INVITED PAPER

Microwave Power Transmission: Historical Milestones and System Components

A comprehensive overview of the key historical developments of microwave power transmission in chronological detail is presented, covering space solar power and SPS background, rectenna invention as well as WPT experiments and demonstrations.

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ABSTRACT | Microwave power transmission (MPT) is the wireless transfer of large amounts of power at microwave frequencies from one location to another. MPT research has been driven primarily by the desire to remotely power unmanned aerial vehicles (UAVs) and by the concept of space solar power (SSP) first conceived by Dr. Peter Glaser of the Arthur D. Little Company in 1968. This paper attempts to reveal, in adequate chronological detail, many of the MPT milestones reached over the past 50 years, including those related to SSP. Key components to various MPT systems are presented as well as design schemes for achieving efficient MPT. Special focus is given to rectenna design since this particular MPT component has received the most attention from researchers over the last couple of decades.

KEYWORDS | Microwave power transmission (MPT); rectenna; rectifying antenna; retro-directivity; solar power satellite (SPS); space solar power (SSP)

Manuscript received November 29, 2011; revised September 4, 2012; accepted February 2, 2013. Date of publication March 13, 2013; date of current version May 15, 2013. This work was supported by both NASA's Jet Propulsion Laboratory, Pasadena, CA, USA and NASA's Marshall Space Flight Center, Huntsville, AL, USA.
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Digital Object Identifier: 10.1109/JPROC.2013.2246132

I. INTRODUCTION

Wireless power transmission (WPT) can be subdivided into either near-field inductive-based WPT or far-field WPT. MPT comprises the microwave-frequency based subset of far-field WPT. In an MPT scenario, significant amounts of power are transferred from one location to another. MPT research has been driven primarily by the desire to remotely power unmanned aerial vehicles (UAVs) and by the concept of space solar power (SSP) first conceived by Dr. Peter Glaser of the Arthur D. Little Company in 1968 [1]. Most MPT breakthroughs have occurred under the umbrella of SSP. Fig. 1 shows a block diagram for the specific application of MPT pertaining to SSP. SSP is an MPT system with the addition of solar cells and magnetrons for microwave power generation.

The SSP idea calls for a constellation of solar power satellites (SPSs) to be placed in geosynchronous orbit (36 800 km above Earth) in order to capture the sun's energy using arrays of solar cells. The satellites, each measuring several miles across, would be located in geo to keep them in view of the sun 99% of the time. This sun exposure is twice that of terrestrial solar cells. This means that power can be readily generated and distributed at night, especially during the evening hours when power consumption peaks. This is of particular importance given that power storage still has severe limitations. In addition, the closer the satellites are placed to the sun, the larger their effective collection area is, since light intensity decreases by the inverse square of distance. Additionally, layered strata of the atmosphere reject and/or absorb varying

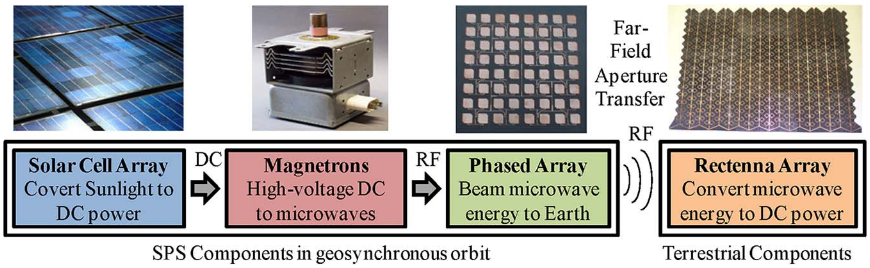


Fig. 1. *Diagram of an SSP–MPT system including a solar cell array, magnetron, circularly polarized (CP) phased array, and a CP rectenna array.*

amounts of frequency-dependent powers contained within the incident solar energy's spectrum. By locating the solar collection panels outside the atmosphere, this rejection and absorption becomes a moot point, except for the energy that is to be transmitted from the SPSs. Thus, choosing the right SPS frequency is paramount to the overall system efficiency. Upon reception of the incident photons, the solar cell panels then output large direct current (dc) voltages. These voltages are then fed to awaiting cavity magnetrons, which are periodically positioned at various subarrays within each of the SPS's phased array apertures. These magnetrons convert the high-voltage dc outputs of the solar panel arrays to microwave power. This microwave energy is then beamed to Earth onto "farms" of rectifying antenna (rectenna) arrays that convert the incoming microwave energy back to dc power [2].

Since its inception, SSP has gained considerable attention because it has the potential of providing clean, renewable, and continuous power for generations to come. With the widespread belief that easily accessible fossil fuel supplies cannot support the projected energy demand based on population growth and increased development, SSP is seen as a possible remedy. In addition, SSP could circumvent pollution problems associated with currently used energy enablers, such as nuclear energy and coal. SSP is also touted as a way of meeting future energy demands where other clean resources such as hydro and wind fall short. As an added incentive, SSP can be delivered to the most remote locations without connective infrastructure, such as pipes or power lines [3].

The fruition of SSP and the present day desire to remotely power unmanned aerial vehicles (UAVs) continue to serve as the main driving forces behind current advancements being made in MPT, particularly the rectenna array components. The use of UAVs for communication and surveillance is seen as an essential capability, especially for the U.S. military. MPT has been experimentally shown to be a way for people on Earth to remotely power unmanned high-altitude platforms such as UAVs. Additional uses for MPT include powering space probes from future space stations into deep space and powering robots to enter dangerous environments, such as nuclear contaminated areas.

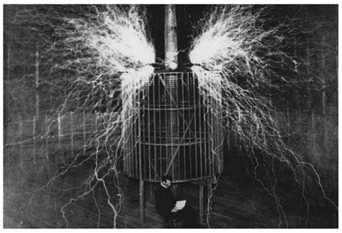
II. HISTORICAL WPT ACCOMPLISHMENTS

A. Early Years

The earliest example of power transmission by radio waves was carried out by Heinrich Hertz [4]. Hertz used a spark gap to both generate high-frequency power on one end and to detect the same power on the receiving end. Reflecting antennas were used for transmitting and receiving the energy. In essence, Hertz created a complete energy transfer system.

Most of the early advances in WPT were achieved at the turn of the 20th century by Nikola Tesla [5]. Using the concepts of resonance first displayed by Hertz, Nikola Tesla demonstrated the transmission of low-frequency electrical power using wires over long distances. Tesla built several alternating current (ac) power grids and proved their numerous advantages over the then commonly used dc systems championed by Thomas Edison. Much to the dismay of Edison, Tesla proved that ac was subject to much lower conductor losses than dc, and therefore, could be transferred over much greater distances. Tesla continued to carry out experiments in his New York City laboratory with special focus on WPT. At his laboratory, Tesla drew up plans to apply alternating surges of current running up and down a metallic mast in order to set up oscillations of electrical energy that would propagate over large areas on Earth. These oscillations would then create a standing wave around Earth into which receiving antennas could be positioned at the standing wave maximum amplitude locations. In other words, Tesla wanted to connect the world without wires. This would become his obsession.

Tesla first attempted to transmit power without wires at Colorado Springs, CO, USA, in 1899. Under a \$30 000 grant from Colonel John Jacob Astor, owner of the Waldorf-Astoria Hotel in New York City, Tesla built the huge "Tesla coil" shown in Fig. 2(a), over which rose a 200-ft metallic mast with a 3-ft diameter ball positioned at the top. The Tesla coil resonated 300 kW of low-frequency energy at 150 kHz. According to Tesla, when the radio-frequency (RF) output of the Tesla coil was unleashed into the mast, 100 MV of RF potential was produced on the


(a)


(b)

Fig. 2. ***Tesla's MPT experiments. (a) Colorado Springs. (b) Wardenclyffe Tower [5].***

sphere. Very large discharges of electrical energy were seen by people living in and around Colorado Springs. Unfortunately, no data were collected on whether any significant amount of power would be available at any distant point.

With the self-heralded success of the Colorado Springs experiment, Tesla obtained financial backing from J. P. Morgan to construct a setup similar to the one in Colorado Springs on 2000 acres of land 60 miles east of New York City at Shoreham, in Suffolk County, Long Island. The building plans called for a 154-ft wooden tower, called the Wardenclyffe Tower [shown in Fig. 2(b)], that would support a giant copper electrode, 100 ft in diameter, shaped like a donut at its top. The structure was nearly completed when the financial resources ran dry, forcing a halt to construction. The installation was eventually torn down during World War I by the U.S. Government due to its belief that the structure could constitute a possible target. Tesla continued to pursue his dream of connecting the world without wires, but his efforts went unnoticed. With little outside interest and no financial supporters, Tesla took a step backwards into seclusion. The first radio transmission was achieved not by Tesla, but instead, by Guglielmo Marconi in 1901. After Tesla's death, the U.S. Government seized Tesla's documented works on WPT. The U.S. Government saw the technology as the scientific basis for their proposed "Death Ray" weapon in which WPT would be used to destroy enemy weapon systems. Many of these concealed records were later released to the general public.

Historically speaking, Tesla was decades ahead of his time. Not until the 1930s was another attempt on WPT carried out. This experiment, performed by H.V. Noble at the Westinghouse Laboratory, consisted of identical transmitting and receiving 100-MHz dipoles separated by 25 ft. No attempts to focus the energy were made, but several hundred watts of power were transferred between the two dipoles. This experiment was demonstrated again to the general public at the Chicago's World Fair of 1933–1934.

