A LINEAR FRESNEL HYBRID PV/THERMAL MICRO-CONCENTRATOR SYSTEM FOR ROOF-TOP INTEGRATION

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ABSTRACT: An overview of the key design features and preliminary electrical performance is presented for a novel implementation of a roof-top friendly linear Fresnel mirror concentrator photovoltaic-thermal (CPV-T) system operating at 15x concentration. This technology, referred to as the Chromasun Micro-Concentrator (MCT) is being co-developed by Chromasun Inc. and the Centre for Sustainable Energy Systems, at The Australian National University. Design decisions have been targeted at eliminating the added costs and complexities normally associated with conventional linear concentrator systems. Low-cost, reliable and mass-producible components, leading technologies, and innovative processes have been adapted from related industries, which will significantly reduce cost and development time to market. The MCT is expected to be commercially available in 2011.

1 INTRODUCTION

In the large and rapidly expanding distributed roof-top solar market, flat-plate PV technology sets the standard for performance, cost, and aesthetic appeal. This marketplace leverages some of the key strengths of photovoltaics: the elimination of transmission losses; and the generation of electricity on the 'retail side' of the meter, where the economic value is greatest. However, in the pursuit of ever-lower levelised cost of energy and energy pay-back times, concentrating photovoltaic (CPV) technology offers a promising alternative.

The fundamental benefit of CPV is the significant reduction in the consumption of expensive solar cells achieved by operating a PV receiver under concentrated sunlight. In addition, the increased receiver power density provides useful source of thermal energy for extraction via such means as a heat transfer fluid. On suitably small-area receivers, a thermal efficiency of over 60% can be achieved at temperatures of up to 220 ºC [1].

However, conventional linear concentrator systems are ill-suited to roof-top applications. The size and weight of such systems often demand specialised infrastructure; and the negative implications of wind loading [2], and the deformation of heavy, composite mirror structures [3] and [4], on system output are well documented. The 'industrial' appearance of conventional concentrator systems further limits their appeal to domestic consumers.

More generally, CPV technology suffers from the lack of an industry-wide adoption of components and manufacturing processes [5]. Furthermore, there has been little or no effort in the industry to develop a set of standards or even to agree on some basic elements of system design. This has severely fragmented the CPV and CPV-T fields, and limited the potential for cost-sharing and rapidly scaling production.

The development of specialist components can be an expensive and time-consuming process, imposing bottlenecks in cost reduction efforts, and hampering the rapid scale-up of production. A key limitation for new CPV and CPV-T system designers is the absence of a ready supply of commercially available specialist, high-efficiency concentrator solar cells, especially for low (< 50X) concentration ratios.

The Chromasun Micro-Concentrator (MCT) is a unique implementation of linear CPV-T technology that has been developed with practical solutions to these challenges at the forefront of the solution matrix [6]. This paper outlines select design features of the MCT at this stage of development.

Further optimisation is a feature of every step of the MCT development process. At all stages, the primary influences have been the factors essential to core commercial viability: (1) long-term system reliability, (2) low-cost, reliable manufacturing processes, and (3) ready commercial availability – at scale - of all system components. The paper will conclude with preliminary electrical and thermal performance data from prototype systems operating on-sun in Canberra, Australia and San Jose, California.

2 THE CHROMASUN MICRO-CONCENTRATOR

2.1 MCT form-factor

The MCT capitalises on the advantages of linear CPV-T technology while avoiding or minimising the challenges by delivering a system that is a marked departure from conventional approaches. Foremost, a sealed, low-reflection glass enclosure isolates all components from the environment. This approach has allowed for a simplified, lightweight structure shown in Figure 1. The total enclosure measures 3.2 m long by 1.2 m wide by 0.3 m high with an area loading of only 28 kg/m^2. The enclosure is entirely manufactured off-site, simplifying on-site installation.

Figure 1: The MCT enclosure.

Practical considerations of cell performance limit the maximum operating temperature of a hybrid-configured MCT. However, individual MCT systems are designed to be modularly deployed in a combination of hybrid and/or thermal-only configurations to suit particular customer requirements. In order to minimise manufacturing costs, the receiver in each configuration is distinguished only by the presence or absence of structurally-independent CPV modules. Figure 2 shows three MCT systems installed as part of the Santa Clara University Solar House, which placed third in the 2009 DOE Solar Decathlon. The MCT units were not installed during the competition, but have now replaced a section of the PV system. The MCT's low form-factor and low weight allowed it to be mounted in the same supporting structure as the accompanying flat-plate PV panels.

