Abstract—One of the key challenges with Space Solar Power (SSP) using low-aerial-mass-density sheet-like structures is the power matching of the photovoltaic (PV) power to the optimal power point for microwave signal synthesis and power generation for wireless transmission. This work demonstrates a power tracking technique that can be readily integrated within the Power Amplifier (PA) operation that concurrently maximizes the power extracted from the PV and the transmitted power. This is done by dynamically duty-cycling the PAs to operate them close to peak efficiency and modulating their supply-impedance presented to the PV. The system does not use inductors and adds no additional mass, which is critical to the practical and economic viability of SSP. It offers higher conversion efficiencies, reduced system complexity, and greater programmability over traditional DC-DC converter solutions.

Keywords—maximum power point trackers, phased arrays, power amplifiers, solar panels, wireless power transmission.

I. INTRODUCTION

Space Solar Power (SSP) [1][2][3] is an ambitious, yet promising, energy generation technique where large two-sided arrays of photovoltaics and RF transmitters orbit around earth collecting massive amounts of power from the sun and transmit it wirelessly to the ground (Fig. 1). Using a focusing array [4] driven by power amplifiers (PAs), power is beamed wirelessly down to desired locations on earth, where the power is converted to DC via rectennas.

Fig. 1. SSP system overview

The sunlight in space is more intense, and is not subject to day-night cycles, clouds, atmospheric attenuation, or seasons, allowing continuous power generation. The wireless, electronically dispatchable power can supply locations that are otherwise difficult to reach and dynamically redistribute power. Microwave transmission has the additional advantage of reduced vulnerability to attenuation from atmospheric effects.

The RF array is composed of tileable units, whose simplified block diagram is shown in Fig. 2. The stacked PAs [5] are driven by a microwave source synthesized on chip with independent phase control. Details on the schematic implementation of the PAs are given in [5]. By dynamically adjusting the phase-shifters, the RF power can be focused on the receiving unit (RU) for efficient power transmission.

The RU is made up of parallel rectennas forming the receive aperture. The rectifiers have input, output, and harmonic matching networks for maximizing their conversion efficiency. In Fig. 3a, labelled artwork of the rectifier circuit is depicted; Fig. 3b shows the circuit implementation of the PA supply switch discussed in more detail in section II and III.

A significant challenge in the implementation of SSP is maintaining efficient DC to RF conversion. In particular, the PV must be operating at its Maximum Power Point (MPP) to deliver all its available power. Even in geostationary orbit, however, the PV will experience varying illumination angles, which reduce their power output and continuously shift the MPP. Operating outside of the MPP will significantly reduce the transmitted power and must be accounted for in the PA operation and the RF focusing algorithm [4].

Traditionally, these issues are solved by DC-DC converters and Maximum Power Point Tracking (MPPT) algorithms [6]. For SSP, however, the focusing arrays must be ultra-lightweight to minimize the cost of the launch required to deploy the system to be economically viable. PV’s DC Power is delivered and converted to microwave locally in the array, necessitating that each tile has a converter. These converters add mass to the tile in the form of passives, ICs, packaging, and...
their associated radiation shielding and heat spreading that raises the aerial mass density. Fully integrated DC-DC converters are a potential solution but are difficult to design with high efficiencies over wide load and conversion ratio ranges in standard CMOS processes [7]. Additionally, a fundamental limitation in DC-DC converter based MPPT occurs when the available power is low, in which case the output voltage is regulated to an unacceptably low value, degrading the performance of the PAs.

In this paper, the Mutual Power Optimization (MPO) method is outlined, which eliminates the DC-DC converter by integrating the MPPT into the PA operation without significant mass overhead and improved conversion efficiency. The power drawn from the PV is maximized via MPPT while simultaneously operating the PAs near their peak efficiency, maximizing the radiated power.

II. POWER AMPLIFIER DUTY-CYCLING

The IV-curve of a typical PV cell is shown in Fig. 4, and the power delivered by the cell at each operating point is plotted on the same figure. The cell delivers its maximum power at \((V_{MPP}, I_{MPP})\). The MPP of the cell is reached when an impedance of \(V_{MPP}/I_{MPP} = R_{MPP}\) is connected at its terminals. Any other impedance will operate below the MPP and thus draws less power.

The impedance of the load is typically transformed using a DC-DC converter. However, the load can also be modulated using a switch and a large parallel capacitor (Fig. 5a). Assuming a DC current input \(I\) and that the capacitor value is large, the steady-state voltage at the input terminals converges to \(V = (R_L/I)\), and \(R_{in} = R_L/I\), modulating the load impedance.

This principle can be applied to any arbitrary PA topology using an integrated switch, as shown in Fig. 5b. The supply-impedance of the PA is modulated by duty-cycling with a control signal. By choosing the appropriate duty-cycle, the PA will present \(R_{MPP}\) to the PV and draw the maximum power. The RF output will be modulated by the same duty-cycling frequency; however, for WPT this is not an issue, and the RF power can be readily collected using existing rectennas provided the bandwidth is not too large. If the duty-cycling frequency is sufficiently high, the existing decoupling capacitance can act as \(C_l\). The PAs will operate at \(V_{dd} = V_{PV}\), so the PA and PV operating voltages must be co-designed.

