OPTIX Module 2 – Basic

Building sophisticated instrumentation with basic optical elements

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1 Objectives:

In this module you will learn about

- how to build a simple microscope;
- how to calculate the magnification of the microscope;
- how to measure the magnification of your microscope.

This module is part of our Modern Physics curriculum and should take about 3 hours to complete. It prepares you well for the more advanced modules in this series and for research in the Altman lab.

Use this manual as you work through the module to keep track of your notes and thoughts. In addition, you may have to add a few printouts or refer to data tables or additional notes in your lab notebook. I'd encourage you to create a Jupyter Notebook for your calculations and plots. Make sure to add all your printouts to the folder in which you keep this manual. Lastly, note that this lab has no formal lab report. Instead, you will turn in and be graded on your notes in this manual.

2 Tests and assessment:

In preparation for this module, read through the whole manual and answer the questions that are marked with a *. When you come to lab, be prepared to discuss your answers to these questions with your classmates and your instructor. You should also watch the VIDEOs that are posted on our website (`www.willamette.edu/cla/physics/info/NSF-OPTIX`. They are meant to accompany this manual and will show you some critical steps of the module.

In addition, in order to assess the success of this module, you will take a short assessment test before you start ("pre-assessment"), and another one after you have successfully completed this module ("post-assessment"). At this point you will also have the opportunity to provide us with feedback about the module that we will use to improve it for the next student generation. Thank you for your support!

3 Equipment:

All of the equipment used for this lab will either be in the box labeled 'Module 2' or in the box labeled 'HeNe'. In addition, you will need basic optics hardware that you can find in the upper cabinets (in the Thorlabs boxes) or in the drawers. Please feel free to ask your instructor if you feel you need any other supplies. Also, we have provided you with all the catalog numbers of the components because the Thorlabs website provides more detailed specs about each item.

In this lab you will use

- a 'Foldscope',
- a mounted plano-convex lens with 100-mm focal length (Thorlabs, LA1509-A-ML), coated with anti-reflective coating for wavelengths ranging from 350-700 nm,
- a mounted plano-convex lens with 200-mm focal length (Thorlabs, LA1708-A-ML), coated with anti-reflective coating for wavelengths ranging from 350-700 nm,
- a white LED light source (Thorlabs, MCWHL5) with a driver (Thorlabs, LEDD1B), and power supply (Thorlabs KPS101),
- a dual filter holder for holding samples (Thorlabs, FH2D),
- various post-holders (Thorlabs, PH2), posts (Thorlabs, TR2), 1-inch lens mounts (Thorlabs, LMR1), and bases (BA1),
- an Olympus stage micrometer, with spacings of 10 μm,
- a CMOS Camera (Thorlabs, DCC1545ML), and
- the ThorCam Software.

4 Introduction:

In this lab you will be challenged to build, understand, and characterize a simple optical system for magnifying a sample. You will be following in the footsteps of Antony van Leeuwenhoek, who in the late 17th century developed a remarkably effective microscope consisting of a high quality glass sphere positioned closely to a sample. Using this simple system, he was the first to observe and describe microorganisms (which he called *animalcules*), and he is thus considered the "Father of Microbiology."

Modern techniques allow for the manufacturing of micro-lenses that are both high quality and cheap. With this in mind, the lab of Manu Prakash at Stanford University was able to develop a microscope that emulates the Leeuwenhoek microscope and costs less than a dollar. Called the *Foldscope*, this paper-based microscope uses principles of origami to allow the user to manipulate the position of a sample relative to a glass sphere. As a result of this innovation (and others), Dr. Parakash was awarded a MacArthur "Genius Grant" in 2016.

5 Build your microscope:

Using the instructions provided, build your Foldscope. Collect a sample (feel free to find something inside or outside of Collins!), and practice viewing the sample by eye. It may be useful to use a flashlight (e.g. a light on a phone) to illuminate your sample. **Take pictures of your sample with your phone, and send the images (along with a description of what you collected) to your instructor. Note that successful completion of this step counts as two boxes.**

6 The theory behind the magnification of your microscope:

To understand how an image is formed with the Foldscope, we will first review how an image is formed by your eye, and then discuss what changes when the image is formed by your eye and an additional lens.

