Development of a Sandwich Module Prototype for Space Solar Power

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Abstract—Space Solar Power (SSP) is broadly defined to be the collection of solar energy in space and its wireless transmission 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 Modular Symmetrical Concentrator (MSC) concept has received considerable attention. It employs an array of modules for performing conversion of concentrated sunlight into microwaves for transmission to earth. While prototypes of such modules have been designed and developed previously by several groups, none have been subjected to the challenging conditions inherent to the space environment and possible solar concentration levels in which an array of modules would be required to operate. The research described herein details our team’s efforts to resolve trade studies associated with the development of a “sandwich” module and its planned implementation and testing under realistic operating conditions.

TABLE OF CONTENTS
1. INTRODUCTION ........................................... 1
2. CRITICAL TRADEOFFS .................................. 3
3. PERFORMANCE METRICS .............................. 4
4. THERMAL ANALYSIS .................................... 4
5. MODULE FABRICATION ............................... 7
6. TEST EQUIPMENT AND FACILITIES ............. 7
7. CONCLUSIONS ........................................... 8
REFERENCES ............................................... 8
BIOGRAPHIES .............................................. 9

1. INTRODUCTION

Global climate change and the consequent need for energy sources that avoid further contributions to climate degradation loom as significant societal concerns. It is widely realized that many sources of fossil fuels are either at risk of depletion or increasingly undesirable because of their contributions to greenhouse gases. While many carbon-free or nearly carbon-free energy alternatives exist, they often suffer from significant problems such as intermittency, locale dependence, or safety risks.

One promising clean power source is the sun, which has an effectively unlimited energy supply. However, terrestrial collection of solar energy poses problems. The diurnal cycle, atmospheric attenuation, and weather effects all diminish access to solar power. Collection of solar energy in space via satellite coupled with its conversion to microwaves for transmission to the ground largely overcomes these limitations, but it poses considerable engineering challenges and serious questions of economic viability. Thoughtful criticisms [1] and counter-criticisms [2] appear in the literature.

Solar power satellite concepts have been examined in depth on several occasions in the past [3][4], and interest has been renewed in recent years [5][6] because of improvements in a number of relevant technologies. These include: solar cell efficiency, solid state power amplifier efficiency, large space structures, and robotic assembly in space. Recent solar power system studies have been significantly limited in their ability to accurately determine the costs and challenges of deploying an operational system by the small amount of actual hardware development that has been done to show the feasibility of key technological elements.

Modular Symmetrical Concentrator architecture

A recent space solar power system design of widespread interest is the Modular Symmetrical Concentrator (MSC) architecture [7]. The MSC approach utilizes optical energy routing and a large microwave transmit aperture constructed from essentially identical elements. This avoids a large, conductive rotating joint and limits wiring mass compared to historical reference concepts. The use of modular elements offers the possibility of economy through mass production. Employing solar concentration could reduce the required launch mass and as a result lower the system cost, but it increases the magnitude of the thermal challenges. Geosynchronous orbit is envisioned for this and most SSP implementations due to its constant ground coverage. A depiction of a proposed MSC SSP satellite is shown in Figure 1. Though this image shows a monolithic structure, it might also be possible to use several satellites flying in formation to dispense with the connecting structures. Assessment of the MSC architecture’s technical soundness is hampered by a dearth of substantive efforts to identify and resolve concerns about its component technologies, most notably those pertaining to the sandwich module. One motivation for this research is the need for a critical examination of the challenges associated with sandwich module development.

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Sandwich Module

The key element in the MSC and other SSP architectures is the “sandwich module”, an element which had originally been investigated in association with the NASA/DOE studies of the late 1970s. The sandwich module performs functions separable into three layers: solar energy collection and conversion to direct current electricity, generation of a microwave signal of suitable frequency and amplitude for transmission, and formation of a spaceborne transmit antenna aperture that provides beam coupling sufficient to provide meaningful energy transfer to the ground. A simple functional representation of a sandwich module appears in Figure 2.

Chief among the design challenges of a practical sandwich module are the integration of the various required elements, allowing for retrodirective phased array beam control, and effective thermal management under adverse conditions. These aspects have received some attention from researchers in the past, but to date there has not been any characterization of a sandwich module’s performance in a realistic space environment scenario, nor has there been a comprehensive analysis of the limitations levied by sun concentration level, thermodynamics, materials, and specific power.

