Spectral and Temperature Sensitivity of Area De-Coupled Tandem Modules

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***Abstract*—Area de-coupling is a recently suggested method for current- or voltage-matching two-terminal tandem modules. It has previously been shown that under standard conditions, area de-coupled modules have the same theoretical efficiency as four-terminal tandem cells for any combinations of band gaps. In this work, the spectral and temperature sensitivity of ideal area de-coupled modules is investigated by detailed balance modeling. Voltage-matched area de-coupled modules are found to be considerably less sensitive to changes in the spectrum than current-matched modules. Current-matched modules are, on the other hand, found to be less sensitive to changes in the temperature. Under normal conditions, the difference in temperature sensitivity has a negligible impact on the efficiency compared to the difference in spectral sensitivity, making voltage-matched modules the preferred choice. The difference in efficiency between an area de-coupled voltage-matched module and a four-terminal device is found to be too small to be of any practical consequence even under changing conditions. This finding is in agreement with earlier work by Lentine et al. on microsystem-enabled photovoltaic modules.**

***Index Terms*—area de-coupling, tandem module, theoretical efficiency, two-terminal.**

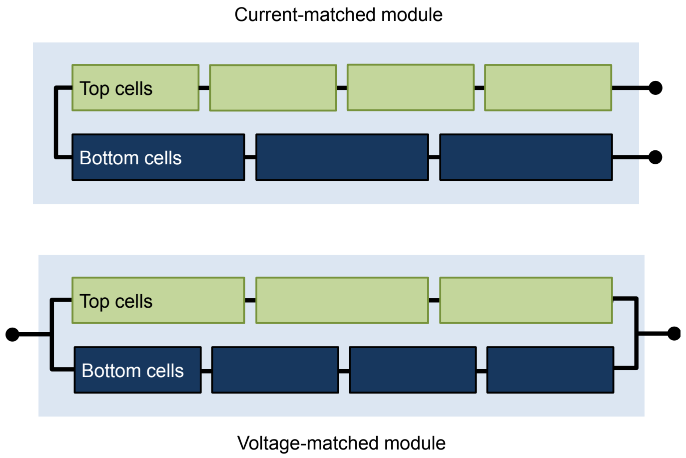

Fig. 1. Sketch of area de-coupled tandem modules. The upper module has current-matched layers, while the lower module has voltage-matched layers.

I. INTRODUCTION

In recent work, the concept of current matching by area-decoupling was suggested [1]. The concept implies having different numbers of top cells and bottom cells in a tandem module. The cells are horizontally series connected in layers as shown in Fig. 1. The cells in each layer cover the same total area. The layers can either be series-connected and current-matched or connected in parallel and voltage-matched. Fig. 1 also shows the difference between current-matched and voltage-matched modules.

In Ref. [1] the theoretical efficiency of both voltage-matched and current-matched area de-coupled double tandem modules was calculated for one set of conditions, that is the AM1.5 spectrum and a module temperature of 300 K. It was found that the theoretical efficiency of area de-coupled two-terminal tandem modules matches that of four-terminal tandem cells where the voltage of the top cells and bottom cells can be varied independently. This result is valid for both current-matched and voltage-matched modules and for any combinations of band gaps. Four-terminal devices have only slightly higher peak efficiency than conventional two-terminal series-connected stacks [2], but high efficiency is achieved for a wider range of band gap combinations. Area de-coupled modules therefore achieve has high theoretical efficiency for a wider range of band gap combinations than traditional two-terminal devices.

A clear advantage of four-terminal devices is that they can easily adapt to changing conditions since the top cells and bottom cells are operated separately. Separate operation is not possible with two-terminal devices. In general one would therefore expect some current- or voltage-mismatch to occur in area de-coupled modules when the actual conditions differ from the design conditions. It has, however, been shown that voltage-matched two-terminal devices are able to perform almost as well as four-terminal devices with varying spectrum and cell temperature, with expected differences in the annual yield of 1-2 % [3], [4]. The cited work considered modules with cells of equal sizes that were horizontally series-connected in strings. The voltage-matching was achieved by adjusting the length of the strings in the top and bottom layers and connect these voltage-matched strings in parallel. The present work extends the analysis carried out in Refs. [1], [3] and [4] by examining how different spectra and module temperatures affect the theoretical efficiency of two-terminal *area de-coupled* modules compared to that of four-terminal devices.

