# Optical Design using Fresnel Lenses

## Basic Principles and some Practical Examples

**The Fresnel lens can be used in a wide variety of applications. The basic principles of the Fresnel lens are reviewed and some practical examples are described. There are definite advantages and tradeoffs that should be considered when deciding if a Fresnel lens is the appropriate component to use in a design. Some basic optimization rules are presented which may facilitate a first order design or feasibility study.**

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### Background

A Fresnel lens is an optical component which can be used as a cost-effective, lightweight alternative to conventional continuous surface optics. The principle of operation is straightforward enough: given that the refractive power of a lens is contained only at the optical interfaces (i. e. the lens surfaces), remove as much of the optical material as possible while still maintaining the surface curvature. Another way to consider it is that the continuous surface of the lens is "collapsed" onto a plane. An example of this concept is shown in figure 1.

The practical aspect of compressing the lens surface power into a plano surface requires a finite prism pitch, a slope angle component (which acts to refract the rays in the prescribed manner) and a draft component (which for the normal refractive lens design is optically inactive but necessary to return the surface profile "back to the plane"). See figure 2 for cross section schematic illustrating these components. The convention is to specify the slope angle with respect to the plane of the lens and the draft angle with respect to the normal. For example, a small slope angle would correspond to a prism with a gradual incline whereas a small draft angle corresponds to a very steep prism decline.

### Focal Length and f-number

A few other concepts typically used to specify a Fresnel lens are focal length and f-number (or f/#).

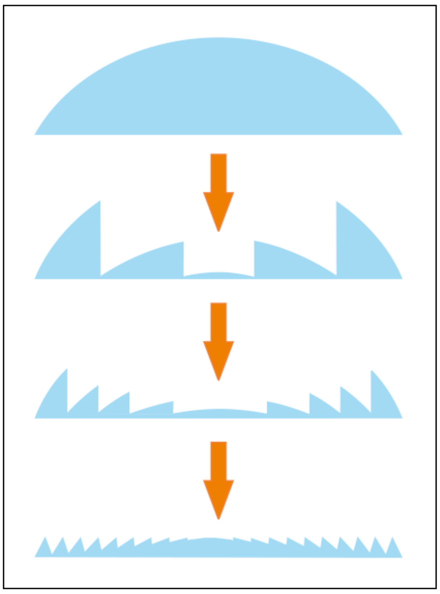
The definition of focal length may depend on the way the lens is used in application (an individual lens may even have variable focal distances across its aperture). Generally though, the focal length is the distance from the lens to where an idealized collimated input beam converges to a point. More specifically, for a lens with prism facets on one side and a flat plano surface on the other side, the *effective-focal-length* is very closely approximated as the distance from the *prism* surface of the lens to the focal point. Also, it is commonplace to define the *back-focal-length* as the distance from the *plano* side of the lens to the focal point.

The f-number is the ratio of the lens focal length ($f$) to the clear aperture diameter of the lens ($\phi$). This term is also referred to as the "speed" of the lens. The lower the f-number, the "faster" the lens and the higher the f-number, the "slower" the lens. This terminology comes from photography where a lens of lower f-number would use a faster shutter speed. Another useful mnemonic is that a lens of smaller f-number will concentrate light *faster* then an equivalent diameter lens of larger f-number (which will concentrate light *slower*). A diagram is shown in figure 3.

