SPECIAL SECTION ON
SPACE SOLAR POWER SYSTEMS

Architectures and Prototyping Laboratory for the Development of Space-Based Microwave Power Transmission Systems

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Abstract

A vision is presented for the generation of enormous (terawatt) power levels using solid-state sources arranged in arrays of devices that are opto-electronically controlled to produce a microwave beam that can be safely directed towards terrestrial receptors. The performance and capabilities of discrete technologies will increase tremendously over the next three or four decades (when SSP systems should be economically feasible), and will be driven both by unrelated technology pulls and by the identification of necessary technologies. Critical are architecture studies for microwave beam forming, which will enable the identification of technology directions and basic feasibility of concepts. Even with a few orders-of-magnitude increase in the power available from solid-state sources (or even alternative devices), the ability to generate terawatt power levels will demand innovative developments in combining power in an inherently safe manner, beaming the power to Earth from low-Earth orbit, and in safe and reliable beam steering using structures that are adaptive, self-monitoring, and self-healing.

1. Introduction

The concept of harvesting energy in space for terrestrial use has captured political, engineering, and scientific imaginations for around three decades. Many system concepts have been proposed and explored, and the economics of solar space power (SSP) have been explored, with feasibility primarily dependent on the amount of power that can be generated for specific weight, and thus launch cost. Many lessons have been learned about the required attributes of such a SSP system [1, 2]. The focus of this paper is the presentation of a vision for an environment

Figure 1. The essential components of a space solar power-collection system. Terrestrial issues must be addressed at early system concept stages.

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that enables future directions of technology investment to be identified. The core elements of an SSP system, Figure 1, are a solar collection mechanism, a space power management and distribution system, and a mechanism for transmitting the energy to Earth. It is essential that we address health and safety issues in a manner with which people can identify. The most promising candidates for the components of the SSP system are semiconductor solar cells (for solar collection) and semiconductor-based microwave transmitters (for energy transportation). Technologies must be developed for ultra-low-weight microwave circuits, optically injection-locked distributed spatial power-combining systems, and, we believe, a virtual prototyping laboratory that will facilitate system exploration, as fielding prototypes is a very expensive undertaking.

2. Prime Directives

The challenge in SSP system research is creating developments that will benefit SSP research in the long term, without being wedded to a particular collection of components that is sure to evolve as technologies evolve. We believe that there are five prime directives for SSP systems: 1) safety and system stability, 2) low weight (optimum performance-to-weight ratio), 3) maximum efficiency, 4) long lifetime, and 5) low cost to first power.

It is abundantly clear that for the foreseeable future, the power from numerous solid-state sources will need to be combined to achieve tens to hundreds of gigawatts from each satellite installation. It is natural to think of using amplifiers in a phased-array architecture to achieve this, as this approach has been successful in fielding radar systems. SSP and radar systems are similar to spatial power combiners. However, with spatial power combining systems (see [3, 4]), the emphasis is on integrating antennas with active devices to achieve what amounts to an array of active antennas. Phased-array concepts are based on modules that are connected to antennas and so have higher losses. In the case of military radars, these losses can be 3 dB or more. These losses result in greatly enhanced system stability, but, of course, at the price of reduced efficiency. Spatial power-combining systems are much more difficult to design, but the much lower output losses clearly place them as a prime consideration. Beam control in spatial combining systems is of paramount importance. The most attractive option is to amplify a precise frequency source, but narrowband amplification can also be effectively achieved by using injection locking of oscillators, which achieve higher efficiencies than do amplifiers.

3. Virtual Prototyping Laboratory and Technology Integration

There is a mandatory requirement to develop revolutionary enabling technologies and to explore radically new system concepts for space solar power (SSP) generation. A virtual prototyping environment will allow concepts to be explored even before enabling technologies have been brought to maturity. We will use physically-based modeling of components and advanced simulation technology to achieve realistic physically-connected system simulation, incorporating complete thermal, circuit, mechanical and electromagnetic analyses. This approach is termed *technology integration* [5], and is an alternative to technology transfer, which more closely described the process of developing basic technologies and seeing where they can be applied (see Figure 2).

