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Abstract. Secondary optics that allow for the integration of a light-emitting diode (LED)-based luminescent light source into various étendue-limited applications—such as projection systems—are investigated. Using both simulations and experiments, we have shown that the optical efficacy of the luminescent light source can be increased using a collimator. A thorough analysis of the influence of the collimator's refractive index on the optical outcoupling and luminance is investigated and it is shown that it is most optimal to use a refractive index of 1.5. The optimal shape of the collimator is equal to that of a compound parabolic concentrator. Experimental results show that by using a collimator, we can improve the amount of outcoupled light with a factor of 1.8 up to 2.1 depending on the used optical configuration of the LED-based luminescent light source.

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Keywords: collimation; light-emitting diodes; luminescence; optical design; sources.

Paper 150006 received Jan. 7, 2015; accepted for publication Apr. 21, 2015; published online May 12, 2015.

1 Introduction

Light-emitting diodes (LEDs) and lasers are both viable light sources in applications where a bright directed beam is required (e.g., spot lights, projectors). Both sources allow a wide color gamut and have a long lifetime, which means that they do not have to be replaced.¹ Projectors are étendue-limited systems, so the biggest challenge in designing them is to achieve as much luminous flux as possible within the acceptance étendue of the projector. However, the luminance of LEDs—i.e., the luminous flux per étendue—is still small compared to arc lamps. This implies LEDs are advantageous for low-lumen applications, but for bright applications—i.e., above 2000 lm—LEDs might not be the best choice. This is especially the case for green LEDs as they typically have a low-internal quantum efficiency in comparison with red and blue.² Lasers on the other hand can allow for a high lumen output, but they are bulky and very expensive. Currently, it is very difficult to find low-cost green lasers on the market.

Recently, we obtained a green LED-based light source that has been developed by Philips N.V. This light source generates a luminance that is higher than achievable with the current state-of-the-art LEDs. It consists of a luminescent rod—throughout this paper also referred to as lumirod—that generates green light over the full volume of the luminescent rod. This technology is comparable with a luminescent solar concentrator, where light is absorbed by a luminescent waveguide, which then generates light via fluorescence and concentrates this light to the edges of the waveguide via total internal reflection (TIR).^{3–5} This luminescent rod consists of a yttrium aluminium garnet matrix doped with luminescent atoms. These luminescent atoms absorb the blue light

from the LEDs and emit green light, whereas the difference in energy (Stokes shift) is converted into heat. The luminescent green light is emitted isotropic in all directions. Part of this light is guided inside the rod—which has a refractive index of 1.8—by TIR. The other part is leaking out of the light guide. Due to the high refractive index with respect to air, a large part of the light is unable to escape, but also only a limited amount of light is able to escape from the exit facet of the lumirod. In this paper, we focus on utilizing different optical components to couple more light out of the lumirod. The consequences, trade-offs, and possibilities are discussed using optical simulations in ASAP⁶ and experimental verification.

Section 2 describes the optical principles of the light source. Section 3 builds on these optical principles to investigate how to couple more light out of the lumirod using collimation optics. The design of a dedicated collimator for this purpose is described in Sec. 4. Finally, an overview of the results and conclusions is provided in Sec. 5.

2 Light Guiding Incoupling and Outcoupling from a Lumirod

The working principle of the luminescent rod is depicted in Fig. 1. The light from the blue LEDs in close proximity with the luminescent rod is coupled into this lumirod (the LEDs are not optically coupled with the luminescent rod). The blue light is absorbed by the lumirod and converted into green light—as a result of luminescence—that emanates in all directions. Part of this emitted green light is guided inside the rod by TIR. The corresponding critical angle (θ_c) can be calculated based on Snell's law

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Fig. 1 Illustration of the luminescent rod where blue light-emitting diodes (LEDs) couple light into the luminescent rod. The blue light is converted through luminescence into green light emanating in all directions. The largest part of the green light is guided inside the rod due to total internal reflection space (TIR). At the left side of the rod, a highly reflective mirror is placed. At the exit facet of the rod (on the right-hand side), an optical component can be used to couple more light out of the luminescent rod and collimate this light.

$$\theta_c = \arcsin\left(\frac{n_{\text{air}}}{n_{\text{rod}}}\right) = \arcsin\left(\frac{1}{1.8}\right) = 33.75 \text{ deg}, \quad (1)$$

where n_{air} and n_{rod} are the refractive indices of air and the luminescent rod, respectively. All rays that hit the sidewalls of the luminescent rod with an angle larger than the critical angle of 33.75 deg are reflected by TIR. On the left-hand side, a highly reflective mirror is placed in order to reflect the light towards the exit facet of the lumirod (on the right-hand side).

