THORLABS

Discovery

EDU-FOP2
EDU-FOP2/M

Fourier Optics Kit

Manual

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5.2. Camera Installation and Settings

Download Thorcam[13] before installing and using the camera. Install the software.

A window for selecting the correct driver will pop up (see Figure 27). Left-click the “x” symbol next to “USB” and select “This feature will be installed on local hard drive.” The “x” symbol disappears as shown in Figure 27.

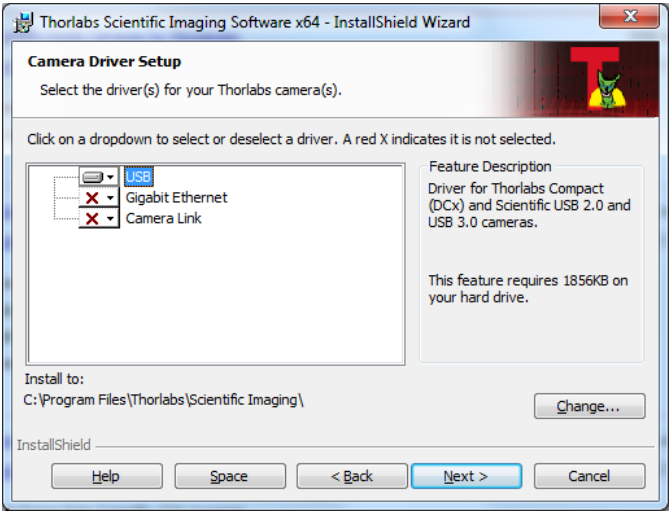


Figure 27: Selection During Installation

Finish the installation. Use the supplied USB cable to connect the camera to a free USB port on your computer. To turn on the camera, open the Thorcam program by double-clicking the corresponding icon. The interface shown in Figure 28 is displayed.

Figure 28: User Interface

Click the “Open Camera” button and select the camera with the corresponding serial number. The user interface shown in Figure 29 is displayed.

[13] https://www.thorlabs.com/software_pages/ViewSoftwarePage.cfm?Code=ThorCam

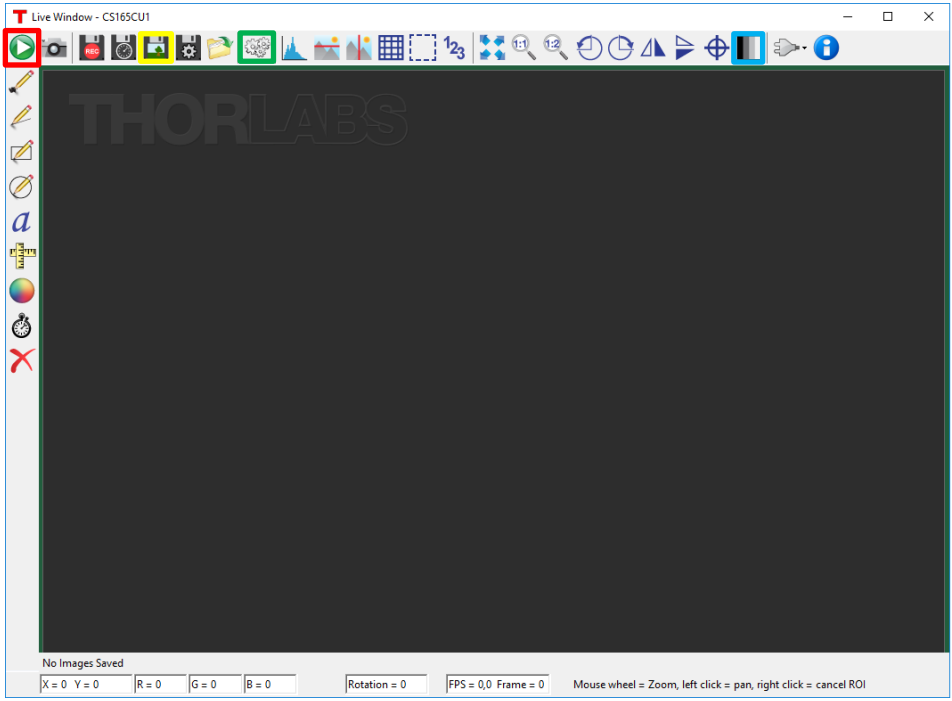


Figure 29: Camera Interface

Click the Live button (indicated in red in Figure 29) to display the live camera image in the window. Click the Save button (indicated in yellow) to open the dialog for saving the camera image to a file. Click the Settings button (indicated in green) and the Display button (indicated in blue) to open the camera menu, as shown in Figure 30, where you can change various settings such as the “Exposure Time”, “Gain” and the color scale.

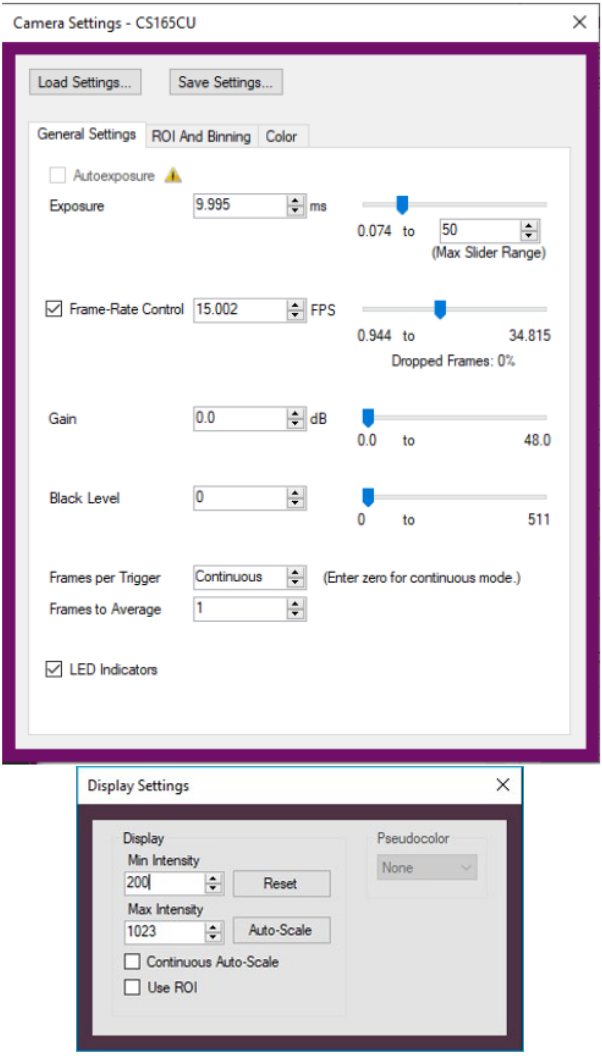


Figure 30: Camera and Display Settings

However, manual adjustment of the exposure time and gain should not be necessary for the test setup. Select “Autoexposure” in the general settings tab and close the camera menu. Please note that this function results in frame rates of about 10 FPS.

Now the camera is fully installed and ready to use.

5.3. Target and Mask

This is a sketch of the target supplied with this kit (outer diameter sector star: 3 mm):

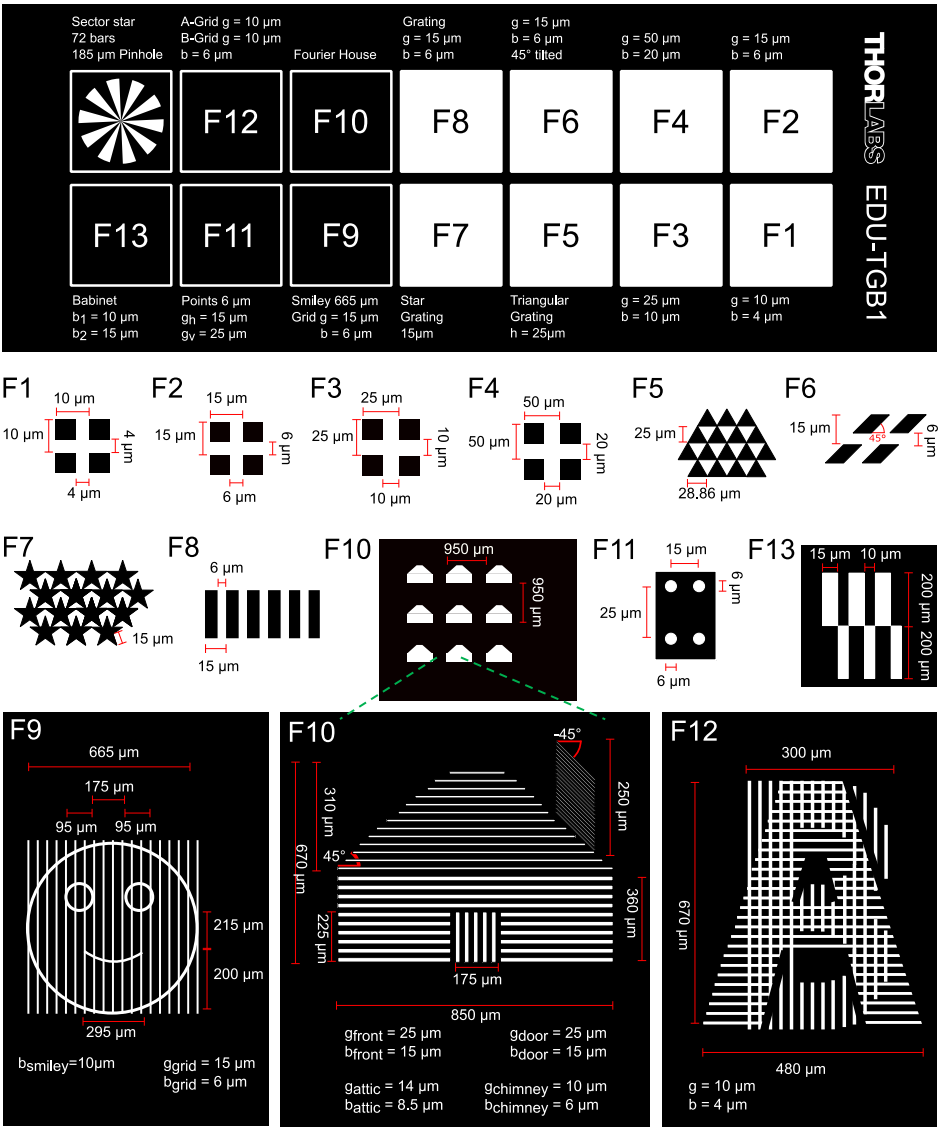


Figure 31: Target EDU-TGB1 with Detail Drawings for Each Section

Fields F10 and F12 feature an arrangement of nine identical structures, a house and the AB structure. The purpose of that is to increase the intensity in the Fourier plane. With only one structure, the pattern would be hardly visible on the screen. Since the houses are all identical, the Fourier plane for one house is essentially the same as the Fourier plane of an arrangement of 9 houses. To understand that, consider the point grating in field F11. The Fourier pattern is a convolution of the pin hole diffraction pattern and the pattern of a periodic, rectangular lattice. When only few pin holes are present (or a lot of pin holes are present in a random arrangement), the resulting Fourier plane is dominated by the pin hole diffraction pattern. Therefore, the arrangement of 9 houses or 9 ABs is also dominated by the Fourier pattern of the single house or the single AB.

In the next chapters, we will often reference the target's fields F1 to F14 from Figure 31. Since it is helpful to have a visual aid when changing between the different fields of the target, we will use the small diagram to the right to indicate which field to use for each exercise. The reference diagram is vertical since the target is installed vertically in its holder. For example, this diagram means that the user is supposed to choose the Triangular Grating from field F5 in Figure 31.

This is a sketch of the mask that is used in the Fourier plane to block portions of the diffraction pattern to alter the resulting camera image.