Today's power systems are some of the largest engineered systems, and yet they are operated with a high degree of reliability. One of the main reasons for this

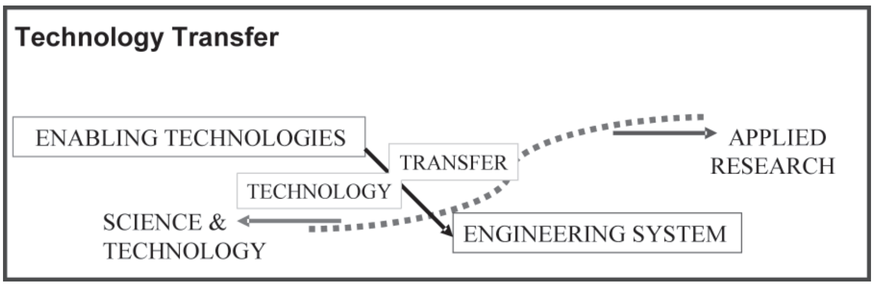

Figure 2a. The traditional approach of technology transfer.

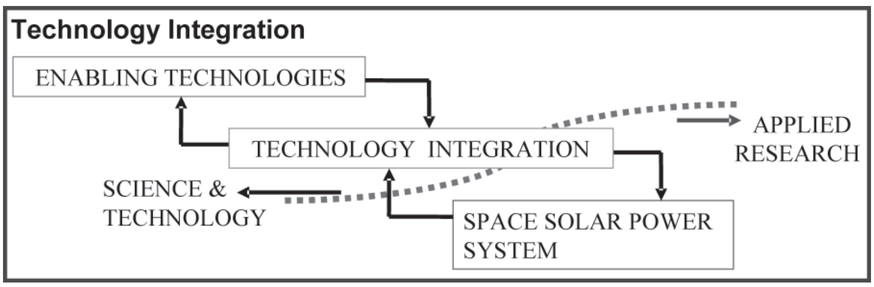

Figure 2b. The research and development process of technology integration, to be contrasted with the approach of Figure 2a.

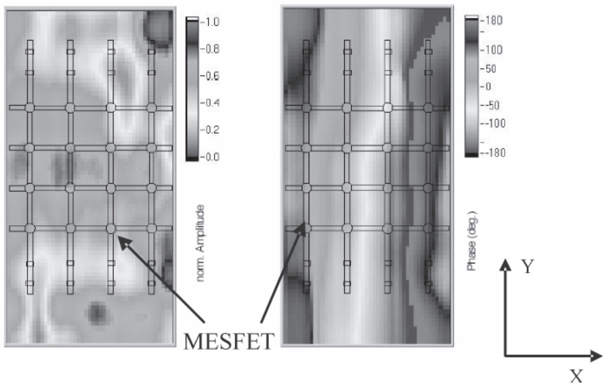

Figure 3. A mapping of the electric field immediately above a free-running quasi-optical oscillator array. The array was designed by Prof. Wilson Pearson and his group at Clemson University, and measured by us at the University of Michigan using electro-optic sampling.

success is the adoption of a well-defined system architecture, which allows the integration of system components into the system with ease, and which provides a high degree of robustness against variations in the system's operating conditions. Thus, for the envisioned SSP systems to be commercially viable, they should have similar features: they should have an architecture that facilitates system integration and management, and a high degree of robustness for handling varying operating conditions. Since the SSP system will provide the base load generation for terrestrial systems, the SSP system should be as easy to manage as the terrestrial generation systems (which consist of power generation stations), and should provide the same level of reliability. For reliability, the SSP must consist of many units that can be independently operated, and must be able to feed the terrestrial system at various locations.

4. Spatial Power Combining

Considerable experience has been gained in spatial power combining, including development of systems, analytic investigation technologies, and global modeling activities. A key insight is that free-running oscillator arrays are problematic, and very low levels of feedback adversely affect the performance of the systems. Amplifier arrays have a similar effect, but this is also manifested as variations of output power and phase across the array.

Figure 3 shows the field above a free-running quasi-optical grid oscillator. The prominent features here are the dramatic variations in amplitude and phase of the output signals, and the consequently poor control of the created beam. This, we believe, is due to low-level feedback effects. This does serve to lock the oscillators, but as feedback is not uniform, amplitudes and phase of each unit cell adjust to create just the right oscillation conditions.

