5.3 Cell Phone Camera

The next design example we discuss is a cell phone camera. These systems have become quite popular, to the point that it is often more difficult to purchase a cell phone without a camera than a phone with one. Early cell phone cameras used relatively low-resolution sensors and often had single-element lens designs. The original use model was that the camera would be for taking “bar shots;” that is, people would be taking pictures of each other while out socializing. As the cameras became more popular and the convenience of using them was understood, increased image quality was demanded. The detector resolution steadily increased to the point that megapixel sensors are used today. This increase in sensor resolution and size drove complexity into the optical designs. Instead of single-element designs, two, three, and even four elements are used. In fact, the newest generation of cell phone cameras will have autofocus and zoom capability.

Figure 5.27 shows an example of a three-element cell phone camera design. These types of designs are usually heavily constrained, with overall length being a driving factor. This often results in thin, tightly spaced elements. During the design process, the edge and center thickness of the elements must be constrained to manufacturable sizes. Additionally, sensors containing microlens arrays may limit the chief ray angle of incidence on the image plane. This can result in unusual-looking (for glass) rear elements, which bend the ray bundles over to meet the angle of incidence constraint.

In this example, we will not focus on the actual design of such systems but instead concern ourselves with one aspect of their tolerance analysis. In particular, we compare the predicted performance for two different surface decenter probability distributions. Most cell phone camera lens designs tend to be quite sensitive to decenter of the elements, their surfaces, or both. As such, the maximum amount and the distribution of the various decentrations will affect the predicted performance. To show this, a predicted performance analysis was run, conducted through the use of a Monte Carlo simulation. As described before, a Monte Carlo analysis models the production of multiple systems by randomly varying parameters within their tolerance ranges according to a defined set of probability distributions. In this case, the probability distribution used for the surface decenter tolerance was varied.

First, a Monte Carlo simulation was performed for a surface decentration with a uniform distribution. This means that the surface decenter is equally likely to be anywhere within its tolerance range. Next, an endpoint distribution for the surface decenter was used. This means that the surface will always be decentered by the maximum amount allowed, with a rotational orientation of the decentration that is random. For instance, on one system, surface 1 on lens 1 may be decentered upward, while surface 2 on lens 1 is decentered to the left. In another instance, both may be decentered upward, which is similar to the entire lens shifting upward.

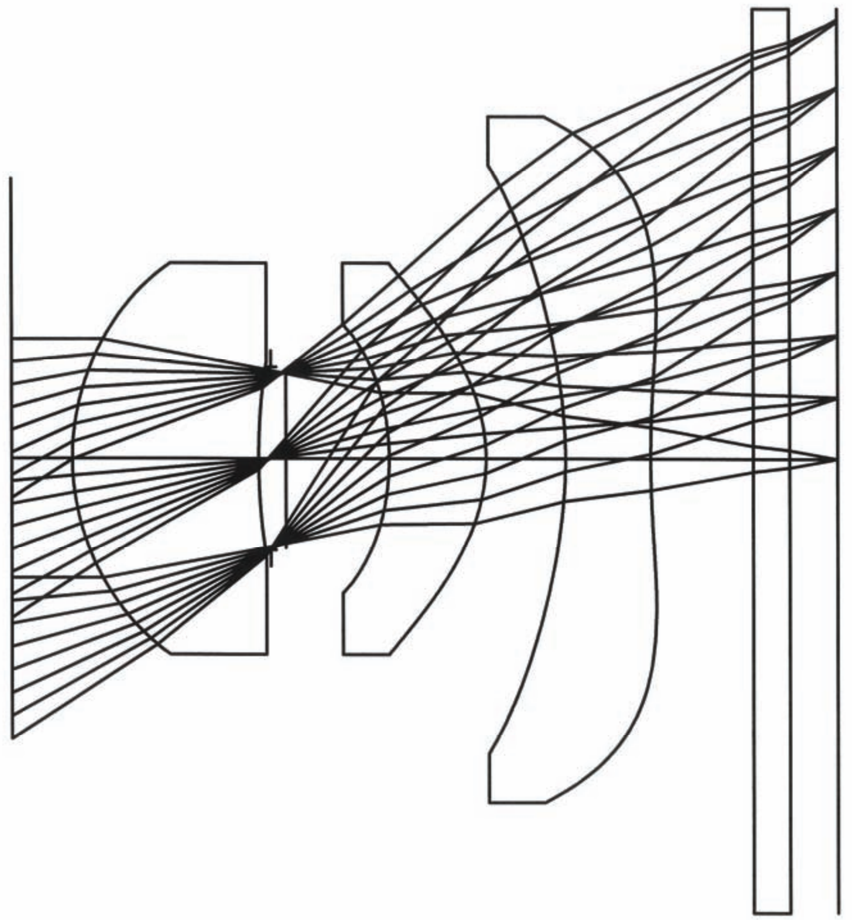

Figure 5.27 Three-element cell phone camera design.

