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REVIEW

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Abstract. The field of concentrated photovoltaics (CPV) has met some remarkable advances in recent years. The continuous increase in conversion efficiency of multijunction solar cells and new advancements in optics have led to new demands and opportunities for optical design in CPV. This paper is a mini-review on current requirements for CPV optical design, and it presents some of the main trends in recent years on CPV systems architecture. [DOI: 10.1117/1.JPE.4.040995]

Keywords: concentrators; solar energy; nonimaging optics; optical design; photovoltaic.

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1 Introduction

Current trends demand that the photovoltaic (PV) concentrators must achieve various goals (lowering costs at all levels and/or increasing the energy yield) in order to reduce the levelized cost of energy (LCOE) (€/kWh).[1] From optical designers' point of view, this implies an efficient and low-cost optical design with maximum tolerances and high concentration that compensates for the expense of triple-junction (3J) solar cells used in these systems.[2–4] The high-concentration photovoltaic (HCPV) industry is focused on commercializing products based on 3J solar cells to take advantage of the high efficiency these cells provide by efficiently partitioning the solar spectrum.[5] Even though the price is continuously reducing, costs are still high enough to require high concentration (geometric concentration C_g higher than 500×) for the systems to be competitive in terrestrial applications.

The continuous increase in conversion efficiency of solar cells is remarkable. It has been achieved by improvements in the cell design and quality of epitaxial layers, as well as by improvements in wafer fabrication processes.[6,7] Multijunction solar cells based on III-V materials have achieved the highest efficiencies of any present photovoltaic devices.[8]

To date, most used commercial 3J cells have a stack of lattice-matched semiconductor layers grown on the germanium (Ge) substrate by metal-organic chemical vapor deposition (MOCVD) (GaInP/GaInAs/Ge).[9] Those lattice-matched 3J cells reach efficiencies of around 39.3% in volume production. Nowadays, 3J cells have reached conversion efficiencies up to 44.5% at concentrations of hundreds of suns under the ASTM G173 AM1.5D low aerosol optical depth (AOD) spectrum.[10] The Solar Junction company developed dilute nitride cell with 44.0% cell efficiency (at 947 suns). Its high level of performance at very high concentrations is outstanding. Peak performance occurs at 400 to 600 suns, and efficiency in excess of 43.0% is recorded at 1000 suns. The last recorded efficiency for inverted metamorphic 3J solar cell (InGaP/GaAs/InGaAs) of 44.4% at 302 suns is reported by the company Sharp.[11]

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Actual recorded value for multijunction cell efficiency is 44.7%, demonstrated with a four-junction solar cell at a concentration of 297 suns (Fraunhofer ISE, Soitec, CEA-Leti and the Helmholtz Center, Berlin).[12]

2 Merit Functions in CPV

Several functions of merit in concentrated photovoltaics (CPV) are used for the optical concentrator's performance analysis.

2.1 *Concentration and Acceptance Angle Product (CAP)*

As CPV has the goal of minimizing energy cost, several aspects have to be taken into account. A key aspect is an efficient and low-cost optical design, which is best met when a minimum number of elements are used, combined with relaxed tolerances and high concentrations, which decrease the size of high-efficiency solar cells for the same energy production. It is a difficult task to reach high concentration and high tolerance at the same time, so we have to find a trade-off between these two parameters.

One of the merit functions in CPV, which is the basis for our previous statement, is commonly interpreted as the CAP, and it is given by

$$\mathrm{CAP} = \sqrt{C_g}\sin\alpha, \tag{1}$$

where C_g is the geometric concentration (the ratio between the concentrator entry aperture and the cell active area) and α is the acceptance angle, defined as the angular span within which the concentrator collects >90% of the on-axis power. The acceptance angle α measures the total tolerance available.

Assuming that n is the refractive index of the material surrounding the solar cell, it should be noted that: $\mathrm{CAP} \leq n$. This provides the theoretical limit on the capabilities of a system to transfer the flux from a source to the target derived from the conservation of étendue theorem.[2] Most concentrators fail to approach this limit. The surrounding medium is sometimes air ($n \approx 1$), and sometimes a clear silicone ($n \approx 1.4$ to 1.5). CAP is useful because for a given concentrator architecture (the same number and type of optical elements), its value is practically constant.

2.2 *Optical Efficiency*

Optical efficiency of the concentrator is defined as the light power transmission efficiency through the concentrator of the light that illuminates the concentrator's entire entry aperture and reaches the target (solar cell). This definition is a wavelength dependent. Usually weighted with the ASTM G173 AM1.5D spectral distribution,[10] it is used by optics manufacturers as it is cell independent.

2.3 *Spectral and Spatial Nonuniformity on Cell Illumination*

Typically, solar concentrators provide nonuniform irradiance on the cell. The nonuniform patterns can create efficiency losses, especially considering that solar cell grids are typically designed for uniform irradiance conditions. This is not because uniform irradiance distribution is optimal in terms of efficiency,[13] but because it is simple and it adapts better to arbitrary irradiance distributions.