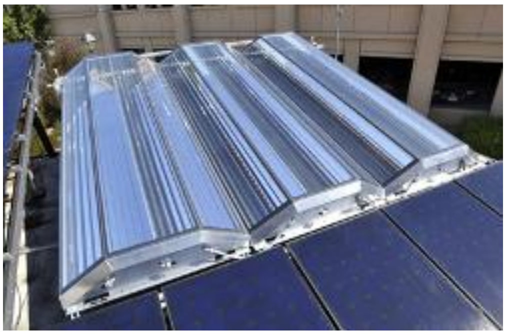

Figure 2: MCT systems installed as part of a domestic rooftop solar power system.

In the standard hybrid configuration, the net direct normal irradiance (DNI) conversion efficiency of the MCT is above 70%. Thermal output at temperatures of between 60 to 220 ºC, and electrical output of up to $500W_p$, can be achieved.

2.2 CPV cells and performance

At the MCT's concentration ratio of 15X there are few, if any, suitable high-efficiency solar cell technologies that are commercially available. However, at this concentration ratio, high efficiency mono-crystalline silicon solar cells can deliver suitable levels of performance [7]. The MCT employs high-efficiency rear contact solar cells that have been carefully modified for installation in the narrow PV receiver. All cell modifications are performed using industry-standard semiconductor processing techniques.

Each PV receiver consists of series-connected substrings of long and narrow 'elongate' solar cells. Each cell has been carefully extracted from the parent wafer to minimise damage to the cell components. Figure 3 plots the performance of several candidate cells as a function of illumination intensity. As expected, the wider cells (samples C and D), where the ratio of cut edge to cell surface area is minimised, demonstrate the highest performance.

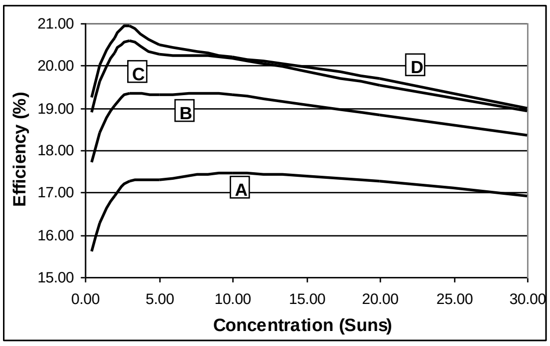

Figure 3: Efficiency as a function of cut length to surface area ratio for several test cell configurations.

From these results we can observe that commercial one sun solar cells can be successfully modified to operate at 19.0% efficiency at up to 30X concentration, reaching approximately 19.8% at the expected operating concentration of 15X. Table 1 lists the key performance characteristics of the highest performing cells that have been successfully modified using present methods.

Table I: Performance characteristics for representative CPV cell at varying concentration ratios

Concentration	5x	20x	30x
Efficiency (%)	20.50	19.7	19.0
Fill-factor	0.768	0.691	0.647
Short-circuit current (A)	0.542	2.19	3.34
Open-circuit voltage (mV)	706	742	751

2.3 CPV Modules

In order to reduce system cost and the development time to market, materials, components and manufacturing processes from related industries, and in particular the power electronics industry, have been adapted for CPV applications.. In order to maximise thermal efficiency, the MCT receiver is less than 30 mm wide, and in order to maximise electrical output a densely packed cell array has been employed. Although the 'active area' of a concentrator cell is often less than the total cell area because of the requirement to accommodate bus bars and interconnections, the MCT cells have a 100% illuminated front surface. This is achieved by implementing the cell and sub-module electrical interconnections using a ball grid array (BGA) assembly technique. Each cell consists of interdigitated p and n electrodes on the rear surface, with each pair, or 'pitch', forming a functional unit cell. The unit cells within each diced cell are connected in parallel to form a functional solar cell. In the absence of common busbars, finely spaced conductive die-attach materials provide electrical interconnection between cells via direct connections of the cell electrodes to a modified high power-density electronic substrate. The substrate technology, common to the power electronics industry, has demonstrated long-term reliability in high power-density applications, with preliminary performance for concentrator applications equally promising [8].

A die attach material is used for both electrical connection and for heat sinking of the solar cells to the substrate. The mounting substrate provides structural support to the module, relaxing handling requirements and providing structurally independent modules that can be readily fitted to the MCT receiver. Figure 4 illustrates an abstracted cross-section of the CPV module. Note that the cells and diodes are coplanar and are effectively surface mounted. In production, a pick-and-place method mounts these devices in a common assembly process.

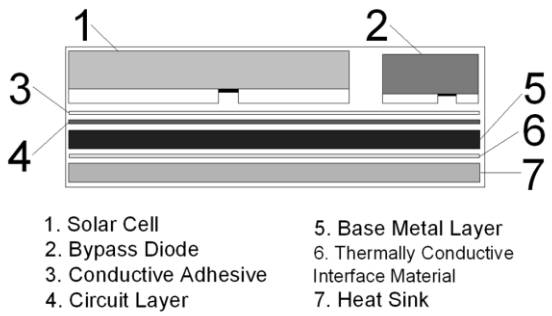

Figure 4: Abstracted cross-section of CPV module.