6.1 Magnification without a lens:

The ciliary muscle in the eye can adjust the focal length of the eye's lens by changing its shape (making it skinnier or bulgier). This is why we can view objects at different distances from us: When the ciliary muscle is relaxed, the lens brings light that is far away into focus on the retina. As the muscle contracts, objects that are closer to the eye can be brought to focus on the retina.

Imagine you want to see fine details of a small object. What do you do? Most people will use a simple method of **magnification** without even thinking about it: By simply moving the object closer to our eyes it is magnified. But how does that work? As shown in Fig. 6.1, moving an object closer to our eye spreads out its image across the retina, thus appearing larger. To characterize this magnification, we will consider the angle subtended by an object at the eye. As the object is brought closer and closer to the eye, it subtends a larger and larger angle, and thus appears magnified (compare the angles θ' and θ!). However, there is a limit to the effectiveness of this method. To experience it, hold a page from the lab manual in front of you and slowly bring it closer to your eyes.

Record the distance when the text begins to get blurry (include an estimate of the uncertainty of this measurement). This is defined as the *near point* of the eye.

$d_{near} =$

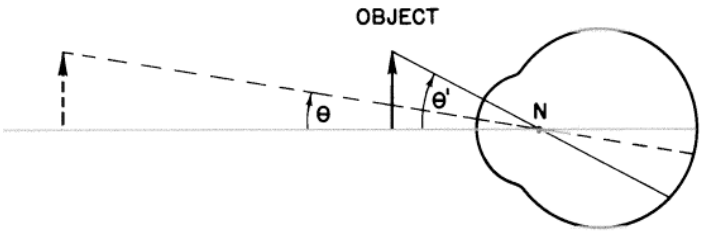

Figure 6.1: *Moving an object closer to the eye increases its size on the retina and it appears larger.*

For the average person, the near point is about 25 cm from the eye, but not everyone has the same near point. In fact, the near point of the eye is determined by the degree to which the focal length of the eye's lens can be adjusted. Especially as we

age, the lens loses its elasticity and we can no longer adjust its focal length over quite the same range. That's why people in their 50's or 60's start wearing reading glasses!

How does your near point compare to this average near point? Do the two values agree within two uncertainties? If not, can you think of a reason why not? (Even if your own near point is slightly different, we will use this average near point of 25 cm in our calculations later in the lab.)

Using an additional lens, we can create an image of the object that is closer than the eye's near point, and that the eye then projects onto the retina. We're thus effectively moving the object closer to the eye than the near point distance, which leads to an increased magnification.

6.2 Magnification using a lens:

The magnification that results from a lens depends on the distances between the eye, lens, and object to be imaged. To get us started thinking about the magnification of this lens-eye system, we will first look at two limiting cases: When the image that the additional lens creates is at the near point and when the image that the additional lens creates is at infinity. For now, we will also only consider biconvex lenses, i.e. lenses that have the same amount of curvature on both sides.

6.2.1 Magnification of an image at the near point of the eye

Imagine holding an object a distance d (see Fig. 6.2) in front of your eye that corresponds to the near point, i.e. d =25 cm. Assume that the object has a height h and that it subtends an angle α at your eye as shown in the figure.

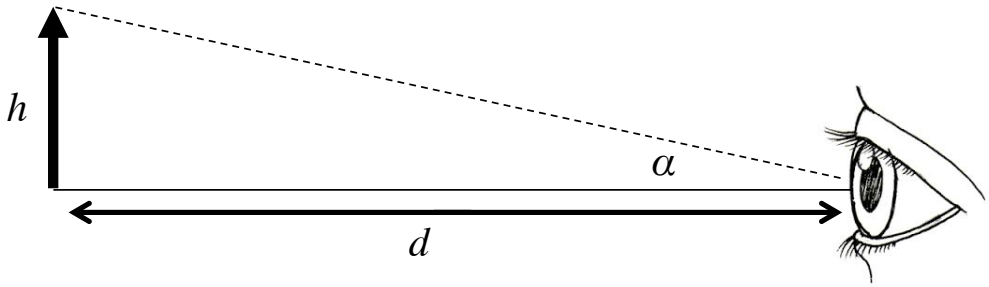

Figure 6.2: *An object of height h placed at the near point d = 25 cm subtends an angle α at the eye.*

