Sandwich Module Development for Space Solar Power

Paul Jaffe, John Pasour, Maria Gonzalez, Sheleen Spencer, Michael Nurnberger, Jeremy Dunay, Marty Scherr[1], and Phillip Jenkins

U.S. Naval Research Laboratory, Washington, DC 20375
202-767-6616
[1]Thomas Jefferson High School of Science and Technology

Abstract. The concept of Space Solar Power (SSP) is broadly defined to be the collection in space of energy from the sun and its wireless transmission from space for use on earth. It has been observed that the implementation of such a system could offer energy security, environmental, and technological advantages to those who would undertake its development. Among recent implementations commonly proposed for SSP, the Integrated Symmetrical Concentrator and Modular Symmetrical Concentrator concepts have received considerable attention. They each employ an array of modules for performing conversion of concentrated sunlight into microwaves for transmission to earth. While prototypes of such modules have been developed previously, none have been subjected to the challenging conditions inherent to the space environment in which an array of modules would be required to operate. The research described herein details our team's efforts to evaluate the trade studies associated with the development of a sandwich module and its planned implementation and testing. Among the primary concerns is the dissipation of waste heat, as at least two of the three layers of the sandwich are expected to have significant heat generated by conversion inefficiencies. The sandwich is partitioned into layers for photovoltaic conversion, direct current to radiofrequency conversion, and radiofrequency emission. Our focus has been on trades concerning these three layers, as well as those examining module geometry and thermal control.

Keywords: Space Solar Power, sandwich module, microwave power transfer
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INTRODUCTION

Space Solar Power is generally considered to be the collection in space of energy from the sun and its wireless transmission from space for use on earth (Brown, 1992). This approach would overcome the atmospheric and diurnal limitations associated with terrestrial solar power. The concept itself has been around for many decades, and has been periodically revisited as technology has evolved and components that potentially would be used in an SSP system have seen performance gains. It has been posited not only as a means of providing utility grid power but also for military or other specialized applications (Johnson, *et al.*, 2009).

Regardless of the potential of this technology, SSP has been criticized as economically infeasible (Fetter, 2004). The costs associated with putting the large amount of mass that an SSP system would almost invariably require are prohibitive. The possibility of efficient large-scale energy storage that could be paired with ground-based clean energy systems threatens even the most optimistic economic analyses for SSP. Counter-arguments include the point that the spacefaring infrastructure associated with the development of SSP would present a tremendous space resource development advantage to the first implementer (Globus, 2009).

One means of reducing launch mass is to use lightweight reflectors to concentrate sunlight collected over a large area on a smaller area photovoltaic (PV) array, effectively reducing the proportion of higher density components required in orbit. Additionally, if the photovoltaic function is directly paired with a means of direct current (DC) to radiofrequency (RF) conversion and an antenna, the collected energy can be transmitted with minimal power distribution complexity. This complexity arises in some implementations because of the need to keep the photovoltaics pointed at the sun and the transmission antenna simultaneously pointed at the earth. Large amounts of current may need to be routed across a harness network and possibly a rotating conductive joint. The approach described above that avoids these problems has been referred to variously as an Integrated Symmetrical Concentrator (ISC) and Modular Symmetrical Concentrator (MSC) (Mankins, 2003). One such implementation is pictured in Figure 1.