Other experiences with spatial power combining systems indicate rather finicky stability issues. Stability and good efficiencies can be achieved in practice, but only after careful manipulation of the structures. For this reason, we undertook a number of system-level studies to determine their basic attributes. Figure 4 shows plots of the output amplitudes immediately above a spatial power combining amplifier array. Here can be seen the effect of low-level feedback from amplifier to amplifier, which principally results from the output of one amplifier being injected into the output of another amplifier. Amplifier mismatch was also considered. In all of our investigations that involved any level of feedback, the variations across the array were much greater than would be expected from the individual

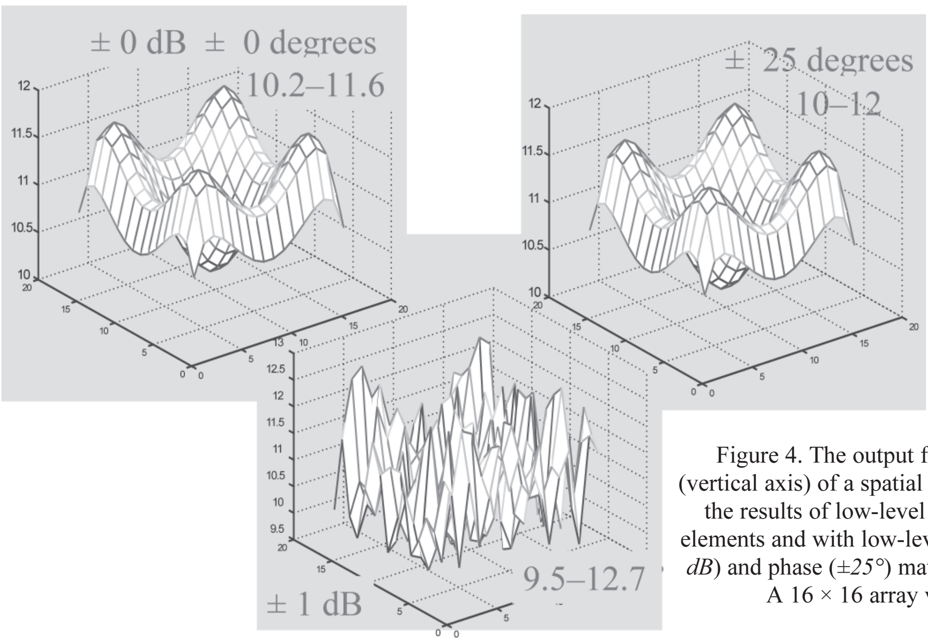

Figure 4. The output field amplitude levels (vertical axis) of a spatial amplifier array, showing the results of low-level feedback between the elements and with low-level variations in gain (±*1 dB*) and phase (±*25°*) matching of the amplifiers. A 16 × 16 array was considered.

amplifier variations. There were even significant variations when the amplifiers were matched. These affects will have an affect on stability, overall system efficiencies, and on beam integrity.

Our conclusions from these studies are that high-power spatial power combining necessitates the use of injection-locked oscillators in a spatial power combining structure with near as well as remote detection of beam characteristics, and with feedback to control the phase of (possibly) an optical injection locking signal applied to each unit cell.

5. Architecture Proposals

We present two possible architectures, based on collections of unit radiators. In essence, we envision arrays of microwave oscillators, with a fiber-optic feed to each oscillator unit cell for an optically injection-locked oscillator. The phase of the unit oscillators will be controlled optically to direct the beam to a terrestrial site.

5.1 Unit Radiators

The number of unit radiators in the system is determined by both the total power requirements and the power available from individual microwave sources. We can expect developments in the primary power-limiting factor: breakdown voltage. With alternative semiconductor technologies (yet to be developed), we could achieve an order-of-magnitude increase in breakdown voltage. This could result from extremely-wide-bandgap semiconductors, which will also enable operation at elevated temperatures, dramatically improving the extraction of waste heat. We then could very reasonably expect 10 kW per device. With circuit-level combining (with circuit-board-like interconnections), we could combine 64 devices, which, in round numbers, would yield an output power of 1 MW per oscillator unit. (Circuit-level combining above 64 units is extremely difficult to achieve.) A panel with 100 oscillating units would produce 100 MW of power. If we were limited to 100 orbiting clusters to provide reliable uninterrupted power of 4 TW, then there would need to be 400 panels per cluster. Each panel would have to operate independently: therefore, we foresee two more means of combining power. We see frequency division combining, where a panel operates at 2.58 GHz (for example), and a neighbor operating at a frequency separated by 1 kHz. A further level of combining would be time-division combining, much the same as is achieved with mode-locked lasers. In this scenario, a panel would generate microwave energy in a cavity formed by a reflector and the vacuum of space, and would periodically dump the energy into an Earth-bound beam.

