SOLID STATE DEVICE TECHNOLOGY FOR SOLAR POWER SATELLITE*

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NASA, Johnson Space Center sponsored a program, "Analysis of S-Band Solid-State Transmitters for the Solar Power Satellite," based on the assumption that a high-efficiency solid-state SPS transmitter may be feasible.

The objectives of the study were to:

- expand the understanding of the SPS transmitter concept and relate it to the possible utilization of solid-state (rather than thermionic) elements in the antenna array;
- explore the need for technology development in the areas of devices, circuits, and interface configurations for a solid-state antenna array;
- recommend specific technology advancement programs that could impact future SPS designs.

An additional task, added toward the end of the program in agreement with the Technical Monitor, was to construct a sample solid-state amplifier, based on existing gallium arsenide FET devices, so that power, gain, and efficiency relationships could be experimentally explored.

The study was designed to explore independently aspects of the devices, the circuits, and the overall antenna system. Only toward the end of the investigations were these three elements brought together to provide an overall view of the solid-state antenna concept and to recommend follow-on technology investigation programs.

DEVICE INVESTIGATIONS

For any system configuration, devices providing the maximum possible power at the highest possible efficiency would obviously be desirable. In practice, however, power must be traded off against efficiency, with efficiency the paramount parameter. When these factors are considered, gallium arsenide rather than silicon appears to be the favored material for the SPS application; the device used would be some kind of field-effect transistor of the type that combines high efficiency and relative ease of fabrication.

Thermal and electrical designs for both Schottky-barrier and junction-type FETs were presented at the conclusion of the study. Their purpose, rather than serve as device designs to be actually developed, was to highlight the considerations likely to influence the choice of future programs. No clearcut preference of one over the other was discerned at that point in the study. Devices providing 4 watts at greater than 80% power-added efficiencies were considered feasible.

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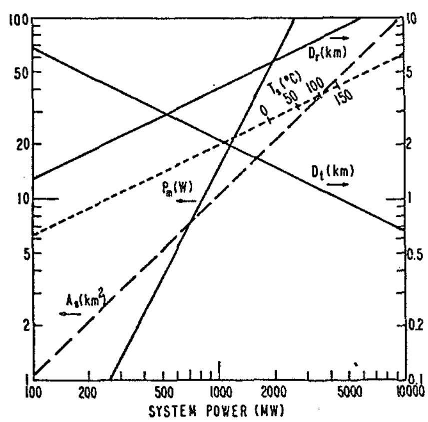
An actual amplifier stage was constructed with commercially available devices. It provided 3 watts of output power at an efficiency of 58% -- results considered very good indeed. The unit was delivered to JSC at the conclusion of the study.

One of the important recommendations of this part of the study was the undertaking of a follow-on experimental and theoretical program to ascertain the factors contributing to high-efficiency operation of microwave FETs. Previous experience with specialized large-signal computerized equipment pointed to the benefits of using this apparatus for the recommended follow-on study program.

ANTENNA SYSTEM INVESTIGATIONS

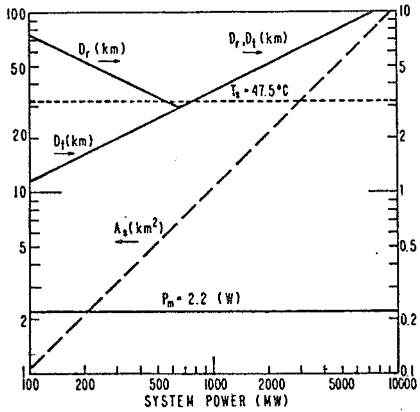
The Reference System (DOE/NASA Report, October 1978) served as a basis for the first phase of the antenna system investigations.

If it is attempted simply to replace the thermionic devices contemplated in the Reference System by clusters of solid-state devices whose power is combined to form equivalent transmitting elements, penalties in voltage-distribution losses, power combining losses, and thermal problems must be seriously considered. From detailed analyses performed during our study, it soon became apparent that a solid-state replacement program of this nature, while it may contribute toward the overall reliability of the system, would fall short in terms of the operational parameters -- particularly in terms of a Factor of Merit measured in watts per kilogram.



