

Invited Paper

Applications of the SMS method to the design of compact optics

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ABSTRACT

New ultra-thin optical designs are presented that comprise discontinuous optical sections (called channels) working in parallel (multichanneling) to provide the desired optical function. Aplanatic (a particular case of SMS-design) multichannel designs are also shown and used to explain more easily the design procedure. Typically, these multichannel devices are at least formed by three optical surfaces: one of them has discontinuities in the shape, a second one may have discontinuities in its derivative while the third one is smooth. The number of discontinuities is the same in the two first surfaces: Each channel is defined by the smooth surfaces in between the discontinuities, so that the surfaces forming each separate channel are all smooth. No diffractive effects are considered.

Keywords: SMS method, thin optics, aplanatic, optical design, lens design

1. INTRODUCTION

Because of their small size and hemispheric emission, LEDs are more suitable for compact optics than incandescent lamps or fluorescent lamps. When compared with incandescents, the operating temperature of LEDs allows plastic optics to be installed near the LED, while their higher radiance makes them much more suitable for collimating applications than fluorescents (which have comparable efficacy). In a quite similar application to LED optics, Concentrating Photovoltaics (CPV) has also explored the world of compact optics: Recently, several companies in CPV have proposed very thin concentrators [1], [2].

The approach to designing very thin concentrator/collimators has not always been the same. All approaches share the idea of dividing the light flow in different “channels” each one of them having its own optics with surfaces that are not shared with neighbouring channels. Ten years ago, multichannel devices called Stepped flow-line optics (SFL) were developed [3], [5]. Designed with the flow-line method [6], they rapidly found applications in backlights [7], [8] and for combining light sources or efficiently distributing light to several locations [9]-[13]. The main disadvantage of these devices lies in their poor manufacturability, due to the flow-line mirrors having deep and complex shapes with much larger lateral area than aperture area.

This paper presents a design procedure for thin optics based in the Simultaneous Multiple Surfaces (SMS) design method [14]-[18], one that solves the aforementioned disadvantage of flow-line based designs. Nevertheless, flow-lines are sometimes used, when they don't create manufacturability complexities. We will describe this procedure by applying it to the design of an LED collimator.

2. DESIGN OF THE MULTICHANNEL RXI

The design procedure explained here is restricted to rotational symmetric cases, *i.e.*, they are 2D designs in the sense that only planar profiles are generated. The multichannel thin optics, based on the SMS method, are characterized by having an optical surface called light distributor \mathcal{L} which collects the light from a source (an LED in our example) and distributes it over a given support surface. The distributor is in general a mirror. The optics to be designed will be confined between two support surfaces whose cross sections are the lines ι and μ (see Fig. 1) which, in this example, are straight lines. Fig. 1 also shows the flow-lines of the input and output beams. The input beam is formed by the rays issuing from the LED and the output beam is the desired collimated beam. In the case of Fig. 1 the flow-lines of the output beam are vertical parallel lines. Once the multichannel RXI is designed, the flow lines must be continuous so every flow line of the input

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beam will be connected with its corresponding flow line at the output beam. The distributor \mathcal{d} is designed so that once it reflects the flow-lines of the input beam, they intercept the “mirror supporting line” m at the point where the flow-lines of the output beam would intercept it if there was a refraction on the surface ℓ (see Fig. 2). In this case, since the surface ℓ is flat, all that is necessary is a straight extension of the flow lines at the output. In this way, the irradiance (flow per unit of surface) on both supporting surfaces will be the same. This requirement is established to avoid discontinuities on the line ℓ , in order to simplify manufacturing, minimize losses, and avoid corners that can get dirty.

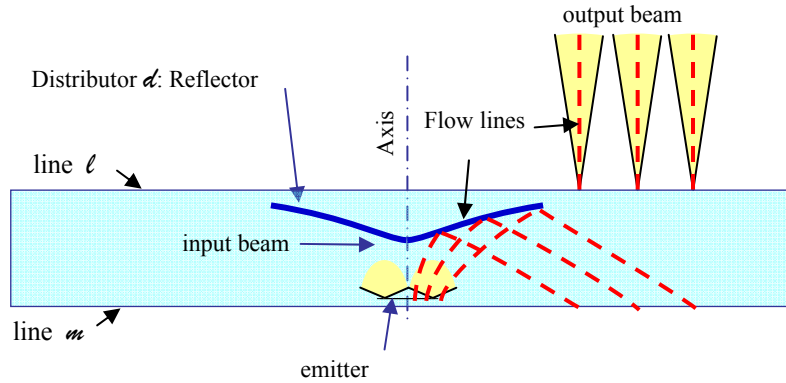


Fig. 1. Design of the distributor \mathcal{d} . The optical system to design is bounded by lines ℓ and m .