5.2 Panel Architecture

We envision a system that transmits energy to Earth in a microwave beam, formed using spatial power combining to combine the power from multiple transmitters (see Figure 5). Each panel comprises one hundred individual radiators, directly driven by microwave oscillators. The limited number of discrete sources is determined from stability considerations. Also, each discrete source is optically controlled, adapting the circuit configuration for maximum efficiency and achieving self-healing. At the same time, electro-optical modulation injection locks each unit. Opto-electronics will also be used for self-diagnosis and self-healing. Each panel will be powered by its own solar collector, to minimize weight and the losses associated with power distribution. A large number of panels will be grouped in a cluster, and a number of clusters will orbit the Earth, with each terrestrial unit receiving power from just one cluster (although a cluster could serve more than one terrestrial unit). A cluster in low Earth orbit will direct the microwave beam, using electronic steering with phase control of individual oscillators realized by the opto-electronic injection-lock system. A failsafe mechanism would result in a random phasing of the individual oscillators and a diffused microwave beam. This would also be an aid in safely switching power from one terrestrial site to another.

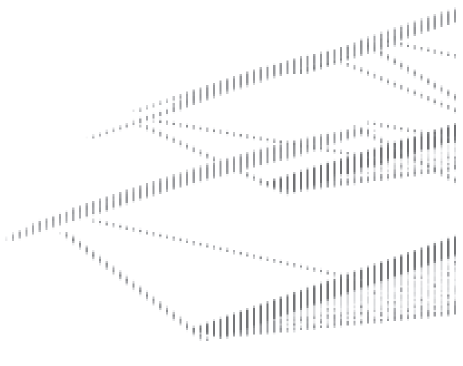

Figure 5a. The microwave beamforming components of an SSP system: a cluster of multiple panels forming one orbiting unit.

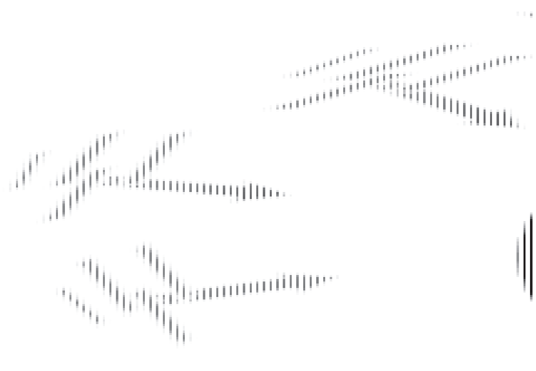

Figure 5b. Multiple clusters per Figure 5a, each directing power at specific terrestrial sites. Oceanic sites could be used for liquid fuel production. Not shown is the solar-collection apparatus.

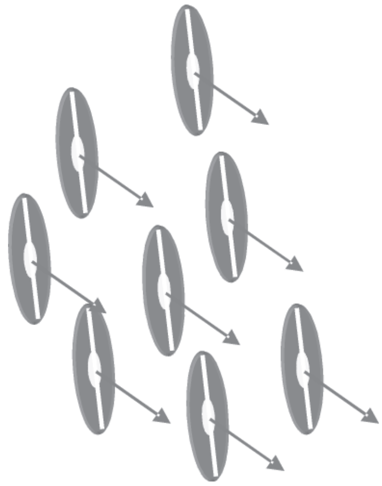

Figure 6a. The microwave beamforming components of an SSP system: a cluster of a multitude of independent sources, each positionally aware of each other, and implementing a distributed phase-locked oscillator control.