If the light is simply emitted into air at the exit facet of the lumirod, only a limited amount of the light distribution that arrives at the exit plane can be extracted, namely that part of the light that is within a cone with a half-angle equal to the critical angle θ_c . The resulting light distribution in air that escapes the lumirod will have an angular cone with a half-angle of 90 deg. It is, however, also possible to use an outcoupling component to extract much more light from the lumirod. In the remaining sections of this paper, it is interesting to relate the described outcoupling component with an inverse optical concentrator, as is illustrated in Fig. 1.

A more thoughtful description of the angular light distribution inside the lumirod, however, is necessary as the previous discussion considers the lumirod as a two-dimensional (2-D) component, while in reality, it is of course a three-dimensional rectangular tube. This component is simulated using the optical simulation tool ASAP. The simulation model uses a uniform volume emitter at the left-hand side of a very long lumirod. The lumirod is modeled as a material with a refractive index of 1.8 without absorption effects, volume scattering, or nonideal sidewalls. The light distribution, in angular space, of the light guided by the lumirod due to TIR that arrives at the exit facet of the light pipe, is depicted in Fig. 2. This figure shows the directional distribution of the rays at the exit facet of the light pipe as a function of the direction cosines A and B with the X - and Y -axes (the optical axis is the Z -axis), respectively. In Fig. 3, the same information is visualized, but unfolded and scaled to spherical coordinates. The horizontal axis ϕ represents the azimuthal angle and θ represents the polar angle of a spherical coordinate system. Based on Fig. 3, one can see that there are rays inside the lumirod that have an angle larger than 56.25 deg as was previously assumed based on Eq. (1). For $\phi = 0$ or ± 90 deg, θ is limited to 56.25 deg, meaning that in the XZ and YZ -planes, the angles are as were expected based on the previous 2-D approximation. The “spikes” in the angular distribution are focused around $\phi = -135$ deg, -45 deg, 45 deg, 135 deg. This implies

that these rays are oriented along the bisectors of the X , Y -plane. These rays are skew rays that perform a spiral propagation.

The angular light distribution, depicted in Figs. 2 and 3, allows to discuss the usefulness of an outcoupling optic with

Fig. 2 Visualization of the angular (direction cosine) distribution of the rays arriving at the exit facet of the light pipe due to propagation inside the lumirod via TIR. The black circles show the amount of light that can be coupled out depending on the refractive index of the material used as the outcoupling structure. In the case of coupling out into air ($n = 1$), only 16 of 65 possible percentage points couple out. In the case a glass outcoupler is used ($n = 1.5$), 45% points can be coupled out and in case an outcoupler is used with the same refractive index as the lumirod, all of the 65% guided inside the lumirod is coupled out.

Fig. 3 Angular distribution of the light arriving at the exit facet of the light pipe, represented in angular form by the azimuthal angle ϕ and the polar angle θ .

a specific refractive index. Using Eq. (1), if no outcoupling optic is used (extraction into air), all rays within an angular cone of 33.75 deg are able to couple out. A circle representing the rays within an angular cone of 33.75 deg is drawn in Fig. 2, i.e., the smallest circle. This amount of rays corresponds with a luminous flux of 16% compared to the 65% of the light guided via TIR inside the lumirod. In Fig. 3, this fraction of 16% is shown under the lowest dashed line. In case an outcoupling optic with a refractive index of 1.5 is used, all rays within an angular cone of 56.4 deg are able to couple out. This corresponds with a luminous flux of 45% and is visually represented in the figure by the middle black circle. If one wants to couple out all of the rays inside the lumirod, an outcoupler with a refractive index of 1.8 is needed.

