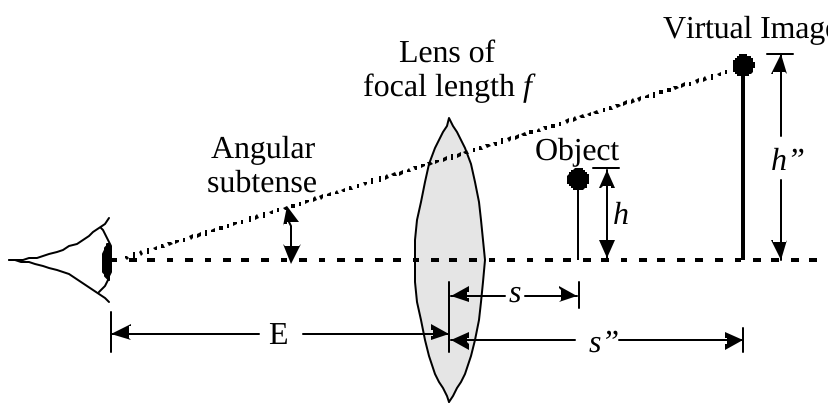
Viewfinder Optics for Microdisplays

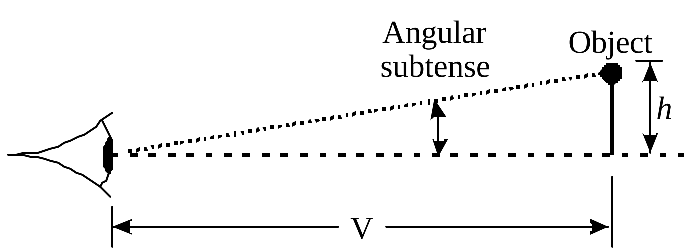
For camcorders and digital cameras, a viewfinder consisting of a miniature display and magnifying optics offers some distinct advantages over a directly viewed LCD panel. For example, the magnified miniature display appears much larger to the viewer's eye, making it easier to see detail. Also, the enclosed optics of a magnified display are not affected by ambient light, resulting in excellent contrast even when used out in direct sunlight. On the other hand, this approach requires some sort of viewing optics. Fortunately, it is possible to create relatively simple, inexpensive, compact viewing optical systems.

The Simple Magnifier

The simplest magnifier is a positive lens placed a distance less than or equal to its focal length away from the object to be viewed. Such a system produces a virtual image, that is, an image that is only seen when the viewer looks back into the optical system. In contrast, projection displays produce a real image. A real image can be put on a screen and seen without having to view through the optical system.



Object viewed through magnifier



Object viewed directly

The first step in specifying or designing a viewing system for miniature displays is to thoroughly understand the operation of the simple magnifier. A schematic of one is shown in the figure. As with any lens system, the magnification is defined to be image height divided by object height:

$$\text{magnification} = m = \frac{h''}{h} = \frac{s''}{s}$$

However, the apparent size of the viewed image depends upon the viewing distance (just as any object appears smaller when seen from a greater distance). To quantify this, the size of a viewed object is defined by the tangent of its angular subtense:

$$\text{tangent angular subtense} = \frac{\text{object size}}{\text{object distance}}$$

Because, for magnifiers, the perceived size of the viewed image depends upon viewing distance, the traditional definition of magnification is not that useful. Instead, it is common practice to define a quantity called **magnifying power**:

$$\text{Magnifying Power} = \frac{\text{Tangent angular subtense of virtual image}}{\text{Tangent angular subtense of object viewed directly}}$$

Using the variables defined in the drawing yields:

$$\text{Subtense of virtual image} = \frac{h''}{s'' + \mathrm{E}}$$

and

$$\text{Subtense of object viewed directly} = \frac{h}{\mathrm{V}}$$

From these, magnifying power can be calculated:

$$\text{Magnifying Power} = \frac{\dfrac{h''}{s''+\mathrm{E}}}{\dfrac{h}{\mathrm{V}}} = \frac{h''\mathrm{V}}{h(s''+\mathrm{E})} = \frac{m\mathrm{V}}{s''+\mathrm{E}}$$