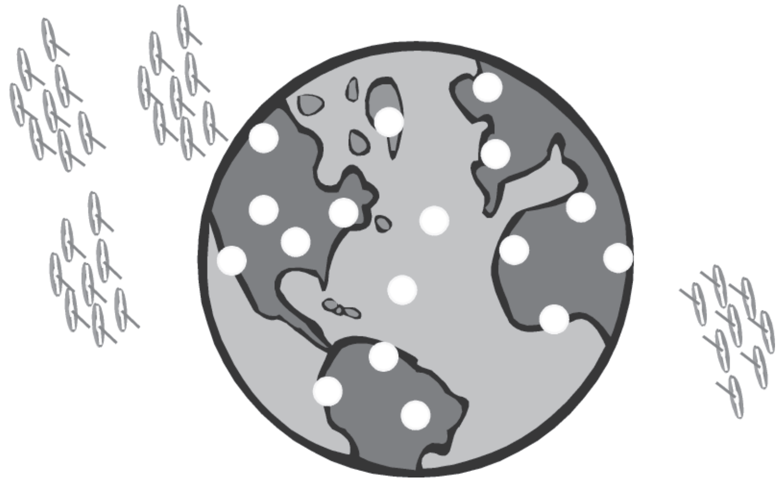

Figure 6b. Multiple clusters of the components shown in Figure 6a, each directing power at specific terrestrial sites.

Efficiency is paramount, and we see the development of microwave electronics that do not need power conditioning (in much the way that RF transmitters in cellular phones are powered directly from the battery). Ideally, there would be no dc/dc converters or voltage regulators in the system. Opto-electronic control will present optimum microwave circuit conditions, and will enable efficient harmonic control without using output filtering.

This system design has another attribute. A system could be fielded with just one panel per cluster, with subsequent panels parked as required. The initial panels would not need to use exotic time-division combining. Terrestrial receiving antenna (rectenna) farms would not need to be fully deployed, as the defocusing mechanism would enable microwave power to be directed away from the Earth during non-receive periods. As we rely on opto-electronic sensing and control of the panels rather than array-level combining (through coupled neighbors) with structure-determined dimensions, even a panel could evolve over time, with additional segments subsequently linked into position, or removed from service for maintenance.

5.3 Point Architecture

Figure 6 shows an architecture similar to the panel architecture, but now the system is composed of a large number of point sources. The concept here is that of minimizing the transfer of power via dc current, and using microwave radiation to achieve power distribution. Each unit contributes to the evolving beam. We envision a system where each unit radiator has intelligence and is position-aware of all other components, including other unit radiators of the system. The system is not arranged in a plane, but in three-dimensional space with laser positioning, for example, precisely locating each radiator and adjusting the optical locking reference appropriately. Even a supposed planar arrangement cannot be assumed to be sufficiently planar for array-combining purposes. We suppose that in the next two decades, there will be great developments in the engineering system complexity that can be handled.

6. Electro-Optics for System Diagnosis, Optimization, and Beam Control

There are four main diagnostic and control measurement functions that need to be addressed, as enumerated below. Together, they demand a novel approach to the characterization of RF signals, one that will allow amplitude, phase, and frequency to be distinguished separately, at different locations, and then utilized to ensure proper operation of the power-combining array. The four measurement categories can be summarized as follows:

1. Determine amplitude, phase, and frequency in the near field of individual unit-cell radiators, and compare with expected values in order to verify correct initial beam strength, beam direction, and injection-locking frequency. Incorrect values would prompt the creation of error signals that would be used in a feedback loop to adjust array gain, injection-locking-modulation phase, or injection-locking-modulation amplitude (see Figure 7).
2. Measure the same quantities at crucial points in the far field of the array, in order to confirm that the combined power has formed as expected.
3. Investigate cross-talk effects from neighboring unit cells and their influence on injection locking.
4. Monitor microwave radiation in the proximity of crops that may be part of an environment that is impacted by high-power microwave radiation from space. Electric-field and temperature can be sensed simultaneously, with the same probe, under unusual and harsh conditions,