An initial examination of the sandwich module concept was performed by Owen Maynard in 1980[9]. His paper “Progress Report on Solid State Sandwich Concept – Designs, Considerations, and Issues,” outlines many of the obstacles and sensitivities associated with the sandwich design. Maynard proposed using solid state FET amplifiers instead of the vacuum electronics microwave sources that had been suggested in much of the NASA/DOE study documentation. He identifies the maintenance of low junction temperatures of the solid state amplifiers used in a sandwich approach as a key point in assuring acceptable operating lifetimes result. Solid state amplifier efficiency
plays a major role in determining the amount of heat that must be dissipated, as does the efficiency of the adjacent solar cell layer. Lower efficiencies produce more waste heat and thus raise the junction temperature. Maynard points out that an advantage of the solid state amplifiers over vacuum devices is that they do not require high voltages. The many thousands of volts needed for magnetrons and klystrons are difficult to manage in the space environment and necessitate the inclusion of high voltage power converters, introducing another source of conversion inefficiency. Among the issues and possible resolutions Maynard summarizes, charged particle radiation effects and topological considerations stand out as some that specific part selection and module fabrication could address in a tangible fashion.

This paper reviews our effort to date to investigate, analyze, and address thermal and integration problems inherent in the development of a sandwich module prototype for photovoltaic collection, DC-to-RF conversion, and wireless power transmission for space solar power. Goals include: (1) Illuminating the scale of the challenges involved with sandwich module development from a systems integration perspective, (2) characterizing the performance of a sandwich module prototype under thermal and vacuum conditions resembling space, and (3) contributing to an empirical foundation to inform debates on the technical and economic viability of a prominent class of proposed space solar power systems.

2. CRITICAL TRADEOFFS

Photovoltaics

In order to complete a prototype within a reasonable period of time, commercially available photovoltaics (PV) will be used. Though there exist a multitude of promising high efficiency technologies in laboratory settings, they are not available for inclusion in a prototype. PV cells used for space are readily available from two companies: Emcore Corporation and Spectrolab Incorporated, a division of Boeing. Both offer triple junction cells with conversion efficiencies quoted at 29.5%. Cells from one of these manufacturers will be integrated onto a substrate using techniques to foster high temperature tolerance, employing some of the methods like those used on the MESSENGER mission to Mercury.

DC-to-RF conversion

The conversion electronics must simultaneously achieve cost, weight, efficiency, and output power requirements. Several options are compared in Table 1. While vacuum electronics offer a number of advantages, their bulkiness and need for high voltage may render them less attractive than solid state alternatives. The smaller output power levels per solid state device also allow more latitude in varying the transmit aperture power density while maintaining a more evenly filled aperture. Because high efficiency solid state power amplifier (SSPA) devices have not been demonstrated at the levels of gain required, the construction of a suitable amplifier chain will be central to this layer of the module. Monolithic microwave integrated circuit (MMIC) and commercial off-the-shelf (COTS) options for making the chain shall be examined.

The frequency source can be either a voltage controlled oscillator (VCO), or may be derived from a pilot signal used for retro-directive beam steering.

Due to emerging wide band-gap semiconductors, SSPAs are beginning to encroach on applications where formerly only traveling wave tube amplifiers (TWTs) were feasible. SSPAs offer system designers significant benefits and challenges to system integration. Besides being small and light weight, an SSPA can be a factor in reducing the cost of a system requiring significant power levels, in particular in an array configuration, where the transmit aperture gain and large numbers of moderately powered devices can be coherently combined to provide a microwave beam of substantial power. Although Gallium Nitride (GaN) offers the benefits of higher operating temperatures and power densities over other semiconductors, it also brings challenges that arise from its generally lower gain per stage, potentially requiring a multistage architecture. As SSPAs based on GaN have continued to push power limits while offering high efficiency, they also pursue applications throughout the frequency spectrum including mm-wave. However, it should be noted that both efficiency and output power drop as frequency is increased, due to carrier trapping and other phenomena.

Table 1: Comparison of selected means of amplification and DC to RF conversion

<table>
<thead>
<tr>
<th>Method</th>
<th>Solid State Amp</th>
<th>Magnetron</th>
<th>TWT</th>
<th>MBK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>43-70%</td>
<td>44-73%</td>
<td>66-70%</td>
<td>50%*</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>&lt;0.1</td>
<td>0.9-4.3</td>
<td>0.7-3.0</td>
<td>1.0*</td>
</tr>
<tr>
<td>Power Output (W)</td>
<td>25-220</td>
<td>900-5,000</td>
<td>20-300</td>
<td>1,000*</td>
</tr>
<tr>
<td>Input voltage (V)</td>
<td>28-50</td>
<td>4,000-20,500</td>
<td>5,000-20,000</td>
<td>2,000-4,000*</td>
</tr>
<tr>
<td>Manufacturers</td>
<td>Cree, TriQuint</td>
<td>Toshiba, Hitachi</td>
<td>L3, Thales</td>
<td>CCR</td>
</tr>
</tbody>
</table>

TWT = Traveling Wave Tube, MBK = Multiple Beam Klystron. Values (except for MBK) taken from data sheets of potential models in the 2-10GHz frequency range, some available from Richardson Electronics. Masses exclude voltage conversion components. *Rough estimates
Antenna Elements

A wide variety of antenna types might be appropriate for the microwave transmission face of the module. Slotted wave guide antennas offer high power handling capabilities. Patch antennas offer a slim profile. The number and type of antenna elements will be driven not only by the output power level of the RF chain, but also by the desired power density on the transmission face. As the antenna surface will need to double as an effective thermal radiator, it should be compatible with performing in this capacity.

