

# ESTIMATING AND CONTROLLING CHROMATIC ABERRATION LOSSES FOR TWO-JUNCTION, TWO-TERMINAL DEVICES IN REFRACTIVE CONCENTRATOR SYSTEMS

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## ABSTRACT

Although previous studies have measured and calculated chromatic aberration losses and proposed methods for reducing these by modifying the optics, significant work remains to be done toward understanding how to quantify the losses and how various parameters affect this loss. This paper presents an analytical definition and calculation method for chromatic aberration losses. The effects of sheet resistance of the midlayers of the cell, total irradiance, incident spectrum, cell width, and diode quality factor are studied. A method for measuring the midlayer resistance in finished cells is described.

## INTRODUCTION

Although commercial concentrator systems based on two-junction  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}$  cells are not yet a reality, several companies are interested in their development. Both Applied Solar Energy Corporation (ASEC) and Spectrolab have developed production capabilities of these cells for space applications and could quickly produce adequate supplies for concentrator systems. The New Millennium space flight is planned to use a photovoltaic system [1] based on  $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}/\text{GaAs}$  cells made by ASEC and linear Fresnel lenses developed by ENTECH [2]. The success of this system could lead to widespread use of this concentrator technology in space. For terrestrial applications the cells are still quite expensive, implying the need for very high concentration ratios (1000X). Companies such as Solar Research Corporation [3], ENTECH, and EDTEK could incorporate the two-junction cells into their concentrator systems. Outdoor efficiencies of 27% have been measured [3]. However, two-junction, two-terminal devices present a special problem in that they must be current-matched to attain their best efficiencies. This implies that variations in the spectrum caused by the focusing optics are a potential problem. Development of concentrator systems using the two-junction technology depends on an ability to mitigate the chromatic aberration (CA) losses. Previously, we showed [4] that the CA losses in the ENTECH terrestrial system were significant, but could be controlled to 4% if the alignment of the system was optimal. We suggested that small amounts of CA could be controlled by lateral current flow in the layers connecting the two junctions. James proposed [5] that the CA losses could be minimized by Fresnel elements that alternately focus red and blue

light or that use an optical secondary. Concentrator systems based solely on reflective optics are immune to CA losses. If any refractive element is used there will be some small CA loss that should be quantified and controlled. The purpose of this paper is to provide tools and a working knowledge of how to quantify the losses both analytically during the design phase and experimentally. Although the calculations are 1-dimensional, simulating a linear focusing element, the methods and conclusions should help to understand CA losses in point-focus systems as well.

## CALCULATION METHODS

Accurate calculation of the CA loss must include the effects of various cell parameters. Fig. 1 shows a schematic of the diodes and resistors in the simplest situation, assuming a linear concentrating element. This simple model can be solved for each tandem cell voltage by adjusting the voltage at point 1. Starting with an estimate of the voltage at point 1, currents  $T_1$  and  $B_1$  are calculated and their difference defines both the current and the voltage drop for  $R_1$ . Working across the network, the solution is obtained when the adjusted voltage at point 1 results in equal currents through  $T_{20}$  and  $B_{20}$ .

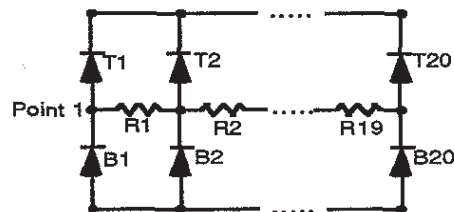


Fig. 1. Schematic indicating network of top- and bottom-cell diodes and connecting resistors. The resistors represent the combined sheet resistances of the bottom-cell emitter, the tunnel junction, and the top-cell base and are referred to in the text as the midlayer resistances or simply as sheet resistance.

Difficulties arise with this calculation in two cases: First, for tandem-cell voltages causing one or both cells to go strongly into forward bias, the voltage at point 1 must be adjusted to a very high precision, sometimes a higher precision than double-precision data storage allows. In the present study, for high sheet resistances, this problem sometimes prevented convergence at the maximum power point. Convergence is much easier in reverse bias, since

relatively large changes in voltage may cause only small changes in current. The second limitation of this method of calculation occurs when the complexity of the network is increased, i.e., when a 2-dimensional network is used. In either case an alternative calculation method involves adjusting lateral currents. This approach is much more challenging since the number of variables to be adjusted is greatly increased and the step sizes needed to adjust each current element may differ and vary exponentially as the tandem I-V curve is scanned.

