DIRECT CONVERSION FOR SPACE SOLAR POWER

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DIRECT CONVERSION FOR SPACE SOLAR POWER

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LIST OF SYMBOLS AND ABBREVIATIONS

SSP	Space Solar Power
DC	Direct Current
AC	Alternating Current
EM	Electromagnetic
RF	Radio Frequency
SAW	Surface Acoustic Wave
Laser	Light Amplification by Stimulated Emission of Radiation
Maser	Microwave Amplification by Stimulated Emission of Radiation

SUMMARY

Space Solar Power (SSP) is a powerful yet nearly untapped resource with revolutionary potential. SSP systems currently have several roadblocks to their implementation. With the technology in use today, converting solar power to useable energy is inefficient, the required converters have a large mass per unit power, and launching those converters is expensive. More fundamentally, in all current SSP systems, energy is generated in the form of a direct current before being converted again into whatever form is necessary. In addition to the large mass per unit energy of this conversion equipment, such conversion involves significant efficiency losses, further resulting in the prohibitive cost of launching these converters into space. If techniques could be discovered for converting broadband sunlight directly to a useable narrowband application dependent frequency, many fundamental breakthroughs in aerospace endeavors can be achieved.

This project studied a large number of options that might lead to direct conversion. Those technology options were analyzed according to which would warrant further exploration from the point of view of aerospace systems applications and possible power per unit mass. Based on these technologies, several advanced concepts were considered. It is also important to make an estimate of the possible power per unit mass that could be achieved with each concept, so that architecture developers can proceed with the development of applications enabled by direct conversion technology. Accordingly, estimates of the possible power per unit mass of potential direct conversion

systems were made, and future applications that would benefit from those direct conversion systems were identified.

Three possible concepts were developed. These concepts include: a shocked photonic crystal system; a solar pumped maser based on naturally occurring astronomical masers; and an optical antenna array with central signal processing. The optical antenna array and the solar pumped maser were estimated to have a specific power approximately 15.0 and 10.8 times greater, respectively, than conventional photovoltaic systems.

Several applications were identified that would benefit from direct conversion systems. The most obvious would be an orbital SSP grid. In addition to the rise in specific power, and therefore resulting cost savings, direct conversion would enable the output of higher frequency transmissions with less beam spreading and subsequently smaller ground based infrastructure. Electric propulsion systems would also benefit directly by drastically reducing on board mass both from higher specific power and direct conversion to the necessary ionization frequency. Additionally, the inclusion of solar sails opens possibilities for possible hybrid designs incorporating integrated propulsion and energy collection.

As with any sufficiently advanced concept, it is impossible to be certain where the problems, roadblocks, and successes may lie in the future. This said, this project has shown that several direct conversion concepts warrant further exploration and study based on their revolutionary potential. They are a true shift from the paradigm of conventional SSP.

CHAPTER 1

INTRODUCTION

Space Solar Power (SSP) is a powerful yet nearly untapped resource with revolutionary potential to address the energy needs and environmental concerns of humanity. SSP systems currently have several roadblocks to their implementation. With the technology in use today, converting solar power to useable energy is inefficient, the required converters have a large mass per unit power, and launching those converters into high orbits is prohibitively expensive. More fundamentally, in all current SSP systems, captured energy is converted to direct current (DC) before being converted again into whatever form is necessary. If techniques could be discovered for converting broadband sunlight directly to a useable narrowband application dependent frequency, many fundamental breakthroughs in aerospace endeavors can be achieved.

This study will explore, propose, and analyze possible concepts that would provide great benefits to SSP systems through the use of direct conversion. The process and goals include:

I. Identify Applicable Technologies: Explore several options that might lead to direct conversion. No single solution might be the answer, so several types of conversion technology must be explored.

II. Develop System Concepts: Following the analysis of applicable technologies, a few space solar power direct conversion concepts will be developed.

III. Analyze for Aerospace Applications: In preliminary review of this field, it is evident that little attention has been paid to high power/low mass systems. Even after finding a technology, and proposing a related concept that would warrant further exploration, it must be looked at from the point of view of aerospace systems applications and possible power per unit mass. The key is to develop estimates, however rudimentary, of the possible power per unit mass achievable with each concept, as this is the most significant metric for aerospace systems intended for launch into orbit.

IV. Estimate Specific Power: Provide a justifiable estimate of power per unit mass of future direct conversion systems. This will further enable the development of concepts involving direct conversion simultaneously to the development of direct conversion technology itself.

V. Future Applications: Identify possible future applications that would benefit from direct conversion technology.

CHAPTER 2

LITERATURE REVIEW

There exists significant background information as to the general concept, advantages, and problems involved with historical SSP systems. This background information is necessary to establish the rationale for developing direct conversion systems. There are also many natural and technological analogs to the direct conversion process. These technologies will be adapted for use in, and the development of, SSP direct conversion concepts.

2.1 Historical Space Solar Power Systems

For decades, many space solar power (SSP) concepts have been proposed that show great potential for revolutionizing energy production on Earth.[1-6] SSP in general has several advantages. As fossil fuel supply dwindles, and concerns about pollution and global warming heighten, the clean, plentiful energy from the sun becomes increasingly attractive. Satellites in high orbits receive intense solar energy around the clock, regardless of weather or seasonal variations. Additionally, the essentially infinite area of space is available for solar arrays, in contrast to the relatively limited area on Earth. Finally, in some SSP concepts, the collected power can be transmitted to multiple sites around the Earth.[4-6]

2.2 Roadblocks to Space Solar Power

Despite the great potential, several practical and technological roadblocks have prohibited the implementation of SSP concepts. The two most critical problems, which play into and further cause other areas of difficulty, are the nature of current photovoltaic technology and high launch costs. Present-day photovoltaic technology is theoretically limited in its achievable efficiency, and produces its useable energy in the form of DC only, which is inefficient to transmit over cables and unsuitable for wireless beaming. The production of DC also means that any SSP concept must also incorporate heavy converters to transfer the collected power to Earth. This power transfer is commonly accomplished through radio or microwave beaming, after conversion to alternating current (AC).

The problems with conventional photovoltaic technology coupled with high launch costs define the guidelines around which SSP direct conversion systems can be designed. The system must convert broadband radiation directly to low frequency narrowband radiation for transmission, and it must have a low mass per unit power. In addition, this output frequency must be tailored for maximum atmospheric transmission. A previous deterrent to higher frequency space transmissions is the availability of atmospheric transmission windows. This is a problem in that generally lower frequency implies higher beam spreading, which requires a huge ground antenna as a receiver.

2.2.1 Current Photovoltaic Solar Cell Technology

The current method for solar power generation is based upon essentially the same technology as the original silicon photovoltaic cells. These cells work by using photons to excite electrons in a semiconductor to produce an electric current. This method is fundamentally limited for several reasons. Sunlight is broadband energy and only photons with certain energy can dislodge an electron. To become part of the circuit the electron must jump a band gap specific to the material. All the energy put into jumping this band gap is converted to waste heat. Because of this, traditional photovoltaic cells already have around a 55% theoretical efficiency loss.[7]

In addition, photovoltaic cells produce only direct current, and consideration must be taken that many space applications require electromagnetic (EM) radiation or other waveform currents. This re-conversion system would require extra mass and add an extra factor for efficiency loss, compared to something that already has an outgoing alternating current. When the initial power is generated from free space solar radiation, and the end goal is another form of radiation for power transfer, it is logical that complexity and mass could be saved by directly converting.

Table 1 specifies a range of solar cell performance values from literature. It is important to note that this is simply a characteristic range of available solar arrays for space use. There may be specific, newer technology, examples that may be outside this range. However, this range serves well for estimation purposes. Additionally, new photovoltaic concepts that may provide higher performance would theoretically still have the same problem of generating power in direct current which would need to be converted again for transmission.

Table 1: Space Rated Si and GaAs Solar Array Performance Survey[8-10]

Beginning of Life Values	Minimum	Maximum
Specific Mass (kg/m^2)	0.23	2.88
Efficiency	0.09	0.26
Specific Power (kW/kg)	0.12	1.01
Specific Power (kW/m^2)	0.12	0.36

2.2.2 High Launch Costs

Probably the most critical roadblock to a presence in space is the high launch costs. Because of this, when dealing with SSP systems the specific power of a system is a make or break metric for the success of the system as a whole. This can be magnified even further to the point that a SSP satellite with a given high specific power may not be able to recuperate its launch costs from power sales over its lifetime, therefore making it cost prohibitive. This launch cost problem is also further exacerbated by conventional re-supply and stabilization problems.[11] SSP satellites in orbit will continually require fuel and navigation to correct perturbations to their orbits due to solar pressure, orbital decay, and other destabilizing factors. Thus the launch cost for launching additional propellant must also be taken into consideration, perhaps further decreasing the necessary specific power. Some current prices for low earth orbit launches are shown in

Table 2.[12-14] It is important to note that the cost of launching to geosynchronous Earth orbit, which would be applicable to certain SSP concepts, is generally greater that launching to LEO by a factor of two or more.