The primary reason that WPT received little interest in the first part of the 20th century was that knowledgeable engineers and scientists knew that, in order to achieve efficient point-to-point transmission of power, the electromagnetic energy had to be concentrated into a narrow beam, reducing what is commonly referred to today as spillover loss. It was theorized at this time that the only way to obtain such confined energy would be to utilize energy at high frequencies and use radiating elements of reasonable size. The other problem was that the existing sources that created high-frequency energy outputted only a few milliwatts of energy, which is not enough for a feasible WPT system.

In the late 1930s, two inventions were made that solved the high-frequency source problem. The first was the velocity-modulated beam tube first described by O. Heil, which, after a few modifications, became the well-known klystron tube. The second invention was the microwave cavity magnetron developed by Randall and Boot in Great Britain in 1940 and passed to the United States under great secrecy during World War II [6]. These developments allowed the transition of WPT from lower frequencies to microwave frequencies or MPT. During World War II, with the advent of radar made possible by the introduction of both the klystron and the magnetron, antenna development and microwave generation technologies, so basic to MPT, improved greatly. The U.S. Government took notice of the emerging technologies and started proposing applications for the new capabilities.

B. Modern U.S. Contributions (1950–1980)

In the late 1950s, a number of developments occurred which revealed that WPT approaching 100% was possible. Calculations and experimental results gathered by Goubau and Schwering demonstrated that microwave power could be transmitted with close to 100% efficiency by a beam waveguide consisting of lenses and/or reflecting mirrors [7]. These findings dispelled the previously held assumption that power density always decays by the square of the distance. Another vital development was the high-powered microwave tube amplifier or Amplitron. Last, the realization of the growing need to communicate by line of sight over long distances, which a platform placed at high altitudes in the Earth's atmosphere could afford, called for further MPT research. Later satellites would be used for this purpose.

The combination of the aforementioned developments motivated the Raytheon Company to propose the Raytheon Airborne Microwave Platform (RAMP) concept in 1959 to the U.S. Department of Defense as a solution to surveillance and communication problems. The proposed platform was a large helicopter positioned at 50 000 ft in a region above the jet stream where the atmospheric winds are almost nonexistent. To fly at this altitude, the helicopter needed to be powered from Earth by an Amplitron having an output of 400 kW of energy at 3 GHz with an efficiency over 80%. This high-powered Amplitron was developed at Raytheon's Spencer Laboratory in 1960 by William Brown who is largely regarded as the principal

Fig. 3. ***U.S. Air Force/Raytheon MPT-powered helicopter.***

pioneer of practical MPT [8]. The only capability missing was the ability to convert microwave energy to dc power in order to drive motors attached to the rotor blades. The U.S. Air Force awarded several contracts to study this rectification problem. One of the studies carried out by R. George and E. Sabbagh at Purdue University (West Lafayette, IN, USA) showed that a semiconductor diode could be used as an effective rectifier [9]. At the same time, W. Brown at Raytheon carried out research on using a thermionic diode rectifier [10]. Now that both high-powered sources on the transmitting side and efficient rectifiers on the receiving side were obtainable, MPT for the first time became both a feasible and possibly useful technology.

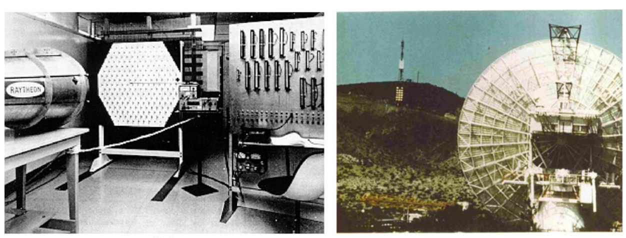
The U.S. Air Force continued to partner with W. Brown and Raytheon during the early 1960s in order to pursue the emerging MPT technological possibilities. One of the most well-known examples of MPT occurred on July 1, 1964 inside Raytheon's Spencer Laboratory. There, a microwave powered helicopter much smaller than the one proposed in RAMP was flown a few inches off the ground. It was the first heavier-than-air vehicle to be flown and was sustained solely by a 2.45-GHz microwave beam. This helicopter experiment was demonstrated again to the mass media on October 28, 1964. The helicopter shown in Fig. 3 was flown for 10 h at an altitude of 50 ft [11]. The presentation was covered by Walter Cronkite's CBS news program and displayed to the world the real possibilities of MPT. Dipole antennas were used to collect the incoming microwave energy, and the dc energy that powered the propeller was obtained using 4480 semiconductor diodes. This rectifying circuit was built and tested by R. George at Purdue University. It was the first demonstration of a rectifying antenna array in which each antenna element and its corresponding semiconductor rectifying diode circuit are integrated together. Today such integrated circuits are known as rectennas.

After the helicopter flight, the U.S. Air Force elected to discontinue their MPT endeavors. In 1967, W. Brown began to court Dr. Werner von Braun and his staff at NASA's Marshall Space Flight Center (MSFC, Washington, DC, USA) on MPT possibilities in space. In 1970, MSFC awarded Raytheon a contract to improve the overall dc-to-dc efficiency of the MPT system. This dc-to-dc efficiency includes the conversion from dc to RF in the magnetron, the aperture transfer efficiency, and the RF-to-dc conversion of the rectenna array. By multiplying these three efficiencies, an overall system efficiency can be determined.

Raytheon continued to improve various rectenna designs throughout the 1970s under the MSFC contract. Another vital improvement to the MPT system was the design of a dual-mode horn by P. D. Potter of the Jet Propulsion Laboratory (JPL, Pasadena, CA, USA) [12]. The modified horn launched a Gaussian beam with negligible sidelobes to improve the aperture transfer efficiency. Advances to solid-state rectifying diodes in the 1970s improved the RF-to-dc conversion significantly. The MSFC program resulted in drastic improvements in MPT system efficiency.

In 1971, Brown of Raytheon and Glaser, the SPS mastermind, along with members of Northrop Grumman and the solar photovoltaic company Textron carried out a six-month study on the SPS concept and concluded that the idea was sound. A letter was then sent to the Director of NASA requesting funding [13]. As a result, NASA's Lewis Research Center (LeRC) awarded a small contract to Brown and his Raytheon colleagues to improve the overall efficiency of existing MPT systems in order to meet the stringent requirements necessary for a fielded SPS. During the early 1970s, NASA began to shift more and more focus to SSP with JPL, under the guidance of Richard Dickinson, playing a major role in the process. The culmination of efforts occurred in 1974 with the MPT setup shown in Fig. 4(a) having an overall dc-to-dc conversion efficiency of 54% $\pm$ 1%. The operating frequency was 2.446 GHz, and the rectenna's output dc power level was 495 W. This efficiency was certified by JPL's quality assurance organization and to this day stands as the highest MPT end-to-end efficiency. The breakdown of the 54.18% $\pm$ 0.94% overall efficiency is 68.9% for the dc-to-microwave power conversion, 95% for the aperture-to-aperture transfer, and 82.4% for the beam collection and rectification [14], [15].

In 1975, another important milestone was shown at the Venus Site of JPL's Goldstone Facility. In this demonstration shown in Fig. 4(b), microwave energy at 2.388 GHz



(a) (b)

Fig. 4. ***Raytheon/JPL MPT experiments: (a) Raytheon setup that achieved 54.18% dc-to-dc system efficiency. (b) JPL Goldstone facility experiment.***

was sent over a 1-mile distance of the Mojave Desert to an awaiting 288 ft^2 rectenna array. The rectenna array was designed by W. Brown at Raytheon and outputted 30 kW of dc power [16]. Both the JPL certified and Goldstone experiments gave NASA the confidence it needed into the viability of MPT and its possible use in Glaser's SPS concept.

Even with the success of Goldstone, LeRC continued to push for improvements to the transmitting antenna array as well as the rectenna. In 1977, Brown improved the design of rectenna arrays by introducing thin-film etched rectennas in which the dc bussing is achieved in the plane of the antennas [17]. Before etched rectennas, the dc networks were attached behind the antennas making previous rectenna arrays more complex, much heavier, and more costly. Almost all currently designed rectennas are etched.

Between 1977 and 1980, NASA worked jointly with the U.S. Department of Energy (DOE) to further evaluate SSP possibilities in providing affordable energy to consumers on Earth. The study concluded in a 670-page document which determined that SSP was a feasible technology and should be pursued in the future [18]. One idea coming out of the study was the idea of retrodirectivity or the ability to keep the microwave beam on target. Unfortunately, the NASA-sponsored program ended in 1980, and thus the U.S. lead in SSP also came to an end.

C. International Involvement (1980s–1990s)

During the 1980s and early 1990s, the center of MPT research and development shifted to Japan and to a lesser extent Europe and Canada. In 1980, a program to develop a long endurance high altitude platform called the Stationary High Altitude Relay Program (SHARP) was proposed in Canada [19]. The platform was to be the first unmanned, fuel-less, lightweight airplane powered remotely by microwaves, thereby enabling it to stay afloat for long periods of time. On September 17, 1987, the 1/8-scale prototype SHARP with a wingspan of 4.5 m seen in Fig. 5(a) flew on beamed microwave power for 20 min at an altitude of 150 m. A 2.45-GHz microwave beam was transmitted by a parabolic dish antenna, providing a power density at the airplane of 400 W/m^2. The dual-polarized rectenna array

(a) (b)

Fig. 5. ***MPT applied to unmanned remotely powered model aircraft: (a) SHARP; and (b) MILAX.***

(a) (b) (c)

Fig. 6. ***Japanese MPT experiments in the 1990s: (a) ISY–METS; (b) ground-to-ground MPT; and (c) SPRITZ.***

received enough microwave energy to generate 150 W of dc power to the electric motor in order to lift and fly the 4.1-kg airplane.