II. THE MODEL

The mathematical model for area de-coupled modules used in this work is a straightforward detailed balance model based on the work of de Vos [5] and Martí and Arajo [6]. The model is described in Ref. [1]. The theoretical efficiency of four-terminal cells is calculated as in Ref. [6] and the theoretical

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efficiency for a series-connected stack is calculated following the work of Brown and Green [2]. For simplicity, spectrally selective reflectors are assumed to be placed between the top cells and the bottom cells. Such reflectors reflect luminescence from the top cell back to the top-cell and slightly increase the theoretical efficiency [6].

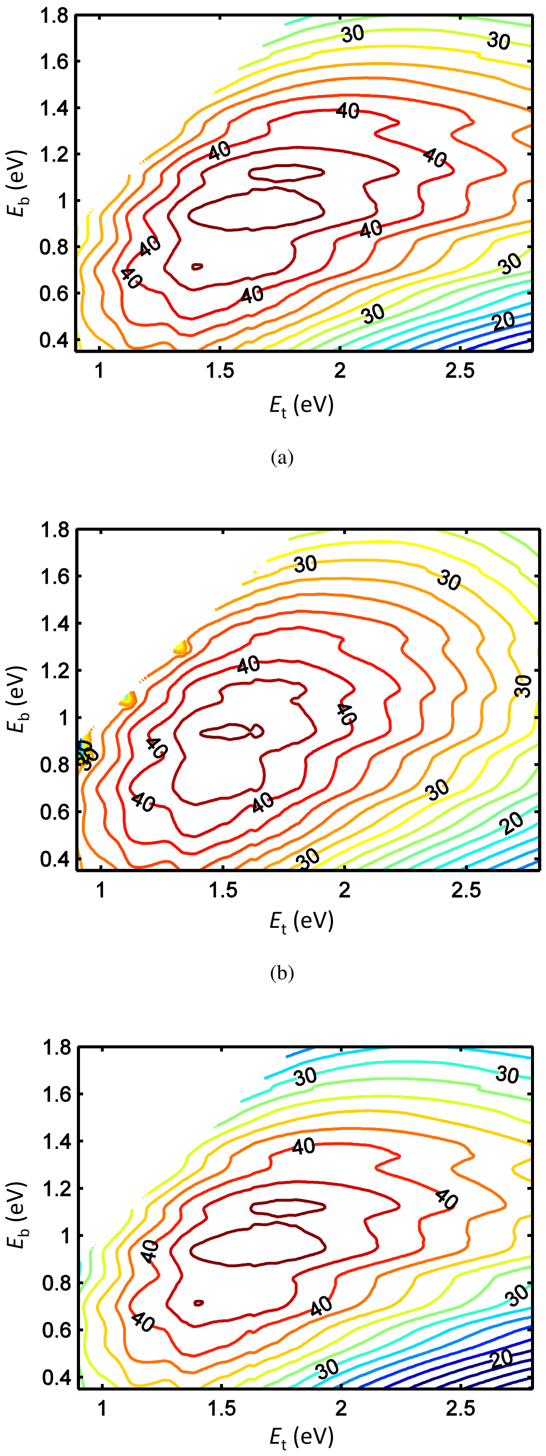
Several spectra have been used in this work. The standard AM1.5G spectrum (ASTM G-173-03) has been used without modifications. The AM1, AM2, AM3, AM5 and AM10 spectra have been calculated using the SMARTS program package [7], [8]. They were obtained with exactly the same settings and conditions as described for the AM1.5G spectrum, but with other values for the air mass.

III. RESULTS AND DISCUSSION

The optimal ratio of the number of top cells to the number of bottom cells was calculated in Ref. [1] for the AM1.5G spectrum and a cell temperature of 300 K. For other spectra and temperatures, the optimal value of this ratio changes, and a module optimized for the mentioned conditions will in general be sub-optimal under other conditions. In the following, this ratio will be called the m/n-ratio since this term was used in the first paper on area de-coupled cells, with m being the number of top cells and n the number of bottom cells. In the following paragraphs, theoretical efficiencies are calculated for modules where the m/n-ratio is optimized to the AM1.5G spectrum and a module temperature of 300 K, but subject to other conditions.

