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Abstract

The making of microscope devices using inexpensive or recovered materials is demonstrated. Examples of images illustrating the performance of such devices are presented. As a project at the undergraduate level, the task is effective in acquiring familiarity with optical imaging concepts and their practical implementation in the laboratory.

Introduction

A classic subject that is treated in almost every optics course is the description of the microscope: the working principle is explained, magnification and resolution are discussed, and major issues on its use are presented. As to laboratory activity, however, the microscope is often taken as an already engineered instrument, so any feeling for its basic set-up and the functioning of its constituent parts is missing. In this respect, making a demonstrative device, putting together the optical and mechanical parts, and looking at its performance under different working conditions, is of great educational value. A simple though effective microscope assembly can be made with inexpensive or otherwise discarded materials. As part of a project aimed at extending the knowledge of practical optics at undergraduate level, here we briefly review the basics of microscope imaging, and then show in detail how to make a simple instrument with readily available materials. Examples of the images produced with such devices are also presented.

Basic optical layout and imaging properties of a microscope

Microscopes are optical instruments used in observing minute details of sample objects. Thorough descriptions of their optical layout and imaging properties can be found in optics chapters of physics textbooks [1, 2], in standard optics textbooks [3] and in technical literature [4]. For the purpose of quick reference, here we briefly review the basic concepts that are involved in laboratory work. In particular, we refer to the so-called 'compound' microscope, made of two main lenses: the objective and the eye lens (figure 1). The objective is a short focal length lens (typically shorter than 40 mm) that makes a real image of the sample object; such an image is called 'intermediate', and it is magnified and inverted with respect to the object. The eye lens is also a short focal length lens (typically a few centimetres focal length) that is used to look at the intermediate image. We indicate by f_o the focal length of the objective, and by f_e that of the eye lens.

As regards magnification, the objective provides a factor m_o given by

$$m_o = \frac{d_i}{d_o}, \qquad (1)$$

where d_o and d_i are the conjugate distances of the object and the image from the lens, respectively. In turn, the eye lens provides a factor m_e that is conventionally expressed by

$$m_e = \frac{25\ \text{(cm)}}{f_e\ \text{(cm)}}. \qquad (2)$$

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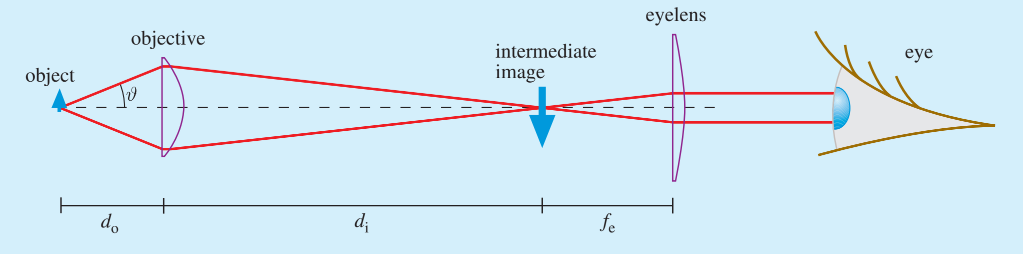

Figure 1. Optical layout of a basic compound microscope.

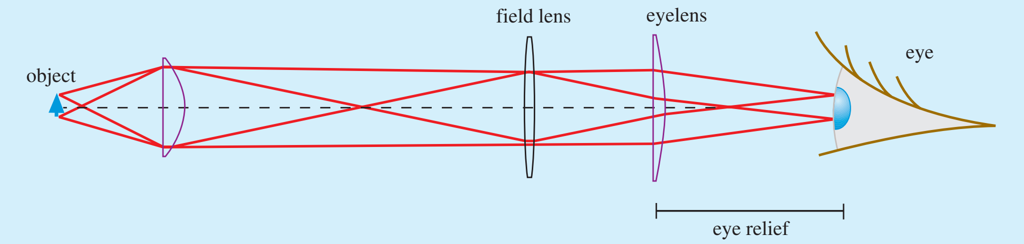

Figure 2. Optical layout of a compound microscope with field lens.

The overall magnification m of the microscope is given by the product of the above factors:

$$m = m_o m_e. \tag{3}$$

For example, with $m_o = 20$, $m_e = 5$, one obtains $m = 100$.

