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Abstract. Most cost-effective concentrated photovoltaics (CPV) systems are based on an optical train comprising two stages, the first being a Fresnel lens. Among them, the Fresnel-Köhler (FK) concentrator stands out owing to both performance and practical reasons. We describe the experimental measurements procedure for FK concentrator modules. This procedure includes three main types of measurements: electrical efficiency, acceptance angle, and irradiance uniformity at the solar cell plane. We have collected here the performance features of two different FK prototypes (ranging different f-numbers, concentration ratios, and cell sizes). The electrical efficiencies measured in both prototypes are high and fit well with the models, achieving values up to 32.7% (temperature corrected, and with no antireflective coating on SOE or POE surfaces) in the best case. The measured angular transmission curves show large acceptance angles, again perfectly matching the expected values [measured concentration acceptance product (CAP) values over 0.56]. The irradiance pattern on the cell (obtained with a digital camera) shows an almost perfectly uniform distribution, as predicted by raytrace simulations. All these excellent on-sun results confirm the FK concentrator as a potentially cost-effective solution for the CPV market. *© 2012 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.JPE.2.021806]

Keywords: concentrators; optical design; optical engineering; solar energy.

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1 Introduction

The optical engineering group at Universidad Politécnica de Madrid (UPM)* and light prescriptions innovators (LPI)† have focused part of their recent common concentrated photovoltaics (CPV) research activity on the design and development of a family of Fresnel-Köhler (FK) concentrators. Figure 1 shows the FK working principle, with its particular fourfold two-stages optical train [comprising a Fresnel lens primary optical element (POE) and a refractive secondary optical element (SOE)], splitting the light into four Köhler channels[1] to achieve uniform irradiance on the cell without the need of mixing rods. Figure 2 shows a detailed view of SOE collecting rays from the sun, with its fourfold structure providing four different POE foci on the SOE surface, while Fig. 3 shows an example of calculated irradiance profile on the cell surface for an FK design.

As explained in a previously published paper showing raytrace simulation results,[2] the FK features a set of advanced characteristics, desirable in CPV: high optical efficiency, large acceptance angle, insensitivity to manufacturing tolerances, very good irradiance uniformity on the cell surface and easy cell to SOE gluing. All these features are achieved without the need of any kind of additional complexity: this system is still a Fresnel-based system whose primary

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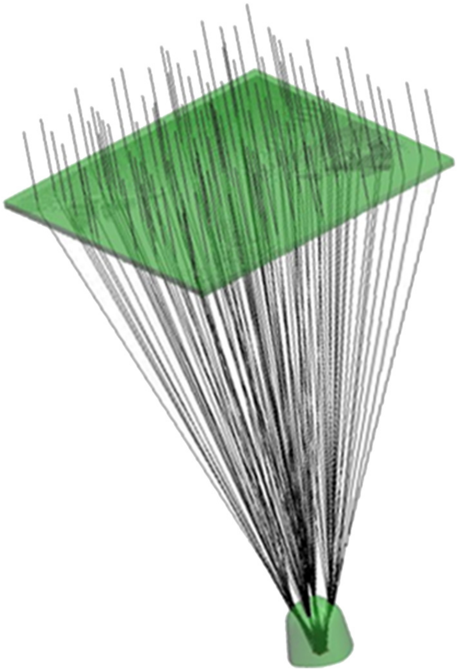

Fig. 1 Performing FK concentrator rendered view.

concentrator stage can be manufactured in large inexpensive panels and, as other CPV systems, utilizes a secondary lens to attain the necessary enhanced characteristics to achieve cost-effectiveness: high CAP to minimize the investment of solar cells but assuring the performance at array level. A previous publication[3] shows a detailed analysis of the cost of energy associated to the FK concentrator and other conventional CPV modules, with a higher cost-effectiveness in the case of the FK. Besides, the FK also shows benefits when it comes to gluing the SOE onto the solar cell. Indeed, in this device, glue leakage around the lens does not provoke light spillage—and therefore losses—like in those designs that end up with a prism on top of the cell. Additionally, the cell, along with other parts of the CCA—wire bonds, contact surfaces—are embedded within the SOE and isolated from the surrounding to prevent electrical problems linked to humidity; for instance, as detailed in Ref. 2.

