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Hybrid Dome with Total Internal Reflector as a Secondary Optical Element for CPV

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Abstract. Secondary optical elements (SOEs) are used in Concentrator Photovoltaic (CPV) modules to allow the concentration ratio to exceed those typically achievable by Fresnel lenses, reducing cell costs, without sacrificing tolerance to tracking errors. One option is a "dome" SOE: a simple, single surface refractive optic that images the primary lens onto the cell while immersing it. In this article, we explore the limits of this type of SOE and propose an evolved version, which we dub the Hybrid Dome Reflector (HDR), which offers advantages especially for high concentration modules with large cells, where reflective secondaries do not offer sufficient acceptance angle, but other dielectric secondaries, such as the Dielectric Totally Internally Reflecting Concentrator DTIRC, may be too large for economical manufacture. We discuss aspects of HDR design and share selected ray-tracing simulations and experimental results. We show that the new HDR design improves acceptance angle and tolerances to manufacturing error and lens temperature as compared to a reflective SOE built while offering similar efficiencies.

INTRODUCTION

During the last decade, the explosive growth of multi-junction solar cell efficiency has led to resurgence in concentrator photovoltaics (CPV). At the same time, a focus on keeping costs low has led most recent designs using concentration ratios of 1000X or higher. These levels far exceed that which a Fresnel lens, the most common Primary Optical Element (POE) used in modern high-concentration photovoltaics, can achieve, so Secondary Optical Elements (SOEs) are used. [1] The two general types of SOE are *reflective*, which are air filled, and use reflection off metal surfaces and *dielectric*, composed of a transparent medium and employing either total internal reflection (TIR) or refraction to concentrate the rays. The latter offers better performance, because, according to the conservation of étendue, the maximum achievable concentration increases with the index of refraction that the receiver is surrounded by. However, glass optics are more expensive. For the largest 1cm cells employed by many manufactures, the height of existing Dielectric Totally Internally Reflecting Concentrator (DTIRC) [2] type SOEs makes cost prohibitive, while classical "dome" or "SILO" [3] type SOEs cannot offer sufficient performance improvement in order to be used for concentrations levels nearing 1000X In this paper we introduce a new SOE concept that we call the Hybrid Dome Reflector (HDR) SOE and demonstrate its advantages.

DESIGN OF THE HDR

The use of what we are calling a "dome" design for CPV secondary optics was first proposed by Sandia Labs in 1989 [3], where James referred to it as a SILO (for SIngLe Optical surface) optic. In this section, we discuss its fundamental aspects and how a dome profile can be derived for a given lens and solar cell at a given distance. Fundamentally, a dome is an imaging lens with the image forming plane immersed within the optic. The basic concept is to form a real image of the lens onto the solar cell. Since both the cell and SOE are placed at or near the focus of the lens, the entire surface of the lens will appear brightly and uniformly illuminated to them. Therefore, we

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should be able to create an image of the POE, which is a perfectly uniform square field of light, cell onto the cell surface.

The outer profile of the SOE must be such that all rays originating from a point on one extreme edge of the lens are redirected to a point on the opposite edge of the cell. Fermat's Principle can used to calculate this profile given the sizes of the cell and lens, the focal distance, and the starting height. The reader is directed the work of Victoria [4] for an in-depth discussion. Often, the initial height, y_0, is constrained such that $\left.\frac{dy}{dx}\right|_{x=0} = 0$, which leads to a fixed dome design, which we will refer to as *nominal height* domes. If we calculate the entire profile (note all domes here use an example systems with a 1cm cell and 1000X geometric concentration), we obtain an asymmetric figure (Figure 1a), and we must choose to revolve either the left hand or the right hand figure around the optical axis to obtain a solid. These two choice were referred to by Victoria as "Dome A" and "Dome B", a convention that we will continue in this work. Dome A refers to a dome that is imaging the near edge of the lens (to the far corner of the cell), while Dome B images the opposite edge of the lens (to the near edge of the cell).

