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Citation for published version (APA):
De Jong, T. M., de Boer, D. K. G., & Bastiaansen, C. W. M. (2016). Diffractive flat panel solar concentrators of a novel design. Optics Express, 24(14), A1138-A1147. https://doi.org/10.1364/OE.24.0A1138

DOI:
10.1364/OE.24.0A1138

Document status and date:
Published: 11/07/2016

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
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Diffractive flat panel solar concentrators of a novel design

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Abstract: A novel design for a flat panel solar concentrator is presented which is based on a light guide with a grating applied on top that diffracts light into total internal reflection. By combining geometrical and diffractive optics the geometrical concentration ratio is optimized according to the principles of nonimaging optics, while the thickness of the device is minimized due to the use of total internal reflection.

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OCIS codes: (050.1950) Diffraction gratings; (220.1770) Concentrators; (350.6050) Solar energy.

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1. Introduction

Solar concentrators attempt to reduce the costs associated with power generation from solar energy by concentrating incident sunlight onto a small area, thereby reducing the required surface area of costly photovoltaic elements. Conventional concentrators are based on reflective and refractive optical elements [1]. By applying the geometrical principles of nonimaging optics [2,3] these can achieve high concentration ratios, but the dimensions of such devices are generally impractical and the resulting systems relatively expensive.

Alternatively, the use of diffractive optics has been proposed to design concentrators with a low concentration ratio, but which have the additional benefits of being inexpensive, compact and lightweight [4–8]. A possible concept is to couple sunlight into a light guide using a diffraction grating and subsequently guide it towards a solar cell via total internal reflection (TIR). In previous work [9–11] it has been shown that so-called slanted gratings are promising for use in this kind of diffractive concentrators, because efficient diffraction occurs for a single order and over a wide range of incident angles. However, although it has been demonstrated that light can be coupled efficiently into TIR, the focus was only on the design of the grating and the (geometrical) design of the concentrator was not considered. Diffractive concentrators are subject to the brightness theorem, which limits the maximum achievable concentration [12,13]. Therefore the geometry of the optical system should be matched to the angular dependence of the grating in order to achieve efficient diffractive concentrators. Doing so requires a combination of diffractive and geometrical optics. The optimization of such a combination is considered in this paper.

2. Limits on concentration by diffractive systems

There is a fundamental limit to the concentration ratio of optical systems, imposed by the brightness theorem (also referred to as conservation of étendue) [2,3]. Essentially it says that the concentration of an optical system cannot exceed the ratio between the solid angles of divergence of the outgoing and the incident beam. Like conventional concentrators, diffractive concentrators are subject to this limit [12,13]. The brightness theorem implies that in order to optimize the concentration ratio, the concentrator should be designed according to two principles. First, at the exit aperture, the bundle should extend over all possible angles. Secondly, outcoupling of guided light upon subsequent encounters with the grating should be minimized when the angle of incidence in air is within the desired acceptance angle of the concentrator and maximized when it is outside the desired acceptance angle.

This paper assumes the use of a slanted grating, see Fig. 1(a). Furthermore it considers the design of diffractive concentrators based on the two principles stated above. This is done assuming a two-dimensional (2D) geometry. That is, in the diffraction geometry of Fig. 1(b), the diffraction plane with $\phi = 0^\circ$ is considered. This assumption is justified by the fact that in a 2D geometry concentrators can often be designed by analytical methods, allowing exact comparison with the limits imposed by the brightness theorem. Furthermore, the design of three-dimensional concentrators is often based on extending a 2D concentrator to three dimensions. A proper understanding of concentrators therefore generally starts with a 2D design.

To determine the consequences of the brightness theorem for diffractive concentrators and the maximum possible concentration ratio for a device based on a slanted grating [9–11], one first has to determine the acceptance angle of the grating that is to be used for the diffractive concentrator. For a grating, the acceptance is given by the range of angles for which efficient diffraction can occur. Previously [11], it was noted that for short-pitch surface-relief gratings, which are assumed in this paper, efficient diffraction occurs when the angle of diffraction sat-
Fig. 1. (a) Sketch of a slanted grating. (b) Grating for in-coupling showing the ±1st orders \((m = \pm 1)\) diffracted into TIR and the undiffracted 0th order \((m = 0)\) leaving the light guide. For the considered slanted grating, the \(m = +1\) order is much more intense than the \(m = -1\) order.