As regards resolution, the size a of the smallest detail that can be viewed under ideal imaging conditions (i.e., in the absence of aberrations) depends on the angular aperture of the objective according to

$$a = 1.22\frac{\lambda}{2n\sin\theta}, \tag{4}$$

where λ is the wavelength of light, n is the refractive index of the medium between the sample and the objective (in air, with 'dry' objectives, $n = 1$), and θ is the semi-aperture angle; the quantity $n\sin\theta$ is the so-called 'numerical aperture' (NA) of the objective. The eye lens usually only affects resolution by a negligible amount. As an example, with NA $= 0.1$, $\lambda = 0.55$ μm (centre of the visible spectrum), $a = 3.4$ μm.

In addition to the objective and the eye lenses, and generally presented in connection with the eye lens itself, a third lens is often used, the 'field' lens, located in the vicinity of the intermediate image. The function of such a lens is to match the aperture of the instrument to the eye of the observer, also increasing the extent of the intermediate image that can be viewed (figure 2). In practice, the exit light beam narrows to a waist (the 'exit pupil'), to which the eye can approach to receive light from the entire field of view.

The distance between the eye lens and the exit pupil is the 'eye relief'; for easy observation, such a distance should be at least one centimetre. Computer simulations show that, under customary working conditions, for comfortable observation the focal length of the field lens should be somewhat longer than that of the eye lens.

Making an essential microscope

A basic microscope with no field lens can be made with a very limited budget by making use of simple items such as those listed in table 1. However, short focal length lenses can be difficult to provide, unless one refers to optics catalogues or to optical workshops. Fortunately, a good and low-cost source is offered by single-use disposable cameras: by dismantling a pair of such cameras after use, one can recover two plastic lenses of

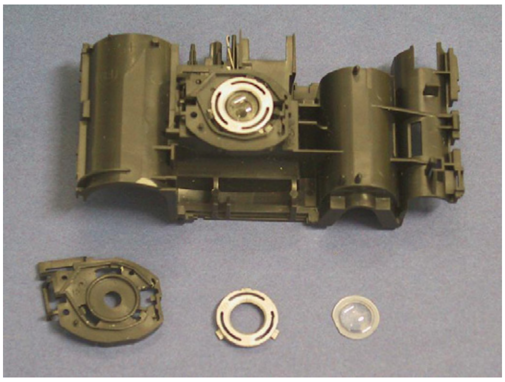

Figure 3. Dismantling a single-use disposable camera to recover the objective lens.

Table 1. Optical and mechanical components needed to make the microscope device described below.

2×	lenses, focal length 3.3 cm
2×	washers, diameter 1.7 cm
1×	black paper diaphragm, 1.7 cm diameter with central opening 0.4 cm diameter
1×	plastic tube, length 16.5 cm, inner diameter 1.8 cm
1×	black paper sheet, 16×5.6 cm^2
1×	wooden board, $14 \times 14 \times 1$ cm^3
2×	wooden slats, $15 \times 3 \times 1$ cm^3
4×	screws, wood type, length 2 cm
1×	foldable plastic sheet 14×5 cm^2
Plus a small quantity of sticky tac.	

reasonably good quality (the objectives) that can serve as the microscope objective and the eye lens (figure 3). Typical focal lengths are of the order of 3.3 cm; the magnification of the eye lens is then $m_e \approx 7.6$. So as to avoid a very poor and dark image, the magnification of the objective should be maintained at a low value, for example $m_o \approx 3$, which produces an overall magnification $m \approx 23$ (most commercial demonstrative microscopes do not exceed $m \approx 10$). Using the lens equation [5], and also imposing the conditions $f_o = 3.3$ cm, $d_i/d_o = 3$, it is found $d_i = 4f_o = 13.2$ cm; since in our case $f_e = f_o$, the tube length should be then $d_i + f_e = 16.5$ cm. The distance between the sample and the objective (the 'working distance') is $d_o = 4.4$ cm.

To reduce the aberrations (mainly colour and spherical aberration) the aperture of the objective needs to be reduced. We used a diaphragm cut from a sheet of black paper, with a central hole of 0.4 cm in diameter; alternatively, the mounting—and the stop—of the disposable camera can also be adapted. Referring to the diameter above, and to the working distance $d_o = d_i/3 = 4.4$ cm, we compute $\theta = 2.6°$. Under ideal conditions, according to equation (4) the size a of the smallest detail that can be viewed is then approximately 15 μm.

Figure 4. Essential microscope set-up with two recovered lenses from single-use disposable cameras. The object is a dry leaf. Illumination is from ambient light.

The tube we used is a piece of plastic conduit commonly used in electrical wiring, 1.8 cm inner and 2.0 cm outer diameter. A piece of matt black paper, rolled up into a cylindrical shape, is inserted into the tube to absorb stray light. The lenses are mounted with the help of two metal washers 1.7 cm in diameter, and some Plasticine or sticky tac (the latter is a removable gum-like material that is commonly used in place of pins to post notes on boards; it is advantageous here because it does not make the lens dirty) [6]. To keep the aberrations under control, care has to be taken to properly mount the lenses as shown schematically in figure 1, respecting their orientation.

