculate the sine values of all angles of incidence and transmission for the air-glass system. Plot $\sin\theta_1$ on y-axis and $\sin\theta_2$ on the x-axis. Find the slope. This is the refractive index of glass of which the cylindrical lens is made.

(3) Calculate the sine values of all angles of incidence and transmission for the glass-air system. Plot $\sin\theta_1$ on y-axis and $\sin\theta_2$ on the x-axis. Find the slope. This is $\sin\theta_c$. From this determine the critical angle θ_c for the glass-air system. Compare with the value found in step (8) above. Find percent error.

(4) Compile the “Results”.

Conclusions and Discussions

Write your conclusions from the experiment and discuss them.

What Did You Learn in this Experiment?.

A hearty and thoughtful account of what you learned in this experiment by way of the principle and the techniques of experimentation, should be given.

Data & Data Tables

Name.................................... **Date**..............................

Instructor.............................. **Lab Section**....................

Partner.......................... **Table #**..........................

Table 1: Data for Reflection & Transmission Studies

Trial #	Law of Reflection		Trial #	Transmission: Air-Glass System		Trial #	Transmission: Glass-Air System	
	θ_i	θ_r		θ_1	θ_2		θ_1	θ_2
1	5^0		1		4^0	1	4^0	
2	10^0		2		8^0	2	8^0	
3	15^0		3		12^0	3	12^0	
4	20^0		4		16^0	4	16^0	
5	25^0		5		20^0	5	20^0	
6	30^0		6		24^0	6	24^0	
7	35^0		7		28^0	7	28^0	
8	40^0		8		32^0	8	32^0	
9	45^0		9		36^0	9	36^0	
10	50^0		10		40^0	10	40^0	
11	55^0							
12	60^0							
13	65^0							
14	70^0							
15	75^0							
16	80^0							

Critical angle (determined as per step 8 of Procedure):

Additional information or data (if any):