Without changing the focus of your eye's lens (i.e. without contracting or relaxing your ciliary muscles), you then insert a biconvex lens of focal length f in front of your eye as shown in Fig. 6.3. Because you are not changing the focus of your eye's lens, your eye is still poised to image an object at its near point, a distance $d = 25$ cm away from the eye. To see the object clearly with the lens in place, you must adjust the position of the object until its *image* is located exactly at the near point, as depicted in Fig. 6.3. As shown in the figure, the lens produces a virtual, upright image of the object (labeled as h'), that is then imaged onto your retina. The dashed lines that are shown in the figure represent two of the principal rays that are used to determine the position of the image. Because you had to move the object closer to your eye, the angle β in Fig. 6.3 is larger than the angle α in Fig. 6.2, and thus the image you see is enlarged (the magnification is increased).
We define the **magnification** M of a lens as the ratio of the angle subtended by the image at the eye and the angle subtended by the object in the absence of a lens when it is located at the near point, i.e. $M \approx \alpha/\beta$. We're writing $\approx$ here because the second angle is not exactly equal to β.

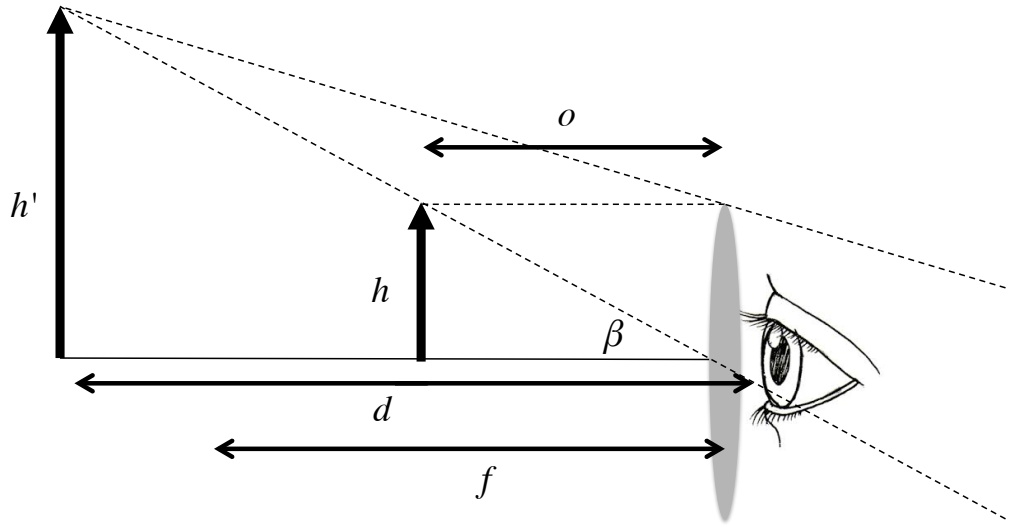

Figure 6.3: *A lens creates an image at the near point of the eye. The magnified image now subtends an angle of approximately β at the eye.*

Why is that? Hint: β is the angle in air, before the light ray hits your eye's lens.

But as long as the lens is close to the eye, β (the angle subtended by the image at the lens) will be close to the angle subtended by the image at the eye.

*** Using the small angle approximation (review this if you forgot what that means!) and the diagrams in the previous two figures derive a relation for the magnification $M \approx \frac{\beta}{\alpha} \approx \frac{\tan(\beta)}{\tan(\alpha)}$ in terms of d and o, the distance between the object and the lens as shown in Fig. 6.3.**

To eliminate o from our result, we'll make use of the lens equation, $1/f = 1/o + 1/i$, where f is the focal length of the lens, o the distance between the lens and the object, and i the distance between the lens and the image. Note that the notation here is slightly different from the notation used in the first module where we used s and s' instead of o and i, respectively. The physics is the same, though!

*** What is i for the situation depicted in Fig. 6.3? Carefully think about the correct sign of i! Insert this into the lens equation and solve it for o.**

We can now find an expression for the magnification that depends only on the focal length f of the lens and the near point distance d.