All other tolerances used the same set of probability distributions (uniform) for both Monte Carlo runs. A total of 25,000 lenses were created in each Monte Carlo run, and the MTF data at several field points was collected. The tangential and sagittal MTF values for one off-axis field were averaged, and a histogram was generated from the data, which is shown in Fig. 5.28.

We can see from the histograms that the choice of probability distribution for surface decentration has an effect on the predicted performance distribution of the system. The uniform distribution, shown as the dashed line, has its peak at an MTF value at 50 cycles/mm of 0.465. The endpoint distribution, shown as the solid line, has its peak at an MTF value of 50 cycles/mm of 0.450. The effect of using the endpoint distribution is a general skewing to the left of the predicted performance distribution curve. This can be more clearly seen by plotting the normalized number of systems above a certain MTF value, which is shown in Fig. 5.29.

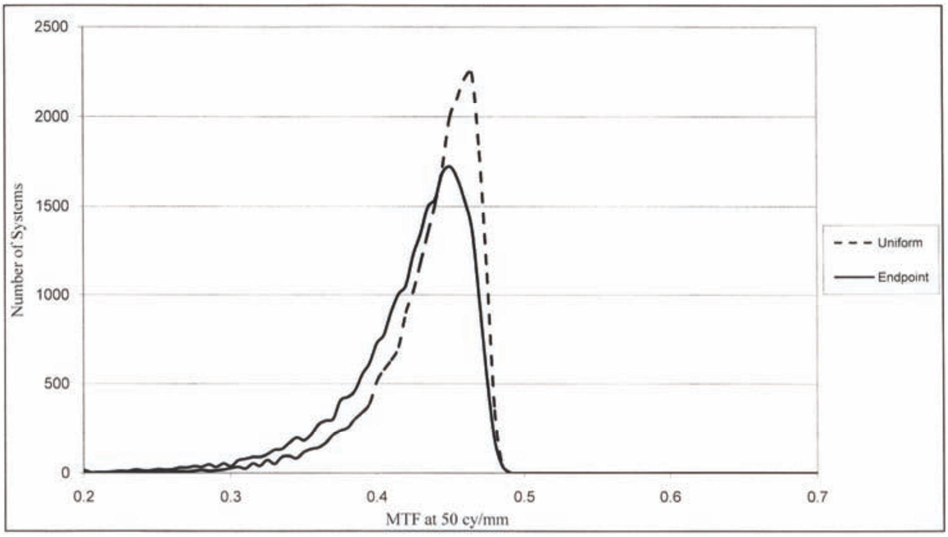

Figure 5.28 Histogram of data collected from Monte Carlo runs.

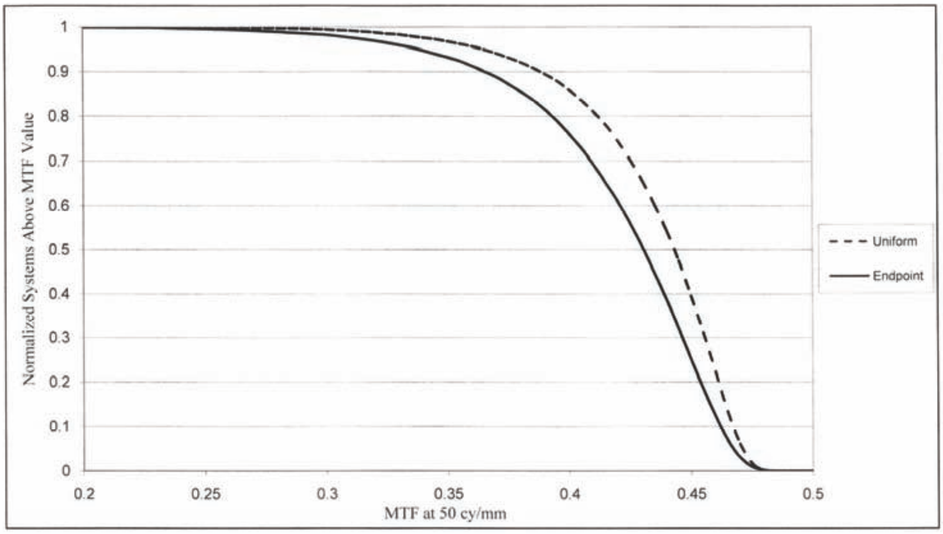

Figure 5.29 Normalized number of systems above a certain MTF value.