Another example of driving a model airplane using microwave power was the MIcrowave Lifted Airplane eXperiment (MILAX) conducted by Japan in 1992. The experiment was the first to use an electronically scanned phased array to keep the 2.411-GHz microwave beam on the moving target or, in this case, the airplane shown in Fig. 5(b). Two charge-coupled device (CCD) cameras recognized the airplane's outline revealing the location to a computer which scanned the array to the appropriate location. The transmitting array was located on a sports utility vehicle which was also in motion during the tests. MILAX received nationwide well-deserved media coverage in Japan and endeared SSP favorably on the Japanese public [20].

Since Japan was and remains a large energy consumer with little natural energy resources, the promise of SPS has been the driving force behind some very well-funded programs. A couple of these programs have involved in-space experiments. The first of Japan's in-space experiments was the Microwave Ionosphere Nonlinear Interaction eXperiment (MINIX) conducted by Matsumoto and colleagues in 1983. MINIX focused on how the plasma wave dynamic spectrum changes when high-powered microwave energy is transmitted into ionospheric plasma [21], [22]. The second in-space experiment shown in Fig. 6(a) was the International Space Year—Microwave Energy Transmission in Space (ISY–METS) in 1993. In ISY–METS, microwave energy was transferred from microstrip antenna arrays on one rocket to a second rocket carrying two different rectenna arrays, one of which had been designed at Texas A&M University (College Station, TX, USA). ISY–METS represented the first example of MPT in space [23].

Another Japanese MPT program was the aptly named Ground-to-Ground MPT program [24], seen in Fig. 6(b), which resulted in a 2.45-GHz rectenna array having 2,304 elements and measuring 3.4 m × 7.2 m. Last, the SPRITZ program at Kyoto University (Kyoto, Japan) culminated in 2000 with a fully integrated solar power radio transmitter. This system seen in Fig. 6(c) was exhibited at the 2002

World Space Congress in Houston, TX, USA. It remains one of the most advanced rectenna systems. The system uses 133 75-W halogen lamps to provide the photons for illuminating the solar cells. These solar cells output around 166 W at 5% efficiency. The microwave transmitter has 3 b of phase control and operates at 5.77 GHz while outputting 25 W. The rectenna array has 1848 individual rectennas illuminating light-emitting diodes (LEDs) [25].

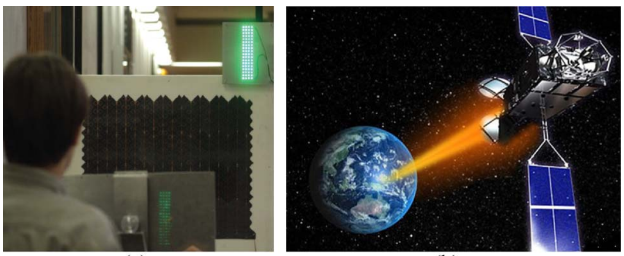
Finally, the ability to supply power to remote communities, wherever they may be, continues to be the focus of a yearly challenge in MPT. SSP "X-prizes" are given out to those who can demonstrate the delivery of 10 kW of solar power wirelessly over a distance of 700 m. These numbers are chosen because they match the needs of the isolated island La Reunion located in the Indian Ocean. The main idea is to generate the necessary power without harming the environment.

D. NASA's Recent MPT Focus (1990s–2000s)

NASA took notice of the noteworthy Japanese successes and in 1995 undertook the Fresh Look Study to reconsider the challenges of large-scale SSP systems. The study emphasized recent technological advancements which made SSP more viable than it was at the end of the 1980s [26]. In 1998, NASA conducted the SSP Concept Definition Study in which experts within NASA and outside the agency were engaged. This second study backed up findings from the Fresh Look Study, but it also narrowed the SSP concepts by invalidating some of the earlier ideas. In 2000, NASA MSFC conducted the SSP Scientific Exploratory Research and Technology (SERT) program. The program broadened the scientific community's involvement and resulted in successful demonstrations on a variety of system level components.

The SERT program addressed numerous concerns previously outlined by Glaser. Some of these issues relate to economic and societal assessment, environmental effects, resource requirements, and legal issues. The economic assessment studies resulted in a cost-effectiveness analysis of an SSP system. The societal assessment included the understanding that SSP is for everyone even in the most remote locations where SSP has an obvious advantage. This avoids the situation where a country monopolizes the technology. SERT discussions on environmental issues focused on human exposure to the microwave energy, especially those people slated to work at or near the rectenna array. Studies have shown that the rectenna arrays can be designed to accept power densities within human exposure limits. Questions still remain on how birds would be affected when flying through the microwave beam, and how birds could be convinced not to roost on the warm rectenna arrays. Some focus was also given to possible SSP-generated climate change, although studies have shown negligible effects even in heavy rainstorms when the absorption of microwave power in the troposphere is expected to increase. Another concern that resonated during SERT meetings was the impact of reradiated harmonic energy arising from the rectenna arrays. Some of this energy could interfere with other electronic devices operating in the same frequency bands, especially given the large number of rectenna elements. Research in this area is ongoing, but it has been shown that rectennas can be designed to minimize harmonic energy reradiation by using harmonic filtering. The land that a rectenna may need is also a concern. The rectenna would most likely be placed in an arid environment since rain can reduce rectenna efficiency. Desert placement would in turn mitigate the radiative effects on birds and people since both reside primarily along the coasts and waterways. Another concern is that the astronomers will be upset that a large object that reflects sunlight is appearing in the night sky. This is a viable concern especially since an SSP system will call for a myriad of very large satellites. Last, the transport of materials to space to construct the SPSs is a daunting task. How to use future transport payload bays more efficiently and the elevator to space concept [27] are both being studied for transporting the crucial supplies. With recent nanotube technological breakthroughs, the elevator idea is not as outlandish as it might seem.

With the renewed U.S. involvement and continuing efforts by Japanese researchers and others, SSP is progressing steadily. Much of the research since 1990 has focused on producing extremely efficient rectennas and rectenna arrays. One such etched rectenna array design, introduced by Texas A&M University researchers in 2000 under SSP SERT funding, accepts circularly polarized energy at 5.8 GHz and outputs dc at 82% efficiency [28]. This efficiency was made possible by the recent advances made in reducing the parasitic losses of flip-chip Schottky diodes. The frequency 5.8 GHz was chosen for its ability to propagate through the atmosphere with relatively low loss and because the receiving and transmitting antennas become reasonably small from the point of SPS construction feasibility. Circular polarization (CP) was chosen because of atmospheric depolarization effects such as Faraday rotation. Consequently, linearly polarized (LP) systems used for SSP would most likely see significant degradations in efficiency. A cascaded array of these CP rectennas is shown in Fig. 7(a). This is the same rectenna array as that shown



(a) (b)

Fig. 7. *MPT systems: (a) Texas A&M University demonstration; and (b) SSP concept.*

in Fig. 1. The interrogating CP phased array, also the same as that shown in Fig. 1, is being focused toward the center of the rectenna array resulting in the illumination of 72 GaN diodes. This demonstration was shown to the media and to members of the U.S. Congress at the 2002 World Space Congress in Houston, TX, USA. While all of the aforementioned successes show great MPT promise, the leap from experiments like the Raytheon/JPL, SHARP, MILAX, SPRITZ, and the Texas A&M demos to the ultimate goal of a fully functional SSP system, like that illustrated in Fig. 7(b), is still decades away and fraught with difficulty.

E. The Last Decade

In the last ten years, numerous articles have been written about SSP, but supportive research has been sporadic at best. The main reason for the dearth of activity is the usual culprit, funding limitations. However, there have been a couple of experiments worth discussing. Two of these experiments are the inductive near-field work by Soljacic's team at the Massachusetts Institute of Technology (MIT, Cambridge, MA, USA), and John Mankins' Hawaii MPT demonstration.

Reminiscent of Telsa's work 100 years earlier, the 2006 MIT experiment, carried out by physicist Marin Soljacic and his colleagues, involved the inductive near-field coupling of power from a primary ac-excited coil to an awaiting secondary coil located 2 m away. A 60-W light bulb attached to the secondary coil was successfully lit, as seen in Fig. 8(a). However, the MIT researchers quantified the power transfer efficiency at 15%. In addition, the measurable power levels at 10 MHz were 14 times higher than the safety standards put forth by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Regardless of these concerns, MIT researchers see this induction work as a possible way to remotely charge Wi-Fi devices [29]. This MIT work does not come under the realm of MPT due to its operational frequencies, but it is a WPT experiment worth noting.