Fig. 2. Diffraction efficiency for unpolarized light, calculated using Rigorous Coupled-Wave Analysis, of the +1st transmitted order as a function of the normalized wavelength \((\lambda/\Lambda)\) and of the angle of incidence \(\theta_{in}\) in air for a slanted surface-relief grating in SU-8 \((d/\Lambda = 1.37, \gamma = 21.87^\circ, n_{in} = 1, n_{out} = 1.6)\). For the region bounded by the dashed lines the angle of diffraction will satisfy \(1/n_{out} \leq \sin \theta_m \leq n_{eff}/n_{out}\).
Fig. 3. Diffraction efficiency for unpolarized light, calculated using Rigorous Coupled-Wave Analysis, of the $\pm 1^{st}$ and $\pm 2^{nd}$ orders as a function of the normalized wavelength ($\lambda/\Lambda$) and of the angle inside the light guide for a slanted surface-relief grating in SU-8 ($d/\Lambda=1.37, \gamma=21.87^\circ, n_{\text{in}}=1, n_{\text{out}}=1.6$). The dashed lines correspond to $\sin \theta = \pm 1/n_{\text{out}}$ and $\sin \theta = \pm n_{\text{eff}}/n_{\text{out}}$.

isfies (see also Fig. 2):

$$\frac{1}{n_{\text{out}}} \leq \sin \theta_m \leq n_{\text{eff}}/n_{\text{out}}$$

where $n_{\text{eff}} = (n_{\text{rel}} + 1)/2$ is the effective refractive index of the grating, with $n_{\text{rel}}$ the index of the relief grating material and $n_{\text{out}}$ is the refractive index of the light guide medium. This is illustrated in Fig. 2, which shows the calculated diffraction efficiency as a function of the angle of incidence in air and of wavelength for a slanted grating, see Fig. 1(a), like that discussed in [11] with thickness/pitch ratio of $d/\Lambda=1.37$, a slant angle $\gamma=21.87^\circ$, $n_{\text{in}}=1$ and $n_{\text{out}}=1.6$. Efficient diffractive incoupling occurs in the region between the dashed lines. We note that it has been found [6] that for real gratings made in SU-8 the diffraction efficiencies can be close to those calculated. Figure 3 shows the same data as a function of the angle of incidence inside the light guide. Since Eq. (1) defines the angular acceptance of a grating in terms of the refractive indices $n_{\text{eff}}$ and $n_{\text{out}}$, both the acceptance angle and the maximum concentration ratio of the resulting diffractive concentrator depend on the choice of materials. The analysis in this paper is done for arbitrary values of $n_{\text{eff}}$ and $n_{\text{out}}$ and specific results are given for $n_{\text{eff}}=1.295$ (corresponding to a slanted relief grating in SU-8, $n_{\text{rel}}=1.59$) and $n_{\text{out}}=1.6$. From the grating equation $n_{\text{out}} \sin \theta_m = \sin \theta_m + m\lambda/\Lambda$, it follows that the range of angles of incidence in air corresponding to Eq. (1) is given by:

$$1 - m\lambda/\Lambda \leq \sin \theta_m \leq n_{\text{eff}} - m\lambda/\Lambda,$$

where $\Lambda$ is the grating period and $\lambda$ the wavelength of the diffracted light. Since the use of a slanted grating is assumed the diffraction order is set to $m=+1$ (i.e., one can assume a single efficient order). To determine the maximum concentration ratio, note that the angle defined by Eq. (2) is symmetric around $\theta_m=0^\circ$ for $\lambda=\lambda_c$, where the central wavelength is defined by:

$$\lambda_c = \frac{n_{\text{eff}} + 1}{2} \Lambda.$$

According to Eq. (2) the acceptance angle $\theta_{\text{acc}}$ for $\lambda_c$ satisfies:

$$\sin (\theta_{\text{acc}}(\lambda_c)) = \frac{n_{\text{eff}} - 1}{2}.$$

The maximum geometrical concentration ratio of a diffractive concentrator is then equal to the maximum concentration ratio imposed by the brightness theorem for the acceptance angle
above. In 2D, the brightness theorem can be written as [2]:

\[ C_{\text{max}} = n_{\text{out}} \frac{1}{\sin \theta_{\text{acc}}}. \]  