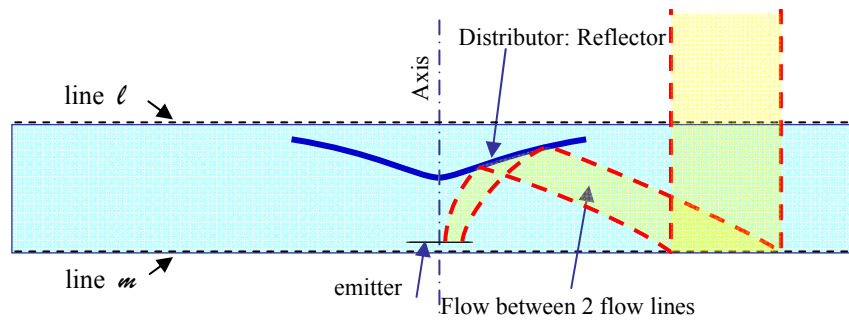


Fig. 2. The distributor ensures that the average irradiance on the supporting surface m is equal to that on the supporting surface ℓ .

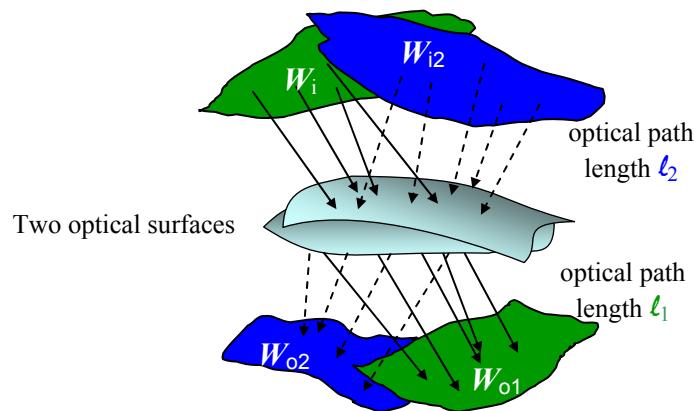


Fig. 3. The simplest version of the SMS 3D method provides two surfaces that transform two input congruences onto two output ones.

Once the distributor is known, a refractive and a reflective surface transforming the edge rays of the incoming beam onto edge rays of the output beam has to be designed. Since there are two edge rays bundles at the input beam (and two at the output beam), this is a classical two-surface SMS design problem. This is schematically shown in Fig. 3, where each

edge ray bundle is represented by a wavefront normal to it. As shown in this Figure, the optical path lengths between wavefronts at the input and at the output can be selected. Each selection of optical path lengths gives a different solution of the problem. In general the solutions are mathematically correct but physically possible only in some cases, as happens in the classical Cartesian oval problem [19], [20]. By selecting different optical path lengths we will be able to design the different channels with the condition that the optical surface supported by the line ℓ be continuous. Fig. 4 shows the final design with the trajectories of some rays. These trajectories show how the bundle is chopped by the mirrors of the multichannel and then rebuilt by the lenses.

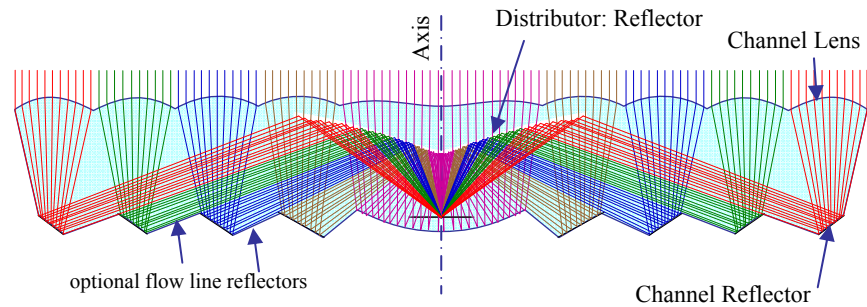


Fig. 4. Multichannel RXI.