If we take the difference between the two curves, as is shown in Fig. 5.30, we can see the percentage difference in systems above a certain MTF value (at 50 cycles/mm) for the two distributions. For instance, consider the number of systems for the uniform distribution that have an MTF value at 50 cycles/mm above 0.35. This value turns out to be just under 97%. So if our system MTF specification were set at 0.35 (and we only considered this field), we would

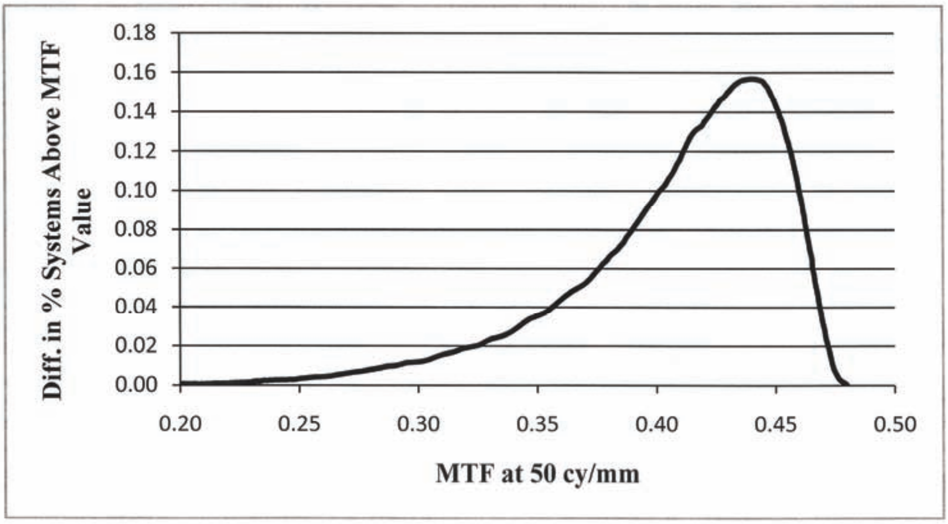

Figure 5.30 Difference in percentage of systems above a certain MTF value (for 50 cycles/mm).

expect a 3% yield loss during production. For the endpoint distribution, the percentage of the system that would meet this criterion is just over 93%. Thus, if the distribution of surface decentration had an endpoint distribution instead of a uniform distribution, we would see an additional 3.5% yield loss or double our uniform distribution prediction.

While 3.5% may not seem like a large value, it can have a significant impact on production, particularly when many thousands or millions of systems are being produced each month. A large amount of wasted material, time, and energy would go into producing and testing these systems. In this analysis, an endpoint distribution was used, which is a conservative selection. A parabolic distribution, which may be considered a compromise between endpoint and uniform distributions, may be more appropriate. Nevertheless, the fact that we saw a potential doubling in yield loss (for only a single field) should serve as a warning to the designer to carefully consider the choice of tolerance probability distributions in their analyses.

5.4 Infrared Multiorder or Harmonic Diffractive Lens

A question that frequently comes up with regard to plastic optics is why they are not seen more often in military or civilian IR systems. These systems, typically operating in the 3- to 5- or 8- to 12-μm region, often use lenses made from germanium, silicon, zinc sulfide, or other expensive materials. Since plastic optics are generally less costly, why not use them for these regions? The answer to this question is transmission. Currently available optical plastics do not transmit or, more correctly, do not transmit well in these regions. Published transmission measurements[35] show poor transmission in these bands, particularly for material thickness on the order of 5 mm, which is in the general range for molded plastic parts.

It has been a dream of plastic optic designers, and probably material scientists as well, to have a plastic optical material that transmits well in the mid- and long-wave infrared. Whoever invents such a material will likely become famous (at least amongst the optics community) and, quite possibly, rich. The cost savings that could be achieved using such a material are significant, even with a material cost multiple times that of existing optical plastics. For the moment, however, such a material does not exist, and the only reasonable way to use optical plastics in the IR is to make very thin elements. An example of this is the type of Fresnel lenses used on security or convenience lighting systems. These systems detect the change in the infrared scene when a person enters the field of view of the sensor. Transmission spectra for a number of materials for thicknesses of 0.38 mm (0.015 in.) can be found at the websites of manufacturers of Fresnel lenses.[89] In addition to Fresnel lenses, diffractive microlenses can also be used.[90]

