PASSIVE MASSIVE MIMO HYBRID RF-PEROVSKITE ENERGY HARVESTING FRONTEND FOR LEO SATELLITE APPLICATIONS

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INTRODUCTION

Low-Earth orbit (LEO)-based small satellites, including CubeSats and nanosatellites, have garnered significant interests due to their low SWaP-C (size, weight and power and cost-effectiveness) characteristics. These satellites enable low-latency remote sensing applications and have spurred the development of ground stations tailored for CubeSat Internet of Things (IoT) supplementary and complementary services. Operating at altitudes between 350 and 1,200 kilometres, LEO constellations offer reduced latency, broad beam footprints, and increased coverage capabilities compared with higher-altitude satellites. LEO satellites require substantial power for their onboard instruments, communication systems, and propulsion mechanisms [1]. Power consumption varies significantly, from a few watts for CubeSats to several kilowatts for larger satellites. Managing energy consumption is particularly challenging during eclipse periods when satellites are in Earth's shadow and solar panels are inactive. These eclipse periods, lasting up to 35 minutes in each 90-minute orbit, necessitate the use of stored battery energy, limiting satellite autonomy, lifespan, mission capabilities and post-mission reuse due to finite battery capacity and degradation over time [2]. LEO satellites operate in a low-altitude orbit, face a critical energy sustainability challenge. These space-borne devices consume power variably, necessitating efficient in-orbit battery charging for mission success and potential post-mission reuse. The energy reserves of CubeSat-IoT systems are diminished during eclipse periods, posing a significant challenge [3].

RF energy harvesting captures ambient radio frequency (RF) signals and converts them into usable electrical energy. This technology offers several advantages: RF signals are ubiquitous, originating from various sources such as communication towers, satellites, and Wi-Fi networks; it can be scaled to meet different power requirements by adjusting the number and arrangement of antennas; and it uses relatively simple and robust components, making it suitable for integration into small satellites [4,5]. However, RF energy harvesting also has limitations, including low power density, as the amount of energy that can be harvested is relatively low, and regulatory challenges, as systems must operate without causing interference to existing communication systems. Perovskite photovoltaic (PPV) cells represent a significant advancement in solar energy technology [6]. They offer high power conversion efficiencies, flexibility in application due to their ability to be deposited on flexible substrates, and low-cost production [7]. Nonetheless, PPV cells face challenges such as degradation under environmental factors like moisture, oxygen, and UV radiation, as well as sensitivity to the harsh conditions of space, including extreme temperatures and radiation. By combining RF and perovskite photovoltaic energy harvesting technologies, the proposed hybrid system aims to overcome the respective drawbacks of each technology, enhancing overall energy capture efficiency. This hybrid approach leverages the complementary nature of RF and solar energy sources, ensuring continuous energy harvesting regardless of the satellite's position relative to the Earth and the Sun [8]. Integrating multiple energy harvesting methods maximizes the energy capture potential, improves overall efficiency and reliability, and provides redundancy, increasing the system's resilience to failures in one of the energy harvesting subsystems [8].

The massive multiple input multiple output (mMIMO) technology, which uses multiple antennas to transmit and receive signals, offers significant advantages for RF energy harvesting. mMIMO systems can increase the capacity and efficiency of wireless communication links, improve signal quality through beamforming and spatial diversity techniques, and be scaled to accommodate more antennas, enhancing energy harvesting potential [9]. In the context of LEO satellites, mMIMO technology can significantly improve RF energy capture by using multiple antennas, employing beamforming techniques to focus RF energy harvesting on specific sources, and enabling efficient inter-satellite communication, facilitating energy sharing and distribution among satellites in a constellation [10]. The use of passive components in LEO satellites offers several benefits, including reliability, as passive components like resistors, capacitors, and inductors have no moving parts and are generally more reliable than active components; low power consumption, as passive components do not require external power to operate; and miniaturization, with advances in fabrication techniques allowing for the development of miniaturized passive components crucial for space-constrained satellite designs through the implementation of integrated passive devices technology [i.e., monolithic microwave integrated circuits (MMICs) containing only passive elements such as resistors, capacitors and inductors with no active elements (including transistors and diodes)].. In the proposed hybrid system, a passive power combiner is used to integrate the harvested energy from RF and perovskite sources efficiently, maximizing the total harvested energy, reducing system complexity, and enhancing overall performance and reliability [11].