Table 2: Launch Cost Survey[12-14]

	Payload LEO (kg)	Cost ($M)	Year	Specific Cost ($K FY07/kg)
Ariane 44L	22400	125	2000	3.1
Atlas V	12500	138	2004	11.1
Delta II	5089	60	1999	97.0
Delta IV Medium	8600	133	2004	16.7
Saturn V	118000	431	1967	3.1
Space Shuttle	24400	245	1988	83.6
Titan	21680	432	1999	6.5
Average			2007	31.6

2.2.3 Atmospheric Transmission

As evident in Figure 1, there are several frequency ranges where a large percentage of transmission energy is lost in the atmosphere, mainly due to absorption by water vapor. This is particularly important to this project in that the output frequency of any viable system must be tailorable. It also defines the target frequencies for which the direct conversion concepts will be designed.

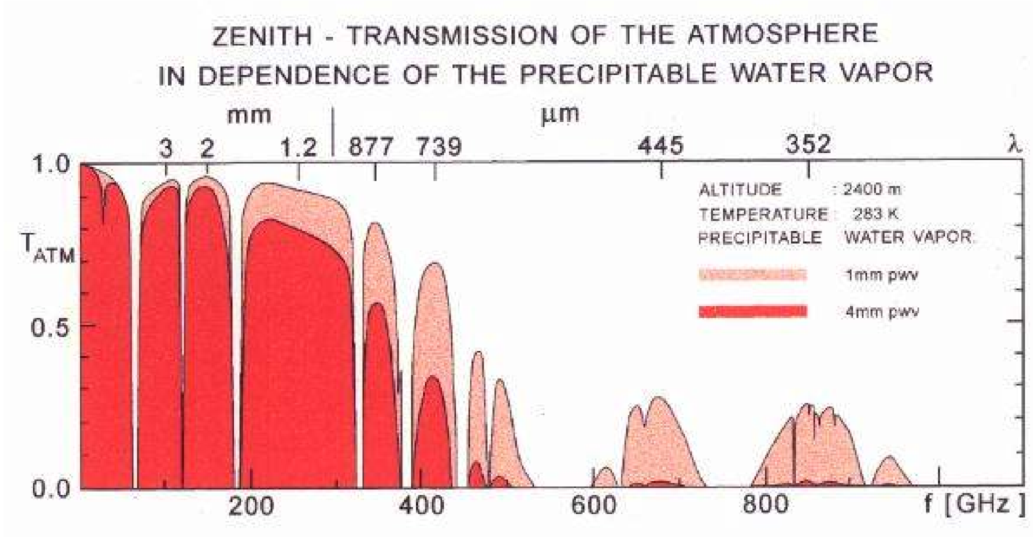

Figure 1: Atmospheric transmission as a function of frequency[15]

2.3 Technologies for Direct Conversion

Several technologies have been identified as potential candidates for a direct conversion system because of similar natural mechanisms that provide frequency shifting and bandwidth narrowing. The direct frequency conversion from broadband radiation to low frequency narrowband radiation could lower complexity and mass per unit power of an SSP system. The specific natural and technological analogs that were analyzed in this project include, signal processing solutions, interactions with rapidly ionizing plasma, nanofabricated optical antennae and rectennae, optical resonators, shocked photonic crystals, solar pumped lasers and masers.

2.3.1 Signal Processing Solutions

Signal processing solutions would initially seem to be the most obvious solution to frequency conversion, but unfortunately none of these by themselves are very efficient or much of an improvement from the existing photovoltaic plus microwave transmitter system. Generally they are intended for low power applications, where issues such as low conversion efficiency or heat generation do not affect their use. These signal processing devices are common in all sorts of electronic devices used in every day life. A perfect example is a travel AC frequency converter. This might convert 120 Hz power to 240 Hz power. However the conversion efficiency is poor, and much energy is lost through heat. All following devices are relatively common circuit configurations, of extrapolations there upon, and therefore will not have specific citations. These examples were generated through discussions with electrical engineering professors, and are important background to rule out certain direct conversion possibilities.

Assuming that broadband sunlight could be coupled to an antenna, a configuration of diodes in the form of a mixer powered by an oscillator could achieve a frequency shift. The output would be the sum and difference of the input and oscillator frequencies, one of which would need to be filtered out. The oscillator would also require its own power source. Aside from the need for an undetermined quantity of power to be supplied to the oscillator, this system would be inherently inefficient due to the incorporation of a filter, and there is no obvious way to tailor this to a broadband input.

Other options include modulating the input signal with a radio frequency (RF) signal, which is very inefficient. In addition there are many products on the market today that provide a small range of frequency translation such as SAW filter circuits, but again these have a very low translation range and efficiency.

Tube, Cyclotron, and Magnetron type devices also fall into this category. These devices fundamentally work by producing an EM field by crossing a magnetic field with electrons produced by a DC power supply from a cathode to an anode. These devices are the current and most common way of producing microwave radiation. There are several problems however with this setup in relation to SSP systems. These problems include mechanical tolerances, scaling problems, quality decay over time, weight, impedance mismatching, and breakdown fields. Most of these problems get amplified as higher frequency output is attempted, further decreasing the efficiency. These higher frequency issues would be especially pertinent to this application considering the success of many of the applications depend on limited beam spreading during transmission which is minimized at higher frequencies. In addition the whole concept of direct conversion strives to eliminate just this type of DC to AC step.

An alternative method of signal processing may be useful to direct conversion concepts. Assuming that high frequency broadband current could be analyzed in real time, signal processing solutions could potentially reconstruct the high frequency part of the signal into a higher intensity low frequency wave. This idea is similar to that of a Fourier approximation, and should be theoretically possible as per the Nyquist–Shannon sampling theorem. The Nyquist–Shannon sampling theorem specifies that a wave can be characterized with sampling at twice the wave frequency. Although potentially difficult because a system would be dealing with THz radiation, it should be theoretically possible. Such a concept, although advanced, would work well with optical antenna array systems. It should be noted here that the above need not be done with active digital signal processing using computers. Optical Fourier Transform elements (a prism separating various colors spatially is a simple example) are available, and can separate broadband sunlight into discrete, narrow bands with high efficiency. Reconstructing these into a narrow band in a frequency range far below that of visible light, is what poses the challenge.

2.3.2 Rapidly Ionizing Plasma

Studies have shown that an interaction between EM radiation and rapidly ionizing plasma can cause a simultaneous frequency up-shift and down-shift.[16] This concept seems particularly applicable. However, it would be difficult to develop a viable concept considering that a large amount of energy would be required to continually re-ionize the plasma.

2.3.3 Nanofabricated Antenna

EM radiation of lower frequencies (microwave and lower) has traditionally been generated and then transmitted through antennae in the classical physics sense. EM radiation of higher optical frequencies has been more difficult because of decreasing size to the realm where quantum mechanics must be taken into consideration. Developing a beam in the optical frequencies has been accomplished by lasers but is somewhat inefficient due to the population inversion. If nanofabricated antennae were possible perhaps radiation collection and emission could be enabled in the classical sense. This is theoretically possible considering that ITN Energy Systems asserts that this can be done with its optical rectenna with additional nanofabricated rectification components.[17] Although ITN is only attempting it in the collection direction by absorbing the radiation, it should be theoretically possible also to symmetrically re-emit it in a similar fashion with tailored geometry for the emission of a focused beam. A nanofabricated antenna such as this should be given focus as an initial step without rectification. Just coupling broadband radiation to an antenna array would be an important breakthrough in itself. This is important because it allows concepts to move away from traditional means of microwave transmission such as cyclotrons and gyrotrons. Instead, assuming the signal has already been converted to the necessary frequency and that nano-fabrication techniques become practical in the near term, it can be transmitted in radiation form by a simple and low mass mechanism.

2.3.4 Optical Resonator

Optical resonators take broadband light and convert it to an amplified narrow band. Resonators have a clear benefit to applications needing EM radiation amplification, but also might be used in direct frequency conversion. There is a Jet Propulsion Lab proposal for a toroidal or disk-like optical resonator made of an optically non-linear material for parametric frequency conversion.[18] One of the main benefits of resonators in general is the simplicity and low weight. A simple resonator can be made out of two parallel plates of reflective material. The broadband frequency will approach a frequency proportional to the length of the resonating cavity, along with the corresponding sub-harmonics. However, resonators in general have the critical drawback that they work by amplifying the resonant frequency and rejecting the non-resonant frequency. This non-resonant frequency rejection thereby implies an energy and efficiency loss.