Module Architectures

Most previous sandwich module concepts have taken a hexagonal shape, ostensibly to maximize the usage of the volume of a cylindrical launch vehicle fairing. A preliminary analysis of current launch vehicle fairing volumes and throw weights suggests that a module of any reasonably achievable density will exceed the launch vehicle throw weight before exceeding the fairing volume. Because of this, module shape can be selected based on other factors, such as photovoltaic cell coverage. Since currently available PV cells are rectangular, a square or rectangular panel surface can be more efficiently filled than a hexagonal one. The module thickness is driven by the need to accommodate the DC-to-RF conversion electronics and the antennas, as well as by its ability to manage the transport and radiation of waste heat.

Thermal Control Methods

There are available many effective and novel means to transfer heat from one part of the module to another: diamond heat spreaders, pyrolitic graphite structures, microchannels, and two-phase heat pipes. Regardless of the transfer method, the waste heat will need to be radiated from the module. An appropriately anodized antenna surface closely approaches the emissivity of a black body. The area available for radiation of heat can be increased with judicious module design.

3. PERFORMANCE METRICS

Performance metrics are tied to economic considerations, but also can be used to help set targets for pushing technological boundaries. Listed below are some of the likely figures of merit for a sandwich module that could provide a basis for performance goals or requirements:

- Mass per unit area [kg/m2].
- Specific power [W/kg]
- Combined conversion efficiency [%].
- Survival temperature range [°C]
- Continuous operation duration [hours]
- Solar concentration acceptance [number of suns]

While not necessarily numerical performance metrics, other module qualities of possible interest for the prototype and certainly for a flight unit include:

- Adaptability for control of the microwave power beam
- Susceptibility to space radiation environmental effects
- Susceptibility to solar wind and space weather effects
- Rate of degradation due to solar ultraviolet light exposure
- Spacecraft charging behavior
- Susceptibility to parts aging effects
- Avoidance of radio frequency multipactor effects
- Launch acoustic and vibration environment tolerance
- Electromagnetic compatibility and interference susceptibility
- Manufacturability
- Ease of integration with other modules in space
- Ability to transfer heat from other modules
- Ability to transfer electrical power from other modules
- Outgassing qualities that could affect PV performance
- Structural rigidity
- Reliability
- Durability
- Serviceability

4. THERMAL ANALYSIS

A preliminary study of the thermal problem for the sandwich module shows some of the limitations imposed by the radiative heat transfer relation:

\[ P = \epsilon \sigma A T^4 \]

Where \( P \) is the heat power transmitted, \( \epsilon \) is the emissivity of the material, \( \sigma \) is the Stefan-Boltzmann constant, \( A \) is the radiating area, and \( T \) is the temperature. Assuming that a flat sandwich module can only use the top and bottom for radiating heat, since it would be adjacent to other modules needing to also dissipate heat at its edges, bounds can be established by specifying the desired operating temperature. The sun’s power flux in space in earth orbit is approximately 1400 W/m². Multiplying probable
efficiencies of the component layers gives a rough total module efficiency as shown in Figure 3. In this case, a square module made of four rows of seven cells with each cell measuring 4 cm x 7 cm is assumed for simplicity.

If the sun concentration value is varied for different emissivities for modules at different desired operating temperatures, the resulting required radiator area can be found. The simulation results for this variation are shown in Figure 4. Because this is a somewhat idealized model, the temperature effects on the efficiency of the layers, most notably the photovoltaic and DC-to-RF conversion layers, are not accounted for. The efficiencies of these two layers will tend to decrease with rising temperatures, in turn resulting in more heat that must be dissipated, further raising the module temperature.
Inserting more or less optimistic combined module efficiencies allows plotting the resulting temperatures as a function of sun concentration. The plot of this simulation, seen in Figure 5, shows that to operate below 150°C with reasonable efficiency assumptions limits the sun concentration to around three suns or below, unless the radiator area is increased somehow. The reduction in slope in this plot as sun concentration increases is due to the $T^4$ term in the radiative heat transfer relation.