When a nonuniform irradiance distribution creates a local photocurrent exceeding the peak tunneling current density, efficiency drop may occur.[14,15] Apart from this situation, if the irradiance distributions corresponding to spectral bands of the different junctions are matched, it is not a severe problem, even if these distributions are not uniform.

A different situation happens when the spectral irradiances over the different junctions are not matched for all points of the cell. Internal currents spreading perpendicular to the main current appear to balance the local photocurrent mismatch between junctions caused by mismatch of irradiance in their bands.[16,17] The sensitivity of multijunction cells to spectral irradiance distribution is expected to increase in the future, for four- and five-junction cells.

3 Materials Used for Optics in CPV

Most CPV systems on the market use Fresnel lenses as primary optical element (POE). Fresnel lenses have traditionally been made of polymethylmethacrylate (PMMA). PMMA lenses are sensitive to oxidative photodegradation,[18] lightweight, and easily manufactured.

Silicone-on-glass (SoG) Fresnel lenses were developed in the 1970s.[19] SoG lens is a two-component system, in which silicone Fresnel facets are attached to a glass cover. The glass cover, which has almost the same refractive index value as the silicone (and hence avoids Fresnel losses), serves as a protection to the external environment and provides a stable support structure. Recently, SoG lenses have gained a considerable market share, as many CPV companies use SoG Fresnel lenses as primary optics.[19–21]

These lenses have higher optical transmission and a broader spectrum response, compared to PMMA lenses. SoG lenses present a higher resistance to external factors, such as scratching and hale impact, greater chemical stability, but have the disadvantages of potential to solarization or corrosion of glass, and a higher weight. These lenses are also more suitable for spectrum-splitting (SS) systems (wider high-efficiency range compared to PMMA). An extended review covering the advantages and disadvantages of SoG and PMMA Fresnel lenses can be found in Ref. 20.

Thermal expansion changes the material density and thereby alters its optical density. The refractive index dependence on temperature affects chromatic aberration effect produced by lenses. Linear chromatic aberration increases with temperature.[22] This effect is considerably high for SoGs.[23,24] Nevertheless, an appropriate optical design can decrease these aberrations and mitigate the effects of temperature in irradiance distributions.

Another option for POE element is a mirror. Currently, there are not many companies that use mirror as primary optics in their systems. Some companies used mirrors in low-concentration systems with silicon cells, but since the cost of standard PV modules dropped in the last years, these silicon-based systems are no longer LCOE competitive. Mirrors can be made of aluminum, with a special coating for surface protection or for higher reflectivity (silver), or glass. Both have a good reflectivity for the majority of the electromagnetic spectrum.

Regarding secondary optical elements (SOEs), render glass is the most used material for CPV refractive SOEs, while for reflective surfaces aluminum or silver is commonly used. Typically, B270 glass is used for molded parts, while BK7 glass is used for flat surfaces. Recently, Evonik developed a competitor to conventional molded glass, Savosil,[24] which consists on a colloidal suspension of silica particles. This material presents an excellent UV stability, high optical transmission over the whole solar spectrum wavelength range, lower thermal expansion than glasses, and it can be shaped to freeform surfaces.

4 Concentrator Designs

In this section, we focus on high-concentration systems. Classical high-concentration systems use the same concepts as imaging optics. These systems consist of only one component, a reflective parabolic dish or a refractive Fresnel lens (see Fig. 1). For the former, all the sun rays are sharply imaged on a point, and for a maximum CAP their focus must be located at the center of the receiver. A parabolic mirror suffers strongly from coma optical aberration, which limits the CAP to the small acceptance angle at the paraboloid rim. This configuration creates a strongly nonuniform illumination on the receiver.

Flat Fresnel lenses are very popular in CPV. Since it is essentially an image-forming optics, it produces an image of the sun inside the solar cell, which must be large enough to allow for tolerances (acceptance angle). Moreover, due to its discontinuous nature, its magnification is nonconstant, so the image of the sun is blurred and the irradiance distribution is not stepped but bell-shaped. Furthermore, chromatic aberration of Fresnel lenses causes significant differences of the irradiance distributions for the different junction spectral bands, and it limits CAP. Nevertheless, due to its simplicity, Fresnel lenses without secondary elements are still a

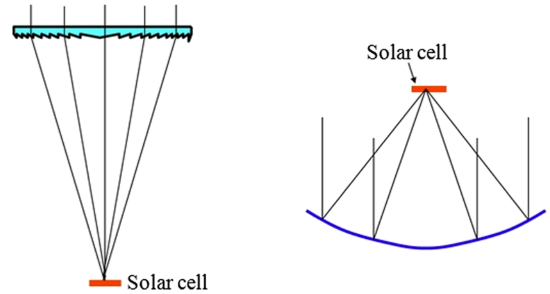

Fig. 1 Fresnel lenses and parabolic reflectors are the classical concentrators in concentrated photovoltaics.

competitive solution at moderate concentrations ($C_g \approx 300 - 500\times$). The company Soitec, using the technology developed by Concentrix, utilizes this approach.[25] With the concentrator system of 500× together with the high-efficiency multijunction solar cells, their module efficiency reaches 31.8%.