In order to make this equation truly useful, it is best to eliminate the variables *m* and *s"*, which are both often infinity (because the object is often positioned at the focal point of the magnifier). This is accomplished by first substituting for *m* in the numerator:

$$\text{Magnifying Power} = \frac{\frac{s''}{s}\text{V}}{s'' + \text{E}},$$

and then rearranging the paraxial lens equation:

$$\frac{1}{f} = \frac{1}{s} - \frac{1}{s''}$$

(where *f* is the lens focal length) into the following form:

$$s'' = \frac{fs}{f - s},$$

to enable a final substitution for *s"*. The end product is the relationship:

$$\text{Magnifying Power} = \frac{f\text{V}}{fs + \text{E}(f - s)}$$

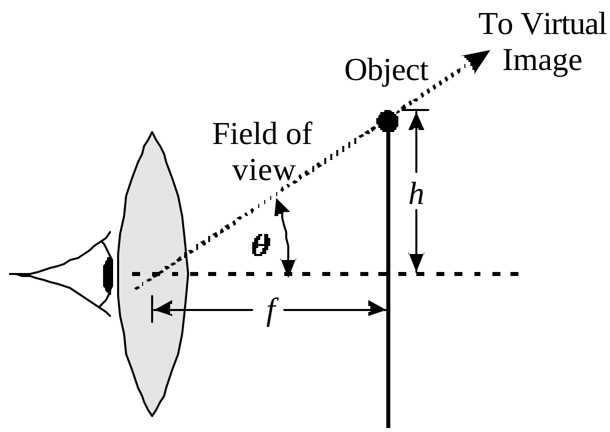
The most common use of a simple magnifier is with the eye placed right up at the lens (E = 0). Also, it is typical to design so that s = f , which causes the image to appear to be at infinity, resulting in a sharp image with a fully relaxed eye, i.e., maximum viewer comfort. Setting E = 0 and s = f, simplifies the expression to:

$$\text{Magnifying Power} = \frac{\text{V}}{f}$$

To obtain a number from this equation requires arbitrarily setting the viewing distance, V, for the case when the object is viewed directly. By convention, the value of 250mm (10 inches) is commonly used, resulting in the final, simple expression for magnifying power:

$$\text{Magnifying Power} = \frac{10}{f}$$

When designing the viewing optics for a miniature display, it is actually more common to begin by specifying the field of view (angular subtense) defined by the virtual image, rather than the magnification. The field of view is then used to determine the required system focal length. The relationship between these quantities can easily be calculated from the equations already given. Again assuming that the eye is placed directly at the lens (E = 0) and the object is put at the focal point ($s = f$) and centered on the optical axis, as shown in the figure,



Definition of field of view

then the equation for (half) field of view (q) becomes:

$$\tan(q) = \frac{h}{f}$$

Keep in mind that q is the **half** the total field of view of the system, and h is **half** the size of the display. This equation can now be arranged to enable the required system focal length as a function of d, the full diagonal size of the display:

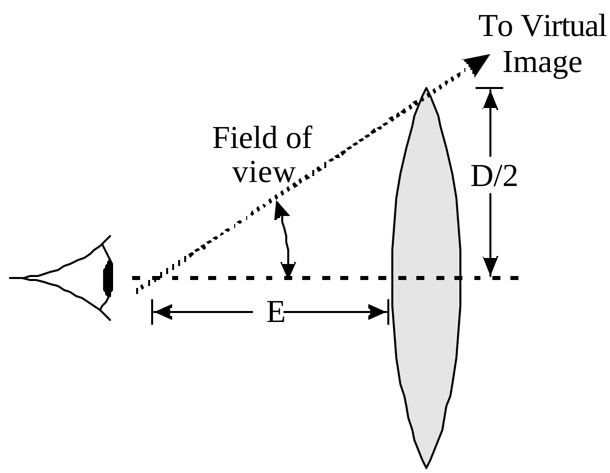
$$f = \frac{d}{2\tan(q)}$$

Optics Size

In a practical viewfinder, other factors can be just as important as focal length. For example, optical system size is a particularly important factor in the design of viewfinders for mass market, portable products such as camcorders and digital cameras, because as lens diameters increase, so does system size and weight (and to a certain extent, cost). Thus, in general, it is desirable to the diameter of the optical system. There are three primary design parameters – field of view, eye relief and eye box – that are all interrelated, and together determine the minimum diameter for the lens system.

Eye Relief

Eye relief is the distance from the eye to the first surface of the magnifier. The relationship between eye relief (E), field of view (q) and optics diameter (D) can be approximated using the simple magnifier example, as shown in the figure:



A longer eye relief enables eyeglass wearers to position their eyes a distance from this lens and still see the full field of view of the display. However, longer eye relief increases optics diameter.