2.3.5 Shocked Photonic Crystals

In 2003 a group at MIT used a simulation to show that non-relativistic reversed Doppler Shift with near 100% efficiency in light occurs when light is reflected from a moving shock wave propagating through a photonic crystal, as shown in Figure 2.[19]

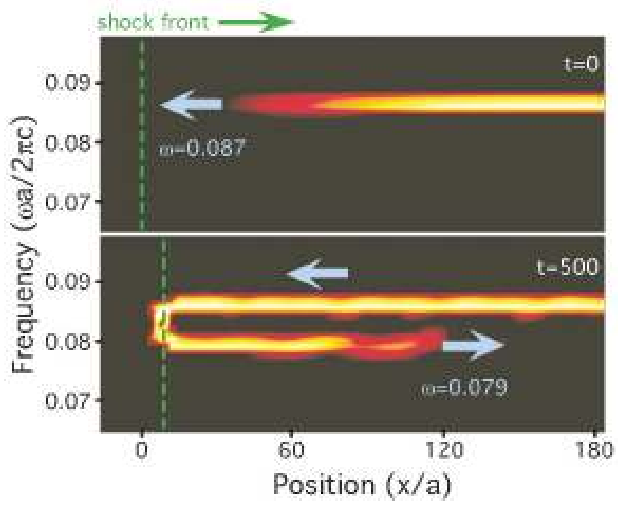

Figure 2: Simulation of Frequency Shift in a Shocked Photonic Crystal by Dr. Joannopoulos[19]

The overall concept of photonic crystals and their applications is described in Dr. Joannopoulos' book "Photonic Crystals: The Road from Theory to Practice."[20] He explains that photonic crystals, which can be fabricated on the nano scale and through the creation of the correctly placed defects and tailored geometry, can create perfect resonant cavities or waveguides depending on the design of the crystal structure. The efficiency of such devices largely depends on the quality of fabrication, but simulations show near 100% efficiency in theory.[19-21]

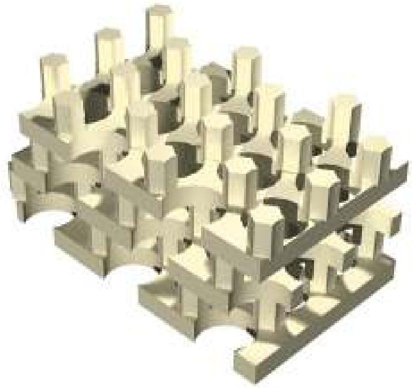

Figure 3: Model of 3D Photonic Crystal by Dr. Joannopoulos[19]

The system potentially offers tunable pulse rate and carrier frequency based upon artificial band gap size and can narrow the bandwidth of the incident radiation. This is exactly the effect that is desired for direct conversion. After a significant amount of iterations light could be dramatically shifted in frequency. Additionally, this system has high theoretical efficiencies, and it was proposed that a similar system be used in micro-electrical-mechanical devices.[19-21] This technology will be utilized and further described in the direct conversion system concepts.

2.3.6 Solar Pumped Lasers and Masers

Respectively, the acronyms stand for Light or Microwave Amplification by Stimulated Emission of Radiation. Both function in essentially the same way. Energy from the pumping mechanism, which is solar radiation in this case, causes excited states in the molecules of the gain medium. Enough excitation causes a population inversion and the emission of EM radiation as the particle falls to a lower energy state. This transition can be excited by collisions with photons of the same energy as the difference between the two states, so that each successful collision generates a photon at the same energy and phase as the colliding photon. This amplification of the beam can be increased by passing the beam multiple times through the cavity containing the lasing medium, as occurs in a resonator. The net gain is the balance between the release of energy at the right frequency during collisions with the stimulating photons, the losses due to absorption of the photons at cavity walls or by molecules without emission, and spontaneous emission at random phase. At high intensities, the spontaneous emission is negligibly small compared to the absorption and the stimulated emission. While present-day ion, and metal vapor lasers use electronic state transitions, masers use ro-vibrational transitions. These transitions between two rotational energy levels associated with different vibrational energy levels are also used in high-power gas lasers with mediums such as carbon dioxide, water, and nitrogen. A critical argument can be made that because of scale, maser transitions should be much easier to control and therefore potentially more efficient. Also, empirical evidence on lasers shows that the efficiency achievable with a laser is much higher at lower frequencies, such as infrared, than in the visible or ultraviolet range. This observation suggests that masers operating in the 100 GHz regime, should in principle be capable of higher efficiencies than those demonstrated with lasers. This concept is well suited for direct conversion in that a broadband energy source can be re-emitted non-linearly in a narrowband form.

Natural analogs exist in the form of astronomical masers. Astronomers for some time have been discovering bright spectral emissions created by naturally occurring interstellar masers.[22-23] This naturally occurring phenomenon is particularly suitable to the application of direct conversion. Essentially a low density molecular gas is excited by collisions from photons and molecules from a broadband radiation source and emits an intense narrowband in the microwave region. Intensity and frequency of the emission varies nonlinearly with the pumping radiation.

The big drawback is that there is a fundamental inefficiency associated with population inversion. The photon-molecular interactions that keep the population in the correct energy state for continual maser emission are somewhat unpredictable, which makes it difficult to have 100% efficient use of the incoming radiation. Additionally, a stable population conversion cycle usually contains three or more sub-transitions, which could present a potential problem for keeping a medium in a uniform state, and producing a narrowband emission. However, the efficiency losses described above would take the form of thermal energy, and could therefore be possibly recycled through another energy collection mechanism such as a heat engine.

Despite the potential problem of inefficiency there are several previous concepts which show decent efficiencies from solar pumping. In 1963 Z.J. Kiss, H.R. Lewis, and R.C. Duncan Jr. published a paper entitled “Sun Pumped Continuous Optical Maser.”[24] Although this experimental efficiency is low and the device is different conceptually, it is an example of maser system feasibility. Another more recent system concept, presented at the Space Technology & Applications International Forum conference 2005, was Taku Saiki’s “Development of Solar-Pumped Lasers for Space Solar Power Station.”[25] It describes a solar pumped solid state Nd/Cr:YAG ceramic laser with optical to optical conversion efficiencies up to 38%.[25] The most promising thus far is a proposal for a mid-range infrared continuous wave laser from DARPA that cites a 50% wall plug efficiency.[26] These concepts will also be investigated and incorporated into later design concepts.

2.3.7 Optical Rectenna

An optical rectenna is an antenna that couples with and rectifies optical radiation to DC. Before ITN, in the 1960's W.C. Brown pioneered the field of wireless power transmission with his work on microwave rectennae.[27] He successfully developed a helicopter powered by a microwave rectenna.[27-28] The rectenna demonstrated efficiencies from 85-91%.[27-28] It had directive properties similar to the half-wave dipole in that there was little variation in capture efficiency based on the angle of incidence of the incoming radiation. His design for a light weight and flexible thin film etched circuit rectenna weighed approximately .25 kg/m^2.[28]

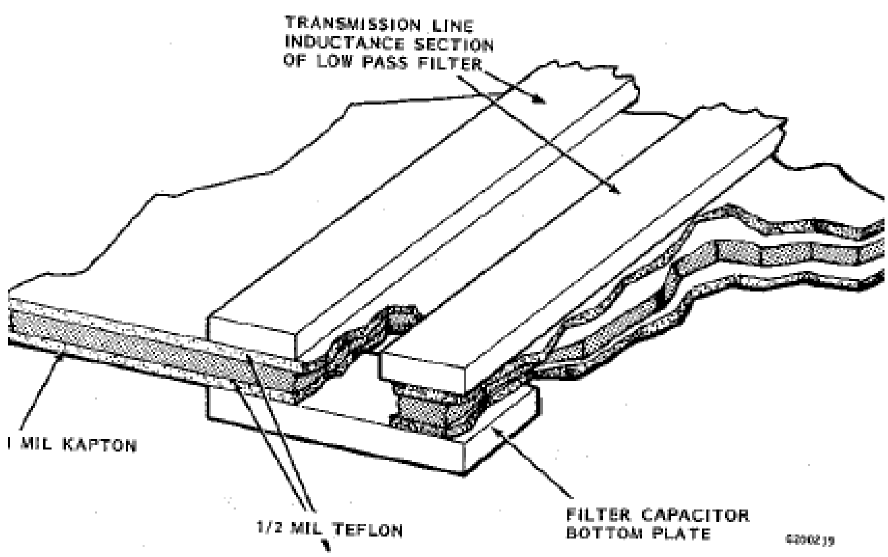

Figure 4: Diagram of W.C. Brown's Thin Film Etched Circuit Rectenna[27]

In 2002 ITN Energy Systems published its work on optical rectennae. The design consisted of an antenna array and a high frequency metal-insulator-metal diode to rectify the broadband field across the antenna to DC power. ITN estimated theoretical conversion efficiencies greater than 85%. For antennae on the optical scale, ITN found that a majority of the energy in the surface modes is carried in the dielectric above the antenna so surface losses must be taken into consideration. Also the antenna must be designed to couple with a complex, broadband waveform. Unfortunately only 1% efficiency was actually achieved during testing which can be attributed at least partially to problems associated with early stages of nanofabrication.[17]

Additionally, according to antenna theory, antenna length will scale linearly with the wavelength of the incoming radiation.[17] The theory is that an antenna array of a certain scale can capture radiation of wavelengths greater than the smallest dipole resolution of the array but no greater than the size of the whole array, much in a manner similar to a Fourier transform. It is believed that a correctly designed and constructed antenna array could absorb solar radiation with 100% efficiency.[17] For broadband solar radiation the antenna would be an array of tiny half-wave dipoles, corresponding to wavelengths of approximately 2-0.3 μm.[17] At this scale the rectenna could also couple with other radiation sources such as albedo encountered by planetary passes or Jupiter's radiation belts. The incident radiation induces a waveform current into the antenna array which would be traditionally converted to DC by a non linear element such as a diode. However, in combination with signal processing solutions and nanofabricated antennae for transmission, the non-linear rectification elements could potentially be removed, in favor of a central signal analysis and conditioning system. This concept will be further explored in later system designs.

