Optical materials for lens concentrators of solar radiation

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Abstract. “Solar” Abbe number is proposed to operate in assessing the suitability of optical materials at sunlight concentrators manufacture. Comparative results are presented for materials practically used in concentrator photovoltaics from the point of view of designing Fresnel lenses from them with a high average concentration in the focal spot of the minimum size and at the same time with minimum focal length.

1. Introduction
Active penetration of modern additive technologies in various fields of science and production provides accelerated development of innovative approaches to the creation of new devices. Immediately, the advantages of 3D printing have found their application in the manufacture of functional optics elements, where users benefit from fast and flexible design iterations, as well as freedom of choice of optical forms.

The concentrator photovoltaic technology is a widely used application of both the classical and the free-form [1, 2] optical components. Attracting 3D printing capabilities significantly expands both the range of concentrators manufacturing procedures (for example, presently the hot-pressing method for the PMMA lenses and the diamond cutting technique for negative matrices with subsequent formation of the silicone profile on glass are the most widely used methods for practical Fresnel lenses) and the range of optical materials that can be involved in optics manufacturing for concentrator photovoltaics tasks [3, 4].

For the high-performance small-sized optical components manufacture with characteristic (micron) requirements to reproduce the profiles of refractive surfaces with high precision, it is necessary not only explore the potential of various technologies, select (synthesize) optical materials with controlled refractive index, low dispersion and high light durability, but also design the shape of radiation concentrators, which most fully uses the technological potential of the equipment and satisfies the criterion of minimizing the optical radiation losses at maximizing the concentrating capability.

When determining the design parameters of the Fresnel lenses (FL) as sunlight concentrators, the maximum average concentration of radiation is the target indicator. At the same time, the optical efficiency of the concentrator is also monitored, which is the higher, the greater the proportion of radiation passed through the lens is delivered to the focal spot of the minimum size. The chromatic aberration that arises due to the spectral dependence of the refractive index for an optical material is the main obstacle in achieving maximum geometric (focal spot size) and optical energy indicators. When constructive (side size $a$ and design choice of focal length $F$) and technological (profile pitch $t$ and the method of its formation) limitations are established for the lens being designed, $n(\lambda)$ refractive index of the optical material is the main parameter controlling the inclination angles of the refractive edges of the profile. The correct choice of the $n^{\text{opt}}(\lambda_{\text{opt}})$ value on the dispersion curve for the calculation of the entire Fresnel profile is a necessary and sufficient condition ensuring high
performance for average concentration \( C_{av} \) at diameter \( d \) for the focal spot \( d \). As shown in [5, 6] for FL from the selected material, there is only one value \( n_{\lambda opt} \) for synthesizing the profile, which simultaneously ensures the achievement of maximum average concentration \( C_{av max} \) and minimal diameter for the focal spot \( d_{min} \). It is obviously that the smaller the dispersion of the optical material the less the light spot is blurred and the more optically effective the lens is in terms of concentrating radiation in a given wavelength range, which should be matched by the sensitivity range of the solar cell intended for concentrated sunlight conversion.

Thus, when calculating the FL profile, the dispersion dependence of the optical material in a certain wavelength range, i.e. overall dispersion \( n_{\lambda 1} - n_{\lambda 2} \) is taken into account. The profile itself is projected according to the selected value \( n_{\lambda opt} \). All these three values can be related through the coefficient of relative dispersion (the Abbe number) [7].

In this paper, to assess the effectiveness of optical materials used in the manufacture of solar concentrators, it is proposed to operate with so-called “solar” Abbe number [8]. Comparative results are presented for materials practically used in concentrator photovoltaics from the point of view of obtaining Fresnel lenses from them, in which the \( C_{av max} \) and \( d_{min} \) are simultaneously achieved.

2. Solar Abbe number
The basic requirements to a material used in manufacturing the FL are its optical transparency in the range of solar cell photosensitivity, possibility of forming a profile with given geometrical parameters, as well as optical (light)/temperature/mechanical stability, accessibility and low cost in mass production. Currently, the most widespread are the “silicone-on-glass” and PMMA lenses [9]. Technologies are also being developed for formatting the Fresnel profile from glass, polycarbonate, and photocurable materials. It is obvious that each of the approaches has its own advantages and disadvantages.

So the advantages of the combined “silicone-on-glass” FL include:
- stability of the geometric and optical characteristics of the lens during long-term operation under the influence of environmental factors;
- high mechanical strength of glass that protects the Fresnel profile;
- high optical efficiency of lenses at low cost of their manufacture and easy adaptation to mass production of lens panels by copying from negative matrices [10].

The disadvantages of the combined lenses include significant differences in the values of the refractive indices of glass and silicone, which does not allow reaching the limiting optical efficiency of the lenses due to the Fresnel losses at the “glass-lens” interface, as well as the temperature dependence of the refractive index of silicone [11].

PMMA lenses are simple and cost-effectiveness, however they have not high mechanical strength and stability of optical characteristics during long-term operation under the influence of environmental factors.

One of the main disadvantages of glass as a material for manufacturing FL is the impossibility of forming from it during mass production a working profile with a small pitch, which is a necessary condition for achieving high energy efficiency of such lenses. In particular, in modern FL based on polymers , the profile pitch can be 0.3 mm or less. To ensure the possibility of using the technology of mass production of glass FL (for example, injection molding), it is preferable to have the profile pitch of the lens is sufficiently large, i.e. the order of several millimeters.

The use of additive technologies for formation of 3D optical objects somewhat expanded the range of the materials promising for application in photovoltaics. However, the temperature and mechanical resistance of photo-curable materials remains insufficient for long-term operation of the lenses.
From a physical point of view, the choice of design (mono-material or a combined SOG-type design) is determined by the ability to reduce the negative effect of chromatic aberration on the concentrating ability of FL.

