WIS-79/54-ph

Color Corrected Fresnel Lens for Solar Concentration

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ABSTRACT:

A new linear convex Fresnel lens with its groove side down is described. The design philosophy is similar to the highly concentrating two focal Fresnel lens but including a correction for chromatic aberration. A solar concentration ratio as high as 80 is achieved. For wide acceptance angles the concentration nears the theoretical maximum.

In a previous article (1) a convex linear Fresnel lens was proposed to concentrate incoming radiation to a level close to the ideal limit (2). This lens was a two focal point lens, which stigmatically focused a collimated beam coming from either edge of the acceptance field on the respective edge of the Gaussian image of the field. In a subsequent examination it was found that due to dispersion polychromatic radiation could not be sharply focused by the lens (3); this decreases significantly the capability to concentrate solar radiation.

Since the chromatic aberration cannot be avoided, in order to maintain high concentration capability we require that the aberrated rays of either edge beams should fall only inside the interval between the respective Gaussian two focal points. Obviously, due to the symmetry of the lens, it is sufficient to investigate the beam that comes from the right edge of the acceptance field. We can require that the left side of the lens should focus the spectral portion of this beam, which relates to the minimal index of refraction N_{min}, on the edge of the Gaussian image, while the right side focuses the spectral portion relating to the maximal index N_{max} (Fig. 1); these spectral portions of the light will be regarded from here on as the red and blue, respectively, since in most of the transparent material the refractive index behaves as an inversely monotonic function of the wavelength. Mathematically, our requirement can be written as

$$-F\cdot\tan\theta_0 = x - y(x)\cdot\tan\eta_{\xi}^{N_{min}}(x) \quad (x<0)$$
$$-F\cdot\tan\theta_0 = x - y(x)\cdot\tan\eta_{\xi}^{N_{max}}(x) \quad (x\geq 0) \qquad (1)$$

where F is the height of the lens' top above the focal plane, θ_o is the edge angle of the acceptance field, x and y(x) are the coordinates of the lens. $\eta_{\theta_o}^{N}(x)$ is the exit angle of the ray and is a function of $dy(x)/dx$ and $\phi(x)$ given by geometrical optics. The left side of eq.1 represents the x coordinate of the Gaussian image of the beam while the right side describes the intersection of the refracted ray with the focal plane; the unknowns are the shape y(x) and the primary groove's angle $\phi(x)$. Alternatively, based on the symmetry of the lens about its optical axis, we can transform this set of differential equations to a set in the positive region $x \geq 0$, as follows:

$$-F \tan\theta_o = x - y(x)\ \tan\eta_{\theta_o}^{N_{max}}(x) \tag{2}$$

$$F \tan\theta_o = x - y(x)\ \tan\eta_{-\theta_o}^{N_{min}}(x) \quad ,$$

which, together with the boundary condition y(o)=F, have a single valued solution. Obviously, the lens that conforms to this set of equations refracts every ray, which is included in the angular acceptance field and the predetermined spectral region inside the Gaussian image of the field; because if the ray comes from the edge $+\theta_o$ of the field and impinges on the left side of the lens, it is refracted just to the left Gaussian focal point or right to it, as the actual index of refraction is equal to or higher than N_{min}. If it impinges on the right side, again it will be refracted to the left focal point or right to it, as the refraction index is equal to or lower than N_{max}; if the ray comes from inside the field (still from the right of the optical axis) it is refracted more to the right because of the monotonic diffraction of the grooves; and finally the symmetry of the lens about the optical axis excludes the possibility that the ray will exceed the right focal point.

Figure 2 illustrates the refraction of a lens that was designed with the values $\theta_o = 0.5^o$, $N_{min} = 1.485$, $N_{max} = 1.495$, which are common for tracking solar equipment which concentrates the visible radiation; the input radiation are monochromatic collimated beams from the edge θ_o of the field, associated with the refraction indices N_{min}, $N_{av} \equiv (N_{min}+N_{max})/2$ and N_{max}. The figure shows a collector with a Gaussian image width $a = 2 \cdot F \cdot \tan\theta_o$ and small segments of the rays near the focal plane. As expected no ray exceeds the boundaries of the collector. The nature of eq.1 is revealed by the stigmatic focus of the red radiation (N_{min}) that is refracted by the left side of the lens, and of the blue radiation by the right side.