Each FK concentrator is designed and optimized by looking at realistic performance characteristics. The performance of the FK is modeled exhaustively using ray tracing combined with cell modeling, taking into account the major relevant factors. Among them are the spectrum and angular subtense (± 0.265 deg) of the sun, the variation of the refractive index and absorption

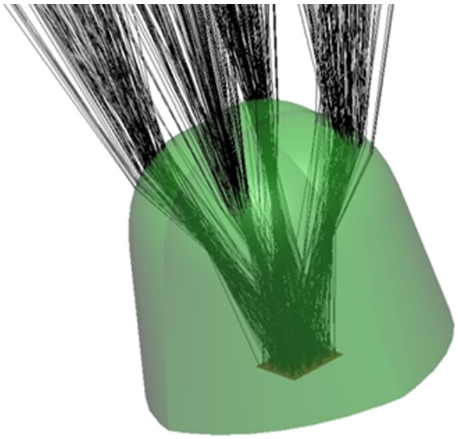

Fig. 2 Close up of the FK SOE.

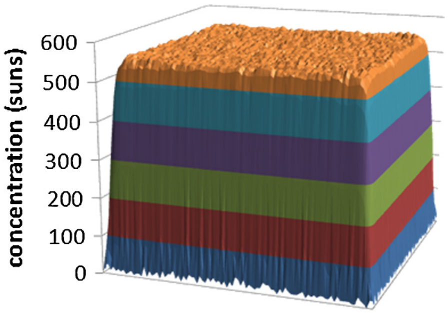

Fig. 3 Calculated uniformity on the cell surface, for the visible wavelengths range.

coefficient with wavelength of POE and SOE materials and the draft angles (2 deg for all our prototypes) on the Fresnel vertical facets (needed to withdraw the lenses from the molds). Other second-order details, such as Fresnel facets tip radii (typically 5 μm, and therefore with negligible effect on performance) or surface roughness (whose real shape and effects are difficult to predict and model) have been neglected in the simulations. The reliability of these simulations has been confirmed with the on-sun measurements shown in this work, which fit fairly well. This almost perfect matching is a consequence of not only the simulations precision, but the tolerances of the CPV system as well, able to absorb module—imperfections—shape errors, roughness of optical surfaces, concentrator module assembly imprecision, tracker structure limited stiffness, and sun-tracking accuracy—not taken into account in the models.

LPI has manufactured two FK prototypes so far, including the commercially available Ventana™ Optical Train (Ventana prototype from now on), and an additional module that we are naming *A* in this work. Both of them utilize solar grade [ultraviolet (UV) protected] poly-methyl methacrylate (PMMA) Fresnel lenses manufactured by Evonik[4] and 10×[5] using roll-to-roll embossing. The SOEs are made in different versions of Schott B270 glass. These two modules have been measured with commercial triple junction solar cells (efficiency of ~38.5%) at Cedint-UPM facilities in Madrid. Their concentrations, f-numbers and cell sizes are different, which gives us the opportunity of getting a full picture of this optical train's features in a wide range of situations.

For a better comprehension and an easier comparison between the different measurements, all the results presented in this paper are normalized to standard values of irradiance ($900\ \mathrm{W/m^2}$) and cell operation temperature ($T_{\mathrm{cell}} = 25\,°\mathrm{C}$).

2 Modules Parameters and *F*-Number Comparison

The CAP, efficiency, and irradiance uniformity on the cell for an FK concentrator are rather constant independently of other parameters such as cell size or concentration factor. Even when we take into account the f-number (defined here as the cell to POE distance over the POE diagonal), a parameter to which other Fresnel-based concentrators are sensitive, the FK keeps good performance features within a wide range of values. For this reason, the aim of this section is to present the two manufactured prototypes (Ventana and *A*, designed with different f-numbers) by describing their main properties and dimensions and showing their peak efficiency IV curves. Table 1 summarizes parameters and dimensions for the prototypes. Moreover, both prototypes include commercial multijunction (MJ) cells presenting similar electrical efficiency values around 38.5%.

