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Optimization of a four junction solar cell CPV system using ray tracing and SPICE modeling

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***Abstract* — Concentrating optics generally produce spatially and spectrally non-uniform optical profiles across the multijunction solar cells (MJSC) typically used in a concentrator photovoltaic (CPV) systems, degrading fill factors and thereby reducing module efficiencies. These effects maybe more pronounced if the primary-to-receiver working distance is sub-optimal and if the system does not track the sun accurately. We integrate ray tracing with a distributed equivalent circuit model to simulate the performance of a four junction solar cell under a Fresnel-lens-based CPV system of 1250X geometric concentration. The impacts on system efficiency of varying both the primary-to-receiver working distance as well as the tracking accuracy are evaluated. Our results indicate a relative enhancement of 6.67% when we optimize the working distance based on an integrated systems approach using the full optical distribution as an input to a 2-D distributed equivalent circuit model of the MJSC, as opposed to a uniform profile 1-D treatment. With a more optimized system, we find a relative reduction in efficiency of 10.7% for a tracking error of 1º, with the penalty for improper tracking increasing for sub-optimal primary-to-receiver working distances.**

I. INTRODUCTION

Multijunction solar cells (MJSCs) have been reported to yield the highest optical efficiencies under concentration as compared to other available technologies. A four junction solar cell (4JSC) manufactured using wafer bonding technology presently holds the record efficiency of 44.7% under 297-suns concentration [1]. However, the maximum overall module efficiency has been reported to be only 36.7% for a similar MJSC [2]. For CPV systems based on point-focus Fresnel lenses, this large reduction in efficiency has been attributed to losses arising from the non-uniform illumination and chromatic aberrations induced by the optical train. These effects lead to a degradation in fill-factor and hence a loss in efficiency of the system [3].

Optimal MJSC performance requires the current matching of individual subcells, where subcell charge production depends on the spectrum and distribution of photons produced by the particular concentrating optics. Therefore, optimal module efficiency is a system optimization problem. Various authors have studied systems based on triple junction solar cells [4,5] to understand the effect of CPV optics. Since new materials and novel designs have emerged, the optimization process needs to be revisited.

In previous works, we modeled lattice-matched, triple junction and four junction solar cell (4JSC) structures using SPICE [6,7] and compared their performances with an inverted metamorphic, triple junction solar cell under non-uniform illumination [8]. In this paper, we integrate ray tracing with a two-dimensional (2-D) distributed equivalent circuit model for 4JSC and perform a tolerance analysis under the influence of spatial and spectral non-uniformities. Simulations are carried out at different primary-to-receiver working distances and the optimal working distance is determined. The system tolerance to tracking errors (alignment variation from direct normal incidence) is also evaluated.

II. NUMERICAL AND DISTRIBUTED CIRCUIT MODEL

Equivalent circuit parameters are obtained for a lattice-matched 4JSC structure composed of GaInP, AlGaAs, and InGaAsN on a doped Ge substrate simulated using a drift-diffusion-based device simulator [7]. The structure is modeled as a 2-D symmetry element with a gridline shading of 4.2%, and the external quantum efficiency (EQE) curves thus obtained are shown in Figure 1. Under an AM1.5D spectrum at 1 sun (1 sun = 1000 W/m^2), the top two subcells are current matched at 12.5 mA/cm^2, with overproducing InGaAsN and Ge subcells, at 13.3 and 15.3 mA/cm^2, respectively. Discounting the losses due to CPV optics, an efficiency of 42.5% is obtained at 1000 suns and 298K for a 1cm^2 cell.

Equivalent circuit representations have been used in the past to model distributed effects in triple junction solar cells [9, 10]. Our simulations here employ a two-dimensional, distributed equivalent circuit model for 4JSC that we have previously introduced [7].

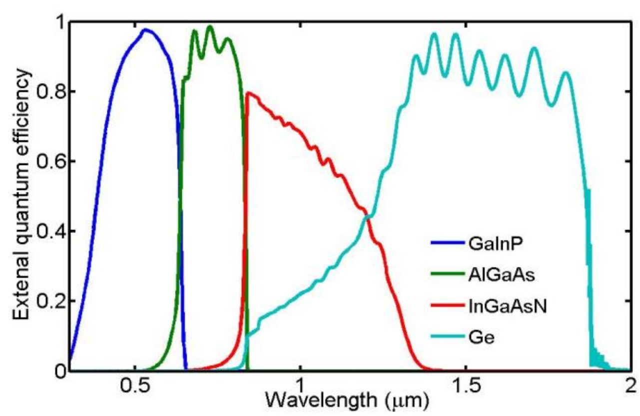

Fig. 1: External quantum efficiency curves for each subcell in a lattice-matched 4JSC.