As a comparison, the uncorrected two focal point lens designed with $\theta_o = 0.5^o$, $N = N_{av}$ is also ray traced, showing that half of the red and blue radiation overpasses the collector boundary. A further comparison is made with the conventional flat Fresnel lens (grooves down) designed to stigmatically focus an on-axis collimated beam with $N = N_{av}$. This lens suffers from strong coma and chromatic aberrations, limiting strongly the capability of concentration.

Figure 3 represents the functions $y(x)$ and $z(x)$ of the color corrected lens, the two focal point lens and flat lens. The corrected lens is the narrowest and has the shape of a lemon.

Figure 4 compares the marginal (local) and total efficiencies of the three lenses as a function of f/No (F over the aperture A). For small acceptance angles there is no blocking, and thus efficiency here means transmission; the only cause of loss was assumed to originate from Fresnel reflections on the two optical surfaces neglecting absorption in the bulk of the material. The efficiency is practically independent of the input angle ($0 \le \theta \le \theta_o$) and of the color of the radiation.

Figure 5 shows the concentration capability of the three lenses; the geometrical concentration is defined here as the ratio of A over the minimal segment that includes all the refracted radiation at the focal plane. In addition the effective concentration (geometrical concentration multiplied by total efficiency) is drowned. Clearly the corrected lens enables the highest effective concentration which exceeds the value of 55.

Figure 6 shows the functions $y(x)$ and $z(x)$ of lenses of different θ_o. The lens enlarges with θ_o and its f/No approaches zero when θ_o approaches 90^o. Table 1 summarizes the f/No and geometrical concentration c of these lenses and the truncated half lens ($y(A/2) = F/2$), along with the ideal concentration ($c_{id} = 1/\sin\theta_o$). It is shown that that the color corrected lens enables a concentration of 80 for $\theta_o = 5$ miliradians, which is the solar half angular extent. For higher values of θ_o, the concentration nears the ideal limit.

Acknowledgement

I would like to thank Mr. Abraham Englander for his enlightening remarks.

References

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2. R. Winston, "Light collection within the framework of geometrical optics", J. Opt. Soc. Am. 60, 245 (1970).
3. E.M. Kritchman, A.A. Friesem and G. Yekutieli, "Highly concentrating Fresnel lenses", App. Opt. 18, 2688 (1979).

Table 1

θ_o	Truncation	f/No	c	c_{id}	c/c_{id}
0.25°	whole	1.3	88.1	229.2	38.4%
	half	1.5	78.0		34.0
0.286 (5 mrad)	whole	1.25	80.0	200	40.0
	half	1.4	71.5		35.7
0.5	whole	1.0	57.3	114.6	50.0
	half	1.1	52.1		45.5
1	whole	.87	33.0	57.3	57.6
	half	.94	30.5		53.2
10	whole	.68	4.18	5.76	72.6
	half	.75	3.78		65.6
20	whole	.62	2.22	2.92	75.9
	half	.69	1.99		68.1
30	whole	.54	1.61	2.0	80.5
	half	.60	1.44		72.0
40	whole	.45	1.33	1.56	85.5
	half	.51	1.17		75.2
50	whole	.36	1.17	1.31	89.6
	half	.41	1.02		78.1
60	whole	.27	1.08	1.15	93.5
	half	.30	.96		83.1

Table legend

1. f/No and geometrical concentration c of the color corrected lenses for various θ_o, along with the ideal limit c_{id}

Figure captions

1: A transverse cross-section of convex Fresnel lens, with two grooves magnified.

2: Ray-tracing near the focal plane of the three types of lens with $\theta_o = 0.5^o$. Red (N=1.485), average (1.49) and blue (1.495) collimated beams come from the edge θ_o of the acceptance field.

3: The shape y(x) and groove's angle Φ(x) of the same lenses.

4: The total and marginal efficiencies of the same lenses.

5: The concentration of the same lenses.

6: y(x) and Φ(x) of the color corrected design with various θ_o.

