Laboratorieøvelse TFY4195 Optikk, Institutt for fysikk, NTNU - English version, ver 3.
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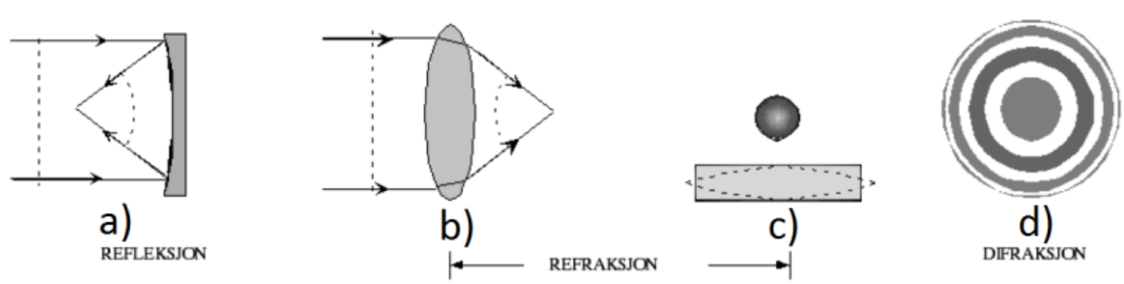
Lab exercise 1. Lenses and imaging

Preparation

- Register to a lab-session following instructions posted on BB.
- Read chapters 2 and 18 in Pedrotti and use as reference (Ch3 is also good). These chapters will be discussed during lectures the weeks 35 and 36 (Ch 3 week37).
- Read carefully all the instructions (this lab manual) beforehand to be prepared.
- Set up and solve relevant ray-transfer matrix according to section 2.
- Solve problems in section 4.

1. Measurements of focal length and determination of principal planes

In order to image an object that emits or scatters light it is required an optical element that collects the light at some point at the object and then transfer and reconstruct it at the corresponding point in the image plane. This can be accomplished with a curved mirror, Figure 1a), where the surface is spherical, ellipsoid, or similar. The most common imaging system is by lenses or light refraction in curved surfaces, , Figure 1b). To obtain the lens effect the thickness of the object is varied, but it is also possible to have an element with constant thickness and change the refractive index, Figure 1c). It is also possible to image through diffraction/phase-plates, such as in Figure 1d). The curvature of the surfaces and refractive index is crucial for the optical quality. Also, there is *dispersion* i.e, the refractive index depends on wavelength, and more advanced imaging systems contains several elements in conjunction, where the different material parameters can be used to improve the negative effects from e.g. dispersion.



Figur 1: Principles for optical imaging. a) Reflection, b) refraction with lens where thickness is varied, c) refraction by changing the refractive index distribution, d) zone-plate (combines diffraction and phase changes.

Commonly the lenses can be positive or negative depending on how they spread a planar wave-front. The positive lens will collect light into a focal point in the image plane. The negative lens will spread the light as originating from a virtual focal point in the object plane. Usually, light is coming in from the left (the object side/plane) and emerges at the right side, the image side/plane. Sign conventions (as we studied in Pedrotti Ch 2) are then used to keep track on the various situations.

In this exercise, we will study the most common type of glass lenses, where the refractive index is constant and the thickness varies, giving the lens a spherical surface. Such surfaces can be combined in different ways to give positive or negative focal lengths, as shown in figure 2. In addition to the diameter of the lens, the focal length with both *sign* and *magnitude* is the most important parameter when characterizing an imaging system. For thin, positive lenses measuring the focal length with good accuracy is straightforward. The most common method is to send a plane wave (collimated light) through the lens and determine where the light is most concentrated. Plane waves corresponds to an object at infinity, but in practice we will have to do with an object reasonably far away – the assumption of infinite object distance when placing the object a few meters from the lens leads to errors which are usually significantly smaller than the read-off error for the focal lengths we usually work with. Alternatively, we can image an object at a given distance, and use the thin lens equation to calculate the focal length.

Measuring the focal length of negative lenses is more complicated, due to the fact that the focal point is placed in front of the lens (virtual image) relative to the travel direction of the light. Therefore, we cannot determine the position of the focal point by placing a screen there. Most used methods to measure the focal length of diverging lenses are therefore based on combining the negative lens with a converging lens with known focal length. In this way the imaging system gives a real image.