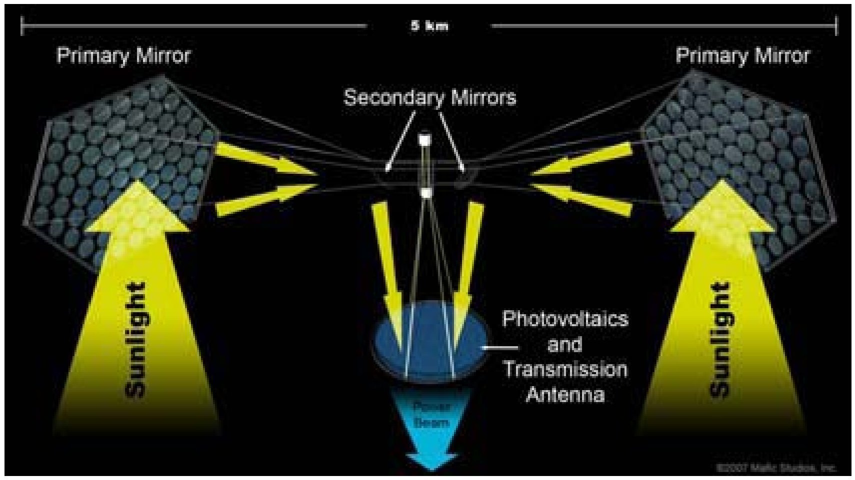

FIGURE 1. Modular Symmetrical Concentrator concept (NSSO, 2007).

One of the key components in these concepts is the sandwich module. This component integrates the functions of photovoltaic collection, DC to RF conversion, and RF emission into three layers configured as depicted in Figure 2.

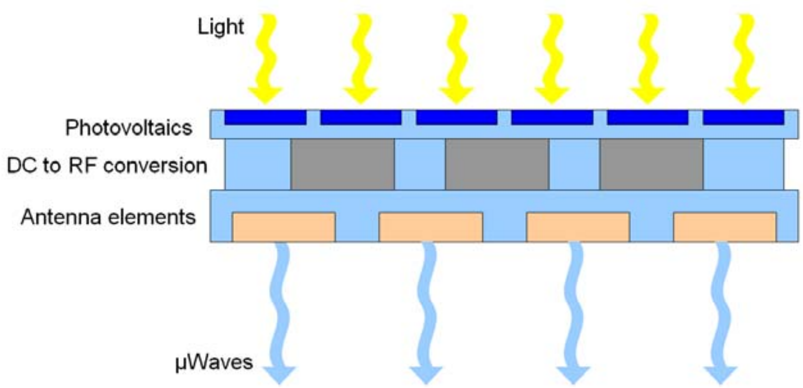

FIGURE 2. Functional components and notional configuration of a sandwich module for space solar power.

This configuration has been examined previously by a number of investigators. Owen Maynard of Raytheon considered trades following the NASA/DOE SSP effort of the late seventies (Maynard, 1980) and several Japanese efforts appear in the literature of the early 2000's, including those of H. Matsumoto and N. Kaya.

In our research effort, we endeavor to execute trades for the sandwich module layers and architecture, based on current and near-term available technology, to culminate in the production of a prototype to be tested in a realistic thermal and vacuum environment. Out of necessity, we have made assumptions about the system context of the module based on having limited resources and lacking a point design from which to derive requirements; the development of which is beyond the scope of our effort. This paper describes the status of this effort as of September, 2010, following the initial year of the investigation.

KEY IMPLEMENTATION TRADES

As expected, the component choices for the three layers (photovoltaics, DC-RF conversion, and antennas) figure prominently in our trade evaluation. Additionally, the formidable challenge of managing thermal control permeates each of these trades as well as being a trade unto itself. Likewise, the configuration and geometry of the module itself have a massive effect on final module performance and interplay with the other trades. Following are overviews of each of these trades.

Photovoltaics (PV)

One of the greatest limitations on our research effort is the near-term availability of the components to support a prototype build that meets our system requirements. Several PV materials were considered during the course of this work, resulting in the choice of current state-of-the-art (SOA) III-V multijunction technology. In these devices, materials of different III-V bandgaps are combined, enabling an efficient capture and conversion of a wide range of the solar spectrum. Moreover, due to the high absorption coefficient displayed by most III-V materials, such efficient conversion of light occurs in a considerably reduced material thickness when compared with other PV materials, *i.e.* Silicon (Si). III-V multijunction solar cells efficiencies have reached values of 34% under one-sun AM0 (space) conditions (Cornfeld, *et al*., 2010) and over 42% in terrestrial concentrator systems, in which lenses and mirrors are used to focus sunlight into a small area cell (press release Oct. 6th 2010, Spire Corporation) Currently, commercially available triple junction GaInP/GaAs/Ge solar cells are used in the space PV market with AM0 efficiencies up to 29.5%.

