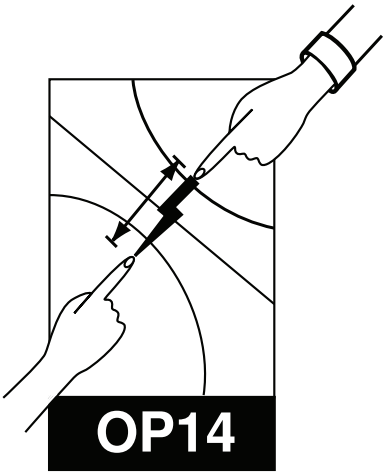
Fraunhofer Diffraction



Edited MT, JJL January 2019

This experiment uses optical pointers or pins. Always take care when using sharp objects, especially when working in the low ambient light levels required in the Optics laboratory. Always leave the optical pins with their pointed end towards the wall and moved clearly out of the way when not in use.

1 Introduction

The name *diffraction* is given to all departures from rectilinear propagation of light. These departures are due to the wave nature of light. The name *Fraunhofer diffraction* is used to describe diffraction effects observed in the image plane of any optical instrument. So, although diffraction effects can be observed elsewhere, Fraunhofer diffraction is by far the most important case because it is concerned with the quality with which an optical instrument can reproduce an object in the form of an image. Fraunhofer diffraction leads to blurring of images, and represents the fundamental limit of performance of instruments. It is therefore a vital part of any practical course in Optics.

In the first part of this experiment, you will study the effect of diffraction on an optical image in the special case that the object is a very fine slit. According to geometrical optics, the image should also be a fine line of illumination; however, what is seen is a series of fringes. This pattern, which will become very familiar, is called the Fraunhofer diffraction pattern. The question arises: if it is so universal an effect, why doesn't one see it when looking at objects with the naked eye, or with optical instruments such as telescopes or binoculars? The answer is that it is there, but the scale of the pattern under these circumstances is very small; the larger the aperture of the optical system, the smaller the pattern. For this experiment, therefore, the effect is exaggerated by artificially restricting the aperture of the system to make diffraction more obvious. However, don't be misled by this.

If you only take away one piece of information from this practical, make it this: *Fraunhofer diffraction sets a fundamental limit to the resolution achievable with any optical system whatever its aperture*.

2 Theory

This is an experimental study, and is not designed to teach you the theory of Fraunhofer diffraction. However, it is intended to illustrate the main results of that theory, and the practical importance of the phenomenon, so you must understand this section before doing the experiment. Of course, if you have already covered the theory in lectures or tutorials, so much the better.

2.1 The basis of Fraunhofer Diffraction

It is simplest first to consider a single thin positive lens (figure 1), though the discussion applies to any image-forming system. We are forming an image of some object; consider any point P on that

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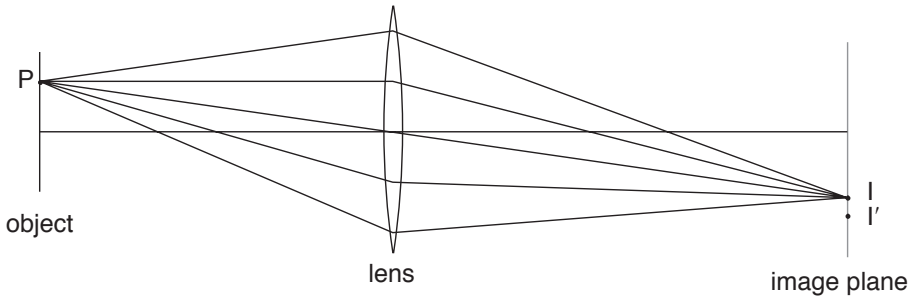


Figure 1: Simple thin lens system imaging an object P in the *(real)* image plane. The image is at a position I and I′ denotes another point near I.

object. The point to appreciate is that such a system forms an image of P at a position I, where the light diverging from P, having passed through the system, all comes back together again in phase. The laws of geometrical optics all follow from this simple idea. The fact that the contributions to the light amplitude at I are in phase means that the interference is constructive at I; hence the location of the image. Now if we consider some other point I′ in the plane of the image, slightly separated from I, the interference is not entirely constructive, so the intensity is reduced. However, it may still be appreciable. Hence, a point source is blurred out into a finite-sized image. This phenomenon is called Fraunhofer diffraction.