We can also imagine larger domes with starting positions at $y_0 > y_{nom}$, which will thus have non-zero slope at the center. Such domes will have a larger overall diameter and therefore a greater concentration ratio (C_g). For a given POE and cell size, this equates to a larger overall acceptance angle. As the initial height, y_0, is increased, we observe that the "A" domes start with a positive slope (leaving a small central dimple), whereas "B" domes start with a negative slope, and therefore come to the point. When we draw such domes (Figure 1b) it becomes apparent that we can find sets of A and B domes, with different starting heights, which share a tangent point. By combining these profiles we can create a *hybrid* dome, composed of Dome A in the central portion and Dome B on the periphery, which has a smooth surface (no abrupt change in slope). This combination *maximizes the domes radius* (and therefore C_g) while *minimizing the domes height*, and therefore volume. This is an advantage because manufacturing costs are related to both volume and maximum thickness.

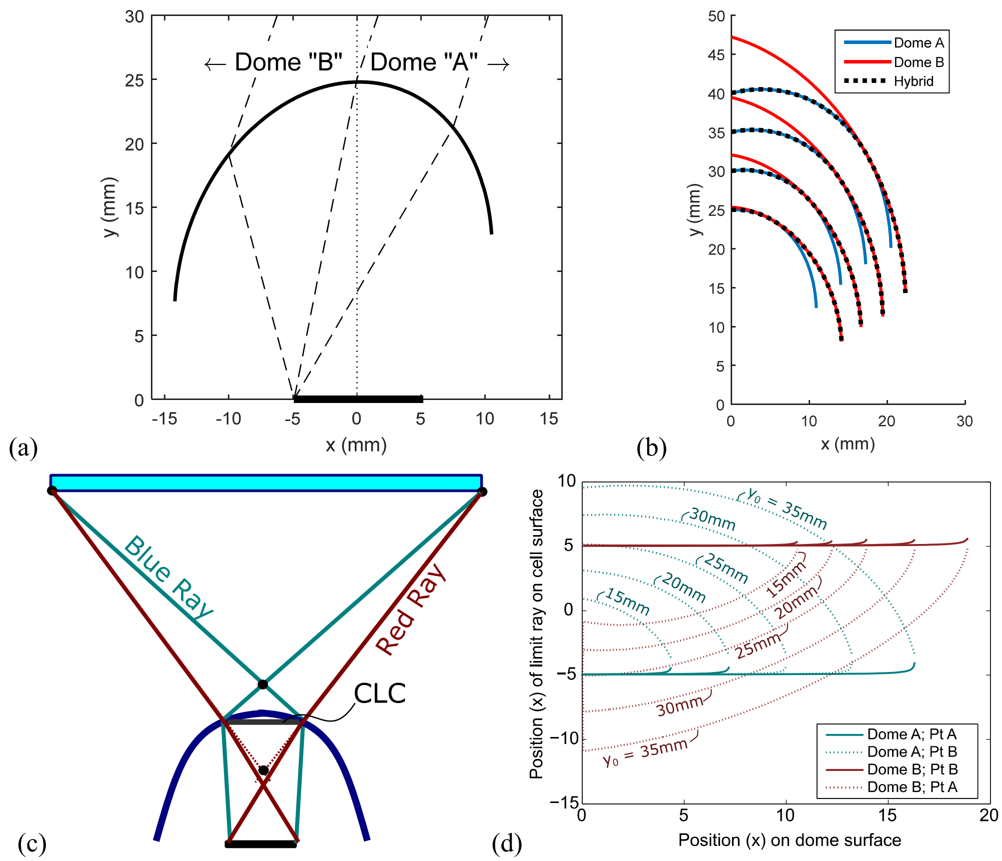


FIGURE 1. (a) Asymmetric profile obtained when starting from the center of the dome and tracing in either direction (b) Hybrid domes found by combining A and B profiles with tangency. (c) The dome receives both imaged and non-imaged rays over its surface (d) The position of the edge ray on the cell vs position, for blue and rays and for varying height A and B type domes.