The second experiment that has garnered much attention in recent years is the Hawaii MPT experiment carried out in 2008 by John Mankins of Managed Energy Technologies in conjunction with researchers at Texas A&M University and the University of Kobe (Kobe, Japan). It should be mentioned that John Mankins is a longtime advocate of SSP, having spearheaded the previous SERT efforts while at NASA. The Hawaii demo was covered live by Discovery Communications, a TV channel. The experiment transmitted power from the Maui-based array, seen in Fig. 8(b), to the big island of Hawaii, over a distance of 148 km [30]. This length set a new distance record, but the amount of power received at the big island was less than 1/1000th of 1% of the power transmitted from Maui [31]. This, from an MPT standpoint, is considered by many a failure. However, the poor performance was predicable since the transmitting and receiving arrays were far too small for efficient transfer over the 148 km. In other words, massive spillover loss was the culprit. John Mankins' experiment was done on a budget of less than $1 million, which, in all fairness, limited what could be accomplished.

(a) (b)

Fig. 8. ***Recent WPT systems: (a) MIT near-field demonstration; and (b) Managed Energy Technologies, Texas A&M University, University of Kobe 2008 Hawaii MPT experiment.***

Last, Japan has a keen interest in developing SSP because of its resource limitations. Japan Aerospace Exploration Agency (JAXA) has begun developing numerous hardware subsystems that will be integrated into a working SPS by the year 2030 [31], [32]. In the near term, Japanese researchers at the Taiki Multi-Purpose Aerospace Park in Hokkaido will attempt to use a 2.4-m-diameter antenna to send microwave energy over 50 m to a rectenna in order to operate a household heater [31]. If this experiment proves successful, the next step is to scale the 50-m distance to 36 000 km and the 2.4-m antenna to 3 km. This scaled-up version would be enough to receive 1 GW of electricity which could conceivably be enough to power 500 000 homes.

Currently, the part of the SSP system that warrants the greatest focus is the photovoltaic solar cells. The state of the art for solar cell sunlight to dc efficiency has remained around 30% for the past couple of decades. The other 70% is predominantly heat loss, which can heat the transmitting aperture, thereby lowering the radiated power. Improvements in solar cell efficiency, using techniques such as thin film and quantum dot technology, are essential before fielding any functioning SSP system. Since MPT/SSP funding over the last decade has been limited, it might make sense to focus on specific subsystem improvements before another full blown MPT test is attempted.

III. MPT SYSTEM ARCHITECTURE

A. Transmitting Phased Array

1) Amplitude-Quantized Aperture: In order to achieve maximum transfer of the microwave energy from the source to the receiver, the transmitting antenna must be designed such that its sidelobes are reduced to the lowest acceptable levels and that its proper beamwidth keeps

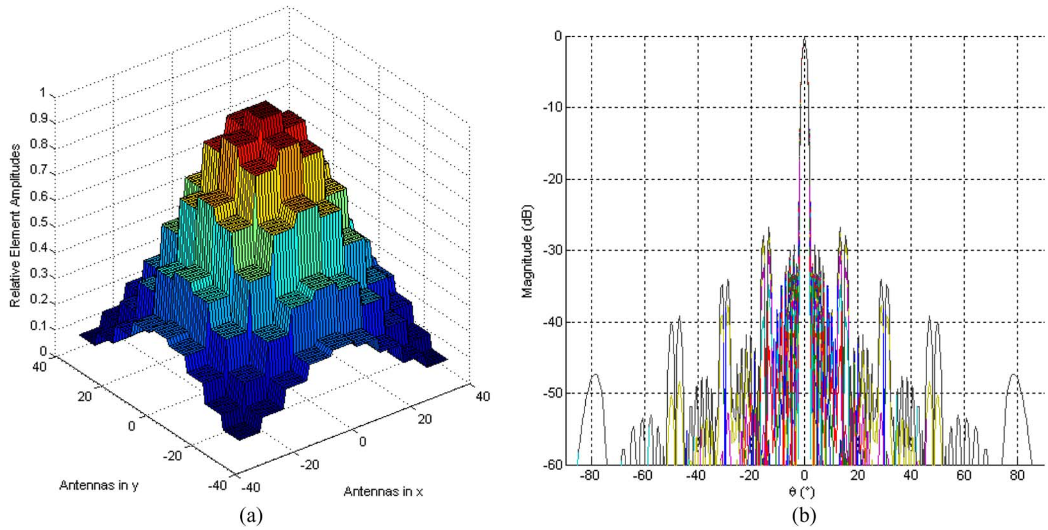


Fig. 9. ***SSP array: (a) amplitude taper for proposed array; and (b) corresponding array factor.***

spillover losses to a minimum. In the past, high-gain reflectors and horns antennas have been used to transmit large amounts of power; however, modern systems call for electronically steered phased arrays for greater flexibility in keeping the microwave beam on target.

In one such proposed SSP system, equivalent magnetrons, used for RF source generation, are attached in a nonuniform manner to equal-amplitude subarrays positioned along a 30-dB Taylor-weighted taper. Fig. 9(a) shows a particular array aperture composed of 9 × 9 subarrays. Each subarray has 8 × 8 elements with all 64 elements driven by the same level of RF power. Thus, the total transmitting aperture consists of 72 × 72 antenna elements. If the 72 × 72 antenna elements are spaced $\lambda_0/2$ in both $\hat{x}$ and $\hat{y}$ directions with no progressive phase shift, the resultant elevation array patterns shown in Fig. 9(b) are generated. These patterns represent 90 different elevation cuts with each rotationally stepped to bisect the $\hat{x}$–$\hat{y}$ plane every 2°. These 2-D elevation pattern cuts convey sidelobe and pattern shape information for the entire upper radiation hemisphere. This array has worst case sidelobes of −27 dB at ±13.5° along the principal plane cuts. Single element rolloff is accounted for using a typical raised-cosine pattern. The double-hump sidelobes, typical of subarray amplitude quantization, are readily seen. The sidelobe suppression can be improved by reducing the subarray size or by increasing the overall size of the array.

The magnetron placements are determined by the "plateau" power level of the various subarrays. Assuming all of the magnetrons are equivalent, placing one at each subarray will result in the entire array being uniform, which would result in 13-dB sidelobes. To accomplish the taper, magnetrons need to be placed in a nonuniform manner. For instance, the centermost subarray could be tied to a single magnetron, but the subarrays moving away from the center need to be grouped in various ways to single magnetrons in order to accomplish the "domed" power distribution across the aperture. The overall size of the transmitting aperture is based on the desired transmitting gain and the beamwidths necessary to avoid unnecessary spillover losses. Obviously, an SPS 5.8-GHz transmitting array will be much larger than just 72 × 72 elements. However, similar ratios of overall array size in 1-D to subarray size in the same dimension will result in similar sidelobe levels. A myriad of phased array architectures exist so other solutions may yield better results.

2) Split-Gaussian Transmitting Aperture: The transmitting aperture temperature becomes an issue in SSP and other MPT applications where the generated power fed to the transmitting array is significantly large. Any array inefficiencies will result in heat being propagated through the transmitting aperture. This heat can destroy sensitive electronics such as phase shifters and could potentially melt the array elements. The array radiation pattern discussed in the previous section is formed using an aperture taper with maximum current weighting delivered to the centermost antenna elements. Consequently, the centermost elements are more susceptible to melting than those away from the center.

Two solutions to reducing the temperature at the center of the transmit array are the split Gaussian and the Gaussian with an attenuated center region [33]. These two distributions are illustrated in Fig. 10. These novel weighting schemes distribute power throughout the aperture more uniformly than the aforementioned traditional transmitting aperture case. As a result, the heat caused by losses in the transmitter is distributed more evenly in the aperture lowering the chance of failure. The split Gaussian of Fig. 10(a) has a center weighting equal to the outermost

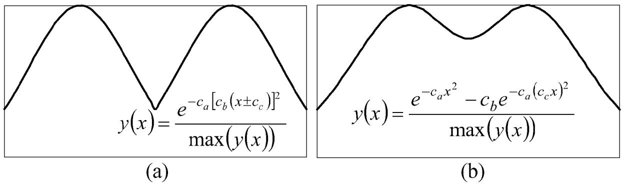


Fig. 10. *(a) Normalized split Gaussian taper. (b) Normalized Gaussian taper w/ attenuated center region.*

edges. The distribution in Fig. 10(b) has a center level that can vary. Both of these tapers are radially symmetric in the azimuth planes.

These tapers were analyzed in great detail by Zepeda [33] for a transmit array 250 m in diameter with an operating frequency of 5.8 GHz. The power density of the array's aperture versus center power reduction is adjusted by varying the equation coefficients. The coefficients affect the sidelobe performance of the array. Surprisingly, sidelobe levels on the order of 20 dB are possible with this unconventional aperture distribution. Thus, this split Gaussian taper produces sidelobes about 7 dB worse than the aforementioned conventional "Taylor" case with great heat reduction, which is vital to the reliability of the SPS transmitting array.

B. Aperture-to-Aperture Transfer

1) Friis Free-Space Transmission: For MPT systems, the transmitting antenna is normally either a high gain reflecting antenna, a horn antenna, or a large array consisting of many individual elements. Historically, the receiving unit in MPT systems has been a rectenna array made up of cascaded rectennas. Each of these rectennas is a combination receiving antenna and rectifying circuit consisting of a rectifying semiconductor diode. A typical MPT setup is shown in Fig. 11.