The degree of blurring depends on how much of the light leaving the object gets through the optical system. In figure 1, this is set by the size of the lens; in other cases, it could be set by a stop.

The smaller the aperture of the system, the less information gets through to the image, and the larger the blurring becomes.

Normally, an object is not a point, but of course the argument applies to each point making up an object. Each has its own image, which is then blurred out by diffraction; as a result, closely-spaced points on the object will produce images which overlap, so that detail is lost. There are therefore two reasons for having telescopes with large apertures: first, one collects more light, and second, the ability to distinguish detail is improved.

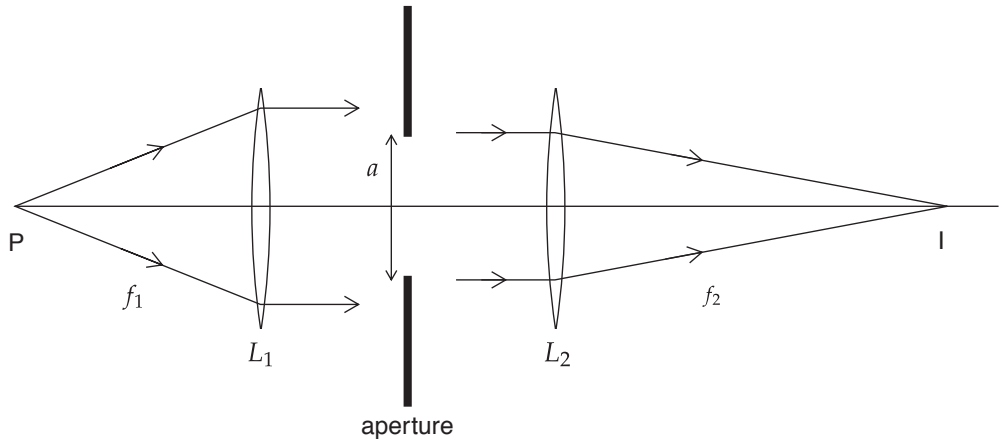


Figure 2: The experimental setup. L_1 and L_2 are two lenses with a narrow aperture of width a between them. P is the object at a distance f_1 from L_1 and I is the image at a distance f_2 from L_2.

This experiment uses a slightly more complicated lens system (see figure 2) - two lenses, with the object in the focal plane of one and the image in the focal plane of the other - and the aperture is set by a narrow slit, rather than either of the lenses. The reason for the two lenses is that the results of the theory are easier to state if one has a collimated (parallel) beam of light falling on the limiting aperture of the system, though we stress that this is not a necessary condition - or even a usual situation - for Fraunhofer diffraction. As mentioned earlier, the reason for having a narrow diffracting aperture, rather than simply using the finite size of the lenses themselves, is that diffraction effects are so small that if we tried simply using the lenses to set the aperture, the fringes would be too closely spaced for us to see, even though they still set the fundamental limit on the sharpness of the image.

2.2 Quantitative relations

The most important result can be summarised as: if a collimated beam of light of wavelength λ has a width a, diffraction causes there to be an angular spread of $\sim\frac{\lambda}{a}$.

In figure 2, a collimated beam of light of wavelength λ from a point source, which we take for the moment to be on axis, falls on the limiting aperture of the system, which consists of a slit of width a. Because of diffraction, the light acquires an angular spread on passing through the aperture. The distribution of intensity with angle q to the axis is shown in figure 3.