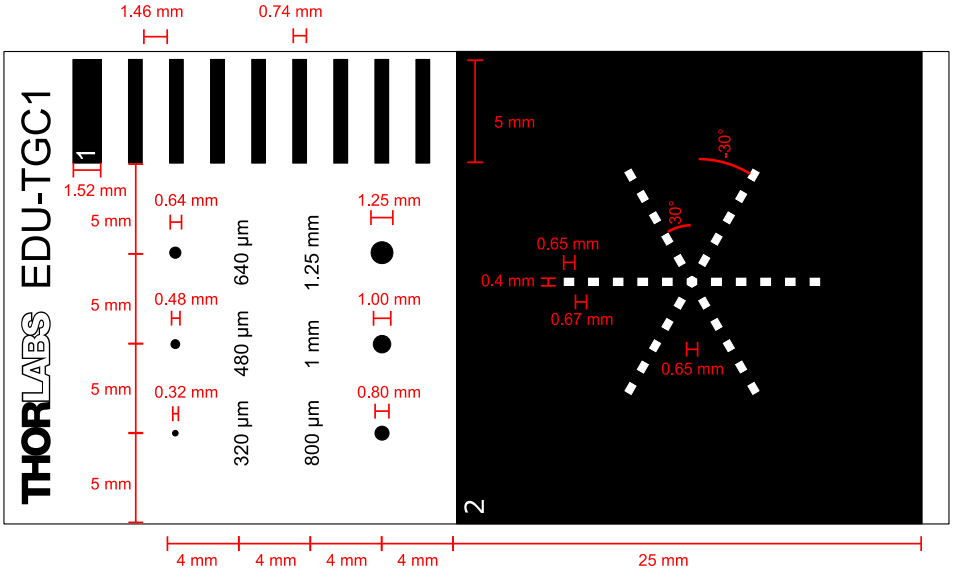


Figure 32: The EDU-TGC1 Cutting Mask: the red lines and red labels are not part of the mask.

5.4. DO AFTER 6.1 & 6.2 Setup and Adjustment of the Experiment

This section describes the setup and alignment of the main experiment.

For students, however, we recommend starting with the introductory exercises in Section 6.1 to get acquainted to the system's parts and their individual function.

To prevent possible shifting of the components, we recommend securing all parts in their final place with the clamps and screws. Reset all camera settings before you start (see Figure 30). To ensure optimal clamping, the clamps should not protrude from the breadboard.

Step 1: Height Adjustment

- Set the height of all components to 10 cm using the LMR1AP alignment plate and a ruler, measured from the breadboard to the center of the optical element (filter mount flipped sideways).
- The maximum height that is allowed by the components is 11 cm; the minimum height is 9 cm (measured from the top of the breadboard to the center of the optical element).[14]

Step 2: Camera and Tube Lens

- Place the camera at the right end of the breadboard, facing along the 4th hole line counted from the long edge closest to the user.

Figure 33: Placement of the Camera

- Switch on the camera software and start the live camera image (see Figure 29).
- Place the tube lens (f = 150 mm) at approximately 150 mm from the camera chip along the same line of holes (see Figure 34).
- The next step is to get a sharp image of a faraway object onto the camera. Make sure the room is lit well, so you have a high enough intensity on the camera. Adjust the camera's exposure time to the lighting conditions in the room. To place the tube lens, you have three options, the first and second being the preferred methods (see Figure 34).

[14] If you have chosen to setup on an optical rail instead of the breadboard, the center of the optical components should be 7 cm above the upper side of the rail.

1. Point your breadboard at an object on the other side of the room, preferably at least 4 m away. Move the tube lens forward and backward until you see a sharp image of the object on the camera.

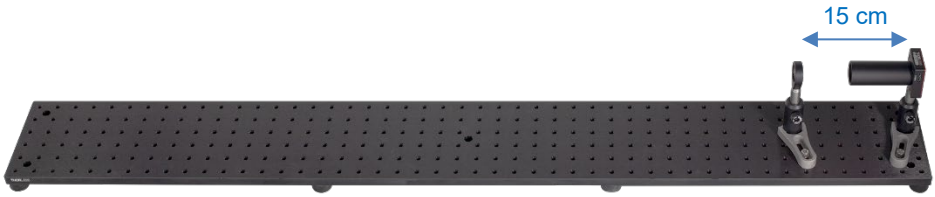


Figure 34: Placement of the Tube Lens

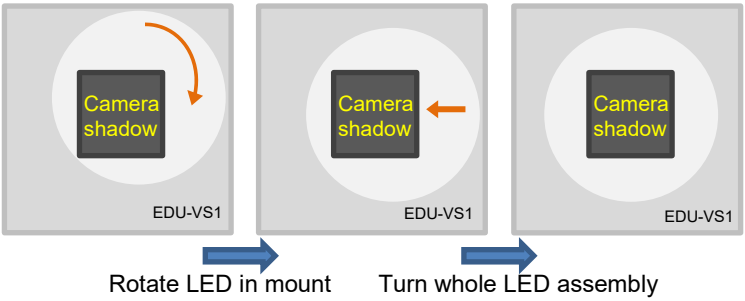


Figure 36: Centering the LED Light Around the Camera Shadow

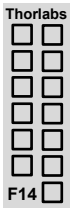
Figure 37: Placement of the LED

Step 4: Objective Lens

- Place the objective lens (f = 30 mm) 18 to 20 cm away from the tube lens, measured from the center of the lenses. The correct lens orientation is depicted in Figure 24 and Figure 38.
- Attach it to the board with the clamp oriented as shown in Figure 38.
- Rotate the SM1ZM zoom housing, so that the lens can travel in both directions.

Figure 38: Placement of the Objective Lens; See Figure 24 for Lens Orientation

Step 5: Target



- Move the target up to the highest possible position by turning the height adjustment screw clockwise.
- Adjust the height of the post that holds the XYF1(/M) so that the sector star (lowest row on the target, field F14 in Figure 31) has the same height as your optical axis (10 cm according to Step 1).
- Make sure that the lens in the SM1ZM zoom housing is approximately in the middle of the SM1ZM's travel range.
- Place the target approximately 2 cm away from the objective lens mount. Move the target back and forth until you obtain a sharp image of the sector star in the camera. You may have to reduce either the light intensity of the LED or the exposure time in the camera settings to avoid saturating the camera (see Figure 39 and Figure 40).
- Make sure the target is perpendicular to the optical path. Fix the assembly onto the breadboard.
- If the camera image is not sharp, adjust the objective lens by rotating the SM1ZM zoom housing.

- Move the target with the two adjustment screws of the XYF1(/M) to field F10 (c.f. Figure 31), an arrangement of nine houses. Move the target until the center house is seen on the camera.
- Since the camera has a good sensitivity, you will always pick up some stray light. We suggest to set the minimum of the color scale (see Figure 30) to 200.

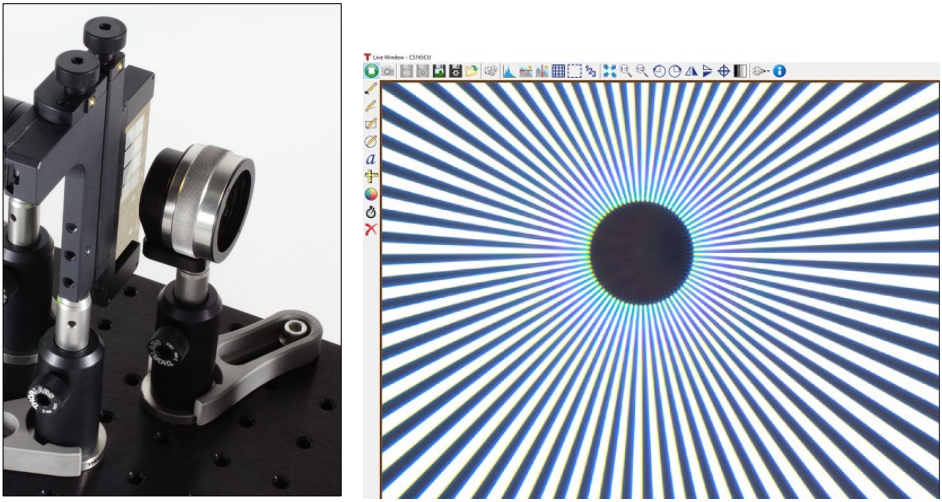


Figure 39: Placement of the Target and Image on the Camera (with 2 ms Exposure Time and Min Intensity 100, c.f. Camera and Display Settings)

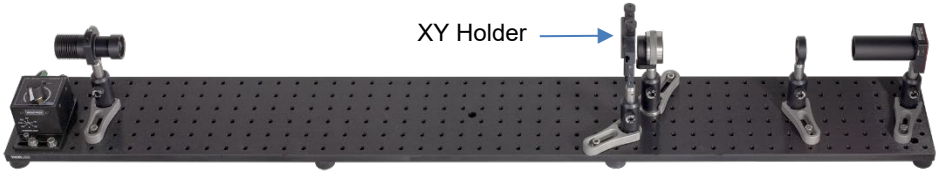


Figure 40: Placement of the Target in the XY Holder

Step 6: Condenser Lens

- Place the condenser lens (f = 50 mm) 50 mm away from the target, measured approximately from the center of the lens (see Figure 41).
- Move the lens forward and backward and observe the spot size on the target. It can be helpful to hold a small piece of paper directly in front of the target, as shown in Figure 44. Reducing the LED intensity is often helpful as well.
- Adjust the location of the condenser lens to achieve the minimum spot size.
- Remove the piece of paper and make sure the spot is centered around the center house of the 9 house array on the target (field F10 in Figure 31). If that is not the case, adjust the lens height accordingly.

Figure 41: Placement of the Condenser Lens; See Figure 23 for the Lens Orientation

Step 7: Aperture Iris

- Place the aperture iris [the smaller one, ID12(/M)] approximately 50 mm away from the condenser lens, measured from the iris to the center of the lens (see Figure 42).
- Close the aperture iris and set the height so that the iris' shadow is centered on the condenser lens mount as shown in Figure 45 (the stray light at the lower edge of the lens mount is eliminated by the field lens in the next step).[16]

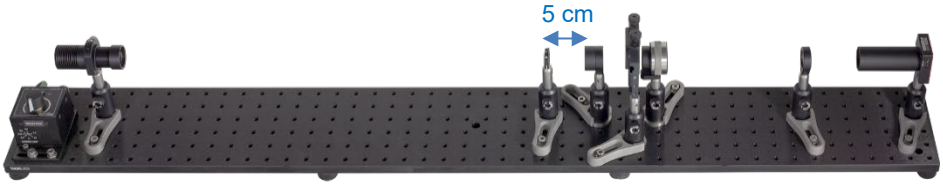


Figure 42: Placement of the Aperture Iris

Step 8: Field Lens

- Place the field lens (f = 150 mm) approximately 150 mm away from the aperture iris (see Figure 43).
- Place a piece of paper in front of the iris.
- Move the field lens until you see the LED chip on the paper (array of black spots). You may need to reduce the LED intensity to see the spots.[17]
- Check the height of the field lens. The spot on the aperture iris should be centered, see Figure 46.

[16] When the iris is fully closed and in the focal plane of the condenser lens, then the light transmitted through the condenser should be collimated. You can check that by moving a piece of paper from condenser lens to target.

[17] It can be difficult to see the LED chip. If you cannot see it, aligning the field lens so that it is 15 cm away from the aperture iris is sufficient.