In addition to their enhanced optical conversion capabilities, III-V materials display a far superior resistance to damage induced by radiation present in space when compared to other currently available PV technologies (Stan, *et al.*, 2000). This aspect is especially critical for long lasting missions since PV space arrays must consider not only beginning-of-life (BOL), but also end-of-life (EOL) performance, as well as a manageable power profile for the duration of a given space mission. III-V multijunction solar cells will be used in our SSP prototype and will likely be provided from Emcore or Spectrolab.

To account for the trades in our system, we have studied how the efficiency of each component affects the overall performance of the SSP module. Figure 3 shows the predicted efficiencies for each of the layers in the system and the final calculated performance of the module. Considering commercially available 28% multijunction cells, an overall module efficiency of 14% is obtained. As observed from the figure, photovoltaics are the least efficient element in the chain and thus have the greatest room for improvement. Given the recent advancements and rapid growth of PV research in the past few years, an increase in efficiency in the next couple of years for commercial III-V multijunction cells to 33% is expected. Such an increase in solar cell efficiency would result in an increase of module performance to 17%.

Quantity	Value
Sunlight Concentration Factor	3
Module Area (m^2)	0.36
PV Efficiency	28%
DC-RF Conversion Efficiency	60%
Power Distribution and Control	95%
Antenna Efficiency	90%
Module Combined Efficiency	14%

FIGURE 3. Predicted and calculated efficiencies for the elements in the prototype giving rise to a 14% module efficiency.

Other considerations besides availability and efficiency of the PV devices include temperature performance characteristics, concentration ratio tolerance, efficiency, power output per unit mass ratio, and high voltage capabilities. As data is often not available for many of these qualities, we plan to collect our own.

DC-RF Conversion

Similarly to photovoltaics, emphasis on the selection criteria for the DC-RF conversion focuses on efficiency and availability. The NRL SBSP study examined broad classes of devices, shown in Figure 4.

RF Source	Power/ module (kW)	Efficiency (%)	Comments
Klystron	10-100's	70 – 75	High voltage, heavy, moderately expensive
MBK	10-100's	70 - 75	Moderately high voltage, expensive
TWT	0.1-0.3	65 – 75	Space qualified, relatively compact, moderately expensive
Magnetron	0.5-5	75 - 85	Inexpensive, compact, phase controllable
GaN SSPA	0.01 – 0.1	50 - 70	Compact, expensive, thermal issues
(MBK: multiple beam klystron, TWT: traveling wave tube, SSPA: solid state power amplifier)			

FIGURE 4. Source technology for 2.4 - 6 GHz SBSP RF transmission (Johnson, et al., 2009).

The findings of the NRL SBSP study largely mirror those of previous studies (McSpadden and Mankins, 2002). In looking at commercially available devices, we found unsurprisingly that efficiencies are quoted lower than those in the lab, such as for GaN HEMT Class F amplifiers (Schmelzer and Long, 2007). Figure 5 shows selected performance figures gathered from various manufacturers' datasheets.

Method	Magnetron	SSPA	TWT
Efficiency	44-73%	43-70%	66-70%
Mass (kg)	0.9-4.3	<0.1	0.7-3.0
Power Output (W)	900-1500	25-220	20-300
Manufacturer	Richardson Electronics, L3, CPI	Cree, Triquint, Aethercomm	L3

FIGURE 5. Values from manufacturers' datasheets for the 2 - 10 GHz range.

Our current prototyping efforts focus on assembling a chain to achieve the required gain that includes solid state power amplifiers (SSPAs) from Cree. As the gain for commercially available devices in our range of interest tends not to exceed 15 dB, a multi-stage approach is required. Among the reasons for our focus on SSPAs are that their small size lends them to packaging in a range of module geometries, as well as allowing flexibility in handling a range of power throughputs. That is, it may be possible merely to increase the density of devices used to accommodate increased power from higher solar concentrations, provided the thermal control can handle the required dissipation needs. One of our earliest test configurations is shown in Figure 6 and is not intended to be representative of the final implementation. Our current design also includes the frequency source, notional phase control, and strives to operate each different amplifier in the chain at a peak efficiency point.