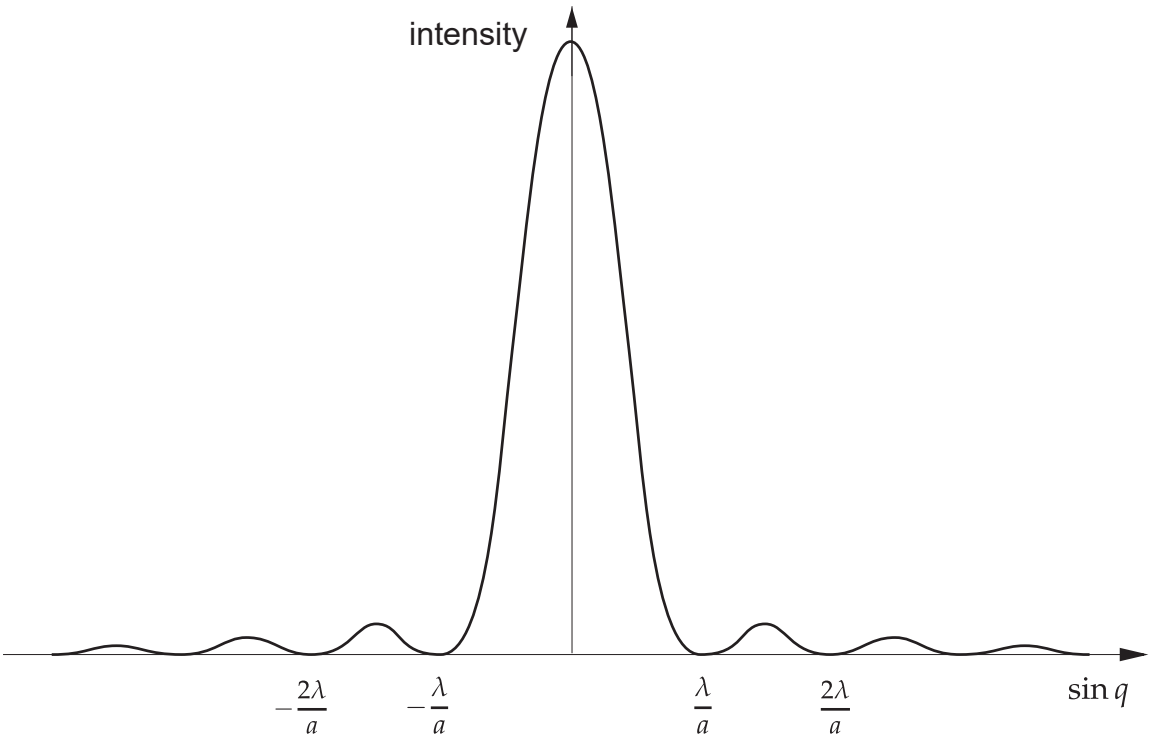


Figure 3: Angular distribution of intensity from light of wavelength λ passing through a finite aperture of width a.

The highest intensity is in the direction $q = 0$, corresponding to the direction in which the light was travelling before it reached the aperture. However, there is now a distribution, falling to a minimum (zero, in fact) for the first time at angles given by $\sin q_1 = \pm\frac{\lambda}{a}$. In this experiment, and in most practical cases, the angles we are concerned with are very small, and it is an excellent approximation to simplify this result further to

$$q_1 = \frac{\lambda}{a}. \tag{1}$$

This is by far the most important result in the theory of Fraunhofer diffraction (and is the basis for this entire experiment); it sets the angular scale of the blurring of the image formed by an optical system.

Estimate q_1 for an optical system with an aperture of size 10 mm. Visible light has wavelengths centred on ∼500 nm.

To find the extent of blurring in the image plane, we simply have to multiply this angle by the focal length f_2 of the lens L_2.

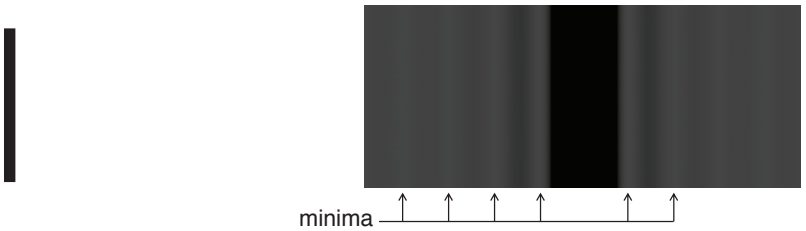
Draw a ray diagram of two collimated beams of light, travelling at a small angle ϕ to each other, falling on a lens of focal length f. Hence prove that the separation of the positions at which the two beams come to a focus is ϕf. [Hint: remember that a ray passing through the centre of a thin lens is undeviated.]

There are further minima (zeroes of intensity); the important angles are:

(a) $q = 0$ (maximum)

(b) $q_p = \frac{p\lambda}{a}$ (minima), where p=1, 2, 3...

There are thus also secondary maxima, but, as figure 3 shows, their intensities are very small compared with that of the principal maximum. The net result is that if we have a very narrow slit source and the aperture of the system is also a slit, parallel with the source slit, the image in the limit of large a would simply be a narrow line (figure 4(a)). As a result of diffraction, however, the line spreads into a pattern (figure 4(b)), with intensity variation as shown in figure 3.



(a) Image seen if a rectangular aperture with $a \to \infty$ is used.

(b) Diffraction effected image seen when a rectangular slit of finite slit width is used.