As regards the vertical placement, a stand was made with a wooden base and a pillar. The tube was loosely secured to the pillar by means of a folded plastic sheet. Moving the tube up and down to focus was done by hand, gently making it slide through the folded plastic sheet. The overall set-up is shown in figure 4. A typical image obtained from a sample object (a bar resolution target) is

Figure 5. Pattern from a bar resolution target observed with the microscope device in figure 4. The third pattern from the top on the left corresponds to a 15.8 μm period, and the fourth to a 20.0 μm period (see footnote 2).

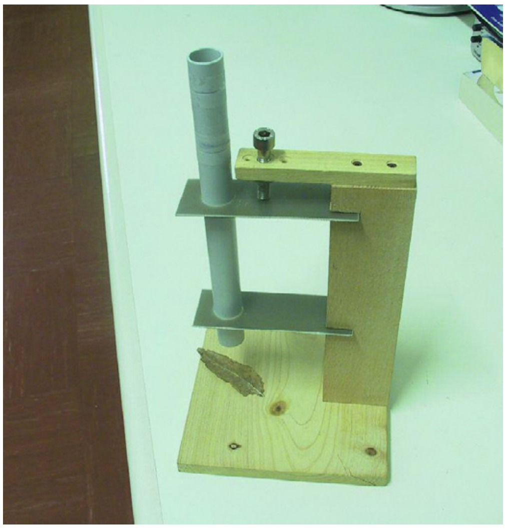

Figure 6. A microscope device with a field lens and screw-controlled focusing mechanism.

shown in figure 5. It is noted that the actual resolution that is achieved at the centre of the field of view is of the order of 16 μm, (the third pattern from the top in figure 5 corresponds to 15.8 μm period[2]).

The field of view, measured using a stage micrometer as the object [7], is approximately 1.5 mm; illumination is, however, uneven (the centre is brighter than the edge). Also, pin-cushion distortion is noticeable. The device can be used to observe minute details of sample objects such as leaves, crystal powders (salt), and so forth.

Further improvements with a field lens

Budget permitting, a somewhat more sophisticated version of the microscope including a field lens can be set up. We made a second device with glass lenses available in the laboratory. The measured focal lengths are $f_o = f_e = 4.0$ cm for the objective and the eye lens, and $f_f = 6.5$ cm for the field lens. We used a tube made of three sections, with lengths of 17.0 cm, 4.0 cm and 1.8 cm. The first (longer) section accommodates the objective; the second (middle) section is for the field lens and the eye lens; the third (last) section is just an extension to help locate the exit pupil. The three sections are put together by means of adhesive tape externally wound around the tube at the joints. Magnifications obtained are $m_o \approx 3.2$, $m_e \approx 6.3$, $m \approx 20.2$. As regards resolution, we still used a diaphragm of 0.4 cm in diameter on the objective, so $a \approx 17$ μm.

To hold the tube in place and to be able to focus we made a slightly different stand, maintaining the wooden base but using a pillar with two notches and a top bar (figure 6). The notches accommodate two pieces of flexible sheet (we used a fibreglass board for printed circuits), with holes for the tube. The latter could slide with friction, for coarse focusing. Fine focusing was done with a screw on the top bar pushing and flexing the fibreglass sheets. Although somewhat elaborate, this mechanism proves quite effective in controlling the vertical movement of the tube to obtain the best focus.

An image of the bar resolution target taken with this device is presented in figure 7. The performance in terms of resolution is not

[2] 22-8635 high-resolution test target, Ealing Corporation, St Asaph, North Wales, UK. Also available from other manufacturers, at a typical cost of US$50 for a heavy white paper version, and twice as much for a slide version.

