N91-22179

Applications of Thin Film Technology Toward a Low-Mass Solar Power Satellite

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Abstract

Previous concepts for solar power satellites have used conventional-technology photovoltaics and microwave tubes. We propose using thin-film photovoltaics and an integrated solid-state phased-array to design an ultra-lightweight solar power satellite, resulting in a potential reduction in weight by a factor of ten to a hundred over conventional concepts for solar power satellites.

Introduction

The concept of a Solar Power Satellite (SPS) to provide power for Earth was proposed in 1968 by Peter Glaser [1]. Glaser proposed to solve the energy crisis and provide abundant electrical power for Earth by putting large (1-10 Gigawatt) solar collectors into geosynchronous Earth orbit, and to transmit energy to the surface using a microwave beam. Solar power satellites based on this concept were extensively analyzed in the period around 1978-1981 [2-4].

The solar power satellite concepts examined in the late seventies had two significant difficulties: capital cost and weight.

In this paper we discuss the potential for two technologies currently under development to considerably reduce the mass-to-orbit required for such a satellite power system: thin-film photovoltaics and solid-state microwave electronics. It may be possible to design a solar power satellite to be constructed entirely by thin-film technology, consisting of thin (one to two micron) active components on a plastic substrate, with the microwave phased-array components integrated directly with the photovoltaics.

In essence, we propose discarding the "bridge-builder" mindset adopted by the initial designers of a SPS system, and adopt a thin-film, integrated-circuit mentality: why can't a solar power satellite be a single, integrated assembly deposited on a thin, lightweight substrate?

Thin film photovoltaics

Thin-film solar cells consist of thin (thickness ~1-5μ) films of photovoltaic material deposited on a supporting substrate In the 1980's a considerable research program has been devoted to development of thin-film photovoltaics for terrestrial power generation. Efficiencies over ten percent have been achieved on amorphous silicon and copper indium diselenide thin-films, and encouraging results achieved on other thin-film technologies such as CdTe and $CuInS_2$. Table 1 showsthe historical progress in efficiency of several of the thin-film materials over the last few years [5].

Because of the high optical absorption constant, for thin-film solar cells the active material may be as thin as one to two microns, and hence the materials inherently have the potential to be extremely light. However, very little current research is aimed at depositing thin-film cells on lightweight substrates, since most of the applications being currently considered are for terrestrial applications, where weight is not important.

Preliminary results show that thin-film solar cells appear to be inherently radiation tolerant, and may not require a glass cover for radiation protection [6]. They also are highly tolerant of small damage areas, such as due to micrometeoroid or debris impact.

A conservative projection would be to project use of a 5% efficient thin-film cell on a 25 micron thick Kapton substrate. This yields a photovoltaic blanket specific power of 1.7 kW/kg. An optimistic projection might be 15% thin-film cell on a 7 micron thick Kapton substrate, leading to a photovoltaic blanket specific power of 15 kW/kg. These numbers compare favorably to current technology spacecraft solar arrays, *e.g.*, 67 W/kg at the array level for the flight-tested SAFE array.

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Solar cell cost was highlighted as one of the single most critical improvements needed for a SPS in the NRC analysis. In addition to low mass, thin-film photovoltaics are also projected to have considerably lower costs. Materials cost is reduced due to the reduced amount of materials required; the cost of labor and assembly is reduced by the fact that large-area, integrated assemblies are directly produced on the substrate sheet.

For typical existing systems the photovoltaic blanket weight is only about a quarter of the total power system mass, with the array structure and power management and distribution (PMAD) accounting for the remaining three quarters. This provides a powerful incentive to integrate the PMAD elements directly to the solar array, and to design new array structures to take advantage of the ultralight blankets.

Historical progress of thin-film solar cell efficiency. Experimentally achieved efficiencies (at AMO, in %) as of 1978, 1983, 1988, and projected values for future performance.

Material	1978	1982	1988	1990's
CdS/Cu$_2$S	7.3	8.2	9.	10
CuInSe$_2$	5.3	8.5	11.2	12
CuGaSe$_2$	-	-	4.6	12.5
CuInS$_2$	2.9	2.9	6.1	12.5
CdTe	4.1	8.4	8.6*	12.5
a-Si	4.4	8.1	9.0	11.5
CASCADES	-	-	12.5	17+

*(9.8% reported in May 1989)

Microwave electronics

Use of thin-film solar cells will reduce the satellite mass only if the mass required for the power management and the microwave beaming system can be reduced as well. This may also be achievable using solid state electronics. In the last ten years we have seen development of microwave integrated circuits, thin-film transistors, and thin-film microwave rectennas

Solid-state electronics has developed considerably, and it is now reasonable to consider that the microwave source for a SPS may be able to be manufactured from thin-film electronics.