2.1 Aplanatic design

Aplanatic systems are axisymmetric optical designs free from on-axis spherical aberration and linear coma. These two conditions entail two further design conditions: (1) stigmatic on-axis image and (2) the Abbe sine condition (note that all the rays involved in these conditions are exclusively tangential). The converse is also true: a design forming a stigmatic on-axis image and fulfilling the Abbe sine condition is aplanatic. Aplanatic designs have long been known through the work of Schwarzschild [21], Wassermann and Wolf [22], Welford [23], Mertz [24], [25] and others. Recently Lynden-Bell and Willstrop derived an analytic expression of more general aplanats [26], [27]. The Abbe sine condition can be derived from the condition of zero linear coma, but this is just one possible approach. For instance, Clausius, who derived the Abbe condition in 1864, did it from thermodynamic arguments [23] (we can also say that he used the conservation of etendue theorem [6]). In 1884, Hockin gave a proof using path differences along tangential rays [23].

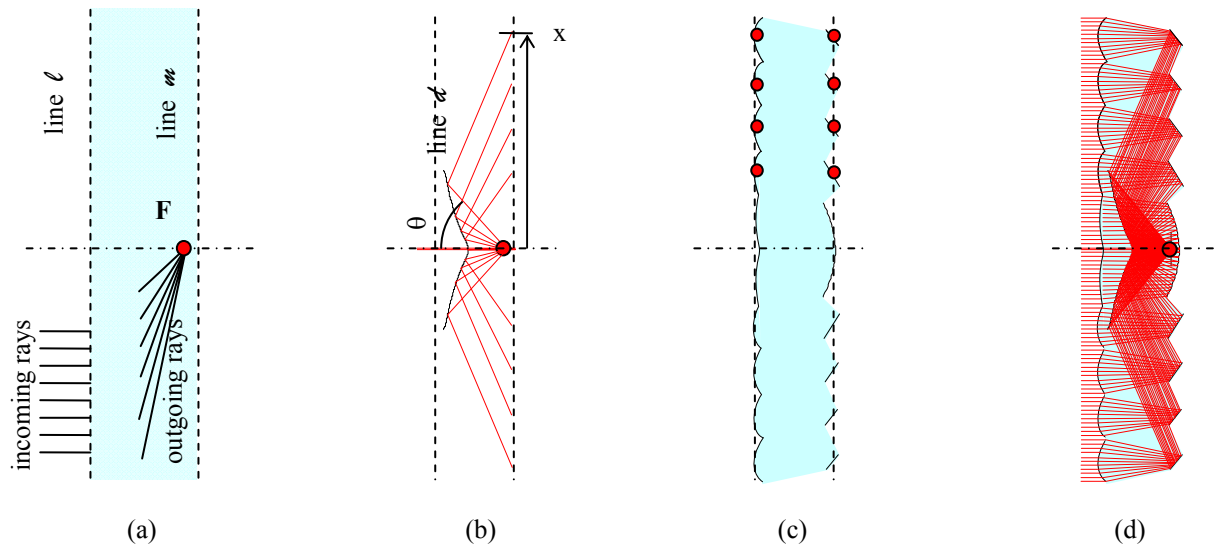


Fig. 5. Design process of an aplanatic multichannel RXI: (a) point F and lines ℓ and m are chosen, (b) the distributor is designed so the rays from F after reflection on it find line m at a point with coordinate x such that $x=f \sin \theta$, (c) aplanatic designs of focal lens f are calculated with different optical path lengths so their refractive surfaces are continuous and tangent to the line ℓ . (d) View of the on-axis ray trajectories.

Aplanatic designs are particular cases of two-surface SMS 2D designs [6], [14]-[19]. An SMS design is a more general case, which in its simpler version can form a stigmatic image of two off-axis points. When these two points of the (two-surface) SMS design are at an infinitesimal distance apart around the axis, the SMS design becomes an aplanatic design [16].

Two rotationally symmetric surfaces give enough degrees of freedom to meet both the Abbe sine condition and the Fermat principle, so that two optical surfaces are enough to produce an aplanatic design. The most well known examples are aplanatic lenses (two refractive surfaces) and Schwarzschild’s mirrors. Once the refractive indices of the different media are established, there are only two constants to determine uniquely the two profiles of the aplanatic design. Of course, the optical system may have more than two surfaces. In general it is possible to design an aplanatic system by designing only two of them, *i.e.*, considering all other surfaces prescribed. These other surfaces can be used for different purposes. In this work we use an additional surface (the distributor) to design ultra thin aplanatic systems with a continuous optical surface (that supported by ϵ) in which the incident wavefronts are separated, individually focused, and rebuilt in different optical channels that operate in parallel.

