Forty simple experiments with an He-Ne laser for High School students

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ABSTRACT

Recently optics courses have been implemented at the High School of the UNAM. For these courses, the school purchased commercial optics kits to develop illustrative and simple experiments. In education, lasers play a dominant role for many examples of optics, for instance, interference experiments are easily performed and visualized using an inexpensive laser diode or an He-Ne laser. Teacher participation in workshops is very important to make them confident in the use of lasers and other optics tools so their students have a proper guide for hands-on optics experiments in classroom. In the case of the UNAM this kind of workshops started at the beginning of 1997 with 25 high school teachers as the initial phase for designing didactic activities in optics. As part of these activities we have developed forty additional experiments, apart from the ten projects included in the kit manual. In almost all of them, we used a He-Ne laser. Experiments such as air refractive index measurements, irradiance measurements using simple and inexpensive photodetectors, optical activity and polarization, retardation plates, photoelasticity, diffraction and interference, scattering and polarization of light in a scattered medium, and many others were developed. They are performed using the elements provided by the kit and additional and simple items easy to obtain or to make.

Key words: optics education, high schools, projects, simple experiments.

1. INTRODUCTION

The National Autonomous University of Mexico (Universidad Nacional Autónoma de México) has 270,000 students, of those 120,000 are enrolled in its High School system. Of these 120,000 students, 65,000 belong to the College of Humanities and Sciences (Colegio de Ciencias y Humanidades -CCH-) distributed in five campuses around Mexico City.

As an effort of modernizing the type of teaching, the study programs of the CCH were changed three years ago. In this process the teaching of sciences has played an important role and for that reason an integral plan of teachers training and modern laboratories have been implemented. The current study programs include four semestral physics courses. In particular, the teaching of optics has become important as part of the curricula and so it includes a semester course of Optics shared with Electromagnetism. Before this change, the topics of optics were not formally treated but just by very few teachers despite the fact there were not the best laboratories conditions.

One of the aspects that leads to the change of studies programs of the CCH was that the enrollment in science careers have been reducing systematically from several years, this happening in the context of a country like Mexico where the scientific community is very small. As a rule the Physics, Chemistry, Biology and particularly the Mathematics courses, frighten and disappoint to the students and cause that they reject this type of careers. In this way persists among students the generalized idea that sciences courses are something not to enjoy. Obviously the solution to this problem is complex, and for the case of CCH it is related to the specific reality of education in Mexico, but one of the reasons of this problem is the conditions under which the science teachers work (lack of well equipped laboratories). In the teaching of the Physics, Optics is an attractive matter since with simple experiments the students experimentally can see the theoretical formalism and allow the scientific apprenticeship to be funny and interesting. Taken into account this aspect the CCH acquired commercial optics kits for equipping their physics labs.

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In *Sixth International Conference on Education and Training in Optics and Photonics*, J. Javier Sánchez-Mondragón, Editor, SPIE Vol. 3831 (2000) • 0277-786X/00/$15.00

On the other hand, for the new strategy of teaching sciences in CCH, the training courses or workshops imparted to teachers are pretty important. Due to the fact that most of the teachers had not had formal optics courses (most of them are engineers) and previous experience with the kind of acquired equipment for the new CCH labs, then training courses have been designed to cover both aspects: a revision of some theoretical aspects of Optics and experimental ones, where the latter has been the most important. The courses for teachers have been imparted during two years, trying in principle to encourage them with new didactic experiences for the teaching of optics. This training was imparted to 25 teachers (5 from each CCH campus) during two years, so that they at the same time transmit the experience to their colleagues through theoretical and experimental workshops.

The new Experimental Science Laboratories of CCH have been equipped with optics kits (Newport, model M-OEK-STD) that incorporate an He-Ne laser. The particular characteristics of intensity, coherence, monochromaticity and directionality makes that the experiments done with them be very easy to observe compared to experiments done with normal sources of light, without darkening totally the laboratory.

The optics equipment is very complete and includes a handbook with ten basic projects. In this work we shortly present forty additional projects, some of them that were performed by teachers during the training courses. The basic idea of these projects is to demonstrate (to teachers and to students) that the possibilities to make simple and attractive experiments are very large. Some experiments have been designed in complement to the capabilities of the optics kits.