Figure 2 shows efficiency maps for tandem cells illuminated with the AM3 spectrum as a function of the band gap of the top cells, E_t, and the band gap of the bottom cells, E_b. The module temperature is 300 K. The upper graph shows the theoretical efficiency of a four-terminal device. The graph in the middle shows the efficiency of a current-matched module with area de-coupled cells and the lower graph shows the efficiency of a voltage-matched area de-coupled module. From figure 2 it is seen that voltage-matched area de-coupled modules gives higher efficiency than current-matched area de-coupled modules, when the incoming spectrum changes to the AM3. It is hard, if not impossible, to see any differences between chart a) and chart c) in figure 2. The actual difference is typically around 0.02 % absolute, and hardly of any practical consequence.

Modules with a bottom layer of silicon cells are particularly interesting due to the possibility of boosting conventional silicon modules with a top layer of bi-facial thin-film cells. To better visualize the differences between different tandem concepts, the theoretical efficiency of four device types with $E_\mathrm{b} = 1.11\,\mathrm{eV}$ are plotted for six different spectra in figure 3. The device types are: 1) Four-terminal devices where top cells and bottom cells are operated individually. 2) Traditional series-connected tandem stacks where the top cell and bottom cell has the same area. 3) Area de-coupled modules with current-matched layers. 4) Area de-coupled modules with voltage-matched layers. The area de-coupled modules are optimized for the AM1.5G spectrum, which results in an overlap



(a)

(b)

(c)

Fig. 2. Efficiency as a function of the band gaps for three types of double tandem modules exposed to the AM3 spectrum. The modules in (a) have top and bottom cells that are operated individually (four-terminal cell). Chart (b) shows the results for a *current-matched* two-terminal module with the m/n-ratio optimized for the AM1.5G spectrum. The efficiencies in (c) are calculated for a *voltage-matched* two-terminal module which also has an m/n-ratio optimized for the AM1.5G spectrum.