Figure 4: The two extreme cases of imaging: a) as $a \to \infty$ and b) when $a \approx \lambda$.

It is important to remember that in practice we are usually concerned with a circular aperture. In that case, with a point source, we get a circular fringe pattern, with the first minimum at an angle of $\frac{1.22\lambda}{a}$. This is much harder to show theoretically than the simple one-dimensional result, however, and the latter is close enough for most purposes.

▶ Discuss your understanding of Fraunhofer diffraction and the exercise above with a demonstrator.

2.3 Optical resolution

Suppose now we have two narrow slit sources, P_1 and P_2 at distance f_1 from L_1, which subtend an angle α at L_1 (figure 7). We need to know, firstly, can we tell from what we observe in the image plane that there are indeed two sources, and secondly, will we see two distinct images? To answer this we firstly need to find the angular separation of the images I_1 and I_2, that is, the angle they subtend at L_2.

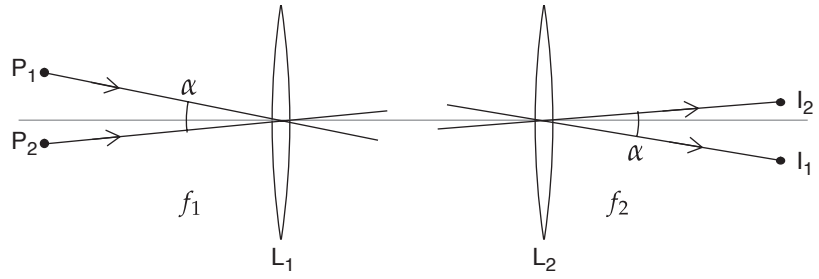
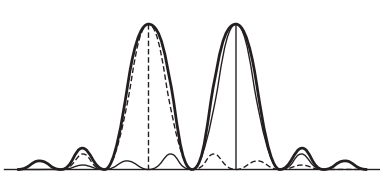


Figure 5: Two sources, P_1 and P_2, are imaged through two lenses L_1 and L_2 to give I_1 and I_2

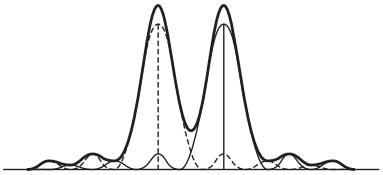
Draw a ray diagram to show that this separation is also α, as shown in figure 7.

Next, we consider how small α can be before the two diffraction patterns merge. Figure 6 shows what happens as α is successively reduced (remember that $q_1 = \frac{\lambda}{a}$ is the angle between the principal maximum and the first minimum of either pattern considered individually). In figure 6(c), when $\alpha = q_1$, the maximum of one diffraction pattern falls on the first minimum of the other, and it turns out that the intensity halfway between them drops by about 20%.



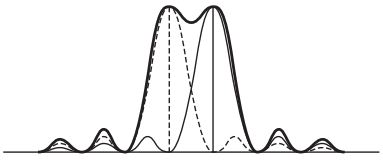
$\alpha = 2q_1$

(a) Well resolved image where all the minima coincide.



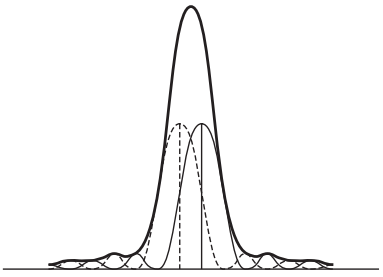
$\alpha = \frac{3}{2}q_1$

(b) Well resolved image where first order maxima coincides with zeroth order maxima.



$\alpha = q_1$

(c) Just resolved image.



$\alpha = \frac{1}{2}q_1$

(d) Not resolved image.

Figure 6: Dependence of image resolution on the aperture size.

Lord Rayleigh suggested that we take as a rule of thumb that under these circumstances we should

consider them just resolved (the so-called "Rayleigh criterion"). This is clearly reasonable, since if the patterns were much closer, as in figure 6(d), we certainly would not be able to distinguish them, while if they were much further apart (figure 6(a) and 6(b)) we could do so easily.

▶ Discuss the last exercise with a demonstrator, along with anything else you are unclear about.

