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A Dual-Band Simultaneous RF Energy Harvesting System With Globally Optimized 3-D MPPT and Efficiency Enhancement

Xianguang Li[✉], Qing Miao, *Member, IEEE*, Shiheng Yang[✉], *Member, IEEE*, Tianting Zhao, *Member, IEEE*, Sijun Du[✉], *Senior Member, IEEE*, Xiaoyang Zeng[✉], *Senior Member, IEEE*, and Zhiyuan Chen[✉], *Member, IEEE*

Abstract—This article presents a globally optimized radio frequency (RF) energy harvesting system that leverages the novel concepts of 3-D maximum power point tracking (3-D MPPT) and collaborative source reconfiguration to achieve high MPPT accuracy and a wide input power range. The proposed 3-D MPPT coordinates the energy sources, optimizes the rectifier outputs, and regulates the rectifier stages for global efficiency optimization. A multi-level regulating DC–DC converter integrated with a reconfigurable rectifier enables synchronized dual-band RF energy harvesting. The reconfigurable buck–boost converter employs hysteretic control to regulate each rectifier output voltage at its respective maximum power point (MPP) and delivers a stable output through pulse-frequency modulation (PFM) with adaptive inductor ON-time. The DC–DC converter dynamically connects a rechargeable battery (emulated by a power source and a resistor) to either the source or the load, supplementing insufficient energy or recovering surplus energy, thereby significantly extending the input power range. Fabricated in a 180-nm CMOS process, the prototype dual-band RF energy harvesting interface achieves a peak end-to-end efficiency of 71%, a sensitivity of -24.1 dBm, and wide high-power conversion efficiency (PCE) input power ranges of 15.5 and 20.5 dB at 433 and 900 MHz, respectively.

Index Terms—Cross-coupled rectifier, dual-band, maximum power point tracking (MPPT), radio frequency (RF) energy harvesting.

I. INTRODUCTION

WITH the proliferation of wireless sensor networks (WSNs) and the Internet of Things (IoT) applications, ultra-low-power devices are increasingly deployed in diverse and often unattended environments [1], [2], [3], [4], [5]. These systems typically require sustained autonomous operation, imposing stringent constraints on energy availability. Among various energy harvesting solutions, radio frequency (RF) energy harvesting has emerged as a promising approach by converting ambient electromagnetic radiation into usable electrical power, thereby enabling battery-less or maintenance-free operation. Compared with conventional battery-powered systems, RF energy harvesting offers distinct advantages, including reduced maintenance, extended operational lifetime, and lower system costs, especially in scenarios where battery replacement is impractical.

However, the availability of ambient RF energy is highly dependent on spatial and temporal variations, making single-band harvesting insufficient to sustain continuous system operation. To overcome this limitation, multi-source collaborative harvesting (MSCH) techniques have been proposed, wherein energy from multiple RF bands is synchronously harvested and managed to improve input power stability and overall system reliability [9], [10], [11].

In practice, ambient RF energy exhibits weak and nonuniform spatial distribution due to environmental factors such as weather conditions, structural obstructions, and electromagnetic interference. Moreover, RF signals from multiple frequency bands typically coexist within the same space, as illustrated in Fig. 1(a). Efficient utilization of such distributed energy requires concurrent multi-band operation. Multi-band collaborative harvesting effectively extends the energy acquisition range by leveraging the complementary availability of RF sources in different spectral regions. By aggregating energy from multiple RF sources, the system enhances both power conversion efficiency (PCE) and operational stability, particularly in low-signal or frequency-diverse environments. Motivated by this need, MSCH has been proposed as a key enabling technique. It dynamically coordinates multiple RF sources through adaptive mode control and source synchronization, significantly improving energy acquisition capability [17], [18]. Fig. 1(a) illustrates the typical RF

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Xianguang Li, Xiaoyang Zeng, and Zhiyuan Chen are with the State Key Laboratory of Integrated Chips and Systems, College of Integrated Circuits and Micro-Nano Electronics, Fudan University, Shanghai 201203, China (e-mail: chen_zy@fudan.edu.cn).

Qing Miao and Tianting Zhao are with Beijing Smart-Chip Semiconductor Technology Company Ltd., Beijing 102200, China.

Shiheng Yang is with the School of Electronic Science and Engineering, University of Electronic Science and Technology of China (UESTC), Chengdu 610054, China.

Sijun Du is with the Department of Microelectronics, Delft University of Technology, 2600 AA Delft, The Netherlands.