Keeping the module temperature below 150°C will help limit the efficiency degradation due to temperature of the photovoltaics and the DC-to-RF converters. In practice, individual efficiency degradations will be dependent on the temperature gradient across different parts of the module. This model does not distinguish between DC-to-RF converter junction temperature, case temperature, solar array surface temperature, or differences in temperature between any parts of the module.

The limits imposed by the first order thermal analysis presented here offer two possible paths to the creation of a sandwich module suitable for SSP: (1) a high specific power module at moderate sun concentration (below three suns), or (2) a departure from the flat sandwich module to allow for an increase in radiator area. Both options will be investigated. Draft designs are depicted in Figure 6 and Figure 7, respectively.
5. Module Fabrication

Upon satisfactory closure of the design tradeoff studies, the module will be fabricated. The build process will proceed iteratively, with breadboard level prototyping used initially to verify expected performance of the selected RF and supporting power architecture components. Any needed modifications to the design would be identified and implemented prior to proceeding to the engineering model level prototype build. In tandem, the mechanical design and related incorporation of the solar array, antennas, and thermal control means would proceed first through scaled and then full mockups to identify possible design problems. Lessons from these exercises will be applied to the construction and integration of the engineering module.

6. Test Equipment and Facilities

It is anticipated commercial and custom lab equipment will be required for development and testing. For RF development and characterization, commonly used lab equipment will be needed: spectrum analyzers, power meters, a harmonic load pull system, and microwave frequency sources. Testing of the integrated module will be performed initially in an RF anechoic chamber at the Naval Research Laboratory (NRL), such as the one shown in Figure 8. Vacuum testing will be accomplished using the thermal vacuum test chamber at NRL shown in Figure 9(a) in conjunction with a specialized door (Figure 9(b)) with a large fused silica window (Figure 9(c)) to allow simulated solar illumination by lamps using for spacecraft solar array testing.

Alternately, if the desired illumination sun concentration level cannot be achieved with the NRL chamber, there is a vacuum chamber at the NASA Glenn Research Center (“Tank 6”) that can provide solar concentration levels in excess of ten suns over a sizable area if required. Fused silica effectively passes the solar spectrum, as can be seen by comparing its transmission curve with the solar radiation spectrum.

In the vacuum case, special vacuum-rated high power RF absorbers or a rectenna array will be used to capture the transmitted microwave energy from the module.

Figure 8: NRL RF Anechoic Chamber

Figure 9: (a) Thermal vacuum testing chamber, (b) chamber door for fused silica window, (c) fused silica window
7. CONCLUSIONS

This paper summarizes selected highlights from our research efforts of the past year in performing tradeoff studies, developing designs, and executing analyses for a prototype sandwich module for space solar power. Each was iterated as new discoveries and realizations came to light. Tradeoff studies continued the examination of the three functional layers inherent in the sandwich module: photovoltaic conversion, DC to RF conversion, and power radiation via antenna; as well as for thermal and architectural concerns. A solid state amplifier chain has been designed, and components have been characterized. Mechanical drawings 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 testing of a sandwich module in environmental conditions simulating space.

REFERENCES


**Paul Jaffe** is an electronics engineer, researcher, and integration and testing section head at the Naval Research Laboratory. He has worked on over a dozen NASA and Department of Defense space missions, including SSULI, STEREO, TacSat-1, TacSat-4, and MIS. He developed standards and lead spacecraft computer hardware development as part of the Department of Defense’s Operationally Responsive Space effort. He served as a coordinator and editor of NRL’s Space Solar Power (SSP) study report and is presently the principal investigator for an SSP-related research effort. His current primary role is as the Electrical Segment Lead for the Microwave Imager/Sounder (MIS) in which he manages a large, multidisciplinary team and a program budget exceeding $100M. Paul is also active in educational and STEM outreach. He has a B. S. from the University of Maryland and a M. S. from the Johns Hopkins University, both in Electrical Engineering. He is currently pursuing a Ph.D. at the University of Maryland.

**Jason E. Hodkin** received a B.S. from Georgia Institute of Technology in 2002 and a M.S. from Johns Hopkins University in 2007, both in Electrical Engineering and is an RF & Microwave R&D engineer with the U.S. Naval Research Laboratory (NRL) Radar Division where he currently works on transmit/receive (T/R) module architectures for digital array radar, monopulse test bed development for advanced pulse doppler waveforms, GaN MMIC design, packaging, and high temperature applications of GaN semiconductors. Prior to joining NRL he designed transmit and receive circuits and RF front-ends for ViaSat as well as participated in T/R module and high power array driver development for phased array radar systems at Northrop Grumman Electronic Systems.

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