*** Insert the expression you found for o in the previous box into the expression you found for M two boxes prior and simplify your result.**

Based on your result, why was it important for Leeuwenhoek to make his spheres as small as possible? Hint: The focal length of a lens and its curvature are related through the lens maker equation, $\frac{1}{f} = \frac{2(n-1)}{R}$, where n is the refractive index of the lens and R its radius of curvature (the above equation assumes that the radii of curvature on the two sides of the lens are the same). What does a smaller size imply for the radius of curvature and thus the focal length of the lens?

6.2.2 Magnification of an image at infinity

For our second scenario, imagine that you are holding an object at the near point of your eye just as before and as depicted in Figure 6.2, and that you again insert a lens in front of your eye. But this time, after inserting the lens, you relax your ciliary muscle so that the eye is able to image an object located at infinity.

How does the magnification change? Hint: Start with the thin lens equation and use that in this case, the image is located at an infinite distance from the eye. Thus, what must o so that the image is located at infinity? Substitute this value for o into the relation you found for M and simplify, so that M again is only a function of f and d. Show your work.

These two equations set the limits for the magnification that can be achieved with your microscope. For distances in between, the magnification takes on a value that is in between these two extreme values.

6.3 Calculating the magnification of your microscope

As you can see, the magnification of a lens is set by its focal length and the distance to the near point of the eye. To calculate the magnification of your simple microscope, it is thus necessary to know the focal length of the glass sphere you are using. So far, you've used lenses that were fairly thin, and for those lenses it doesn't make much of a difference whether you measure distances from their front or back surface. The glass sphere is... well.. a sphere, though, and measuring distances from either the front or back makes quite a difference. We thus define the **effective focal length (EFL)** as the distance from the *center* of the sphere to the point where the sphere brings collimated light to a focus (see Fig. 6.4).

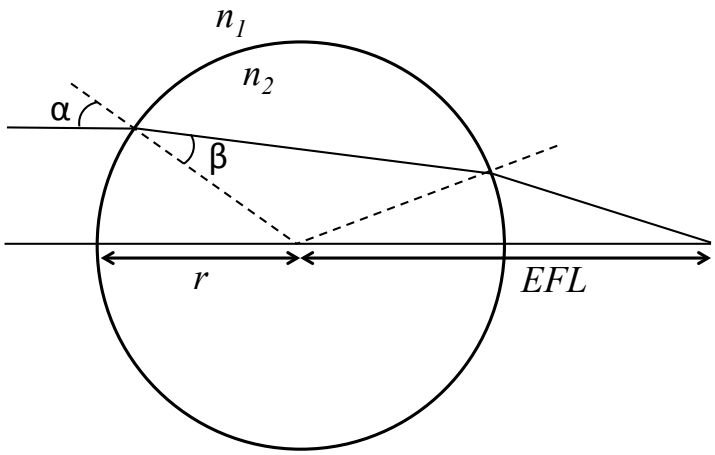

Figure 6.4: *The effective focal length (EFL) is the distance from the center of the spherical lens to the point where collimated light is brought to a focus.*

Although we will not derive it here, we can use geometrical arguments, Snell's law, and the paraxial approximation to show that

$$EFL = \frac{1}{2}\frac{nr}{n-1}, \tag{6.1}$$

where n is the index of refraction for glass (for our spheres, $n = 1.517$) and r is the radius of the sphere.

Measure the radius of your glass sphere using calipers and record it here:

$r =$

Then calculate its EFL and record it here:

EFL =

Lastly, use this value to calculate the range of magnifications you can achieve with your microscope:

$M_{NP} =$ $M_\infty =$

You can use the space below for scratch work (or use a Jupyter notebook!)

7 Measuring the magnification of the Foldscope

To measure the magnification of your Foldscope, we will set up a "Model Eye" consisting of a single lens and a CCD camera that represent your eye's lens and retina, respectively, and do measure the magnification of an object of known size when a second lens is inserted. The following subsections will guide you through the experimental setup.

7.1 Setting up a model of your eye:

Your model eye will consist of a CCD camera (which will be the retina) and a single 100-mm focal length plano-convex lens (which will be the lens of your eye). The object you are imaging is a micrometer slide, which is a slide with markings separated by 10 μm. The pattern is shown in Figure 7.1.