### Design of a Fresnel Lens

An evident disadvantage to using a lens with grooves is the possibility of lost light due to incidence on the draft facet. The first step one may take to minimize this so called draft-loss is to make the facet perfectly vertical (i. e. perpendicular to the plane of the optic). The reality of manufacturing however requires at least a few degrees of tilt to the draft to facilitate mold release. Nevertheless, loss can be minimized by very

FIGURE 1: **Conceptual illustration (in side-profile) of collapsing a continuous surface aspheric lens into an equivalent power Fresnel lens.**



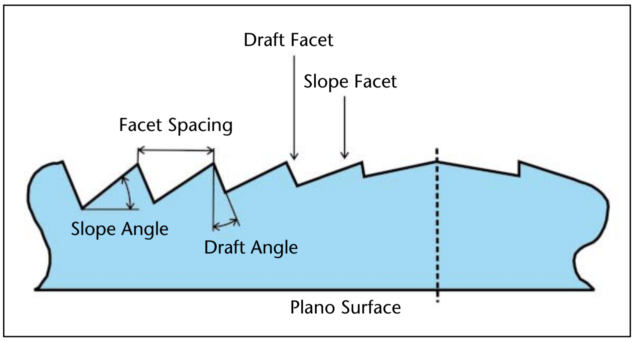



FIGURE 2: **Side-profile schematic of Fresnel lens prisms with nomenclature conventions.**

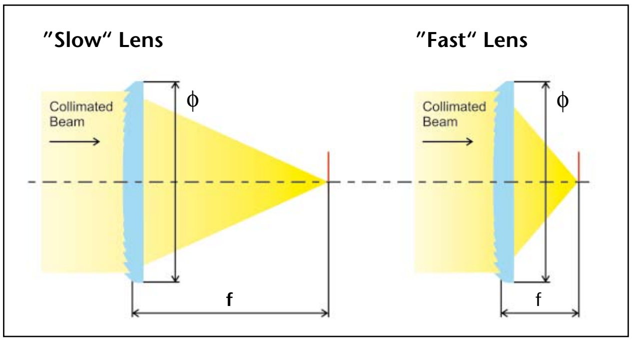



FIGURE 3: **Demonstration of f-number. The lens focal length is f. The lens diameter is ϕ. The "fast" lens has a lower f-number than the "slow" lens.**

judicious design which optimally locates the draft facet within the "shadow" of a slope facet. Although this keeps the total transmission efficiency high, the luminance is necessarily reduced because of beam "voids" as described in reference [1].

Based on the direction the Fresnel lens facets face, it is possible to calculate the ideal transmission efficiency versus the lens f-number by taking into account the surface reflections and the draft-loss. An example computation is shown in reference [2]. A collimating lens converts a point source to a beam of parallel light and a concentrating lens collects a collimated input beam onto the focal point. A *grooves-out* design directs the facets towards the side of the collimated beam (also called the infinite conjugate or the long conjugate) and a *grooves-in* design orients the facets towards the focal point (also called the short conjugate). As shown in figure 4, selection of the facing direction of the grooves, especially for fast lenses, plays an important role in determining the lens transmission efficiency.

When a Fresnel lens is used in some component of a display application (or any application in which an observer will be "looking-through" the lens), care must be taken to minimize the visual impact of the grooves. This is first achieved by making sure to pick a facet pitch less than or equal to the resolving power of the human eye. In other words, make the prisms smaller than can be seen. A typical healthy human eye has a visual acuity of around 1 arcminute (or 1/60°). This can be used to compute the maximum pitch size that will be visible for a given distance from the eye:

$$d \leq z \cdot 2.91 \times 10^{-4}$$

Where $d$ is the maximum visually resolvable pitch size (a smaller value should be selected) and z is the effective distance of the lens to the eye. As an example, for a lens 1 meter away, the facets will be unresolvable for a pitch size of 0.29 mm or smaller. A convenient rough approximation to this formula is to take a quarter of the distance the lens is to the observer and then move the decimal three places smaller (using the example above, this yields a pitch size of around 0.25 mm).

Using the minimum resolvable pitch as a limit, the next step is to ensure that the pitch of the Fresnel lens does not create a beat frequency with any of the other microprismatic components of the system. This is called a Moiré pattern and an example is shown in figure 5. A rule of thumb is to select the pitch as:

$$d = (m + 0.35) \cdot d_2$$

Where again, $d$ is the Fresnel lens prism pitch, $m$ is an integer (the larger the better) and $d_2$ is the pitch of the other micro-prismatic component in the system. As indicated, the larger the value you can choose for m, the less moiré will be visible. However, in order to keep the pitch d smaller than the minimum visually resolvable pitch, usually only a value of $m = 1$ or 2 is feasible.