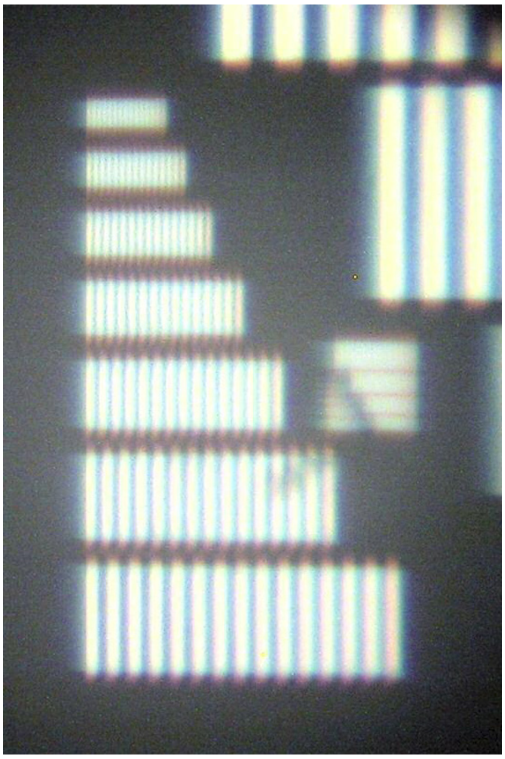

Figure 7. A pattern from a bar resolution target observed with the microscope device of figure 6.

significantly different from that of the simple device with two plastic lenses. Chromatic aberrations are perhaps more severe; this can be related to the use of glass lenses (dispersion is typically higher in glass than in plastic). The advantage of this configuration over the previous one is a wider field of view, which in our case is 4.2 mm; again it is measured with an object stage micrometer. Viewing samples is then made easier, as the object can be found right away, and observed in a larger ground.

As a further improvement, one might slightly vary the configuration so that the field lens is somewhat out of focus with respect to the intermediate image; in this manner, any dust or contamination on the lens surface is not seen sharply in focus across the object but tends to disappear. Conversely, if a reference pattern such as a crosshair is desired, it can be superimposed on the object by arranging the pattern at the intermediate image. These tasks are, however, more involved, introducing concepts that are developed in classical eyepieces.

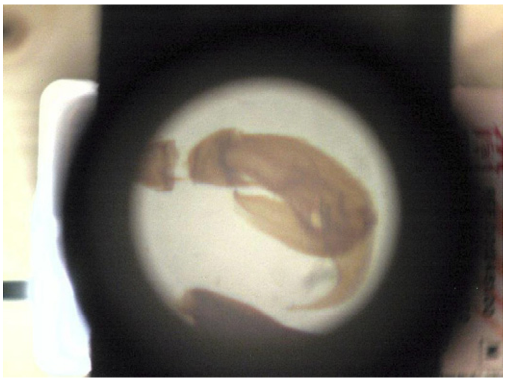

Figure 8. A photograph of a sample (a bee's leg) taken with a digital camera through the microscope of figure 6.

As a note concerning the way to take photographs through the microscope, figures 5 and 7 were made by mounting a digital camera on a tripod, and placing the camera above the microscope in a downward-looking position (like the observer's eye). To view the scene, the liquid crystal display of the camera was used instead of the viewfinder. The manual focus operating mode was selected. A major inconvenience is that the field of view is significantly reduced with respect to eye observation; this is due to the fact that the stop of the camera is inside the lens, and it cannot approach the eye lens as closely as the observer's eye can. One should then move the camera lens as close as possible to the eye lens, paying attention not to get in contact with it, in order not to damage the optics. An example of a sample object (a bee's leg, from a selection of amateur microscope slides) that has been photographed with this arrangement is presented in figure 8. A way of making a low-cost microscope camera in a simple manner is also described in the literature [8].

Conclusions

We have reported on the making of microscope devices with readily available materials, giving in detail the constructive particulars and relating them to the basic parameters characterizing the instrument from the point of view of theory. Examples of images illustrating the performance that was obtained have been presented. As an activity project at undergraduate level, this exercise proves useful in understanding the lens equation in practice, and the meaning of magnification and resolution. It is also valuable for stimulating a practical attitude in optics works, and allows imaginative solutions for mechanical mountings and instrumental approaches.

According to our experience, this project takes approximately two weeks of work in the laboratory, using two units of 2 h each week. This time can be reduced if the components of table 1 are prepared in advance and made available in usable form (i.e. lenses already removed from cameras, tube sawn to length, wooden parts with drilled holes). Groups of no more than three students are recommended, due to the waiting time between alternating observations. Before proceeding to the laboratory activity, a classroom presentation of optics principles and the practical task is necessary; although this is seldom sufficient to enable students to do the job, it helps as a basic introduction to address the many questions that are then raised. Particularly common are questions related to the role of the eye in visual instruments; other typical questions are about aberrations, negative lenses (although not used here), lens manufacturing, ways of illuminating the sample (in transmission or in reflection, in bright or dark field), and so on. While only some of these questions can be appropriately answered within the context of this project, the fact that similar questions are raised may be taken as evidence of the curiosity and stimulated interest in practical optics, which was the aim of the project in the first place.

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[7] 036126 19-mm microscope reticle, Edmund Scientific Company, Barrington NJ, USA
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