(5)

Substituting Eq. (4) into Eq. (5) results in:

\[ C_{g,\text{max}} = \frac{2n_{\text{out}}}{n_{\text{eff}} - 1}. \]  

(6)

Here the subscript \( g \) emphasizes that Eq. (6) considers the geometrical concentration ratio,

\[ C_{g} = \frac{\ell_{\text{in}}}{\ell_{\text{out}}}, \]  

(7)

where \( \ell_{\text{in}} \) is the length of the entrance aperture and \( \ell_{\text{out}} \) is the length of the exit aperture. For a grating that is produced in SU-8 and applied on top of a medium with \( n_{\text{out}} = 1.6 \) the maximum geometrical concentration ratio is:

\[ C_{g,\text{max}} = 10.848 \quad (n_{\text{eff}} = 1.295, n_{\text{out}} = 1.6). \]  

(8)

The corresponding acceptance angle for the central wavelength is \( \pm 8.482^\circ \).

Equation (6) assumes that the bundle is allowed to extend over all possible angles at the exit aperture of the concentrator. When the angular extent of the bundle at the exit aperture is limited by the critical angle of the light guide, the maximum concentration ratio becomes:

\[ C_{g,\text{max}}^{\text{TIR}} = n_{\text{out}} \frac{\cos \theta_{c}}{\sin (\theta_{\text{acc}}(\lambda_{c}))} = \frac{2 \sqrt{n_{\text{out}}^2 - 1}}{n_{\text{eff}} - 1}. \]  

(9)

Inserting the parameters used before results in:

\[ C_{g,\text{max}}^{\text{TIR}} = 8.468 \quad (n_{\text{eff}} = 1.295, n_{\text{out}} = 1.6). \]  

(10)

3. Construction of a diffractive light guide concentrator

This section aims at the design of a concentrator for which the fact that light is diffracted into total internal reflection is exploited to optimize the dimensions of the device. Inevitably, TIR leads to multiple encounters with the grating [5]. However, by using a properly shaped light guide it is possible to limit the losses that result from these re-encounters. This is demonstrated below.

To limit losses that result from guided light diffracting out of the light guide, one can assure that light encounters the grating the second time under a different angle than its initial angle of diffraction. When the second encounter with the grating occurs under an angle of incidence outside the region where efficient diffraction occurs, most of the light remains inside the light guide. This can be done by using a wedge-shaped light guide [4]: if the bottom side of the light guide subtends an angle \( \beta < 0^\circ \) (measured from the x-axis, which is taken to coincide with the grating) then \( |\theta_{\text{in}}| = |\theta_{m} + 2|\beta| \) when light encounters the grating the second time (see Fig. 4).

In order to determine the required wedge angle, note that the range of angles inside the light guide where efficient diffraction occurs is equal to \( \theta_{-} \leq \theta_{m} \leq \theta_{+} \), where the largest and smallest angle of incidence inside the medium are given by (cf. Eq. (2)):

\[ \theta_{-} = \arcsin \left( \frac{n_{\text{eff}}}{n_{\text{out}}} \right), \quad \theta_{+} = \theta_{c} = \arcsin \left( \frac{1}{n_{\text{out}}} \right). \]  

(11)
The required wedge angle of the tapered light guide is therefore given by:

$$\beta = -\frac{\theta_+ - \theta_-}{2} = -\frac{1}{2} \left[ \arcsin \left( \frac{n_{\text{eff.}}}{n_{\text{out}}} \right) - \arcsin \left( \frac{1}{n_{\text{out}}} \right) \right].$$ \tag{12}

The dimensions of the tapered light guide (TLG) follow from:

$$\frac{\ell_{\text{TLG}}}{h_{\text{TLG}}} = \tan |\beta| = \left( \tan \left[ \frac{1}{2} \arcsin \left( \frac{n_{\text{eff.}}}{n_{\text{out}}} \right) - \frac{1}{2} \arcsin \left( \frac{1}{n_{\text{out}}} \right) \right] \right)^{-1},$$ \tag{13}

where $h_{\text{TLG}}$ denotes the height of the tapered light guide (see Fig. 4), since, as shown later on, it will deviate from the height $h$ of the final device.