The design procedure of an aplanatic multichannel RXI is just a application of the procedure described before: The flow-lines now become the on-axis rays, the flow-line continuity condition becomes the Abbe sine condition, the emitter is the focus point F , and the output beam is the beam of parallel on-axis rays. This design procedure is schematically shown in Fig. 5

The distributor plays no role in the bundle “cut-and-paste” procedure, *i.e.*, the bundle of an aplanatic lens can be chopped and rebuild without any distributor. This is because the Abbe sine condition can be fulfilled with different optical path lengths, namely a different one for each channel, as shown in Fig. 6. The figure shows two aplanatic lenses of the same f-number. The one on the left has continuous surfaces (one channel) while the one on the right has two channels. Every on axis ray fulfills the Abbe sine condition with the same focal length.

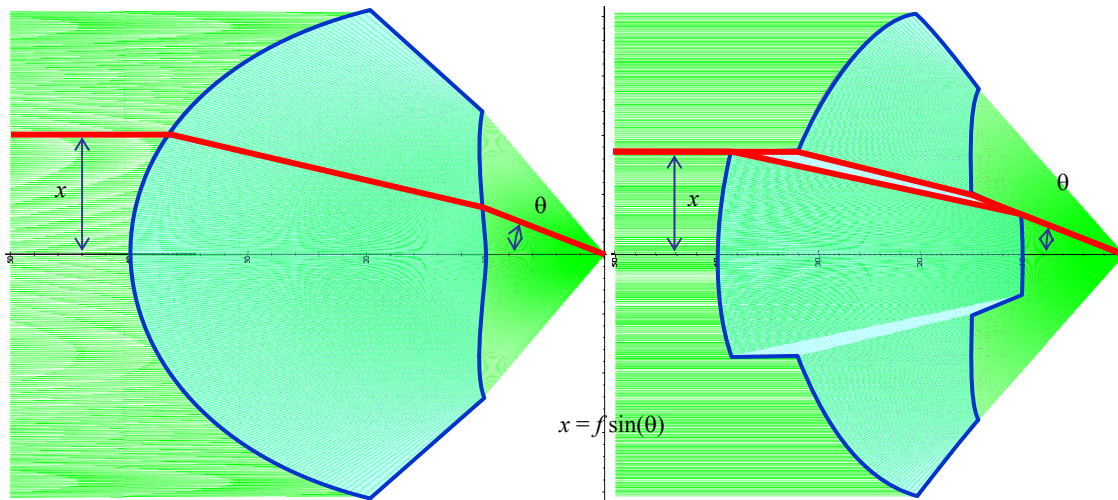


Fig. 6. Continuous aplanatic lens (left) and 2-channel aplanatic lens (right) with the same f-number.

2.2 Distributor options

The distributor is often placed so it blocks the trajectory of incoming rays after refraction at the lenses. To avoid this problem there are two solutions that can be used together or alternatively:

1. Eliminate the channels the outgoing rays of which are blocked by the distributor ϵ . This would eliminate the central channel of Fig. 7 and, partially, its adjacent channel. When the central channels are eliminated, the central part of the distributor becomes useless. This is important because this central part cannot be made to work by TIR. In most of these cases, the usable part of the distributor can work by TIR. Additionally, we can place a lens in the deleted central part of the distributor to help with efficiency. This central part won't have the same degree of collimation as the remaining parts of the multichannel RXI, *i.e.*, in the aplanatic limit, this central part won't have the same focal length.