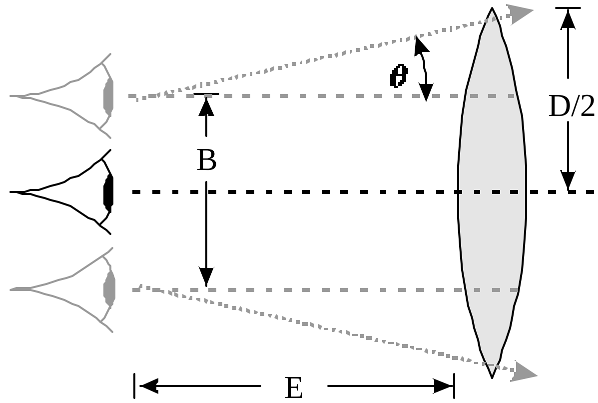
From the drawing, it can be seen that this relationship is

$$D = 2E \tan(q)$$

A typical value for eye relief is 25 mm.

Eye Box

In a real world design, the viewer should still be able to see the full field of view of the display, even when there is some lateral misalignment between their eye and the optical axis of the magnifier. The amount of lateral misalignment that can occur before some of the image is cut off by the edge of the optics is called the eye box. To increase the size (diameter) of the eye box requires increasing the lens diameter beyond the minimum diameter, D, used in the preceding equations.



Definition of eye box

The required lens diameter is obtained by merely adding the desired eye box diameter to the lens diameter calculated from just the axial viewing geometry:

$$D = 2E\tan(\theta) + B$$

This can be rearranged to give eye box in term of the other variables:

$$B = D - 2E\tan(\theta)$$

Like other design considerations, setting the eye box size is a question of trade-offs. Increasing eye box size clearly makes the display easier for the viewer to use, since it relaxes the tolerance on eye position. But this may necessitate the use of a more complex and expensive lens system. This tradeoff between design complexity and eye box size usually leads to eye box values in the 7 mm to 10 mm range for typical viewfinder applications.

Other Design Factors

There are a number of other important design factors that influence system size, weight, cost and resolution. Some of the most important of these include virtual image location, resolution and distortion.

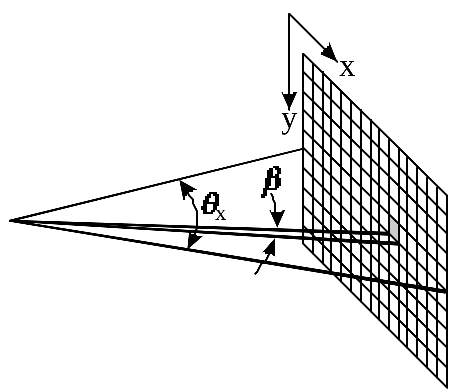
Virtual Image Location

When a magnifier is focused so that the object is at the focal point ($s = f$), then the viewer perceives the image to be at an infinite distance, and collimated light enters the eye. While this arrangement delivers maximum viewing comfort, in can create difficulties in some instances. In particular, bifocal wearers may not be able to focus on such a distant image when viewing through the bottom part of their eyeglasses. Shifting the object (the display) slightly closer to the magnifier will make the image appear closer, and deliver an image that is easier for bifocal wearers to accommodate. For viewfinder applications, the typical image distance is in the 1 meter to 2.5 meters range. Shifting the object away from the focal point will slightly change the magnifying power formula developed earlier, since that equation was reached using the assumption that ($s = f$).

Resolution and System MTF

One arcminute is considered to be the typical angular resolution of the human eye. If the magnifying power of the viewfinder optics makes an individual pixel in the display appear larger than this value, then the user will be able to discern the pixel structure of the display.

The drawing defines the angular subtense of a single pixel.



Definition of pixel angular subtense

For a given display pixel count and magnifier field of view, the angular subtense (b) of an individual pixel is:

$$b = \frac{q_x}{N_x},$$

where q_x is the full field of view in one dimension and N_x is the number of pixels in that same dimension (an analogous equation can be written for the perpendicular direction, *y*).

As an example, for a QVGA display (320 x 240 pixels) that subtends a 20° horizontal field of view, each pixel would subtend an angle of 0.0625° or 3.75 arcminutes. The viewer would clearly detect the pixelated structure of the display, since each pixel appears larger than 1 arcminute. It would be necessary to either reduce the magnification (thus reducing the field of view) or use a same sized display with a higher pixel count in order to remedy this situation.