To conclude the discussion on optical effects due to periodic prism structures, consider the geometric and diffraction limits of the lens performance. Geometrically, the smaller the prism size, the closer small flat prism slope facets come to approximating the idealized aspherical surface. However, operating contrarily are diffractive effects. As the pitch becomes smaller, the prisms become more efficient at acting like a grating which will deliver more light into higher diffractive orders away from the desired focal position. From reference [3] an optimum balance can be achieved by choosing the pitch size d as:

$$d \approx 1.5 \cdot \sqrt{\lambda \cdot f}$$

## THE COMPANY

**Reflexite Optical Solutions**

Reflexite Optical Solutions Business (consisting of Reflexite Display Optics in Rochester, NY, USA, and Fresnel Optics GmbH in Apolda, Germany) combines expertise in optical engineering, microreplication and polymer processing to provide microstructured polymer optics for Display, Lighting, Instrumentation, Solar Collection and many other light management applications. Reflexite Corporation is a globally operating world leader in the development and production of optical microstructured components and films.

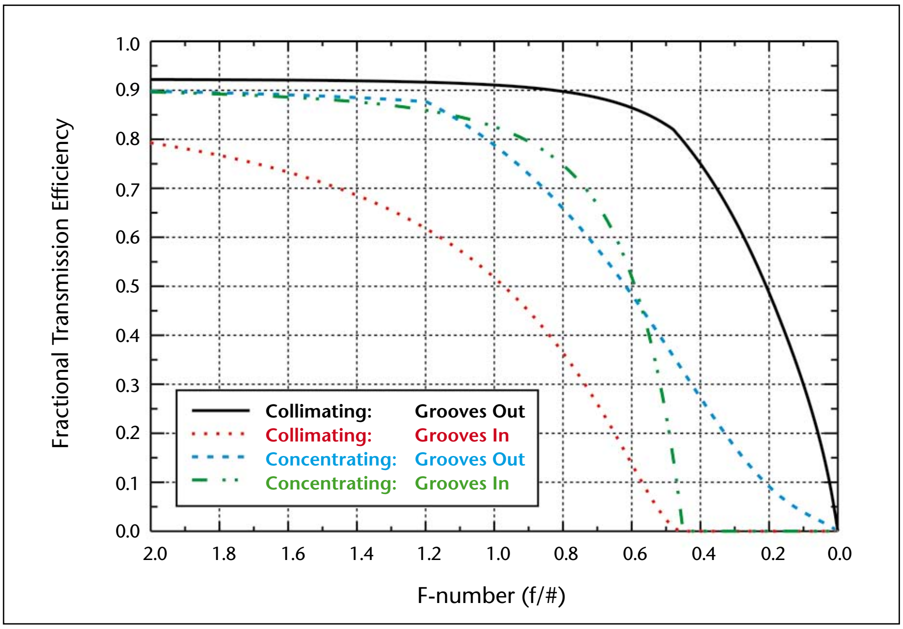



FIGURE 4: **Idealized efficiency values of Fresnel lenses in various configurations. The curves are computed based on the surface reflections and the draft-loss. The chart can be read by selecting an f-number on the abscissa and then seeing what the efficiency is at the ordinate for a selected configuration. The read efficiency is the transmission of the lens for the ray bundle at that specific f-number.**