During these two years of teachers training, teachers have presented some experimental projects (not included in this work) and a theoretical exam. The projects demonstrated to have a high degree of creativity and we hope that these experiences and the enthusiasm will be transmitted to students in order to motivate them to follow scientific careers.

2. EXPERIMENTS

The projects made can be divided in two categories, demonstrative experiments and quantitative experiments.

Demonstrative experiments:

1 Images formation (ray theory)
2 Observation of tiny things through a microscope
3 Observation of far away things through a telescope
4 Voice transmission by using light
5 Total internal reflection inside of a water flow (water fiber)
6 The bowl with stratified refractive indexes
7 Structure of a compact disk
8 Fresnel diffraction
9 Images formation (waves theory)
10 Photoelasticity
11 Piezoelectric effect
12 Electric vectors superposition. Fresnel-Arago laws.
13 Laser show
14 Light absorption by dark bodies and white bodies
15 Newton's rings. Radius of curvature of a spherical surface
16 Scattering. Why is the sky blue
17 Polarization by scattering
18 Mach-Zehnder interferometer and the interference of plane and spherical waves
19 Colors of interference
20 A simple and cheap half wave plate. Polarization
21 Three simple and illustrative experiments of reflection and refraction of light
22 Total internal reflection. A prism used like a mirror
23 Diffraction pattern of light surrounding an interference pattern
24 Pulsed light

Quantitative experiments:

25 Hair thickness measurement by image magnification
26 Light reflection study in a prism (refractive index measurement)

27 Water prism and other substances
28 Prisms and the angle of minimum deviation
29 Babinet's principle and hair thickness measurement by using diffraction
30 The optical detector and one example of its applications: energy distribution detection in the diffraction pattern of variable thickness slit
31 Energy profile detection of the He-Ne laser beam (TEM_{00} mode)
32 Mirror reflectivity
33 Glass reflectivity
34 Wavelength measurement of several colors
35 Vacuum detection and measurement of refractive index of air using an interferometer
36 Glass thickness measurement using scattered light interference
37 Ray deviation through a transparent plate
38 Optical activity
39 Determination of body dimensions using a laser
40 Reflection, refraction and polarization of light by a meniscus

As examples of these projects, we detail two of them.

2.1. Vacuum detection and measurement of refractive index of air using an interferometer.

For high school students is usually difficult to visualize that the air is a substance. In part this is due to the fact that the air is transparent for our eyes so, they tend to consider the air as "a vacuum", or at least they think implicitly that air does not affect the light propagation. One easy way to show them that air is made of millions of small particles and then it really affects the light propagation, as does any other substance, is comparing what happens with the interference pattern created by two beams when one of them goes over a small trajectory of vacuum that the students create by themselves. In this project we describe the steps that students can follow in order to detect that air is a substance (that differs from vacuum) and to measure its refractive index.

Michelson interferometer is usually used to measure displacements of the order of wavelengths (λ = 632.8 nm for He-Ne) as we described in project 11 where we detected displacements of $\lambda/4$ for a mirror which is attached to a piezolectric material (that students can get easily from a buzzer). We know that the displacements of the mirrors in the arms of a Michelson interferometer modify the optical path difference (recall that the optical path length is defined as the product of the distance and the refractive index that a beam goes through) between both beams and then the interference pattern is also modified. Based on the definition of optical path length then we can deduce that the interference pattern can also be modified changing the refractive index without changing the distance. In figure 1 it is shown a Michelson interferometer with fixed mirrors and a cell of length L placed in one of the arms. This configuration produces a certain interference pattern but, What happens if we evacuate some of air in the cell? The answer is given in terms of the optical path: when the cell contains air, the optical path length (OPL) for the beam that crosses the cell is:

$$OPL = 2Ln \qquad (1)$$

Where n is the air refractive index; the number *2* appears in the expression since the beam goes twice through the cell. However when we evacuate some of air in the cell the refractive index inside the cell has a new value n' and so, the optical path difference Δ between both conditions is:

$$\Delta = 2L\,(n - n') \qquad (2)$$

This Δ induces a change in the interference pattern as if we had moved one of the mirrors. A special case of interest is when we know one of the refractive indexes of equation (2). Let's take for example the case when we extract enough air from the cell and we can suppose n' equal to 1. Then, if we know Δ we can measure the air refractive index. Experimentally is very simple to determine Δ, we need only to count the number of fringes that appear (disappear) in the center of the interference patters while we are evacuating the air from the cell. In other words, if before we proceed to make vacuum in the cell, the center of the interference pattern is a bright (dark) disc, and during the process of evacuating air we count N bright (dark) rings appearing (disappearing), then we have:

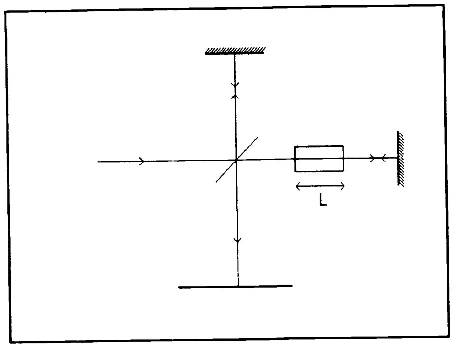


Figure 1. In one of the interferometer arms a cell is placed in order to extract the air. By this procedure, the air refractive index is measured.

$$\Delta = N\lambda \tag{3}$$

and from equation (2) we conclude that

$$n = (N\lambda)/2L + 1 \tag{4}$$

Last expression has been deduced assuming we have counted N rings, in a process that started with a bright (dark) disc and finished with a bright (dark) ring. However, in the case the process does not finish with the same kind of ring we started, equation (4) is transformed to:

$$n = (N\lambda)/2L + \lambda/4L + 1 \tag{5}$$

Next we detail the construction of a very simple vacuum system that students can make easily and, some experimental advises to make measurements of the air refractive index.

Setup

1) Cell construction and simple vacuum system. To make a cell the students need to join firmly five microscope slides using a epoxy glue; four of these slides are the faces of the cell and the other is its bottom. As is indicated in figure 2 the cell has a lid (also glued) with a hole where a small diameter hose is introduced. One extreme of the hose is connected to a syringe. It is recommended a lid made of a rigid metal or plastic.

Note: The experiment will work much better as larger is the volume of the syringe. It must be also indicated to the students not to use an elastic glue and avoid stain with glue the faces of the cell.

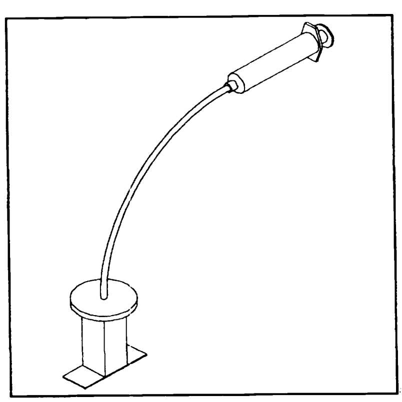


Figure 2. Vacuum system with a cell and a syringe.

2) Once the cell and the syringe have been made the students must try to make vacuum inside the cell pulling the piston of the syringe and check that there are not leaks (for an optimum system the piston returns to its original position when it is released after making vacuum).

3) Using the Newport kit a Michelson interferometer is setup (we indicate the steps to follow by students in project 11)

4) The students must design an ensemble to maintain the cell firm to the breadboard where the interferometer is setup. The cell must not move even when the air is extracted with the syringe or with the movement of hose and syringe. Once this is done the cell is put in one of the branches of Michelson interferometer as is indicated in figure 1.

5) Now the setup is ready to make measurements. Pulling slowly the piston of syringe the students will observe how the interference pattern changes. Depending of the dimensions of the cell and the volume of the syringe there will be a moment where the pattern is no modified any more; this is the maximum vacuum we can produce (we reach the limit of our system but of course we can not say we have a perfect vacuum). Now reintroduce the air to the cell and count the number of rings that disappear (appear) in the center of the pattern. Students will be able to take good measurements when they can count very approximately the same amount of fringes during the air-evacuation process and the air- reinjection process.

6) In based of the introduction for this experiment and the number of fringes counted the students calculate the refractive index for air using equation (4) or (5).

For air we know that n = 1.000293. Students should be able to find an experimental number like 1.000X with X differing from zero. In this way the student will understand that air affects the propagation of light and that there is a physical difference when the light propagates in air or vacuum which is related to the definition of the optical path length. On the other hand, from de simplest definition of refractive index it should be deduced that the speed of light is slower in air respect to vacuum by a factor of 1.000X.

2.2. Reflection, refraction and polarization of light by a meniscus.

In general, optics courses are divided in two branches: geometrical optics and wave theory. Usually we find optical experiments devoted to one of both approaches but here we present one linking both parts.