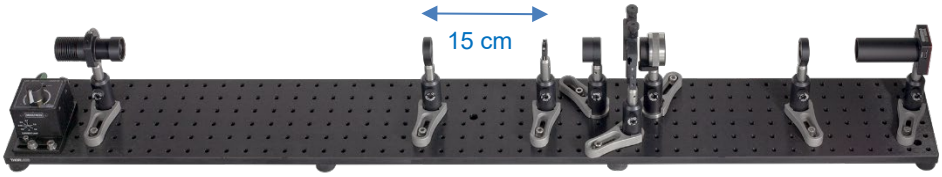


Figure 43: Placement of the Field Lens

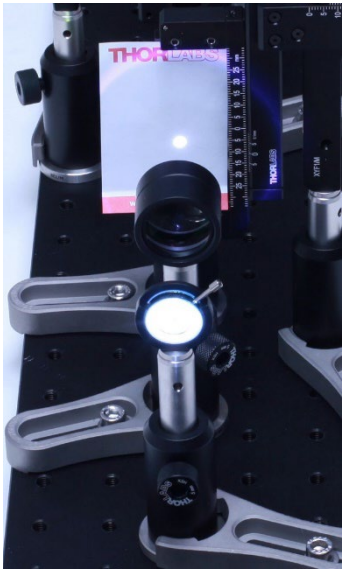


Figure 44: Light Spot on the Target During Positioning of the Condenser Lens

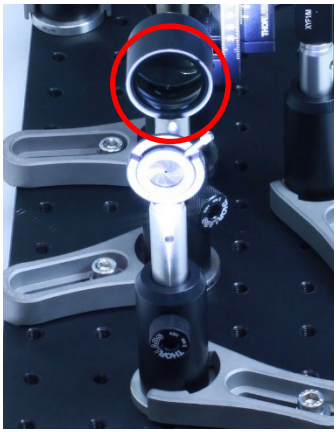


Figure 45: The aperture iris' shadow is centered on the condenser lens and its holder.

Figure 46: Positioning of the Field Lens and Field Iris

Step 9: Field Iris

- Place the ID25(/M) field iris at approximately 150 mm from the field lens (see Figure 47).
- Check the height of the iris by opening or closing the iris in order to verify that the field lens mount is illuminated evenly (by observing the mount itself or by using the LMR1AP alignment plate on the field lens mount).
- Almost fully close the iris.
- Observe the camera image and slightly move the iris forward and backward. Ideally, you would see a sharp image of the iris on the camera, meaning you

would be able to see the edges of the iris blades (roughly a polygonal shape). However, you cannot obtain a sharp image with this setup. Just make sure you see deviation from the circular shape (i.e., some bumps on the edges), as shown in Figure 48.

- If the light spot is not centered in the camera image, adjust the field iris' height.

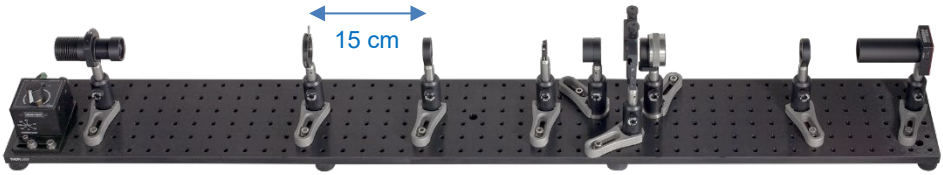


Figure 47: Placement of the Field Iris

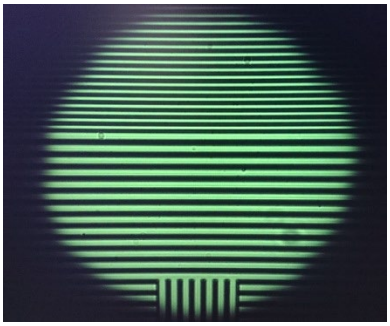


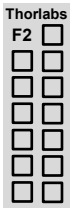
Figure 48: Place the field iris so that the camera image shows a sharp image of the field iris. Since this will rarely be the case, it is sufficient to place the lens such that you see a deviation from the circular shape.

Step 10: Color Filter

- With the mount flipped *sideways,* match the height of the color filter to the height of the collector lens in front of the LED.
- Place the color filter in front of the LED. The close proximity reduces the stray white light; see Figure 49.

Figure 49: Placement of the Color Filter

Step 11: Beamsplitter



- First, set the target to the grating with g = 15 µm and b = 6 µm, field F2 in Figure 31.
- Open the field iris (about 3/4).
- Close the aperture iris.
- Place the beamsplitter approximately 8 cm away from the objective lens (distance measured between objective lens mount and beamsplitter mount). The orientation can be seen in Figure 21 and Figure 50. Do not place it too close to the objective lens or you will not have enough room to manipulate the Fourier plane.
- Close the side port of the beamsplitter that is facing the user with an SM1EC2B plastic cap.

Figure 50: The holder of the beam splitter cube should not be illuminated.

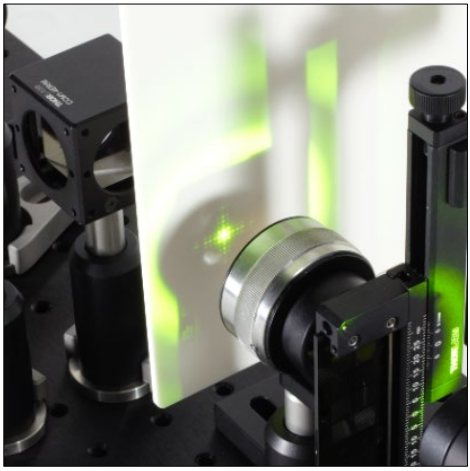


Figure 51: Examining the Fourier Plane Behind the Objective Lens

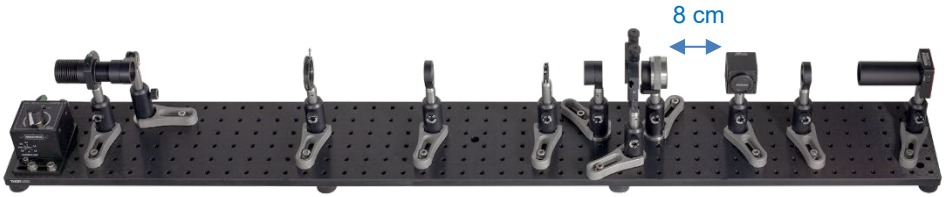


Figure 52: Placement of the Beamsplitter

Step 12: Fourier Plane

- Set the LED to full intensity.
- Use either a screen or piece of paper to find the Fourier plane behind the objective lens (in the focal plane), as shown in Figure 51 (aperture iris closed, field iris open). In the next step, this has to be displayed on the screen using the projection lens.

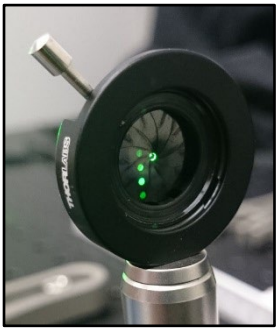
Step 13: Projection Lens and Viewing Screen

- Position the projection lens (f = 75 mm) directly behind the beamsplitter (at a 90° angle to the optical path towards the camera) and fix it to the board.
- Use the viewing screen to find the distance where you see a sharp image of the Fourier plane on the screen.[18]
- If producing a sharp image of the Fourier plane on the screen is not possible, varying the distance between the projection lens and beamsplitter cube may help.
- General remark for the placement of beamsplitter, projection lens and viewing screen: When the screen is moved further away, the image gets larger. However, the projection lens will have to be closer to the beamsplitter to get a sharp image. If there is not enough space between the beamsplitter and projection lens to move it closer, move both the beamsplitter and projection lens closer to the objective lens. Make sure there is enough room between the objective lens and the beamsplitter for manipulating the Fourier plane.

Figure 53: Positioning of the Beamsplitter Cube, Projection Lens, and Viewing Screen

[18] The distance to get a sharp image depends on the object distance g (Fourier plane to projection lens) and the focal length of the projection lens f, and is called the image distance b. It follows the lens equation $\frac{1}{f} = \frac{1}{b} + \frac{1}{g}$.

Step 14: Target Plane Correction



When the target is not placed perpendicular to the light path, there will be reflections on the glass that may appear as additional spots in the Fourier image. The reflections may show in the Fourier plane (double reflection in the glass) and in the light reflected towards the aperture iris.

- Observe the side of the aperture iris that faces the target. When the target is not perpendicular to the beam, you will get reflections similar to the ones in the photo on the right.
- Should these reflections be off-center, please rotate the target in its holder until the reflections align with the center of the iris.
- You may need to slightly move the objective lens in the SM1ZM zoom housing to get a sharp image on the camera again.

You should now see a sharp image of the target on the camera and a sharp image of the Fourier plane on the screen.

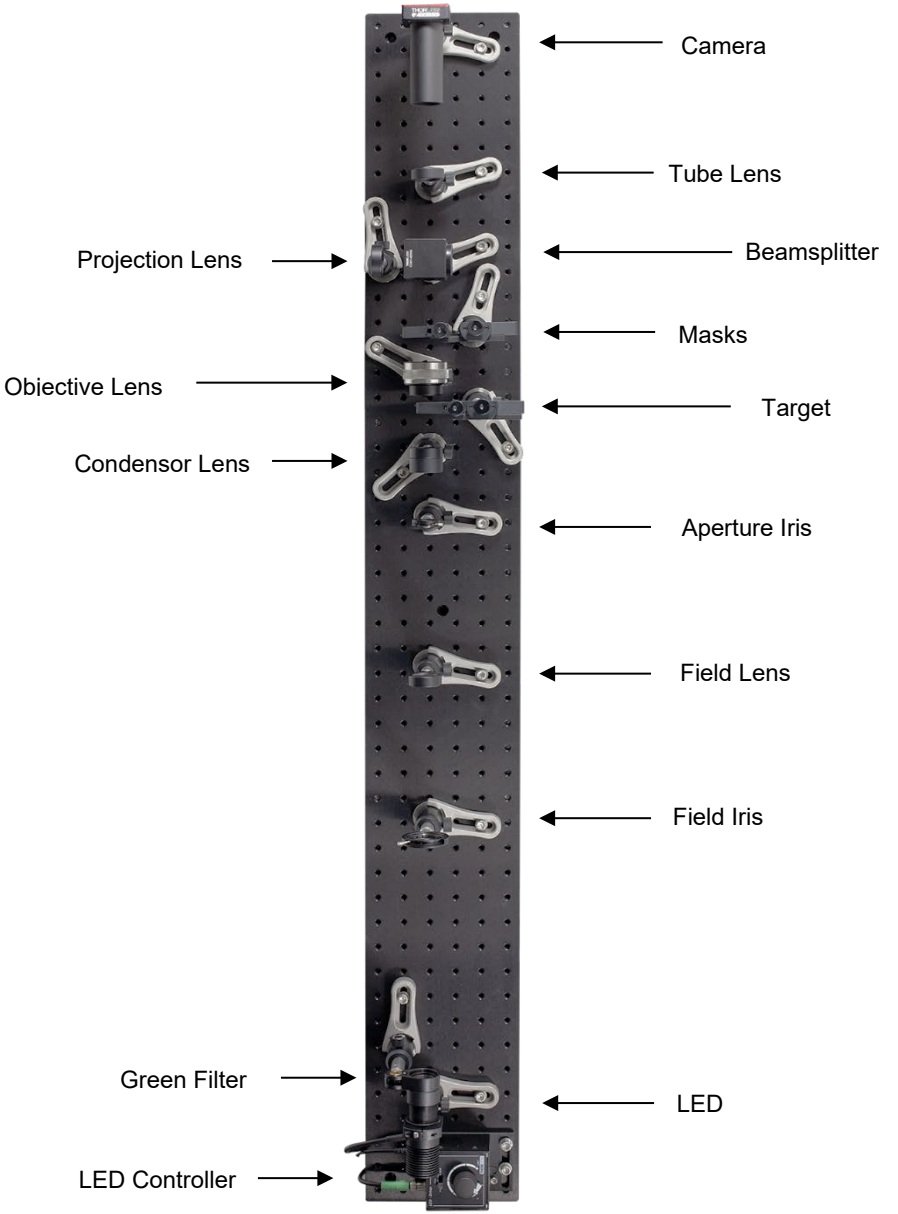


Figure 55: Adjusted Overall Setup

5.5. Function of the Individual Optical Elements

Figure 56: Overall Setup

Collector Lens: The collector lens is attached directly to the LED and ensures the best possible parallelisation of the light from the LED. This results in the greatest possible intensity on the smallest possible area.

Illuminating Optics: In principle, the combination of a field lens and condenser lens with coinciding focal planes is a Keplerian telescope. The lenses in this kit should provide threefold magnification. Since we are effectively using the telescope backwards with the field lens aimed at the light source, the illuminated area after the condenser lens only has one third the original area with the same overall intensity.