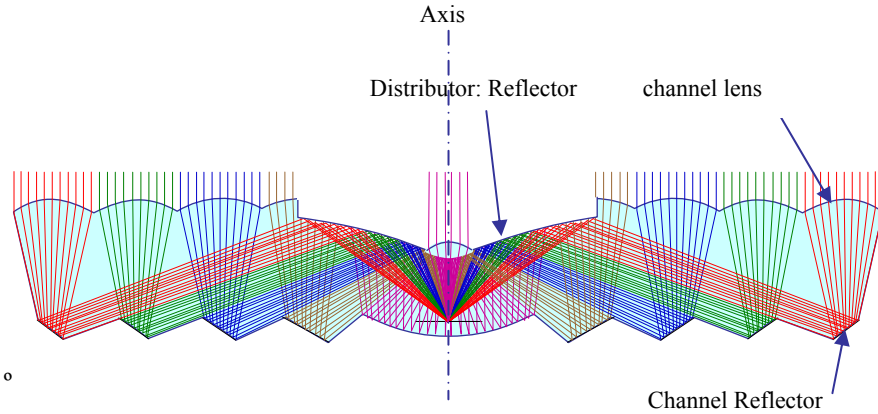


Fig. 7. Option 1: Channels blocked by the distributor are eliminated.

2. Create a thin layer of low refractive index at the position of the distributor, so it works as a TIR mirror for most of the rays issuing from **F** but is transparent for the incoming rays (in a similar way as the front reflector works in the SMS 2D design called XX [6]). This is the case shown in Fig. 4. Again, there is a central part that won't work by TIR. This part can be metalized, which will produce some losses by light blocking (in general very small, <1%).

3. RAY TRACING RESULTS

Fig. 8 and Fig. 9 show two multichannel RXIs whose inner channels have been deleted according to option 1 of the previous section. They are designed for a Platinum Dragon Osram LED (LWW5SN). There is an air gap between the RXI multichannel and the LED encapsulation so the rays enter the multichannel RXI within $\pm \arcsin(1/n)$, n being the refractive index ($n \approx 1.49$). The channel reflectors are assumed to be metalized.

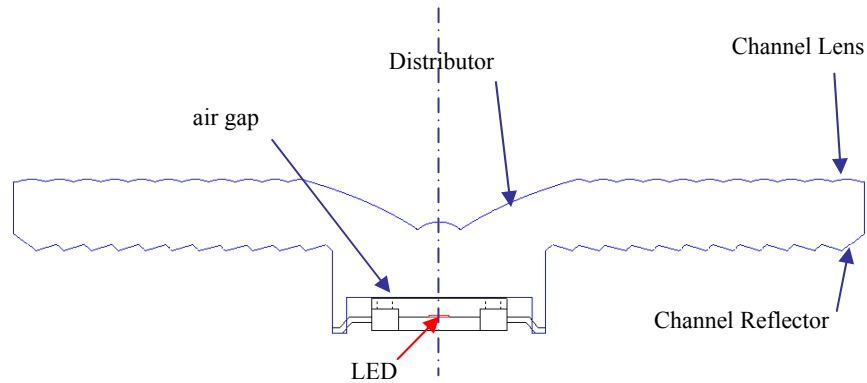


Fig. 8. Multichannel RXI designed for an LED. Emission half angle is ± 2.6 deg.

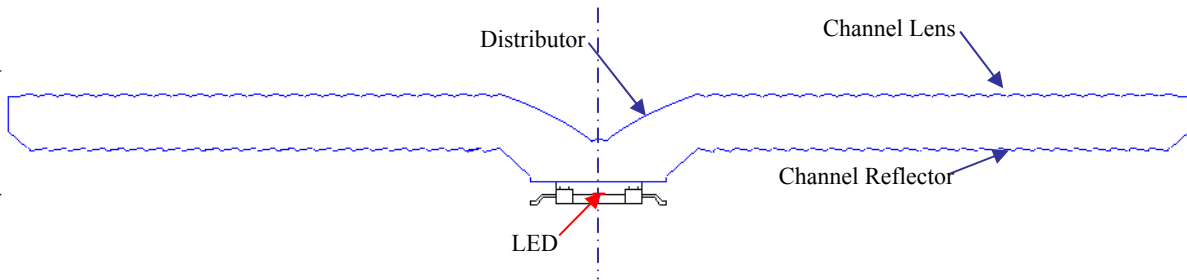


Fig. 9. Multichannel RXI designed for an LED. Emission half angle ± 1.5 deg.

Preliminary results show that losses due to non collimated light (*i.e.*, losses due to absorption in PMMA, emission through the edges and bottom) is 12% for the case of Fig. 8 and 18% for Fig. 9. Fig. 10 shows the intensity pattern of the multichannel RXI of Fig. 9.