As is well known, the Fresnel lenses typically used as a POEs in CPV exhibit chromatic aberration and as such have a different focal distance for each wavelength. To maximize performance of the system, the entrance of any dielectric SOE should be placed at the Circle of Least Confusion (CLC), where the size of the "spot" of light produced by the primary is minimized [5]. Therefore, as shown in Figure 1a and also apparent in Figure 4a and b, the bluest[1] rays will come to a focus above the SOE, and will enter the dome from the opposite edge (and as such would be correctly imaged by a Dome B profile) while the reddest[1] rays will have their focal point placed within the SOE, and thus enter the dome from the near side (and would require a Dome A). Therefore, both the central (Dome A) section, and the outer (Dome B) section of our hybrid dome will receive some rays that are not imaged. In Figure 1b we show the intercept location of these non-imaged rays on the cell plane as a function of the point along the dome surface of ray interception for a variety of dome heights. We observe that all non-imaged rays that pass through the dome at a radius less than the tangency point (the point at which the slope is correctly imaging limit rays from either lens edge) on the dome will not fall onto the cell, but outside of it.[2] We can design a small TIR reflector that redirects the lost rays onto the cell. The design criteria for this reflector is that it must be of the correct slope to preserve TIR for any ray originating from the center (tip) of the dome, since this will be the least vertical of any "lost" ray. Finally, once this reflector is in place, the outer most edge of the dome may be shadowed by it, so we must adjust the dome profile at the edge that is imaged at the last point of the TIR profile (labeled Dome C), to ensure all rays enter the cell. Figure 2a shows the profile of such a Hybrid Dome with Reflector (HDR). In Figure 2b, we show a photorealistic rendering of a prototyped dome with a 30mm height.

Manufacturing Benefits of the HDR Design

It is assumed that a dielectric optic intended for larger cells and concentration ratios (high light flux) would need to be made from glass as opposed to polymers, and therefore it is assumed that this optic would be most likely be fabricated from molded glass. We have learned from glass manufacturers that the protrusion required by the TIR portion is actually an advantage to the manufacturing process, since attaining a flat surface on the order of 20 to 30 mm in extant is difficult. In Figure 3 we can see the size difference between a DTIRC and a HDR SOE of equivalent concentration ratio. Another advantage to the HDR is that the flange (which is located at the mold parting line) is found only 7mm from the plane of the cell. A system design could contemplate a simple supporting ring (made of plastic, glass, or metal) to mechanically couple the SOE to the receiver or cell carrier to support it. Such a mechanical support may be much more difficult and expensive in a DTIRC option, because the latter is much taller.

RAYTRACING AND EXPERIMENTAL RESULTS

Raytracing was used during the design process to verify the correct operation of the optic. We also compared the performance of the HDR to reflective SOEs as well as nominal height domes, using ray-tracing software. One important conclusion of these simulations was that very high acceptance angles (close to ±1°) were expected for the HDR, but that the nominal height domes did not improve acceptance angle significantly as compared to the "conventional" option of a reflective inverted pyramid manufactured from Alanod Mirosun material that would probably preferred from a cost perspective .

Experimental Comparison to Equivalent Reflective SOE

The dome design shown in FIGURE 4b was prototyped in molded glass and experimentally compared to a conventional reflective pyramid: both optics are shown in FIGURE 5. The methods used to explore the change in electrical performance of a single optics-cell unit versus focal distance were similar to those of [6]. Measured results from the prototype HDR showed that the real 90% acceptance angle was still very high (over ±0.8°). Comparing the acceptance curve of a single optics cell unit using of an HDR SOE compared to a system using the reflective option. The tolerance to focal distance was twice that of the reflective optic (a). However, we did not observe the efficiency improvement from the reflexive dome to the HDR that we had predicted from raytracing, and in fact the on-axis

[1] For this discussion, the wavelengths corresponding to "bluest" and "reddest" rays are set by the spectral range of interest, i.e. the spectral response of the solar cell.
[2] A nominal height done has an implicit tangency point at the lens center, due to the design condition. All non-imaged rays fall within the cell.

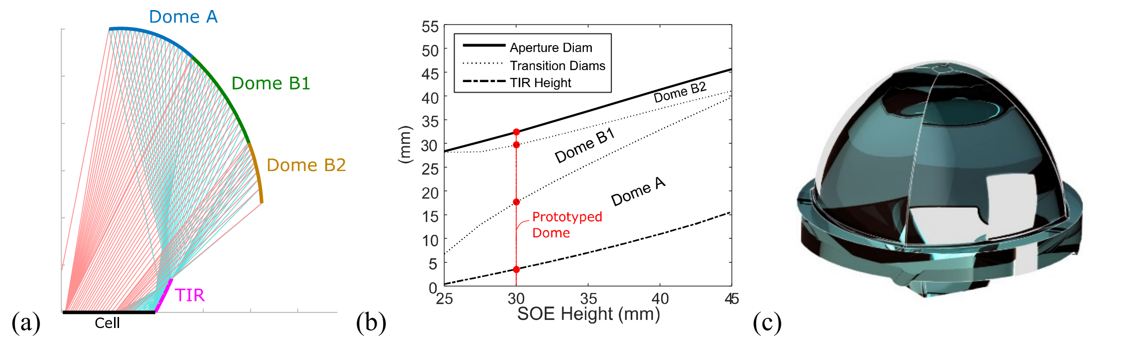


FIGURE 2. (a) HDR dome showing recovery of lost rays (b) Effect of changing initial dome height (y_0) on aperture diameter, the diameter of the profile transitions, and the height of the TIR reflector. (c) Appearance of an HDR