Imaging Optics: The combination of the objective lens and tube lens forms the imaging optics of the setup. It creates a sharp image of the object plane on the plane of the camera chip. Since the object is in one focal plane of the objective lens, the Fourier image of the object can be examined in the other focal plane of the objective lens. Fivefold magnification can be achieved when the focal planes of the lenses coincide. This setup is what is known as an infinity-corrected microscope. Since the target is in the focal plane of the objective lens, it can therefore be assumed that a parallel light beam is propagating behind the objective lens. Therefore, the tube lens can be set up at any distance from the objective lens to focus the image onto the camera.

Projection Lens: The Fourier image is in the rear focal plane of the objective lens. This plane (or the Fourier image) is displayed on a screen with the help of the projection lens via the beamsplitter. The display and magnification of the image follow the lens equation. When the projection lens is placed at a certain location, the image on the screen is only sharp at a certain screen distance. The magnification corresponds to the ratio of the image distance to the object distance.

Green Filter: The diffraction of white light on small structures leads to spectral splitting of the light in the diffraction pattern. A green filter is needed to prevent spectral splitting and therefore the expansion of the diffraction maxima in the Fourier image. Decreasing the extent of the diffraction maxima makes filtering the Fourier image easier. However, note that all diffraction effects shown here also occur with white light.

Field Iris: Opening and closing the field iris makes the illuminated area on the object behind the condenser lens larger or smaller. This is because the Kepler telescope

consisting of the field lens and condenser lens is positioned so that it projects a sharp image of the field iris in the object plane. Furthermore, changing the field iris opening can alter the brightness in the Fourier image: for example, when a cross lattice is illuminated, opening the field iris causes more gaps in the lattice to be illuminated. This in turn contributes more light to the formation of the Fourier image.

Aperture Iris: The intensity of light passing through the condenser lens can be controlled directly with the aperture iris. This means opening the aperture iris increases the intensity on the object because more light falls onto the condenser lens. Furthermore, the aperture iris is represented in the Fourier plane by the combination of the condenser lens and objective lens. Thus, the Fourier image is an overlay of the aperture iris image and the diffraction pattern of the object. This means the opening of the aperture iris correlates with the extent of the intensity maxima in the Fourier image.

Chapter 6 Exercises and Examples

This chapter is structured the following way:

- Chapter 6.1: A set of preliminary exercises uses sub-configurations of the Fourier Optics setup to demonstrate the purpose of different components in the setup. Students explore how the individual lenses work together to map images onto different planes.
- Chapter 6.2: After assembling the full Fourier Optics Kit, a set of introductory exercises deals with observing the individual function of each element in the setup.
- Chapter 6.3: This is the core of the Fourier Optics setup. The exercises here deal with the various ways that filters in the Fourier plane affect the final image.
- Chapter 6.4: Babinet's Principle is demonstrated with a number of exercises.
- Chapter 6.5: Since the methods of Fourier transformation are often used in modern image manipulation techniques, we demonstrate how image editing such as blurring works with Fourier Optics.
- Chapter 6.6: Specially designed targets allow an image to be displayed in the Fourier plane. This is demonstrated in the setup.
- Chapter 6.7: Small structures result in large diffraction patterns in the Fourier plane. This directly leads to Abbe's fundamental principle of microscope resolution. An example is demonstrated with the setup.

Advanced students that are familiar with microscopy and Köhler illumination may skip Chapter 6.1. For other students, we recommend performing these preliminary exercises first to understand the whole Fourier setup.

START HERE 6.1. Preliminary Tests

Exercise 1: Place first the field lens (f = 150 mm) and then the condenser lens (f = 50 mm) in front of the collimated LED so that the focal planes coincide. Position the target in the LED-side focal plane of the field lens (so that at least one character is illuminated) and examine the image in the rear focal plane of the condenser lens with the observation screen. What optical device is created by the combination of the field lens and condenser lens?

Execution: The image of the target is upside-down and one third the size of the original target (the target should be set up so that at least one of the characters can be recognized). The combination of the field lens and condenser lens is a Keplerian telescope with a magnification $V = \frac{f_{field}}{f_{condenser}} = \frac{150\ mm}{50\ mm} = 3$. Since the light passes through the lens with a long focal length first and then through the lens with a short focal length, the light is effectively passing through the telescope backwards making the image 1/3 the size of the object.

Figure 57 Photo of the Image on the Screen Created by the Keplerian Telescope Formed by the Field Lens and the Condenser Lens

When the full setup is assembled, the field and condenser lens form a Keplerian telescope that images the field iris on the target. This explains the direct effect that opening and closing the field iris has on the target. The intensity of light on the target also increases through imaging with the field lens and condenser lens, since the illuminated area gets smaller but the power remains the same.

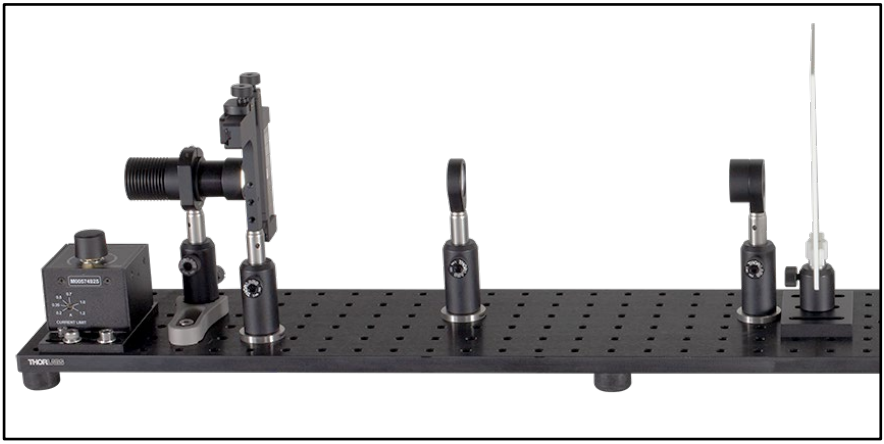


Figure 58: The Field Lens and the Condenser Lens Form a Keplerian Telescope With a Magnification of 1/3

Exercise 2: Place the objective lens (f = 30 mm) behind the condenser lens (f = 50 mm) so that the focal planes coincide. Position the target in the LED-side focal plane of the condenser lens and examine the image in the rear focal plane of the objective lens. What makes the combination of the condenser lens and objective lens different from the combination of the field lens and condenser lens?

Execution: The image of the target is upside-down and three fifths the original size (the target should be set up so that at least one of the characters can be recognized). The combination of the condenser lens and objective lens is a Keplerian telescope with a magnification $V = \frac{f_{condenser}}{f_{objective}} = \frac{50\ mm}{30\ mm} = \frac{5}{3}$. Since the light first passes through the lens with a long focal length and then through the lens with a short focal length, the displayed image is 3/5 the size of the object.

Figure 59: Photo of the Image on the Screen Created by the Keplerian Telescope Formed by the Condenser Lens and the Objective Lens

When the full setup is assembled, the condenser lens and the objective lens form a Keplerian telescope that images the aperture iris in the camera-side focal plane of the objective lens. As we show experimentally in the Chapter 6.3, this plane is the Fourier plane. This explains why closing the aperture iris changes the Fourier image.

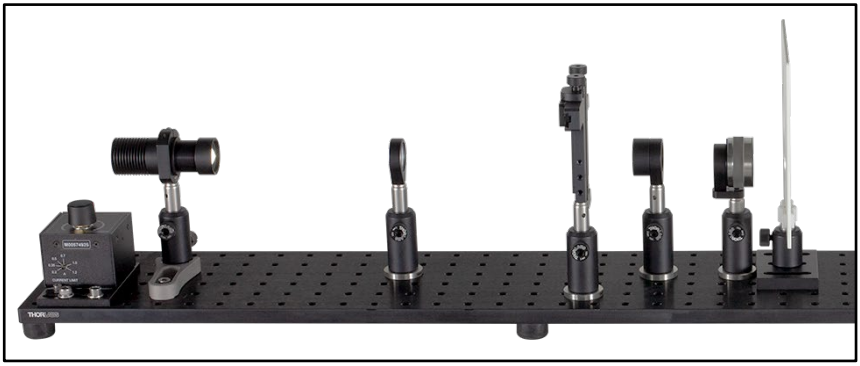
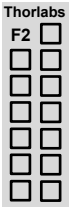


Figure 60: The Condenser Lens and the Objective Lens Form a Keplerian Telescope With a Magnification of 3/5

Note: At this point, dismantle the setup and follow the assembly instructions in Chapter 5.
In theory, it would be possible to install the setup exactly in the sequence described above. However, it turns out that this method is very inaccurate in practice and does not lead to a sharp image on the camera.

6.2. Introductory Tasks



Exercise 4: Adjust the setup according to the instructions in Chapter 5. A lattice (e.g., the g = 15 µm, b = 6 µm lattice in the top row, field F2 in Figure 31) should be visible in the camera image. The Fourier plane should appear sharp on the screen.

Execution: See section 5, subsection 5.4.

Exercise 5: What roles do the irises play? Observe the effect that opening either the field iris or the aperture iris has on the image, the Fourier image, and the illumination of the object.

Execution:

Effect	Action	
	Opening the Field Iris	**Opening the Aperture Iris**
Effects on the Camera Image	Enlarges the visible area in the camera image. If the visible area is as large as or larger than the camera chip, opening the field iris has no further influence on the camera image.	Increases the brightness in the camera image.
Effects on the Illumination of the Target	Enlarges the illuminated area on the target.	Increases the brightness on the target.
Effects on the Fourier Image	Causes larger areas of the structures on the target to be illuminated. This increases the brightness in the Fourier image.	The extent of the intensity maxima in the Fourier image changes because the aperture iris is displayed in the Fourier plane by the Keplerian telescope consisting of the condenser lens and objective lens.

Exercise 6: Select a lattice of your choice in the object plane. Now use a sheet of paper or the screen to find the Fourier plane.

Execution: The Fourier plane is the camera-side focal plane of the objective lens. It is at the distance d = 3 cm from the objective lens. To view the intensity maxima in the Fourier plane separately and with maximum intensity, the aperture iris should be closed and the field iris opened.

Exercise 7: Select the houses as the target, field F10 in Figure 31. Place the screen directly behind the projection lens. Slowly move it away. What do you observe?

Execution: Not too far away from the projection lens, you should see a sharp image of the houses, field F10 in Figure 31. Further away, the image gets less sharp and finally becomes the diffraction pattern until you find the plane where the sharp diffraction pattern can be observed. So the projection lens does not only map the Fourier plane onto the screen, it also maps the image onto a plane close to it. (That's not surprising because that's exactly what the tube lens does for the camera, but it's still noteworthy that the object plane can be observed in the reflected arm as well.)

6.3. Filtering

In the following exercises, we will observe the effect that filters in the Fourier plane have on the camera image. For consistency, we will always show the camera image without the filter first in the upper left image. The corresponding Fourier plane is shown next to it. In subsequent rows, the left side will show the Fourier plane after a mask has been applied, while the image to the right shows the resulting camera image.

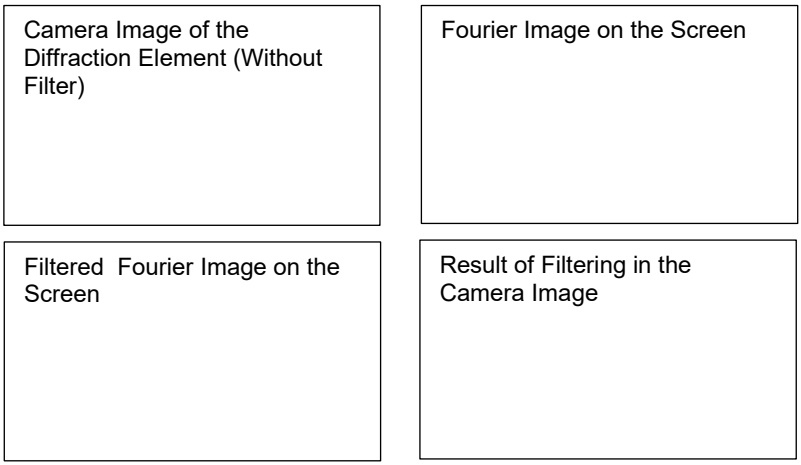
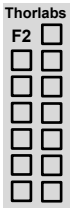


Figure xy



Exercise 8: Position a cross lattice (for instance the cross lattice with 15 µm lattice constant, field F2 in Figure 31) in the object plane and adjust the objective lens if necessary so the camera image is sharp. Position the variable slit in the Fourier plane. Align the central bright spot to the center of the slit in both horizontal and vertical directions. Now adjust it so that light can only pass in a horizontal line along the main maximum. What is the result in the camera/microscope image and why?