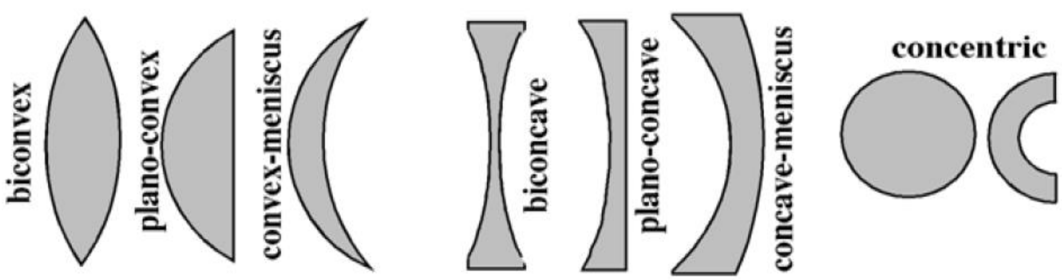


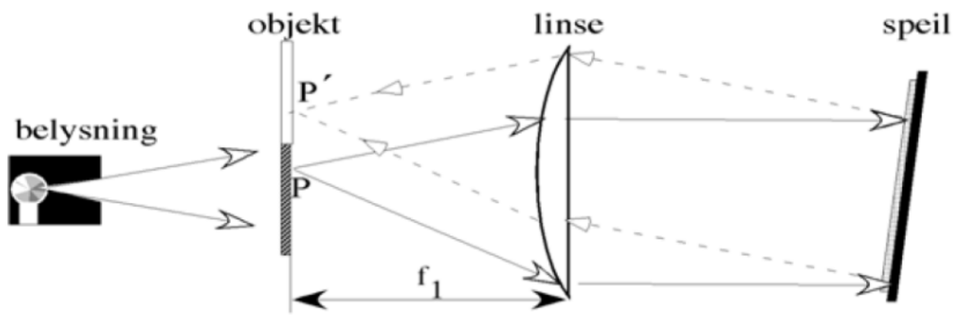
Figure 2: Different types of lenses based on spherical surfaces.

In this exercise we will first determine focal lengths of a positive and negative lens by using different imaging techniques. Then several lenses will be combined into an optical system and we will determine the principal planes from an angle measurement. It will be assumed we are dealing with so called ‘thin lenses’ with the principal planes in the center of the individual lens components.

1.1 Positive lens L_1

The measurement technique is based on the focusing of a plane wave incoming from the object side. However, in most optical systems we can reverse the rays using a mirror, and obtain a similar light path. We recall that rays emerging from a point source (spherical waves) in the focal plane will become parallel after traversing the lens. The technical arrangement is shown in Figure 3. As the object, a transparent image is placed on an optical rail, with a light source behind. A planar mirror is placed behind the lens (right side) where the angle is slightly tilted with respect to the transversal plane. Thus, by adjusting the lens and the mirror we can obtain an image on the opaque region beside the transparency since the rays are incoming essentially parallel at the mirror. Conclusively, this image situation requires that the object is in the focal plane and we will find the focal length f_1 by reading the distance with a ruler. N.b., the mirror can be at any distance behind the lens but if the distance is too large only a part of the object will be imaged.

- **What is the focal length of the blue lens (L_1)?**



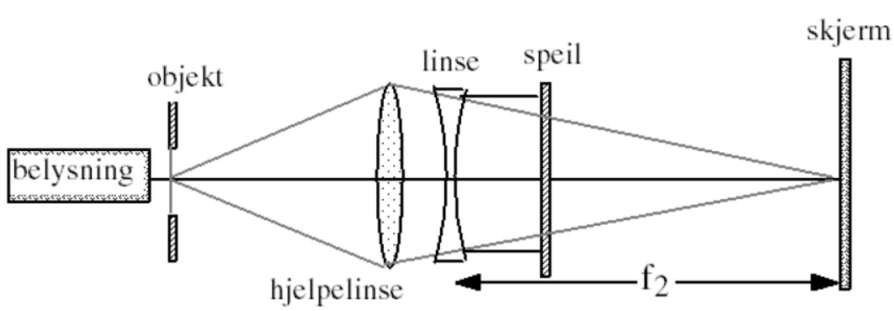
Figur 3: Positiv linse L_1.

Take some time to use this arrangement to investigate the occurrence of images, virtual images, and other phenomena that can be thin lens law and transversal magnification.