3 The Investigation

3.1 Introduction

You are first to set up the simple optical system shown in figure 2, in which an image is formed of an illuminated slit. This image is formed after the passage of the light through two lenses between which it propagates as a parallel beam. This is in fact an important optical system, being the basis of many instruments, particularly in spectroscopy. You will then interpose an aperture (also shown in figure 2) which allows one to study the effects of diffraction on the image. You will also use your measurements to calculate the wavelength of the light source. The slit source is then to be replaced by sources with a more complicated structure (double slits and rasters), allowing an investigation of the effects of diffraction on the resolution of the system. Your measurements with the rasters will be used to calculate the wavelength more accurately.

You should aim to complete your measurements using the single slit source, plot a graph and make your first calculation of the wavelength before lunch.

3.2 The optical components

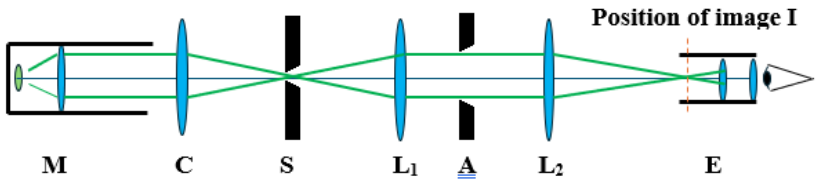


Figure 7: The experimental set-up

The optical system you will assemble is shown in more detail in figure 7. It consists of:

A green LED light source M, mounted at the back end of a black tube. In front of it there is a green filter allowing a narrow range of wavelengths to pass through it, and a lens, to give a roughly collimated beam.

Three lenses, C, L1 and L2, all of focal length 100mm.

An adjustable slit S. Check you can read the micrometer scale, and interpret it correctly in terms of the slit width. A second similar slit, A, will be used eventually in the position shown to restrict the beam width so as to allow diffraction effects to be seen.

An eyepiece E, with crosswires and a micrometer screw. The plane of observation, containing the crosswires, is shown as a thin dashed line. Hold the eyepiece close to your eye – in the air, not on the baseboard - and look through it. Adjust the knurled ring to bring the crosswires into focus with a relaxed eye (that is, do your best to look through the instrument rather than at it). Check you can move the crosswires sideways across the field of view with the micrometer.

Assorted rasters, mounts, etc, not shown, for use later in the experiment.

There are also a few bits and pieces to help with the setting up:

An optical pin P. This is used to ensure all components are centred at the same height above the baseboard. Never put the pin close to your eye, or vice versa – when it is not in use, make sure it is safely stowed.

A mirror M, used to locate the required position for lens L1.

A piece of white card, which can be interposed anywhere along the optical system to check the appearance of the beam.

A more complete description of the equipment supplied is given in the Appendix.

3.3 Overview

The purpose of the lens C is to produce an image of M on S, so this slit becomes the "object" for our system of lenses L1 and L2. S is to be at the focal point of L1, so that light which has passed through S and L1 should be collimated. At first, we have no aperture A in between L1 and L2, so this collimated beam falls directly onto L2. This lens forms an image I of S in its focal plane, which is to coincide with the crosswires of the eyepiece (the thin dashed line in figure 7). The separation of L1 and L2 is not critical, but it is convenient to make it around 200mm to avoid crowding of components. With the system in this configuration, one then interposes a diffracting aperture A in the parallel beam between L1 and L2 to study how the image I is modified by diffraction.

3.4 Lining up the components on an optical axis

The components need to be centred on what is called the optical axis, which can be any line in a plane parallel with the baseboard. First, the height of this plane must be established, and the midpoints of the lenses, and the centres of the slits, made to lie on it. This needs some care, as an error in the height of a lens in particular can throw a beam significantly off axis. For this purpose, you are to use the optical pin. Only one end of the pin is used, and only the tip of that.

Fix the pin in its mount, with the chosen tip well away from the mount. This will allow you later in the experiment to bring the point up to screwed-down components without the mounts competing for space on the breadboard. Bring the components close to the chosen tip, one by one, so that their height above the baseboard can be appropriately adjusted. Put all the components alongside each other, unmounted, before doing this, so that you can choose a height which will accommodate all of them! Getting the slits the right height in particular needs care – open them wide, and observe the pin through them. Don't attempt to get the microscope the correct height by looking at the pin through it, as the observation plane is well inside. It has a circular entrance window – get the centre of that the correct height by putting it close to the pin. The mirror has no axis and therefore its vertical position is not critical, but the axis of the system should pass close to its centre. The card is generally hand-held.

When the heights have all been set, keep the pin handy in a safe place. You will need it when turning round the slit S and possibly also to check the heights of any of the components.