Execution: Shift the target with the help of the x-y holder until a cross lattice is visible on the camera. The projection of the Fourier plane can be seen on the screen. Place the adjustable single slit in the Fourier plane behind the objective lens. (**TIP:** (1) The adjustable slit is exactly in the Fourier plane when the projection on the screen shows a sharp image of the slit. (2) Alternatively, one can observe the extent of the intensity maxima on the edges of the single slit.) Slowly close the adjustable single slit until only a horizontal row of intensity maxima is shown on the screen. Now the camera image shows a line lattice with an orientation that is rotated 90° to the orientation of the intensity maxima. The information about lines with different orientations in the lattice was blocked in the Fourier plane by the adjustable single slit. If necessary, you can adjust the brightness by opening or closing the aperture iris.

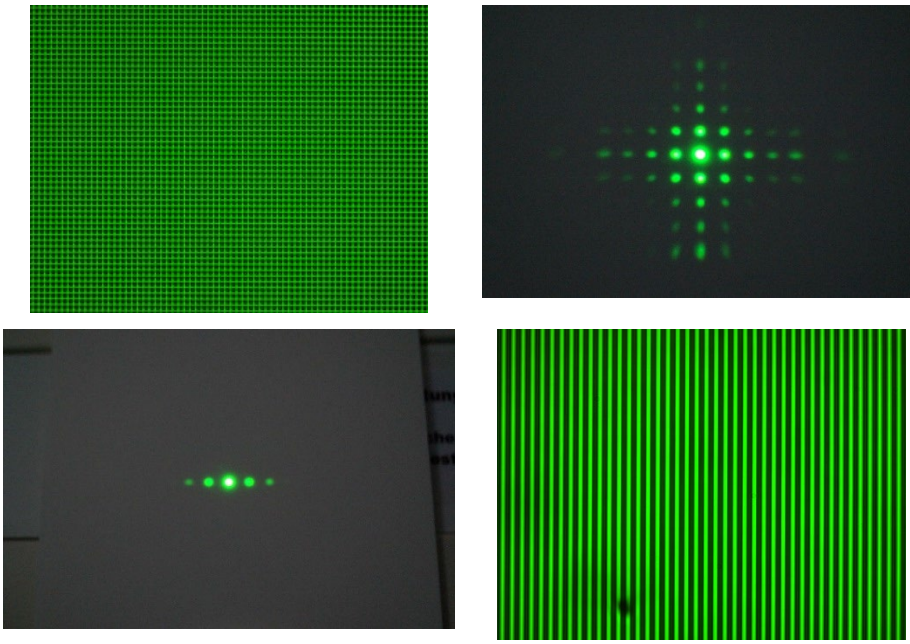


Figure 63: Cross Lattice Filtering 1

Exercise 9: Now turn the slit 90° and once again allow light to pass only along the vertical line of the main maximum. What camera image do you expect?

Execution: The orientation of the visible line lattice on the camera has also rotated 90°. Now the lines are horizontal. If necessary, you can adjust the brightness by opening or closing the aperture iris.

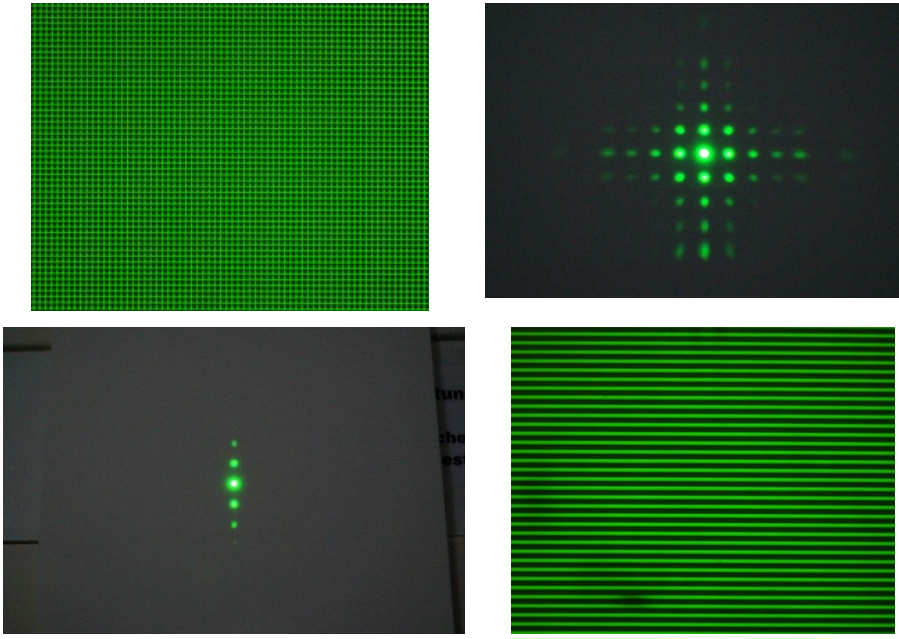


Figure 64: Cross Lattice Filtering 2

Exercise 10: Now rotate the slit to a 45° angle and only let the light of the main maximum and the corresponding diagonal orders pass. What is the resulting image on the camera and why?

Execution: Since all information about lines with a horizontal and vertical orientation is blocked by the adjustable single slit and only the information on a diagonal in the Fourier image passes, the camera image shows a diagonal line lattice rotated by 90° to the slit orientation. You should close the slit further and adjust the brightness by opening or closing the aperture iris if necessary.

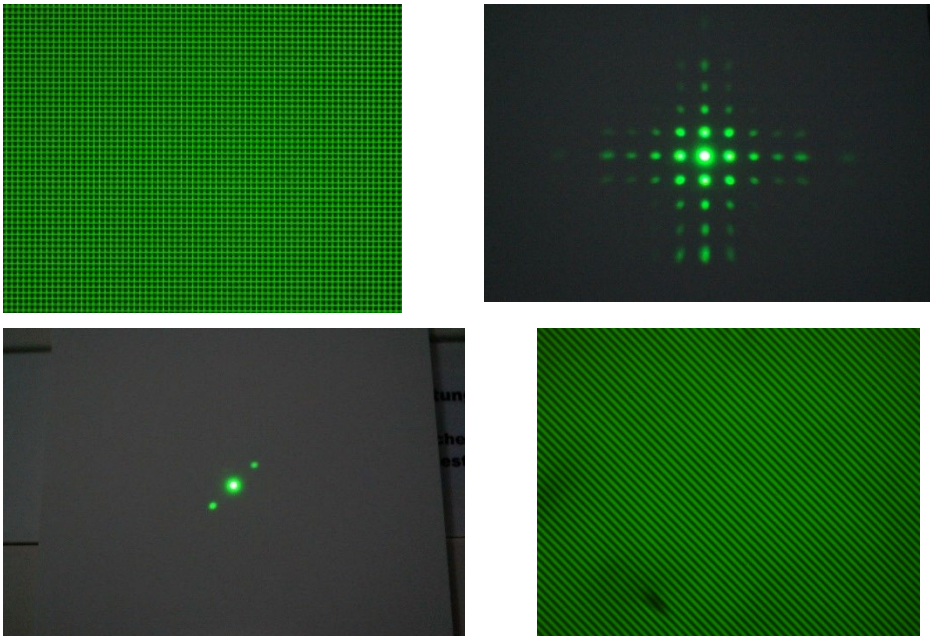


Figure 65: Cross Lattice Filtering 3

Exercise 11: Position the rotated cross lattice (45° tilted, field F6 in Figure 31) in the object plane and, with the variable slit, generate a line lattice on the camera that is not discernible in the structure on the target.

Execution: Examine the rotated cross lattice with the camera. The lattice in question, which is not immediately apparent in the structure, is a vertical line lattice. Turn the adjustable single slit to a horizontal orientation and close it further if necessary. The camera image shows the vertical line lattice in question.

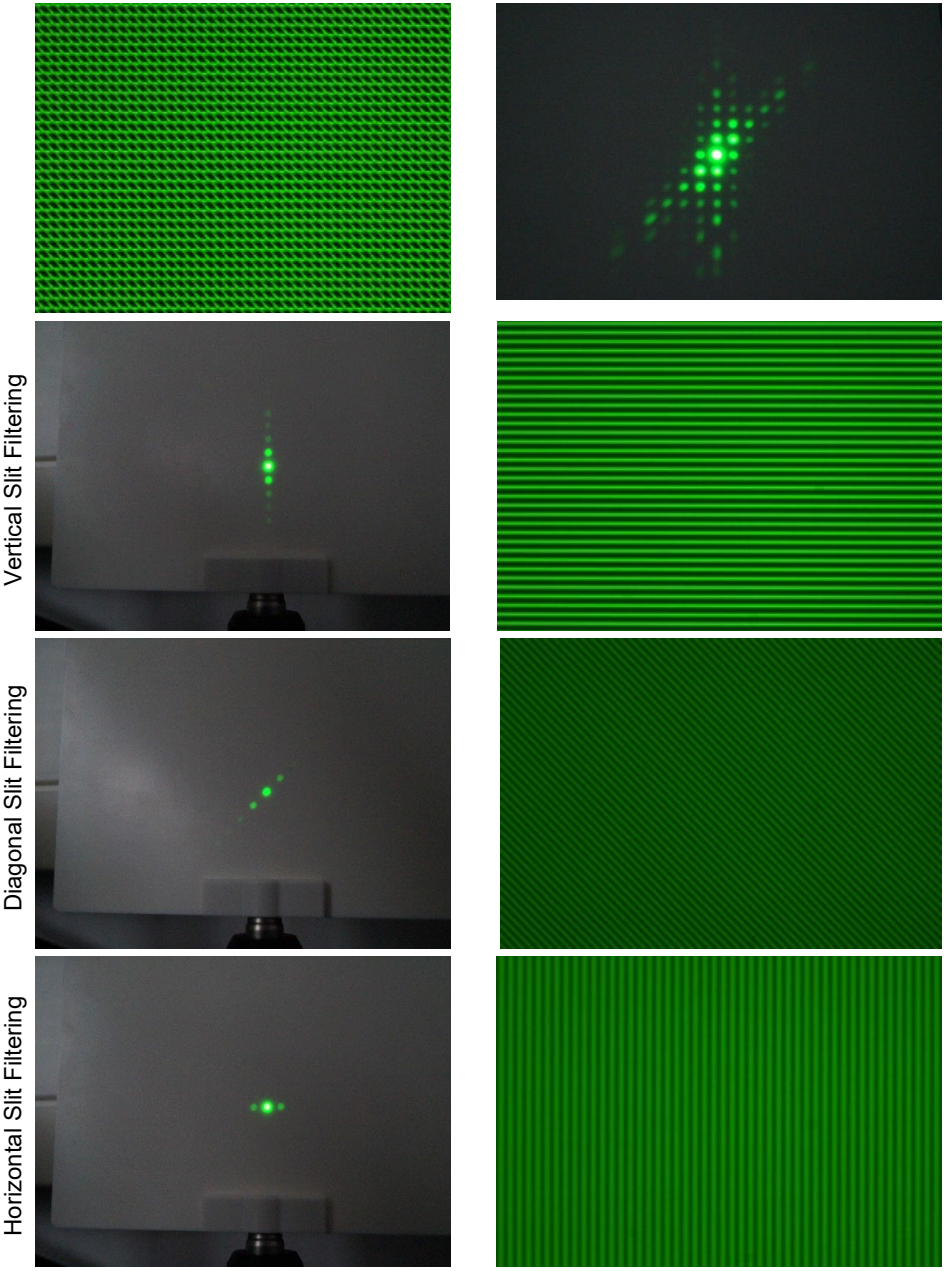


Figure 66: Rotated Cross Lattice Filtering

Exercise 12: Position the star grating in the object plane (field F7 in Figure 31) and adjust the objective lens if necessary so the camera image is sharp. Various line lattices can be generated by placing the variable slit in the Fourier plane and rotating it. Explain how the five line lattices are generated and why their lattice constants are different.