SPS design nomograph - 10-db taper.

At that point in the study, again with the concurrence of the Technical Monitor, emphasis was placed on a concept that considered direct conversion of sunlight into microwave power-generating modules, thereby obviating the need for voltage distribution altogether and essentially solving the thermal problems. Some specific problem areas peculiar to this approach were addressed in the study -- e.g., the relative orientations of the solar array and the microwave antenna, the spacing of the antenna elements and, most importantly, the near-field properties of such an antenna.



SPS design nomograph - uniform distribution.

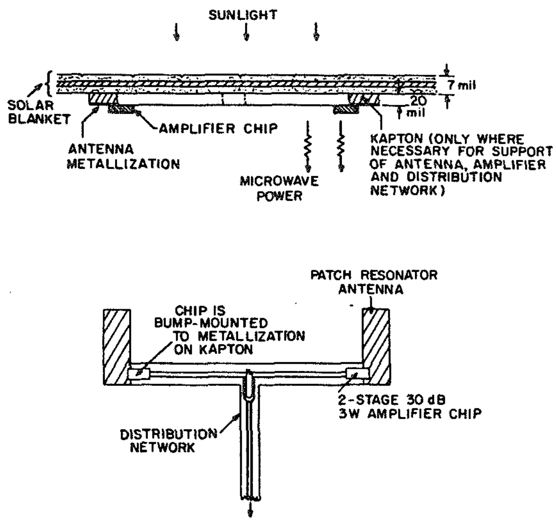
It was concluded that this type of system has Factor of Merit (W/kg) advantages over the Reference System, and that a tubular beam can indeed be created; a judicious choice of phase tapers made it possible to smooth power variations over the rectenna. Computer simulations of this type of antenna beam were performed at the conclusion of the study. Recommendations for adapting this approach, after further study, were made.

We recommended that studies aiming at a fuller understanding of the factors affecting high-efficiency operation of microwave FETs and the circuitry associated with them be vigorously pursued. Large-signal waveform analysis of FET operation was identified as a necessary factor of these studies.

MODULE INVESTIGATIONS

The module study quickly yielded the (not unexpected) notion that the efficiency of the power module is the most important design parameter, since it impacts very strongly the overall SPS cost in terms of dollars per watt of output power. Here again power combining losses and primary power distribution problems pointed toward the concept of the solar-powered module; an analysis of the practical power limits placed the module somewhere between 0.5 and 30 watts, with the power-vs-efficiency tradeoff pointing toward an optimum value of 1.5-3 watts.

Two design concepts were shown in which modules were placed on a 1.3-λ x 1.3-λ grid, with 16-module clusters controlled by a single receiver module and providing 50 watts of transmitter power per cluster. As was the case with the device designs, both module designs (a "high Q" version and a "patch resonator" approach) were meant to represent the approach rather than be specific.



Patch - resonator design.

The most important recommendation resulting from the module study was a strong indication that any future efficiency optimization attempt should consider the device-module interface as part of the problem. Thus the large-signal waveform analysis recommended for the device studies should be combined with similar analyses for the module circuitry.

CONCLUSIONS AND RECOMMENDATIONS

The JSC study program yielded the following conclusions:

o It does not appear prudent to simply replace the thermionic microwave power converters in the Reference System by equivalent clusters of solid-state devices.

o On the other hand, real benefits can be obtained if the system architecture takes full advantage of the operating parameters of solid-state microwave devices. This leads to a concept of direct utilization of the solar-panel-generated power by low-power microwave amplifiers (the so-called SMART concept).

o The postulated 80% power-added efficiency of the microwave amplifiers appears ultimately achievable. Gallium arsenide FETs are the logical device candidates for this service.