III. LABORATORY EXPERIMENT

A block diagram of the experimental setup is shown in Fig. 6. The 4x4 RF tile from Fig. 2 operating at 10 GHz is focused on an RU to measure the RF power. The PA supply is connected directly to the PV. In the current iteration, the focusing is performed at 100% duty-cycle. The duty-cycle is then adjusted to achieve the MPPT for different PV operating conditions. In future designs, the focusing and duty-cycling would be co-optimized. This could be done using the rectenna DC voltage in a feedback loop, as shown in [4].

![Fig. 6. Experimental Setup for MPO validation.](image)

The duty-cycling is controlled through a SPI communication line from a microcontroller (MCU) to the RFIC which opens and closes the PA supply switch (Fig. 3b). Due to limited SPI baud rates, the frequency is \(~16.2\) kHz, with a duty cycle range of \(D \in [0.16, 0.87]\) and decoupling capacitance of \(C_L = 300 \mu F\). The static loss associated with the switch is approximately \(~3\)% of the DC power.

The duty-cycling frequency can be increased by integrating its generation on the RFIC. The on-chip frequency of the duty-cycling is primarily limited by how quickly the switch can drive the PA \(V_{dd}\) line on the rising edge, and the decay of the RF signal on the falling edge. The switch is sized such that it can drive the PA’s \(V_{dd}\) in \(~3\) ns. When the switch is open, the remaining RF energy will decay in a few dozen cycles of the RF carrier frequency (10 GHz) based on the limited Q of the passive components. A 1 MHz duty-cycling frequency should be readily achievable based on this discussion, reducing the decoupling capacitance to approximately \(~5\) \(\mu F\) in future iterations.

A solar cell emulator conducive to laboratory experiments was constructed from the single-diode model in Fig. 7a using a DC supply and rectifier diodes. IV curves of the emulator are shown in Fig. 7b for different DC current levels. The experimental setup using the solar cell emulator is shown in Fig. 7c. The PA supply is connected to the solar cell emulator, and the array is focused on a horn antenna. The power is detected using a calibrated RF power meter (RU).

Plots of the RU power vs. duty cycle are shown for three photocurrents in Fig. 8a. The MPP gradually shifts to higher duty cycles for larger photocurrents as \(R_{MPP}\) decreases. The maximum power received while duty-cycling is extracted from these curves and plotted vs. photocurrent in Fig. 8b. Direct connection without duty cycling \((D = 100\%)\) is provided as a baseline, while power given by an extrapolated DC-DC
converter is used as a comparison. There is a significant increase in the RU power for a wide range of PV powers, with as much as a 10x improvement at low photocurrents compared to the baseline. Duty-cycling outperforms the baseline and the extrapolated DC-DC converter. At higher photocurrents the PAs operate close to the MPP of the PV without the need for load duty-cycling. Similarly, little is gained from the DC-DC converter, and the efficiency loss results in reduced RU power.

Extrapolation was chosen for the DC-DC converter due to the limited commercial options with appropriate specifications. Extrapolation was done with assumptions overestimating the performance of a DC-DC converter, namely: the converter perfectly draws the maximum power from the cell, and constant high efficiency conversion (90%). The extrapolation was done by measuring the MPP of the PV and mapping it to the IV curve of the PAs corresponding to the absorption of that power, with some efficiency degradation \( \eta \). The extrapolated RU power was obtained by measuring the focused RU power at the corresponding PA operating point.

The improved performance of the duty-cycling at low power levels is due to increased PA supply voltage. With duty-cycling, PAs will operate at \( V_{\text{MPP}} \), which is relatively insensitive to the available power. The DC-DC converter, however, is forced to regulate the PA supply voltage to a low value due to the limited available power and is incapable of raising it without adjustments to the PA IV characteristics. The higher \( V_{\text{dd}} \) voltage when duty-cycling leads to higher conversion efficiencies.

**IV. IN-FIELD EXPERIMENT**

A similar experiment was performed using a commercial Passivated Emitter and Rear Contact (PERC) polycrystalline silicon cell. The procedure is the same as the lab experiment, but to vary the PV power, measurements were taken outside periodically every 30 minutes from 8:30 A.M. to 12:30 P.M. A picture of the setup and plot of the PV MPP vs. daytime is shown in Fig. 9. Power detection is done via measurement of the RMS voltage output of a rectenna board. The simulated rectifier efficiency is shown in Fig. 9.

Results analogous to the laboratory experiment are plotted in Fig. 10, with the same assumptions for the DC-DC converter used. Due to the nonlinear efficiency curve of the rectifier (Fig. 9) the duty-cycling performs significantly better at lower powers. For the same average power, a continuous RF output will have a lower peak-power than a duty-cycled output. Thus, the duty-cycled output will operate higher on the rectifier efficiency-curve, increasing the rectified power [8].

**V. CONCLUSION**

MPO, a solution addressing power and impedance mismatch between a PV source and PA load in WPT applications is introduced, and a proof of concept is demonstrated at low duty-cycling frequency. Duty-cycling of the PA allows its operation in higher efficiency while simultaneously tracking the MPP of the PV source.

As it requires no added mass for sufficient modulation frequency, MPO has potential in lightweight WPT applications such as SSP and IoT, with the potential for further scaling and improved operation by integrating all the functionality on a single chip.

**ACKNOWLEDGEMENTS**

The authors would like to acknowledge Austin Fikes for helpful discussion and Caltech’s SSPP for funding and support.
REFERENCES