Another option exists as an alternative to Fresnel lenses and microlenses (refractive and diffractive) to create thin, powered optical elements. This option is a diffractive surface, though not a first-order diffractive, as is usually used for color correction; instead, the lens is designed to operate at a higher diffraction order. Such a lens [known as a multiorder diffractive (MOD) or a harmonic diffractive lens (HDL)] was independently developed by two groups in 1994.[91,92] Additional improvements and applications were shown the following year.[93,94] Whereas a standard (first-order) diffractive has a step height that is designed to impart a phase shift of 2π, the multiorder diffractives have step heights that impart a phase shift of $2m\pi$, where m is the (higher) design order. These higher-order diffractive lenses rely upon several characteristics of diffractive surfaces, particularly the dependence of their focal lengths on wavelength and diffraction order, the narrowing of the diffraction efficiency curve with order, and the appearance of harmonic wavelengths. We first discuss the focal length dependence, then the change in diffraction efficiency with order, and finally consider the effect of wavelengths becoming harmonic.

The focal length of a purely diffractive (no refractive power) surface depends inversely upon the diffraction order. Thus, light in the first order will have a focal length that is twice as long as that in the second order. This can be seen by referring back to Fig. 4.16, which shows rays for multiple orders. When using first-order color-correcting diffractives, as seen in the first design example, we do not usually notice this large change in focal length with order. This is typically because the power of the diffractive surface in these cases is much less than the refractive power, resulting in only a small focus change with diffractive order. In the case of a completely diffractive surface, the change in focal length with order for a given wavelength can be significant.

The focal length of a purely diffractive surface is also inversely proportional to the wavelength of light passing through it. Thus, if we double the wavelength of light going through the diffractive, we again have a focal length of half the original value. This large change with wavelength is the basis for diffractive surfaces possessing a low Abbe number.

Knowing that the focal length depends inversely on both of these factors, it can be seen that we can achieve a (nearly) constant focal length by changing the diffraction order we are operating in as a function of wavelength. For shorter wavelengths, we would use a higher diffractive order; for longer wavelengths, a lower diffractive order. If we keep the product of the order and wavelength constant, the focal length will be constant, and we will have a color-corrected system.

Of course, in order for this to work, it requires that the diffraction efficiency be high for each combination of wavelength and diffraction order that we are interested in. Figure 5.31 shows the diffraction efficiency in the design order, as a function of wavelength, for diffractives designed to work at the 1st, 3rd, 10th and 25th orders. The diffractives all have a design wavelength of 4 µm, but they have increasing diffractive groove height with increasing design order. The diffractive groove height for the 25th-order design would be 25 times that of the 1st-order design height. We can see that the diffraction efficiency curves for the design order narrow significantly as we increase the design order value. The result of this is that only a narrow wavelength range around the design wavelength has high efficiency in the design order.

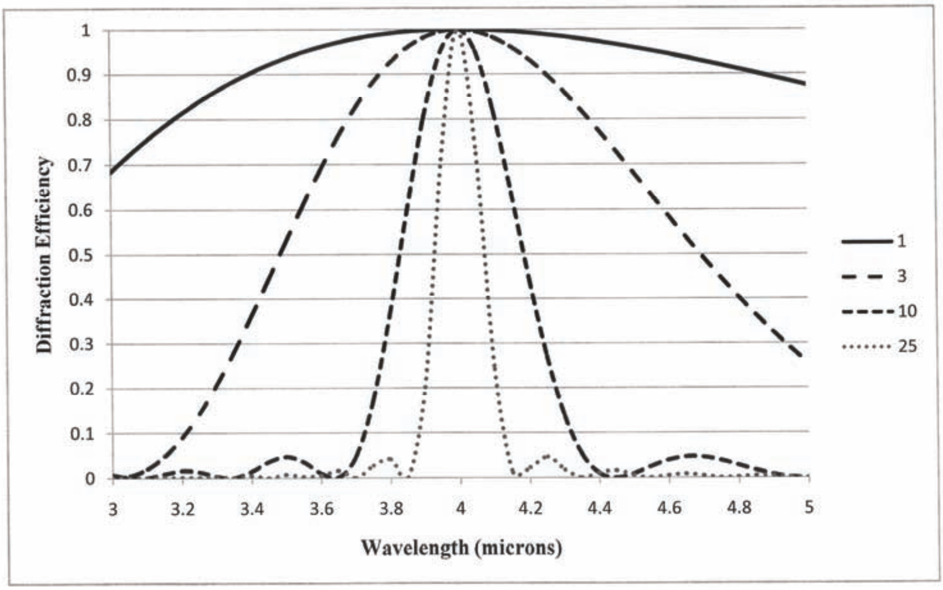

Figure 5.31 Diffraction efficiency in the design order as a function of wavelength and design order value.