The paper provides a comprehensive design of a hybrid RF-PPV EH system for green space-borne assets and missions applications. It discusses the architecture and modelling of a hybrid RF-perovskite energy harvesting system in Section 2, presents results and a discussion on system performance in Section 3, and concludes with key findings in Section 4. The paper covers power dividers-combiners, MIMO RF antennas, PPV technologies, and efficiency optimization for LEO satellite applications, all of which contribute to the potential benefits of the proposed hybrid system.

SYSTEM ARCHITECTURE AND MODELING

This section discusses the architecture of the hybrid RF-perovskite energy harvesting system, which includes the design and integration of the power dividers-combiners, MIMO RF antennas, and PPV technologies. A comprehensive mathematical model will be developed to analyse and optimise the efficiencies of the passive subsystems, considering the variations in solar flux and RF energy availability in the LEO environment.

LEO Satellite Power Consumption and Eclipse Period Analysis

During completing an orbit, LEO satellites experience alternating periods of sunlight and eclipse, affecting their power generation capabilities. The power consumption profile of a typical LEO satellite over 24 hours, considering both operational and idle states, must be calculated to determine the required power. The average power consumption (P_{avg}) can be calculated based on the satellite's operational requirements. Let P_{op} be the operational power consumption, and P_{id} be the idle power consumption. If t_{op} is the time spent in operation and t_{id} is the idle time, the average power consumption over a day can determined using (1).

$$P_{avg} = \frac{P_{op}t_{op} + P_{id}t_{id}}{t_{total}} \tag{1}$$

where t_{total} is the total time (24 hours).

The satellite is in Earth's shadow and relies solely on stored battery power during eclipse periods. It is critical to determine and analyse the duration and frequency of eclipse periods as they significantly impact the satellite's energy reserves and help determine the energy shortfall during the eclipse. For a satellite in a 90-minute orbit, eclipse duration can be approximated as up to 35 minutes ($t_{eclipse\_per\_orbit}$). The total eclipse time ($t_{eclipse}$) over 24 hours is given in (2).

$$t_{eclips} = N_{orbits} \times t_{eclipse\_per\_orbit} \tag{2}$$

where N_{orbits} is the number of orbits per day, hence the energy deficit during the eclipse period ($E_{deficit}$) can be given as:

$$E_{deficit} = P_{avg} \times t_{eclipse} \tag{3}$$

To ensure the sustainability and efficiency of LEO satellites, the proposed hybrid RF-perovskite energy harvester seeks to provide a continuous power supply by addressing power consumption during operational and idle states and analysing the energy deficit during eclipse times.

RF Energy Harvester

The typical RF Energy Harvesting (RF-EH) system captures, converts, and manages RF energy from the environment. This system includes an antenna to intercept ambient RF energy, an impedance-matching network to reduce signal reflections and losses between the antenna and rectifier and a rectifier circuit to convert RF power into DC power. In the case of MIMO, it requires a power combiner. A high-quality matching network and a low-loss, high-efficiency rectifier are essential for effective RF energy harvesting, mainly when dealing with low-input RF signals.

This paper presents the design and simulation of an RF-EH system using Keysight Advanced Design System (ADS) software. The system utilises a varying RF power source component (P_{1Tone}) with input power ranging from -25 to 20 dBm, simulating an antenna and providing input for the rectifier to examine performance at different power levels. The RF Schottky diode SMS 7630, known for its low forward voltage drop and high switching speed, was chosen for rectification. A Delon Quadrupler rectifier, designed for high RF-DC conversion efficiency, was designed and simulated on the ADS software. The efficiency of the rectifier was calculated using established formulas.