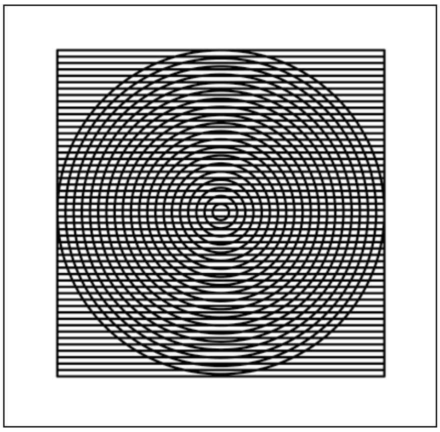


FIGURE 5: **Example of a Moiré pattern generated when a linear pattern (such as the grooves of a lenticular lens) and a circular pattern (such as the grooves of a Fresnel lens) are overlapped. The pattern can be minimized by more carefully choosing the pitch of each component.**

Where λ is the primary wavelength of concern and *f* is the focal length of the lens. As an example, for λ = 550 nm (central value of the visible spectrum) and a lens of focal length *f* = 100 mm, the optimum prism pitch size would be *d* = 0.35 mm.

## Applications

## Fresnel Lens Magnifier

Magnifiers are an example of one of the simplest applications of the Fresnel lens. Typically, a magnifier is a positive lens that forms a virtual upright image. Assuming the object to lens distance and the desired magnification of the magnifier are known, the thin lens Newtonian equation can be used to find an expression for the lens focal length *f* :

$$f = \frac{s_1}{\left(1 - \frac{1}{m}\right)} \qquad (1)$$

Where $s_1$ is the object to lens distance and *m* is the magnification (which is defined as the ratio of the desired object size divided by the actual object size; for instance a magnification of *m* = 2 would make letters on a page look twice as big). See figure 6 for a sketch of the variable definitions.

Next it is necessary to choose a lens size such that the requisite extent of the object is visible. For this we need to add two more variables; the reading distance l which is the distance from the object to the observer; and the preferred visible height h1 of the object. Then the diameter ϕ of the lens is given by:

$$\phi = \frac{m \cdot h_1}{1 + \left(\frac{m \cdot s_1}{l - s_1}\right)} \qquad (2)$$

A typical comfortable reading distance is *l* = 350 mm. Consider an example of a desired magnification of *m* = 2, a visible object size of $h_1$ = 20 mm and a lens to object distance of $s_1$ = 25 mm. Substituting into Equation 1, we find a lens focal length of *f* = 50 mm and then using Equation 2, an aperture size of ϕ = 35 mm is found.

## Fresnel Lens Collimator

Normally a Fresnel lens is cut according to an aspheric surface profile in order to minimize the imaging optical aberrations. The lens can therefore do an excellent job of collimating an idealized point source. In real life, no source is a true point, however solid state emitters such as LEDs can be quite small, so with enough distance between the lens and the LED, it may be approximated as a point source. A Fresnel lens can therefore be used to collimate the LED output. Also, traditional incandescent sources generate a lot of radiated heat which has limited the use of plastic optics in close proximity to the source. Since the majority of the heat generated by an LED is conductive, it is less difficult to apply a plastic lens.

A rule of thumb for the distance at which the LED die can be approximated as a point emitter is given according to the far field region convention:

$$z > \frac{a^2}{\lambda} \qquad (3)$$

Where *z* is the LED to lens distance, *a* is the size of the LED die and λ is the wavelength of the light. As an example, consider an LED die size of *a* = 50 μm at the central visible wavelength of λ = 550 nm. Then, from Equation 3, the lens to die distance should

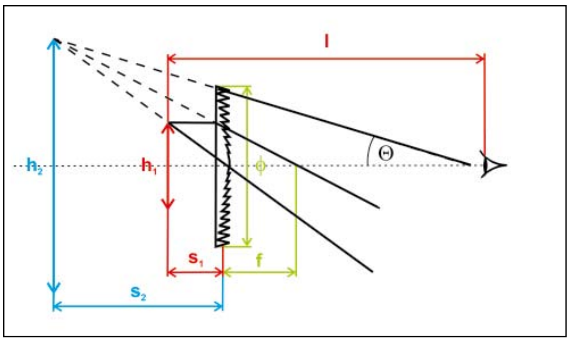



FIGURE 6: **Representation of rays and variable definitions for the magnifier application. The smaller red arrow to the left of the lens represents the object and the longer blue arrow to the far left represents the magnified virtual image.**

be at least $z = 4.5$ mm. Then a Fresnel lens of focal length equal to 4.5 mm should do a very good job of collimating the output.