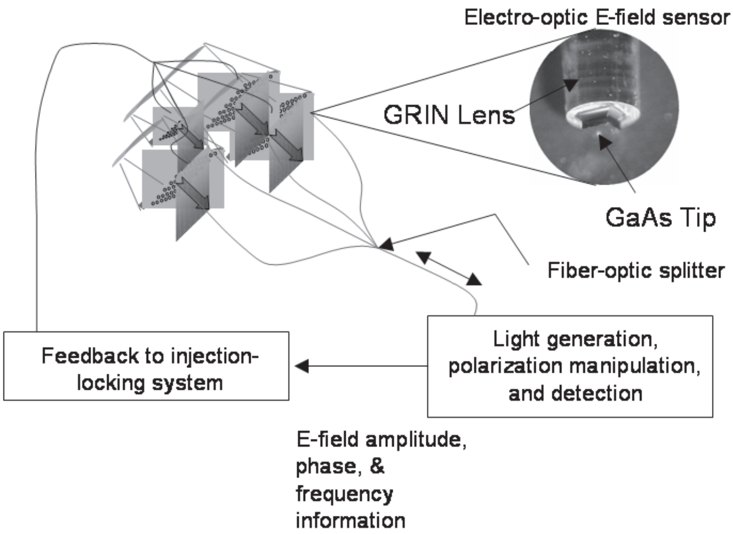

Figure 7. A cluster with an opto-electronic sensor and control system for phase control of oscillators, self diagnosis, and self-healing. The insert shows a low-perturbation field sensor on the end of a fiber that we have developed. This is an electric-field diagnostic-testing and array-correction concept. An optically-based field-sensing system will monitor the amplitude and phase output of the unit cells of the array, in order to maintain the power and directional integrity of the array.

such as in high humidity, within dense foliage, and under the surface of the soil.

Electro-optic (EO) field sensing has attracted attention as a beneficial near-field measurement technique that can extract a great deal of information from micro- and mm-wave integrated circuits [6], antennas, and complex arrays [7]. Electro-optic field sensing was initially suggested as a diagnostic tool for antennas and arrays using free-space-propagating optical beams around 1994 [8]. However, the coupling of a laser pulse train and electro-optic sensors to fibers would be essential for networking a large number of sensors that are spread apart by perhaps hundreds of meters. While it will not be necessary to scan an electric-field sensor and extract maps of electric field from the injection-locked unit cells of a high-power microwave array, it will be desirable to utilize the same laser as a sampling-beam source for all of the individual, fixed electro-optic probes monitoring the array. In sampling the field from different unit cells, the input laser beam will then be split among the fibers leading to the various probes, so that one near-field probe per unit cell and one far-field probe per array can be accessed by the same optical source. This will require a fiber-optic, voltage-controlled switch, which transfers light quickly among different fibers leading to the electro-optic sensors. It will also need to allow light to pass in both directions, so that the modulated light returning from the electro-optic sensors is routed to the photodetector. In the first-generation system, a rotating mirror or a translating fiber-holder can be used to demonstrate flexible access for one laser to a variety of probes. In subsequent embodiments – and certainly by the time such a system was implemented in space – commercial fiber-optic switches or the application of optical MEMS (micro-electromechanical systems) for steering the beam with small, moveable mirrors will be required.

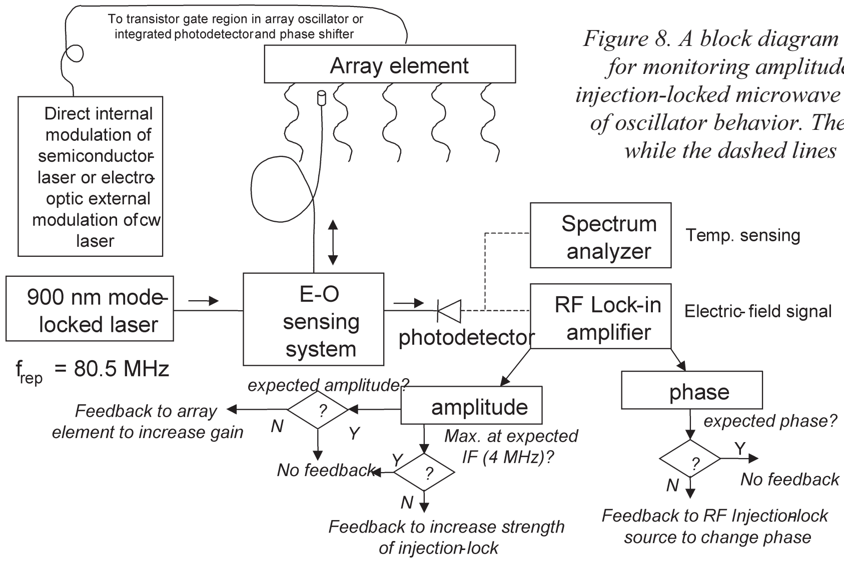

Figure 8. A block diagram of a proposed electro-optic technique for monitoring amplitude, phase, and frequency of a single, injection-locked microwave power source, and subsequent control of oscillator behavior. The red lines represent the optical fiber, while the dashed lines indicate an electrical connection.