The question is whether a refractive index of 1.8 in order to couple out all of the light from the lumirod is really worthwhile. To answer that question, it is interesting to investigate the resulting luminance, i.e., the amount of lumen per étendue, as a function of the refractive index of the outcoupler. The normalized light outcoupling as a function of the refractive index—based on the data presented in Fig. 3—is plotted as the blue curve in Fig. 4. For a source with a Lambertian emission profile, one would expect that the amount of light coupled out of the lumirod increases with the refractive index squared. If the light distribution were Lambertian at the end of the lumirod, the distribution in the projected angular space (A , B) should be uniform. In that case, an outcoupler with a refractive index of 1.5 would have an increase in outcoupling with a factor of $n_{\text{outcoupler}}^2 = 1.5^2 = 2.25$. However, the light distribution in projected angular space (A , B) at the end of the lumirod is not uniform, behaving more as an isotropic emitter. The outcoupling efficiency based on the simulation results is a bit higher than 2.25, namely 2.7.

Focusing again in Fig. 4, it is possible to notice that there is a hitch in the normalized light outcoupling profile around a refractive index of 1.5. This can be explained using Fig. 2 where it is clear that the circle for $n = 1.5$ is the largest one that falls completely inside the angular distribution.

Fig. 4 Normalized light outcoupling and normalized luminance when using an outcoupling optic as a function of the refractive index of the outcoupling optic. The normalized light outcoupling is obtained from the angular light distribution in Fig. 2. One can clearly see that an outcoupler with a refractive index of 1.5 is most advantageous as the luminance obtains a maximum at this value.

As the refractive index is further increased, the angular cone of rays that are able to couple out is further increased but there are not so many rays propagating inside the lumirod with such large angles. As a consequence, the outcoupling increases less for $n > 1.5$. The maximum light outcoupling is obtained for $n = 1.8$.

It is important to note that the usage of an optically coupled component does not only result in an increase of the amount of luminous flux coupled from the light source, but also in an increase of the étendue of the light source. In case no outcoupling optic is used, the half-angle of the light at the exit facet of the lumirod would be 90 deg and the étendue—expressed in $\text{mm}^2 \cdot \text{sr}$ —can be calculated as

$$E_{\text{no out coupling optic}} = \pi \cdot n_{\text{air}}^2 \cdot A_{\text{exit rod}} \cdot \sin^2(90) = \pi \cdot A_{\text{exit rod}} \quad (2)$$

In case an outcoupling optic is used, more light is able to escape from the lumirod and the étendue of the light escaping from the right-hand side of the lumirod–outcoupler interface can be calculated as

$$\begin{aligned} E_{\text{out coupling optic}} &= \pi \cdot n_{\text{out coupler}}^2 \cdot A_{\text{exit rod}} \cdot \sin^2(90) \\ &= \pi \cdot n_{\text{out coupler}}^2 \cdot A_{\text{exit rod}} \end{aligned} \quad (3)$$

As a result, the étendue in case an outcoupling component is used has increased with a factor $n_{\text{outcoupler}}^2$.

From Fig. 4, one can see that the outcoupled light as a function of the refractive index of the outcoupler always increases. However, as the étendue also increases, it is more interesting to look at the normalized luminance (shown as the green curve), which is the amount of lumen per étendue. This curve is calculated by dividing the normalized light outcoupling by the square of the refractive index. One can see that for both a refractive index of 1.5 and 1.8, the normalized luminance is equal. At a refractive index of 1.8, the normalized light outcoupling is in addition higher than at $n = 1.5$. The fact that the normalized luminance increases again near 1.8 is mainly the result of all the skew rays that are taken into account, which corresponds to a low amount of étendue (as can be seen in Fig. 2). In practice, however, the amount of skew rays will be much lower than what is simulated since they are very likely to be absorbed by the material (bulk scattering) before they get to the exit facet. Therefore, it is advantageous to use a low-index ($n = 1.5$) outcoupler. In addition, there are also some technological drawbacks of using a high-index outcoupling optic, such as the fact that they are harder to fabricate and the index-matching glue between the lumirod and the outcoupler is more difficult to make.

3 Outcoupling Component with Good Collimation Efficiency

As concluded in the previous section, more light can be extracted from the exit plane of the lumirod by making optical contact with a medium of a higher refractive index than air in order to avoid TIR. An additional important advantage of an outcoupling component is the fact that this component can be used to transform the light distribution in such a way that it is more useful in a projection architecture, e.g., by providing an angular collimation for the outcoupled light. This is possible by increasing the exit facet of the collimator such

that the angular distribution can be reduced, in accordance with the conservation of étendue.