The Ventana prototype is a complete off-the-shelf optical concentrator developed by LPI, Evonik, and 10×, fully compatible with any CPV receiver based on a MJ solar cell with area greater than $5 \times 5\ \mathrm{mm}^2$. Hence this module presents a great interest for the CPV market. A picture showing the Ventana prototype can be seen in Fig. 4. Figure 5 shows the IV curve for the Ventana prototype, measured at Madrid repeatedly in April 2012, around solar 10:00. Results are outstanding, with a remarkable electrical efficiency of 32.0%. On the other hand, Fig. 6 shows IV curve for prototype A, measured at Madrid in May at solar 16:15.

Table 1 Dimensions and parameters for the two prototypes.

Prototype	Ventana	Prototype A
f-Number	1.05	1.2
POE lens size (mm^2)	160×160	120×120
Cell Illuminated area (mm^2)	5×5	4.5×4.5
Geometrical concentration	1024×	710×

Both prototypes show similar efficiency values (32.0% versus 32.7%). This small difference can be explained by several factors. First, different cell manufacturers have been chosen for both prototypes, leading to slight cell electrical efficiency differences. Second, concentration ratios are not the same: the Ventana prototype's higher value leads to lower cell efficiencies (commercial MJ cells exhibit some efficiency decrease for concentration levels above 300 to 800×). Finally, a more compact Ventana prototype configuration (lower f-number, 1.05 versus 1.2) entails slightly higher POE Fresnel losses. Nevertheless, as stated above, this last factor is almost negligible in the FK concentrator case. The difference in fill-factors is mainly due to the use of a different MJ cell in each prototype. It is important to point out that these results have been achieved without any antireflective coatings on POE or SOE surfaces.

The next three sections will show FK measurements regarding, respectively: efficiency through the day, irradiance uniformity on the cell, and acceptance angle. The measuring procedure is the same for any FK concentrator. Nevertheless, the particular results shown in the next sections refer to prototype A, since it is the prototype for which we have accumulated more experience and measured results.

3 Module Efficiency Through the Day

MJ cells yield high efficiencies by dividing the solar spectrum in different wavelength bands, each one being absorbed by its corresponding subcell. Each subcell shows a higher EQE over its

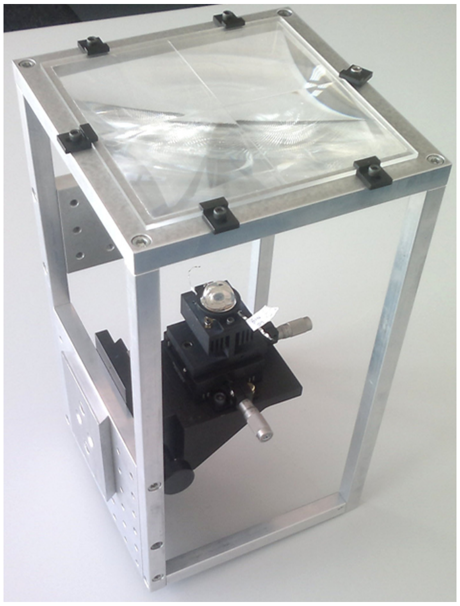

Fig. 4 The Ventana prototype, with its metallic housing to ensure stiffness. The Fresnel lens based POE is shown in the upper part of the picture. In the lower part, the SOE is optically coupled to the cell (contained in the receiver). Underneath the receiver, a black heat sink in order to lower the operation temperature of the cell.

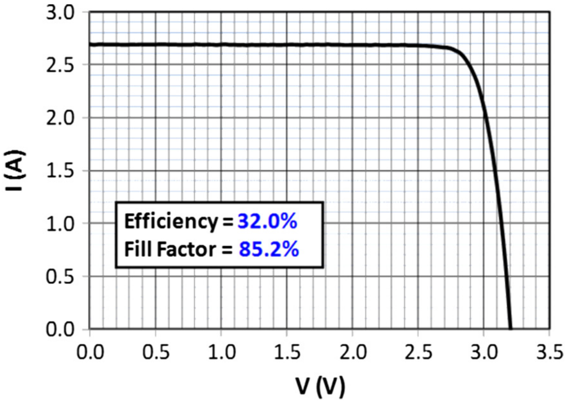

Fig. 5 IV curve for Ventana prototype.

corresponding spectrum band than that of a single cell over the whole solar spectrum.[6] Current commercial MJ cells are typically structured as a 3 series-connected subcells stack, implying that the photogenerated current by the whole device will be limited by the lower photocurrent among the three subcells. This feature, which simplifies cells interconnections, imposes the need of a balance solar spectrum to get the best efficiency.