2.2.1. Refractive index measurement of a circular meniscus through polarization of light by scattering in the medium and the total internal reflection.

We can use any transparent material with a meniscus shape in order to measure its refractive index. Consider the meniscus of figure 3. For a bunch of parallel beams reflecting internally there exist the following cases:

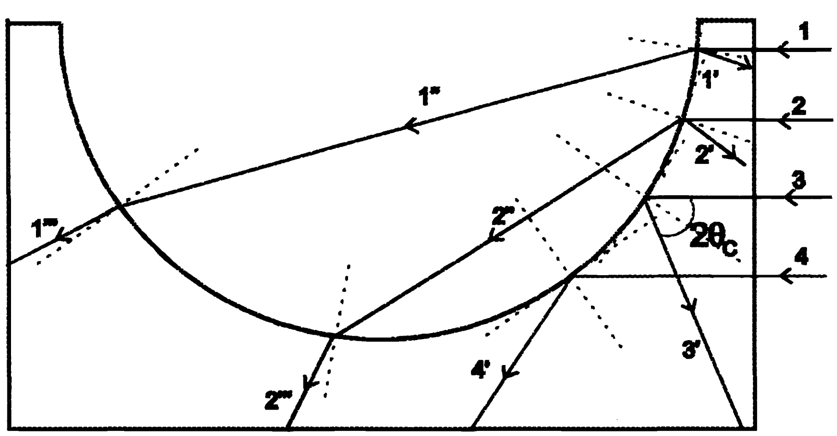


Figure 3. Circular Meniscus.

For beam 1, we have the reflection 1', the first transmission 1'' and the second transmission 1''' (we are not considering the reflection at this second curve interface). Similarly, for beam 2, we have a reflected beam 2', the transmitted beam 2'' and the another transmitted beam 2'''. For beam 3, we will only see the reflected beam 3' in the circular interface, when this beam arrives to the critical angle θ_c. The same is going to happen for any beam below the 3 one, for instance, the beam 4. Note that below beam 3, we will see just one reflected beam inside the material (contrary, for beam 1, we have 2 beams: beam 1' and beam 1'''). Observe also that, above beam 3, the two beams inside the material are closer each other when the incidence beam is closer to the position 3 (beam 2' is closer to beam 2''' than the beam 1' of the beam 1''').

To move the meniscus up and down, we used a micrometry translation stage but in classroom it is possible to use plates of different thickness such as paper sheets or telephone cards and so on. For the refractive index measurement, we can make next procedure: with a small piece of paper (used like a "screen"), we can follow the transmitted beam 1'', the beam 2'', etc., while we go from position 1 to position 2, etc. With this screen, we determine when the transmitted beam disappears in the interface material-air (curve interface), see figure 4, e. g., we determine the position in which inside the material just there is one beam (the reflective one), however, it is easier to follow the transmitted beams with the screen, until their cancellation. In the exact position this happens, we will be at position 3 of the critical angle, e. g., we are going to have total internal reflection. For θ_c measurement, we can proceed in the next way: with a linear polarizer mounted on a graduate rotational stage, we observe, in a perpendicular direction to their paths, the incident beam and the reflected one inside the material. Due to scattering, electric field vector of the beam (polarization vector) is perpendicular to the direction of the original beam when the scattered light is observed at 90° respect to the beam path[1] (see figure 5), then, the polarization by scattering inside the material is going to be perpendicular to the original beam path, see figure 6 (the transmitted light out the material, for instance, beam 1'' or 2'', is not polarized if the incident light is not polarized).

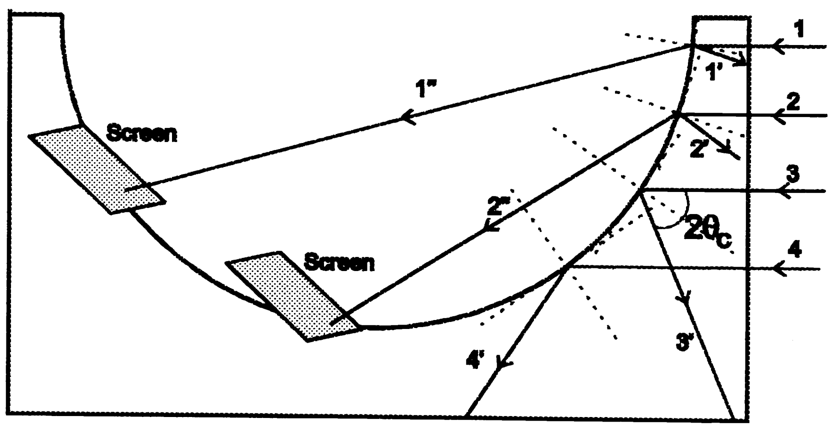


Figure 4. Transmitted beam from the material to the air followed by the screen.