- **Remove the mirror after having determined the focal length and study the image behind the lens. Where is the image? Is it changing depending on what point you are looking from (real or virtual image?)**
- **Move the lens and investigate the transition from real to virtual image. Verify the typical regions of position of the object (so > 2f; = 2f, < f, etc. How can you see the virtual image?**
- **Use the thin lens equation to verify the thin lens equation by measuring the distance between the object and the lens for the determined focal length.**

1.2 Negative lens L_2

Here an alternative arrangement is used, see Figure 4. The lens L_1 with known focal length is used as a 'reference' to bend the wavefront and is placed in front of the negative lens L_2. The mirror is placed behind the negative lens.



Figur 4: Measuring focal length of negative lens L_2.

The principle of ray-tracing through the negative lens is shown in Figure 5. A planar wave front emerges as if it originated as a point source (focal point) from the left of the lens. The position of this virtual focal point defines the focal length (but with negative sign).

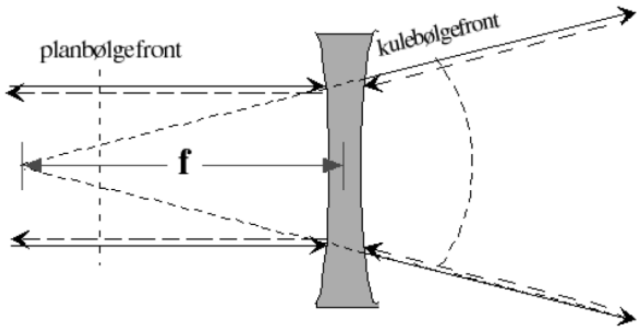


Figure 5: Refraction by negative lens.

By introducing the reference lens (at a distance longer than its focal length) the wavefront towards the mirror will be focused. By introducing the negative lens at the appropriate position the wavefront after the negative lens will again be parallel, giving an image as this planar wave is reflected by the mirror.

Procedure

Move the lenses and the mirror until you see the image. When this is found you note the position of the negative lens. Remove then the negative lens and find the position of the image from the positive lens. Hereby you can determine the focal length of the negative lens.

Thus, the focal length f_2 of the lens L_2 is thereby the same as the distance between the image screen and the position the negative lens was placed before it was removed.

- **What is the focal length of (L_2)?**

2. Imaging

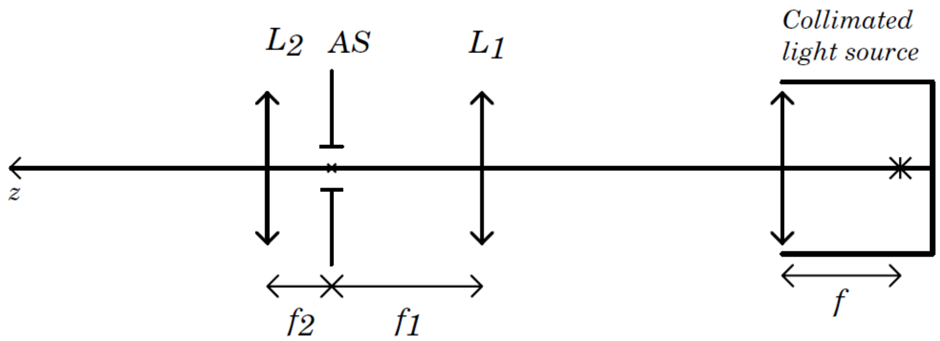
In this experiment we will use to achromatic lenses L_1 og L_2 with focal lengths f_1 = 25 cm and f_2 = 7.5 cm, a variable pin-hole, a collimated light source and a CCD camera connected to a computer. The CCD have a sensor area of 6.6 × 5.3 mm^2 and can be controlled via the software *Ueye* installed on the computer.

2.1 Imaging with one lens

Use one of the lenses to make an image of *suitable size*. Save this on the computer.

- **Check the thin lens law, ok?**

2.2 Telescopic imaging



Figur 6: Teleskopoppsett.

Place the lenses L_1 and L_2 so that the focal points coincide. The distance between the lenses is now $L = f_1 + f_2$, see Figure 6.

- **Show that the beam emerging from the optical system is well collimated at the output. (the system is *afocal*, like a telescope!).**
- **By placing a pin-hole in the common focal point of lenses L_1 and L_2, show that the beam is even better collimated Why?**
- **Determine the paraxial ray transfer matrix for the system (preparation) for the system from input at L_1 to output at L_2!**
  What is the focal length ($-1/f$ is matrix element a_{12}) and the «refractive power» (D) of the system?