In order to alleviate previously mentioned problems, a dome-shaped Fresnel lens instead of flat can be used.[26] The company Daido Steel[27] commercializes this approach. Dome-shaped Fresnel lenses have less geometrical and chromatic aberrations, but their manufacturing is a challenging task.

Nonimaging SOEs increase CAP (as n increases) and improve irradiance uniformity. Two current nonimaging solutions present in the market are shown in Fig. 2. A hollow inverted truncated pyramid reflector (XTP) improves the spectral homogeneity of non-SOEs systems. Company Amonix[28] uses this solution. To date, the highest concentrator module efficiency is claimed by Amonix, the Californian CPV specialist, after the National Renewable Energy Laboratory measured its 35.9% module efficiency.[29] The solid dielectric version of XTP, refractive truncated pyramid (RTP), by using total internal reflection (TIR), improves both the homogeneity and the CAP. Homogenization is obtained through multiple TIRs on the prism walls. Several companies use this kind of SOE, as Daido Steel,[27] Suntrix,[30] and recently bankrupted pioneer CPV firm Solfocus used it as well. For instance, with SOG Fresnel lenses and 39.0% efficient MJ cells, Suntrix module shows 28.0% efficiency.[30] Performance of several different SOEs was the subject of our previous studies.[31]

A compact, easy to assemble, and cost-effective two-stage imaging design is a Semprius concentrator with a plano-convex lens as the POE and a glass ball as the SOE, showing $C_g = 1111\times$ and $\alpha = \pm 0.9$ deg.[32] This company claims a 35.5% efficient HCPV module on a pilot production line, naming it a "record for commercially available solar modules."[33]

One good example of the mirrored POE was a Solfocus two-mirror aplanatic Cassegrain type configuration, where an RTP prism was used as an SOE to increase both CAP and irradiance uniformity.[34] This configuration produces some shading. In order to avoid complete shading, we can use a highly asymmetric mirror as a POE, in addition to hiding the cell receiver and heat sink behind the adjacent mirror as shown in Sec. 4.3.

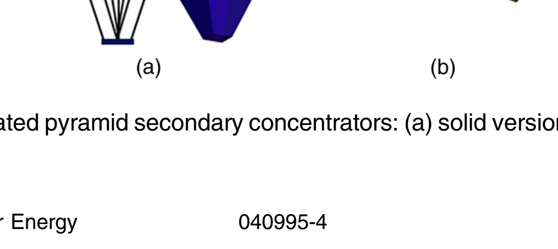

Fig. 2 Inverted truncated pyramid secondary concentrators: (a) solid version (RTP) and (b) hollow one (XTP).

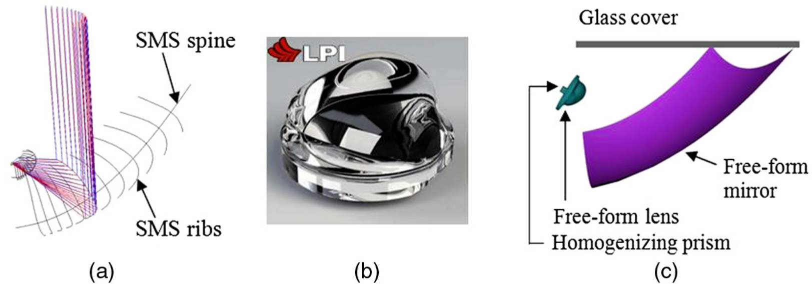

Fig. 3 XR free-form concentrator. (a) CAD design of the concentrator. (b) Free-form lens of the XR free-form concentrator. (c) SMS design method on XR free-form concentrator.

4.1 *Free-Form Concentrators*

Breaking the rotational symmetry allows for an optical performance difficult to obtain with classical approaches. One of the best examples of an extremely asymmetric concentrator is the XR free-form technology, developed by the company LPI using the simultaneous multiple surfaces three-dimensional (SMS 3-D) design method[35] (see Fig. 3).

Two free-form surfaces are designed with the SMS 3-D method [SMS curves contained in these surfaces, called spines and ribs, are shown in Fig. 3(a)]. The SOE is a highly asymmetric free-form surface [see Fig. 3(b)], and the homogenization is performed by a very short TIR prism that protrudes from the lens back (its length is similar to the cell side) [Fig. 3(c)]. Simulation results for XR show the acceptance angle of $\alpha = \pm 1.85$ deg at $C_g = 1000\times$, which implies a CAP ~ 1.0, the highest ever reported to the authors' knowledge.[36]

4.2 *Multifold Köhler Concentrators*

Multifold Köhler systems, proprietary technology of LPI,[37] represent a family of concentrators developed in recent years. Those concentrators work as the Köhler integration arrays produce a uniform irradiance on the solar cell. In CPV, Sandia Labs was the first company to use this concept in 1989.[38] This photovoltaic concentrator has one Köhler integrating pair composed of a Fresnel lens as the POE and a single-surface imaging lens as the SOE, which encapsulates the cell. The secondary lens (single optical surface—SILO) is placed in the focal plane of the primary lens (Fresnel lens) and it images the Fresnel lens aperture onto the solar cell thus providing uniform irradiance distribution on the solar cell as the Fresnel lens aperture is uniformly illuminated by the sun. If the cell is squared, the primary can be a square trimmed without losing optical efficiency. The POE images the sun on the SOE aperture. Consequently, the SOE contour defines the acceptance angle. Concentrations higher than 300× are not adequate because of the incapability of the SILO SOE to image the whole POE properly, whose angular size as seen from the SOE (the SOE "field-of-view" in imaging terminology) and the required magnification (POE to cell ratio) are too large for a single refractive surface to manage, especially for the wide spectrum required. In addition, the spectral uniformity between different junctions decreases with concentration.[39]

One proposed solution to this limitation is a new technology called multifold Köhler concentrators.[40,41] The main idea is to concentrate the sunlight through Köhler integrator pairs, divided into multiple channels, each one comprising two optical surfaces.