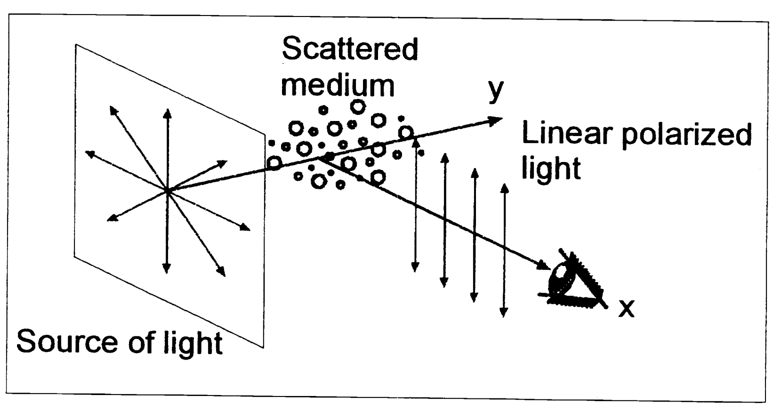


Figure 5. Linear polarization by scattering at *90°*.

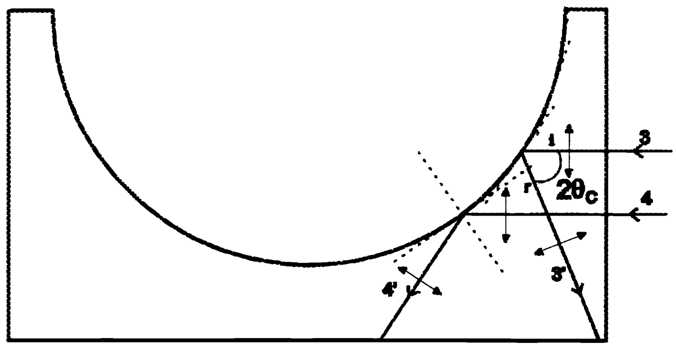


Figure 6. Light polarization by scattering when it is seen perpendicularly to the direction of the incident beam.

Rotating the polarizer, we look for the minimum light intensity of the incident beam i (looking it from a perpendicular direction), it will be our zero. Now, we rotate the polarizer until to have a minimum of the light intensity of the reflected beam r, e.g., we would have rotated an angle of $2\theta_c$, then, through equation:

$$sin\theta_c = \frac{n_t}{n_i} = \frac{1}{n} \tag{6}$$

We calculate the refractive index n of the material (we are assuming the material is immerse in air $n_t \approx 1$). Experimentally, we determined for an acrylic circular meniscus the data shown in table 1:

Table 1. Critical angle θ_c

	θ_c (°)
1	42.0
2	43.5
3	40.0
4	42.0

The average is $\theta_c = 41.9°$, so $n \approx 1.50$. This measure was corroborated in an independent way by using the Snell law of the refraction or Brewster angle (project 1 or 8 of the Newport kit manual), obtaining: $\theta_B = 57°$, e. g., $n \approx 1.54$. Also, the refractive index can be measured through an interferometric method (project 35).

The very interesting point here is that we are using concepts of both: from geometrical optics, reflection, refraction and total internal reflection and, from wave optics: polarization by scattering.