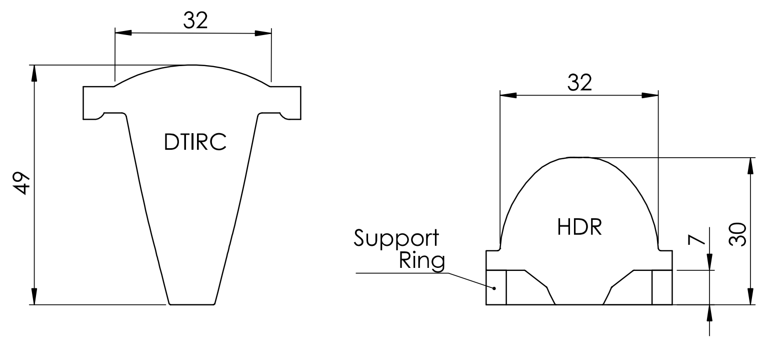


FIGURE 3. Comparison of the size of an HDR done versus a DTIRC dome based on 1cm / 1000 X design. Note that the flange-to-cell-plane distance is only 7mm, allowing easy mechanical coupling to the cell carrier or receiver

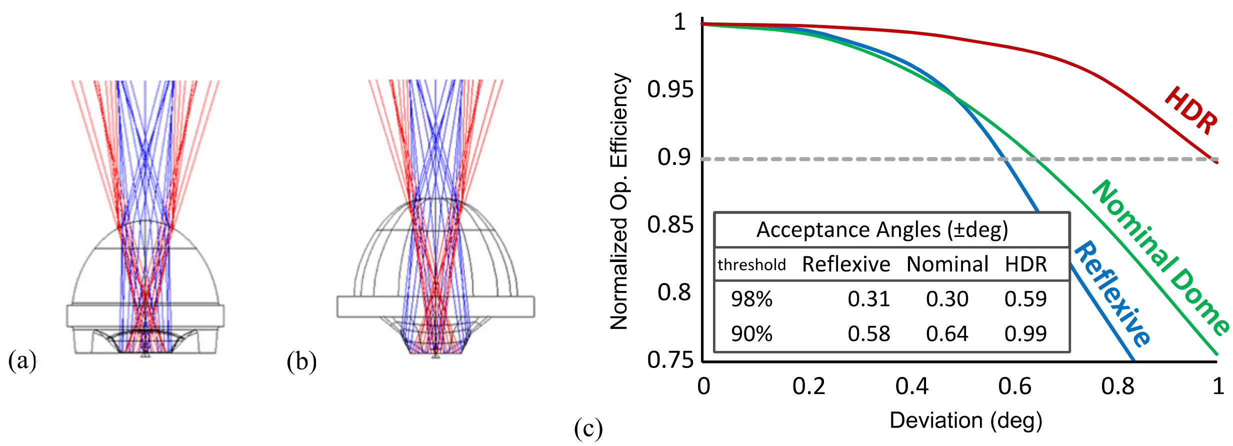
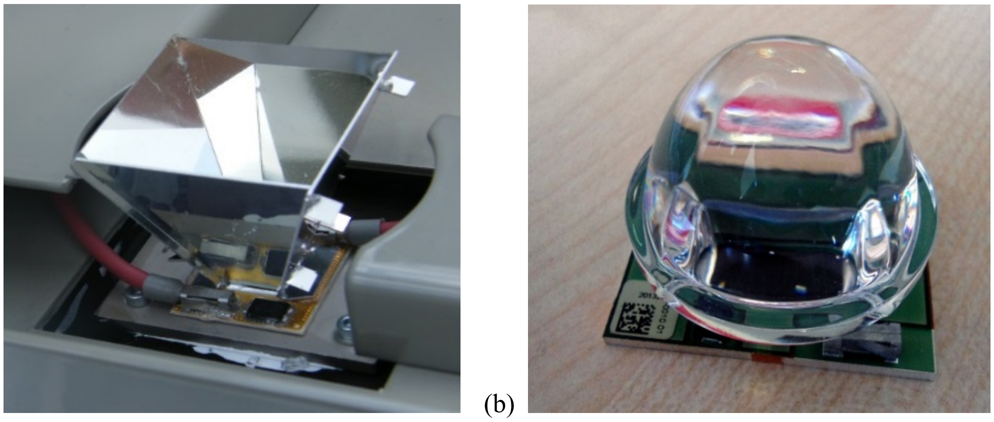