2.4 Conclusion of Literature Review

While many of these technologies for one reason or another are not focused upon in the later stages of the project, many still have a fundamental aspect that lends to possibly solving the direct conversion problem and should be kept in mind for future exploration. These technologies will form the basis for three initial direct conversion system concepts. These concepts include: a shocked photonic crystal system; a solar pumped maser based on naturally occurring astronomical masers; and an optical antenna array with central signal processing or optical Fourier Transform processing. These were selected because it is believed that these are the analogs with the best possibility for satisfying the project goal. The metrics for analyzing and rating these concepts are based on satisfaction of the direct conversion criteria, and power per unit mass.

CHAPTER 3

SYSTEM CONCEPTS

After the analysis of possible technologies and natural analogs, the focus of the project has been narrowed to several potential SSP direct conversion system concepts. These concepts include a shocked photonic crystal system, a solar pumped maser, and an optical antenna system. These concepts will be analyzed in terms of power per unit mass. Additionally, these concepts share several features that will be initially discussed.

3.1 General System Components

The following systems share several components that can be summarized independently of the individual system concept discussions. These components include solar sail parabolic reflectors and casings, along with beam focusing mechanisms.

The inclusion of a solar sail parabolic reflector is important in that it can gather a large area of solar radiation at a relatively low mass per unit area. To get an idea of scale: assuming an average solar energy density of 1.37 kW/m^2, a 125 MW solar power satellite at 100% efficiency would need a circular collector over 170 m in radius. A direct conversion structure or medium this large would most likely negate any benefits of the direct conversion itself via excessive mass. A low mass solar sail parabolic reflector solves this problem by focusing down that same collected power onto a smaller area which could potentially accept higher concentrations of energy. For instance, the material has a very high reflectivity while weighting approximately 7g/m^2.[29] Although such a material does not have high stiffness, it is not especially imperative in the absence of gravity. Additionally, the solar sail material could be supported by distributed structural members such as thin beams. The one exception to the implementation of a solar sail reflector would be the nanofabricated antenna concept. This concept, as will be explained in its corresponding section, involves a collection array that is nearly as light as the solar sail collector and probably could not sustain high energy densities.

The concepts that require light to pass through some large cavity length will be encased in a solar sail's high reflectivity material. This material is again selected around the same rationale. The material is light weight, with high reflectivity and doesn't need significant stiffness. Another important feature to mention is that this casing will also function as an unstable resonator. This is important because it increases the distance traveled by the radiation while minimizing the overall length. Additionally, an unstable resonator can be constructed with the correct geometry to cause the radiation to narrow towards a resonant frequency based on the length of the cavity.

All three concepts will also be equipped with some sort of beam focusing mechanism. Whether this is another smaller parabolic dish or a directed microwave antenna array, it is important to have the ability to point the output of a system as a focused beam. It is especially important in devices where scattering of particles or crystals will be difficult to predict.

Additionally, all three concepts will be equipped with some sort of substrate and structural framing. Considering how large most of these devices will be, it is expected that there will be forces present that need to be mitigated. For the concepts where an estimate was made, this was taken into account by historical percentage data obtained from Space Mission Analysis and Design[30] of the dry mass of a spacecraft being an average of 3.3 times the payload mass.

3.2 Shocked Photonic Crystal System

The shocked photonic crystal system is a SSP direct conversion system based off the work of Dr. Joannopoulos[19-21] as discussed in section 2.3.5. The following sections will describe the basic concepts, the estimation methodology, and discuss further realistic considerations for the implementation of the system.

3.2.1 Concept Description

A diagram of the shocked photonic crystal system is shown in Figure 5. The shocked photonic crystal system concept uses a solar sail material parabolic reflector to focus a large collectable area of solar radiation onto the photonic crystals. The light from the parabolic reflector is focused onto a series of shocked photonic crystals. An alternative to a series would be one large photonic crystal with a gradient. This is important because the functionality of a photonic crystal is based upon its internal, atomic level, structure. There must be some sort of matching between the incident radiation frequency and the photonic crystal. Thus in order to preserve efficiency as the band is narrowed and the frequency downshifted, the photonic crystal will need to be changed either serially or as a gradient. The functionality of the interface of the photonic crystal and the solar cell will be similar to a resonator. The light will pass through the crystal once and then bounce back to where it is reflected off a shock. This reflection will iterate to the desired frequency.

The series of photonic crystals will be shielded by solar sail type material. This is important so that there are not losses at the edge of the crystals as the light passes throughout the possibly long length of the crystal structure. The crystals will also need to be shocked as was an integral point to Dr. Joannopoulos' simulations.[19-21] As shown in Figure 5, this requires some sort of dielectric shocking mechanism, and its own power source. The problems associated with this will be discussed in the following sections. Following the transmission through the crystals it is expected that the emission may need to be focused and directed, so some sort of beam focusing dish is included in the concept.

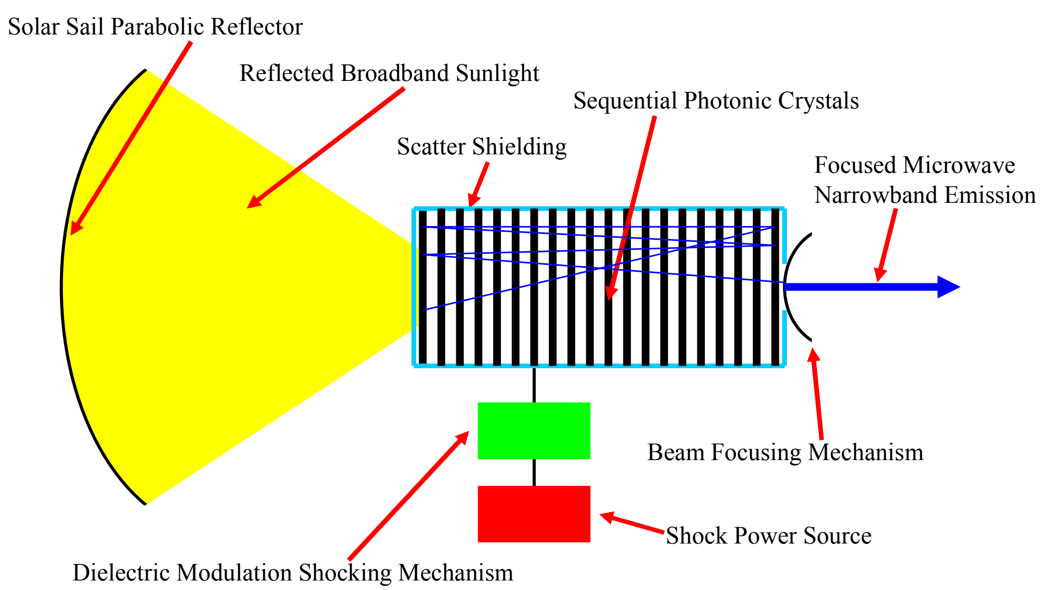

Figure 5: Shocked Photonic Crystal System Concept Diagram

The mechanism through which light will travel and be reflected off a moving shock is not necessarily intuitive. Light will pass into the cavity where it will undergo total internal reflection when it hits the generated shock. The Doppler shift between the incident and reflected light due to the motion of the shock is what causes the frequency shift. The light then bounces off the back wall of the resonating cavity again. This process will repeated continuously until the light is shifted to the desired frequency. It is estimated based on the frequency shift ratios from Dr. Joannopoulos' work[19-21] that it will take approximately 50 shock-radiation interactions to shift the frequency from 500 THz to 100 GHz.

3.2.2 Estimate

The estimation of such a futuristic device has significant complications. First and most importantly is the fact that the Doppler shift in shocked photonic crystal phenomena is at this point observed in simulation only. Realistic efficiencies for each shock-radiation interaction, considering edge effects and nano-fabrication defects would probably be significantly less. This would be amplified by the iterative nature of this process. Other efficiency losses would occur in reflection at the entrance and exit interfaces of the device, and energy lost to heat in the crystal itself.