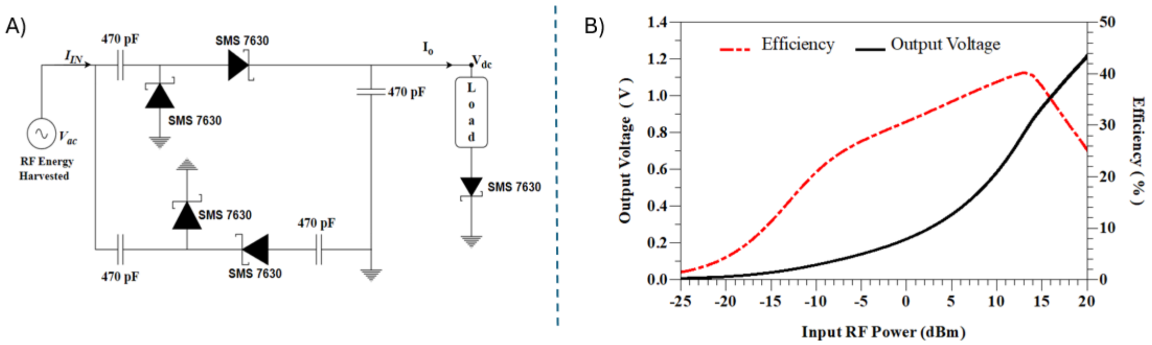

Fig. 1 (A) Delon Quadrupler Rectifier used in the RF EH, and (B) the rectifier's output voltage (V_{dc}) and efficiency for varying input RF power levels.

The power received by an RF energy harvesting antenna (P_{RF_ant}) is given by the Friis transmission equation given in (4).

$$P_{RF\_ant} = P_t G_t G_r (\frac{\lambda}{4\pi R})^2 \quad (4)$$

When the transmitted power is represented by P_t, the wavelength is represented by λ, the distance between antennas is represented by R, and the gains of the transmitting and receiving antennas are represented by G_t and G_r.

The proposed rectifier operates for a full cycle and transferring maximum power with optimal impedance matching. The power conversion efficiency (PCE) of the rectifier is defined as the ratio of input RF power (P_{IN}) to output DC power (P_O) as in (5).

$$PCE = \frac{P_O}{P_{IN}} \times 100 \quad (5)$$

An RF-EH system's total efficiency is determined by its rectifier, impedance-matching network, and antenna performance. The energy harvesting efficiency of an RF-EH system with a single antenna, η_{RF}, can be calculated using (6). Here, PEE_{ant} denotes the antenna's RF capturing efficiency, PCE_{MN} denotes the impedance matching network's efficiency, and PCE represents the rectifier's power conversion efficiency.

$$\eta_{RF} = PEE_{ant} \times PCE_{MN} \times PCE \quad (7)$$

The energy stored in the capacitor (Cout) can be determined using the output voltage, Vdc as below.

$$E_{RF} = \frac{(C_{out} \times V_{dc}^2)}{2} \quad (8)$$

MIMO configurations in RF-EH offer adaptability, spatial diversity, enhanced robustness, and higher efficiency. This study evaluates MIMO technology with 1, 2, 4, 8, and 16 antennas. Each MIMO subsystem, consisting of an antenna, matching network, and rectifier, combines output powers using a power combiner. Efficiency is calculated using probability theory, with each subsystem's efficiency representing the probability of success. The overall MIMO RF-EH efficiency η_{RF_MIMO} is determined as one minus the product of the complementary probabilities $1 - \eta_{RF}$, (9).

$$\eta_{RF\_MIMO} = 1 - \prod_{N=1}^{2^a} (1 - (\eta_{RF})_N) \quad (9)$$

In this context, $(\eta_{RF})_N$ represents the efficiency of the N^{th} antenna in the RF-EH system. Here, N ranges from 1 to 2^a, where a is a variable that can take values from 0 to 4, corresponding to 1, 2, 4, 8, and 16 antennas.

Power Combiner

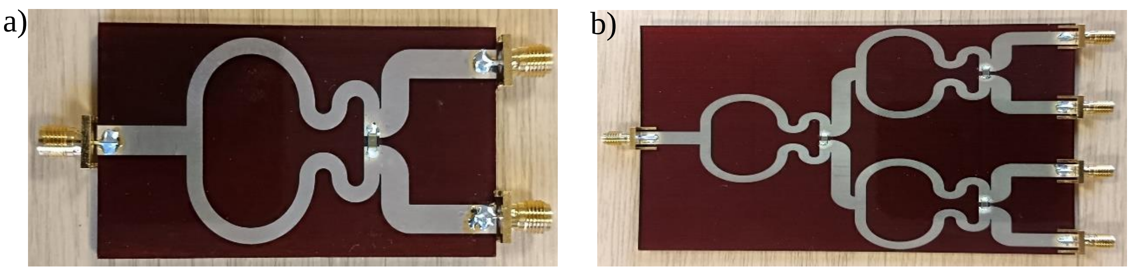

Fig. 2. Additively manufactured power combiner and divider: a) 2 to 1 and (b) 4 to 1.