The power in watts received at the receiving antenna based on Friis free-space transmission equation is

$$P_r = P_t\left(\frac{\lambda_0}{4\pi d}\right)^2 G_t(\theta_t,\phi_t)G_r(\theta_r,\phi_r) \times \left|\hat{\rho}_t\cdot\hat{\rho}_r^*\right|^2\left(10^{\frac{L_a(z)}{10}}\right)\left(10^{\frac{L_{ra}(t)}{10}}\right) \quad (1)$$

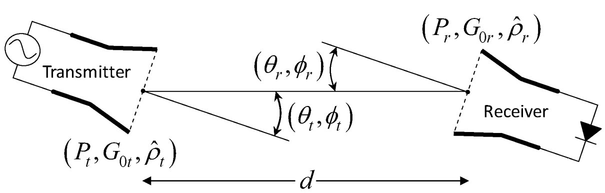


Fig. 11. *Geometrical depiction of a typical MPT setup [34].*

where P_t is the source power transmitted, λ_0 is the free-space wavelength of the energy at the frequency of operation f, and d is the distance separating the phase-center midpoints of the transmitting and receiving antenna apertures. The quantity $(\lambda_0/4\pi d)^2$ is declarative of the path loss between the two antennas, independent of atmospheric conditions.

The variables G_t and G_r are the measurable gains of the antennas in the oriented direction (θ_t,ϕ_t) and (θ_r,ϕ_r), respectively. θ_t and θ_r represent the elevation angles, and ϕ_t and ϕ_r are the azimuth angles of the transmitting and receiving antennas, respectively. If the antennas both have peak gain broadside of the array's aperture (normal to the aperture plane), maximum power transfer will occur if $\theta_t=\theta_r=0°$.

The polarization mismatch is calculated by $|\hat{\rho}_t\cdot\hat{\rho}_r^*| = |\cos\psi_p|^2$ where $\hat{\rho}_t$ and $\hat{\rho}_r$ are the polarizations of the transmitting and receiving antennas, respectively, and ψ_p is the angle between their corresponding ϕ-unit polarization vectors. To avoid polarization mismatch using LP antennas, ϕ_t and ϕ_r must be such that the time-harmonic electric field vectors of each antenna are collinear. This potential polarization mismatch problem can be avoided by making both antennas CP. Circular polarization also avoids "depolarization" effects caused by the polarization rotation of the microwave energy's electric field vector as it propagates through the atmosphere. Depolarization is primarily caused by water present in the propagation path and becomes a serious problem during rainfall.

2) Atmospheric Absorption: Another important consideration in MPT design is atmospheric attenuation. This attenuation is caused by the presence of oxygen and water in the atmosphere during normal calm conditions and increases as the vertical distance z from Earth increases. Attenuation is greatest near sea level since oxygen and water levels decrease moving away from Earth. The atmospheric attenuation is denoted $L_a(z)$ to reflect the height dependence. Other gases such as carbon dioxide can contribute attenuation, but oxygen and water dominate due to their prevalence.

The choice of operating frequency for an MPT system is partially governed by atmospheric absorption. The industrial, scientific, medical (ISM) bands at 2.45 and 5.8 GHz have been chosen for MPT in the past because there attenuation is low relative to higher frequencies and the sizes of the transmitting and receiving antennas are of reasonable size. More importantly, the ISM bands are permissible for individual use by the U.S. Federal Communications Commission. For this reason, consumer microwave ovens have been designed at 2.45 GHz, and, as a result, the technology behind their microwave source magnetrons has matured to the point of providing over 80% dc-to-RF conversion efficiency at 2.45 GHz. Similar source performance at 5.8 GHz still needs some work, but 5.8 GHz appears to be the frequency of choice for future MPT SSP since it allows smaller antenna apertures. An

MPT system designed at 22 GHz would see large amounts of attenuation due to water vapor especially in humid climates near sea level. Similarly, oxygen would hamper MPT at 60 GHz.

Inclement weather further complicates the problem by adding variable amounts of attenuation. The attenuation loss in decibels due to rainfall is [35]

$$L_{ra}(t) = \int_0^{d(t)} a[A(z,t)]^b\, dz$$
$$a = \begin{cases} 4.21 \times 10^{-5} f^{2.42}, & 2.9 \le f \le 54 \text{ GHz} \\ 4.09 \times 10^{-2} f^{0.699}, & 54 \le f \le 180 \text{ GHz} \end{cases}$$
$$b = \begin{cases} 1.41 f^{-0.0779}, & 8.5 \le f \le 25 \text{ GHz} \\ 2.63 f^{-0.272}, & 25 \le f \le 164 \text{ GHz} \end{cases} \quad (2)$$

and $d(t)$ is the time-dependent portion of the path, between the transmitting and receiving antennas, that contains the rain. $A(z,t)$ is the amount of rainfall in millimeters per hour at time t at a distance z km measured from the ground along the path. These atmospheric attenuation problems are well known to satellite communication designers and have the potential of greatly undermining an MPT system. In a dry laboratory environment where d is just within the far field of the transmitter, both $L_a(z)$ and $L_{ra}(t)$ can be neglected from (1).

C. Rectenna

1) Rectenna Functionality: A schematic of the basic rectenna is illustrated in Fig. 12(a). A photo of an actual LP rectenna is shown in Fig. 12(b) to show the corresponding rectenna components etched on a printed substrate. This LP rectenna is designed in coplanar stripline (CPS) which provides obvious placement advantages. An antenna is used to capture the incident RF energy at frequency f. This energy is then passed through the harmonic rejection filter with minimal loss and on to the Schottky diode where the RF energy is rectified to form dc power. The dc energy is then passed through the dc bypass filter to appear as the voltage V_D across the load resistor R_L. The remaining energies at the various harmonic frequencies $2f, 3f, \ldots$ created from the Schottky diode's nonlinear process are reflected back to the diode by both the harmonic rejection filter and the dc bypass filter. This "trapping effect" results in additional mixing of the harmonic frequencies and ultimately in the generation of more dc power. The harmonic rejection filter also keeps unwanted harmonic energy from reradiating into free space via the antenna. If allowed to reradiate, this harmonic energy could interfere with various electronic devices in close proximity to the rectenna that are operating in the same frequency band. Some fundamental f energy passed by the harmonic rejection filter is lost to the antenna for reradiation but has been shown to be minimal since the Shottky diodes used currently have very high RF-to-dc conversion efficiencies on the order of 80%. In past designs, low-pass filters have been used to suppress the harmonic energy with very low loss. However, in the more recent designs, band stop filters have been used in order to provide much greater harmonic suppression while maintaining the low loss in the passband. In addition, the harmonic rejection filter is designed to match the real part of the diode's impedance to the antenna's input impedance Z_A. The dc bypass filter also serves two additional purposes. First, by acting as a short-circuited tuning stub, it tunes out the reactance of the Schottky diode based on the dc bypass filter's position in the rectenna circuit. Second, it blocks any RF signals $(f, 2f, 3f, \ldots)$ from reaching the resistive load. This allows the dc voltage across the load resistor to be level with minimal amplitude versus time variation.

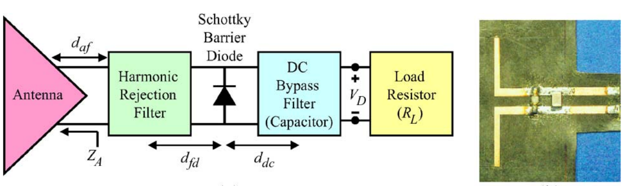


Fig. 12. ***(a) Rectenna schematic with appropriate component distances. (b) Photograph of an LP dipole rectenna. Copper strips (not seen) are etched on the substrate's backside between the dipole and the diode to form the harmonic rejection filter. A chip capacitor forms the dc bypass filter. The load resistor is not shown [36].***

2) Schottky Diode Rectifier: When designing an efficient rectenna, consideration must be given to choosing the proper diode, the type of transmission line on which to distribute the power between the rectenna's various components, the type of antenna, the spacing between the diode and the dc bypass filter (capacitor), and the resistance value of the load. The first component to consider is the nonlinear Schottky diode since the design of the other rectenna parts depends directly upon the diode's performance.

The diode conversion efficiency (η_D) is key in determining the rectenna's performance and is based upon the diode's equivalent circuit diagramed in Fig. 13. The diode efficiency is defined as the following ratio:

$$\eta_D = \frac{\text{dc output power}}{\text{RF power incident on diode}}. \quad (3)$$

The diode's input impedance at the fundamental frequency f is defined as (4), shown at the bottom of the next page [36], [37], where θ_{on} refers to the diode's

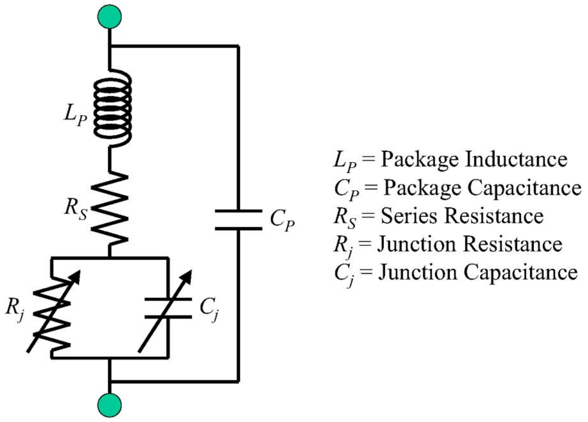


Fig. 13. *Schottky diode equivalent circuit.*

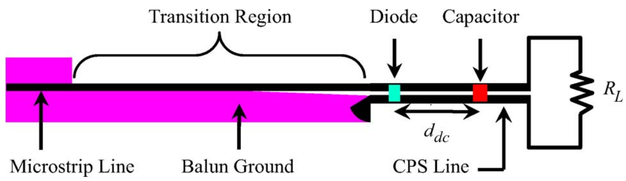


Fig. 14. *Circuit designed for the direct determination of η_D and d_{dc}. The black and pink traces are etched on the top and bottom of the substrate, respectively [38], [39].*

forward-bias turn-on angle. The real part of the diode's impedance from (4) is generally on the order of a couple hundred ohms. This resistance value determines the type of transmission line to use in order for the diode to achieve high RF-to-dc conversion efficiency. By choosing a transmission line with a characteristic impedance equal to the diode's real impedance, RF mismatch at the diode can be eliminated. If mismatch is present, the RF-to-dc conversion efficiency suffers. A commonly used transmission line that can be designed to have characteristic impedances on the order of several hundred ohms is CPS. CPS is composed of two parallel strips which can propagate energy from one location to another with low loss.