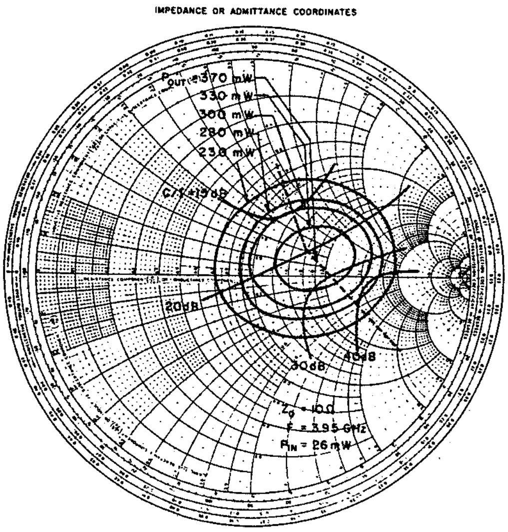
SPS SOLID-STATE AMPLIFIER

NASA, Marshall Space Center through Rockwell International, is presently sponsoring the "SPS Solid State Amplifier Development Program."

This program represents an extension of the effort performed as part of the JSC study: its main purpose is to gain a better understanding of the factors contributing to the high-efficiency performance of GaAs FETs. Large-signal waveform analysis techniques are a major investigative tool in the program.

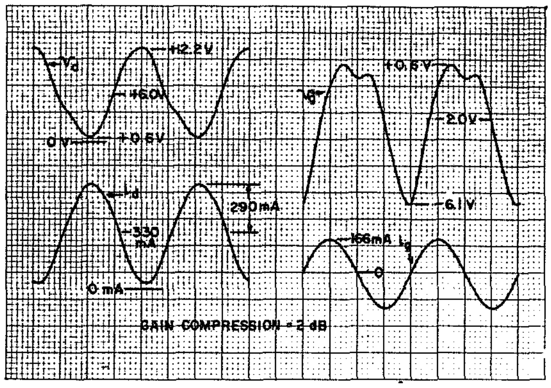
The program is divided into two consecutive tasks, with present effort still under Task A. This calls for the demonstration of an amplifier having an output power of 5 watts, a gain of 8 dB, and a power-added efficiency of 50%. In Task B the power output, gain, and efficiency to be demonstrated are increased to 10 watts, 10 dB, and 65%, respectively. To date a survey of available devices from a total of six domestic and foreign manufacturers of GaAs FETs was made, and circuits using various devices are being built and analyzed as the transistors are received. While "Class E" operation was and continues to be of interest for the SPS application because of its potential for very high efficiency, it is by no means certain that such mode of operation can be obtained at microwave frequencies, and the work under the program is not restricted to multipole operation of the FETs.

As previously mentioned, computer-aided analysis techniques are used extensively in the program, not only in the normal small-signal device characterization mode, but also to define the available tradeoffs under large-signal operating conditions. Examples of such techniques are the automatic plotting of circles of constant efficiency, constant gain, constant power output, and constant intermodulation distortion on special instrumentation which exists at RCA Laboratories.



Microwave CAD large-signal analysis.

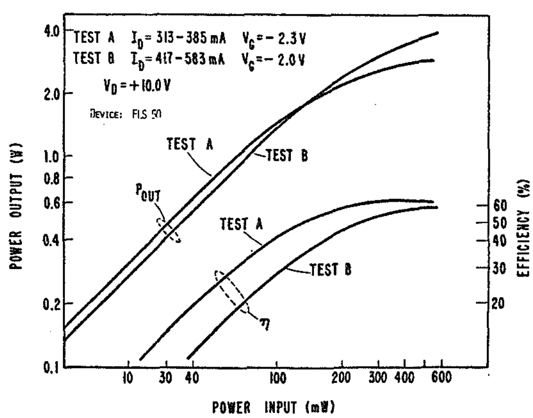
In addition, we have demonstrated a technique for synthesizing current and voltage waveforms under FET amplifier full operating power. This approach is also a powerful analytic tool in our investigation.