In order to optimize the concentration, the bundle of guided light should extend over all possible angles at the exit aperture. Light reflected by the tilted surface extends over the angles inside the light guide satisfying $|\theta| \geq \theta_+$ and after sufficient encounters it subtends the entire range of angles $\theta_- \leq |\theta| \leq 90^\circ$. Note that inside the tip of the wedge an infinite number of reflections occurs, assuring that indeed this entire range of angles is obtained. However, since for a light guide concentrator the only limitation results from the critical angle for TIR, the bundle should extend over all angles $\theta_{\text{c}} = \theta_- \leq |\theta| \leq 90^\circ$ in order to optimize the efficiency.

To obtain the angles within the range $\theta_- \leq |\theta| \leq \theta_+$ that are not present after the tapered light guide, one can extend the light guide with a flat part. The length of this part is chosen such that light does not encounter the grating twice:

$$\frac{\ell_{\text{FLG}}}{h} = \tan \theta_- = \frac{1}{\sqrt{n_{\text{out}}^2 - 1}}. \tag{14}$$

After both the tapered light guide and the flat light guide (FLG), the bundle extends all angles within TIR and the concentration ratio can be found by adding the length of the tapered light guide and the length of the flat light guide. However, adding Eqs. (13) and (14) for $h_{\text{TLG}} = h$ results in a concentration ratio $(\ell_{\text{TLG}} + \ell_{\text{FLG}})/h$ which is not equal to the maximum concentration ratio $C_{\text{TIR}}^\text{max}$ given by Eq. (9). The difference occurs due to the discontinuity in the reflecting surface at the transition between the tapered light guide and the flat light. To see this, note that in order to optimize the efficiency, the concentrator should not only accept all rays with $|\theta_{\text{in}}| < \theta_{\text{acc.}}$, but also reject all rays with $|\theta| > \theta_{\text{acc.}}$, where $\theta_{\text{acc.}}$ is the acceptance angle of the system. Now note that close to the end of the wedge some rays diffracted by the grating under an angle smaller than the desired acceptance angle, i.e. with $\theta_{m} < \theta_-$, can still be reflected onto the tilted surface and proceed under an angle $\theta < -\theta_+$. As a result, these rays are not diffracted back out.

To improve the concentration ratio, the transition between both parts of the light guide has to be smoothed. This is done by replacing the last part of the tapered light guide by a curved
section. At the end of the wedge, the tangent of this curve coincides with the bottom surface of the tapered light guide. At the other end its tangent is parallel to the x-axis. Setting \( x = 0 \) at the exit aperture, the transition between the curved part and the flat part should occur at the point \((x, z) = (-h \tan \theta_-, h)\). Furthermore, the curved surface should reflect all rays with \( \theta_m < \theta_- \) onto the grating, so that they are diffracted back out, while all rays with \( \theta_m > \theta_- \) should be reflected towards the exit aperture. This requires a parabolic surface. The axis of the parabola is parallel to \( \theta_- \) and its focus is at the upper end of the exit aperture (see Fig. 5).

From the geometry of this parabola, it can be derived that it is given by:

\[
\left( \frac{x}{h} \right)^2 + \left( \frac{z}{h} \right)^2 = \left( \sin \theta_- \frac{x}{h} + \cos \theta_- \frac{z}{h} - 2 \cos \theta_- \right)^2
\]

(15a)

\[
= \frac{1}{n_{\text{out}}^2} \left( \frac{x}{h} + \sqrt{n_{\text{out}}^2 - 1} \frac{z}{h} - 2 \sqrt{n_{\text{out}}^2 - 1} \right)^2.
\]

(15b)