The power combiner is a crucial component in RF-EH-based MIMO configurations, effectively aggregating power. In this study, 2 to 1 and 4 to 1 power dividers-combiners were designed, their performance analysed in ADS and manufactured using additive manufacturing technology with a substrate dielectric constant of 2.78. The 3D-printed passive hybrid power combiner-divider operates at resonance frequencies of 2.4, 5, 5.8, and 6 GHz. Figure 2 presents the printed device, with detailed measurements and simulation results in the results section.

Perovskite Energy Harvesting

Perovskite photovoltaic (PV) cells have seen significant advancements over the past decade, achieving efficiencies from 5% to 33% [12]. The performance of these cells is typically represented by *I-V* and *P-V* curves, which are essential for optimising solar energy conversion efficiency. A single perovskite cell generates low output power, but the power output can be increased by configuring multiple cells [13,14]. Series connections of cells boost voltage, while parallel connections enhance current, forming perovskite modules and arrays respectively. The characteristics of these configurations are determined by multiplying the voltage of a single cell by the number of cells in series and multiplying the current by the number of parallel modules [15].

The I-V characteristics of a perovskite cell can be modeled using the diode equation given in (8.1).

$$I = I_{SC} - I_0\left(e^{\frac{qV}{nkT}} - 1\right) \tag{10}$$

where I_{sc} is the short-circuit current, I_0 is the reverse saturation current, q is the charge of an electron, V is the voltage, n is the ideality factor, k is the Boltzmann constant, and T is the temperature[16].

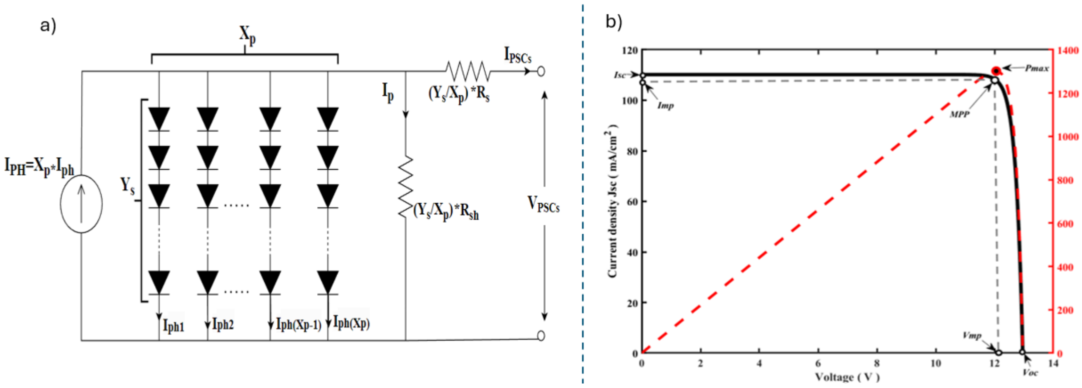

Fig. 3. (a) Perovskite photovoltaic array equivalent circuit, where: R_s (series resistor), R_{sh} (shunt resistor) and V_{PSCs} (output voltage of the PSCs array) and (b) I-V and P-V characteristic curve of the perovskite-on-Si tandem solar array (6X6), MATLAB simulation.

The general setup for perovskite configurations varies based on the number of series (Y_s) and parallel (X_p) diodes given in Fig. 3(a). The photon currents of the modules are equal to the incident light on the unit PSCs, denoted as I_{ph}. Using the total incident current of the perovskite array given in (11), the output current (I_{PSCs}) can be calculated as (12) based on the configurations.

$$I_{PH} = \sum_{k=1}^{X_P} I_{ph_k} \tag{11}$$

$$I_{PSCs} = I_{PH} - (X_P \times I_d) - I_P \tag{12}$$

Perovskite cells can generate electricity during their operational time (t_{PSCs}), which is the maximum operation time (t_{max}) minus any periods without sufficient light, eclipse period for LEO satellites, (t_{off}). The electrical power (P_{PSCs}) and total energy harvested (E_{PSCs}) by a perovskite array can be determined by (13) and (14) respectively.

$$P_{PSCs} = \frac{I_{PSCs}^2}{R_L} \tag{13}$$

$$E_{PSCs} = P_{PSCs} \times t_{PSCs} = P_{PSCs}(t_m - t_{off}) \tag{14}$$

The array's efficiency (η_A) is derived from the efficiencies of its modules (η_M), which in turn depend on the efficiencies of the cells (η_c) connected in series.