In parallel with the SSPA chain prototyping effort, we are also performing analyses regarding the possible use of compact, low-voltage multiple beam klystrons (MBKs). Initial results show promise in terms of achievable specific power densities, approaching perhaps even 1kW/kg, including a magnet, an electron gun, an RF circuit, and an electron collector. Overall efficiencies should be in the range of 40-50% at operating voltages of 3-4 kV. For a specified output power, the efficiency will increase with operating voltage, but at the expense of power supply and distribution complexity. One possible implementation at the Ka-band is depicted in Figure 7. The size and weight of the device are determined primarily by the magnet, which in this case are 3x6x9 cm and about 0.75 kg. Compact MBK's of this general parameter range have been demonstrated in Russia, but the overall efficiency has been limited to 30-35% (Kotov, Gelvich and Zakurdayev, 2007). Recent results at NRL on multiple beam klystrons (Nguyen *et al.*, 2009) and extended interaction klystrons (EIKs) (Pasour *et al.*, 2010) suggest that by implementing a multiple stage depressed collector together with an EIK structure, we can significantly increase the overall efficiency. Electromagnetic simulations of the device shown in Figure 7 predict an output power of 1 kW and a saturated gain of 56 dB at an operating voltage of 4 kV.

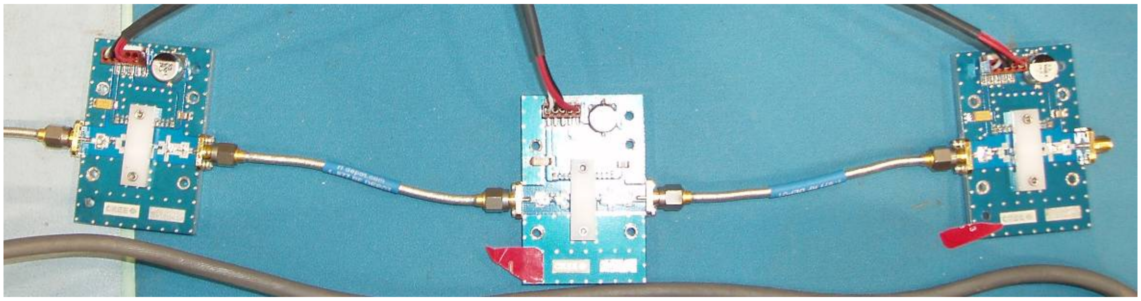

FIGURE 6. Preliminary test chain of Cree CGH55030 evaluation boards.

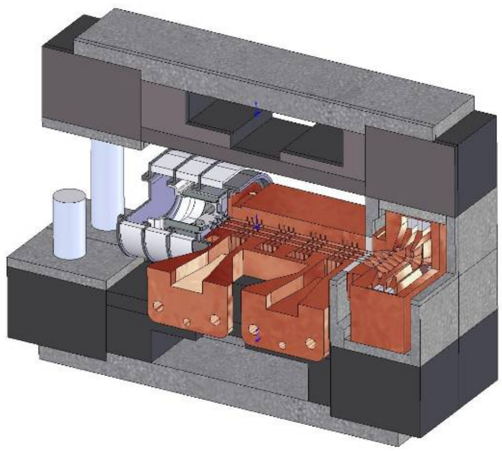

FIGURE 7. Notional MBK at Ka-band showing magnet, RF cavity, electron gun, and electron collector.

The sandwich module's thermal challenges begin with the high solar concentration applied to the photovoltaic panel. The intense solar fluxes can only be radiated back up by the PV panel or conducted to the nadir panel (electronics panel). The small size of the current sandwich module design leads to higher than usual temperatures. The keys to reducing the temperatures of the PV panel and electronics panel for the current design are varying the conduction path between the panels and the size of the radiator area of the module. Figure 8 depicts the heat paths for the module.