2.2.2. Curvature radium measurement of a meniscus.

In figure 7, for an incident beam i at a height h respect to the lower part of the circular meniscus, we have:

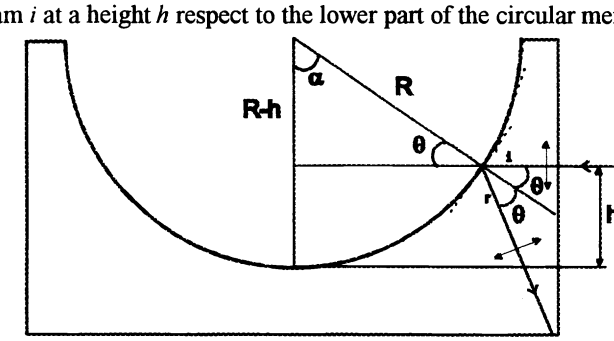


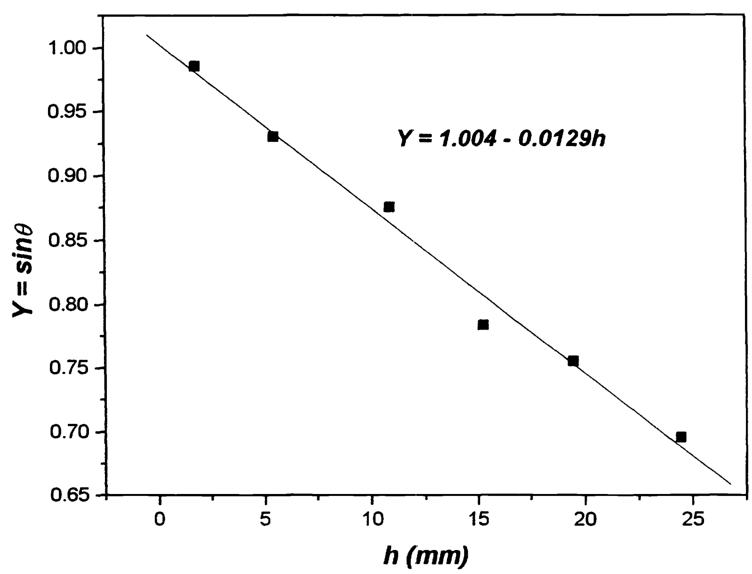
Figure 7. An incident laser beam to a height h.

$$sin\theta = \frac{R-h}{R} = 1 - \frac{1}{R}h \qquad (7)$$

Then, if we plot the sine of the angle as a function of h, we have a straight line whose slope is $m = -1/R$, so $R = |1/m|$. In table 2, we can see the measurement done for the angle θ (by using the linear polarizer as was explained in section a), for the incident and reflected beam r at the circular interface) as a function of h. In graph 1, we can see the plot of $sin\theta$ as a function of h (h was measured with a micrometry translation stage, which we could moved the meniscus "up" and "down"):

Table 2. Angle θ, height h and, $sin\theta$

	θ (°)	***h (mm)***	***sinθ***
1	80.0	1.8	0.985
2	68.5	5.5	0.930
3	61.0	10.9	0.875
4	51.5	15.3	0.783
5	49.0	19.5	0.755
6	44.0	24.5	0.695



Graph 1. The sine of the incident angle as a function of the height h (see figure 7). Also, we can see the numerical fit.

From graph 1 and the linear regression (by square minimums method) we have:

$$R = \left|\frac{1}{m}\right| = \frac{1}{0.0129} mm = 77.5mm \approx 7.8cm \qquad (8)$$

The real and direct measured value, by using a ruler, is $R = 8.4\ cm$ (the difference is mainly due to the way under the angle was measured: with the polarizer we need to do several measurements and, to obtain an average of the angle value). Rewritten equation 7:

$$R = \frac{h}{1 - sin\theta} \qquad (9)$$

Then, a relatively simple and direct measure of R is when $\theta = 45°$ (see figure 7).

2.2.3. Description of the reflection, refraction and polarization observed in a light beam by a meniscus of a liquid that produces scattering.

Due to the different viscosity degrees that show the liquids (for instance, the oil has bigger viscosity than the water), the liquid surface is not longer horizontal very close to the container walls. At this region, the liquids present a curve shape (meniscus) as we can see in figure 8.

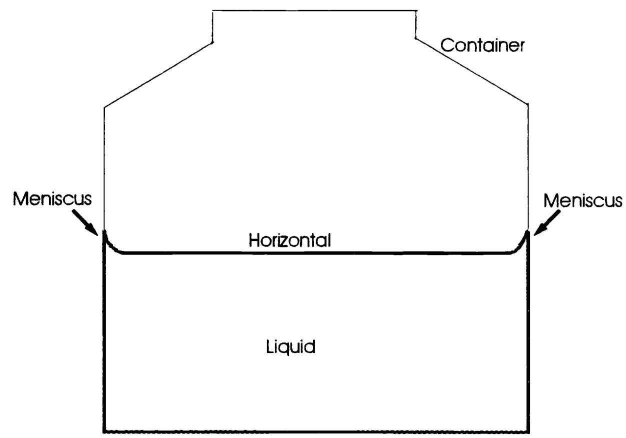


Figure 8. Liquid in a container. We see a meniscus very close to the walls.