$$\eta_M = (\eta_c)^{Y_s} \tag{15}$$

$$\eta_A = 1 - [1 - (\eta_M)]^{X_P} \tag{16}$$

This research employed data from a previously documented perovskite-on-Si tandem solar cell for mathematical analysis and evaluation. MATLAB is used to generate I-V and P-V curves, while ADS software is utilised to simulate a diode model to replicate PV properties. The individual cells in this investigation exhibit I_{mp}, V_{mp}, and P_{max} values of 21.69 mA, 1.99 V, and 43.36 mW, respectively. Cells were arranged in series and parallel configurations to meet the power requirements of LEO satellites. A 6x6 perovskite array was developed using these cell data and combined with the RFEH to create a hybrid system for powering LEO satellites. The array's I-V and P-V characteristic curves were generated using MATLAB and are shown in Fig. 2(b).

Hybrid RF-Perovskite Energy Harvesting

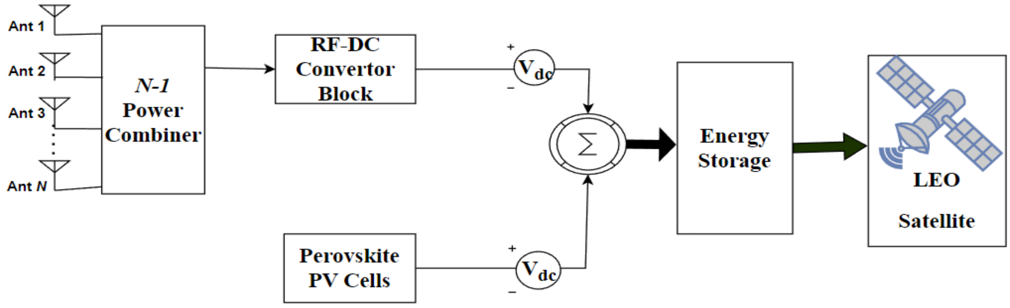

Fig. 4. Block diagram of hybrid RF-Perovskite energy harvesting system for LEO small satellites

The Hybrid RF-Perovskite Energy Harvesting system enhances efficiency and directly addressing the power constraints of LEO during the eclipse period. It enhances the longevity of satellites in orbit. It supports the long-term viability of small satellites by considering the fluctuations in solar radiation and RF energy in the LEO environment. The total energy harvested over a 24-hour period is calculated by adding together the energy captured by each component as in (17).

$$E_{hybrid} = E_{RF} + E_{PSCs} \tag{17}$$

For MIMO and array configurations, this is expanded to:

$$E_{hybrid} = \sum_{N=1}^{2^a} E_{RF,N} + \sum_{k=1}^{X_p} (P_{PSCsK} \times t_{PSCsk}) \tag{18}$$

Here, N represents the number of antennas in the MIMO system (expressed as 2^a) and k denotes the number of modules in an array. The hybrid system ensures uninterrupted power harvesting, even during subsystem failures or inadequate power generation, enhancing overall efficiency. The mathematical determination considers the efficiencies of the RF harvester (η_{RF}) and the array (η_A).

$$\eta_{hybrid} = 1 - [(1 - \eta_{RF}) \times (1 - \eta_A)] \tag{19}$$

RESULTS AND DISCUSSION

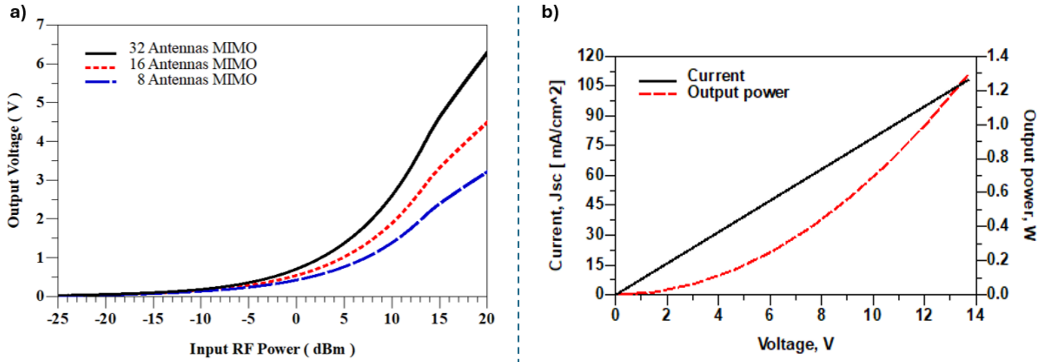

Fig. 5. (a) Output power of the MIMO RF-EH at various RF input levels and (b) I-V and P-V characteristic curves of the perovskite-on-Si tandem solar cell, based on ADS simulation.