The MJ cells employed in our prototypes present a GaInP/GaAs/Ge 3-layer structure, where GaInP is the top subcell material, GaAs is the middle subcell, and Ge is the bottom subcell. Due to the characteristic band gaps of these three materials, the solar spectrum portion used by the bottom subcell produces much more photocurrent than the other two subcells (top and middle). This is the reason why in general only the top or middle subcell are the ones limiting the cell current. Thickness of subcells, optical concentrator architecture, material optical properties (mainly Fresnel losses and absorption), and solar spectrum will determine which one of these two subcells (top or middle) is the limiting one. When the top subcell is generating the same photocurrent as the middle subcell, we have a current-matching situation. When current-matched, an MJ solar cell presents its maximal electrical efficiency since none of the subcells limit the other's excess of current. If these currents get unbalanced, the cell electrical efficiency will decrease.

Once MJ cell and optical concentrator have been chosen for a particular CPV module, the determination of the limiting subcell will only depend on the solar spectrum. MJ cells are commonly designed to be current-matched when they are performing under an AM1.5D solar spectrum. Nevertheless this optimal spectrum can be somewhat different (slightly bluish or reddish) depending on the already cited factors: thickness of both subcells and concentrator's material optical properties.

The efficiency of the modules might vary not only through the year, but also through a day, due to the significant solar spectrum changes experienced in a single day. These changes are mainly produced by strong variations in the air-mass (AM) value, among other second order factors.

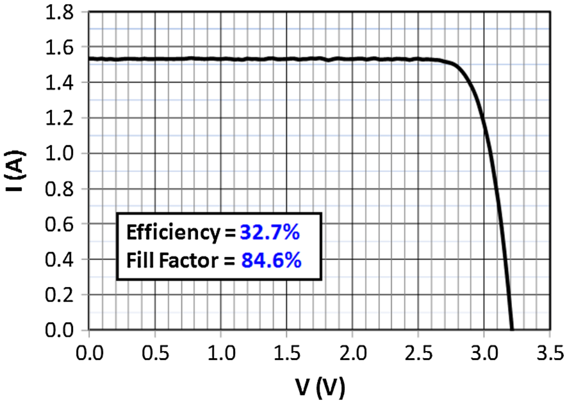

Fig. 6 IV curve for prototype A.

FK concentrator electrical efficiency can be easily measured with an IV curve tracer and a tracking system in order to keep the module aimed. The IV tracer provides the instantaneous power produced by the solar cell. This output power is directly transformed in terms of electrical efficiency if we divide its value by the input power (obtained with a pyroheliometer). Figure 7 shows prototype A variation in electrical efficiency during a single day (one IV curve was measured every 30 min.). Solar time has been taken into account in this graphic and successive ones. There are two local maximum efficiency values, one around 7:15 and the other one around 16:15. As stated above, those moments correspond to current-matching between top and middle subcells situation.

We can define three distinct regions during the course of the day:

(1) From dawn to 7:15: Solar spectrum is rather reddish, so top subcell will limit the whole generated current. The closer to 7:15 we are, the bluer the spectrum will be and top cell generated current will be closer to middle cell current. Hence efficiency will increase.

(2) From 7:15 to 16:15: Solar spectrum is bluish, so middle subcell will limit the photogenerated current. The first part of this region is efficiency decreasing, until the point where the spectrum is the bluest possible along the day (at 12:00, i.e., solar noon). Later on, efficiency will increase until the second local maximum, where top and middle currents will be again balanced (at 16:15). This can be assessed since FF variations are negligible around 7:15 and 16:15 (see Fig. 8), and these measurements have been temperature corrected, so efficiency is mainly ruled by I_{sc} short-circuit current), as Fig. 9 shows.