The maximum performance of a collimator can be theoretically calculated based on the conservation of étendue. The étendue at the exit facet of the lumirod and the étendue of the light at the exit facet of the collimator (in air) should be the same. This can be described as

$$\pi \cdot n_{\text{rod}}^2 \cdot A_{\text{exit rod}} \cdot \sin^2(\alpha_{\text{exit rod}}) = \pi \cdot n_{\text{air}}^2 \cdot A_{\text{exit coll}} \cdot \sin^2(\alpha_{\text{exit coll}}), \quad (4)$$

where n_{rod} is the refractive index of the lumirod, $A_{\text{exit rod}}$ is the area of the exit facet of the lumirod, and $\alpha_{\text{exit rod}}$ is the half-angle of the light arriving at the exit facet of the lumirod. The refractive index of air is denoted as n_{air} , $A_{\text{exit coll}}$ is the area of the exit facet of the collimator, and $\alpha_{\text{exit coll}}$ is the half-angle of the light exiting the collimator at the exit facet. We consider that the exit angular cones are circular. Typically, the exit facet of the collimator will be larger than its entrance facet such that according to the law of conservation of étendue, the angular cone of the light at its exit facet will be smaller than at its entrance facet. The light distribution at the exit facet of the collimator is then transformed using lenses (which essentially scale the spatial light distribution) such that it has a light distribution that can be accepted by the light modulator. We define the étendue efficiency as the percentage of light, emitted at the exit facet of the collimator, that is accepted by the light modulator. If both light distribution have an identical étendue, the maximal attainable étendue efficiency is thus 100%.

Based on the reasoning of an étendue preserving collimator, it is possible to calculate the angular cone within which all the light should be confined, based on the refractive index of the collimator and the area of the exit facet of the collimator. The half-angle $\alpha_{\text{exit rod}}$ of this angular cone (outside the collimator) can be obtained using the following formula:

$$\alpha_{\text{exit rod}} = \arcsin\left(\sqrt{\frac{E}{\pi \cdot n_{\text{air}}^2 \cdot A_{\text{exit coll}}}}\right), \quad (5)$$

where E is the étendue of the source, n_{air} is the refractive index of air, and $A_{\text{exit coll}}$ is the exit facet area of the collimator.

The acceptable extent of the light for a projection system is defined by the size of the light modulator and the f-number of the projection lens. These values define the acceptance étendue of our projection system. To efficiently transfer light from a light source into a projection system, the étendue of the light source should not be larger than the acceptance étendue of the projection system, otherwise part of the light from the source will never reach the projection screen anyway.

3.1 Experimental Verification of the Outcoupling Efficiency

The usability and efficiency of a collimator to couple more light from the lumirod was experimentally evaluated by making use of an off-the-shelf compound parabolic concentrator (CPC) with a rectangular entrance surface area that is slightly larger than the exit aperture of the lumirod (see Fig. 5).^{7,8} The lumirod is illuminated by 15 blue Luxeon Z LEDs.⁹ Each

Fig. 5 (a) Side view of the setup consisting of a blue LEDs illuminating the lumirod. A CPC is brought into optical contact with the exit facet of the lumirod and an integrating sphere is used to measure the lumen output. (b) Outcoupling efficiency from the exit of the rod with and without the use of a CPC.

LED is driven at 2.8 V and 300 mA. The lumirod has a cross section of $2.1 \times 3.7 \text{ mm}^2$ and a length of 22.7 mm is glued onto the LEDs using a silicone with a refractive index of around 1.5. An index-matching gel of 1.5 is used to ensure optical contact between the lumirod and the CPC, which has a refractive index of 1.5. The blue light from the LEDs is re-emitted within the wavelength range of 475 to 600 nm. The optical conversion efficiency from blue to green light—also taking into account the Stokes shift—is currently around 83%. An integrating sphere is used to compare the outcoupling efficiency with and without the usage of a CPC. The integrating sphere measures the relative lumen output of the exit facet of the lumirod—in case no CPC is used—and the exit facet of the CPC—in case a CPC is used. For both measurements, an aperture is placed at the exit facets of both the lumirod and CPC in order to avoid that we also measure light that escapes through the sidewalls of the lumirod or the CPC. The results of both measurements are depicted in Fig. 5.