Then, if a laser beam hits the meniscus (with the transversal section diameter smaller than the meniscus size), we observe series of reflected and transmitted beams similar to those described in figure 3. If we refer to the experimental configuration of figure 9 (in reality we see series of spread rays and not just one). When we see the light at the A path through the linear polarizer (we need to remember that this light seen at $90°$ respect to the original trajectory, is linearly polarized by scattering), we observe that in the maximum of light at A, the light at B is notoriously decreased and vice-versa. In the case of $2\alpha = 90°$, the polarization vectors of both beams: A and B, are perpendicular (we need to emphasize again, it is not that the beams A and B are linearly polarized, it is the light we observe coming from them at $90°$), then, through the polarizer, when we see the maximum of light at A, exist a minimum of light at B and, vice-versa. The liquids we used were water with one droplet of disinfectant for food and water and, water with shampoo. These mixes produce and excellent scattered light when it cross them.

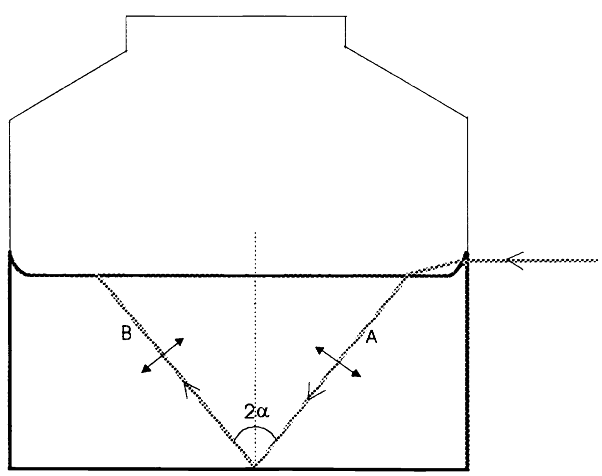


Figure 9. Reflection and refraction of light, produced by the meniscus of the liquid very close to the walls container.

Another important fact is that the meniscus height depends of the material container. It is due to the difference in density between the liquid and the container and, also, due to the liquid adhesion to the wall container[2]. We used two equal Petri boxes with same dimensions but one made of glass and the another one made of plastic (see figure 10).

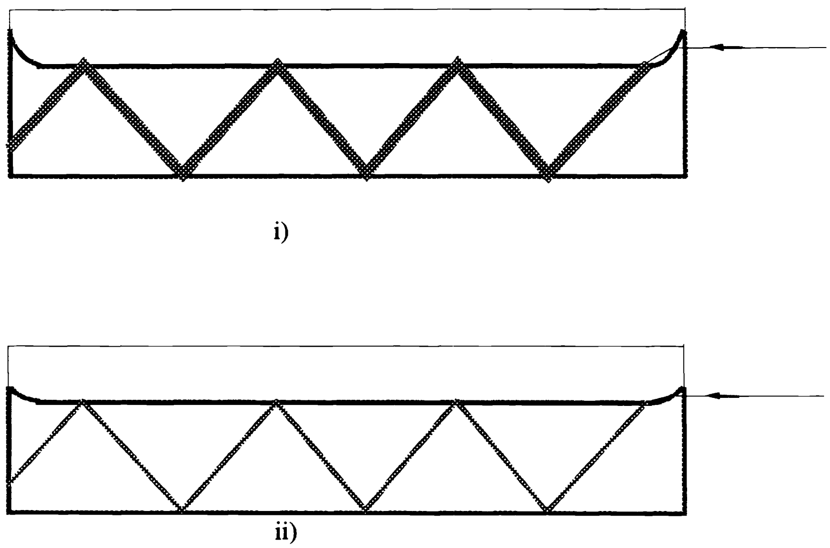


Figure 10. A Petri box containing scattered water, i) glass container, ii) plastic container.