The most explored multifold Köhler concentrator is known as the FK4 concentrator[40] that contains a Fresnel lens as the POE, and one free-form refractive surface as the SOE (see Fig. 4).

The FK4 is fourfold symmetric. A standard version of this optics developed by companies Evonik and LPI, called Ventana™, in its first variant uses PMMA as POE material. It operates at 1024× with an acceptance angle of ± 1.1 deg.[40,42] Outdoors electrical efficiency of 32.0% was measured with this Ventana™ when uses a 39.2% efficient Spectrolab C3MJ+ cell.[43] The FK prototype with SOG Fresnel lens and Solar Junction A-SLAM™ cell using dilute-nitrides (cell efficiency approximately 42.0%), showed a single-cell concentrator maximum peak efficiency of 36.0% and regressed 35.6% efficiency,[43] proximate to the current world record shown in Ref. 29.

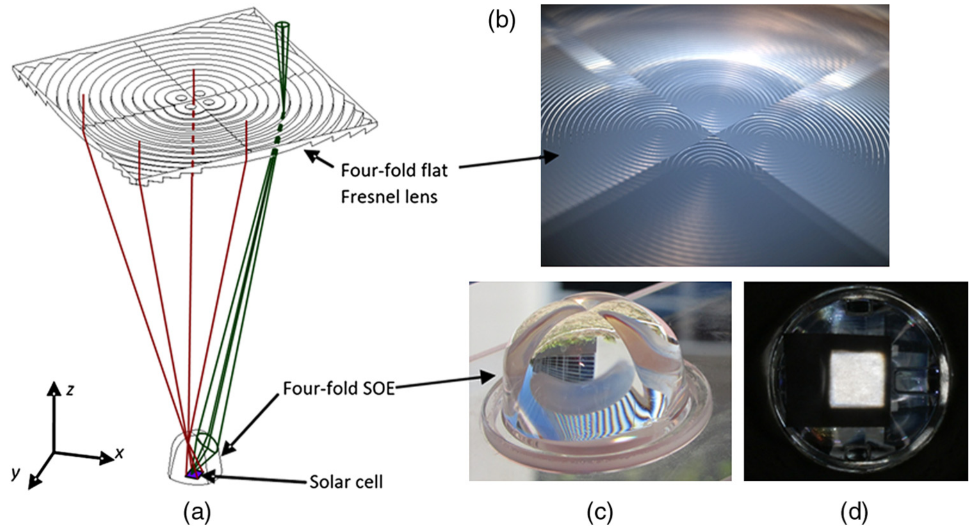

Fig. 4 The FK4 is an advanced fourfold Fresnel-Köhler concentrator. (a) The optical system is illustrated together with the edge-rays distribution. (b) Actual manufactured Fresnel lens POE and free-form SOE, both fourfold, are shown. (c and d) Actual CCD image of the cell plane under outdoor sun tracking. It is a white square illumination, indicating the excellent spatial and spectral uniformity provided.

Other types of multifold Köhler are designed for both refractive and reflective POEs. For instance, a fourfold Köhler approach to an asymmetric mirror was developed to address the reflective configuration[44] [see Fig. 5(a)]. A fourfold Köhler FK4 configuration has a domed Fresnel lens[45] in order to increase the acceptance angle of its flat Fresnel lens predecessor [see Fig. 5(b)]. Quite remarkable is Fresnel-RXI Köhler whose POE is a flat Fresnel lens and whose SOE is a fourfold free-form SMS 3-D RXI lens which contains two free-form surfaces [Fig. 5(c)]. It leads to a CAP = 0.85, the highest reported for flat Fresnel POEs to the authors' knowledge.[46] Recently, a Fresnel-Köhler of ninefold was developed[47] [shown in Fig. 5(d)]. This system was developed to pave the way for four-junction cell–based systems, and it keeps excellent spatial and spectral irradiance uniformity even for very high concentrations and very high temperatures, which affect the refractive index of the SOE.

High CAP value (shown in Fig. 6) may be used for maximizing other functions of merit in CPV not directly related with C_g and α (e.g., the electrical efficiency), described in Sec. 4.3.

4.3 *Advanced Designs*

Two main sources of conversion losses in present HCPV three-junction (3J) cells are: (1) still inefficient utilization of the solar spectrum and (2) the reflection losses of concentrator cells, mainly due to the grid line shading factor.