Using the solution of the circuit shown in Fig. 1 for enough voltages to define the maximum power point, we propose to define the CA loss as the difference in the maximum power output from a network with all of the lateral resistances set to zero compared with the maximum power from the network of interest. It is also possible to define the loss relative to uniform flux profiles with the same average irradiance, but then losses associated with the non-uniform flux profile will also be lumped into the CA loss. A more complicated definition could be used that has the average shape of the top- and bottom-cell flux profiles, but gives equal currents to both the top and bottom cells at all locations. We choose to use the zero resistance definition both because it is convenient and because it is the one method that quantifies the CA loss and no other loss factors. This definition is very precise and convenient when calculating CA losses, but is impractical for experimental measurements. Direct measurement of the CA loss by itself is very difficult. Experimental measurement methods are discussed below.

The lateral resistances represent the combined sheet resistances of the bottom-cell emitter, the tunnel junction layers, and the top-cell base. For GaInP/GaAs cells the combined sheet resistance is usually in the range 50 - 1000  $\Omega$ /sq. Lower values should be achievable. The shapes of the bottom- and top-cell I-V curves were calculated assuming one-sun  $J_{sc}$  values of 15 mA/cm<sup>2</sup> and  $V_{oc}$  values of 0.95 and 1.35 V for the bottom and top cells, respectively. These values are suitable for GaInP/GaAs tandem cells. Similar results may be obtained for other materials systems, but the losses are expected to be lower for lower-band-gap materials because these have higher

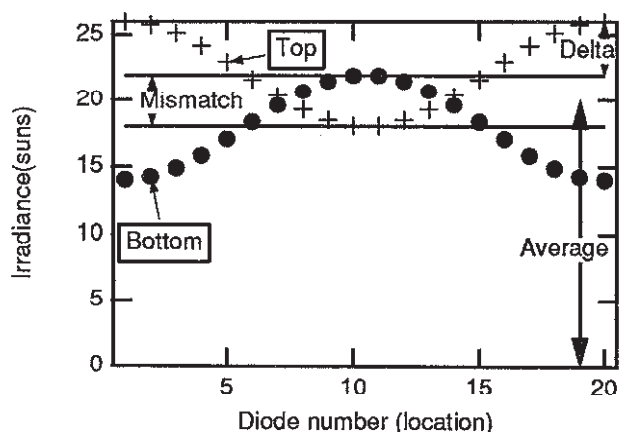


Fig. 2. Cosine-shaped flux profiles for irradiance relevant to top and bottom cells. The parameters Average, Delta, and Mismatch were varied for the calculations.

dark currents (lower fill factors). For the same reason, the diode quality factor has a significant effect on the CA loss. Unless otherwise noted, its value was set to unity. The effects of shunt and series resistances are discussed briefly.

We previously [4] defined the CA loss as the difference between the powers expected for a device connected in a 2-terminal configuration compared with the 4-terminal configuration. In practice, this definition will also incorporate losses from not only CA current mismatch, but also any current mismatch that exists on average. Thus, if a cell has been optimized for operation under the AM1.5 direct spectrum and the test spectrum deviates from this standard spectrum, the cell will become current mismatched even under uniform irradiance, causing a difference between the 2- and 4-terminal powers. Thus, it is convenient to quantify the CA loss by comparison with the zero sheet resistance case, as described above.

### CALCULATED RESULTS

As shown in Fig. 2, flux profiles for the 20 diodes were defined by

$$\text{Flux} = \text{Average} \pm \text{Mismatch}/2 \pm \text{Delta} \cos[2\pi(x-1)/19],$$

where  $x$  is the diode number (location) and values for Average, Delta, and Mismatch are in units of suns and are shown schematically in Fig. 2.