The imaginary part of the diode impedance that results from (4) is tuned out using the length of transmission line between the diode and the dc bypass filter (chip capacitor). The capacitor acts electrically as a short to RF energy. Therefore, the combination of the capacitor and the length of CPS transmission line between the diode and capacitor form a short-circuited tuning stub. The CPS has a topology that is readily suited to construct the short-circuited tuning stub. This tuning stub's length is adjusted by changing the capacitor's placement on the CPS. With the tuning stub counteracting the diode's reactance and the characteristic impedance of the CPS matching the real impedance of the diode, the RF energy that is incident upon the diode will ideally see no reflection or mismatch across the terminals of the diode.

3) Diode-to-Capacitor Distance (d_{dc}) *and Resistance* R_L*:* An experimental technique described by Strassner and Chang [38], [39] and shown in Fig. 14 utilizes a microstrip to CPS balun to determine the distance between the diode and the capacitor in conjunction with various source powers and load resistances. This circuit provides a direct approach for experimentally determining the diode's RF-to-dc conversion efficiency versus the microwave power incident upon the diode. In essence, it allows for a way to design the RECTifier portion of the rectenna. Microwave energy is inputted into the microstrip line at a predetermined level based upon the CP antenna gain and the assumed power density levels at the rectenna array's surface. The electromagnetic fields are then rotated in the pink transition (balun) region in order to match the microstrip line to the CPS. Once the energy strikes the diode, dc power is formed and passed through the capacitor to the load R_L. Various values for R_L are tried for maximum efficiency determination. The distance between the capacitor and R_L can be arbitrary since only dc energy is propagated between the two. This direct measurement approach has the advantage of including the effects of the higher order harmonics created from the diode mixing.

4) Radiating Element: The final rectenna component is the antENNA. The impedance Z_A looking into the terminals of the antenna must be purely real and must match the characteristic impedance of the transmission line that connects the antenna to the harmonic rejection filter. The antenna is chosen based on the necessary polarization, gain, and bandwidth as well as how the antenna is to be connected to the rest of rectenna circuitry. As far as printed rectennas are concerned, the ones that have achieved the highest efficiencies have used dipole antennas etched on thin substrates over ground planes. These types of antennas are easily fed using CPS. A reflecting plane is normally placed approximately a $\lambda_0/4$ behind the dipole antenna in order to focus the antenna's energy in one direction. Since air acts as the dielectric between the dipole and the reflecting ground plane, the antenna can achieve close to 100% radiating efficiency. Having such a

$$Z_D = \frac{\pi R_S}{\cos\theta_{\text{on}}\left(\frac{\theta_{\text{on}}}{\cos\theta_{\text{on}}} - \sin\theta_{\text{on}}\right) + j\omega R_S C_j\left(\frac{\pi - \theta_{\text{on}}}{\cos\theta_{\text{on}}} + \sin\theta_{\text{on}}\right)} \tag{4}$$

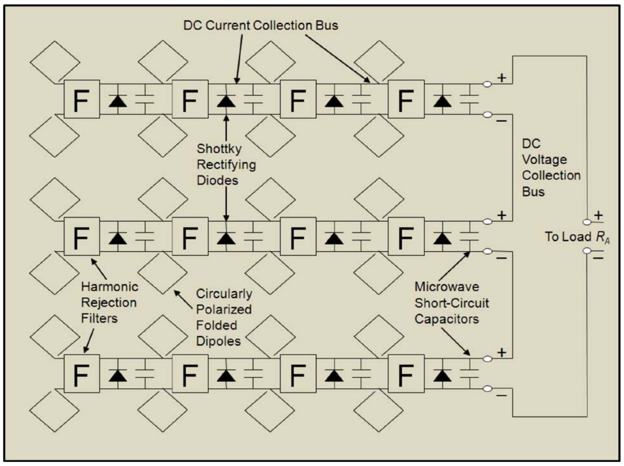


Fig. 15. ***Array consisting of 12 individual rectennas.***

high radiation efficiency is key in achieving the best possible rectenna efficiency.

5) Rectenna Array: The rectenna array serves as both the absorber of the microwave energy from the transmitter and the rectifier of the microwave energy to dc power [40]. A diagram of a typical rectenna array is shown in Fig. 15. The antennas in this case are CP folded dipoles that send captured microwave energy at frequency f through the harmonic rejection filters (Fs) to the Schottky rectifying semiconductor diodes. The dc power, which then arises from the diode rectifiers, is passed through the capacitors along the current collection bus to the peripheral voltage collection bus. Each of the CP folded dipoles is essentially two antennas positioned at the same spot. This reduces the number of rectennas needed to cover an area by one half when compared to an LP system. Thus, the number of capacitors and diodes is also cut in half resulting in significant savings, especially when considering the eventual size of one of these rectenna arrays (miles across), not to mention that CP has the depolarization advantages.

In designs where dipoles and CPS transmission lines are used, columns of parallel-cascaded rectennas are joined in series to produce large dc powers at the output of the array. The rectennas on each column produce dc currents that are summed at the end of that column. The dc voltages of each column are summed resulting in the voltage V_A across a load resistor R_A. The rectenna array's load resistance necessary for achieving the maximum rectenna array RF-to-dc conversion efficiency η_A is defined by

$$R_A = R_L \frac{N_x}{N_y} \tag{5}$$

where N_x is the number of columns in the array, N_y is the number of rectennas in each column, and R_L is the optimal load resistance for each individual rectenna. The diodes are connected in parallel in each column, and the columns are connected in series. Equation (5) assumes that the incident power striking the surface of the rectenna array is arriving as a plane wave and that the number of rectennas in each column is the same.

6) Antenna-to-Capacitor Distance ($d_{\rm ac}$) Determination: Each CP rectenna is isolated RF-wise from the next adjacent rectenna by the capacitors which appear as short circuits to the incident microwave energy that strikes them. Energy that is accepted by a particular CP antenna travels to both the nearest capacitor as well as the nearest filter F. The antenna-to-filter distance $d_{\rm af}$ and the filter-to-diode distance $d_{\rm fd}$ can be arbitrary, but the antenna-to-capacitor $d_{\rm ac}$ distance, illustrated in Fig. 16, must be properly determined to allow for efficient rectenna array operation. The test circuit for determining the proper $d_{\rm ac}$ is shown in Fig. 16(a). This circuit includes the antenna, filter, and a microstrip-to-CPS balun. The Fig. 16(a) components are simulated in a electromagnetic simulator without the capacitor and tweaked for a desired input match at 5.8 GHz. This circuit is then etched. Placing the capacitor at various $d_{\rm ac}$ locations on the fabricated circuit results in the experimental input port S_{11} matches shown in Fig. 16(b). For this specific example, the distance $d_{\rm ac} = 8.5$ mm gives the same measured input match at 5.8 GHz as the measured case when no capacitor is used [28]. As expected, this distance corresponds to a quarter wavelength within the CPS environment.

7) Free-Space Measurement: The setup for determining the rectenna array's η_A is depicted in Fig. 17.