An external confinement cavity can recover the light reflected from 3J cells. By adding the external confinement cavity, the light reflected by both 3J cell metallic grid-lines and semiconductor surface is recovered. In this way, the concentration is reduced, the acceptance angle is maintained, and relative electrical efficiency is boosted. The proof-of-concept concentrator CFK was developed,[48] and a relative efficiency increase of about 6.0% was measured at 18.45 $\mathrm{W/cm^2}$ with C3MJ+ solar cells[43] (see Fig. 7). With higher concentrations and optimized grid-lines shading factor (fs), we may reach an important relative electrical efficiency boost. For instance, if we use the FRXI architecture with external cavity, for irradiance level of 130 $\mathrm{W/cm^2}$ on the solar cell with the semiconductor reflectivity set to 3%,[49] grid-lines and mirror reflectivity of 90% and $fs = 11.45\%$, we model a relative electrical efficiency gain of 11.4%.[50]

Spectrum splitting (SS) features address more efficient spectrum partition. An advanced SS concentrator was developed with a flat filter that works at 40 to 50× (in order to be cost-effective), and the use of two coplanar commercial 3J and silicon cells that can share the same heat spreader, simplifying the heat management and wiring (see Fig. 8).[50] Other benefits provided by

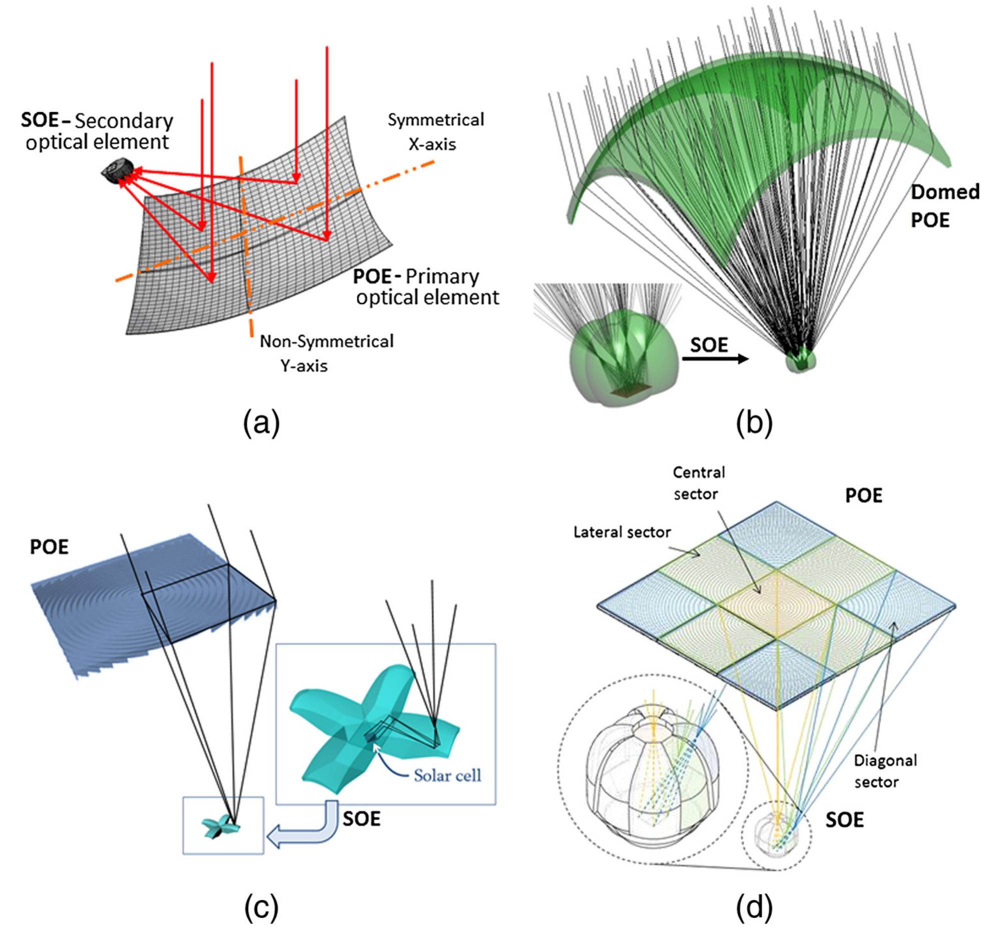

Fig. 5 Different configurations of multifold Köhler family: (a) shadow-free mirror-based fourfold XR Köhler concentrator; (b) the domed-shaped fourfold Fresnel-Köhler; (c) Fresnel-RXI Köhler; and (d) ninefold Fresnel-Köhler.