However, if an estimate were to be made, it could be constructed around several design constraints. First of all, it would be necessary to focus as much light onto the smallest area of crystal as possible. This would be limited by the melting point of the material, how much flux the crystal could accept, and how fast that radiation would pass out. Between the reflections needed, the shock speed, density of the material, and the thermal parameters previously specified, a estimate of the geometry and mass of the cavity could be created. If the previous parameters could be defined a viable estimate could possibly be made.

3.2.3 Implementation Analysis

In addition to the problems listed in the estimation section, there is a theoretical problem involving the pulsed nature of this concept. It seems unlikely that all the light will be able to be fully converted through interactions with a shock simply because the radiation source is constant, and the shock creation and interaction is transitory. However, perhaps a solution to this and other problems could be found, through storage in a resonator or some other mechanism.

Despite these problems, the fact that there is a simultaneous bandwidth narrowing and frequency shift shows that this concept is worth further study. There are several applications where this could be vastly superior to current conventional methods. Photonic crystals in another form could also potentially be utilized for a SSP concept in other facets such as sharp angle wave guides[20] among a whole other array of uses. However, in comparison to other options, this concept is not as effective considering the resulting probable high weight and effective lower efficiency. The ultimate answer is that the further nanotechnology fabrication progresses, the closer actual efficiencies from experimentation may approach simulated values.

3.3 Solar Pumped Maser System

The solar pumped maser system is essentially an artificial analog to a naturally occurring astronomical maser. Astronomical masers are generally caused by the interaction of interstellar light and a low density gas cloud around a star or supernova.[22-23] The following sections will describe the basic concepts, the estimation methodology, and discuss further realistic considerations for the implementation of the system.

3.3.1 Concept Description

A diagram of the solar pumped maser is shown in Figure 6. As can be seen, the broadband free-space solar radiation is again focused down onto the direct conversion medium. In this case the medium is contained in a long cylindrical resonator, covered and encased by solar sail material. This casing is very important in that it will contain the unpredictable emissions from the radiation-molecule interactions and converge them towards the resonant frequency of the cavity. The medium will be a low density molecular vapor. For this concept the vapor was selected as SiO, because of the transitions near our desired frequency output of 100 GHz, as can be seen in Table 3. This is one of the benefits of the solar pumped maser system, in that different mediums could be selected for applications with different desired frequencies. Again the output will also be controlled with some sort of beam focusing and pointing dish or mirror.

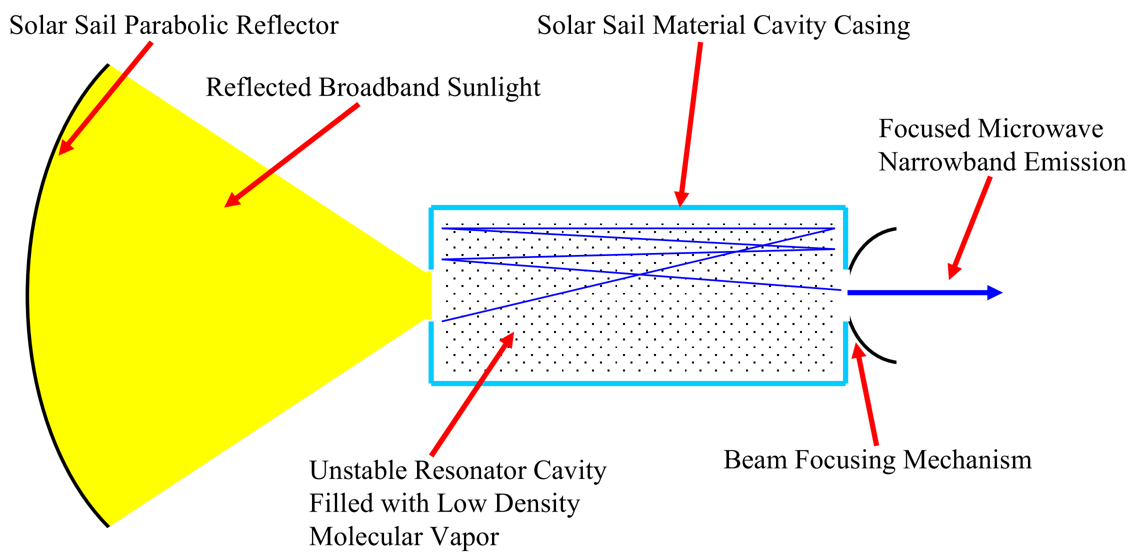

Figure 6: Solar pumped maser system concept diagram

Table 3: Sample astronomical maser transitions and frequency output[23]

		Interstellar masers		Stellar masers	
Molecule	Frequency (MHz)	Number known	Number mapped	Number known	Number mapped
OH	1612.231	20	1	250	7
OH	1665.402	100	7	50	2
OH	1667.359	100	1	50	4
OH	1720.53	60	4	0	0
OH	4660.42	10	0	0	0
OH	4765.562	10	0	0	0
OH	6030.747	6	0	0	0
OH	6035.092	20	2	1	0
OH	13441.417	1	0	0	0
H2O	22235.08	194	19	100	5
SiO	42519.3	0	0	3	0
SiO	42802.54	1	0	20	2
SiO	43122.03	1	1	60	2
SiO	86243.35	1	0	60	0
SiO	129363.26	1	0	0	0
SiO	86846.89	0	0	1	0
CH3OH	25124.87	1	1	0	0

3.3.2 Estimate

One of the cruxes for a solar pumped maser system is an efficiency argument based upon the scale of the transitions. A tested efficiency of 38%[25] by a solid state laser and a hopefully soon to be proven 50% wall plug efficiency[26] implies that even higher efficiencies are possible for a low density molecular vapor. This is due to the fact that a laser uses electronic transitions to excite electrons through different optical modes, whereas a maser would use molecular rotation and vibration modes of excitation. The fact that a maser involves modes and transitions on the molecular level, whereas a laser uses subatomic transition, should imply higher efficiency purely based on the size of the particles dealt with. In addition the maser system would produce much longer wavelengths, which would again simplify the system just based upon scale. The only reason that this hasn't been proven is that there has been no driving force to develop an efficient high frequency, high power maser. Given a fraction of the energy, time, and money that has been expended on developing lasers, maser systems should be able to cite higher efficiencies. For this specific case output at 129 or 86 GHz shows atmospheric transmission efficiency at approximately 90% from Figure 1. This efficiency factor would be multiplied to the base efficiency selected from this historical laser data previously mentioned.

Aside from the efficiency the maser could be estimated around an energy balance. Essentially, the molecular vapor has to be at some base energy level and pumped up to another desired energy level. This rotation between energy levels must form a sort of equilibrium state for the maser to work constantly over time. This equilibrium will be balanced between energy flux in and out of the vapor and the required energy level of the vapor itself, and its corresponding pressure, temperature, and density levels.

The size of the cavity was selected based on cylindrical maser models as shown in Figure . Essentially the maser is non linear in terms of intensity up to the point of saturation. It would therefore appear that the system would get the most performance by operating at this boundary.

Given the proceeding information, an estimate was made for the solar pumped maser system. The end result was a specific power of 3.54 kW/kg. This is approximately an increase in specific power by a factor of 10.8 over a standard photovoltaic system. This estimate was based on a standard SiO astronomical maser density of 1E10 particles/cm^3 an aspect ratio of 35, and a power output of 125 MW. This puts the cavity length at approximately 4 km. This is obviously long, but entirely in the size range of SSP stations, yet far less massive.

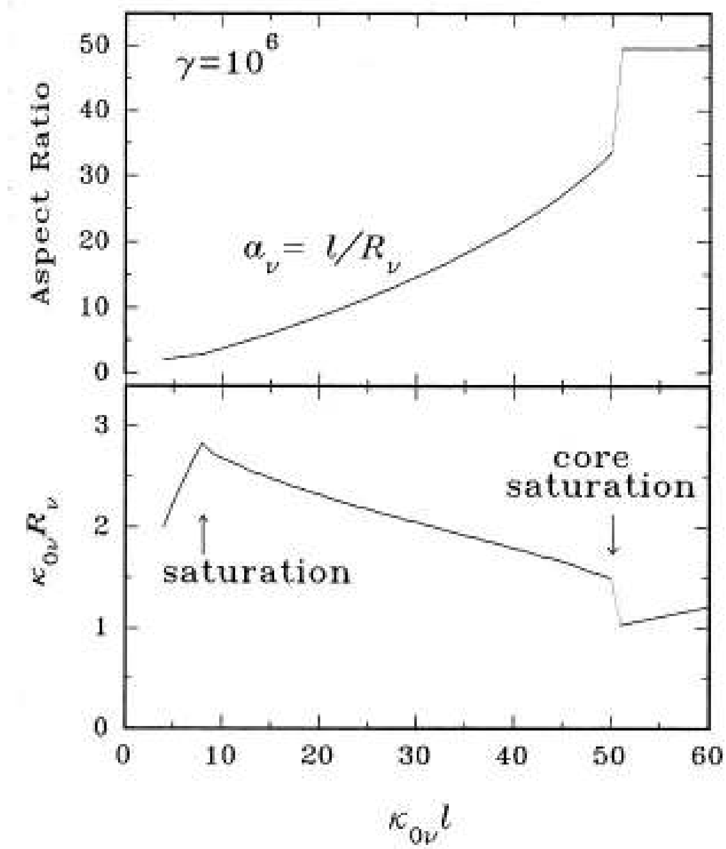

Fig. 5.6 Parameters of cylinder equivalent to spherical maser with radius ℓ

Figure 7: Cylindrical aspect ratio relation to maser saturation[23]