The required part of the parabola extends between the intersection with the rays that subtend angles \( \theta_\pm \) with respect to the grating surface and that pass through the origin, as illustrated in Fig. 5. Setting \( z = x_\pm / \tan \theta_\pm \) in Eq. (15) and solving for \( x \) results in:

\[
x_- \frac{h}{h} = -\tan \theta_- = \frac{1}{\sqrt{n_{\text{out}}^2 - 1}};
\]

(16a)

\[
x_+ \frac{h}{h} = -2 \frac{n_{\text{eff}} \sqrt{n_{\text{out}}^2 - 1}}{n_{\text{out}}^2 - n_{\text{eff}} + \sqrt{n_{\text{out}}^2 - n_{\text{eff}}^2 \sqrt{n_{\text{out}}^2 - 1}}}.
\]

(16b)

The parabolic light guide (PLG) now increases the concentration ratio of the complete device by adding a segment \( h_{\text{PLG}} = h(x_- - x_+) \) to the total entrance aperture.

For the combined device, the height of the tapered light guide is given by:

\[
h_{\text{TLG}} = \frac{x_+}{\tan \theta_+} = \frac{n_{\text{eff}}}{\sqrt{n_{\text{out}}^2 - n_{\text{eff}}^2}}.
\]

(17)

Inserting this into Eq. (13) and combining with Eq. (16b) shows, after some algebra, that the
Fig. 6. Sketch of a combination of a tapered light guide (TLG), a parabolic light guide (PLG), a flat light guide (FLG) and a Compound Parabolic Concentrator (CPC). All geometrical components are drawn to the same scale assuming a grating in SU-8 and $n_{\text{out}} = 1.6$.

total geometrical concentration ratio of compound light guide (CLG) is given by:

$$C_{\text{CLG}}^g = \frac{\ell_{\text{TLG}}^\text{in}}{h} + \frac{x_+}{h}$$

$$= \frac{2}{n_{\text{eff}} - 1} \sqrt{n_{\text{out}}^2 - 1} = C_{\text{TIR}}^g.$$  \hfill (18a)

Therefore, the combined light guide performs according to the limit imposed by the brightness theorem (cf. Eq. (9)).

In order to further increase the concentration ratio, an additional compound parabolic concentrator (CPC) [14,15] can be attached to the end of the light guide to include angles outside TIR (this CPC does require reflectors). A similar concept has been used in the context of luminescent solar concentrators [16]. Doing so increases the concentration ratio by a factor

$$C_{\text{CPC}}^g = \frac{1}{\cos \theta_c} = \frac{n_{\text{out}}}{\sqrt{n_{\text{out}}^2 - 1}}.$$  \hfill (19)

The length $w$ of the complete device is then extended with the length of the CPC. In terms of the refractive index $n_{\text{out}}$ this additional length is given by [2]:

$$\frac{w_{\text{CPC}}}{h} = \frac{\sqrt{n_{\text{out}}^2 - 1} + n_{\text{out}}}{2(n_{\text{out}}^2 - 1)},$$  \hfill (20)

where $h$ is height of the complete device and therefore equal to the length of the entrance aperture of the CPC. Note that the gain in concentration, but also the increase in length, resulting from the addition of the CPC becomes less when the refractive index $n_{\text{out}}$ increases.

The complete diffractive light guide concentrator (D-LGC) is depicted in Fig. 6. Combining Eqs. (18) and (19) shows that its geometrical concentration ratio is ideal (cf. Eq. (6)):

$$C_{\text{D-LGC}}^g = C_{\text{CPC}}^g C_{\text{CLG}}^g = \frac{2n_{\text{out}}}{n_{\text{eff}} - 1} = C_{g,\text{max}}.$$  \hfill (21)

The sketch in Fig. 6 is drawn to scale assuming a grating in SU-8 and $n_{\text{out}} = 1.6$. For these parameters the geometrical concentration ratio of the diffractive light guide concentrator is $C_{\text{D-LGC}} = 10.848$ and the contributions of the various parts are given by:

$$\frac{\ell_{\text{TLG}}^\text{in}}{h} = 7.141, \quad \frac{\ell_{\text{PLG}}^\text{in}}{h} = 0.526, \quad \frac{\ell_{\text{FLG}}^\text{in}}{h} = 0.801, \quad C_{\text{CPC}}^g = 1.281.$$  \hfill (22)

Eq. (20) results in $w_{\text{CPC}}/h = 0.913$. The dimensions of the complete concentrator are now given by:

$$\beta = 7.676^\circ, \quad \frac{w}{h} = 9.381.$$  \hfill (23)
It is thus seen that the D-LGC is indeed relatively flat.