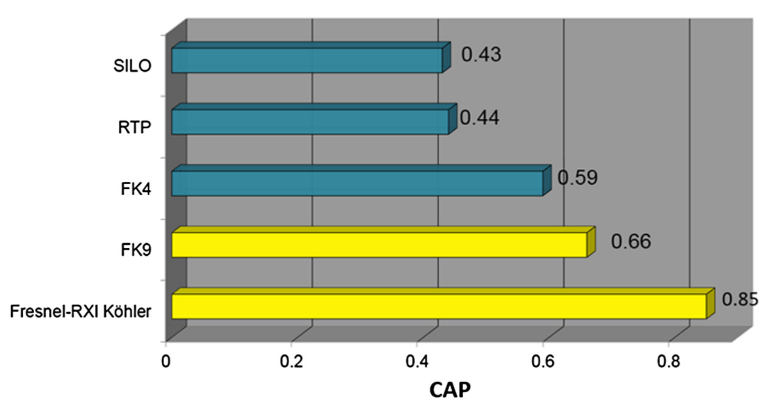

Fig. 6 Concentration and acceptance angle product values of different Fresnel-based systems with rather good to excellent irradiance uniformity.

this concept are: (1) use of an external confinement cavity that recovers light reflected by 3J cell; (2) SOE working with two cells, filter and cells, forms a single piece of dielectric, which simplifies its mounting; (3) this advanced Köhler concentrator addresses tight tolerances (at high concentration); and (4) cells work at high geometrical concentration (500×) and in this way contribute to the cost-effectiveness of this SS concept.

Last few years many different approaches with the dichroic beam-splitting system were proposed. The Very High Efficiency Solar Cell program (VHESC, funded by DARPA) developed

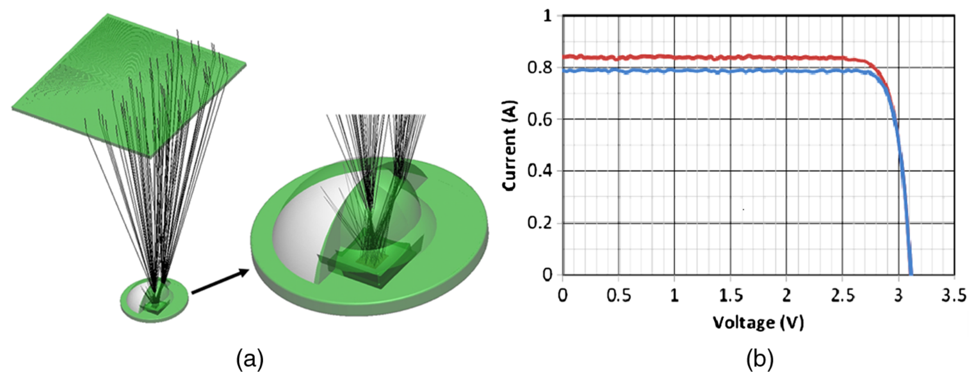

Fig. 7 (a) CFK in operation. The POE is placed in upper part. Some simulated rays impinging on the solar cell are reflected onto its surface and recovered by the cavity. (b) Measured IV-curves for CFK (higher current level, red curve) and FK (lower current level, blue curve), both corrected for the CSTC standard conditions: DNI $= 1000\ \mathrm{W/m^2}$ and $T_{\mathrm{cell}} = 25$ deg. The CFK shows $I_{\mathrm{sc}} = 0.839$ A and a module electrical efficiency $\eta = 32.5\%$, while FK presents $I_{\mathrm{sc}} = 0.791$ A and $\eta = 30.8\%$.

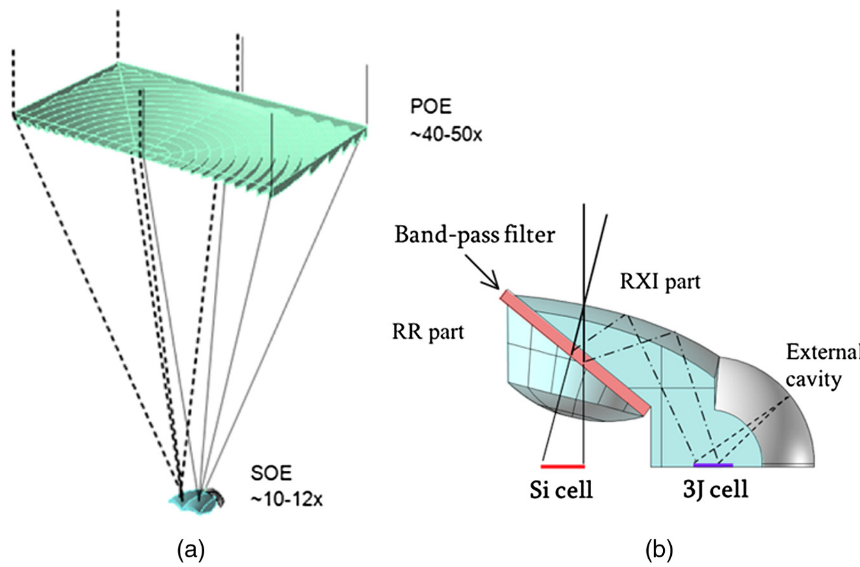

Fig. 8 (a) Asymmetric twofold Köhler-Fresnel lens illuminating the corresponding twofold RXI-RR SOE. (b) Onefold SOE RXI-RR with dichroic filter and external cavity.

different cell designs for four-, five-, and six-junction systems, for a nontracking system (i.e., low concentration) (see Fig. 9). The five-junction system composed of a two-terminal/two-junction (GaInP/GaAs) cell, a silicon cell, and a three-terminal/two-junction (GaInAsP/GaInAs) cell led to 42.7% computed efficiency at 20× for the two-junction cells and 8.7× for the silicon cell.[51]