Execution: Since the stars are made up of five lines with different orientations, a maximum of 5 line lattices with different orientations and lattice constants can be displayed. It is discernible with the naked eye that parallel lines of two neighbouring stars are at different distances. This is where the different lattice constants come from. Place the adjustable single slit in the Fourier plane behind the objective lens. Adjust the size of the slit to a fixed value that makes it possible to see a line lattice. Now slowly rotate the single slit by hand and examine the camera image at the same time. If necessary, you can adjust the brightness by opening or closing the aperture iris. Figure 67 shows the 5 lattices of the stars and their different lattice constants.

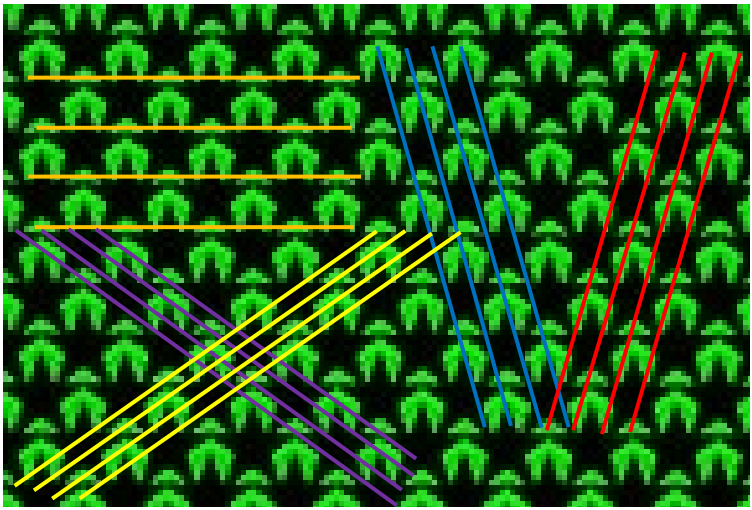


Figure 67: Different Lattice Planes in the Star Pattern

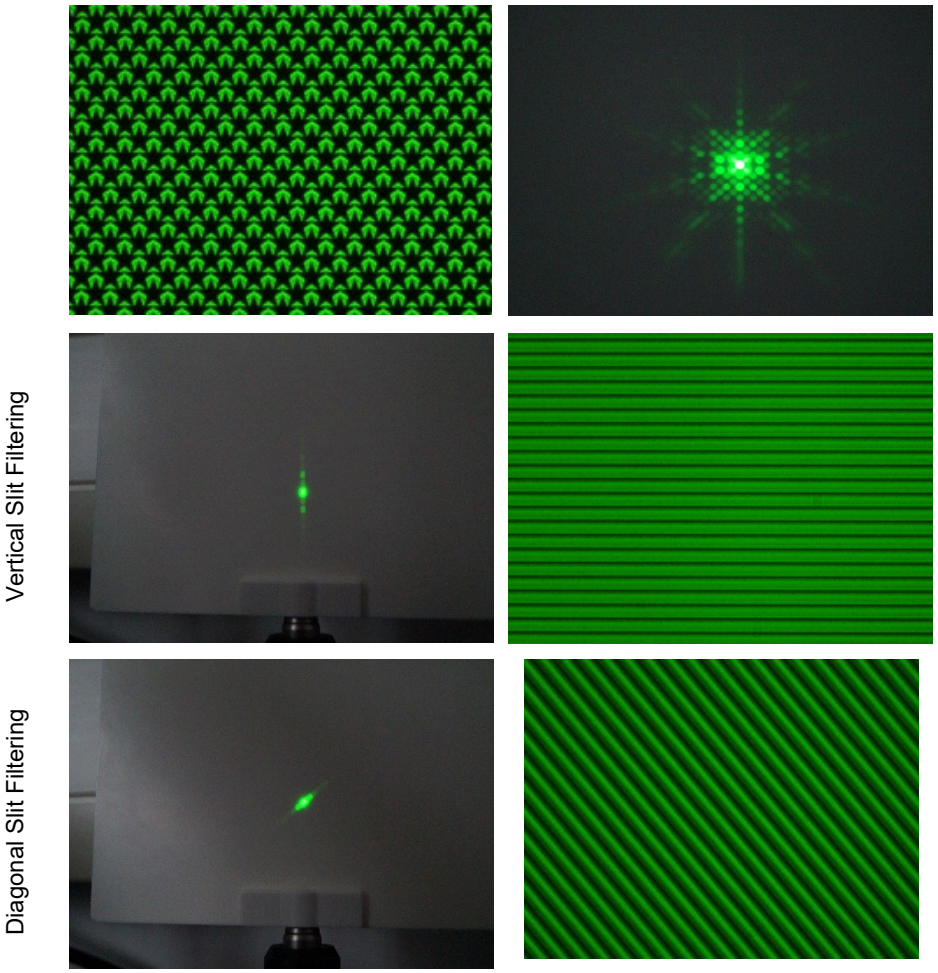
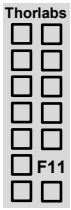


Figure 68: Star Filtering

Exercise 13: Position the point lattice in the object plane (field F11 in Figure 31) and adjust the sharpness with the objective lens if necessary. Place the variable slit in the Fourier plane and rotate it. Also vary the slit width while doing so. What do you observe and why?



Execution: Due to the regularity and symmetry of the point lattice Fourier image, a line lattice can be made visible in almost any orientation. The adjustable single slit has to be rotated in the Fourier plane to do so. The slit width and opening of the aperture iris may have to be adapted to make all line lattices visible.

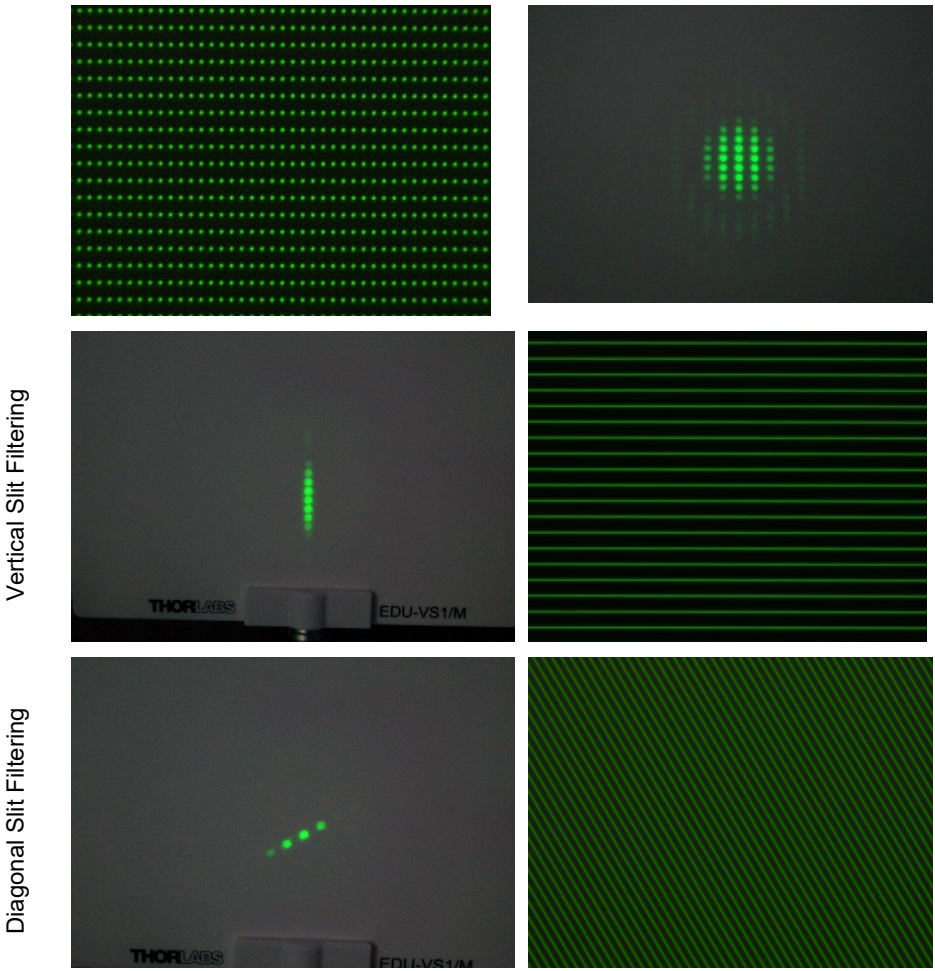
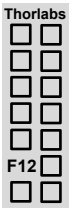


Figure 69: Point Lattice Filtering



Exercise 17: Position the overlapping letters “A” and “B” in the object plane, field F12 in Figure 31. By adjusting the variable slit accordingly, make the lattice structure of one or the other letter disappear. Why is the respective masked letter still slightly visible anyway?

Execution: The Fourier plane shows intensity maxima similar to a cross lattice. By filtering in the horizontal or vertical direction, the lattice structure of one of the two letters can be masked. Nevertheless, the letter remains visible as an evenly illuminated area. The information about the approximate shape of the letters is stored in the main maximum and is not influenced by filtering the lattice maxima.

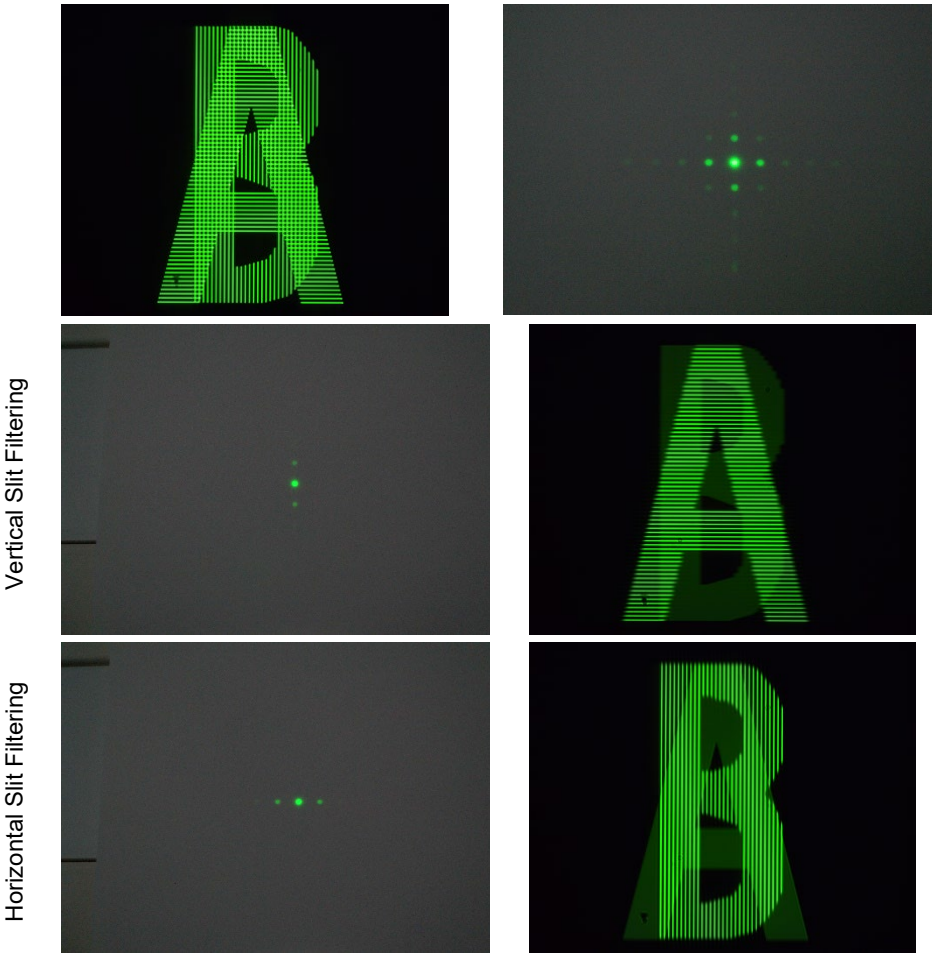


Figure 73: A-B Filtering

Exercise 18: Adjust the variable slit so that only the overlap of the letters “A” and “B” is visible. Which orientation does the resulting lattice have?