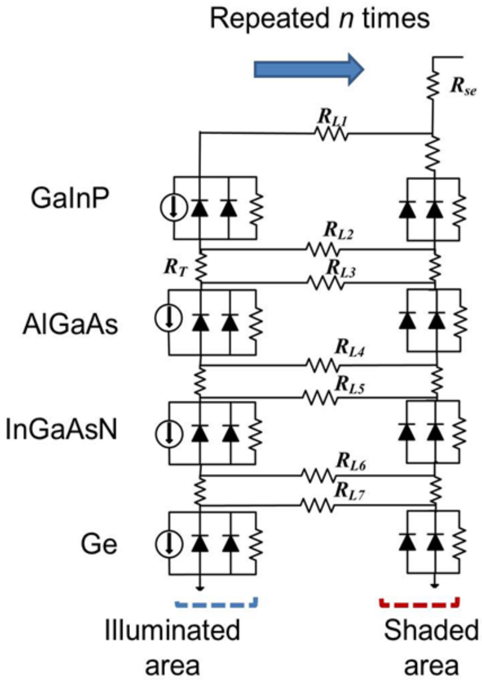

Fig. 2: A functional block in a 2-D distributed equivalent circuit model for a four junction solar cell. A functional block is repeated *n* times to generate the model of a complete 4JSC in SPICE.

Figure 2 shows one functional block of this model with an illuminated region and a shaded region representing the area underneath a grid finger. Two-diode models for each subcell along with series and shunt resistances are included. Low resistance idealized tunnel junctions are also incorporated, along with electrode resistances.

II. OPTICAL DESIGN

We consider a CPV system with a geometric concentration of 1250X, employing a primary optical element (POE) for concentration and a secondary optical element (SOE) for homogenization. The POE is assumed to be a polymethylmethacrylate-based Fresnel lens and the SOE a truncated pyramid of BK7 glass. This optical system is modeled using commercially-available ray tracing software, and we have included losses due to material absorption, dispersion and Fresnel reflections in the simulations. The Fresnel lens is modeled as a geometrically ideal lens, that is, one with no groove losses. Ray tracing is performed with 1 million rays using virtual spectra derived from the product of subcell EQE with the AM1.5D solar spectrum [4]. This allows for the direct estimation of the relative photocurrent, as suggested by Victoria *et al.* [4], and is used an input to the distributed equivalent circuit model. A solar angle of 0.29º is also included in our simulations. The height of the secondary optical element is kept constant for all simulations.

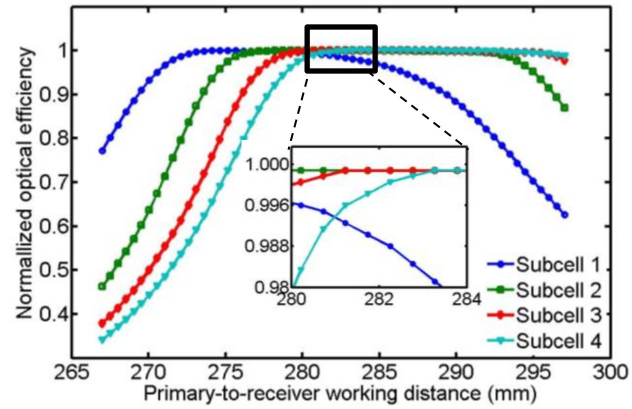

Fig. 3: Normalized optical efficiency relative to each subcell as a function of primary-to-receiver working distance. The zone within which the normalized efficiency for all subcells is greater than 98% is highlighted. Inset shows the enlarged view of the optimal zone.

II. RESULTS

A. *Effect of primary to receiver working distance*

An optimal primary-to-receiver working distance may naïvely be determined using only the optical efficiency as a metric. Incorporating the average spectral mismatch between the cells, but disregarding the spatial inhomogeneity (i.e., a 1-D approach, averaging the spatial distribution across each subcell), we have determined the normalized optical efficiency for each subcell as a function of the primary-to-receiver working distance as shown in Figure 3. The results indicate an optimal zone (black rectangle) where the relative optical efficiency of all subcells is within 2% of the maximum. We take the middle point of this zone (enlarged in inset), 282 mm as the optimal working distance ignoring the spatial non-uniformity. Extending the analysis to a full system optimization that includes the spatial non-uniformity as well requires the use of our 2-D model.