Full-power-measured voltage and current waveforms.

While the effort is still in progress and any attempts at projections of final results (even in Task A) are still considered premature, some very significant findings have already been made. When optimized for maximum efficiency at the SPS frequency, a power amplifier stage using a transistor designed for 12 GHz operation yielded 71% power-added efficiency, a very impressive figure that exceeds the requirements of Task B.

This result was obtained at a power output close to 1 watt and a gain in excess of 11 dB. The mode of operation may be described as an inverted Class AB, since the drain current is highest at low rf drive and lowest at full rf drive -- the rf voltage turns off the device during a substantial fraction of the rf cycle, hence the high efficiency. However, when the same type of operation was attempted with a transistor of the same manufacturer (but rated at somewhat lower power output at 12 GHz), low efficiency was observed at 2.45 GHz, but at a power output much closer to the rated value. These results are presently



Test results - max. power and max. efficiency tuning.

under intensive investigation. The current and voltage waveform analyses are expected to shed some light on the hitherto unexplained aspects of this type of FET performance.

Both Task A and Task B will make use of power-combining circuits in the final amplifier configuration. A study of such circuits is included in the program.

SOLID-STATE SPS TECHNOLOGY FORECAST

Solid-State Technology is in a period of rapid growth in both the microwave and the signal-processing areas. Specific applications of this technology in a variety of spaceborne systems occur with increasing frequency and effectiveness. The roots of this great interest in solid-state devices, components, and integrated circuits have been, on the one hand, the commercial computer industry and its integrated-circuit logic components and, on the other, the military-systems interest in microwave solid-state devices. This trend is quite independent of the SPS concept. Thus the SPS will reap tremendous benefits from the very large investments made in this technology, investments that are certain to continue in the future.

The directions of technology research pertinent to the SPS concept span the entire gammut of fields familiar to the solid-state industry--materials, devices, circuits, processing methods, and automated test procedures. In the semiconductor materials area, gallium arsenide is presently the most important compound for microwave applications, while ternary and quarternary materials are being investigated for use, particularly at the higher microwave frequencies. The silicon-on-sapphire technology is likely to provide the SPS solid-state antenna with an excellent technology base for substrate materials.

New device concepts, in addition to the FET which presently appears to be the best candidate for amplifiers at the SPS frequency, are the vertical FET, the power MOS transistor, the SIT, and matrix transistors, all of which are in advanced stages of exploration at the present time.

The most important area in circuit development is the return, after a hiatus of some years, to the concept of microwave lumped-circuit design. Lumped circuits designed for microwave frequencies extend FET operation to very high microwave frequencies. At 2.45 GHz, they permit extreme miniaturization of the amplifiers, making large distributed antenna arrays feasible.

Finally, modern processing methods -- e.g., ion-beam milling and plasma etching -- are likely to extend the techniques of the integrated-circuit chips to microwave circuits, while the selective implantation of impurities by means of ion implantation and laser annealing techniques point toward the fabrication of monolithic components directly on semi-insulating gallium arsenide.

These comments are not intended to imply that the SPS components -- both for signal-processing and for conversion to microwaves -- will not require specific and vigorous development. The attached diagram is a rough indication of the various microwave components which require study, development, and refinement in manufacturing techniques. We feel that the two most important areas requiring immediate attention are the following:

o THE CONFIRMATION THAT A SMART-TYPE SOLID-STATE ANTENNA IS INDEED WORTHY OF SERIOUS CONSIDERATION AND SHOULD THEREFORE FORM PART OF THE MAINSTREAM OF SPS STUDIES.

o THE INITIATION OF A SOLID-STATE POWER AMPLIFIER DEVELOPMENT PROGRAM AIMED SPECIFICALLY AT HIGH-EFFICIENCY SPS APPLICATION. THIS EFFORT SHOULD INCLUDE THE ACTIVE DEVICE AND THE MICROCIRCUIT MATCHING, INCLUDING ANTENNA, IN A SINGLE PACKAGE.