Microwave rectifying antennas (rectennas) for receiving microwave power and converting it to DC power have been demonstrated using thin-film techniques on a thin-plastic substrate [7]. Using such a technology as a microwave source requires replacement of the GaAs diodes by appropriately phased microwave transistors.

Thin-film microwave electronics are a reasonable extrapolation of the union of two recent developments: solid-state microwave electronics, and thin-film transistors. Microwave integrated circuits are currently available which can operate in the gigaherz band proposed for SPS power transmission, and have been demonstrated by many different laboratories for operation at the tens and hundreds of gigaherz [8].

Thin-film transistors have been developed for other applications such as display screens, where many millions of devices can be integrated on a large-area sheet. Thin-film transistors are made from amorphous silicon or polycrystalline silicon, and could in principal be manufactured integrated onto the same substrate as the solar cells. Current technology only allows frequencies in the range of kiloherz to at most megaherz [9], but this will likely increase with further research. Development of gigaherz-speed thin-film transistors would allow the transmitter elements to be deposited on the thin substrate at the same time as, and possibly using the same materials as, the thin-film solar cells.

The concept for integration of the solar cell with the microwave oscillator and antenna is shown in schematic in figure 1. A slightly more complex version, where the solar cell metallization is used for the antenna in a "push-pull" configuration, is shown conceptually in figure 2.

Even without the development of thin-film microwave transistors, conventional microwave solid-state integrated electronics would be able to perform the function at a cost considerably below that of the microwave tube approach. Each element need operate only at a power level of a watt or less, well within the capability of microwave integrated circuits.

An alternate approach to operation of the solid-state microwave source at even higher frequencies is the use of superconducting electronics. Such technology is currently being researched; for example, a superconducting circuit operating at 33-37 GHz has been developed at NASA Lewis using thin-film YBaCuO at 77°K [10].

Micro-phased array distributed thin-film SPS

In an highly-integrated SPS design, microwave oscillators and dipole antennas are be integrated directly on the plastic sheet with the solar cells, using phased-array techniques to steer the beam back along a pilot beam generated at the receiving antenna on the Earth. Rather than a smaller number of high-power microwave tubes, the integrated SPS will have billions of integrated transmitters, each operating at a power of no more than a watt. This integration would eliminate the power conditioning elements and the wiring used for power distribution.

The proposal consists of the following elements:

--Total integration. Microwave transmitters are integrated directly at the solar cell level. No wires or power management/distribution system is required.

--Thin-film technology. Lightweight photovoltaic films on a thin plastic substrate are used.

--Phased array technology. The antenna does not need to be physically "aimed" at the receiver.

The distributed thin-film SPS applies the integrated circuit approach to the satellite solar power concept.

Table 2 shows a comparison of the mass of an integrated thin-film solar power satellite compared to a baseline system. Using the "conservative" technology extrapolation the reduction in weight is by more than a factor of ten; assuming a more advanced technology a reduction in weight by over a factor of a hundred is achieved.

Table 2:
Mass Comparison

Baseline SPS (1980):

2.6 kg/kW	Transmission and control
6.5 kg/kW	Silicon Solar Array
0.6 kg/kW	Power Conditioning
9.7 kg/kW	

Thin-Film SPS (1990's): (5% efficient solar cell on 25μ Kapton)

0.7 kg/kW	Solar array + integrated transmitter

Thin-Film SPS (2000+): (15% efficient solar cell on 7μ Kapton)

0.08 kg/kW	Solar array + integrated transmitter

It is important to design new, low mass structures in order to reduce the structural mass of the system proportionately to the photovoltaic and transmitter mass reductions. Many structural designs for such a system are possible. Two, the "bicycle wheel" configuration (shown in figure 3) and the "sphere" configuration (shown in figure 4), shown. The phased array microwave elements mean that the microwave antenna does not have to face directly toward the receiving station, as long as the antenna is not edge-on to the receiver. The "bicycle wheel" concept uses centrifugal force to place a thin circular membrane in tension. Since the size is large and the tension required small, a very low rotation rate, <<1 RPM, is sufficient to provide tension. Bracing cables to a central hub provide the requisite out-of-plane stiffness. If necessary, a counter-rotating flywheel can compensate for angular momentum.