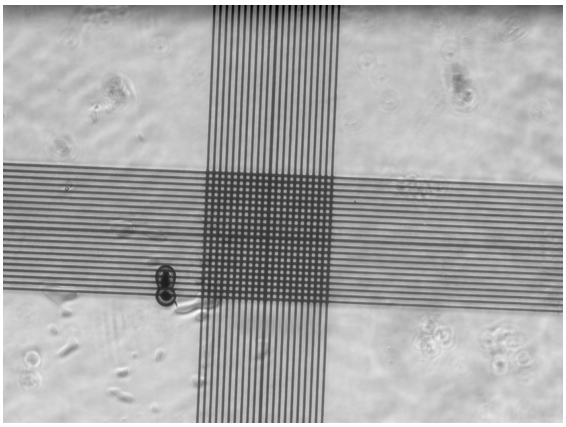

Figure 7.1: *Pattern on the stage micrometer.*

To turn this micrometer slide into an object, you need to illuminate it from behind. Your illumination source is a white LED. To turn on the LED, simply plug the controller unit (shown in Fig. 7.2) into an outlet and turn the knob on the controller clockwise. The light that emerges from the LED is strongly divergent, so use a single plano-convex lens of 50 mm or 100 mm focal length to collimate it. Ask your instructor for help if you are unsure how to do this and don't waste a lot of time on this step.

Figure 7.2: *Controller for the LED*

Mount the collimated LED on one side of the optics table. Mount the stage such that the collimated light beam hits it in the center, and then mount the eye lens 25 cm behind the stage (since that is the average near distance). Again, make sure that it is nicely centered. Lastly, mount the camera behind the eye lens and move it around carefully until you see an image of the stage that looks like the one shown in Fig. 7.3. To succeed in this task, you *must* make sure that

- the centers of the LED, stage, lens, and camera are all at the same height, and
- the LED, stage, lens, and camera are all in one straight line.

Take a snapshot of the target and attach a printout of it to your manual and/or send it in electronic form to your instructor.

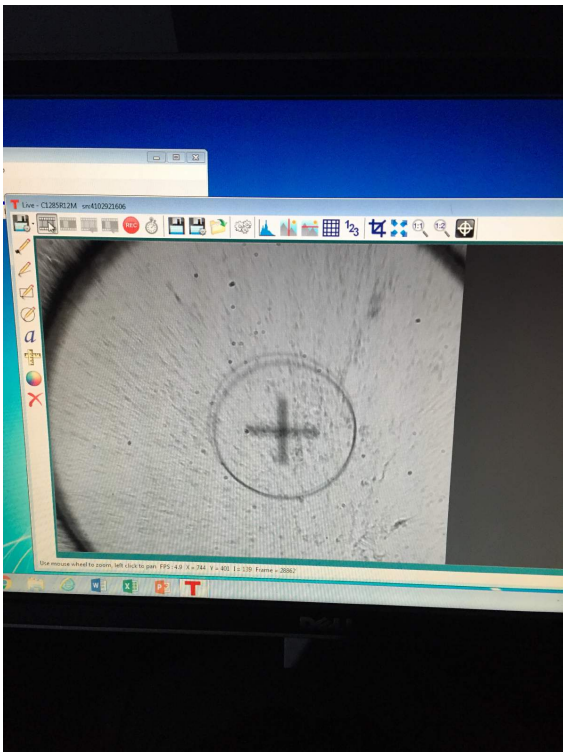

Figure 7.3: *Image of the stage micrometer without magnification.*

As you can see, without the aid of our microscope, it is very difficult to see the lines that make up the pattern (all you can see is the bigger cross-shaped pattern).

Measure the width (in pixels) of one entire arm of the pattern using the ThorCam software and record it here:

$l_{arm} =$

This measured length corresponds to 21 lines, or a separation of 200 μm. Divide l_{arm} by twenty to determine the number of pixels that separate an adjacent pair of lines in the unmagnified image. Record this value here as well:

$l_{pair} =$

At this point, **do not change the distance between the camera and the (eye) lens**.

7.2 Magnifying the image:

When you calculated the EFL of the Foldscope, you may have noticed that the number was very small. You may also remember from Figure 6.3 that the object must be *closer* to the lens than the focal length, i.e. $o < f$. That means that the sample to be imaged must be placed *very* close to the spherical lens of the Foldscope. So instead of placing the lens first and then bringing the object closer to the lens, we'll directly glue the lens to the object and move the combination of lens and object closer to the eye lens as described in the next paragraph.