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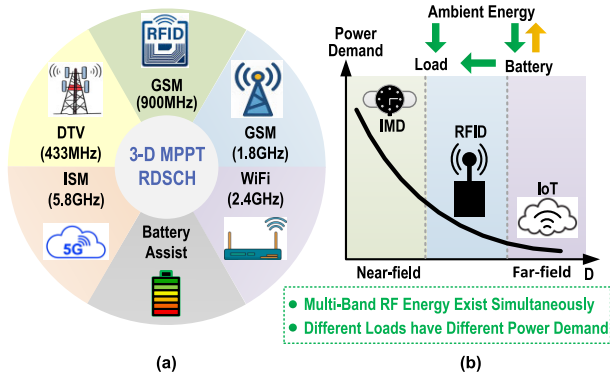


Fig. 1. (a) Typical RF energy bands radiated in the atmosphere. (b) Energy requirements in different application scenarios.

energy bands radiated in the atmosphere. The proposed 3-D maximum power point tracking reconfigurable dual-source coordinated harvesting (3-D MPPT RDSCH) system supports collaborative operation, synchronous harvesting, and dynamic mode switching based on real-time input power levels of different frequency bands, thereby enabling wide-range and high-efficiency ambient energy harvesting.

As shown in Fig. 1(b), different application scenarios impose varying power demands, which may require single-source harvesting, multi-source synchronous harvesting, or battery-assisted supply [12], [13], [14]. The proposed system is designed to intelligently switch among these modes according to real-time energy conditions and load requirements.

Despite notable advances, several challenges persist in RF energy harvesting system design. Conventional architectures often rely on a single energy-flow path or a fixed frequency band, resulting in degraded performance under low-power or dynamically varying ambient conditions.

Although techniques such as multi-band matching networks and reconfigurable rectifiers have been proposed, existing systems still suffer from a limited input power range and insufficient MPPT accuracy, which restricts their adaptability across different operating environments. In [1], a multi-band RF energy harvesting system based on a tri-band matching network is introduced. However, due to its single energy flow path, the system can only harvest energy from one frequency band in the same time period, making synchronous multi-band energy harvesting infeasible. Additionally, the lack of MPPT circuitry further narrows the high-PCE operating range. In [2], a rectifier array is cascaded with a DC-DC converter, and MPPT is achieved by reconfiguring the number of active rectifier stages based on the input power. Nonetheless, the system exhibits low MPPT accuracy and high control overhead, which leads to reduced sensitivity and overall PCE. Furthermore, its single-dimensional MPPT strategy limits its ability to achieve global efficiency optimization. In [3], a 3-D MPPT-based RF energy harvesting system is presented, which simultaneously optimizes three parameters: the matching network configuration, rectifier topology, and rectifier output voltage. While this approach improves system-level efficiency, it still operates within a single frequency band and

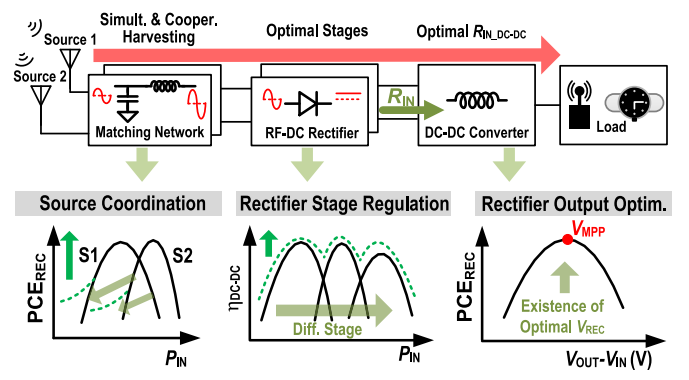


Fig. 2. Conceptual diagram of the proposed 3-D MPPT strategy.

lacks support for coordinated multi-band synchronous energy harvesting.

To address the aforementioned challenges, this article presents a globally optimized RF energy harvesting system that integrates 3-D MPPT with a dual-band RF source cooperative reconfiguration strategy, to achieve efficient dual-band RF energy synchronous-cooperative harvesting. The proposed system enhances MPPT performance through coordinated optimization along three dimensions: 1) energy-source coordination control; 2) rectifier output optimization; and 3) rectifier stage regulation. This work is an extension of [4]. This article is organized as follows. Section II illustrates the proposed 3-D MPPT and collaborative source reconfiguration strategies, while Section III describes the RDSCH architecture overview and the event-driven control circuits. Section IV describes the measurement results, and Section V presents the conclusion of this article.