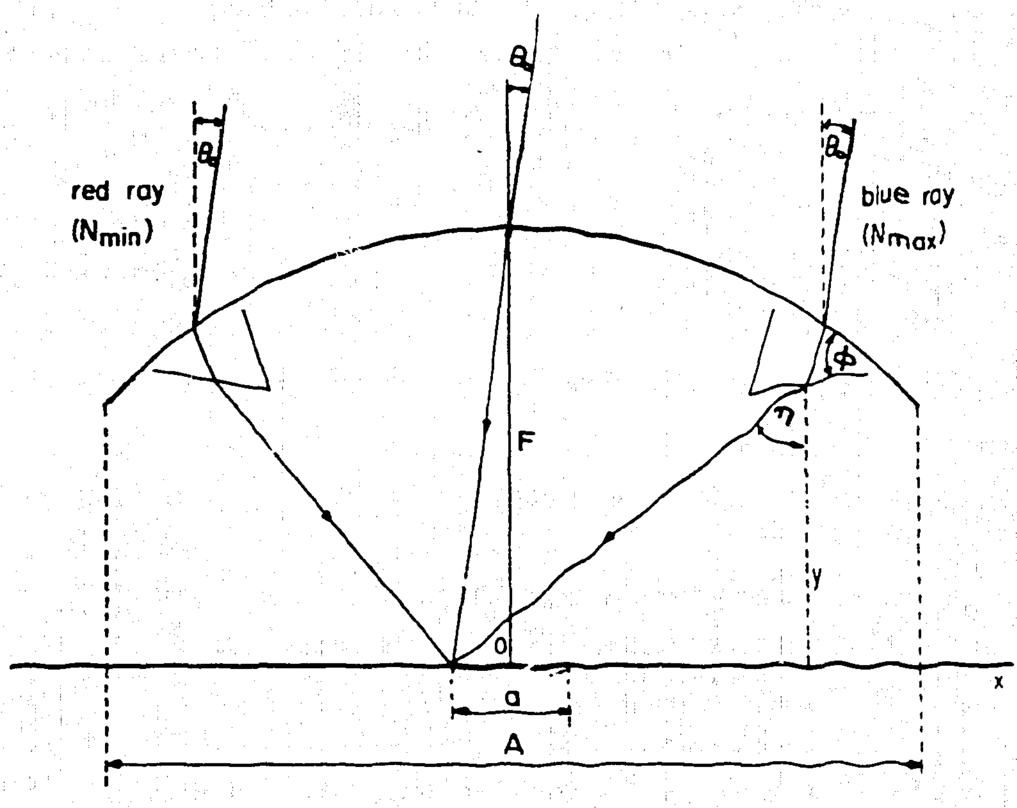

Figure 1

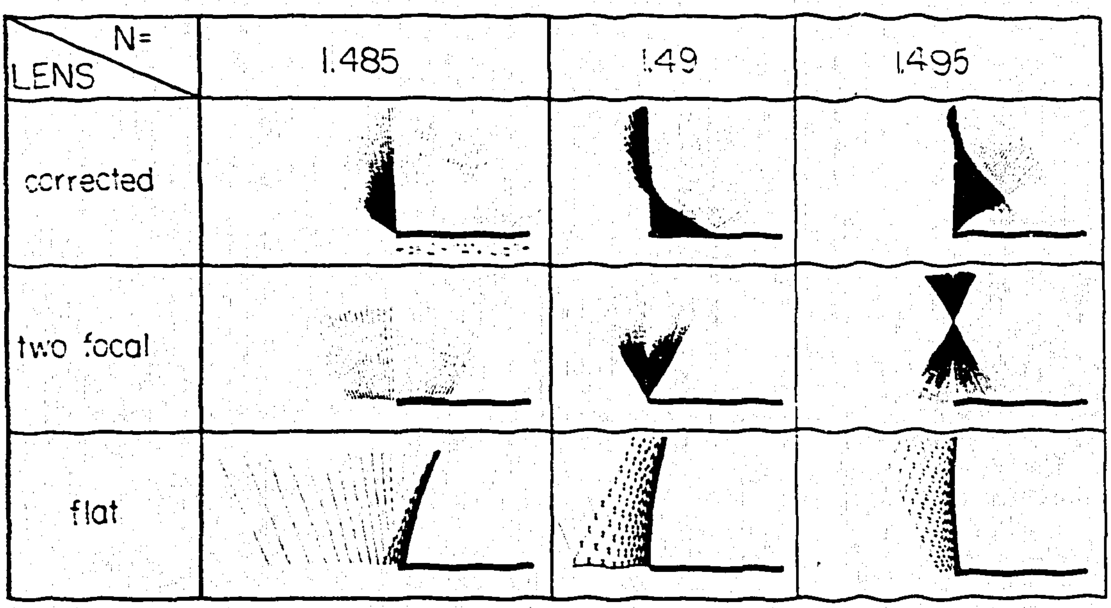

Figure 2