The thermal studies currently conducted include a comparison of the sandwich designs' temperature in various orbital beta angles, variations of the panel-to-panel conduction, and residual effects of multiple modules. The orbital environmental fluxes come from solar, planetary albedo (solar reflection off the planet), and planetary infrared (IR) fluxes. In the expected geosynchronous orbit, the planetary effects are neglible; the solar fluxes increase as the orbital beta angle decreases. When the beta angle is 0^{o}, the nadir panel (or electronics panel) will absorb solar fluxes during a larger portion of the orbit. At a beta angle of 90^{o}, the nadir panel does not face the sun during the orbit. Therefore, the hot and cold cases in the GEO are considered beta 0^{o} and 90^{o}, respectively.

The current thermal characterization model for the project is being analyzed in Thermal Desktop/SINDA and TRASYS. The original single node, single panel model has been expanded to a model which includes a PV panel, electronics panel, and side panels with multi-layer insulation (MLI). The side panels are covered by MLI, since the modules will be attached side by side, blocking each other's view to cold space. A model of a single sandwich module was duplicated to research the compound effects of neighboring modules. The current model includes four sandwich modules. The modules are not conductively connected to each other in the current thermal model. The radiation and shadowing effects of neighboring modules is included in the thermal analysis. The temperatures of a single module did increase when neighboring modules were added.

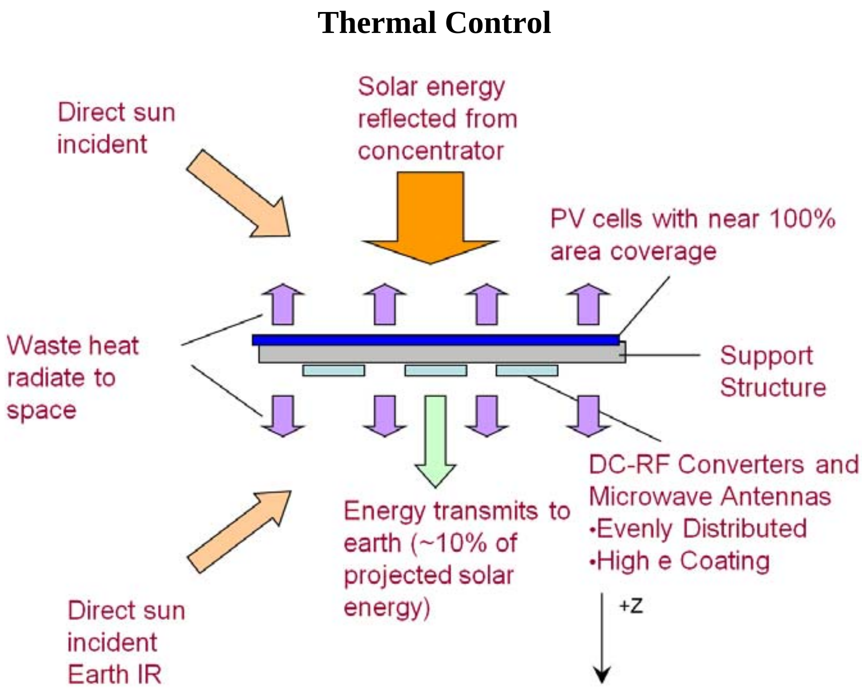

FIGURE 8. Heat inputs and radiation from a sandwich module for SSP.

Figure 9 shows the results of the thermal trade on structural conductance from the PV to the electronics panel. As the conductance was increased, the PV panel temperatures decreased; however, the electronics panel temperatures increased. This study indicates that special design of the PV panel and electronics are necessary to survive higher than usual temperatures. Future trades will likely include the addition of radiator area to the PV panel, possibly by adding radiator patches between the solar cells to aid in the heat rejection directly from the PV panel or the addition of an auxiliary radiator.