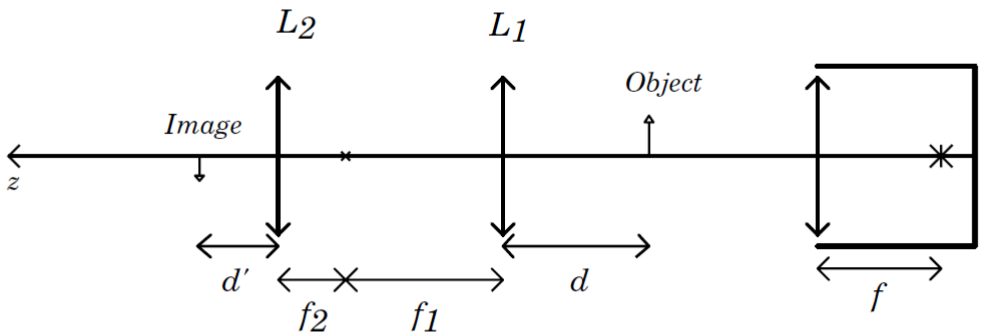
In Figure 7 we use the system to image an object. Determine the ray transfer matrix from the object plane to the image plane (as we discussed on the lecture). For imaging one of the matrix elements must be zero. Show that the classic **Show that the classical 4*f* system, where $d = f_1$ og $d' = f_2$ fulfills this criteria.**

- **What is the transversal magnification of the system (M_T)?**
- **What is the angular magnification of the system (M_α)?**
- **Where are the principal planes?**

Arrange this system (without pin-hole) and record the image with the CCD chip.

- **Verify the magnification *M*.**

Move the object to $d = 2f_1$ (no pin-hole).Find the new camera position for imaging, verify from ray transfer calculations. Check what happens when the object is moved in and out of the imaging condition.



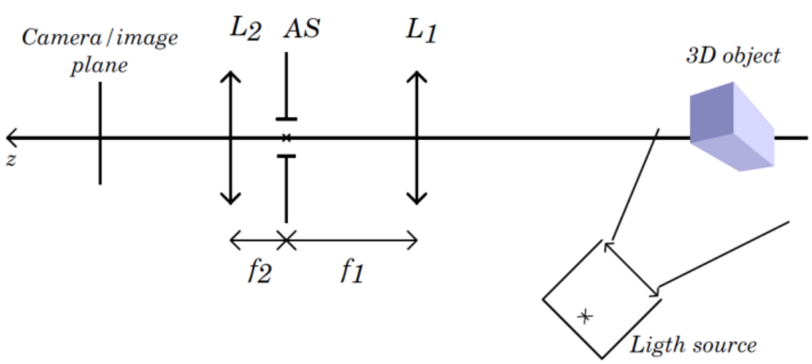
Figur 7: Imaging with telescopic system.

2.3 Telecentric imaging

By putting a pin-hole in the focal point of the systems you will establish a telecentric imaging system (use a variable pin-hole).

- **Where is the in- and out-pupil of the system?**
- **What happens when the object is moved back and forth (try with different size on the pin-hole)?**
- **What can this system be used for, what are the advantages and disadvantages?**

2.4 Optical illusion



Figur 8: Setup to create an optical illusion.

Create an optical illusion by using the telecentric imaging system. Image a 3D object with suitable illumination, see Figure 8. Save an image of the illusion.

3. Microscope

Prepare a microscope using two positive lenses (check in Pedrotti/lecture notes how it is arranged). Here one lens is used to first create a real image between the two lenses. The second lens is then used as an eyepiece (forstørrelsesglass) in order to magnify the real image created by the first lens. Hint: Use the lens with the shortest focal length as ‘objective’. You will find examples of microscope set-up in Pedrotti Ch 3.

4. Problems to solve beforehand as preparation

a) An object will be images through two thin lenses both with focal length f = 100 mm. The two lenses are placed with the distance d = 270 mm between. Where is the image when the object is placed s_0 = 300 mm in front of the first lens? What is the magnification? Describe the image (inverted, real, etc?) (The problem can be solved in several ways: 1) thin lens law step-by-step. 2) By using a compound focal length and principal planes, and 3) ray transfer matrix.)

b) A positive lens (f_1 = 150 mm) and a negative lens (f_2 = -150 mm) are used as an optical system with the distance d = 100 mm between. Calculate the effective focal length. Find the principal planes (See Hecht Chapters 6.1-6.2). Make a Figure with the ray tracing through the lenses. (scale 1:5) for imaging of an object s_0 = 500 mm in front of the first lens. Show the principal planes and show that the same imaging ray tracing can be constructed from this. Calculate the image plane using the lens formula with all distances related to the principal planes.