The shape of the I-V curve was found to depend on the midlayers' sheet resistance as shown in Fig. 3. The voltage at the maximum power point first decreased since small CA losses result in I-V curves similar to what is expected for any small series resistance loss. For higher sheet resistances, the CA loss increases and the shape of the I-V curve shows an apparent shunt (see Fig. 3), causing the maximum power point to move to greater voltages. This dramatic change is caused when the subcell with the (locally) larger photocurrent is forced locally into forward bias. Bringing the tandem cell into reverse bias far enough will eventually move the forward-biased regions closer to their maximum power points, allowing for greater current collection.

For curves similar to those shown in Fig. 3, the power loss was calculated and is plotted in Fig. 4 along with data for other average irradiance values. Delta was always chosen to be 20% of average for this set of curves. In general, under close examination, a slow increase in power loss is observed for small sheet resistances. This is

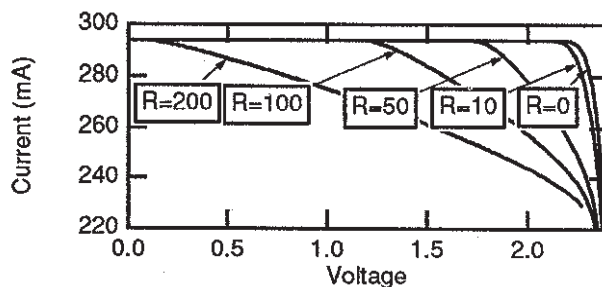


Fig. 3. Change in I-V curve shape as a function of sheet resistance,  $R$ , in units of  $\Omega$ /sq for Average = 20 suns, Delta = 8 suns, Mismatch = 0 suns, and Cell width = 1 cm.

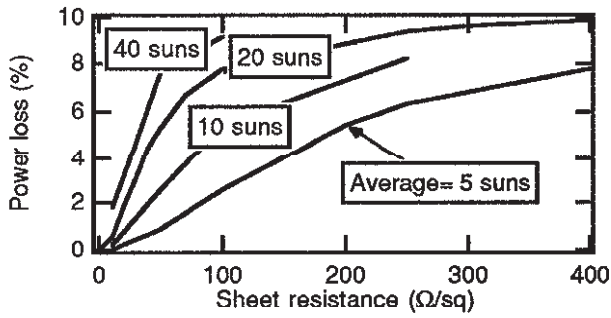


Fig. 4. Power loss from CA for various irradiance levels. Values for other parameters were Delta = 20% of Average, Mismatch = 0, and Cell width = 1 cm.

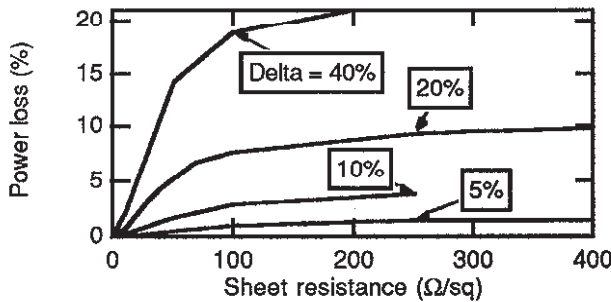


Fig. 5. Effect of size of CA on the power loss. Average = 20 suns, Mismatch = 0 suns, and Cell width = 1 cm.

the region for which the I-V curve shows an apparent small series resistance loss and a decreased voltage at the maximum power point. As local regions begin to be driven into forward bias the loss increases more steeply, eventually leveling off toward the maximum loss, about half of Delta in this case. In general, the maximum loss is obtained for infinite sheet resistance and can be estimated by adding the lower of the top- and bottom-cell currents for the 20 diodes and comparing this with the sum of all of the bottom-cell currents (or with the sum of all of the top-cell currents if that number is lower). This simple method of estimating the maximum loss from the current loss will overestimate the loss since the voltage at the maximum power point will increase slightly. The midlayer conductance needed to mitigate the power loss strongly depends on the size of the CA (see Figs. 4 and 5).