3.3.3 Implementation Analysis

One of the most promising implementation attributes of a maser system is that theoretically any molecule can undergo this maser transition, with nearly infinite transition combinations between multiple molecules and energy levels. So in theory, given further study, different molecules could be tailored or chosen to provide any desired output frequency. The ability to provide application dependent frequencies is extremely important to the success of the overlying concept as a whole. In addition assuming the correct correlations and relationships could be made, it would theoretically be possible to create or choose a molecule with the most preferential properties. The most preferred properties would be dictated by properties related to the energy balance and mass of the system. For instance, a molecule with low molecular weight may be preferable. Or perhaps, a molecule that has dense maser emission lines at a higher energy level would be desirable to keep the volume of the gas low by pumping more light through a smaller area.

Despite the possibilities and benefits previously listed, and aside from the massive resonator cavity tube length, some important implementation problems were discovered. These include, the general high velocities in maser regions, and the general three level requirement for optical pumping.

The high velocity problem is that often in maser regions the population inversion occurs because particles accelerate into regions of high velocities; expanding out from a star or a supernova.[23] In such regions, the energy that was contained in random thermal motion of the molecules is now present in directed motion, and the density also has come down, so that collisions between molecules become rare. Under such conditions, molecules that were excited to high energy levels in the hot regions, continue to carry these energy levels into the cooler, fast-flowing regions, ready to give up the energy as radiation. If this high velocity is a requirement for maser functionality, then the system design will have to be fundamentally changed perhaps past the point of practicality. In the simplest terms, creating and sustaining this velocity would probably take some measure of energy which would detract from the overall efficiency of the system.

The other large problem is that masers have not been found to function from optical pumping with under three energy levels. Now depending on the tailoring the system could result in output with two frequencies very close to the desired, but for resonation this is probably not optimal. The solution to that would be thermal pumping, which allows two energy levels, but that would be another design issue.

3.4 Optical Antenna System

The optical antenna system is based on classical antenna theory scaled down to optical frequencies. Whether the concept involves dispersed rectification components, or a central processing unit, they both couple with broadband radiation through a nanofabricated optical antenna array. The following sections will describe the basic concepts, the estimation methodology, and discuss further realistic considerations for the implementation of the system.

3.4.1 Concept Description

As shown in Figure , there are two possible methods involving an optical antenna array. The first would be more similar to the conventional rectenna design and therefore to ITN's concepts.[17] However, this would be potentially more difficult considering the need for nano-fabrication of not only the antenna array, but distributed rectification components as well. Once the induced current is rectified, it becomes DC, and there will be the same initial problem; that the current must be re-oscillated which requires mass, energy, and a loss of efficiency. For the purposes of this project it would not be a true direct conversion system.

A possible solution is that the incoming broadband radiation could be filtered at least at the highest incident frequency or preferentially even a multiple of the highest frequency, and then additively restructured to form a lower frequency signal. It would be effectively similar to a Fourier Approximation. This concept is roughly demonstrated in Figure. Once formed into a lower frequency wave it could be retransmitted using a simple microwave antenna such as is used in many current applications.

Another benefit given a high enough sampling rate and the ability to process data at that speed would be a tunable signal. This would be extremely important when trying to adapt the same overlying concept to various applications that have their own application dependent frequency. Optical Fourier Transform computing components offer possible solutions here. Also, a system with a central sampling system would entail significantly less mass and complexity without the need for incoming wavelength scale rectification components such as dispersed filters and diodes. This could potentially increase both efficiency and specific power.

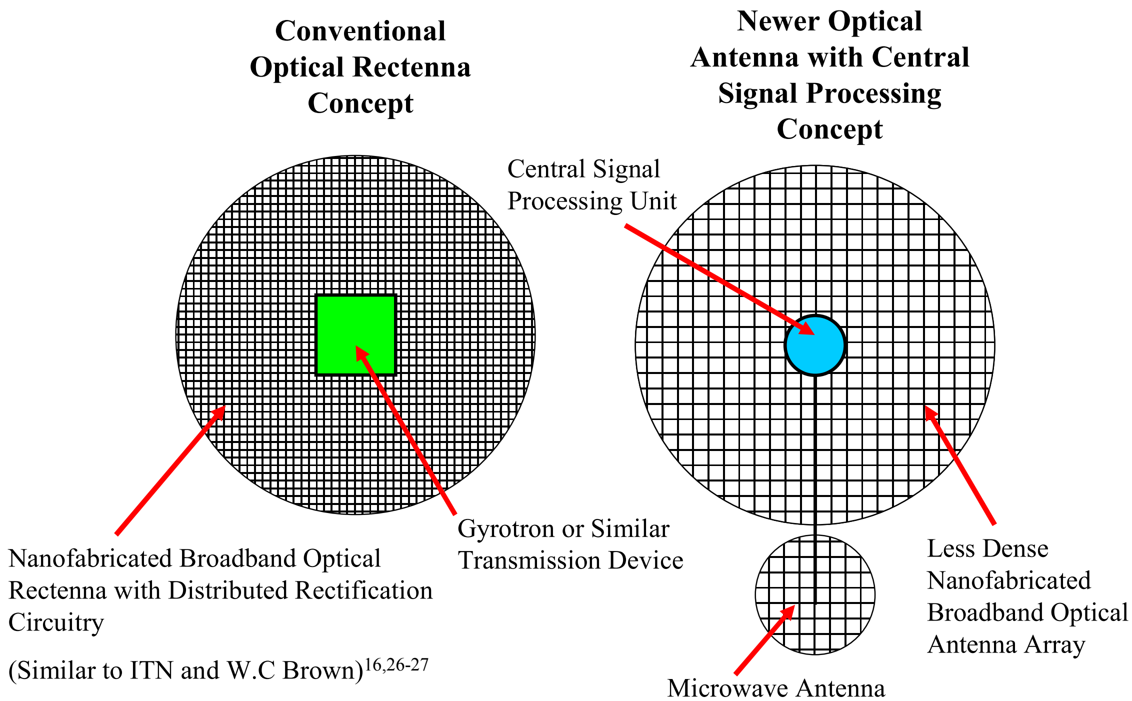

Figure 8: Optical antenna and rectenna concept diagrams

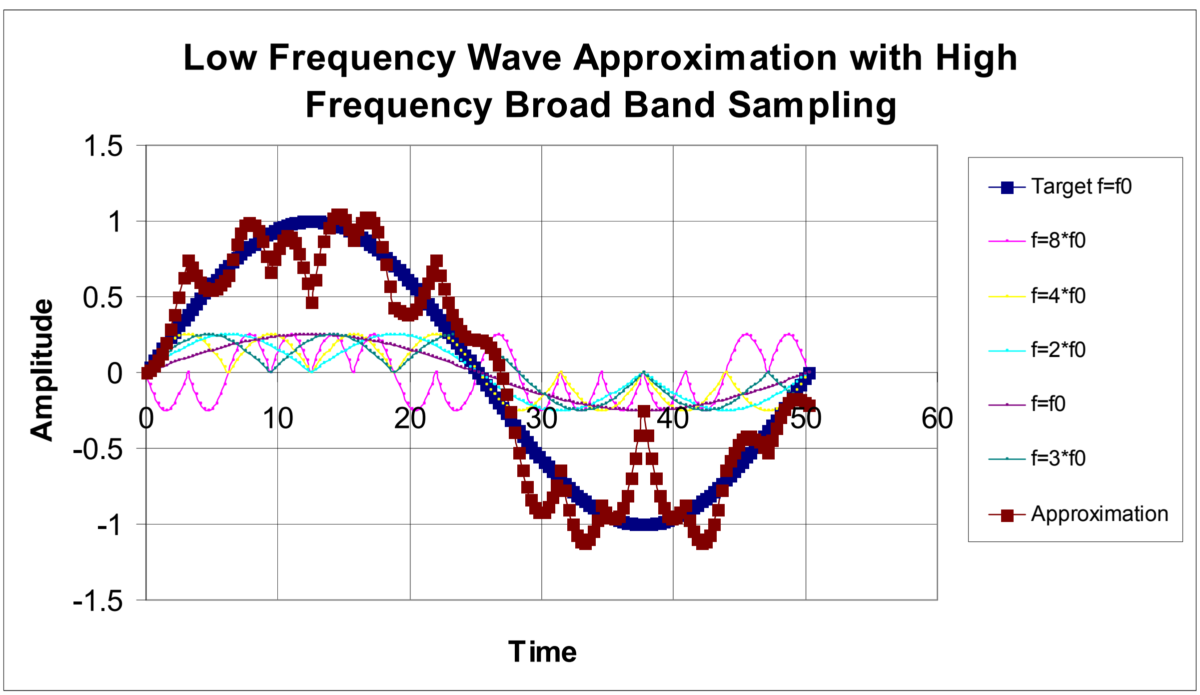

Figure 9: Simulation of low frequency wave approximation by 2x max frequency sampling

3.4.2 Estimate

Simply based on of cited numbers from W.C. Brown and ITN,[16,26-27] an estimate for a SSP system incorporating an optical antenna can be made. ITN cited a range of theoretical coupling efficiencies of 85-100%. Taking the low end of this range, using W.C. Brown's estimated weight for a thin film etched circuit rectenna, and assuming an average solar energy density of 1.37 kW/m2 gives the following attributes: a power density of 1.165 kW/m2 and a specific power of 4.658 kW/kg.