Antennas

The design of the antenna portion of the sandwich module is the subject of an on-going trade based on the continuing evolution of the module. The antenna's function is to take the RF energy generated in the module and radiate it towards its intended destination. Important requirements for the antenna include maximum efficiency, low mass, compactness and/or the ability to be compactly stowed before launch and simply deployed once on orbit, and the ability to work as part of a much larger array. Current antenna concepts are all circularly polarized to allow more freedom in orientation of the overall system. The prevention of multipactor and multipactor-induced corona is also being addressed in the design, as is a desire to use the antenna as a means to distribute and radiate waste heat. The only considerations for retrodirective tracking made inside the antenna are to provide a receive function to supply phase information to the power amplifier (PA) driver circuitry – due to its size the sandwich module is at most a single element (constant aperture phase) in the larger phase-controlled array. Other than the possibility of using the main antenna to receive this phase information on a nearby carrier, bandwidth of the main antenna is not currently a significant requirement.

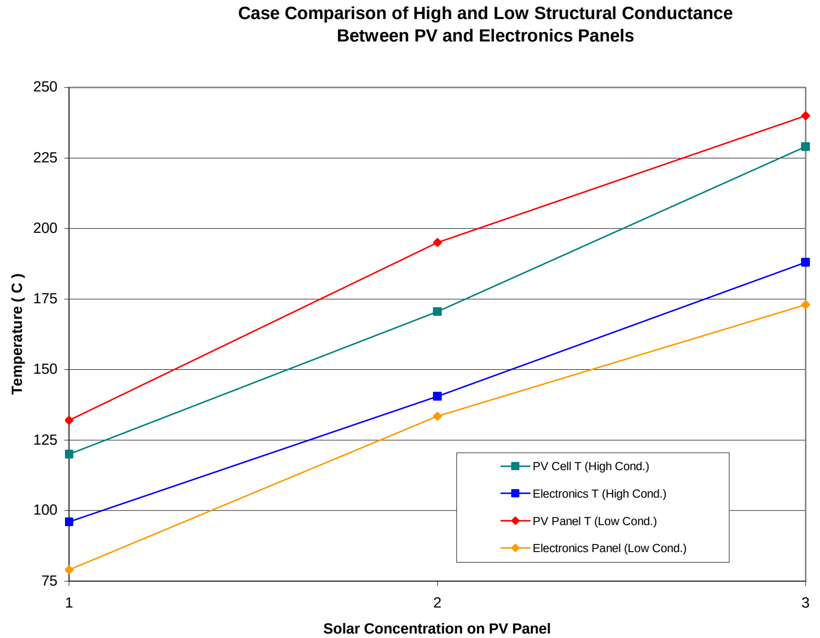

FIGURE 9. Structural conductance comparison plot for sandwich module.

To help ensure maximum efficiency, power distribution networks between the RF sources and the antenna must be either eliminated or made extremely efficient. For the case of the SSPA-based sandwich module, an array design with individual elements (or possibly very small groups of elements) at each SSPA output seems to be indicated. For the high-power tube case, either a space-fed higher-gain element (e.g. parabolic reflector or similar, with a single feed) or a single point-fed array with a minimal waveguide feeder network (e.g. waveguide-fed array of slots or helices) seems to make sense.

The SSPA-based approach to module design and RF power generation has initially been investigated more thoroughly. Based on the operating frequency of 5.8 GHz, sandwich module size, and number of SSPAs per module, an antenna array of medium-gain elements, with each element fed directly from its own SSPA, is currently being studied. Some of the elements that are being considered include a short backfire antenna (relatively shallow for its gain), helical antenna (inherently circularly polarized), and various types of Yagi (lightweight and simple to deploy). An array of medium-gain elements in this configuration has the advantages that no distribution network is required, and that mutual coupling between elements can be disregarded.

Module Geometry and Mechanical Layout

As the sandwich modules are envisioned to be used in a large, repeating pattern array, a desired shape should be selected that tessellates in a plane and lends itself to mass production. Lacking a detailed SSP system point design, we necessarily made assumptions about the homogenous use of identical sandwich modules in the array. In reality, solar concentration might vary as a normal distribution across the surface of the array to effect smaller transmit sidelobes, resulting in a wide range of sun concentrations that any given module could be exposed to.