Within the same VHESC program, another simpler four-junction system concentrator unit module was developed. It consists of a single-sided convex lens working at approximately 20× and a dichroic filter to split the concentrated light between a two-junction/three-terminal (GaInP/GaAs) cell and another two-junction/three-terminal (GaInAsP/GaInAs) cell. It has the current world record for this type of a submodule (shown in Fig. 9) with an efficiency of 38.5% ±1.9% under the ASTM G173.[52] The VHESC module architecture is a good illustration of the beam division systems' wiring and assembly complexity. The placement of the GaInP/GaAs cell in an oblique downward position well inside the module makes the heat sink design challenging.

Another approach[53] is a system using a two-terminal/two-junction (GaInP/GaAs) cell and a GaSb infrared (IR) solar cell within a Cassegrain-type concentrator (see Fig. 10). The SS is done on the curved surface of the secondary mirror. The GaSb IR cell is placed after the secondary

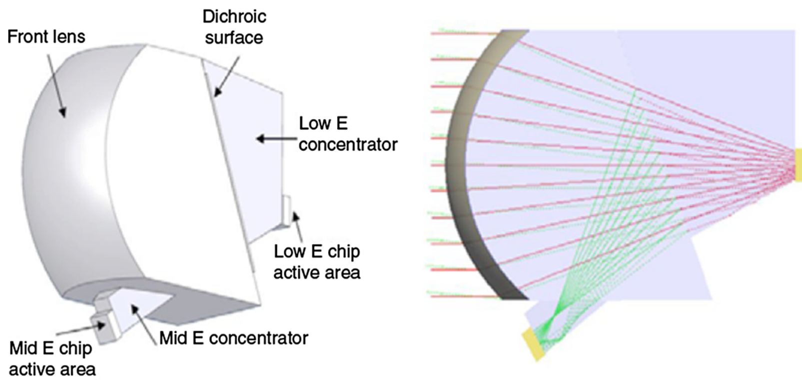

Fig. 9 A 37.5% efficient, 40× concentrator unit developed in the VHESC program.

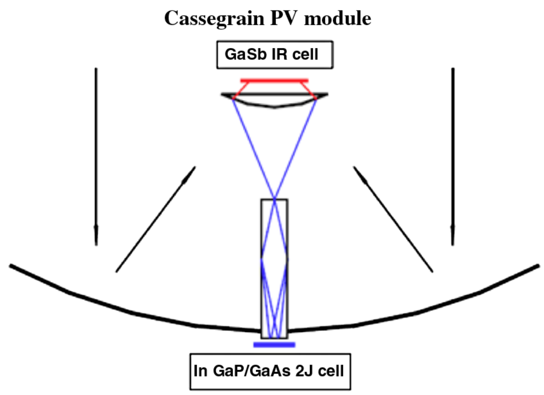

Fig. 10 Dual-focus Cassegrain module concept.[53]

mirror. The GaInP/GaAs is set close to the apex of the primary. Independent heat sinks and wiring for the module are used (so the whole set is four-terminal). However, the difficulty of manufacturing and the cost of the multilayer dichroic filter needed on the curved surface (the one of the secondary mirror) represent drawbacks regarding this module.

There are many different proposed SS solutions that represent different challenges: heat management for noncoplanar cells arrangement, assembling complexity, correspondence between experimental and simulated performance, cost-effectiveness (use of dichroic filters), etc. High concentration of sunlight allows the use of complex filters and multiple PV materials. In order to guarantee cost-effectiveness, the filter can be deposited directly on top of the PV cell, but due to thin film stress (possible cracking or flaking) this option requires careful attention to material mismatch and to the influence of temperature and flux gradients across the device.

SS systems of potentially higher practical efficiency than MJ cells are of special interest, due to the limits to the number of PV cells that in practice may be stacked on top of each other, as well as due to electrical, cooling, and material constraints.

Several photovoltaics SS systems for terrestrial applications have been prototyped, but in most cases, measurement results have not demonstrated the predicted efficiencies. There is also a lack of practical systems to demonstrate the feasibility of this technology and to bring the cost down. Practical experience leading to more efficient solutions and a larger production volume is necessary. This is true for all CPV systems.

For SS systems, it is especially hard to compete with tandem or MJ cells since large research efforts have recently been put in constant improvement of electrical conversion efficiency for those devices. Due to demonstrated high efficiency and simplicity of the tandem cell, this approach has a benefit on the market in comparison with the SS systems. The SS systems have added requirements to optics and do not have the same history of long-term operation.