Next, we need to choose a line in space at the chosen height and place the components so that their centres lie on it. The following procedure is suggested, but (as they say) other methods are available and if you want to try something else consult a demonstrator.

There is a steel rule screwed to the baseplate. The component mounts have a circular flange at the bottom to allow clamping. These are to rest against one edge of the rule, and as the centres of the components are to sufficient accuracy directly above those of the flanges this approach defines an axis. In more critical experiments, one needs precise adjustments on the components themselves, but here we can manage, since although Rome was not built in a day, this optical system has got to be.

We first arrange the source M so that the beam from it travels in the correct direction along the

length of the baseboard. Place M against the rule very close to the end further from the edge of the baseboard. By eye, arrange the tube to be parallel with the rule. Don't clamp it down. Switch on. Now place the lens C against the rule, a few mm from the end of the tube, and clamp it down. The exact position is not critical. Check using the white card that an image of the LED is formed some distance from C. The sources are sufficiently different that the location of this image varies significantly from one apparatus to another. If you are unsure about yours, ask a demonstrator.

Replace the card with the slit S so that the image falls on its surface. For this purpose, the slit should be closed, and have its broad face towards C. Move the slit as needed, maintaining contact with the rule, to bring the image into focus. We want this image to be centred on the slit. If it is found to be slightly off-axis, this can only be because the source tube is not quite parallel with the axis. Rotate the source tube as needed, then clamp it down. If the height of the centre of the image does not match that of the slit, then re-check your components with the optical pin.

For convenience later, we actually want to have the slit in this position but the other way round. Put the optical pin on the baseboard so that its point is very close to the slit, near to the centre of the broad surface. Then simply turn the slit around, open it as wide as possible, and observe the pin through it. Put the slit in a position such that the point of the pin is in the same place relative to the plane of the slit as before. S can now be clamped down.

The next step is to put L1 in such a position that S is in its focal plane. This is done using the mirror M, as follows. Close S, and then open it slightly to a width at which significant light comes through it – the exact value is not critical. Put L1 in roughly the right place, that is, about 100mm from S. Put the mirror with its mount against the rule, a few centimetres further along the axis, so that the reflected light returns through L1. Rotate the mirror, bodily or with the screws, until the image of S, formed on the flat slit surface, is adjacent to S itself. Move L1 along the rule until the image is at its sharpest. Then clamp it down, and remove the mirror.

Widen S once more, and check with the card the shape of the beam which emerges from it, and through L1. One should have a diverging roughly circular uniform beam which has an almost constant width once it has passed through L1.

We turn to L2. The position of this lens relative to L1 is not critical, since it is intercepting a parallel beam. Put it around 200mm from L1, to avoid overcrowding of the components, but do not clamp it down. Check with the card that the beam falling on L2 now comes to a focus some 100mm from it, forming an image I of S. To study Fraunhofer diffraction, we need an image to look at; we now have one.

We want this image inside the eyepiece, coincident with the crosswires. Procedure: first, reduce the image brightness by putting a piece of ordinary paper just before S. Then put the eyepiece against the rule in roughly the right place and look through it. Check that you can see the image and the crosswires, the latter being in sharp focus from your earlier adjustment. We want them to coincide. To achieve this, first clamp down the eyepiece. Then move L2 along the rule until there is no parallax between the image and the crosswires. (If you haven't come across the "no parallax" method, ask a demonstrator to explain it.) When you have done this, clamp down L2.

▶ **The optical system is complete; get a demonstrator to check it.**

3.5 Observation of diffraction

Narrow down the slit S to produce a very fine object. Remove the piece of paper which attenuated the light, open the diffracting aperture as wide as it will go, and put it on the bench roughly midway between L_1 and L_2. You should still see a good image of S in the eyepiece (though you may be able to see the effects of diffraction if you look carefully enough). Slowly close down the aperture, and the image will broaden, giving the fringe pattern shown in figure 3.

Describe what you observe through E for different widths of the aperture A.

> Set A as wide as it will go, so that the image of S is essentially the fine line predicted by geometrical optics, and observe through E as you move A a few centimetres along the optical axis. Explain your observations.
>
> Repeat this experiment moving A a few millimetres perpendicular to the axis.
>
> Repeat the steps above but with the aperture closed sufficiently for there to be an obvious diffraction pattern.
>
> Put the aperture back on the axis.

▶ Check your observations and explain them to a demonstrator.