Thin-film PV elements are light enough that high power to weight ratios may be maintained even if the satellite does not track the sun. In the sphere configuration, the solar cell/microwave transmitter elements cover the surface of an inflated sphere as in the Echo satellite. For a sphere radius of many hundreds of meters the surface/volume ratio is extremely low, and the gas pressure required to hold the form, and the associated leak rate, can be made small.

Applications

The main application of a solar power satellite envisioned by Glaser and by most of the later advocates of satellite solar power was to provide baseline electrical power for terrestrial use. However, it is quite likely that some of the most important applications, and certainly some of the initial applications, will be in space. Existing power sources for use in space provide power at a considerably higher effective price than terrestrial power sources, and a remote power station would be able to serve several critical needs. Some of these are:

(1) Beamed power for lunar base night operation
(2) Inter-orbital ion-engine propelled transport spacecraft
(3) Power for Earth-orbital stations [11]
(4) Support for Mars missions and solar system exploration and exploitation.

Difficulties

So far we have only discussed the potential advantages, and not the problems. The concepts outlined above have been schematic, not detailed engineering designs of how such a system could be built, and many problem areas remain to be addressed. We will only briefly identify some of the issues here, without attempting to detail all of the possible approaches.

A phased array system requires a pilot beam from the target to be directed to the microwave source. The pilot beam need not be at the same frequency as the output beam. A pilot beam at, or near, the same frequency as the power beam has the advantage of automatically correcting for atmospheric effects. A disadvantage of a pilot beam at the output frequency is the difficulty of distinguishing pilot beam from output (*e.g.*, by polarization difference). Failure to adequately isolate the pilot beam from the output beam would result in undesirable self-stimulated oscillations of the transmitter. One way to eliminate this problem would be to use a pulsed laser as the pilot beam. Each laser pulse would be used to set the phase signal.

The issues involved with phase-conjugation of the reference beam, including the problem of providing a reference clock signal and distributing the phase signal have not been addressed. This could be done either with analog processing or with digital circuitry. The difficulty of this problem is decreased if it is assumed that significant amounts of integrated processing capability is available at low cost.

If the elements are equipped with local oscillators, then the phase signal is only required to keep the local oscillators in correct phase. If the system does not have local oscillators, or if the local oscillators have poor frequency stabilty, a continuous phase signal is needed.

Off-angle losses have not been discussed. The antenna elements will be tuned to radiate at best efficiency at a given angle. Also, polarization issues have not been discussed. Finally the question of a backplane for the microwave antennae has also not been addressed. The shorter the wavelength used, the less difficulty this provides.

In general, all of the problem areas are amenable to engineering solutions. The important question is whether resolution of the problem areas would unacceptably increase the complexity, weight, or cost of the system.

Conclusions

Thin-film photovoltaics and microwave solid-state devices have the potential to create a revolutionary improvement in solar power satellite design, with possible improvements in power to weight ratio of a factor of ten to a hundred. Thin-film photovoltaics alone could cause a significant performance improvement, however, to take full advantage of the technologies being developed, we have suggested design of a fully integrated photovoltaic/microwave system, where the phased array microwave elements are deposited integrally to the solar cells, eliminating all the power management and distribution.

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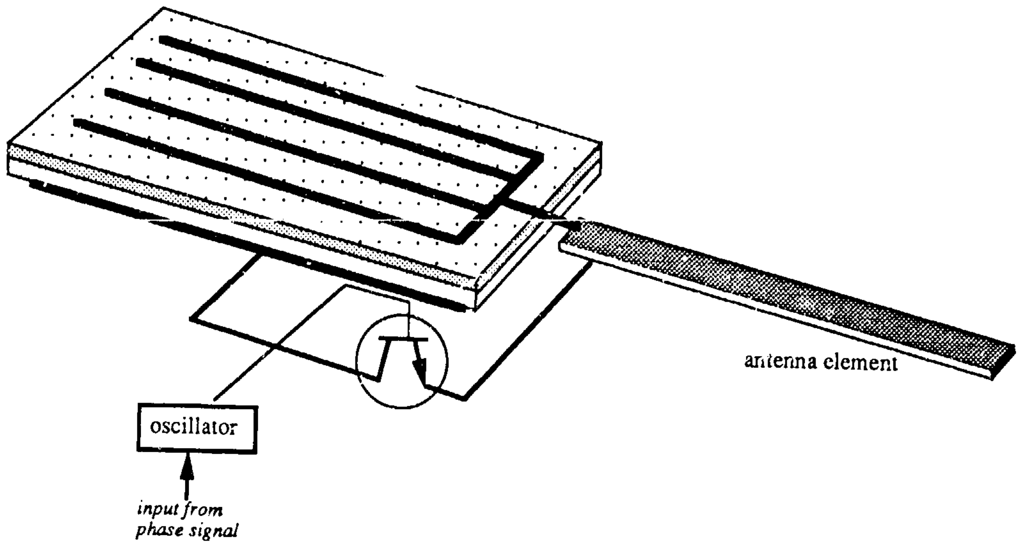