This computation is valid considering an LED die which is not otherwise magnified by an encapsulant. However, most commercial LED products include the die chip contained within some form of dome lens. This lens effectively acts as a magnifier for the die and the far field region must be found by calculating the die size based on the magnified image formed by this dome. A straightforward geometric method for calculating this magnified image is presented in reference [2].

When attempting to collimate the beam pattern for an LED emitter with a wide angle, it is most likely advantageous to use a reflector in combination with a Fresnel lens in order to minimize the package volume of the optics. However reflector design is not within the scope of this discussion. Here we will compute the necessary lens diameter for a Fresnel lens without a reflector:

$$\phi = 2 \cdot z \cdot \tan\theta$$

Where $\phi$ is the necessary lens diameter, $z$ is again the LED to lens distance (or as described previously, the effective lens to LED die image distance) and $\theta$ is the emission half angle of the LED. Continuing the earlier example where $z = 4.5$ mm, consider an LED of half angle $\theta = \pm 30°$, we calculate a necessary lens diameter of $\phi = 5.2$ mm.

## Fresnel Lens Concentrator

An optical system in which the goal is to converge light from a relatively large regional area to a significantly smaller aperture can be labeled as a condenser or concentrator. For a concentrator system a Fresnel lens design will be thinner and lighter weight than an equivalent continuous surface optic. The gain is most evident at especially large area applications (200 x 200 mm$^2$ or larger for example) in which solid core continuous refractive lenses will become very heavy and unwieldy indeed.

A field in which this advantage is of great importance is solar concentration. The simplest way to think of a solar Fresnel concentrator is to consider a lens with the focal point located right on the solar cell. When lens is pointed directly at the sun, the light will be focused onto the cell with increased concentration thereby requiring less active cell area which can be an economical advantage. A Fresnel lens design of this type is referred to as imaging because there is a fixed finite focal length across the whole aperture of the lens.

Because the real task for maximizing solar radiation onto a cell for electrical conversion does not require minimizing the imaging aberrations, it is actually advantageous to design the Fresnel lens for maximum flux transfer without regard for image quality. A Fresnel lens design of this type is referred to as nonimaging. The design and optimization of nonimaging Fresnel lenses is discussed in detail in reference [4].

Typical for solar Fresnel lens concentrators is to orient the grooves towards the solar cell. This is opposite to the normal sense as described by the earlier collimator application in which the grooves face the long conjugate. With the grooves-in there is the potential advantage of minimizing the impingement of solar radiation on the draft and also to avoid buildup of dirt and debris within the facets.

## Summary

Just a few applications of the Fresnel lens were discussed. Many more are possible. The formulas and examples presented here can be used as guidelines for the initial design phase of a custom application. For more examples of applications and additional technical discussions, more information is freely available at the weblinks in reference [5].

## References

[1] *O. E. Miller, J. H. McLeod, W. T. Sherwood*, Thin sheet plastic Fresnel lenses of high aperture, Journal of The Optical Society of America, Volume 41, No. 11

[2] *A. Davis*, Light Emitting Diode Source Modeling for Optical Design, Intertech-Pira LEDs 2004, http://display-optics.com/pdf/LensDesignForLeds_WorkBook_Davis3.pdf

[3] *John R. Egger*, Use of Fresnel lenses in optical systems: some advantages and limitations (1979), Proc. SPIE, 193, 63–68

[4] *R. Leutz, A. Suzuki*, Nonimaging Fresnel Lenses: Design and Performance of Solar Concentrators (2001), Springer

[5] display-optics.com/literature.htm & display-optics.com/technical_papers.htm