3.6 Measurements

According to the theory outlined in section 2, the separation of the principal maximum from the minima either side of it, and the separation of successive minima on either side of the pattern, are both $\frac{\lambda f_2}{a}$.

> Check this by plotting a graph of the width a against the inverse of the separation of adjacent minima in the diffraction pattern. Note that the reading on the micrometer controlling the aperture may have a zero offset; this will not alter the slope of your graph. Use at least 5 different values of a. For each value, measure from a minimum on one side of the pattern to one on the other at least 4 times. Use different minima each time as a check against systematic error. The focal length of L_2 is written on the mount. From your slope, calculate the wavelength λ of the green light, including experimental errors. Ask a demonstrator for the correct value of the wavelength and compare this with your result, are the values consistent?

Some tips are listed below:

(a) Micrometers are easily misread - satisfy yourself that you know what you are doing, and check your readings for consistency as you go along to make sure that they make sense.

(b) To avoid systematic error in a, start with a value around 1 mm and successively reduce it, so that the micrometer movement is always in the same direction. Aim to cover a sensible range of values of a.

(c) To allow you to check your data later, write down all micrometer readings as you take them.

(d) Always identify clearly the minimum you are measuring, e.g. *L3* would refer to the *third minimum on the left side of the pattern*.

(e) For maximum accuracy, count as many fringes as you can. There is a trade-off between increased accuracy from more fringes, and increased difficulty in viewing the minima of the fringes as you get further out.

▶ If you have any issues, or your graph isn't as expected, check with a demonstrator. Otherwise move on to the next section and discuss your findings at the next demonstrator prompt.

3.7 Optical resolution: the double slit

Open A again as wide as it will go, and check that you still have a good image of S on the crosswires. Remove S, and replace it with one of the double slits. Adjust the position of the holder until you have a sharp image of the double slit system on the crosswires. Move the light source slightly if necessary to make sure that its image falls on both slits.

Measure the separation of the two images using the eyepiece micrometer. Hence find the angle α which they subtend at L_2. Use this, together with the Rayleigh criterion, to calculate the smallest value of a which would allow them to be resolved.

Find the smallest value of a for which it is clear there are two distinct images, and compare this with your calculated value. Remember to allow for any offset you found earlier in the micrometer controlling the aperture.

Repeat the above for two other double slits.

▶ Check your findings for a with a demonstrator.

3.8 Optical resolution: the raster grid

As you are likely to have discovered in working through the previous section, deciding when two images are just resolved is subject to large uncertainty. It it much easier to assess when the image of a set of equally-spaced parallel lines degrades into a uniformly illuminated area, and the Rayleigh criterion applies in the same way.

Put one of the rasters in the slide-holder, and, with A fully open, check that you have a sharp image of the raster in the field of view. Then gradually close the diffracting aperture just far enough for the image to appear uniformly illuminated. The sudden loss of detail is quite striking. Note the value of a. Repeat the experiment four or five times with the same raster, then carry out the whole procedure for the other rasters provided. Plot a graph of a against n, the number of lines mm $^{-1}$ on the raster (given on the mount), and find its slope. Start with the finest raster, and work towards the coarsest, again to avoid as far as possible systematic error associated with the measurement of the aperture size.

Calculate what you would expect the slope to be according to the Rayleigh criterion, as follows. Find an expression for the separation of adjacent lines in the image of the raster in terms of n, f_1 and f_2. If these lines are to be resolved, they must be separated by more than $\frac{f_2\lambda}{a}$. Use your calculated gradient to work out another value for λ, including errors.

▶ Confirm your value for λ with a demonstrator.

▶ Now hand-write a brief summary of the experiment in your logbook. State the aims of the experiment, the method used, quantitative results, and your conclusions, in not more than about half a page. Show this to a demonstrator as part of your assessment.

Appendix A Equipment

- Optical Bench
- Post Holders x7

- Tuning Fork Bases x7
- LED Assembly
- 100mm Lens x3
- 50mm Lens
- Raster Holder
- Eyepiece with Crosshairs
- Adjustable Single Slit x2
- Rasters
  - 2.5 l/mm
  - 5 l/mm
  - 7.5 l/mm
  - 10 l/mm
  - 15 l/mm
  - 20 l/mm
  - 25.59 l/mm
- Slits
  - 0.35mm
  - 0.6mm
  - 0.86mm
  - 1.14mm
  - 1.35mm
- Optical Pin
- White Screen
- Lamp