Figure 1. Solar cell with integrated microwave antenna element (conceptual diagram). The local oscillator receives a phase signal to make the output signal coherent as part of a phased array beam.

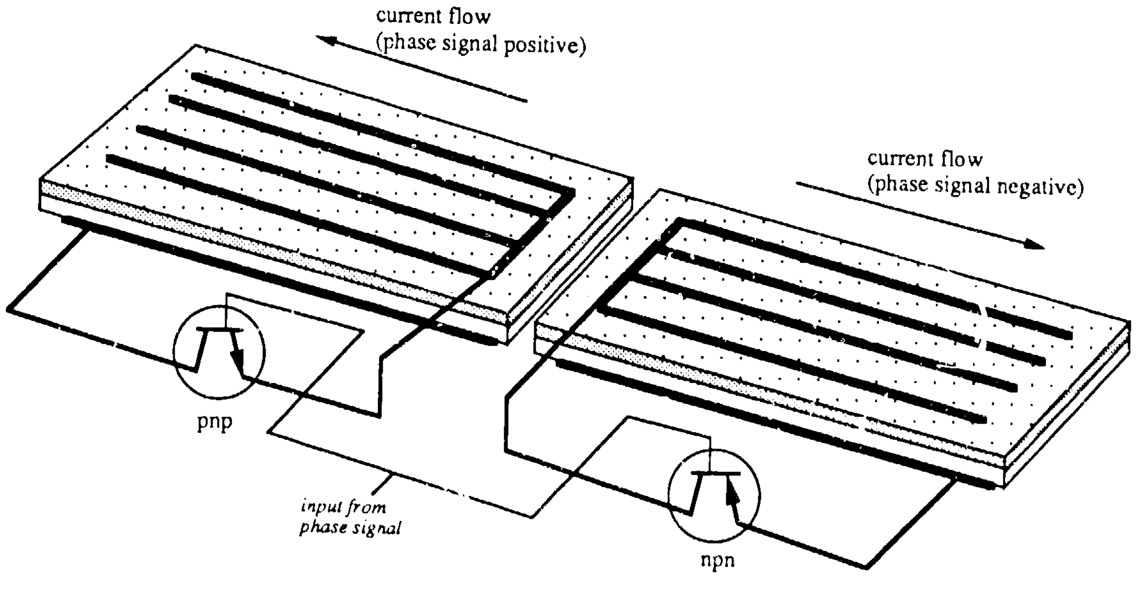

Figure 2. Schematic diagram for integrated solar cell/transmitter conmination in a push-pull configuration. The contact metallization of the solar cells serves as the antenna element for the integrated microwave transmitter. Complementary pnp and npn transistors receive the same phase signal