Hexagons been examined previously as a favored shape for sandwich modules for SSP. It has been observed that hexagons would maximize the use of available payload volume in a circular launch vehicle fairing. In fact, a hexagon inscribed within a circle fills about 82.7% of its area, while a square inscribed within a circle fills only about 63.7%. However, our analysis of the probable density of SSP sandwich modules and an assessment of current launch vehicle throw weights and payload fairing volume capacities suggests that the payload mass limit of any given existing launch vehicle will be exceeded before the fairing volume will be filled. Consequently, the efficient use of payload fairing cross-sectional area is of little concern.

Our initial efforts at effectively filling hexagonal module areas with photovoltaics were also thwarted because available solar cells are approximately rectangular and do not lend themselves to filling completely non-rectangular areas. Combined with the analysis from the preceding paragraph, we determined that a rectangular module shape was preferred. For simplicity and symmetry, we have proceeded with a square module design.

Both PV cell manufacturers under serious consideration provide cells approximately 4cm by 7cm. For square modules, we examined 4 by 7, 8 by 14, and 9 by 16 cell arrays. We are currently proceeding with a 4 by 7 cell array because its compact size reduces cost and allows for a wider range of usable test facilities.

CURRENT MODULE DESIGN

Our current baseline module design for the solid state power amplifier conversion approach employs a single string of 28 solar cells in series. Depending on the resulting thermal performance, the module should be able to accommodate two to five suns of concentration using four power amplifier chains. For five suns incident, the power converted and dissipation requirements are shown in Figure 10 when using the efficiency figures from the last five rows of Figure 3.

Total Power Received (W)	537.0
Power Converted By Cells (W)	150.4
Power Converted by DC-RF Converters (W)	90.2
Power Output from Antenna (W)	81.2
Waste Power from Solar Cells (W)	386.7
Waste Power from DC-RF Converters (W)	60.1
Waste Power from Antenna (W)	9.0
Total Power Needed to be Dissipated (W)	455.8

FIGURE 10. Power in each layer resulting from five suns of concentration on a square module with 28cm sides (0.0784m^2).

The current functional electrical block diagram with notional parts selection is shown in Figure 11.

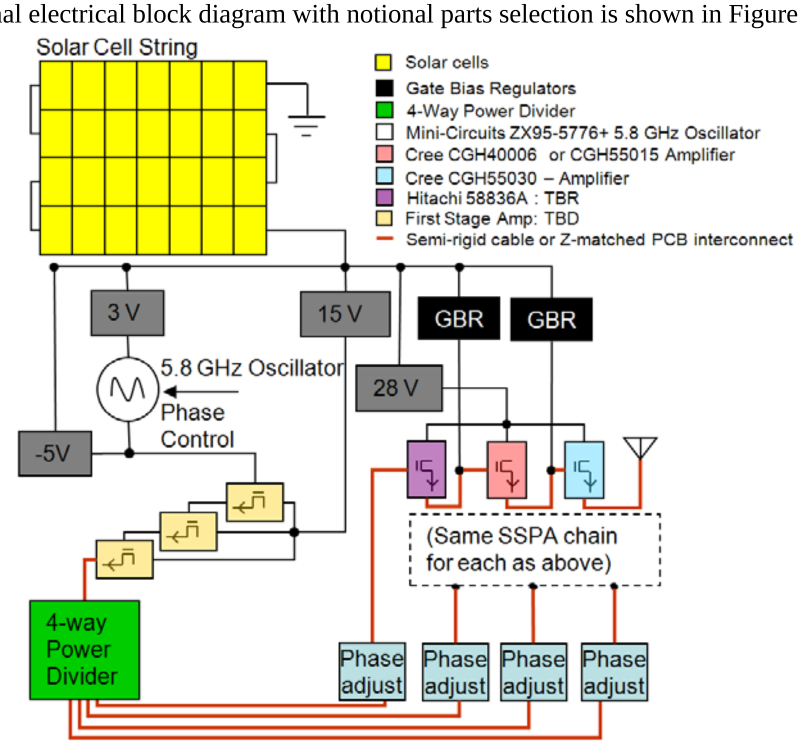

FIGURE 11. Functional electrical block diagram.