The RF and perovskite systems were developed and analysed separately in ADS to develop the hybrid system. The MIMO system's output voltage is shown in Fig. 5a, indicating that MIMO systems can generate voltage even from -10 dBm input power. However, practical voltage levels are only achieved at higher RF inputs. At 20 dBm, maximum voltages are 6.3 V, 4.5 V, and 3.2 V for MIMO configurations with 32, 16, and 8 antennas, respectively. Lower RF inputs result in reduced output due to power dissipation across rectifier diodes. The I-V and P-V simulations of the 6x6 perovskite array, conducted in ADS and MATLAB, are shown in Fig. 5b and Fig. 3b. The simulations yielded Imp, V_{mp}, and P_{max} values of 108 mA, 12.1 V, and 1.3 W, respectively, with V_{oc} at 12.9 V and I_{sc} at 110 mA.

Various MIMO configurations were explored to enhance power output and the simulation results, shown in Fig. 6a, indicate a consistent increase in output power as the number of antennas increases. The efficiency of the MIMO designs is assessed using (9), and Fig. 6b illustrates a significant rise in efficiency with an increasing number of antennas. Efficiency exceeds 75% at higher input power levels for configurations with 8, 16, and 32 antennas, reaching up to 98%

for the 32-antenna setup, showcasing the system's effectiveness. The output voltage and power of the 32-antenna MIMO RF-EH, depicted in Figs. 5a and 6a highlight the system's capability to power LEO satellites during eclipse.

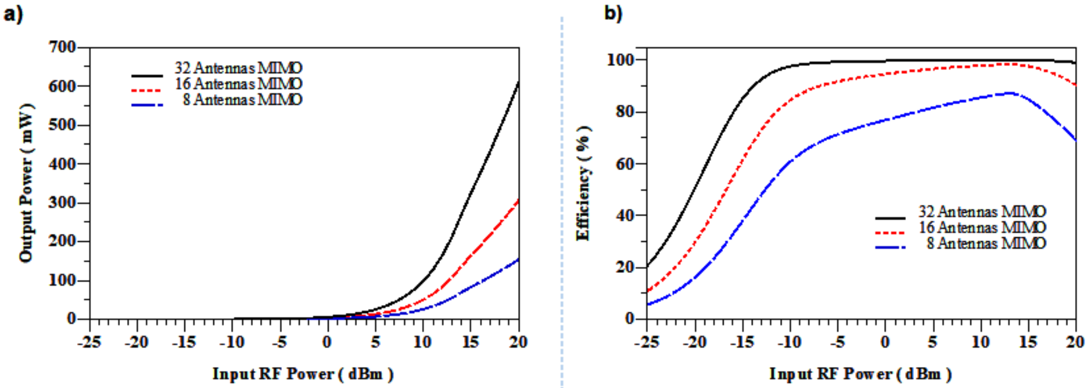

Fig. 6 (a) Output power and (b) efficiency of the MIMO RF-EH at different RF input power levels.

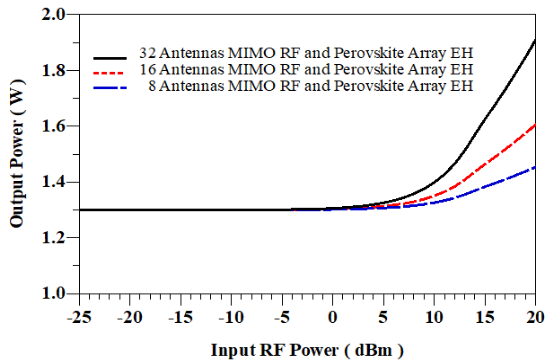

Fig. 7. Power output of Hybrid RF-Perovskite systems at various RF input power levels and at the perovskite array's peak power point under 1000W/m² irradiation.