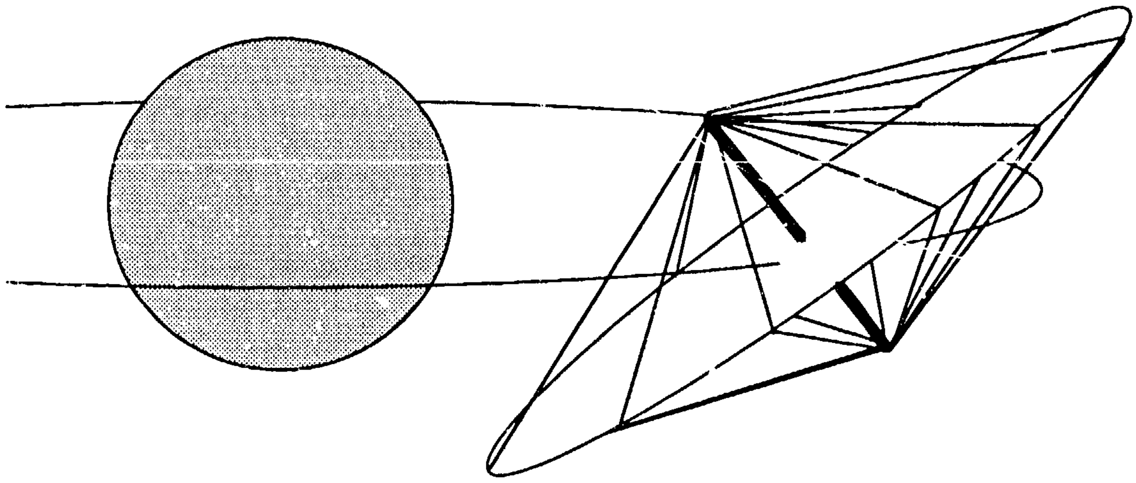

Figure 3: "Bicycle-Wheel" SPS Configuration

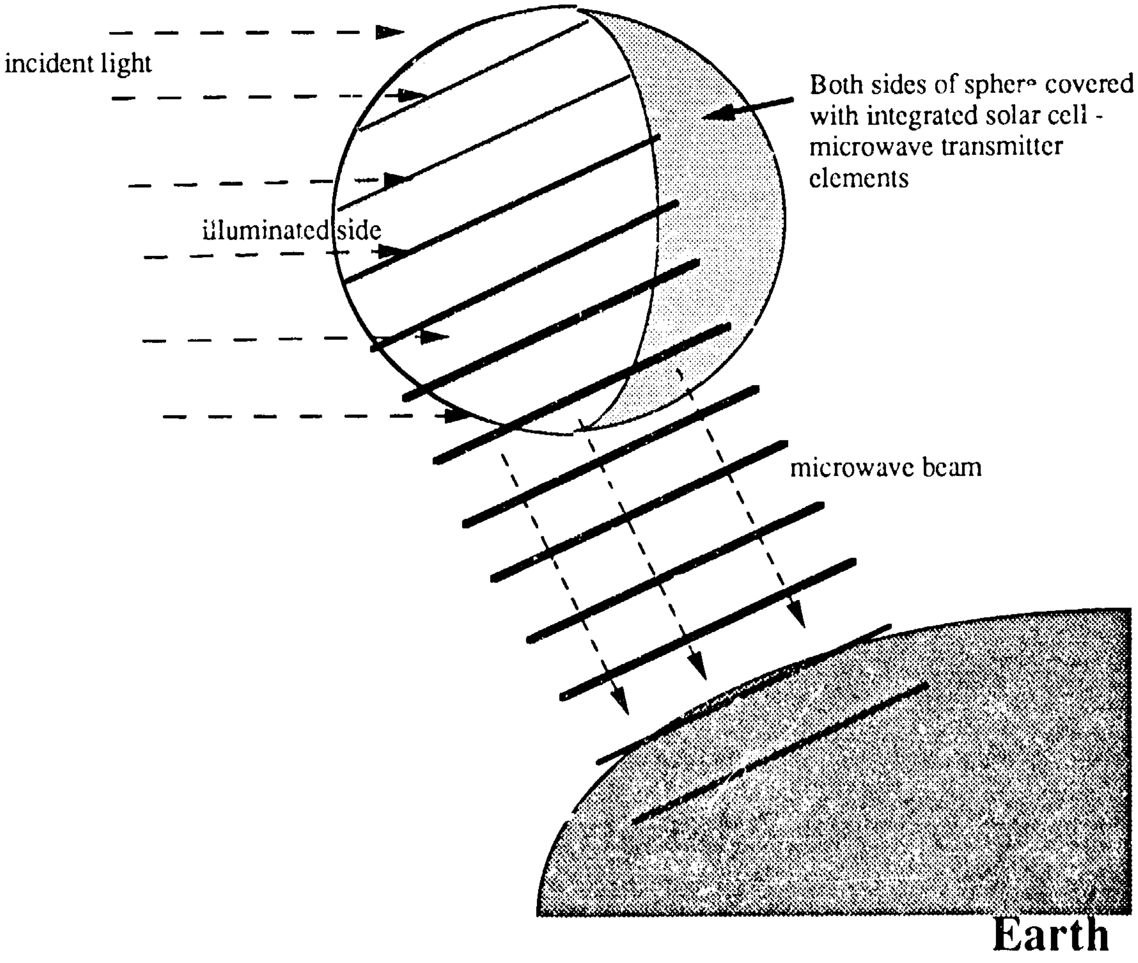

Figure 4: "Sphere" configuration for SPS.