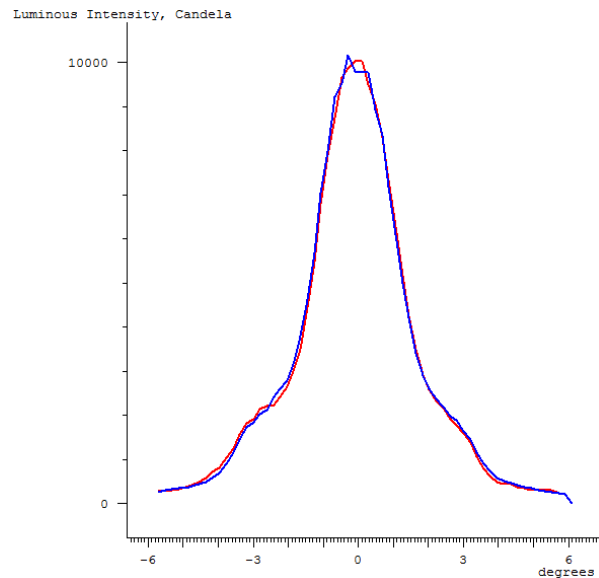


Fig. 10. Intensity pattern of the device of Fig. 9.

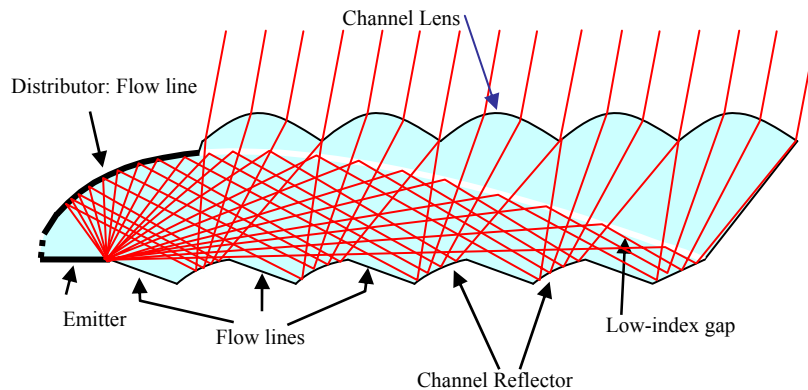


Fig. 11. Example of multichannel RXI in which the distributor is a non-sequential mirror designed as a flow-line. This type of distributors requires in general the lines between channel mirrors to be flow-line reflectors for better collimating performance.

4. MULTICHANNEL RXI COMBINED WITH NON SEQUENTIAL MIRRORS

Thinner devices can be obtained if the distributor is a flow line. In this case, and particularly in very thin devices, the surface between reflector channels must be flow-line reflectors of the flow emitted by the source for a higher efficiency. This is shown in Fig. 11. These flow lines between channel reflectors can also be used in the configurations of Section 2. The distributor is designed in the same way as before, *i.e.*, to get flow lines continuous with those obtained by refracting the flow lines where they output on the lens supporting surface. The difference is that this distributor design is now based on flow-lines. Channel lenses and channel reflectors are designed with the SMS method. This multichannel RXI still shares with the preceding ones its simplicity for manufacturing when compared with thin devices with channels that are designed with the flow-line method.

The main disadvantage of non-sequential distributors is that the performance of a rotational symmetric device generated from it may be quite poor due to the mismatch between the etendues of the bundles of rays with the same skew invariant.

5. CONCLUSIONS

We have presented a procedure to design thin optical devices and in particular a thin RXI. The designs contain a distributor element that makes the thinness possible and ensures continuity of one of the surfaces. The remaining optical elements are grouped in channels. In the multichannel RXI each channel comprises a reflector and a lens. The bundle of rays is chopped so each part is processed by a different channel and rebuilt at the exit of the channels. Unlike previous thin optics designs for LED illumination and CPV, now each channel optic is designed with the SMS method. This generates devices which are much simpler to manufacture.

Initial results show that this design concept is an efficient way to collimate light in very thin devices whose manufacturability is improved with respect other thin design alternatives.