Execution: To show the overlap, one needs diffraction orders of both the vertical and the horizontal lattice. The slit needs to be in 45° orientation, and the filtered image will show this:

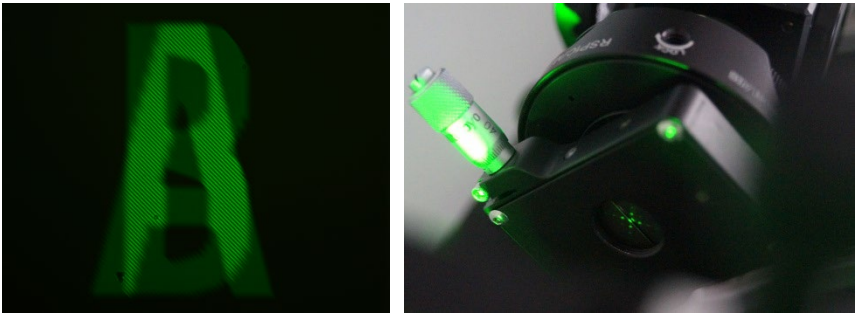


Figure 74: Overlap of “A” and “B” Letter on Left and 45° Slit Orientation on Right

Exercise 19: Position the field with the Fourier house in the object plane (field F10 in Figure 31) and adjust the sharpness if necessary. Now examine the Fourier plane. Rotate the variable slit to block different sections of the diffraction pattern. Find out which orientations change the camera image of the door, the attic, the front of the house, and the chimney, respectively.

Execution: The Fourier image shows intensity maxima of various orientations. Here the horizontal maxima represent the door of the house and the diagonal maxima the chimney. In the vertical direction, two patterns are overlaid with different distances between the maxima. The maxima with small distances between them are assigned to the front of the house, while the maxima with the large distances represent the attic. Different aspects of the Fourier house can be masked by changing the width and orientation of the adjustable single slit.

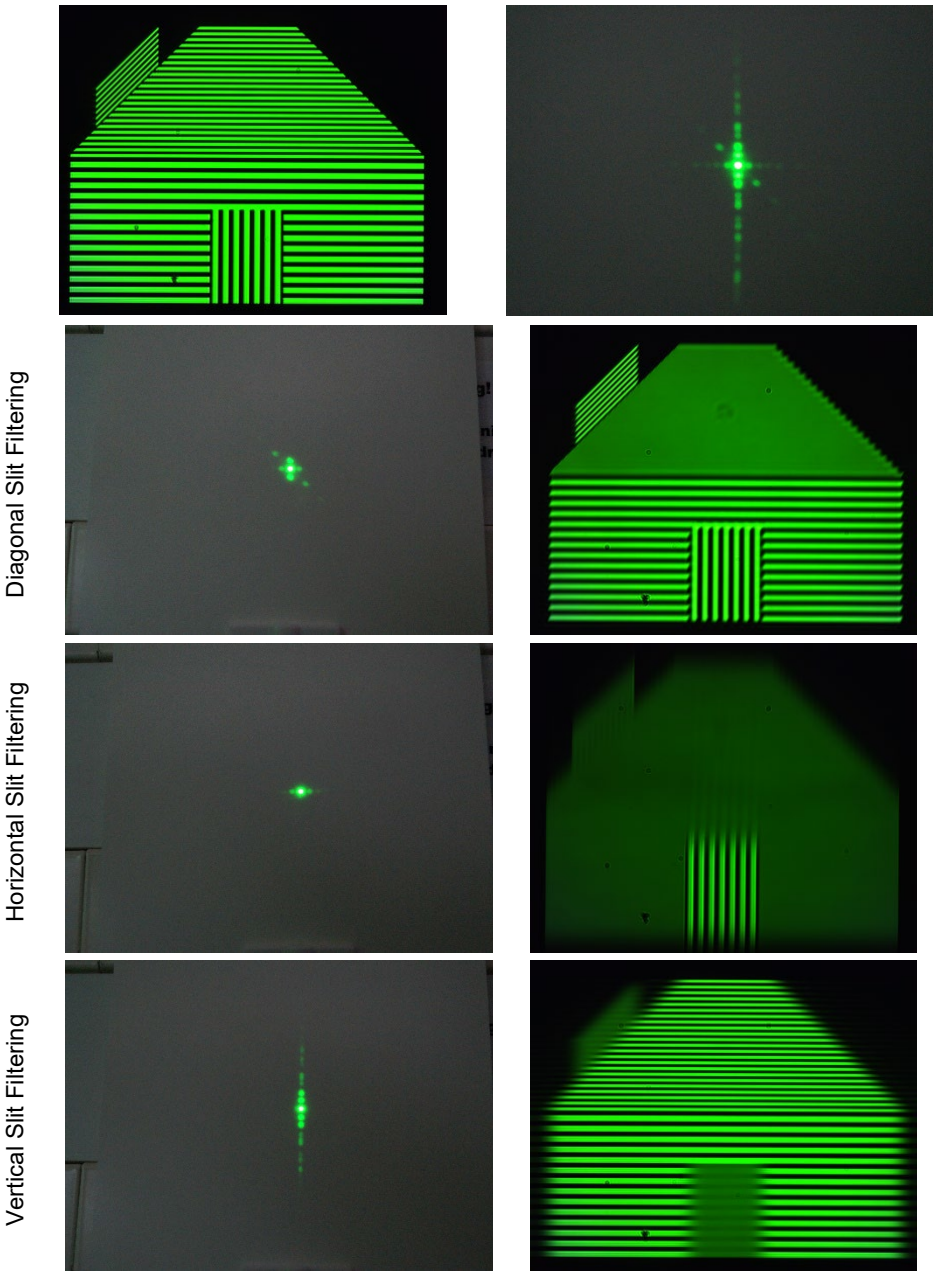


Figure 75: Fourier House Filtering

Exercise 20: Position the line lattice (15 µm lattice constant, field F8 in Figure 31) in the object plane. Replace the variable slit assembly with the EDU-TGC1 mask for cutting [in the second XYF1(/M), see Figure 25 and Figure 32]. Use mask no. 1 on the mask target and filter out every other maximum in the Fourier plane. What do you expect to see on the camera and why?

Execution: Holding a piece of paper onto the surface of the mask helps in finding the Fourier plane. By blocking the maxima of the odd (first, third, fifth, etc.) orders, information about the lattice constant of the line lattice is lost. Only information about a line lattice with double the distance between the intensity maxima reaches the camera. This cuts the lattice constant in half.

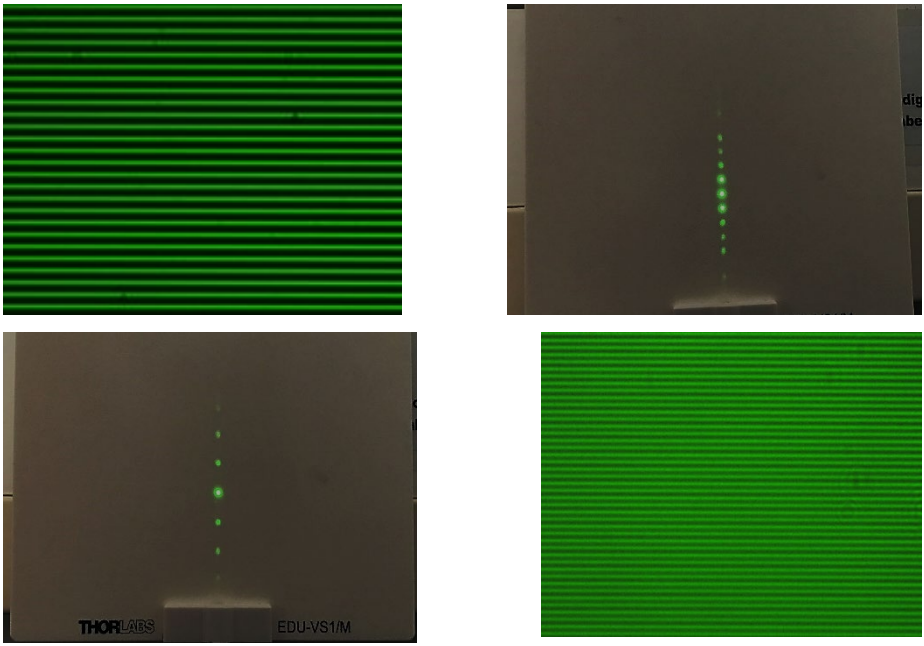


Figure 76: Line Lattice Filtering

6.5. Image Editing

Exercise 26: Select a character on the target and position it in the object plane. First soft-focus the image with the ID12(/M) iris. Fully close the aperture iris.

Execution: By closing the ID12(/M) iris in the Fourier plane, high spatial frequencies that represent fine structures in the image are masked. The low spatial frequencies that represent coarse structures in the image predominate. The image is soft-focused.

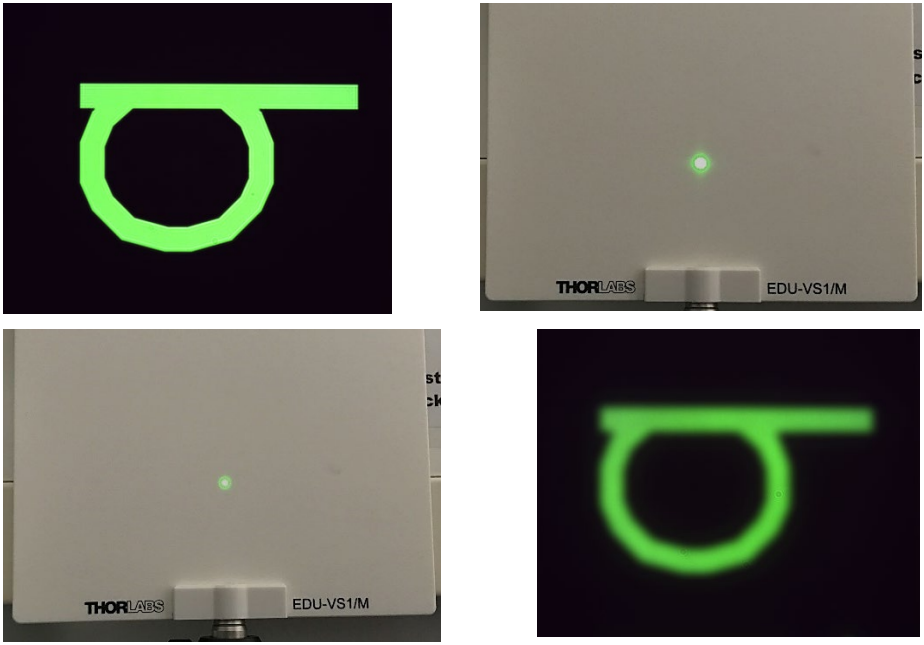


Figure 83: Soft-Focusing Through an Optical Low Pass Filter

Exercise 27: Use the same character as in the previous exercise and highlight the edges.

Execution: The edges of an image can be highlighted by blocking the central spot. The size of the central spot will vary depending on the adjustment of your system. Therefore, you will need to test a few spots on the mask to find one that blocks enough light to achieve the result shown in Figure 84.