Using the same micrometry translation stage than in section b), we determined the average height *d* of the meniscus by displacing "up" and "down" the Petri box with the liquid and, verifying when the laser beam crossed the liquid or the air, without suffer any deflection. For these measurements, we also took into account the laser beam thickness $D = 0.8\ mm$ (see figure 11).

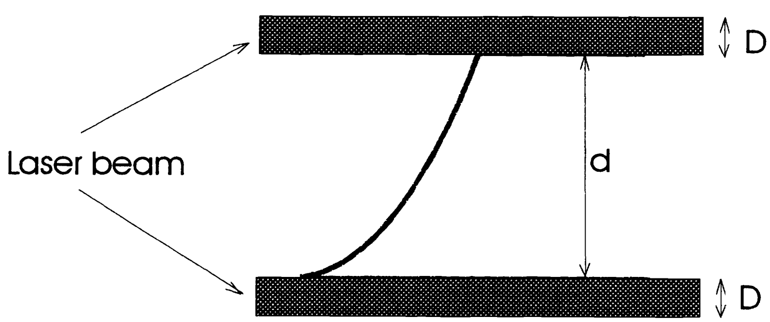


Figure 11. Meniscus height *d*.

For case i) of figure 10, we measured: $d = 3.3\ mm$ and for the case ii): $d = 1.3\ mm$

Another interesting point is that the reflections in case ii) are less spread than in case i), e. g., the first ones look more like "lines" than like "tubes". Of course, it is related with the meniscus size. Also, in order to increase more the intensity of the reflected beams on the floor of the container, we can put on the bottom (inside the liquid) a plane mirror, for the case there is not total internal reflection on the floor.

Finally, with the procedure described above and with a similar method mentioned in b), we can try to measure the floor curvature of the container when it does not be plane (see figure 12).

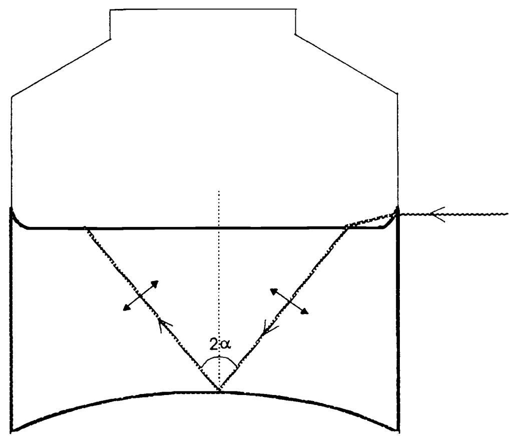


Figure 12. Curve floor of a container.

3. CONCLUSIONS

Due to the optics courses have been implemented at High School of our University, teachers have been involved in training courses. We had developed forty simple experiments in order to make attractive the teaching of optics for students in these Colleges by using the commercial optics kits acquired, and additional simple items easy to obtain or to make. In this process we have tried to design experiments that combine creativity with the capabilities of an educational commercial kit. Here we describe in detail two of them. In the first experiment we showed how to measure the refractive index of the air by using a Michelson interferometer, obtaining a value of n = 1.000X. In the second one, by using concepts of both: geometrical optics and wave theory, we determined the curvature of a circular meniscus through the reflection, refraction and polarization by scattering of a laser beam. Also, we observed how the liquids show a meniscus near of the walls of their containers and that the meniscus size depends of the material of it.

The contribution of teachers, researchers and graduate students who have been involved in the workshops described in this work, rather than a concluded process, is just what we expect as the origin of a new teaching of sciences in high school (CCH). Many problems have to be still overcome to get an optimum teaching of sciences in CCH, but we consider a real progress has been made. In particular, in optics education an important experience has resulted from the equipping of labs and designing of workshops for CCH teacher that was possible thanks to the establishment of a relationship between high school teachers and people working in the optics field.

ACKNOWLEDGMENTS

The authors want to thanks to our colleagues C. García-Segundo, R. Castañeda-Guzmám; V. Torres-Zúñiga, E. Carrillo-Ramírez and, A. Y. Flores-Espinoza, within the program "Youths to Investigation" ("Jóvenes hacia la Investigación"); and E. López-Sánchez within the "Program of Support, Update and Improvement of High School Educational Staff ("Programa de Apoyo a la Actualización y Superación del Personal Docente del Bachillerato" -PAAS-) for their help in the realization of the experiments and finally to the grant IN 110998 from DGAPA, UNAM, México.

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