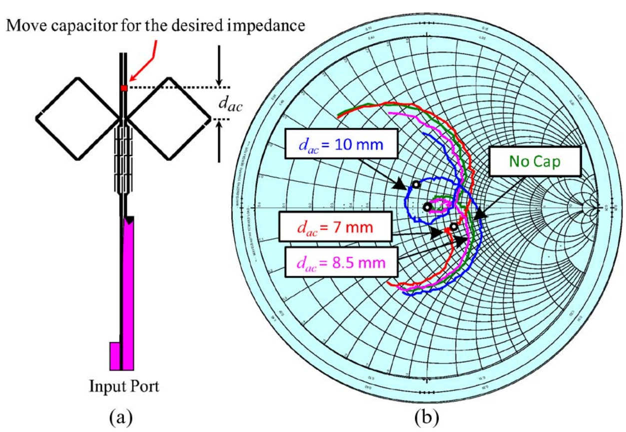


Fig. 16. ***(a) Circuit for determining antenna-to-capacitor spacing. (b) Resulting input match.***

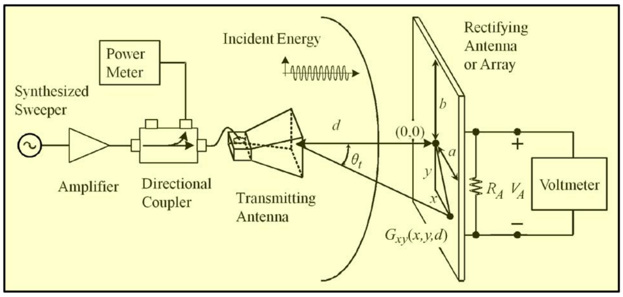


Fig. 17. ***Laboratory setup for measuring η_A. The rectenna array output power is defined by the square of the voltage V_A divided by the load resistance R_A.***

The RF-to-dc conversion efficiency η_A is defined in terms of the rectenna array's aperture area A_A^{eff} as

$$\eta_A = \frac{P_{\mathrm{dc}}}{P_r} = \frac{4\pi d^2\left(\frac{V_A^2}{R_A}\right)}{P_t G_t(\theta_t,\phi_t) A_A^{\mathrm{eff}} \left|\hat{\rho}_t \cdot \hat{\rho}_r^*\right|^2 \left(10^{\frac{L_a(z)}{10}}\right)\left(10^{\frac{L_{ra}(t)}{10}}\right)} \quad (6)$$

where $A_A^{\mathrm{eff}} = 4ab$. It is important to make sure the rectenna's aperture is positioned such that each of its antennas point toward the transmitter, i.e., $\theta_r = 0°$. The rectenna array is composed of numerous rectenna elements, each receiving power according to the transmit gain distribution $G_{xy}(x,y,d)$. The average transmit gain seen across the rectenna array's aperture is [39]

$$G_{\mathrm{avg}}(a,b,d) = \frac{1}{4ab}\int_{-b}^{b}\int_{-a}^{a} G_{xy}(x,y,d)\,dx\,dy. \quad (7)$$

This takes into account the fact that the power striking the rectenna array's aperture is normally not a plane wave. In other words, the transmit power density is greatest at (0,0) and decreases toward the rectenna array's edges. The RF-to-dc conversion efficiency can now be expressed as [39]

$$\eta_A = \frac{\pi d^2\left(\frac{V_A^2}{R_A}\right)}{ab P_t G_{\mathrm{avg}}(a,b,d)\left|\hat{\rho}_t \cdot \hat{\rho}_r^*\right|^2 \left(10^{\frac{L_a(z)}{10}}\right)\left(10^{\frac{L_{ra}(t)}{10}}\right)}. \quad (8)$$

Some past designs compensate for the tapered power density present at the rectenna array's surface to increase η_A. One way this compensation is accomplished is by tuning the load resistance or by changing the lengths between various components within each rectenna individually.

In 2002, as a result of NASA'a SERT study, Strassner and Chang developed the printed CP rectenna array shown in Fig. 18(a) [39]. The array uses a MA/COM MA4E1317 Schottky diode and a chip capacitor to achieve 78% RF-to-dc conversion for an incident power density of 8 mW/cm^2 at 5.61 GHz. The rectenna uses folded dipole antennas called dual rhombic loops which have the advantages of being circularly polarized, giving them higher gains than traditional dipole antennas, and being easily implemented into CPS circuits. The antennas are placed $\lambda_0/4$ above a ground plane for a 3-dB radiation enhancement in the desired direction. A 3 × 3 inner section of the array was connected, and the resulting measured data are shown in Fig. 18(b)–(d). Fig. 18(d) shows that there is a plateau to the efficiency curves. In addition, the array's load resistance is very important in obtaining high efficiencies. These curves are very typical of rectennas operating in the microwave frequency range.

The same measurement setup for measuring the rectenna array's efficiency can be applied to singular rectennas as well although quantifying the effective radiating area is a bit more difficult. The chart in Fig. 19 shows the best efficiencies that have been achieved over the last 50 years for the frequencies 2.45 GHz [41], 5.8 GHz [36], and 35 GHz [42]. The plot illustrates how the efficiency flattens as the operating frequency increases. Predicting the conversion efficiency of higher frequencies from measured data gathered at 2.45 GHz works reasonably well. This scaling prediction is based on the effective area differences at the various frequencies. During scaling, the antenna gain is held constant at 6.4 dB. This gain is typical for an LP dipole antenna located $\lambda_0/4$ over a ground plane. The main limitations on increasing the RF-to-dc conversion efficiency lie in the device physics of the Schottky diode.

8) Recent Rectenna Developments: Over the last decade or so, researchers have come up with a variety of rectenna and rectenna array designs, including some dual and CP rectennas. In 2000, a group at JPL was able to operate a 50-V dual-polarized rectenna array composed of nine patch antennas and 18 diodes to around 52% RF-to-dc conversion at 8.51 GHz [43]. The array was designed to produce high voltages > 50 V in order to drive electrical actuators. Stacked patches, each with two slot-coupled feed points, were used to achieve the dual polarization.

In 2001, the University of Colorado at Boulder (Boulder, CO, USA) published the two novel rectenna arrays, shown in Fig. 20, for ambient power collection over large bandwidths [44]. The first is a grid rectenna array operating from 4.5 to 8 GHz, and the second is a spiral rectenna operating from 8.5 to 15 GHz. The grid array had a maximum η_A of 35% at 5.7 GHz for an incident CP power density of 7.78 mW/cm^2. The spiral array used alternating RHCP and LHCP spirals to achieve a maximum η_A of 45% at 10.7 GHz for 1.56 mW/cm^2. The lower efficiencies are due to the relatively low gain of the radiating elements

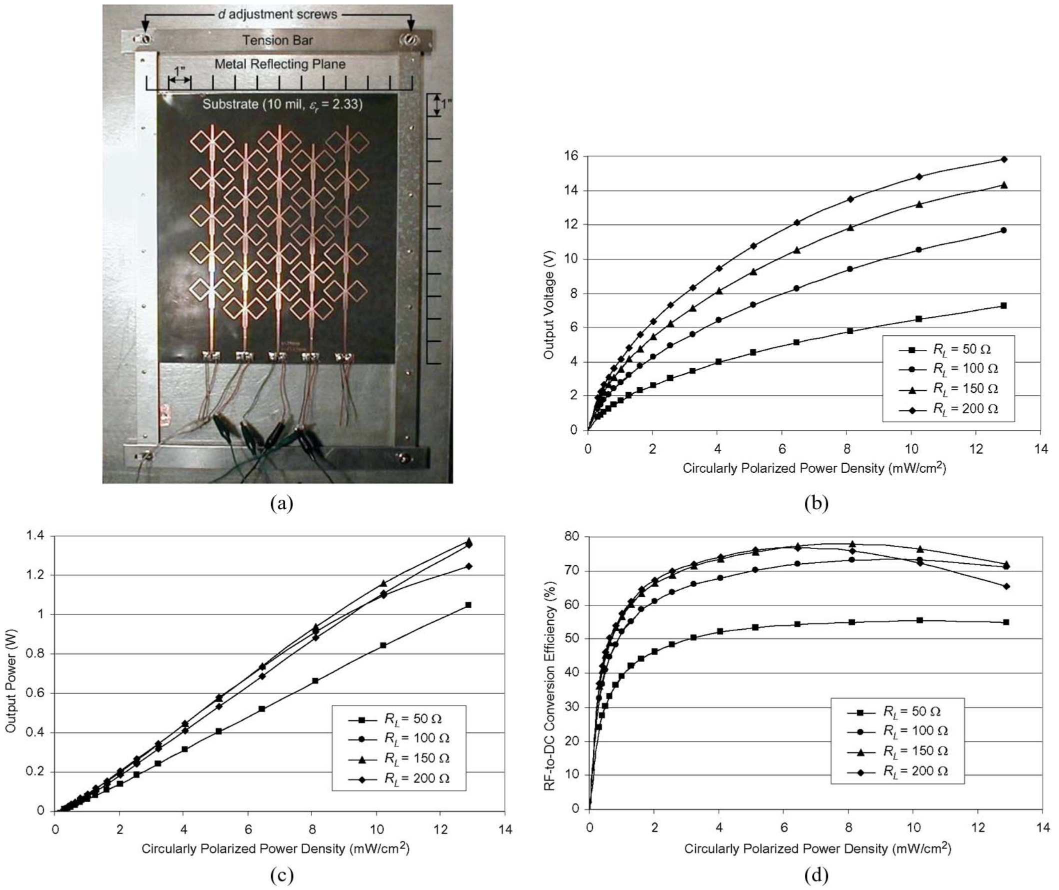


Fig. 18. ***(a) CP rectenna array. Rectenna array CP measured performance: (b) rectified voltage, (c) output power, and (d) η_A for various resistive loading*** $(R_L = R_A)$.

since both arrays have radiators that are electrically large. The idea of ambient power collection is to recycle ambient RF noise for use in functioning systems.