(3) From 16:15 to dusk: Spectrum is reddish again, implying a top cell limiting situation. Efficiency values will decrease progressively until dusk.

Figure 8 shows the fill-factors (FF) corresponding to the measurements of Fig. 7. As can be seen in the figure, the FF keeps excellent values always around 85%. The FK is able to keep high FF values thanks to outstanding irradiance uniformity achieved independently of the color of light, as will be explained in Sec. 4.

Figure 9 shows a comparison between I_{sc} measurements and simulations results for prototype A (external quantum efficiencies of the MJ cell employed for these simulations have been taken into account). This comparison is held within the 13:00 to 18:00 time range, around the second efficiency local maximum. The figure shows three different curves: points represent on-sun measurements taken every 30 min, while the other two curves correspond to simulations. One of these curves has been calculated by simulating the prototype A with the measured radiometric spectra available at the time of each measurement. The other curve corresponds to simulations carried out with spectra generated by SMARTS software.[7] Notice that, while on-sun measurements place the current-matching situation at 16:15, both simulation methods predict it for 16:45. Besides this small difference, measured and simulated results fit very well.

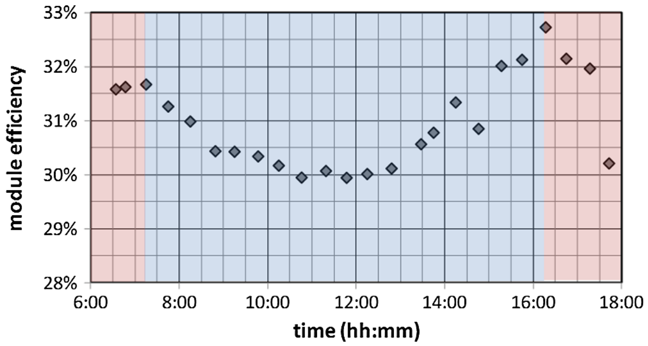

Fig. 7 Evolution of module efficiency on May 17 in Madrid, Spain. Areas shaded red denote red-rich solar spectrum (i.e., limiting by top subcell); blue-rich spectrums are represented by blue color (i.e., limiting by middle subcell).

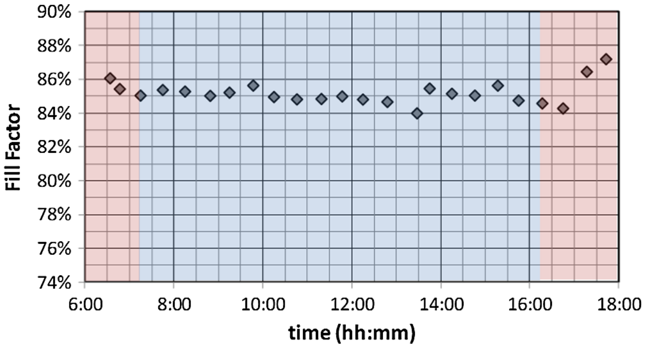

Fig. 8 Evolution of fill-factor on May 17 at Madrid, Spain.

4 Irradiance Distribution Measurement

As stated in the introduction, irradiance distribution on the cell surface is an important issue in CPV modules. Uniform irradiance patterns help to achieve higher cell efficiencies than nonuniform ones, especially when the uniformity is achieved throughout the entire sun spectrum, preventing the module from chromatic dispersion.[8] Moreover, uniformity also contributes to cell reliability and efficient performance over its lifetime. As mentioned before, when dealing with concentrating photovoltaics, Köhler integration is a good option in order to provide almost perfect irradiance uniformity on the cell, over other conventional alternatives (i.e., kaleidoscope homogenizers).

In order to show the irradiance distribution achieved by FK concentrator, we have again used prototype A. Figure 10 shows a square-shaped light spot: this is a picture taken from the bottom part of the SOE, where we have replaced the solar cell with a white diffuser acting as a screen to analyze the irradiance pattern the concentrator would provide onto the cell surface. The image information is processed and converted into an irradiance distribution (Fig. 11) demonstrating the even irradiance achieved within the visible range, as predicted by simulation showed in Fig. 3. Further simulations have also shown that this great uniformity is kept over the entire CPV wavelengths range of interest (350 to 1800 nm).