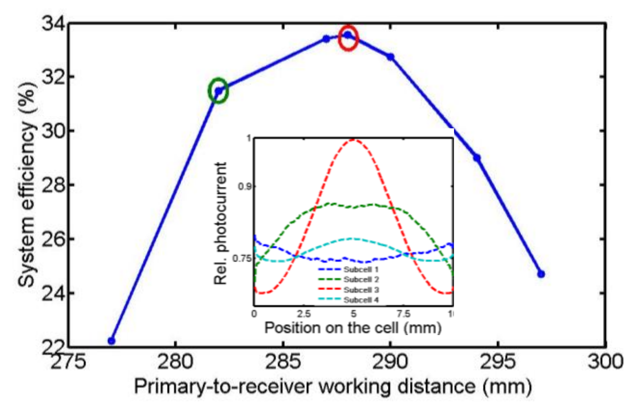

Fig. 4: Overall system efficiency as a function of primary-to-receiver distance including the effects of spatial and spectral non-uniformities. Efficiencies at a working distance of 282 mm (obtained ignoring spatial non-uniformity) and 288 mm (obtained using integrated optimization) are highlighted. Inset shows the relative photocurrent distribution as a function of cell position for each subcell at the optimal working distance of 288 mm.

The spatial distribution of rays is explicitly considered within the 2-D distributed equivalent circuit model, which determines a spatially-dependent photocurrent within each subcell. For each primary-to-receiver working distance, these local photocurrents lead to an aggregate cell response that is representative of the system efficiency. Figure 4 shows the variation in system efficiency with primary-to-receiver working distance, revealing an optimal working distance of 288 mm at an overall efficiency of 33.6% (highlighted red oval). If the cell were to be placed at a working distance of 282 mm, as a naïve optimization would suggest, the efficiency drops to 31.5% (highlighted green oval). Thus, system optimization leads to an enhancement in efficiency of 2.1% absolute (a relative enhancement of 6.67%).

The inset in figure 4 shows the relative photocurrent distribution obtained using ray tracing at the optimal distance. The cell is current-limited by the top subcell in certain areas and by the dilute nitride subcell towards the edges. Note that the overall efficiency is not only dependent on the severity of the nonuniform illumination [11], as mismatch in the local currents would suggest, but also on sheet resistance components. It is therefore critically necessary to use distributed circuit models to more carefully assess such effects.

B. Tolerance to tracking errors

Typical CPV systems are designed to operate at normal incidence under uniform illumination. However, the systems may suffer from tracking errors, making the irradiance non-uniformity worse and leading to greater current-mismatch between the subcells [11]. We investigate the impact of tracking errors by tilting the system between 0 and 1.5 degrees with respect to the optical axis. A comparative analysis is performed at the primary-to-receiver distances obtained above.

Figure 5 shows the effect of tracking errors on the efficiency of the CPV system at the two working distances. For the integrated system optimization (red data points), our results indicate a less than 3% drop in relative efficiency for a tracking error of 0.25º, increasing to a drop of 10.7% relative for a 1º offset. The penalty for tracking error is much higher if the spatial non-uniformities are neglected in the optimization than otherwise (green data points).

IV. CONCLUSIONS

Our results indicate that an integrated analysis of optics and cell is necessary to determine the optimal performance of a CPV system. Enhanced efficiencies (6.67% relative for our design) can be obtained if the cell and optics are optimized together. We also looked at the tracking tolerance of the system. A relative efficiency drop of 10.7% is obtained with a tracking error of 1º at the optimal working distance obtained using the system optimization approach. Thus, a properly optimized system is more tolerant to tracking error.

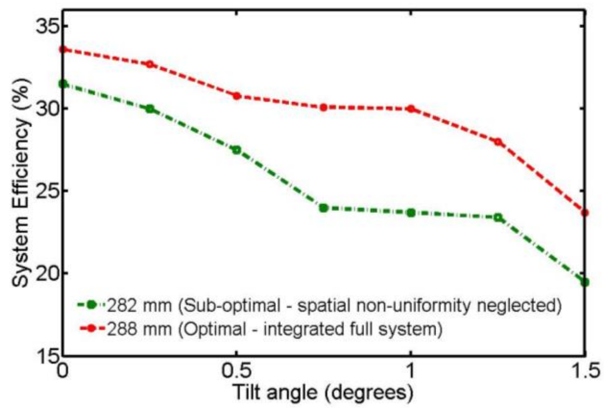

Fig. 5: Overall efficiency as a function of tilt angle with the sub-optimal and optimal working distances.

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