Figure 7 illustrates the output power of Hybrid RF-Perovskite systems at various RF input power levels, demonstrating that configurations with higher antenna counts yield greater output power. Specifically, the 32 antennas MIMO RF and Perovskite Array EH configuration achieves nearly 2 W at the highest RF input power level (20 dBm), outperforming the 16 antennas and 8 antennas configurations, which peak at around 1.7 W and 1.5 W, respectively. These results indicate that the hybrid system is a promising solution for providing continuous power to LEO satellites during eclipse periods when solar energy is unavailable. The substantial output power from the higher antenna configurations ensures that satellites have sufficient energy to maintain operations. The efficiency and reliability of the hybrid system, with its ability to produce significant power under varying RF input levels, make it an ideal choice for sustaining LEO satellite functions, thereby enhancing the overall sustainability and reliability of satellite operations.

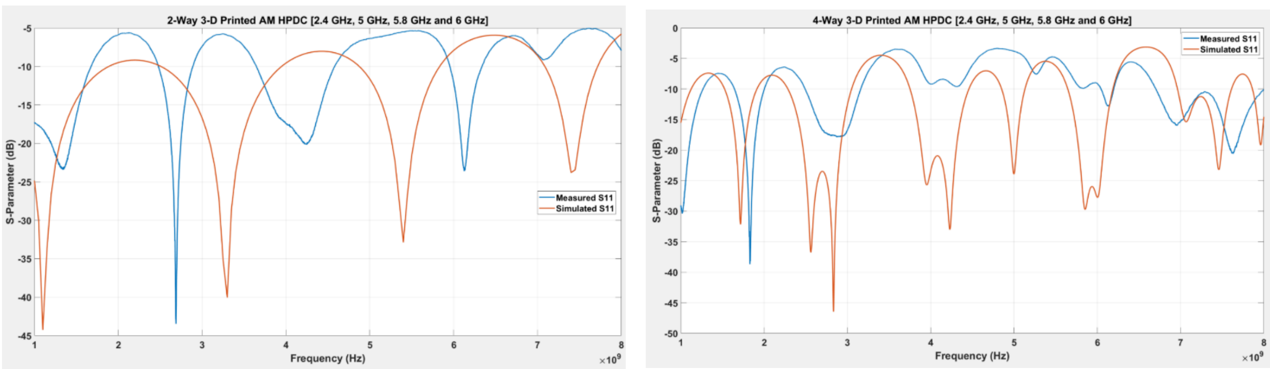

Fig. 8. Measured and simulated insertion loss (S11) results: (a) 2-way, and (b) 4-way power combiner and divider.

The performance analysis of the 2-way and 4-way power combiner and divider shows that, despite discrepancies between the measured and simulated insertion loss (S11) results, the devices perform well at the selected frequencies of 2.4, 5, 5.8, and 6 GHz. The variations between the measured and simulated results can be attributed to factors such as soldering imperfections. These findings are promising for developing hybrid RF and perovskite passive energy harvesters. The successful implementation of these combiners and dividers enhances the feasibility of integrating such systems into practical applications, particularly in energy harvesting for space-based and LEO satellite operations. The ability to efficiently combine and divide power at these frequencies underscores the potential of this technology in advancing sustainable energy solutions for space exploration.

CONCLUSION

This study explored and analysed RF and perovskite energy harvesting systems individually, ultimately combining them into a hybrid system. The results showed that MIMO systems can produce voltage from as low as -10 dBm input power and, with 32 antennas, can generate a maximum voltage of 6.3 V at 20 dBm. The efficiency of these MIMO systems improves with more antennas, reaching up to 98% for the 32-antenna configuration. Simulations of the perovskite tandem array achieved 12.1 V and 1.3 W for V_{mp} and P_{max}, respectively. The hybrid system with 32 antennas produces nearly 2 W at the highest RF input power (20 dBm), outperforming the 16 and 8 antenna setups.

The high output power from larger antenna configurations ensures satellites have adequate energy when solar power is unavailable. The hybrid system's efficiency and reliability across various RF input levels make it ideal for maintaining LEO satellite functions, thereby improving satellite sustainability and reliability. The design and 3D-printed passive hybrid power combiner-divider supports space-based Wi-Fi networks (4/5/6/6E/7) for simultaneous energy and data exchange. This advancement, enabled by additive manufacturing, enhances the performance and practicality of passive energy harvesting systems for space applications. Overall, these findings advance passive energy-efficient technologies for sustainable space exploration and LEO satellite-cellular convergence, with integrated low-frequency passive components and innovative high-frequency layouts resulting in a compact device ideal for space use.

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