5 Angular Transmission Curve Measurement

The acceptance angle can be easily deduced from the concentrator angular transmission curve. For the angular transmission curve on-sun measurement, the module is placed in a fixed position (without tracking the sun), letting the sun traverse the module from negative misalignment angles towards positive angles, passing through the on-axis position (0 deg). Tracing the entire transmission curve (negative and positive angles) is compulsory, since the FK transmission curve is flat at the top, and the maximum transmission is difficult to locate and center. In our case, this measurement has been carried out on May 18 around 11∶00 solar time, just the day after efficiency measurements were obtained, so the spectral distribution was almost identical to that on

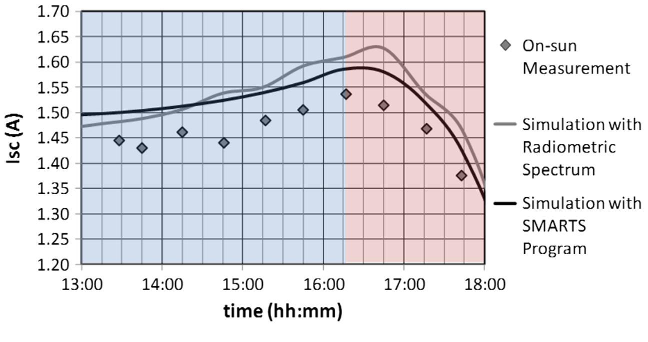

Fig. 9 Comparison of module efficiency evolution: on-sun measurements (points), simulations taking into account the measured radiometric spectrum (grey line) and simulations carried out with solar spectra provided by SMARTS program (dark line).

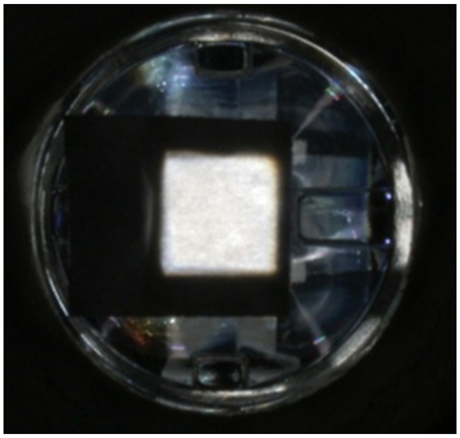

Fig. 10 Picture of SOE bottom.

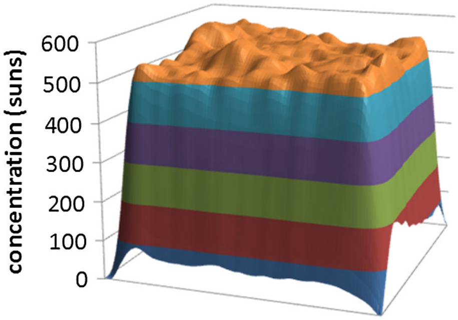

Fig. 11 Irradiance profile from picture-processed data.

May 17 at 11:00. At that particular moment the middle subcell was limiting the generated current (see Fig. 8), so this measured transmission curve corresponds to the middle subcell. Consequently, we will use the transmission curve simulated for the middle subcell (and not the top one) in order to establish a fair comparison with measured results.

Figure 12 analyses measured and simulated transmission curves for prototype A. Both curves represent the I_{sc} values evolution with tracking misalignment, expressed in degrees. The first conclusion is that both measured and simulated curves are pillbox-shaped, which ensures high efficiency for the module even for large misalignments. The second conclusion is that the curves are almost identical, with close values of acceptance angle (measured ± 1.27 versus simulated ± 1.35 deg), achieving an outstanding measured CAP $= 0.56$.