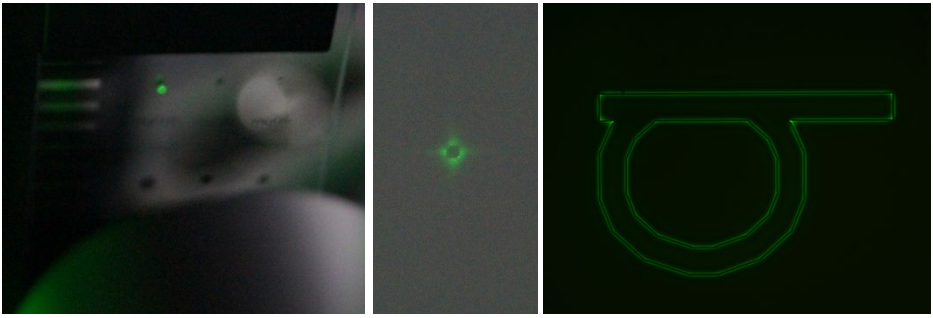


Figure 84: Edge Highlighting

Exercise 28: Now position the diatom slide in the object plane. Bring out the edges of the diatoms in the microscope/camera image by bringing the points on the mask target into the Fourier plane and blocking the central maximum there. Slightly open the aperture iris and regulate the brightness with the LED controller.

Execution: You may have to readjust the aperture iris multiple times to obtain a good result. A lot of patience is required since this effect is easy to miss. A spot on the mask target blocks the low spatial frequencies that represent the coarse structures in the image. The larger the blocking spot in the Fourier plane, the easier it is to see the effect. Make sure you do not mask the Fourier plane entirely. If this is the case, you can rectify it by slightly opening the aperture iris. The high spatial frequencies that represent the fine structures in the image predominate. The image appears sharper overall. Fine structures are more easily discernible. Transparent specimens are very well suited for this.

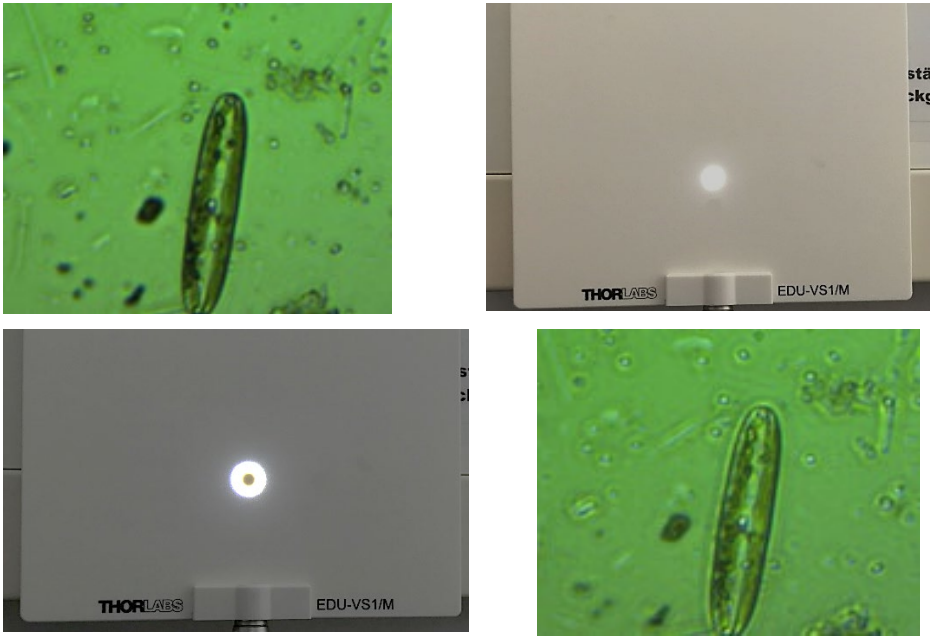


Figure 85: Bringing Out Edges and Increasing Contrast with an Optical High Pass Filter

9.3. Measuring the Diffraction Pattern of a Single Slit

The variable slit is set up for this purpose instead of the target. All optical components behind it can be removed. Now the camera has to be positioned at a distance to the slit so that significant parts of the single slit diffraction pattern lie on the camera chip. Then the image can be sectioned and the intensity profile can be read using the ThorCam software.

9.4. Spectrometer

When the green filter is removed from the LED and an optical lattice with a small lattice spacing is used as the target, the setup can be converted into a simple spectrometer. To do so, remove all optical components behind the lattice and displace the camera so that an entire colored maximum lies on the camera. In addition, the aperture diaphragm should be replaced with a variable slit. When a light source other than the LED is then used, one can analyze the spectrum of the other light source by comparing it with the LED spectrum.

9.5. Slide Projector

With a suitable selection of lenses, the lattice can be projected onto a wall behind the setup. To do so, place the lattice in front of the LED and remove all other optical components. Now the lattice can be displayed on the wall with two carefully positioned lenses.

9.6. Darkfield Microscopy

With the microscope in this kit, it is also possible to perform darkfield microscopy. The image produced by this microscopy method is distinguished by a dark background with illuminated sample details. It is necessary that all undiffracted background light is blocked in the Fourier plane. To do so, remove the target from the object plane between condenser and objective lens and block all light in the Fourier plane behind the objective lens with a spot from the mask target. It is advisable to use one of the largest spots on the mask target and open the aperture diaphragm until the spot is fully illuminated. To check the illumination, look at the screen behind the projection lens. Position the diatom sample in the object plane between condenser and objective lens so that you get a sharp image on the camera. The camera image shows illuminated diatoms on a dark background like in Figure 97. Undiffracted light (background light) is blocked by the spot while diffracted light from the diatoms (object light) passes the Fourier plane.

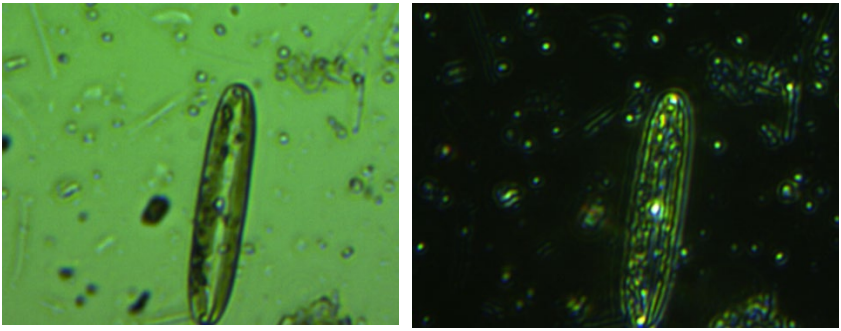


Figure 97: Diatom sample shown with brightfield microscopy on the left and darkfield microscopy on the right.

Generally, darkfield microscopy is performed with a ring aperture in front of the condenser lens and a ring mask in the Fourier plane. The dimensions of the necessary ring aperture and ring mask for the Fourier setup are shown in Figure 98. We tested the ring aperture and ring mask printed on a photographic slide, but the results were not as good as the results using the ID12(/M) iris and a spot from the mask target. This was mainly due to the low printing quality of the black areas on the slide with the ring aperture and mask.

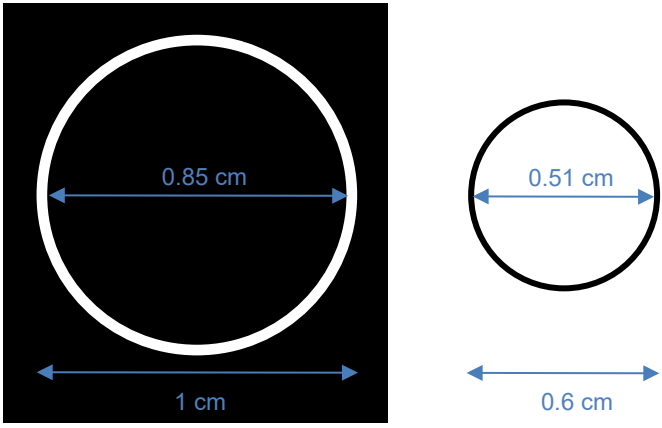


Figure 98: Dimensions of the ring aperture and the ring mask.

Have you performed other experiments with the parts in this kit? Let us know by contacting techsupport@thorlabs.com and we'll add them to the manual!

Chapter 7 Condensed Setup Instructions

1. Set all components to a height of 10 cm using the LMR1AP alignment plate (measured from the center of the optical element to the breadboard).
2. Place the camera at the right end of the breadboard (4th hole line) and place the tube lens (f = 150 mm) approximately 150 mm from the camera chip. Get a sharp camera image of an object that is more than 4 meters away.
3. Aim the LED at a wall or the ceiling and use the variable lens tube to position the collector lens so that you can see the LED chip (a pattern of black spots). Place the LED 100 cm away from the camera (post-to-post distance).
4. Place the objective lens (f = 30 mm) 18 to 20 cm away from the tube lens, measured from the center of the lenses.
5. Move the target up to the highest possible position by turning the height adjustment screw clockwise. Adjust the post's height so that the sector star (lowest row on the target, field F14 in Figure 31) has the same height as your optical axis (10 cm). Place the target approximately 2 cm away from the objective lens mount. Move the target until you obtain a sharp image of the sector star in the camera (fine adjustment may be done by rotating the objective lens' mount). Move the target downward until you see the center house of the arrangement of nine houses, field F10 in Figure 31.
6. Place the condenser lens (f = 50 mm) 50 mm away from the target (measured approx. from the center of the lens). Place the condenser lens to achieve the smallest spot size on the target. Make sure the center house is illuminated (otherwise change condenser lens height).
7. Place the closed aperture iris [the smaller one, ID12(/M)] approximately 50 mm away from the condenser lens. The iris' shadow should be centered on the condenser lens mount.
8. Place the field lens (f = 150 mm) approximately 150 mm away from the aperture iris. Move the field lens until you see the LED chip on the iris.
9. Place the almost fully closed field iris at approximately 150 mm distance to the field lens. Move back and forth until you see an image of the iris' edge on the camera (hard to see, mainly just a deviation from the round shape).
10. Place the color filter directly in front of the LED
11. Open the field iris (about 3/4). Place the beamsplitter approximately 8 cm away from the objective lens.
12. Position the projection lens (f = 75 mm) directly behind the beam splitter (at 90° with respect to the main beam path). Use the screen to find the distance where you see a sharp image of the Fourier plane.
13. Observe the aperture iris' side that's facing the target. When the target is not perpendicular to the beam, you will get reflections that are off-center.

Chapter 8 Troubleshooting

- **The PC does not recognize the camera.**
  Unplug the camera from the PC and test different USB ports. Wait until the device is recognized by the PC.
- **No camera image is visible.**
  Select a structure and make sure you do not close the field iris completely. Furthermore, the beamsplitter should be positioned so its holder is not illuminated. If this does not eliminate the problem, it may be that the condenser lens is illuminating a different spot on the target than what is displayed on the camera by the combination of the objective lens and tube lens. Remove the field lens from the setup and adjust the condenser lens so that the camera displays an image.
- **The camera image is distorted.**
  Distortion of the camera image usually indicates that a lens is not in linear alignment with the other lenses. In most cases, this is the objective lens or tube lens. Always ensure the setup is aligned along a single optic axis. Otherwise the target may also be out of alignment. Examine the reflection of the target on the side of the aperture iris facing the target. Turn the target so that the reflection lies in the opening of the iris as exactly as possible.
- **The camera image cannot be sharpened.**
  Check the alignment of the target in the objective lens.
- **Interfering reflections are visible in the Fourier image.**
  The aperture diaphragm may be sitting too high and should be adjusted. Without the field lens, the condenser lens and its holder should be evenly covered by the iris' shadow. Check that the target is perpendicular to the optical axis.
- **Intensity maxima that do not match the chosen structure are visible in the Fourier image.**
  Make sure that the illuminated section of the target covers only one field of the target. If the illuminated area is larger than a field of the target, the size of the illuminated area can be corrected by adjusting the field iris.
- **The light spot on the target is not round.**
  The field diaphragm or the field lens is in the wrong position. Try to adjust the height of the field diaphragm and the field lens.
- **The Fourier plane is too close to the objective lens.**
  Make sure you have chosen the right orientation of the lens in the mount and of the mount itself.
- **The camera image flickers in various colors.**
  Open the camera settings and, on the "Image" tab, uncheck "Auto White Balance". Then set the controls for red, green, and blue back to 0.

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