Of course, this example assumes that the optical system itself has an angular resolution sufficient to clearly show the smallest detail in the object (in this case, better than 3.75 arcminutes). One of the best ways to quantify whether or not this is the case is to determine the modulation transfer function (MTF) of the optics. MTF is basically a measure of the contrast of the optics (with 100% being perfect) as a function of spatial frequency. MTF can be calculated for a lens system under a specific set of conditions (e.g. magnification and field angle) by most optical design programs. MTF is used to determine system resolution by picking an arbitrary value for the minimum acceptable contrast under these conditions, and then determing the highest spatial frequency at which that contrast can be obtained.

In the case of a miniature display, the finest detail that needs to be resolved consists of an on/off pixel pair. The spatial frequency (F_{Limit}) of this pair can be calculated using the Nyquist Frequency definition,

$$F_{Limit} = \frac{1}{2p},$$

where p is the size of an individual pixel. For typical displays (such as the Displaytech Model QDM-0076), the pixels are 12 microns square. Therefore, the limiting resolution in the horizontal and vertical directions is

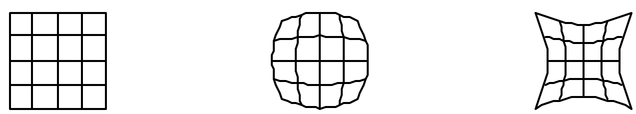
$$F_{Limit} = \frac{1}{2(0.012)} = 41.7 \text{ line pairs/mm}$$

Thus, it is not necessary to evaluate the MTF at higher spatial frequencies than this when evaluating an optical design for a display with these pixel dimensions. However, the desired value of the MTF at this spatial frequency depends very much upon application.

Since obtaining a higher MTF at a given spatial frequency will, in general, require a more complex, sophisticated and (typically) expensive optical system, it is very important that this value not be over specified for the application. For example, a viewfinder may require only modest resolution (say 50% at 38 lp/mm) at the center of the image, since it is primarily being used just as a framing device. In contrast, the required MTF at this same spatial frequency might be much higher, across the entire field of view, for optics for a personal monitor. This is because there is important information at the corners of the monitor as well at the center.

Distortion

Optical distortion is fairly common in non-symmetric optical systems. Distortion is a measure of how well a square object pattern is reproduced in the viewed virtual image. It should be noted that distortion does not effect image resolution, just image shape. Typical examples of distortion and their nomenclature are shown in the figure; most magnifier systems exhibit pincushion distortion.



Types of distortion

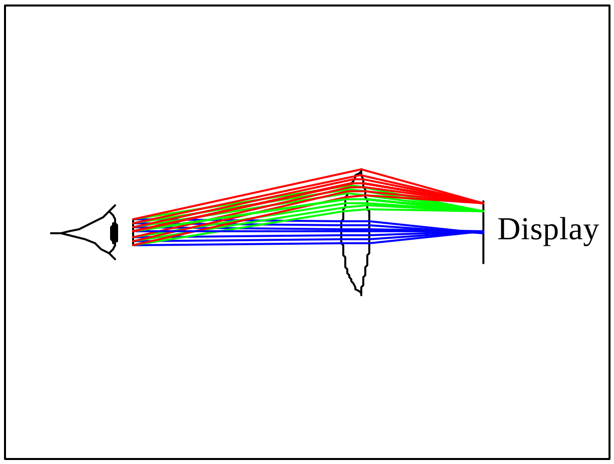
In general, attempting to reduce optical distortion to very low levels (<1%) in a design will cause other off axis aberrations (such as astigmatism) to increase. Thus, it is very important not to overspecify the level of allowed distortion in a viewfinder design. Fortunately, a moderate level of distortion can be tolerated in a viewfinder without adversely affecting its functionality. Typically, the level of distortion in a quality viewfinder should not exceed 4%.

Basic Magnifier Designs

Real world magnifier designs cover a large range in terms of size, complexity, performance and cost, depending on the demands of the application. This section briefly reviews some basic configurations that can serve as a starting point for a viewfinder system design.