An additional advantage of this surface-mount approach is the ability to harness the self-alignment technique commonly employed with 'flip-chip' components [9]. The surface tension present when the die attach material is in liquid phase during reflow seeks to minimise the surface area to volume ratio. This effect produces a restorative force, which pulls any misaligned solar cells and bypass diodes into position. Consequently, the mounting, electrical interconnection and thermal sinking of the solar cells and bypass diodes is achieved in a single step. In the completed cell array, the separation between adjacent cells is less than 100 micron, with a total CPV receiver active area in excess of 97%. Figure 5 shows a segment of a completed CPV module.

Figure 5: Close-up of an un-encapsulated section of an MCT sub-module.

The die attach material joints bear the majority of the mechanical stresses caused by the mismatched expansion of the various materials in the structure. The joint thickness strongly affects their reliability under these conditions. Fortunately, the implementation of industry-standard manufacturing processes allows for precise control (and uniformity) of the overall thickness of the die attach material. In the MCT receiver, the thickness of the die attach material was varied to explore the influence that it had on the stability of system performance under accelerated lifetime testing. Figure 6 plots the change in performance of an MCT sub-module as a function of thermal cycling under the IEC61215 standard for varying joint thicknesses.

Preliminarily optimization of joint thickness has shown a decline in performance of 3% relative after an initial 8 cycles, with performance stabilizing during subsequent cycling. Further experimentation will continue in order to optimise the die attach material to withstand accelerated lifetime testing.

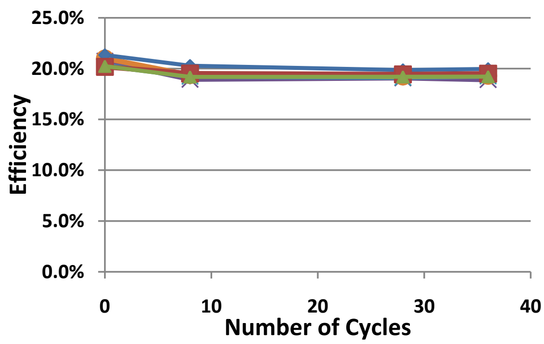

Figure 6: Change in performance of MCT sub-modules as a function of thermal cycling

2.4 Optics and Tracking

Protected from soiling, warping, wind and mechanical loads, the optical component of the MCT consists of a parallel array of ultra light-weight, 97% efficient, front surface silvered aluminium-based reflectors (Fig 7). The reflector array improves flux uniformity, optical performance, and manufacturability by using differential width mirrors, each width varying with focal length in inverse proportion to the distance from the receiver.

The focal characteristic of each reflector is varied in order to limit flux peaks, and reflector astigmatism is actively harnessed to improve lateral flux uniformity. The reflector design has the unique capability to accept a torsional force from one end of the reflector to the other, allowing for precise corrections of twisting induced during manufacture. The new reflector design eliminates image instability arising from the differential expansion of composite mirror structures, which are commonly used in conventional linear concentrators.

The tracking system incorporates a single-axis, motor driven controller to rotate the ganged mirrors at a common angular velocity during tracking. The tracking mechanism integrates a two-bar linkage system actuated with a zero backlash linear stepper motor. The ultra lightweight tensile design of the primary reflectors enables precise positioning of their centre of gravity about their axis of rotation to produce a perfectly balanced optical system.

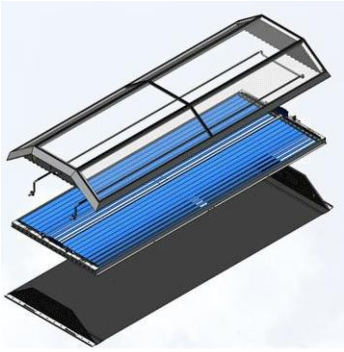

Figure 7: MCT optics and receiver configuration. Note the mechanical separation of optics and receiver.

The MCT tracking system was designed to high industrial grade specifications with a 20 year lifetime operation requirement. The linear stepper motor is automotive grade, rated for continuous operation at up to 120 ºC, and operates at a little over 1% of its rated lifetime load specification. The minor links are made from stamped sheet metal in a highly repeatable manner which means that any inaccuracy in the length is the same across all parts and therefore has no effect on tracking accuracy. The mirror shafts incorporate bearings at each end which reduces the force required to rotate the mirrors to only 15 N. The over-all design concepts reduce backlash that can be introduced through mechanical stress.