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REFERENCES

- [1] Karp, J. H., Tremblay, E. J. and Ford, J. E., "Planar micro-optic solar concentrator," *Opt. Express* 18, 1122-1133 (2010).
- [2] <http://www.morgansolar.com/fulldescription.php>
- [3] Chaves, J., Collares-Pereira, M., "Ultra flat ideal concentrators of high concentration", *Solar Energy*, **69**, 269-, (2000).
- [4] Chaves, J., Collares-Pereira, M., "Ideal concentrators with gaps", *Appl. Opt.*, **41**, 1267-, (2002).
- [5] Chaves, J., [Introduction to Nonimaging Optics], CRC Press, (2008).
- [6] Winston, R., Miñano, J.C., Benítez, P., [Nonimaging Optics], Academic Press, New York, (2005).
- [7] Miñano, J.C., Benítez, P., Chaves, J., Falicoff, W., Parkyn, W., "Etendue-conserving illumination-optics for backlights and frontlights", US patent application
- [8] Miñano, J.C., Benítez, P., Chaves, J., Hernandez, M., Dross, O. and Santamaria, A., "High-efficiency LED backlight optics designed with the flow-line method", *Proc. SPIE* 5942, (2005).
- [9] Chaves, J., Falicoff, W., Miñano, J.C., Benítez, P., Parkyn, W., Alvarez, R., Dross, O., "Optical manifold for light-emitting diodes", United States Patent 7380962
- [10] Chaves, J., Falicoff, W., Dross, O., Miñano, J.C., Benítez, P., Parkyn, W., "Combination of light sources and light distribution using manifold optics", *Proc. SPIE* 6338, (2006).
- [11] Cvetkovic, A., Dross, O., Chaves, J., Benítez, P., Miñano, J.C., and Mohedano, R., "Etendue-preserving mixing and projection optics for high-luminance LEDs, applied to automotive headlamps", *Optics Express*, **14** (26), 13014-13020 (2006).
- [12] Dross, O., Miñano, J.C., Benítez, P., Cvetkovic, A., Chaves, J., "Non-imaging optics combine LEDs into one bright source", *SPIE Newsroom*, <http://newsroom.spie.org/x3596.xml> (2006).
- [13] Dross, O., Cvetkovic, A., Chaves, J., Benítez, P., Miñano, J.C., "LED Headlight Architecture that creates a High Quality Beam Pattern independent of LED Shortcomings", *Proc. SPIE* 5942, 126-135 (2005).
- [14] Miñano, J.C., González, J.C., "New method of design of nonimaging concentrators", *Appl. Opt.* **31**, 3051-3060 (1992).

- [15] Miñano, J.C., Benítez, P., Wang-Lin,, Muñoz, F., Infante, J., Santamaría, A., "Overview of the SMS design method applied to imaging optics", Proc. SPIE **7429**, 74290C (2009).
- [16] Benítez, P., Miñano, J.C., "Ultra high-numerical-aperture imaging concentrator," J. Opt. Soc. Am. A **14**, 1988-1997 (1997).
- [17] Miñano, J.C., González, J.C. and Benítez, P., "A high-gain, compact, nonimaging concentrator: RXI," Appl. Opt. **34**, 7850-7856 (1995).
- [18] Miñano, J.C., Benítez, P., Wang-Lin,, Infante, J., Muñoz, F., Santamaría, A., "An application of the SMS method for imaging designs," Opt. Express **17**, 24036-24044 (2009).
- [19] Luneburg, R. K., [Mathematical Theory of Optics], University of California Press, Berkeley, (1964).
- [20] Stravoudis, O.N., [The Optics of Rays, Wavefronts and Caustics], Academic Press, New York, (1972).
- [21] Schwarzschild, K., "Astronomische Mitteilungen der Königlichen Sternwarte zu Göttingen **10**, 3 (1905) ", Reprinted: Selected Papers on Astronomical Optics SPIE Milestone Ser. 73(3), (1993).
- [22] Wassermann, G. D. and Wolf, E., "On the Theory of Aplanatic Aspheric Systems," Proc. Phys. Soc. B **62**, 2-8 (1949).
- [23] Welford, W.T., "Aplanatism and Isoplanatism," Progress in Optics **13**, 267-293 (1976).
- [24] Mertz, L., "Geometrical design for aspheric reflecting surfaces," Appl. Opt. **18**, 4182-4186 (1979).
- [25] Mertz, L., "Aspheric potpourri," Appl. Opt. **20**, 1127-1131 (1981).
- [26] Lynden-Bell, D., "Exact Optics: A Unification of Optical Telescope Design," [MNRAS **334**, 787-796 \(2002\)](#).
- [27] Willstrop, R.V., Lynden-Bell, D., "Exact Optics — II. Exploration of Designs On- and Off-Axis," [MNRAS **342**, 33-49 \(2003\)](#).