Comparing against the upper end of the range of data cited in Table 1 for photovoltaic specific power shows that an optical rectenna could provide a 1763% increase in specific power over conventional photovoltaics.

It must be noted that this estimate, like all other estimates in this paper, has a large uncertainty that highly depends on which end of the range is used. Because of this, finding a specific uncertainty value would be unproductive. However, the estimate can still serve as an example as to the providence of the concept. In addition these estimates generally take values at the ends of the ranges in favor of traditional photovoltaics.

3.4.3 Implementation Analysis

It is also important to note that the optical rectennae should still be seriously considered with respect to conventional space solar power without the need for THz sampling. Just based off the specific power improvement, if SSP concepts utilizing microwave generators had their standard photovoltaics replaced with optical rectennae, the system might be improved to the point where it is actually feasible.

Optical rectennae could possibly also be applied to more futuristic concepts. For instance in the case of a problem with direct sunlight pumipng, an optical antenna grid could be used to pump a laser for re-transmission using the broadband signal. Despite this possibility, the reasoning was made that if any laser or maser type device could be pumped by a broadband signal from an antenna array, then it should still be able to be as easily pumped directly by sunlight focused by a parabolic reflector. This reflector could be built out of solar sail type material and would be theoretically lighter and significantly easier to construct than a nanofabricated optical antenna.

In general the optical antenna or rectenna array appears to be the most promising direct conversion concept. Nanofabrication is advancing rapidly and actual functional tests may be possible in the near future.

3.5 Conclusion of System Concepts

Three futuristic SSP direct conversion system concepts were explored. Following the analysis an estimate for specific power was made where possible, and an underlying decision as to the feasibility of the concept was made. These estimates and decisions, along with the corresponding rational are shown in Table 4.

Table 4: Summary of direct conversion system concepts specific power estimates and conclusions

Concept	Specific Power (kW/kg)	Decision	Rationale
Shocked Photonic Crystal	Not enough data	Unresolved Issues	Won't realistically see these efficiencies, difficulty with pulsed functionality and shock creation
Solar Pumped Laser	3.34	Unresolved Issues	Difficulty in the creation of an equilibrium of efficient transitions at desired frequencies
Optical Antenna	4.66	Possible	Need nano-fabrication and or THz wave sampling
Conventional Photovoltaics	0.31	Possible	Technology is there, but may not be economically feasible

CHAPTER 4

SELECTED APPLICATIONS

Applications for which direct conversion for space solar power would be useful are plentiful. Essentially any architecture that needs power would possibly serve to benefit from direct conversion. Two major architecture categories that are the most obvious benefactors of direct conversion are space-based power grids, and electric propulsion. It is important and interesting to note, that direct conversion would enable even further possibilities, such as a combination of the above. For instance, space power grids and electric propulsion could possibly be used together to create a network of power supply to enable expansion throughout the solar system and beyond.

4.1 Space Solar Power Grid

Aside from “saving the world,” space solar power is a great idea that has been around for a fairly long time. It ultimately offers nearly free and unlimited energy. In response to skeptical comments as to a space based solar power grid, further explanation as to the benefits of a SSP grid versus ground based solar power system will be reiterated. Primarily the SSP system gets 24 hours per day sunlight versus a terrestrial maximum of 8, resulting in an initial factor of three times the generating capacity. Additionally, there are atmospheric effects as that drastically reduce the solar energy density at the ground by 30-40%. Ground based solar power is also affected by seasons, weather, and land availability. Functional SSP would be a tremendous breakthrough. The main issue faced by such a project is the state of current technology. Specifically, launch costs, solar cell efficiency, and an infrastructure that would be receptive to such a grid.

Based on the estimates listed in Table 5, the benefit of alternative SSP technologies is evident. Cost savings of this magnitude transform any SSP concept into feasibility. Systems designed around 100 GHz would significantly reduce ground based infrastructure and therefore cost by limiting beam spreading. Compared to a commonly cited 2.4 GHz system the ground “foot print” of the beam should be nominally 2.4% as large.

Cost comparisons were created through the average values of photovoltaic specific power and launch costs from Table 1 and Table 2 respectively. The specific power values for the direct conversion options were calculated as described in the proceeding sections and shown in Table 4.

Table 5: Cost comparison of direct conversion concept implementation on a 125 MW solar power satellite

125 MW Output SSP Satellite	Specific Power (kW/kg)	Mass (MT)	Cost ($M)	Cost of PV (%)
Conventional Photovoltaics	0.31	403.23	12741.94	100.00
Nanofabricated Optical Antenna	4.66	26.82	847.64	6.65
Solar Pumped Maser	3.34	37.43	1182.63	9.28

The SSP system most preferred by NASA to-date is based on placing very large photovoltaic arrays in geosynchronous Earth orbit, which are positioned to beam power down to large ground stations around the equator. The primary problem with this approach is that until the system in GEO is operational, no revenue can be generated. The initial cost is extremely large. Even at an unrealistic estimate of $100 per pound launch cost to geosynchronous Earth orbit, the cost to first power was estimated at $300 billion. With launch costs today, as shown in Table 2, it is easy to see why SSP has not been implemented.

With the savings cited in Table 5, combined with a revenue-generating evolutionary path to SSP could solve the chicken and the egg issue of developing such a system. Prof. Komerath has detailed such an evolutionary path in several papers.[5-7] The evolutionary path is to develop a space based power transmission system, which would pay for itself from the savings from transmission costs. This would be accomplished by allowing ground-based renewable energy plants to trade their output to where it fetches the best prices, thus enabling the development of new renewable energy plants at better locations. These locations are typically far from metropolitan areas and industrial centers. Additionally, the price differential between off-peak and peak time power costs is more than adequate to offset the lower transmission efficiency of initial SSP systems, so that the SSP grid could pay for itself over a 10-15 year period. Further, such a system would enable green energy sources such as wind and solar plants to become base load sources and exchange power anywhere across the world.[5-7]

4.2 Electric Propulsion

Over the years a multitude of electric propulsion systems have been proposed and developed. The major drawback of these systems is a high mass per unit thrust, due to the power source and transmission system. One of the most commonly known forms of electric propulsion, ion engines, work by ionizing propellant particles by EM radiation such as xenon gas and accelerating them through an electric field.[31] Magnetoplasma engines are a newer concept but work on somewhat similar principles: heating neutral hydrogen gas into plasma using electric fields and contained by magnetic fields, the plasma then passes through an RF booster to further ionize the hydrogen plasma.[32] The University of Washington has also been looking into various other futuristic electric plasma based propulsion methods such as the MagBeam.[33]

These propulsion systems could all be revolutionized by the massive amounts of energy available from the sun that could be harnessed by direct conversion systems. Energy could also be beamed from a solar power grid. This would eliminate one of the important opposition points to electric propulsion; that electric propulsion must often utilize massive on board power systems such as nuclear power generation in order keep power over the long range in which electric propulsion becomes effective. Direct conversion options eliminate the need for an onboard power system, which would both decrease the launch cost and increase the effectiveness of the propulsion system.

Furthermore, direct frequency conversion is especially applicable because of the need for EM radiation to ionize particles. Mass and efficiency could be saved by directly converting to the needed radiation frequency. These mass savings are extremely important because of the low thrust nature of electric propulsion systems.

As specified by the designs the direct conversion systems all either utilize a solar sail reflector or a thin film array. In the case of the thin film array, perhaps with future advances in fabrication technology, direct conversion technology might be combined with a solar sail. Landis suggests a hybrid electric propulsion and solar sail system.[33] In addition to direct conversion applying to the electric propulsion system, it would help as a sail by providing initial thrust and the magnitude of thrust needed for a mission.