Using a mismatched spectrum, i.e., one that produces different photocurrents in the top and bottom cells on average, reduces the CA power loss, as shown in Fig. 6. Whether extra light was generated in the top or bottom cell created negligible difference when the two cells had the same diode quality factor. The smaller CA loss is a direct result of the mismatch loss, as shown in Fig. 7. The highest mismatch case has the lowest power even though it shows the smallest CA loss. When a system is limited by top-cell current everywhere, the extra bottom-cell flux distribution is unimportant.

The cell width has a large effect on the sheet resistance needed to mitigate losses (see Fig. 8). The farther the current needs to travel, the lower the sheet resistance needed to avoid significant voltage variations and forward biasing.

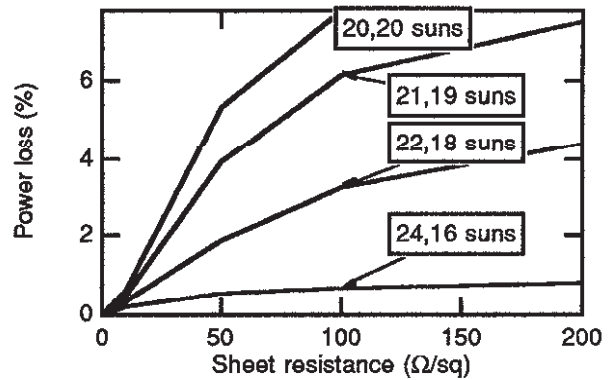


Fig. 6. Effect of current mismatch on the CA power loss; Average = 20 suns, Delta = 4 suns, and Cell width = 1 cm.

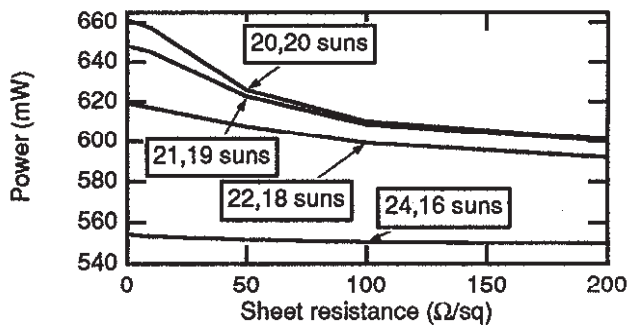


Fig. 7. Power output for mismatch values between 0 and 8 suns. Data are the same as plotted in Fig. 6.

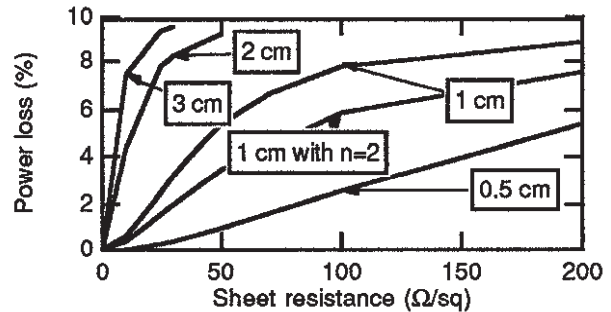


Fig. 8. Effect of cell width; Average = 20 suns, Delta = 4 suns, and Mismatch = 0. The curve labeled 1 cm with n=2 used a diode quality factor of 2.

The shape of the top- and bottom-cell I-V curves can affect the CA losses. The most important parameter is the diode quality factor. Also shown in Fig. 8 is a curve showing that the power loss is less when the diode quality factor is 2 rather than 1. This is because current changes less with voltage drops when the dark current is less steep (n=2 is less steep than n=1). Similarly, changes in temperature will affect the slope of the dark current, although less than the diode quality factor. Shunt and series resistances were included in the calculation for completeness (these are not shown in Fig. 1). However, resistors introducing power losses on the order of 1% typically changed the CA losses by 0.1% or less. Thus, it was practical to omit them in the rest of the calculations.



## EXPERIMENTAL DETAILS

Measurement of the midlayer sheet resistance is demonstrated for a 1-cm-wide tandem cell. Two filters were used, one passing primarily top-cell light while the other passed primarily bottom-cell light. The fill factor and  $J_{sc}$  of the cell were measured as the filters were moved from one side to the other. Fig. 9 shows how the cell  $J_{sc}$  went through a maximum when the filter location was such that the photocurrents from the top and bottom junctions were equal. At this point, the photocurrent flowed laterally across the cell, causing the fill factor to drop by 30%. Fig. 10 shows I-V curves measured for three filter positions, including placement of only one filter over the entire cell.