This effect is manifested the stronger the greater the dispersion of the material, i.e. the difference between the refractive indices of the FL material at the boundaries of the optical range. Quantitatively, this difference is characterized by the Abbe number or \( v \) coefficient of relative dispersion, which is used to characterize and control the quality of glasses and polymers used in the production of lenses. Only in contrast to the values of the refractive indices of the material for standard wavelengths (Fraunhofer lines D, F, and C), in our case, the refractive index values of the material at the “near” \( n_{\text{blue}} \) and the “far” \( n_{\text{red}} \) spectral boundaries of SC photosensitivity range will be used to determine (\( V_{\text{solar}} \)) “solar” Abbe number. The value from the middle of the dispersion curve is \( n_{\text{opt}}^{\text{opt}}(\lambda_{\text{opt}}) \), which is used to calculate the entire Fresnel profile and is a necessary and sufficient condition for ensuring high value for \( C_{\text{av}} \) at minimal \( d \):

\[
V_{\text{solar}} = (n_{\text{opt}}^{\text{opt}} - 1)/(n_{\text{blue}} - n_{\text{red}})
\]

3. Optical materials for efficient Fresnel lenses

When designing the Fresnel profile and calculating the density distribution of concentrated radiation in the focal plane (with the subsequent construction of the optical power characteristic of the lens - OPC), a photometric model of the concentration process was used. The optimization procedure provided a search for a solution for the value of the concentration coefficient and optical efficiency for the area of the focal spot, in which 95% of the concentrated radiation was collected. This approach allows us to design a lens that provide a higher average concentration of radiation at the receiver without any significant loss of the total light flux power transmitted through the lens.

The main characteristics of the optical materials proposed for the manufacture of FL are shown in Table 1. Figure 1 presents the data for the optimal FLs, designed taking into account the characteristic values of the “solar” Abbe number in the wavelength range of radiation of 320–920 nm, corresponding to the photosensitivity range of the top GaInP and the middle GaAs subcells of a highly efficient MJ SC.

| Lens material     | \( \lambda_1 \) = 320 nm | \( \lambda_2 \) = 920nm | Dispersion \( n_{\text{blue}} - n_{\text{red}} \) | Refractive index for lens profile design \( n_{\text{opt}}^{\text{opt}}(\lambda_{\text{opt}}) \) | “Solar” Abbe number |
|-------------------|---------------------------|-------------------------|-----------------------------------------------|-------------------------------------------------|---------------------|
| Nusil LS-6257     | 1.727                     | 1.554                   | 0.173                                         | 1.572                                           | 3.306               |
| Polycarbonate     | 1.670                     | 1.566                   | 0.104                                         | 1.588                                           | 5.654               |
| Luxexcel Opticlear| 1.573                     | 1.518                   | 0.055                                         | 1.531                                           | 9.655               |
| Wacker 604 (SOG) | 1.437                     | 1.400                   | 0.037                                         | 1.408                                           | 11.027              |
| OptiWhite         | 1.553                     | 1.514                   | 0.039                                         | 1.524                                           | 13.436              |
| Schott Glass BK7  | 1.545                     | 1.507                   | 0.038                                         | 1.517                                           | 13.605              |
| Suprasil Standard | 1.484                     | 1.451                   | 0.033                                         | 1.459                                           | 13.909              |
| Urethan polymer   | 1.531                     | 1.496                   | 0.035                                         | 1.509                                           | 14.543              |
| PMMA              | 1.515                     | 1.483                   | 0.032                                         | 1.492                                           | 15.375              |

The concentrating ability of FL linearly depends on the coefficient of dispersion (for polymeric (silicones and plastics) materials. As the Abbe number increases, the values of such important parameters of FL as the optimal focal length and size of the focal spot decrease. At the same time, the achieved average concentration of radiation in the focus increases. This is due to with a decrease in dispersion \( n_{\text{blue}} - n_{\text{red}} \) and a subsequent reduction in chromatic aberrations, since the rays with
wavelengths corresponding to the boundaries of the selected range give less scatter. The graph in Figure 1 also shows that PMMA and Urethan polymer are the most suitable materials (among those studied) for the manufacture of FL. The widespread SOG FLs formed from Wacker 604 on OptiWhite glass are somewhat inferior to the “leaders.” It should be noted with satisfaction that lenses from Luxexcel Opticlear can compete with cost-effective SOG designs when 3D printing technology reaches the required performance in reproducing optical surfaces, especially in terms of sharpness of borders and vertical faces of the Fresnel profile.

**Figure 1.** Dependencies of the average concentration ratio in the focal spot and of diameter for the focal spot containing of 95% concentrated power and of the focal distance on the “solar” Abbe number for optimal FLs (40x40mm2). The following parameters of refractive profile are accounted at ray-tracing analysis: profile pitch is t=0.25mm, profile angular inaccuracies are 5 ang. min., the width of zones of rounding of tooth peaks and troughs is 5µm.

4. Conclusion
Comparative results are presented for materials practically used in concentrator photovoltaics from the point of view of obtaining Fresnel lenses from them, in which the achievement of a high average concentration in the focal spot of the minimum size is ensured. As a criterion in assessing the effectiveness of the optical materials, the “solar” Abbe number is used, which is calculated for the spectral range of photosensitivity of the SC. It is shown that for strongly concentrating FL optical materials with high values of the “solar” Abbe number should be used. It should be noted that composite lenses of the SOG type, despite the low value of the Wacker 604 refractive index chosen for calculation, can provide high optical-energy characteristics comparable to lenses based on mono-materials (Luxexcel Opticlear, Urethan polymer, and PMMA).

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