FIGURE 4. Raytracing was used to compare a nominal-height dome (a), an HDR dome (b) and a standard inverted pyramid (See FIGURE 5a). In all cases the system comprises a standard Silicone-on-glass lens, diagonal f-number of 1.1 and a 1cm cell with 1000X concentration ratio. In (c) the simulated angular transmission curves are shown for all three, with calculated acceptance angle for 98% and 90% efficiency loss thresholds. In (a) and (b), the blue and red lines correspond to the light of the limiting wavelengths considered for the design, 350 and 1000nm respectively. It can be seen in (b) that the small TIR reflector is correctly capturing the blue rays.

efficiency was slightly lower for the HDR than for the reflexive option. We have identified that the performance of the cell using the HDR is limited by a high amount of lateral resistance losses using a comparison of the subcell limitation diagrams (FIGURE **6**a). In this figure, we note that the absolute optical efficiency, compared to the reflexive secondary, is about 2% higher for the HDR in the spectral regions corresponding to both the top and middle subcells. This is evidenced by the fact that the flat portions of the normalized current curves are higher for the HDR. However, we see that near the point at which the subcells are current match, there are greater *additional current losses* for the HDR as the normalized currents cross at the point where internal current matching between



(a) (b)

FIGURE 5. The two SOE types compared in the SOE study. The solar cell and carrier type was the same for all samples. (a) Reflexive inverted pyramid (b) Hybrid Dome with Total Internal Reflector

subcells is achieved. Experience shows that these losses are related to spatio-spectral non-uniformity. Please see [7] for an in depth discussion on subcell limitation diagrams and their interpretation.

In the case of the HDR, we have not yet measured empirically, via imaging measurements, the spectro-spatial distribution over the cell. However, our raytracing simulation predicts that the profile of the photocurrent produced by each cell over a transversal section are those give in (FIGURE 7b). While at first glance the profiles for both SOE types appear similar, looking more carefully we see that the profile corresponding to the top subcell is somewhat squarer for the HDR. This is unsurprising: it is specifically the blue rays that were recovered with the reflector, and it could be expected that this is also partially homogenizing them. The difference is clearer when these profiles are divided by each other to determine the predicted profile of the subcell current ratio (J_{top}/J_{mid}) over the cell. (FIGURE 7c) Here we can see that the effect of the small change in shape of the top profile has caused there to be a ring of area with high current saturation of the top cell. This current must move laterally to areas with middle subcell excess currant in order to escape the cell: depending on the lateral sheet resistance, this will cause ohmic losses that appear as the current losses seen in the subcell limitation diagram. These effects generally are only apparent for the largest cells at high concentration, as is the case in these tests with 1000X on a 1cm^2 cell. Also our observations may only be relevant to the specific cells used in these tests: we cannot predict what would be response for a similar cell from another manufacturer.

CONCLUSION

We propose an evolution of the classical "dome" SOE: the Hybrid Dome with Reflector (HDR). We have analyzed this dome via ray-tracing simulation and experiments, and shown that it outperforms reflective SOEs as well as conventional nominal height domes while providing lower costs than other dielectric SOE types. It also presents aspects that should make it easy to assemble to the solar cell. Measurements performed to date show promising acceptance angle and focal tolerance when used with a high concentration, large cell CPV module. Some limitations due to lateral series resistance in very large cells (1cm), working at high concentration (1000X) have been detected. An in depth study would be required to understand whether the limitations observed are indicative of HDR performance with all 1cm multijunciton solar cells or only the specific cells used in these experiments. We expect that these limitations would not apply if either the concentration or the cell size were reduced and, at the same time, are working on an improved version of the design that should alleviate them even in worse case scenarios such as those presented here.