In 2002, an LP dual-frequency rectenna designed in a CPS layout and operating at both 2.45 and 5.8 GHz was developed by Suh and Chang at Texas A&M University [45]. To resonate at the two frequencies, slight modifications to the traditional dipole structure were made as shown in Fig. 21(a). The rectenna was placed 17 mm above a metal reflecting ground plane to focus the antennas' energy in one direction. The rectenna used a MA/COM MA4E1317 Schottky diode and a chip capacitor to achieve 84.4% and 82.7% at 2.45 and 5.8 GHz, respectively. A combination of CPS low-pass and band-stop filters were

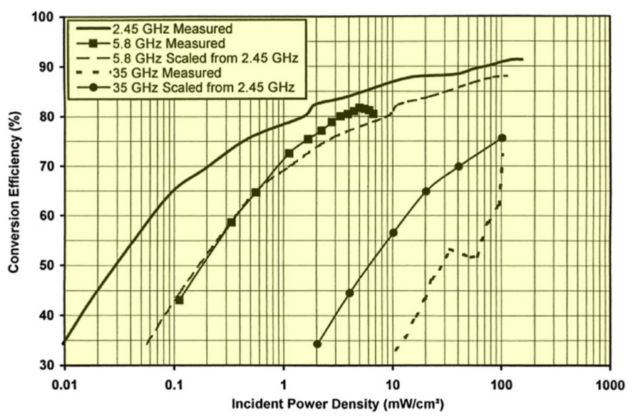


Fig. 19. ***State-of-the-art rectenna efficiencies.***

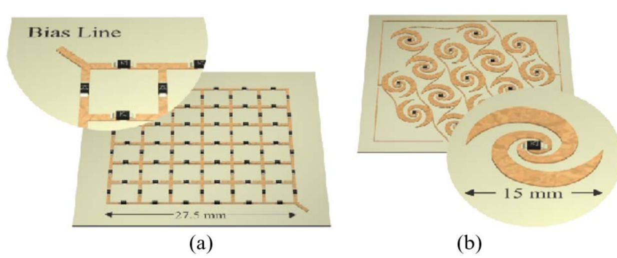


Fig. 20. ***The grid and spiral rectenna arrays. The latter has alternating RHCP and LHCP elements while the former one half cycle of both polarizations equally. The black rectangles are Schottky diodes.***

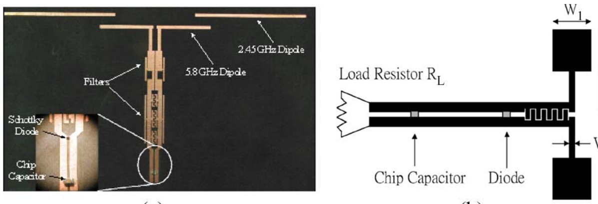


Fig. 21. ***Texas A&M LP rectenna designs: (a) dual-frequency rectenna operating at 2.45 and 5.8 GHz; and (b) 5.8-GHz stepped-impedance dipole rectenna.***

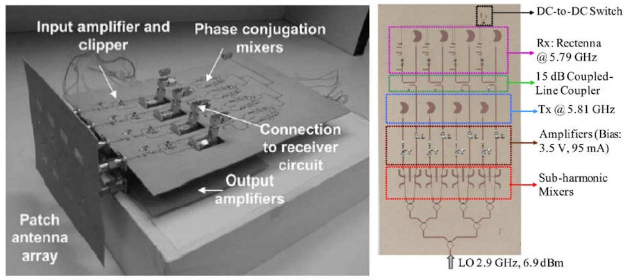


Fig. 23. ***UCLA retrodirective arrays designed: (a) full-duplex retrodirective array; and (b) adaptive-power-controllable retrodirective array.***

used to suppress higher order harmonic energy from reradiating into free space. In 2007, Texas A&M University researchers Tu, Hsu, and Chang designed the compact 5.8-GHz rectenna seen in Fig. 21(b) to obtain an η_D of 76%. A stepped-impedance dipole antenna is used to facilitate a 23% reduction in dipole length [46].

In recent years, several institutions within Asian countries, where MPT research is relatively new, have published rectenna papers. At the National Central University (Jhongli, Taiwan) in 2010, researchers designed the dual-band rectenna shown in Fig. 22(a). For an incident power density of 30 mW/cm^2, this rectenna achieves 53% and 37% conversion efficiency at 35 and 94 GHz, respectively. The linear tapered slot antenna has gains of 7.4 and 6.5 dBi at 35 and 94 GHz. The total rectenna size is 2.9 mm^2 [47]. At the University of Hong Kong, Chin, Xue, and Chan developed the 5.8-GHz rectenna shown in Fig. 22(b). This rectenna achieves 68.5% conversion efficiency [48].

D. Retrodirectivity

The final thing to consider in an MPT design is retrodirectivity. For the SSP example, many of the aforementioned rectenna array designs use fixed panels. Some thought has been given to mechanically steering the rectenna panels to vary θ_r. The SPS is proposed to be in geostationary orbit, but if phase errors occur in the phased array or the SPS through some inertial structural bending, even in the slightest amounts, the microwave beam can veer off of the rectenna array. To avoid this problem, a feedback loop is established by a pilot beam sent from the rectenna array back to the transmitting phased array in order to determine the proper angle θ_t and set the proper aperture phase taper to keep the beam on the rectenna array [49]. In the case of SSP, a microwave beam rampaging through the countryside could cause some public alarm even if the power density at the Earth's surface is at acceptable safe levels. The pilot beam can also relay information about air traffic in the vicinity overhead of the rectenna array so that the microwave beam coming from the SPS can be turned off.

A variety of retrodirective rectenna arrays, not necessarily related to SSP, have been developed by Itoh and his students at the University of California Los Angeles (UCLA, Los Angeles, CA, USA). One of these arrays shown in Fig. 23(a) was published in 2004 by Leong, Wang, and Itoh. It is a full duplex retrodirective array for high-speed beam tracking and pointing. This retrodirective array accomplished 10-Mb/s data reception and transmission as well as

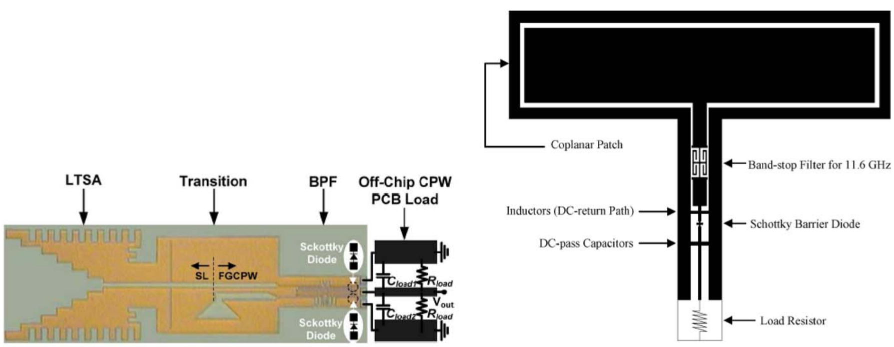


Fig. 22. ***(a) Dual-band 35- and 94-GHz rectenna in 0.13-μm complementary metal–oxide–semiconductor (CMOS). (b) University of Hong Kong design.***

beam-steering functionality [50]. Another novel adaptation of rectenna technology was published in 2005 by Lim, Leong, and Itoh at UCLA. The paper describes the retrodirective antenna array shown in Fig. 23(b), which uses a rectenna array, composed of four distinct rectennas, to awaken the overall array system from an idle mode [51]. Each rectenna uses a circular sector antenna which not only provides the radiating capabilities but also includes lowpass filter functionality for harmonic frequency suppression. The incoming RF power received by the antennas is split between the receiver and the rectenna. Most of this power is directed to the rectenna in order to rectify enough dc to activate a switch connected to a battery. Once the switch is activated, the retrodirective array can operate as intended. UCLA continues to pursue this area of research with impressive results.

IV. OTHER APPLICATIONS OF MPT AND RECTENNAS

Apart from SSP, rectennas can be applied to numerous other applications. One such application mentioned previously is ambient power collection. Another application is in radio-frequency identification (RFID). In RFID systems, power is transmitted from a reader to a tag device that identifies that which it is mounted to. In some applications, the tags are passive, meaning they contain no battery to drive the tag's onboard electronics. Some environments such as those with extreme heat can render batteries useless. Passive tags rectify a majority of the incident RF power to dc with the use of a rectifying diode in order to drive the electronics. In essence, each of these tags is a rectenna combined with identifying digital electronics. The use of MPT has even been associated with such ideas as remotely powering airplanes, tanks, and naval ships. The main problem is that the required power to move such objects is immense and the rectenna arrays would need to be of ridiculous size such that they become impractical. However, MPT applied to lightweight mobile craft is feasible and has been done in the past [52]. Such craft include high-altitude platforms such as UAVs and blimp airships in which helium is used in conjunction with MPT to move the airships. The main criterion for MPT to be applicable is how much power on the receiving end is needed to do a particular task. For space-to-space applications, MPT is seen as a realizable technology since gravitational effects are minimized. MPT could be a real asset in the future with regards to powering space probes from space stations or even other planets.

V. CONCLUSION

Future applications of MPT may apply to SSP, but in the near term, MPT will probably be used to power lightweight UAVs. UAVs are capable of delivering services such as communications and remote sensing and are finding increasing use in synergistic military applications. The idea of powering space probes from transmitters positioned in outer space is seen as a realizable technology. However the "holy grail" for MPT, whether practical or not, is SSP. SSP is seen by some experts as a way of meeting the future's energy demands without some of the baggage associated with current forms of power generation. MPT/SSP-associated systems will remain relevant as long as the world's energy demands continue to increase, and the various supplies of energy remain constrained. ■

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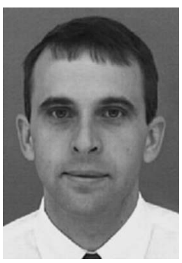

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