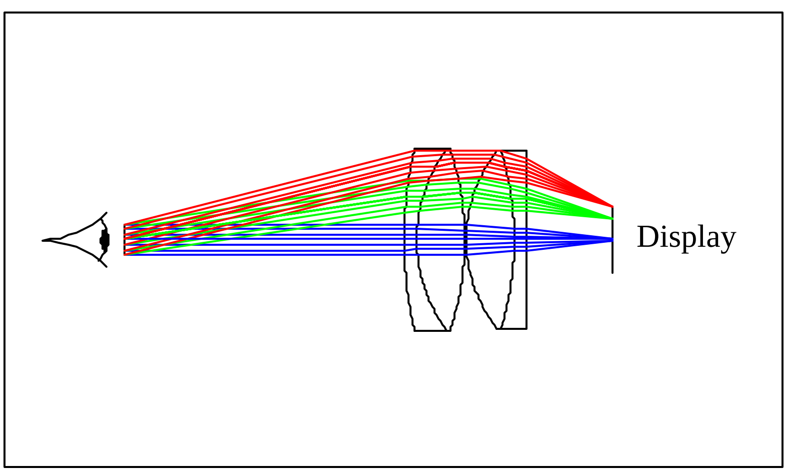
Aspheric Refractive Plastic

The simplest design that can achieve some degree of performance is a single, aspheric plastic lens. The aspheric surface enables correction of spherical aberration, but there is no color correction. This design is very compact and lightweight, and minimizes overall package length. While initial tooling costs for plastic optics can be high, the unit price drops dramatically in high volume. In general, a single aspheric plastic lens would not provide sufficient performance for camcorder and digital camera viewfinders, but including this type of component in a more sophisticated design can lower the overall element count, reducing size, weight and cost.



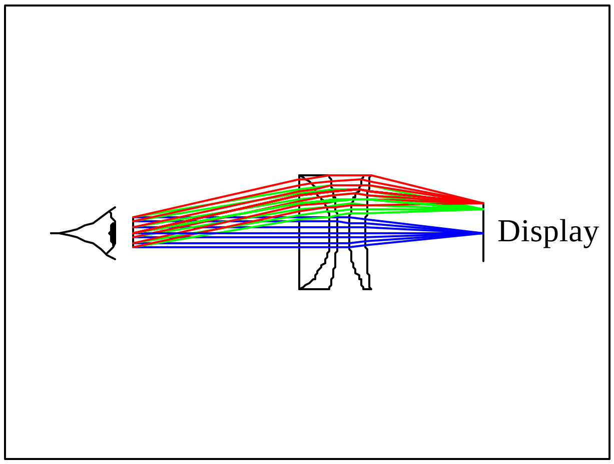
Refractive Glass

This form, which is a Plossl derivative, consists of two cemented doublets, for a total of four glass elements; all surfaces are spherical. The design is well corrected for spherical aberration and chromatic aberration, and typically produces relatively low distortion. Tooling costs for spherical glass lenses are low, but unit costs for high volume production do not drop as steeply for as for molded plastic lenses.



Refractive Hybrid

This glass/plastic hybrid design attempts to combine the best features of the previous two configurations. Color correction is provided by the doublet. The plastic, aspheric singlet provides for image quality correction (primarily spherical aberration), while reducing element count, and minimizing size, weight and cost.

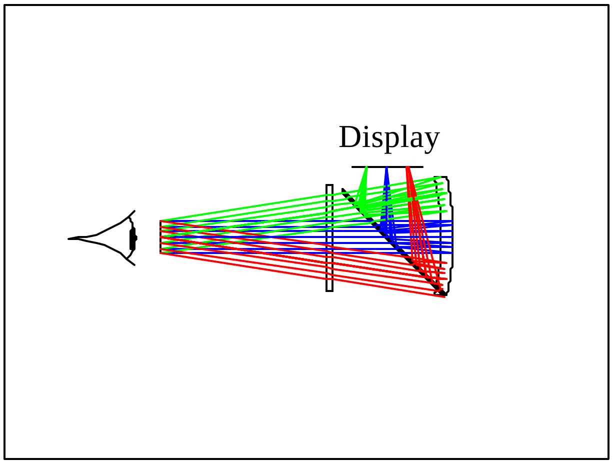


Reflective

This simple reflective system utilizes a single, spherical mirror as the magnifier. A beamsplitter must be used to allow the object to be positioned on axis, and a flat coverglass seals the entire system.

The primary advantage of an all-reflective optical system is that it is completely free from any chromatic aberration. Also, since the spherical aberration of a mirror is much lower than that of a refractive element of equal power, this design performs well with a spherical surface, as opposed to an asphere.

One disadvantage of reflective systems is that they are not efficient. The double pass through the beamsplitter causes a reduction in image brightness. For example, if the nominal reflectance/transmittance ratio of the beamsplitter is 50/50, then only 25% of the light from the display reaches the viewer's eye after two passes.


Display