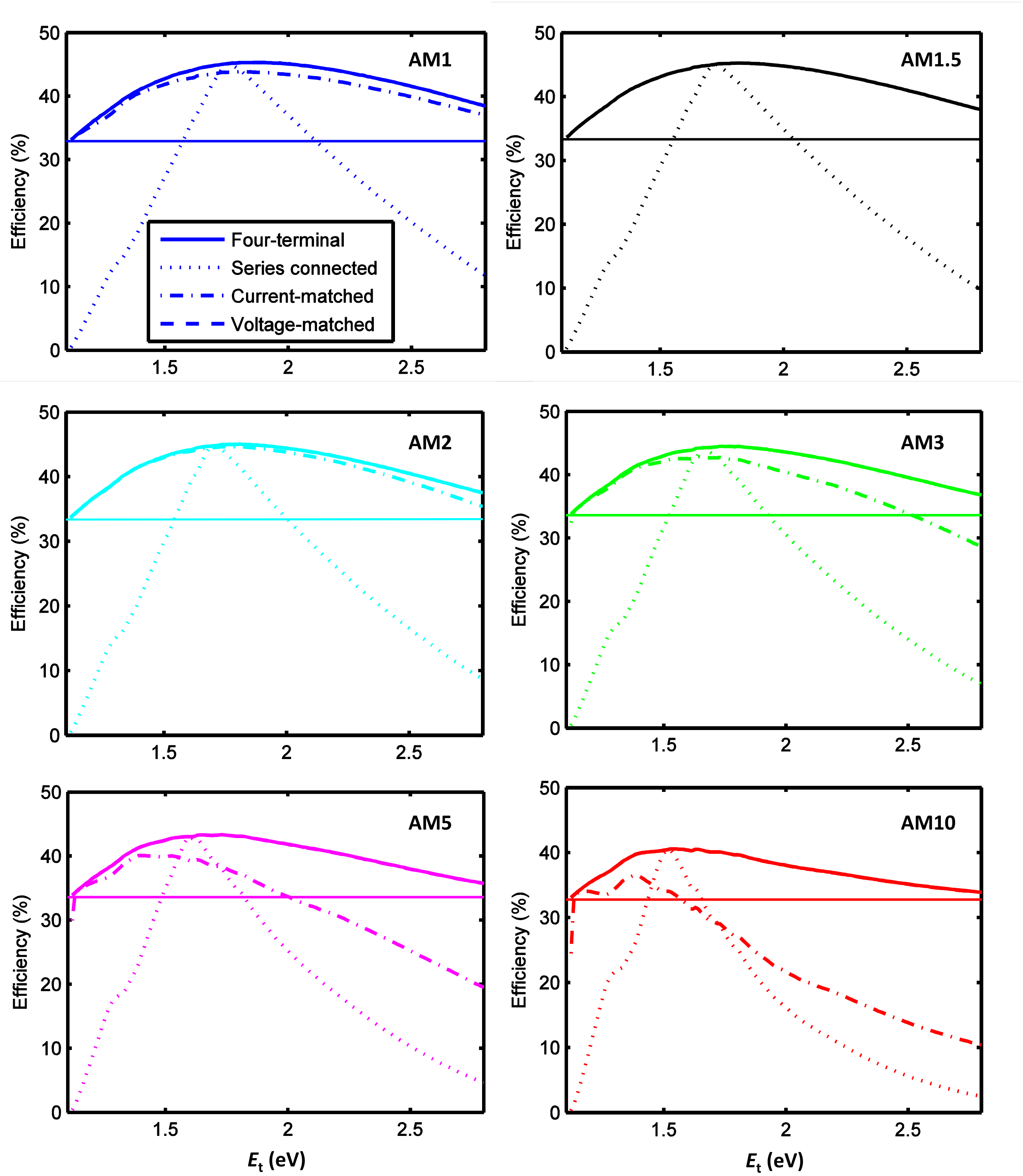


Fig. 3. Plots illustrating the spectral sensitivity of different types of tandem devices. The charts show the efficiency of the different device types when illuminated by six different spectra. The area de-coupled devices have been optimized for the AM1.5 spectrum. The band gap of the bottom cells is set to 1.11 eV and the band gap of the top cells is varied according to the horizontal axis. Solid lines show the efficiency of four-terminal devices and dotted lines the efficiency of traditional series-connected tandem stacks. Dash-dot lines show the efficiency of area de-coupled modules with current-matched layers. The dashed lines, showing the efficiency of area de-coupled modules with voltage-matched layers, are not visible in the charts because they are overlapped by the solid lines of the four-terminal devices. The device temperature is set to 300 K. The straight horizontal lines show the theoretical efficiency of single band gap cells with band gaps of 1.11 eV for the various spectra.

between the curves for four-terminal devices and area de-coupled modules of both types in the chart for this spectrum. For the other five spectra, there is an overlap between the curves for four-terminal devices and voltage matched area de-coupled modules, while the efficiency of current-matched area de-coupled modules is somewhat lower. This shows the superior spectral flexibility of voltage matched devices, in line with the findings of Lentine et al [3], [4].

Note that the peak efficiency of the series-connected stack is moving from chart to chart. For the AM1.5G spectrum the peak is found at 1.72 eV. For spectra with air mass larger than 1.5, the right crossing point between the curves for the current-matched area de-coupled modules and the series-connected stacks is locked to 1.72 eV, which serves as a reference point. In the chart for the AM1 spectrum, 1.72 eV is marked by the left crossing point. Note that the crossing point is below the efficiency for single band gap cells, marked with solid horizontal lines, for the AM10 spectrum.

The reason for the large difference in spectral sensitivity between current-matched and voltage-matched modules can be understood by considering the dependency of the short circuit current and the open circuit voltage on the incoming photon fluxes. It is known from basic solar cell theory that the short circuit current has a linear dependency on the incoming photon flux (see for example Ref. [9]). The red shift of the spectrum accompanying an increase in the air mass therefore has a large impact on the current-matching of the layers of top cells and bottom cells. The open-circuit voltage, however, depends logarithmically on the incoming photon flux which makes voltage-matching less sensitive to changes in the spectrum. IV-curves that visualize this are plotted in Fig. 4. The upper left chart in the figure shows IV-curves for various spectra of the top layer in an area de-coupled module. The right chart shows the corresponding IV-curves for a bottom layer that is current-matched to the top layer when illuminated by the AM1.5G spectrum. With increasing air mass there is a growing mismatch between the current produced by the different layers at the maximum power points. The lower chart in Fig. 4 shows IV-curves for a bottom layer that is voltage-matched to the top layer when illuminated with the AM1.5G spectrum. The voltage giving the maximum power point changes with increasing air mass, but the change is small and relatively equal in the top and bottom layers. As a result, voltage-matched modules are almost insensitive to changes in the air mass.