4.3 Conclusion of Selected Applications

It is evident that between the combination of pure specific power increase and integration advantages that direct conversion systems provide great benefits to many space based architectures. Although based on rough estimates, possible mass savings of this magnitude warrant further exploration and consideration.

CHAPTER 5

CONCLUSION

This project studied a large number of options that might lead to direct conversion. Those technology options were analyzed according to which would warrant further exploration from the point of view of aerospace systems applications and possible power per unit mass. Based off these technologies, several advanced concepts were proposed. Estimates of the possible power per unit mass of potential direct conversion systems were made, and future applications that would benefit from those direct conversion systems were identified.

The project goal, concepts developed, critical enabling technologies, and applications are detailed in Table 6.

Table 6: Direct Conversion for SSP summary table

Direct Conversion for SSP Summary:

Goal: Convert broadband solar radiation directly to lower narrowband frequency

Concepts:

1. **Optical Rectenna System:** Solar radiation is coupled to thin film nanofabricated antenna array including either rectification components or optical-transform components for THz wave reconstruction
    a. **Efficiency:** 85-100%
    b. **Specific Power Estimate:** 4.658 kW/kg
2. **Shocked Photonic Crystal System:** Solar radiation gathered by solar sail-like parabolic reflector is focused through tailored dielectrically modulated shocked photonic crystal which simultaneously narrows the band and downshifts the frequency
3. **Solar Pumped Maser System:** Solar radiation gathered by solar sail-like parabolic reflector is focused through a low density molecular vapor contained in a cylindrical resonator tube constructed from solar sail material producing a non-linear emission
    a. **Efficiency:** > 50%
    b. **Specific Power Estimate:** 3.539 kW/kg

Critical Technologies:

1. **Nanofabrication:** sub 100 nm resolution
2. **Control System:** utilizes incoming power to stabilize SSP systems in orbit
3. **Ultra Thin Solar Sail Fabrication**
4. **Terahertz Optical Computing/Transform Elements:** > 3000 THz

Applications:

1. **Space Solar Power Grid**
2. **Electric Propulsion**

To reiterate, direct conversion offers the potential to realize SSP as a feasible aerospace concept. The ability to convert broadband sunlight directly to a useable narrowband application dependent frequency reduces system mass and complexity while increasing efficiency and specific power. Out of the diverse array of possible technologies and options studied, a handful of concepts have shown potential to warrant further study. They have the potential to be enabling technologies in their own right for SSP systems and be a true paradigm shift for SSP.

REFERENCES

[1] Mankins, J. C., "A fresh look at space solar power: New architectures, concepts and technologies." Acta Astronautica 41(4-10): 347-359. 1997.

[2] Glaser, P. E., "Power from the sun: Its future." Science, 1968 Vol. 162, pp. 857-861.

[3] Itoh, K., Ogawa, Y., Omiya, M., "Project overview and prospect of solar power satellite, SPS2000." Hokkaido Daigaku Kogakubu Kenkyu Hokoku. Bulletin of the Faculty of Engineering, 1995, Hokkaido University Vol. 175, pp.113.

[4] Komerath, N., Boechler, N., Wanis, S., "Space Power Grid- Evolutionary Approach To Space Solar Power." Proceedings of the ASCE Space and Earth 2006 Conference, League City, TX, April 2006.

[5] Boechler, N., Hameer, S., Wanis, S., Komerath, N.M., "An Evolutionary Model for Space Solar Power." In El Genk, Editor, STAIF 05-082, Proceedings of the Space Technology and Applications International Forum, American Institute of Physics Conference Proceedings Volume 813, Albuquerque, NM, Feb. 2006, ISBN: 0-7354-0305-8.

[6] Komerath, N.M., Boechler, N., "The Space Power Grid." Paper IAC06-D3.4.06, Proceedings of the 56th International Astronautical Congress, Valencia, Spain, October 2006.

[7] U.S. Department of Energy, "Bandgap Energies of Semiconductors and Light." Dec 2005. Retrieved 4/14/2007. http://www.eere.energy.gov/solar/bandgap_energies.html

[8] Fatemi, N. S., Pollard, Howard E., Hou, Hong Q., and Sharps, Paul R. (2000). Solar Array Trades Between Very-High Efficiency Multi-Junction and Si Space Solar Cells. 28th IEEE PVSC. Anchorage, Alaska.

[9] Spectrolab Inc., "Spectrolab Photovoltaic Products Data Sheet." Oct. 2004., Retrieved 4/14/2007, from http://www.spectrolab.com/DataSheets/Panel/panels.pdf.

[10] Murphy, D. M., Eskenazi, M. I., White, S. F., Spence, B. R., "Thin-film and crystalline solar cell array system performance comparisons." AEC-Able (ABLE) Engineering. New Orleans, LA, United States, Institute of Electrical and Electronics Engineers Inc. 2002.

[11] Olds, J., Way, D., Charania, A., Budianto, I., Marcus, L., "In-Space Deployment Options for Large Space Solar Power Satellites," IAA-00-R.2.02, 51st International Astronautical Congress, Rio de Janeiro, Brazil, October 2-6, 2000.

[12] Isakowitz, S. J., Hopkins, J. B., Hopkins, J. P., "International reference guide to space launch systems." American Institute of Aeronautics and Astronautics, 2004. Reston, Virginia.

[13] Wade, M., "Encyclopedia Astronautica." 1997-2007, Retrieved 4/14/2007, from http://www.astronautix.com/

[14] Robel, Michael K. "The cost of medium lift". The Space Review. June 1, 2004. http://www.thespacereview.com/article/150/1

[15] ARO (Arizona Radiowave Observatory) Website: "What is Submillimeter Astronomy?" http://kp12m.as.arizona.edu/docs/what_is_submillimeter.htm Accessed 5/1/2006.

[16] Ren, A., Kuo, S.P., "Frequency Downshift in Rapidly Ionizing Media". IEEE, Piscataway, NJ, USA. 1994.

[17] Berland, B., "PhotoVoltaic Technologies Beyond the Horizon: Optical Rectenna Solar Cell". Final Report, NREL/SR-520-33263, February 2003.

[18] Iltchenko, V., Matsko, A., Savchenkov, A., Maleki, L., "A Resonator for Low-Threshold Frequency Conversion". JPL. http://www.nasatech.com/Briefs/Dec04/NPO30638.html

[19] Joannopoulos, John D., Reed, E., Soljacic, M., "Reversed Doppler Effect in Photonic Crystals". Physical Review Letters. Sept 2003.

[20] Joannopoulos, John D., Johnson, Steven G., "Photonic Cystals: The Road from Theory to Practice." Massachusetts Institute of Technology. 2002.

[21] Joannopoulos, John D., Reed, E., Soljacic, M., "Color of Shock Waves in Photonic Crystals". Physical Review Letters. 23 May 2003.

[22] M. Reid, J. Moran, "Masers". Annual Review of Astronomy and Astrophysics 1981.

[23] Elitzur, M. "Astronomical Masers". Kluwer Academic Publishers. 1992.

[24] Kiss, Z. J., Lewis, H. R., Duncan, R. C. Jr., "Sun Pumped Continuous Optical Maser". Applied Physics Letters. March 1963.

[25] Saiki, T., Uchida, S., Motokoshi, S., Imasaki, K., Nakatsuka, M., Nagayama, H., Saito, Y., Niino, M., Mori, M., "Development of Solar-Pumped Lasers for Space Solar Power Station". Space Technology Applications International Forum. October 2005.

[26] DARPA Efficient Mid-wave Infrared Lasers (EMIL) BAA06-20. http://www.fbo.gov/spg/ODA/DARPA/CMO/BAA06%2D20/Attachments.html

[27] Brown, W.C., "The History of Power Transmission By Radio Waves". IEEE Trans.Vol. MTT-32, p:1230 (1984).

[28] Brown, W.C., “Performance characteristics of the thin-film, etched-circuit rectenna”. IEEE MTT-S International Microwave Symposium Digest, p: 365- 367 (1984).

[29] “Solar Sail Technology Development: Mission Senarios” JPL. Mar 2002. http://solarsails.jpl.nasa.gov/introduction/mission-scenarios.html

[30] Wiley L.J., Wertz J.R., “Space Mission Analysis and Design, 3rd Edition” Microcosm Press; 3rd edition (October 1999)

[31] NASA's Human Exploration and Development of Space Enterprise, “Propulsion Systems of the Future”. 15 May 2003. http://www.nasa.gov/vision/space/travelinginspace/future_propulsion.html

[32] Winglee, R., “Magnetized Beamed Plasma Propulsion (MagBeam).” NIAC. March 2005.

[33] Landis, Geoffrey A., “Optics and Materials Considerations for a Laser-propelled Lightsail”. Paper IAA-89-664 at the 40th International Astronautical Federation Congress, Málaga, Spain, Oct. 7-12, 1989. Revised December, 1989.