3 ELECTRICAL PERFORMANCE

Modules were tested under both laboratory and real-world conditions. Laboratory testing was performed on sub-modules removed from the MCT concentrator, with concentrated light provided by a constant voltage flash tester. The testing environment was precisely calibrated to match STC, providing a reference for the normalisation of real-world data to STC. Due to voltage limitations of the flash-tester, only shortened 'substrings' of PV modules could be flash-tested, albeit manufactured using the same components and procedures as the full sub-modules. Figure 8 plots the performance data for a four-cell series-connected substring at a range of illumination intensities. Key performance characteristics are summarised in Table 2.

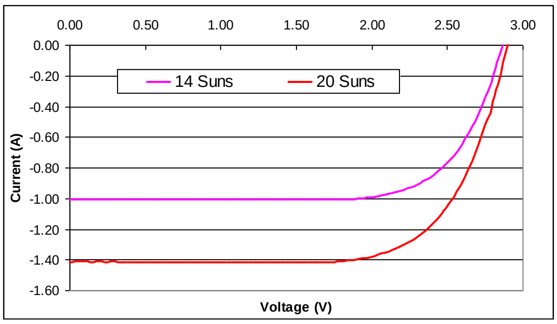

Figure 8: Current-voltage characteristics for MCT substring.

Table II: Substring Performance Characteristics

Concentration	14X	20X
Efficiency (%)	19.4	19.0
Fill-factor	0.704	0.673
Short-circuit current (A)	1.42	2.04
Open-circuit voltage (V)	2.90	2.94

These results indicate that module-level performance remains close to that of individual cells, falling by approximately 0.5% absolute to 19.4% at 14 suns. This is primarily attributable to the minimisation of series resistsance as a result of high-density configuration of contact points, with cell mismatch playing quite a low negative role.

Field testing of the PV receiver was carried out using a 'test-rig' that represents a shortened segment of the complete MCT system, but with production-standard implementation of the optical and tracking systems, as shown in Figure 9.

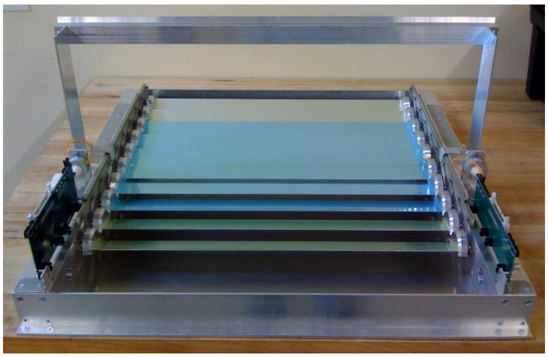

Figure 9: MCT short-form test-rig.

Testing was conducted according to the ASTME 2527-06 standards in Canberra, Australia. DNI during the tests was approximately 872 W/m^2 ±1.2%, typical for a clear day in South-Eastern Australia. The receiver was under approximately 14 suns concentration. Figure 10 plots the current-voltage characteristics for a representative sub-module, consisting of 30 series connected concentrator cells. Performance at the operating temperature of 55 ºC and corrected for STC are presented. Table 3 summarizes the key performance characteristics.

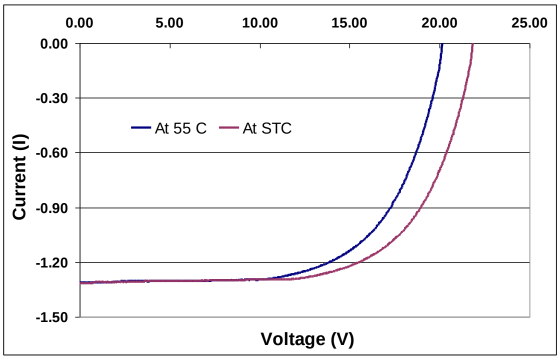

Figure 10: Current-voltage characteristics for an on-sun MCT PV sub-module.

Table III: Substring Performance Characteristics

At 14x Concentration	55 ºC	STC
Efficiency (%)	16.6	18.4
Fill-factor	0.650	0.673
Short-circuit current (A)	1.31	1.31
Open-circuit voltage (V)	20.14	21.84

Module-level efficiencies of over 18% have been achieved. With narrow cell dimensions and dense packing, maximum power point voltage is built at a rate of 55 V/m. At this rate, a total output of $330V_{mpp}$ can be achieved from a single MCT unit, for a total of $500W_p$ electrical output. Further work will optimize the MCT receiver design based upon feedback from field-testing.

4 CONCLUSION

The ANU/Chromasun MCT concentrator is a novel implementation of linear, hybrid CPV technology. It aims to deliver reliable, cost-effective, and flexible solar power generation to residential, commercial and industrial rooftops. Laboratory based testing has demonstrated module efficiencies of up to 19.4% at 14X concentration. In real-world testing with production standard tracking and optics has module efficiencies of 18.4% have been achieved.

5 ACKNOWLEDGEMENTS

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