The sensitivity of area de-coupled modules to temperature variations depends on a number of factors that are not taken into account by the simple detailed balance model applied in this work. The temperature dependence of the size of the band gap is perhaps the most important example. Nonetheless, it is still of interest to study the fundamental temperature sensitivity of ideal area de-coupled modules before material dependent mechanisms are taken into account. Fig. 5 shows the theoretical efficiency of four tandem devices with a bottom cell band gap of 1.11 eV illuminated with the AM1.5G spectrum while holding a temperature of 330 K. As above, the device

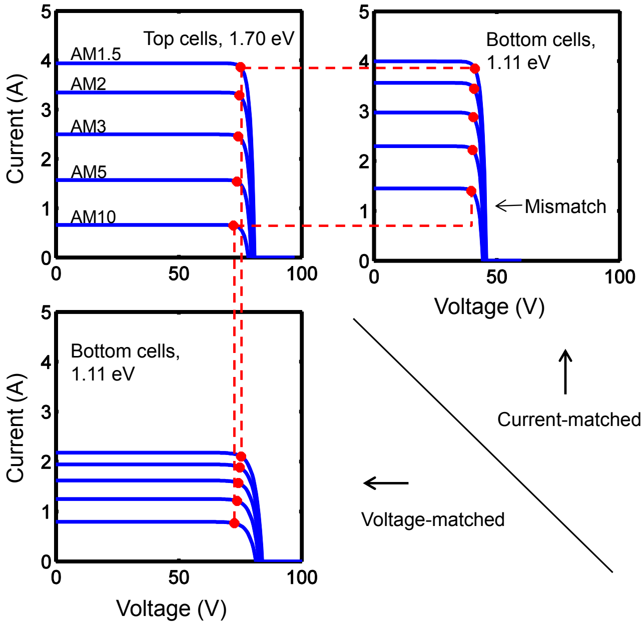


Fig. 4. IV-curves of the top and bottom layers of area de-coupled modules for various spectra. The upper left chart shows the IV-curves for a layer of top cells with a band gap of 1.70 eV. The lower left chart shows the IV-curves of a bottom layer with a band gap of 1.11 eV which is voltage-matched to the top layer. The upper right chart shows the IV-curves of a bottom layer with a band gap of 1.11 eV which is current-matched to the top layer. The maximum power points are marked with red dots.

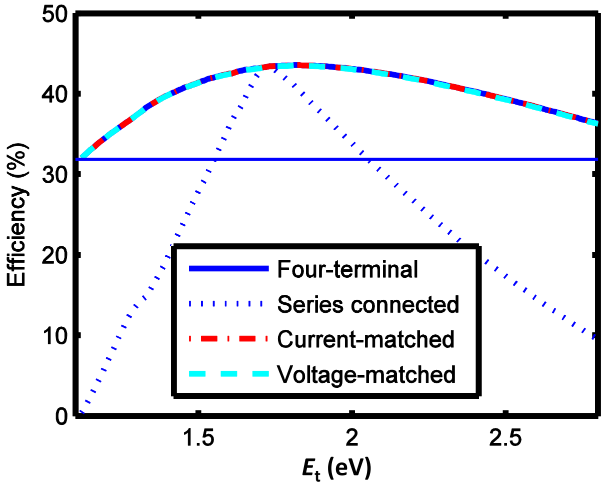


Fig. 5. The efficiency of four types of tandem devices operated at a temperature of 330 K. The band gap of the bottom cells is set to 1.11 eV and the band gap of the top cells is varied according to the horizontal axis. The area de-coupled modules are optimized for an operating temperature of 300 K. The straight horizontal line show the theoretical efficiency of a single band gap cell with a band gap of 1.11 eV operated at 330 K.