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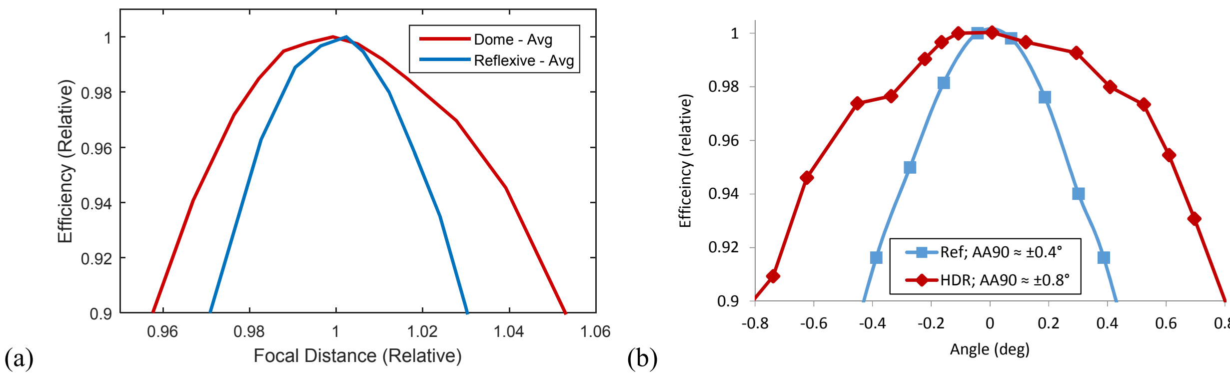

FIGURE 6. (a) Comparison of electrical efficiency of the same CPV system (1000X, 1cm cell) using a reflective SOE and the HDR versus a variation of the focal distance (b) The acceptance angle curves for both SOEs.

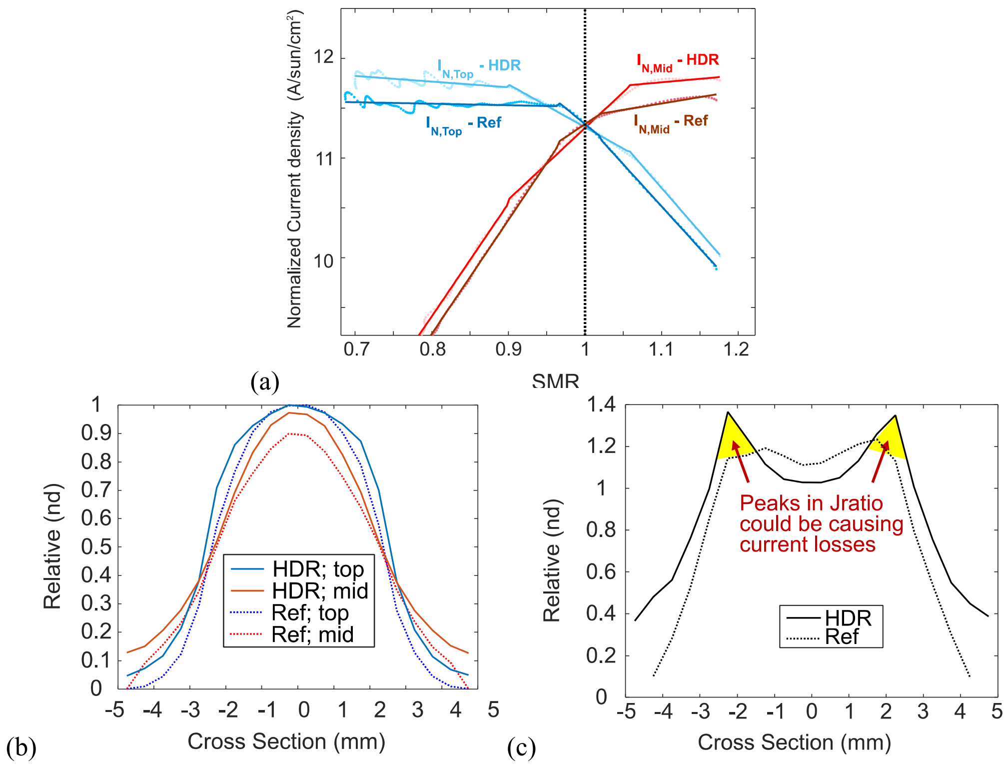

FIGURE 7. (a) Subcell limitation diagrams measured for both SOE types at their respective optimal focal distances. (b) The ray-tracing derived profiles of the photocurrents across the cell for each SOE type. (c) The top/middle current ratios derived from (b), showing that there are areas with excessively high top current.

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