The outcoupling efficiency when a CPC was used is approximately 1.8 times larger than without a CPC. Based on the simulations in Fig. 4, we would expect to achieve an increase in light outcoupling of 2.7. A possible explanation for the factor 1.8 is most probably the fact that the lumirod is glued onto the LEDs. As there is glue on the bottom of the lumirod, the condition of TIR at that interface is changed and a major portion of the rays inside the lumirod with large angles relative to the longitudinal axis will now be transmitted to the LEDs rather than being guided in the lumirod. The surface of the LEDs will reflect a large part of the light, but will also absorb a portion of the light. At the moment of the measurements, only a component with index matching gel between the LEDs and the lumirod was available. Obviously, the rays with largest angles inside the lumirod are the most likely to be absorbed by the LEDs (since they mostly bounce inside the lumirod) and by using an outcoupling optic, it is mainly the large-angle rays that are additionally being coupled out compared to the case of not using an outcoupling optic. As a result, the experimental outcoupling efficiency is lower than the simulated outcoupling efficiency. Nevertheless, the outcoupling efficiency is still quite high compared to not using a CPC. Preliminary experiments using nonglued LEDs showed an increase of outcoupling efficiency by a factor 2.1 when using a CPC, which illustrates that the absorption losses of the LED surface are at

least partially responsible for the lower gain in outcoupling compared to the simulations. This illustrates that the absorption losses of the LED surface are higher than the Fresnel losses the light encounters when it is not optically coupled.

This experimental verification thus proves that the usage of a collimator is indeed advantageous for coupling much more light from the lumirod thereby increasing the efficacy (lumens/watt) of such a luminescent light source considerably. Using simple back-of-the-envelope calculations, one can estimate the attainable lumen output in a projection system. Recently, the lumen output of the lumirod with CPC was measured to be approximately 2500 lm. In combination with the light of the red and blue LED, a white light beam of approximately 4000 lm could be obtained. Thus, if the projection system should have a lumen output above 2000 lm, the optical efficiency of the projector from the light source towards the screen should be above 50%.

4 Design of a Dedicated Collimator

For the application in mind—i.e., a projector—there are special requirements for shape, dimensions, and angular divergence at the exit facet of the collimator. For a projector, we need the exit facet of the collimator to be rectangular, ideally with the same aspect ratio as the microdisplay. Therefore, it makes sense to use a lumirod with a rectangular cross section as in case the entrance and exit facets have the same aspect ratio, the highest optical efficiency can be obtained. As for the rims connecting both the entrance and exit facets, and the length of the collimator, there is some design freedom. However, one should note that since the lumirod is to be used in compact applications, the size of the collimator should be kept as small as possible.

The choice for the shape of the rims of the collimator is to be found in the domain of nonimaging concentration optics. We have analyzed three different contour shapes (see also Fig. 6). A classic choice for the shape of the contour is parabolic, resulting in a CPC for an incoming light cone with a certain angle θ_{in} (inside the dielectric) towards an outgoing light cone with a certain angle θ_{out} (inside the dielectric). Reflective and refractive CPCs are used to collimate the light of LEDs and to concentrate incident (sun)light on

a small detector or solar cell. A CPC is very close to an ideal concentrator in case it is circular symmetric. In case of a rectangular CPC, the efficiency will be slightly lower.¹⁰ Another type of contour that can be used is a straight line, resulting in a tapered light pipe. This component can be interesting since it is very easy to fabricate. Finally, another option is to create a free-form contour that is defined by a Bezier-curve of which the control points are chosen based on an optimization algorithm using the étendue efficiency as a merit function. Similar collimators have been previously investigated to couple light from LEDs rather than a luminescent component.¹¹

The three previously mentioned shapes are simulated in ASAP on the basis of étendue efficiency. As light source, a rectangular emitting plane with the same dimensions as the entrance facet of the collimator is used. The source is immersed in the collimator and has a Lambertian emission profile with a half-angle of 56.4 deg, which corresponds to an outcoupling angle for a collimator with a refractive index of 1.5 (based on the simulations of Sec. 2). This defines the source étendue. At the moment of the measurements, only a lumirod with a square cross section was available. Therefore, we opted for a collimator with a square entrance and exit facets of $3 \times 3 \text{ mm}^2$ and $7.10 \times 7.10 \text{ mm}^2$, respectively. The length of the collimators is fixed at 15.3 mm, which is the corresponding length for an untruncated CPC contour with $\theta_{in} = 56.4 \text{ deg}$ and $\theta_{out} = 17.5 \text{ deg}$. The exit facet dimensions and length are imposed by the design algorithm of the collimator and are also chosen constant for the tapered and free-form collimator designs.