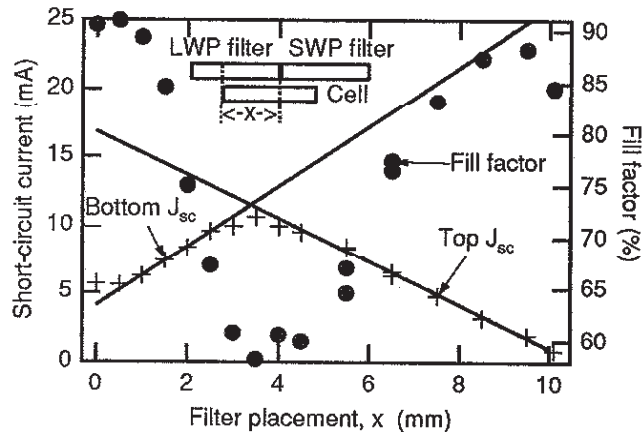


Fig. 9. Short-circuit current and fill factor as a function of the position of two filters (a long-wave pass, LWP, and a short-wave pass, SWP).

The first step in fitting the data in Fig. 10, was to determine the tandem-cell I-V curve parameters (diode quality factor, shunt resistances, etc.) by fitting dark I-V and uniform-light I-V measurements. The second step was to obtain the illumination levels of both the top and bottom cells for each of the filters. The measured  $J_{sc}$  reflects the smaller of the two photocurrents. The larger of the two currents can be obtained graphically from Fig. 9 by using the linear fits for the top- and bottom-cell  $J_{sc}$  values. The top-cell current generated under the short-wave pass filter is about 17 mA, since the 0 location corresponds to placement of the short-wave pass filter across the entire cell. In practice, the squareness of the edges of the filters (and whether the dielectric coating reaches the edge of the filter) limits the accuracy with which the currents can be measured. The parallel sheet resistance of the bottom-cell emitter and tunnel junction was measured to be 235 - 260  $\Omega/\text{sq}$  using a transmission line plated on a sister sample from which the top cell had been removed. This measurement did not include any contribution from the base of the top cell, but this contribution is believed to be fairly small for this n-on-p device. Fitting the dashed I-V curve (the curve with the lowest fill factor) and selecting the value of midlayer resistance which best fit the measured fill factor, the two-filter method gives a midlayer sheet resistance of 260  $\Omega/\text{sq}$ . This is consistent with the measured values, demonstrating the validity of the model.

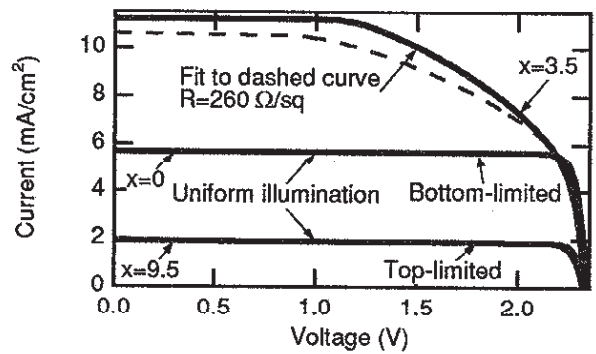


Fig. 10. I-V curves measured and calculated for the  $x=0$ , 3.5, and 9.5 data of Fig. 9. The thick lines were calculated and the thinner lines were measured. The fit for the dashed curve gives better prediction of fill factor than of current.

## SUMMARY

Careful design of the focusing optics is essential to keep the size of the CA small. However, residual power loss from CA can be mitigated by lateral conduction when the sheet resistance of the midlayers is low, the size of the cell is small, and the amount of current that needs to be moved because of the aberration is small. The midlayer sheet resistance can be measured on a finished cell by shining top-cell light on one half and bottom-cell light on the other half, then modeling the resulting I-V data.

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