To do this, we have provided you with a Foldscope lens that is not contained within the paper mount. Using the blue tape provided, **tape the lens directly to the stage micrometer** as shown in Fig. 7.4. Make sure that the *flat side* of the lens is making direct contact with the small circular glass coverslip that is attached to the glass slide. Position the lens so that you can see a portion of the stage micrometer pattern when you look through the lens. Once you are satisfied, place the stage with the attached lens back into your LED beam.

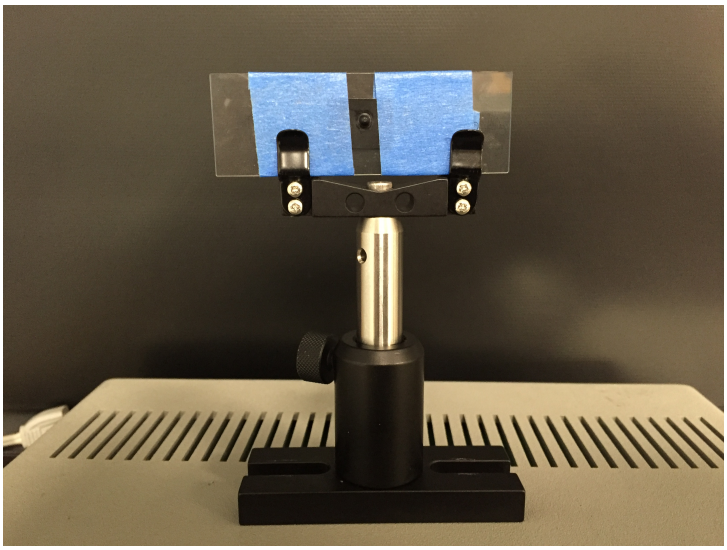

Figure 7.4: *Lens mounted to the front of the stage micrometer slide.*

You now need to move the slide and lens closer to the eye lens until you see the magnified image of the pattern on the CCD camera. This can be a tricky part, so we would recommend going through the following process:

1. Return the slide to its original position on the table. You will no longer see a clear image of the pattern anymore because of the extra lens you just added. However, you should be imaging the aperture of the lens, which will simply look like a small, bright circle. You may have to turn up the intensity of the LED for this portion of the lab.

2. Slowly and in a straight line, move the slide and lens closer to the lens of your model eye. As you do this, watch the image on the computer screen. You should see the bright circle slowly expanding. You will soon see a portion of the stage micrometer's pattern inside the circle. Keep moving the stage until you see a sharp image on your CCD camera. If you have positioned the lens imperfectly, you may need to rotate the slide a bit to see the pattern. The resulting pattern should look like Figure 7.5.

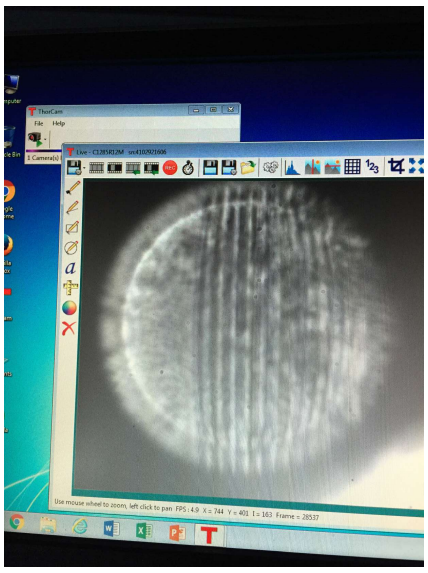

Figure 7.5: *Image of the stage micrometer with magnification.*

Take a snapshot of the target again, attach a printout to your manual and/or send it to your instructor.

Measure the pixel separation of a line pair:

$l_{pair,2} =$

Calculate the magnification of the Foldscope using your two measurements:

$M =$

How does the magnification compare to the maximum and minimum values you calculated earlier? Discuss your results in this context.

And that's it! You made it successfully through this module and are now qualified to perform the more advanced modules. Please leave us any comments, suggestions, or concerns in the box below, so that we can optimize this module for future student generations. Thanks!