II. PROPOSED 3-D MPPT AND COLLABORATIVE SOURCE RECONFIGURATION

With the widespread deployment of multi-band ambient RF sources, RF energy harvesting systems are increasingly exposed to highly dynamic input conditions and diverse load requirements [15]. Conventional MPPT schemes are often inadequate to maintain optimal system performance across varying operating scenarios [16], [19]. In practice, different functional blocks within the system, such as the RF-DC rectifier, matching network, and power management unit, each exhibit distinct optimal operating points, which are critical to the overall efficiency, as shown in Fig. 2. To address these challenges, a multi-dimensional MPPT strategy is required to jointly regulate key system parameters, including source configuration, rectifier output, and voltage conversion stages. Such coordinated optimization significantly enhances the PCE and system robustness under real-world operating conditions [20], [21]. Fig. 3 shows the principle model for 3-D MPPT analysis. Here, V_{RF} is the antenna voltage, V_{RECT} is the voltage at the RF node after ideal matching, and R_{RECT} is the effective rectifier output resistance. Conventionally, the realization of MPPT is to adjust the R_{RECT} by changing the number of rectifier stages or by adjusting the R_{IN} of the DC-DC converter to find the optimal load [2], [22]. Wide-range operation is

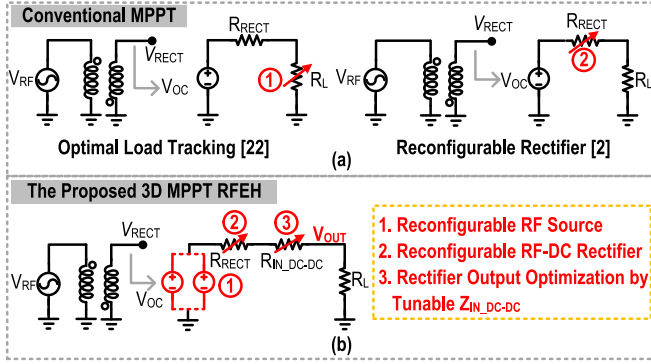


Fig. 3. Conceptual models of (a) conventional MPPT strategy and (b) proposed 3-D MPPT RF energy harvesting system.

also challenging due to the single optimization dimension and the lack of global optimization capabilities. What is worse, the rectifier efficiency is not optimized for wide input power conditions. In this work, we propose a 3-D MPPT scheme that jointly leverages RF source reconfiguration, the effective rectifier stage, and the input impedance of the DC–DC module to match the load. This approach enables a finer implementation of the rectifier’s MPPT requirements, achieves coordinated optimization across multiple modules, and enhances rectifier efficiency with a cost-effective solution.

A. Energy-Source Coordination Control

To enhance overall system performance, the proposed architecture employs an MSCH strategy, enabling RF signals from different frequency bands to be harvested cooperatively. By dynamically coordinating the input sources, the system can sense the relative input power levels of each band and adaptively configure the cooperative harvesting mode based on the instantaneous input power levels. As the first dimension of the proposed 3-D MPPT framework, the source coordination adaptively selects series cooperative, dual-phase cooperative, or parallel synchronous modes (PSMs) according to the absolute and relative input power levels of the two RF sources. This strategy effectively optimizes the DC–DC converter input voltage, conversion ratio, and current stress across operating regimes, enabling efficient energy extraction under ultra-low, asymmetric, and high input power conditions. Consequently, the proposed reconfiguration significantly extends the system’s high-efficiency operating range and improves end-to-end harvesting efficiency.

As illustrated in Fig. 4, three operating modes are defined according to the relative magnitudes of the two input powers: PSM, series collaborative mode (SCM), and dual-phase cooperative mode (DCM). The selection criterion is based on whether the rectifier output can reach the minimum required voltage at the maximum power point (V_{MPP}) under a nominal body bias.

When both input powers are sufficient to meet the V_{MPP} , the system operates in PSM, in which both rectifier units harvest energy simultaneously within a single switching cycle, minimizing switching loss. When neither input can individually reach V_{MPP} , the substrate bias of the rectifiers is adaptively

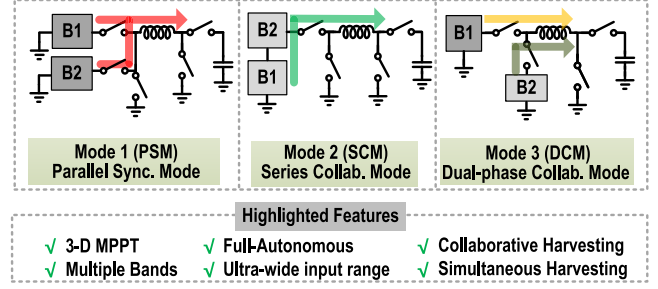


Fig. 4. Proposed collaborative source reconfiguration concept diagram.