4. Discussion

The presented design of a diffractive light guide concentrator is based on slanted gratings that can be realized e.g. in SU-8. It is designed to minimize the dimensions of the device, such that light in the light guide that hits the grating again will not escape by diffraction. As a result, light may encounter the grating multiple times. Although the number of hits is rather limited for a large part of the device, it goes up to infinity at the tip of the wedge. Furthermore, the main contribution to the concentration ratio comes from the tapered part of the light guide. The concentration ratio is therefore strongly dependent on the quality of the grating. For an ideal grating, i.e. with first-order diffraction efficiency equal to one for diffraction angles between $\theta_-$ and $\theta_+$ and other diffraction efficiencies equal to zero, the optical concentration ratio will be equal to the geometrical concentration ratio. However, a realistic grating still has a low diffraction efficiency for angles outside the high efficiency region. Adjusting the concentration ratio and the angular acceptance by choosing a smaller value for $\theta_+$ cannot be done for the D-LGC, since its design requires that the diffraction efficiency of the grating is low outside the acceptance angle. The angular and wavelength acceptance are therefore determined by the grating. Furthermore, it should be noted that the design was done for planar diffraction and that the acceptance along the grating lines of the complete device will depend on the 3D design of the concentrator. The resulting system efficiency should therefore be found by combining ray-tracing with numerical results for the diffraction efficiency of the grating. Such simulations are not trivial, but methods for these are available in literature [17].

Trivial extension of the diffractive light guide concentrator to three dimensions results in a tapered plate with a linear grating (like in Fig. 1(b)). This device will not be ideal, since rays that are diffracted under a nonzero azimuth angle can have a projected angle smaller than $\theta_-$ and therefore require a larger wedge angle. Therefore, a possible adjustment to the tapered plate could be to increase the wedge angle, allowing it to accept these rays. Note that since the range of azimuth angles is limited to about $\pm 45^\circ$ [9,11], the required increase of the wedge angle is limited as well. Still, this approach decreases the concentration ratio. One could also consider introducing a second wedge angle in the direction along the grating lines. However, this can only be beneficial for half of the angles of incidence for which efficient diffraction occurs, since the diffraction efficiency of a slanted grating is symmetrical in the line $\phi_m = 0^\circ, 180^\circ$ [11], while a tapered light guide can only work for light propagating into a single direction. This approach thus limits the acceptance angle. In the end, ray-tracing is required for a proper design of a 3D concentrator.

It should be noted that the designs presented in this paper are only based on the extreme angles inside the light guide. In fact, all the equations can be written in terms of the refractive indices $n_{\text{out}}$ and $n_{\text{eff}}$, or in terms of the angles $\theta_+$ and $\theta_-$. The results are therefore not limited to diffractive systems and can be used for concentrators with geometrical incoupling as well.

In practice, the tapered plates discussed here, which could be used as tiles to cover e.g. a roof, could be of dimensions in the order of $10 \times 10\text{ cm}^2$ with a thickness of 1 cm in the thickest part and a solar cell of $10 \times 0.9\text{ cm}^2$ attached to it.

5. Conclusions

A design for a concentrator with a grating at its entrance aperture, a diffractive light guide concentrator, has been presented. It has been shown that the geometrical concentration ratio is equal to the maximum possible concentration ratio imposed by the brightness theorem (in two dimensions). For the diffractive light guide concentrator the thickness of the device is minimized due to optimal use of total internal reflection.
It is expected that such a compact, slim, light-weight device can find application as a low-concentration solar concentrator.

Acknowledgment
This work is part of the research programme of the Dutch Polymer Institute (DPI), project #630.