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Sandwich module prototype progress for space solar power ☆, ☆☆

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ABSTRACT

Space solar power (SSP) has been broadly defined as the collection of solar energy in space and its wireless transmission for use on earth. This approach potentially gives the benefit of provision of baseload power while avoiding the losses due to the day/night cycle and tropospheric effects that are associated with terrestrial solar power. Proponents have contended that the implementation of such systems could offer energy security, environmental, and technological advantages to those who would undertake their development. Among recent implementations commonly proposed for SSP, the modular symmetrical concentrator (MSC) and other modular concepts have received considerable attention. Each employs an array of modules for performing conversion of concentrated sunlight into microwaves or laser beams 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 the possible solar concentration levels in which an array of modules might be required to operate. The research described herein details our team's efforts in the development of photovoltaic arrays, power electronics, microwave conversion electronics, and antennas for microwave-based "sandwich" module prototypes. The implementation status and testing results of the prototypes are reviewed.

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1. Introduction

The specter of 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.

A potential clean power source is the sun, which has an effectively unlimited energy supply. However, terrestrial collection of solar energy has limitations. 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 wireless transmission to the ground largely overcomes these limitations, but it poses considerable engineering challenges and serious questions of economic viability. Thoughtful criticisms [1,2] and counter-criticisms [3] of this concept appear in the literature.

Solar power satellite concepts have been examined in depth on several occasions in the past [4,5], and interest has been renewed in recent years [6–8] because of improvements in a number of relevant technologies. These include: solar cell efficiency, solid state power amplifier

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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. Our work seeks in part to address this gap.

2. Modular solar power satellite architectures

Recent space solar power system designs of widespread interest include the modular symmetrical concentrator (MSC) architecture [9], solar power satellite via arbitrarily large phased array (SPS–ALPHA) [10], and others that employ a high degree of element modularity. These approaches typically utilize optical energy routing and a large microwave transmit aperture constructed from essentially identical elements. This avoids the need for a potentially failure-prone, 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 enabling of constant ground coverage. A depiction of a proposed MSC SSP satellite is shown in Fig. 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 technical soundness of modular SSP architectures is hampered by a dearth of substantive efforts to identify and resolve concerns about their component technologies, most notably those pertaining to the sandwich module. One motivation for our effort is the need for a critical examination of the challenges associated with sandwich module development.

3. Sandwich module

The key element in the many modular 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 Fig. 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 our knowledge there had not been prior to our effort any detailed physical characterization of a sandwich module's performance in a realistic space environment scenario, nor had 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 [12]. 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 that 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. 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 focuses principally on our prototyping efforts to date in the integration and testing of two varieties of sandwich module prototypes for photovoltaic

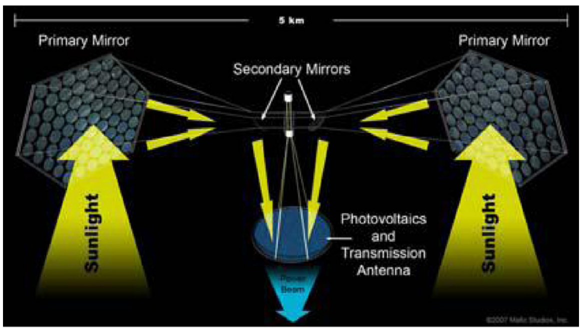

Fig. 1. Modular Symmetrical Concentrator architecture [6].

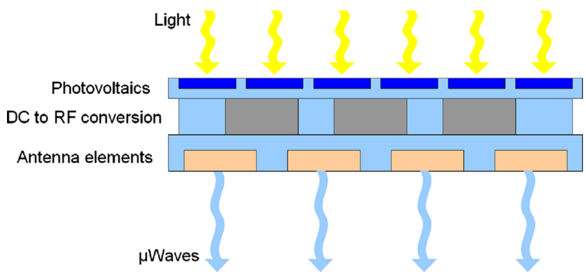

Fig. 2. Depiction of the functional layers of the sandwich module [11].