The source étendue is fixed by the specifications of the source and the system étendue corresponds with a specific size of microdisplay and an according angular acceptance cone. In the simulations, the acceptance cone of the microdisplay is gradually increased and the percentage of light emitted by the source that is accepted by the microdisplay is calculated, i.e., the étendue efficiency. In Fig. 6, the étendue efficiency for the three collimator designs are plotted as a function of the system étendue/source étendue. For a specific acceptance angle of the microdisplay, the source étendue is exactly the same as the system étendue. This area is marked in gray on the figure and is an interesting situation where the sheer efficiency between the different shapes can be evaluated.

One can clearly notice that the efficiency for a ratio of system étendue to source étendue of unity of the tapered collimator is the worst, namely around 74%. This is to be expected as it is not designed to be a good collimator. It is, however, a good reference point to evaluate the other shapes. The efficiency of both the component with the parabolic contour and the free-form contour are basically the same, namely around 92%. The authors have noticed that the free-form design can also be used to create a collimator that is 10% shorter and still has the same efficiency.

Fig. 6 The étendue efficiency of the CPC (parabola) and the free-form collimator is higher than the tapered one.

5 Conclusion

Using both simulations and experiments, we have shown that the optical efficacy of the lumirod can be increased by using a collimator. In case the lumirod is glued onto the LEDs, the amount of light coupled out of the lumirod increases with a factor of 1.8, whereas if the lumirod is not glued onto the LEDs—thus reducing a large part of the absorption losses

by the LEDs—the amount of light coupled out increases with a factor of 2.1. Furthermore, simulations have shown that using a CPC also increases the luminance of the light source. However, in reality, the increase in lumen output is smaller than the increase of the étendue (factor 2.25). Possible reasons for the lower lumen output is the fact that bulk scattering, surface scattering, and LED absorption reduce the amount of light that is able to get extracted from the lumirod. We have performed a thorough analysis of the influence of the collimator's refractive index on the optical outcoupling and luminance. Based on the simulations, the luminances of a collimator with a refractive index of $n = 1.5$ and $n = 1.8$ are equal, but the outcoupled light is higher for $n = 1.8$. However, the extra amount of light that is coupled out are mostly skew rays which are very likely to be absorbed before they reach the exit facet of the collimator. Therefore, a collimator with a refractive index of $n = 1.5$ is most interesting. The shape of the collimator was investigated and a compact and étendue efficient collimator is possible by using free-form contour shapes or a CPC shape.

Acknowledgments

The authors would like to express their great appreciation to Philips N. V. for the opportunity of getting involved in the state-of-the-art research regarding this luminescent light source. Furthermore, the authors would like to acknowledge financial support from the Agency for Innovation by Science and Technology in Flanders (IWT), the Fund for Scientific Research (FWO), the Industrial Research Funding (IOF), Methusalem VUB-GOA, IAP BELSPO VI-10 under Grant IAP P7-35 “photonics@be” and the OZR of the Vrije Universiteit Brussel.

References

1. T. Hager et al., “Power blue and green laser diodes and their applications,” *Proc. SPIE* **8640**, 86400G (2013).
2. M. S. Brennesholtz and E. H. Stupp, *Projection Displays*, Wiley & Sons, West Sussex, United Kingdom (2008).
3. M. J. Currie et al., “High-efficiency organic solar concentrators for photovoltaics,” *Science* **321**(5886), 226–228 (2008).
4. W. G. van Sark et al., “Luminescent solar concentrators: a review of recent results,” *Opt. Express* **16**(26), 21773–21792 (2008).
5. D. K. de Boer et al., “Progress in phosphors and filters for luminescent solar concentrators,” *Opt. Express* **20**(103), A395–A405 (2012).
6. Breault Research Organisation, Inc., “Advanced Systems Analysis Program (ASAP),” <http://www.breault.com> (2012).
7. R. J. Koschel, *Illumination Engineering: Design with Nonimaging Optics*, John Wiley & Sons, Hoboken, New Jersey (2012).
8. R. Winston, J. C. Miñano, and P. Benitez, *Nonimaging Optics*, Academic Press, Waltham, Massachusetts (2005).
9. Philips, “Luxeon Z,” <http://www.philipslumileds.com/products/luxeon-z> (2015).
10. J. Chaves, *Introduction to Nonimaging Optics*, CRC Press, Boca Raton, Florida (2008).
11. F. Fournier and J. Rolland, “Optimization of freeform lightpipes for light-emitting-diode projectors,” *Appl. Opt.* **47**, 957–966 (2008).

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