Beyond irradiance uniformity on the cell, chromatic dispersion is a key issue in CPV modules as well. If the light feeding the different subcells presents different irradiance profiles (i.e., chromatic dispersion), FF will decrease.[8–10] This drop in FF value depends on the

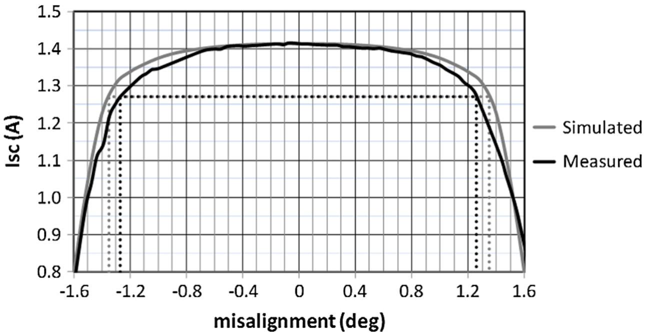

Fig. 12 Comparison between measured and simulated Isc transmission curves for prototype A.

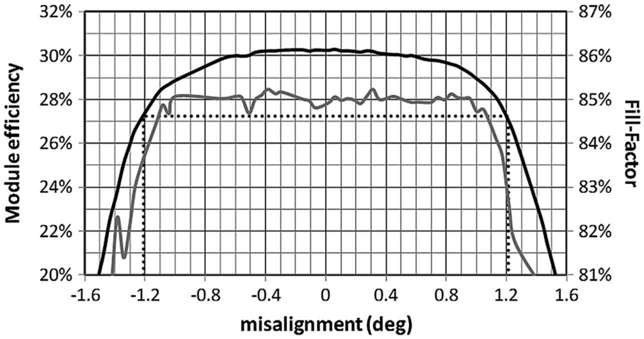

Fig. 13 Measured efficiency and FF versus angle curves for prototype A.

magnitude of dispersion: very dispersive concentrators entail large FF drops, while small FF drops will be attainable with low-dispersive concentrators, as is the case with FK. Moreover, all concentrators show lower dispersion when on-axis than when off-axis.

For this reason, we include here an alternative definition for angular transmission curve and hence for acceptance angle, based on module electrical efficiency instead of I_{sc}. Applying this new definition, we obtain the curve in Fig. 13. This efficiency versus angle curve presents an identical shape as that of I_{sc} versus misalignment (also pillbox shaped), but with a slightly lower acceptance value (±1.21 deg). This is caused by the FF drop effect when dealing with misalignments over ±1 deg, where the negative effects of chromatic dispersion commence. Nevertheless, Fig. 13 shows a constant FF value around 85% within the ±1 deg range; meaning that, inside that cone of acceptance, the chromatic dispersion effects are negligible for FK. Consequently, the acceptance angle drop introduced by the new transmission curve definition is very small, unlike other conventional concentrators (Fresnel-XTP, Fresnel-RTP, SILO) for which FF drops are much greater.

We can verify that results shown for prototype A in Fig. 13 are perfectly consistent with those shown in Figs. 7 and 8 referred to the same prototype). Transmission curve measurements (see Fig. 13), carried out the day after efficiency measurements were obtained (i.e., on May 18 at 13∶00), show identical results for the on-axis situation to those for efficiency measurements at 13:00 (see Figs. 7 and 8): very close to 30% efficiency (30.2% versus 30%) and almost an 85% FF (84.9% versus 84.8%). The efficiency measured here is not the peak one (which has been shown in Sec. 2), but the efficiency measured in a moment of the day where the spectrum variations were negligible (around solar noon in a May day). This is desirable when dealing with a 15-min-long measurement like this one.

6 Conclusions

During the last few years, UPM and LPI have been presenting their common work on the design and development of the FK concentrator, with outstanding simulated results in terms of efficiency, acceptance angle (and thus CAP), and irradiance uniformity on the cell. This paper now presents outdoor experimental measurements for two FK prototypes. These measurements again show excellent performance, fitting well the results predicted by simulations. Efficiencies up to 32.7% (temperature corrected), measured CAP = 0.56 and almost perfect irradiance on the cell have been presented for one of the manufactured prototypes (no antireflective coating on POE nor SOE). All these excellent on-sun results, along with low-cost production of Fresnel-lens-based systems, confirm the FK concentrator as a potentially cost-effective solution for the CPV market.