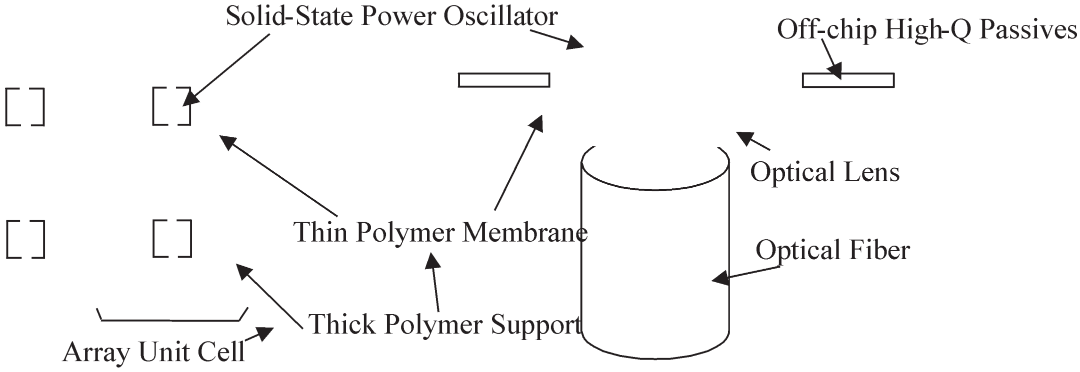

Figure 9. A proposed polymer membrane fabrication technology.

A schematic of the optical and electrical system that could be used to monitor and control one radiating microwave power element is shown in Figure 8. Since the microwave frequency to be used is set at a value of 2.58 GHz – and if we wish to set our IF at 4 MHz – it will be necessary to adjust the laser repetition frequency to 80.5 MHz by slightly decreasing the cavity length, so that we can use the 32nd harmonic of 80.5 MHz (i.e., 2.576 GHz) as the "local oscillator" frequency. This should be easily accomplished, due to the presence of a piezoelectric translation stage on the end mirror of the Ti:sapphire laser used as the mode-locked optical source. If the laser repetition frequency varies from 80.5 MHz, an error signal will be generated, and the cavity will be returned to the correct length. In order to maintain a high degree of synchronization between the laser and the electric-field signal it will be used to measure, both the 80.5 MHz and the 2.58 GHz microwave signal (that will either directly or externally modulate the injection-locking laser) will need to be synthesized from the same 10-MHz RF signal. This 10 -MHz reference signal is available from the same driver that controls the laser piezoelectric translation stage.

In addition to the near-field measurements, the same optical system will be employed to sense other electric fields at a variety of locations. For instance, as the probe is moved increasing distances from the radiating plane it will enter the far field of the antenna. By strategically placing fiber-coupled sensors in the far field, we will be able to detect the direction of the beam's propagation in a fashion that would also allow confirmation that a combined, high-power space-based beam was proceeding towards its target location.

7. Microwave Beam-Forming Structures

A critical aspect of the beam-forming structure is low weight. Membrane polymer processing technology [9, 10] provides a low-weight functional package for the array, as shown in Figure 9. It consists of the following functions: a lens for optical wave-guiding, which is de-embedded in this structure (the lens focuses the light on the high-speed opto-electronic injection-locked oscillator); a thin polymer membrane that supports the solid-state power oscillator and also provides off-chip high-Q passive elements; and a thick polymer support structure that can be partially metallized to reduce coupling between array elements.

8. Electromagnetic Modeling of Large Arrays for Space Applications

The analysis, modeling, and design of quasi-optical power-combining systems has much in common with an SSP system. The theoretical understanding of the operation of spatial combiners started with the open-cavity resonator structure, which contained a planar array of filamentary current sources radiating into a plano-concave open resonator (spherical reflector) [11-16]. The analysis was based on the Method of Moments with the electric Green's dyadic obtained for the open-cavity resonator. The Green's function was derived in terms of paraxial and non-paraxial components, where the paraxial components described the quasi-optical modes. Later, this analysis was extended to the development of a dyadic Green's function for a quasi-optical grid amplifier system with lenses [17-19]. An electromagnetic model of this structure incorporated full electromagnetic coupling, and integrated the EM model into a circuit-level simulation of the amplifier array elements [20, 21]. Similar results have been obtained with other types of power-combining structures, in particular, waveguide-based amplifier arrays [22-32]. The amplifier arrays were placed in an oversized layered waveguide in close proximity to receiving/ transmitting horn antennas. The electromagnetic modeling environment for the complete characterization of waveguide-based spatial-power-combining systems was based on the Generalized Scattering Matrix (GSM) approach, to obtain an overall response of the system by cascading the individual responses of simple modules [22, 23]. The integral-equation formulation for planar antenna arrays with dyadic Green's functions obtained for a multilayered waveguide was discretized using the Method of Moments projection technique [22-27]. This resulted in a complete characterization of finite antenna arrays operating in a waveguide environment, and modeling of all possible resonance, coupling, multimoding, and surface-wave effects. Recently, a global model was