The mechanical design resulting from the 4 by 7 cell configuration is shown in Figure 12, and reflects an edge length of about 28cm. The module thickness and material selection are subject to ongoing trade studies concerning thermal, mass, and RF performance considerations.

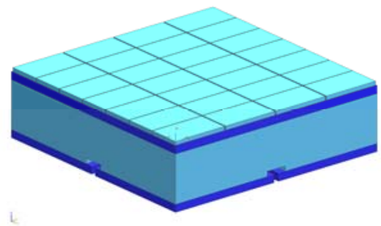

FIGURE 12. CAD model for 4 by 7 cell module.

Figure 13 shows the result of one thermal analysis run that employed a cluster of four modules with the four final stage power amplifiers distributed as shown.

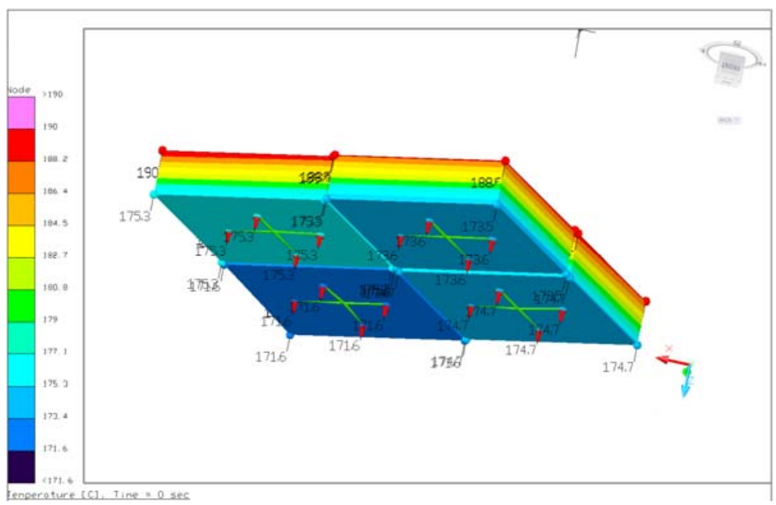

FIGURE 13. Thermal simulation for a cluster of four 4 by 7 cell modules, PV layer on top.

TESTING APPROACH

Preliminary testing of the prototype SSPA chain is anticipated to occur in our laboratory using thermal cycling chambers to assess the electronics performance over temperature. We may be able to test PV performance over temperature using our Spectrolab X-25 solar simulator; however in its factory configuration, it only provides single sun illumination. For later testing of fully integrated sandwich modules, we are investigating the use of NASA Glenn's "Tank 6" thermal vacuum test chamber, which allows for testing under both vacuum and concentrated sunlight conditions simultaneously. For small areas, solar concentration in the Tank 6 facility may approach ten suns, likely more than we would need. Antenna performance can be characterized over temperature in our own facility. The environmental test campaign is currently in the planning stages and remains at least a year in the future.

CONCLUSIONS

This paper summarizes major highlights from our research efforts of the past year in developing trade studies, designs, and analyses for a prototype sandwich module for space solar power. Trade studies were initiated and iterated as new discoveries and realizations came to light. In general, trades started through examination of the three functional layers inherent in the sandwich module: photovoltaic conversion, DC to RF conversion, and power radiation via antenna. As work progressed, thermal and architectural concerns shaped trades or became trades themselves. A solid state amplifier chain has been designed and partially tested, and mechanical and thermal analyses have been performed for several design iterations. Conclusions about module shapes have been reached. Our results affirm the initial impression that thermal concerns are paramount in sandwich module design. Future work will seek to buttress analytical findings with the fabrication and actual testing of a sandwich module in environmental conditions simulating space.

ACRONYMS

DC	-	Direct Current
HEMT	-	High Electron Mobility Transistor
ISC	-	Integrated Symmetrical Concentrator
MSC	-	Modular Symmetrical Concentrator
NCST	-	Naval Center for Space Technology
NRL	-	Naval Research Laboratory
PV	-	photovoltaic
RF	-	Radiofrequency
SSPA	-	Solid State Power Amplifier

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