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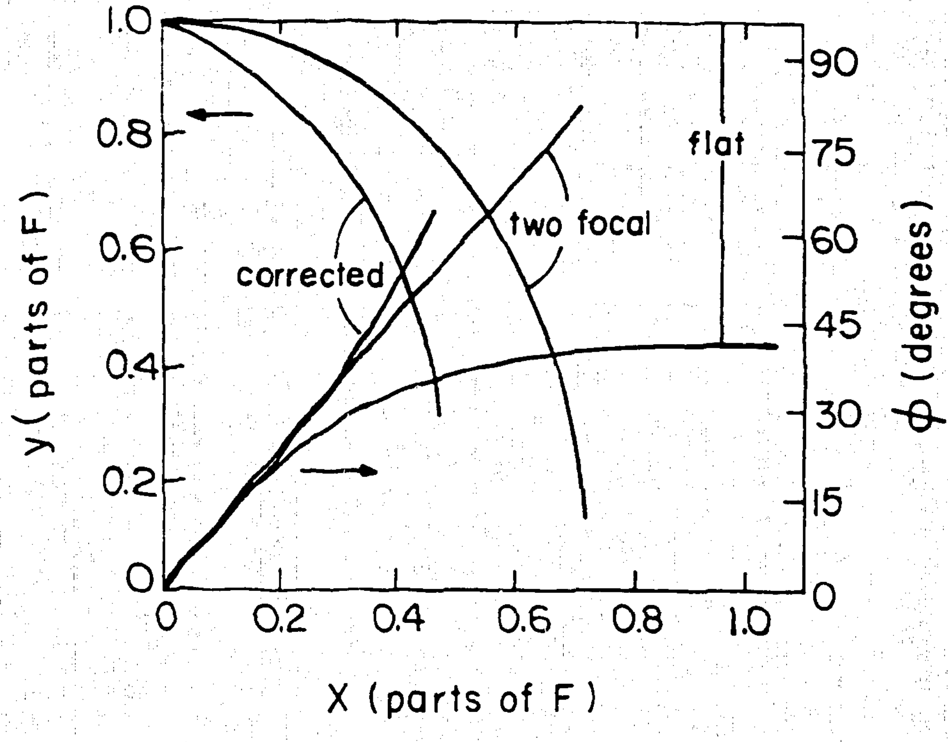