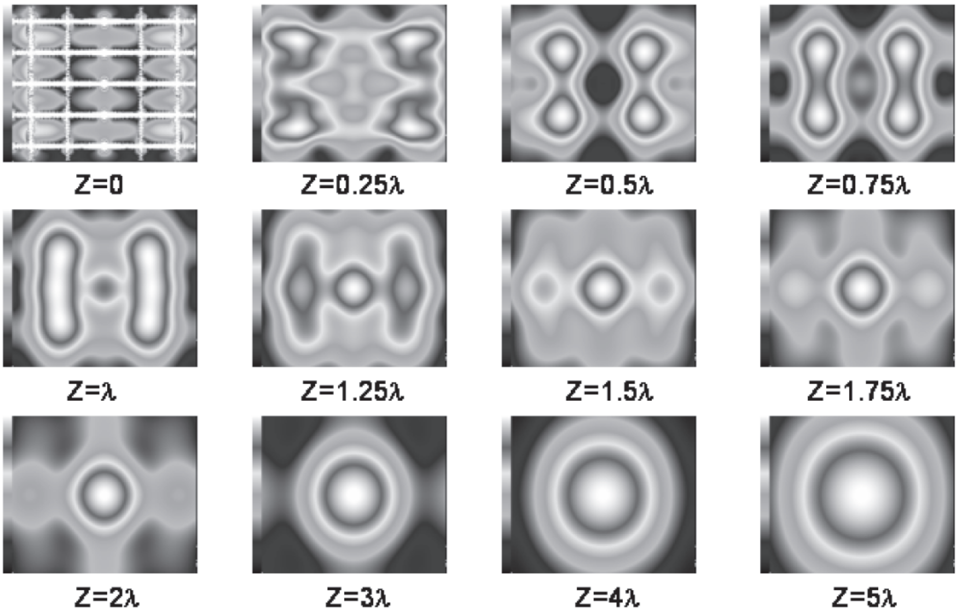

Figure 10. A microwave beam evolving above an antenna array. The plot shows the magnitude of the E field at different distance, z, from the square grid array.

developed for an aperture-coupled patch amplifier array in a multilayered waveguide [32]. This included an interacting electromagnetic-electric-thermal simulation of the power-combining system.

We believe that this integrated level of modeling is essential if we are to understand the dynamics and design criteria of the SSP microwave radiators. For example, we have considered a 5 × 5 grid array with circuit-level models of the active devices. We were able to predict edge and coupling effects, as shown in Figure 10. One issue that is clear here is that edge and coupling effects are important. In this case, the beam produced was not circular due to the nonuniform distribution of charges on the array, which can only be predicted based on the circuit-field interactions and the influence of edge and coupling effects. As was shown in the section on SSP architectures, coupling effects limit the size of the array, as even low-level coupling seriously affects the radiated uniformity.

9. Conclusion

Capturing solar power in orbit and beaming it to Earth will be the grandest engineering endeavor of the 21st century. We envision the generation of enormous (terawatt) power levels, using solid-state sources arranged in arrays of devices that are opto-electronically controlled to produce a microwave beam that can be safely directed towards terrestrial receptors. The performance and capabilities of discrete technologies will increase tremendously over the next three or four decades (when SSP systems should be economically feasible), and will be driven both by unrelated technology pulls and by the identification of necessary technologies. Even with a few orders-of-magnitude increase in the power available from solid-state sources (or even alternative devices), the ability to generate terawatt power levels will demand innovative developments in combining power in an inherently safe manner, beaming the power to Earth from low-Earth orbit, and in safe and reliable beam steering using structures that are adaptive, self-monitoring, and self-healing. Evaluation of the effects of microwave beaming on life needs careful exploration at this early stage of research to frame development and garner the political and public support for future developments.

10. Acknowledgements

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