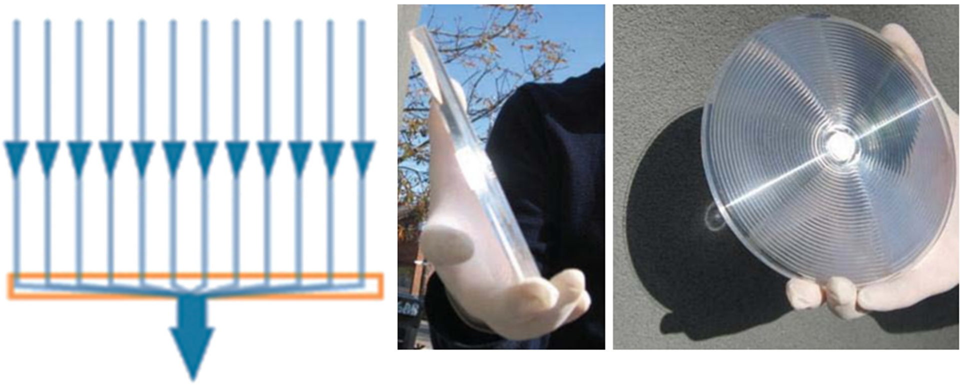

Fig. 11 Light-guide solar optic from Morgan Solar.[54] The light is trapped and redirected to the multijunction cell in the center of the optics, reducing the depth requirements.

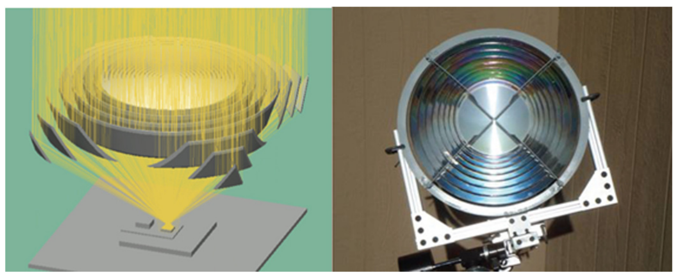

Fig. 12 Ring array concentrator.[56]

4.4 *Other Concepts*

Several other interesting optical designs address parameters such as the efficiency, CAP, etc. Weight and volume are the major concerns in order to decrease the transportation and tracking costs.

Several research groups and start-up companies are focused on planar CPV technologies. There is no commercial product on the market yet. Morgan Solar developed a light guide solar optic, which concentrates the light in planar direction, and has announced the same thickness and weight as a flat PV panel (see Fig. 11). The design eliminates the focal distance between optics and solar cell. With an ultrathin optical structure of acrylic and glass, this system traps the light inside the optics and redirects it onto the MJ cell placed at the optic's center,[54] reducing both depth and weight. This is a monolithic module with the glass SOE embedded in the center of the concentrator physically attached to the MJ cell. Concentrations of 1000 suns and acceptance angle of ± 0.9 deg are claimed.[55]

Vasylyev et al. presented a ring array concentrator (see Fig. 12), a point-focus design based on the concept of a reflective lens, which can be considered as a mirrored Fresnel lens.[56] It combines an optical efficiency over a broad extension of the spectrum by using mirrors (thus avoiding the double refraction of lens) with the design flexibility and rear-focus operation of lenses. This system was designed to operate in a range of $C_g \sim 400\times$ to $1100\times$. Each ring that forms a quasi-Gaussian flux distribution is designed to illuminate a specific part of the receiver area. Hence, when the individual focal spots overlap, the resulting illumination pattern becomes rather uniform across the entire active area of the receiver.

5 Conclusions

We have presented an overview of HCPV systems, predominantly their optical design. Those systems still have to thrive to reach an LCOE able to compete with other energy sources. To accomplish this, it is essential to decrease the production cost and increase the energy collection and power production.

Concentrator optics for CPV modules are lowest-cost high-volume optical elements, which limit considerably the design freedom for optimal optics performance. Designs that have reached high-volume installations are one-stage concentration POE Fresnel lens (Soitec, Suncore), one-stage POE mirror design (Silex), two-stage Fresnel lens and inverted reflective pyramid (Amonix), and two-stage compact plano-convex lens and ball lens (Semprius). During the last 2 years (2012 and 2013) Amonix's 30MW Alamosa in Colorado, and Suncore's 50MW CPV power plant in Golmud, China (the world's largest CPV plant), started their work. Soitec's 44MW CPV power plant in Towsrivier, South Africa, is expected to begin commercial operation in June 2014.

Continuous advances in MJ cells manufacturing procedure and current trends of the market dictate the development of optics for HCPV. A world record efficiency of 44.7% obtained by a four-junction cell developed by Fraunhofer ISE suggests that these cells will have increasing importance in the near future. Optical designs will have to take into account the spectral sensibility of these cells to chromatic aberrations, and some designs are already meeting this criterion. Also, the significant market share that SoG lens has gained in recent years led to designs that have to meet specific criteria in terms of temperature dependence, etc.

A short review of solar beam-splitting systems has been presented as well, pointing out the variety of techniques and implementations that have been proposed over the last few years. The large flexibility in receiver design and produced energy output, together with very important experimental results and cost-performance evaluations, will determine whether the added cost of the beam-splitting approach can be justified.

The CPV field is still developing and, only recently, we have the possibility to obtain feedback from the operation of installed CPV modules in high volume. There is a variety of designs under development. The most promising ones will be included in the next generation of CPV modules. The authors would like to highlight the FK4 concentrator design (Fresnel lens as POE and free-form lens as SOE, both fourfold) due to its high performance, simplicity, and high tolerance.

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