Figure 3

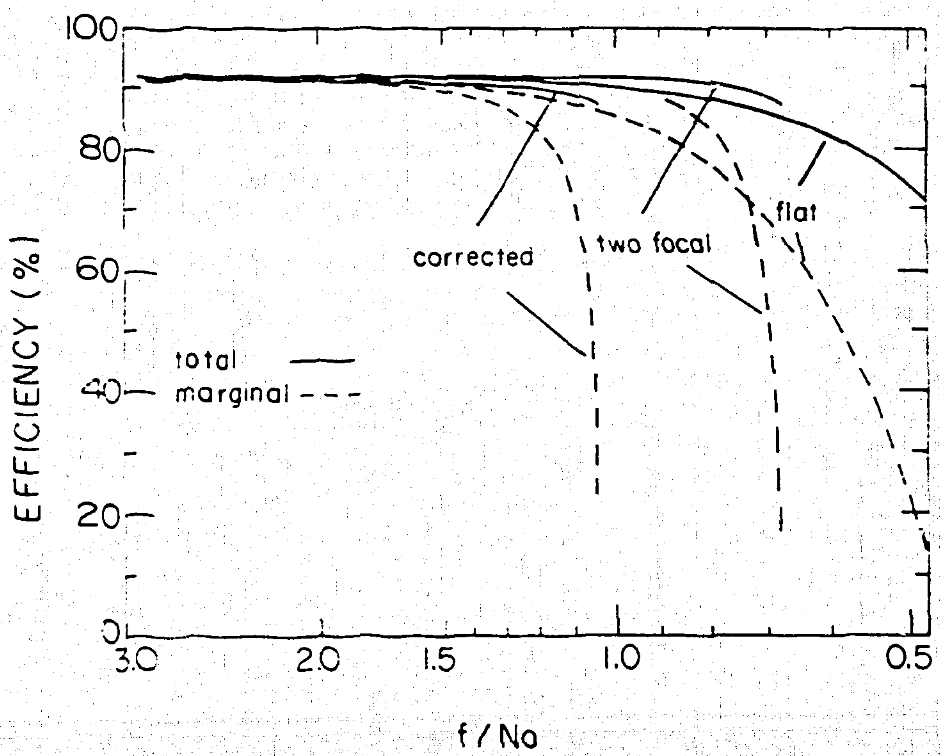

Figure 4

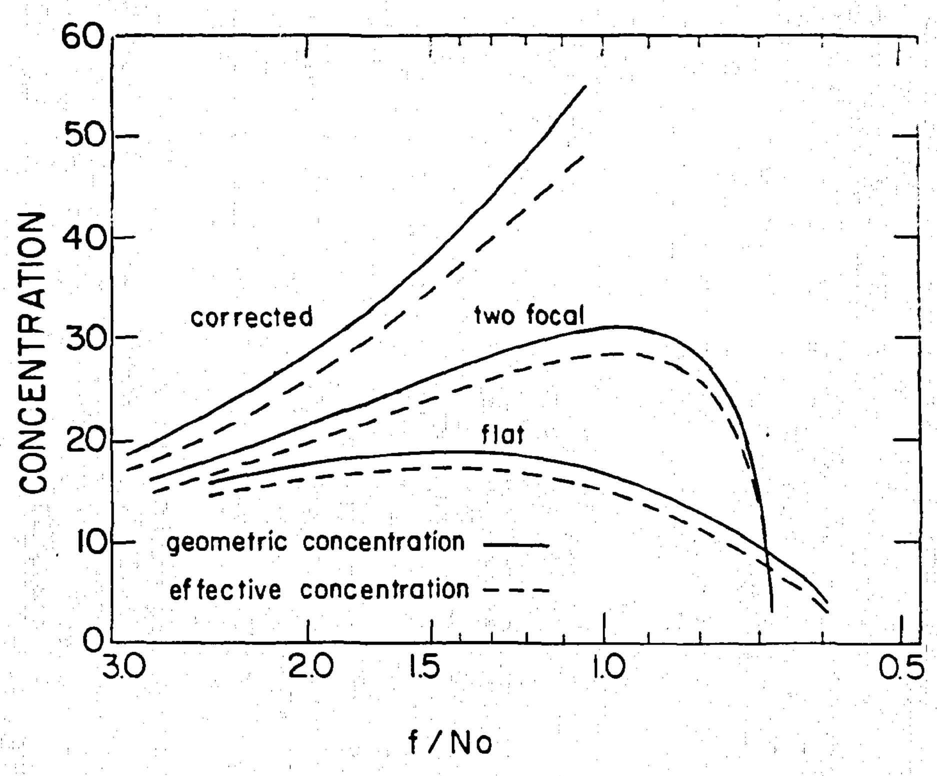

Figure 5

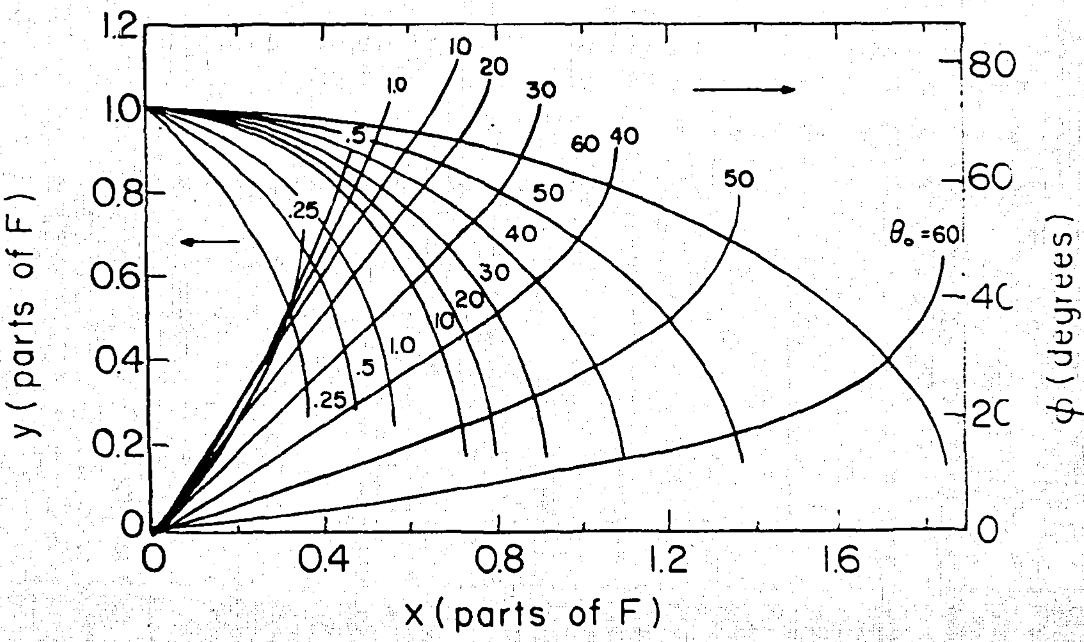

Figure 6