Acknowledgments

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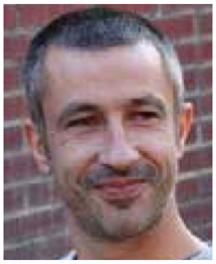
Pablo Zamora received his degree in telecommunication engineering in 2005 from Universidad Politécnica de Madrid (UPM). Since 2007 he has been a researcher in the Optical Engineering Group at UPM. His research is focused on optical design of nonimaging devices, with application to concentrating photovoltaics and illumination. He is co-author of one paper in international journals, over 15 communications in congresses, and one patent. He will obtain his PhD title by the end of 2012.

Pablo Benitez is a professor at the Universidad Politecnica de Madrid. His research is devoted to optical design, particularly in Nonimaging Optics for CPV. He is co-inventor of the SMS design methods and the Fresnel-Köhler CPV technologies, and co-author of the book *Nonimaging Optics* (Academic-Elsevier, 2004). He closely collaborates with the US company LPI.



Rubén Mohedano got his PhD degree in January 2002 with Summa Cum Laude, his research being focused on nonimaging optics design, manufacturing, and applications. He is currently the managing director of LPI-Europe, an intense R&D company that he joined by 2002. He has been involved in more than 20 projects since then, mostly in the concentration photovoltaics (CPV) and illumination fields. He has led projects for various major automotive and CPV companies: most of the systems developed are already available in the market. He is the author of one book, co-author of two books, more than four patents, six papers, and several congress publications.

Aleksandra Cvetković got her PhD degree from Universidad Politecnica de Madrid in April 2009 with Summa Cum Laude, her research being focused on nonimaging optics design, manufacturing, and applications. She has been developing different applications of SMS-3D design method in concentration photovoltaic (CPV) and solid-state lightning (SSL). She joined LPI-Europe in June 2009, since when she has been involved in various projects, both CPV and SSL. She has recently led two projects for development (design, prototyping, and manufacturing) and quality control of CPV modules. She is the author of four articles, two patents, and more than 20 conference publications.

Juan Vilaplana obtained his degrees in engineering of materials (2003) and mechanical engineering (2006) by Universidad Politécnica de Valencia (UPV). Since he joined LPI-Europe in 2008, he has been working as a mechanical engineer for the prototyping and manufacturing of PV concentration systems. He is co-author of several communications for international congresses.

Yang Li is a student from the Department of Optical Engineering in Zhejiang University, China. He has been collaborating with Universidad Politécnica de Madrid as an exchange student for more than one year, supervised by Professor Benitez. His research interest includes antireflection coating for solar cells, nanostructured solar cells, and concentration photovoltaics.

Maikel Hernández got his PhD degree for the Polytechnic University of Madrid in July 2003 with Summa Cum Laude. His research is aimed at nonimaging optics design, manufacturing, and applications. Since 2000 he is collaborating with Light Prescriptions Innovators USA. He joined LPI-Europe in 2003. He has been involved in several projects in CPV, automotive, and illumination applications. He is the co-author of one book, more than five patents, five papers, and several congress publications.

Julio Chaves received his PhD in physics from the Instituto Superior Técnico (Higher Technical Institute), Lisbon, Portugal. He joined LPI-LLC in 2003 and LPI-Europe in 2006. Chaves is the author of the book *Introduction to Nonimaging Optics*. He developed the new concepts of stepped flow-line optics, ideal light confinement by caustics (caustics as flow lines), and new Fresnel solar concentrators for multiple receivers. He is the co-inventor of several patents and the co-author of many papers in the field of nonimaging optics. He also participated in the early development of the simultaneous multiple surface design method in three-dimensional geometry.

Juan C. Miñano has been involved in CPV since 1982, when he started his PhD activities. Since then, he has been working in all the different concentration strategies of CPV from static concentration with silicon cells up to high concentration PV with multijunction cells acquiring a deep insight in the field, particularly in optics for CPV. He has developed several optical design techniques with immediate application to CPV, being the most well known of them the so-called SMS design method. He has published more than 50 journal papers, 100 congress presentations, and several dozens of patents, most of them directly related with CPV. Since 1997 he has been a professor at the Universidad Politécnica de Madrid; since 2000 he has collaborated with LPI as senior scientist. In 2010 he was honored with the A. E. Conrady Award (2010) given by SPIE "in recognition of his exceptional contributions in developing new design methods and devices in nonimaging optics."