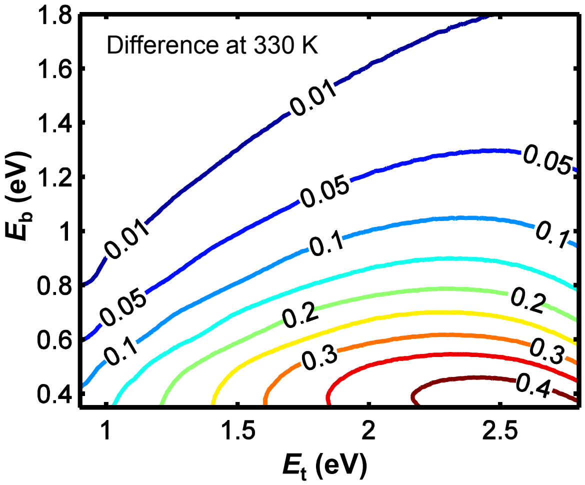
types are a four terminal device (solid line), a series-connected stack (dotted line), voltage-matched area de-coupled module (dashed line) and a current-matched area de-coupled module (dash-dot line). The area de-coupled modules are optimized for a temperature of 300 K. It is seen from the figure that the curves of both types of area de-coupled modules overlap with that of the four-terminal device. So with a bottom cell band gap of 1.11 eV, the fundamental temperature sensitivity does not lead to a difference of practical importance between four-terminal devices and area de-coupled modules.

The difference in theoretical efficiency between a four-terminal device and a voltage-matched area de-coupled module optimized for a temperature of 300 K, when operated at 330 K, is shown in Fig. 6 a) for a more complete range of band gap combinations. The difference is given as percentage points. It is seen from the figure that for most band gap combinations resulting in high efficiency, the difference is small and below 0.2 $\%_{\mathrm{abs}}$. A larger difference is found in the lower right part of the chart, but only for band gap combinations that are out of interest anyway due to low theoretical efficiency. Fig. 6 b) shows the the difference between a four-terminal device and an area de-coupled module, optimized for the AM1.5 spectrum, when illuminated with the AM5 spectrum. Also here the differences are very small for all interesting combinations of band gaps, and smaller than the difference when operated at 330 K.

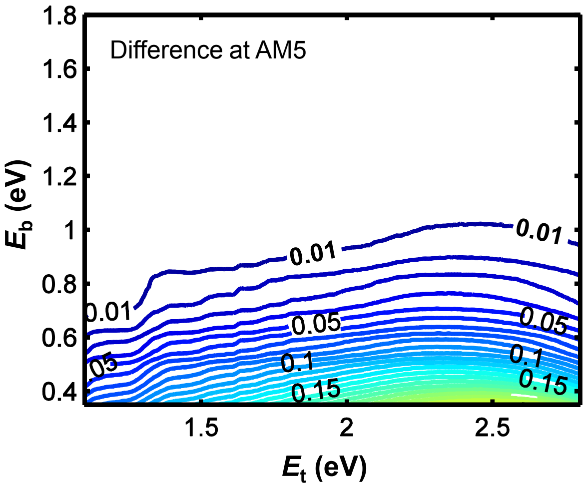
The prospect of making two-terminal tandem modules with practically the same efficiency as four-terminal devices, even under changing conditions, is an intriguing possibility which might facilitate the integration of tandem modules with high annual yield into existing infrastructure. Such tandem modules can be connected by conventional two-terminal connectors and cables and can be operated by conventional inverters. By area de-coupling, voltage-matched modules can be based on traditional silicon cells and module architecture, which is another attractive feature of area de-coupled modules.

IV. CONCLUSIONS

Idealized voltage-matched area de-coupled modules turn out to be very robust to changes in the temperature and spectrum. The difference between such voltage-matched modules and four-terminal devices is too small to be of any practical consequence. Current-matched area de-coupled modules are somewhat less sensitive to temperature changes than their voltage-matched counterparts, but show a significant drop in efficiency upon spectral changes. All in all, the results show that voltage-matched modules should be the preferred type of area de-coupled modules. This finding is in agreement with the work of Lentine et al. [3], [4], who also found that voltage-matched tandem devices perform excellent under changing conditions. The reader should bear in mind that the model used in this work does not take non-ideal mechanisms, like the temperature dependence of semiconductor band gaps, into consideration. The conclusions above will not necessarily hold when all properties of real materials and real cells are taken into account.



(a)



(b)

Fig. 6. The difference in efficiency between a four-terminal device and a voltage-matched area de-coupled module, where the latter is optimized for the AM1.5 spectrum and 300 K, at two different operating conditions: a) at 330 K, and b) under the AM5 spectrum. The difference is given in percentage points ($\%_{\mathrm{abs}}$). Note that the scale of the color code is the same, but the equidistance between the iso-lines is not the same in the two charts.

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