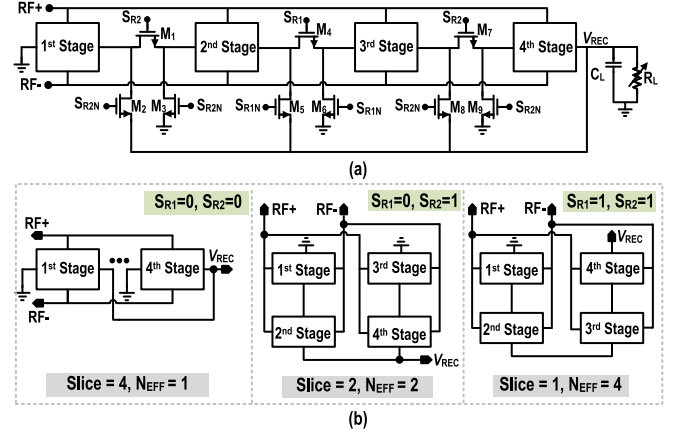


Fig. 5. (a) Schematic of the reconfigurable rectifier and (b) its stage-dependent configurations.

tuned to lower the effective V_{MPP} , and the two sources are connected in series to boost the rectifier output voltage, constituting the SCM. In the intermediate case where one source provides sufficient input while the other does not, the system adopts the DCM. Here, the weaker source is activated during the inductor’s discharging phase, which helps reduce current ripple and improve the efficiency of the DC–DC converter.

B. Rectifier Stage Regulation

The proposed scheme enables reconfiguration of the number of stages in the RF–DC rectifier by utilizing all sub-blocks that are already connected to the differential RF input, as illustrated in Fig. 5. To minimize insertion loss on the RF side, reconfiguration is implemented on the DC side of the rectifier.

In general, for a system comprising N sub-blocks, the total number of possible stage (N_S) configurations is given by

$$N_S = \lfloor \log_2(N) \rfloor + 1 \quad (1)$$

where $\lfloor \cdot \rfloor$ denotes the floor function.

Based on the estimated open-circuit output voltage, the rectifier controller generates a binary control signal to dynamically configure the RF–DC rectifier. This control signal selects the appropriate number of rectifier stages to achieve the desired output voltage, thereby ensuring efficient power conversion under varying input conditions.

The details of the rectifier stage reconfiguration are shown in Fig. 5, bottom. The rectifier stage cells can be connected either

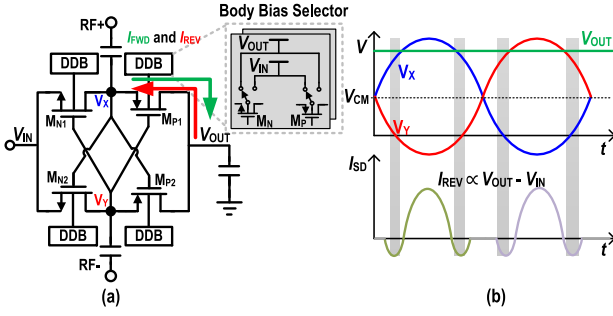


Fig. 6. (a) Implemented DBB RF-DC rectifier and (b) corresponding node voltage and current waveforms.

to the next stage in the cascade phase or directly to the final output in the parallel phase through a dual-path multiplexer. The effective number of stages dynamically adjusts between 1, 2, and 4, depending on the input power. This mechanism ensures good impedance matching over a wider input power range by adapting to variations in input power. The number of active rectifier stages is dynamically configured based on the input power level. When the input power is low, fewer stages are activated to reduce the rectifier's voltage at the maximum power point V_{MPP} , thereby minimizing sensitivity to input fluctuations. As the number of rectifier stages increases, the peak efficiency shifts toward higher input power levels. By using different numbers of stages for different input power levels, the system significantly widens the input power range over which high conversion efficiency is maintained. To satisfy the MPPT requirements of the rectifier unit, its output voltage must be regulated and stabilized around the corresponding V_{MPP} . The operating principle of MPPT for the rectifier and the associated output voltage control strategy are discussed in detail in Section II-C.

C. Rectifier Output Optimization

The proposed design adopts a cross-coupled configuration to preserve high sensitivity under low input power conditions. To enhance performance adaptability, a dynamic body-biasing (DBB) mechanism is implemented using a body-bias selector, enabling threshold voltage (V_{TH}) adjustment of the rectifying transistors. In this differential architecture, the ON-resistance of the switches decreases as the input voltage amplitude increases. The ON-resistance (R_{ON}) of a transistor is given by

$$R_{ON} = \frac{1}{\mu C_{ox} \frac{W}{L} (V_{GS} - V_{TH})} \quad (2)$$

where μ is the mobility of the electron/holes; C_{ox} is the oxide capacitance; W/L is the ratio of width to length of the transistor; and V_{GS} is the gate-to-source voltage of the transistor. Consequently, at low input power levels, the relatively high ON-resistance degrades the PCE. However, as the input power continues to increase, the PCE eventually declines. This degradation is primarily attributed to reverse leakage currents introduced by the cross-coupled configuration, where both NMOS and PMOS devices may conduct undesired reverse currents, as illustrated in Fig. 6. Therefore, for a given input

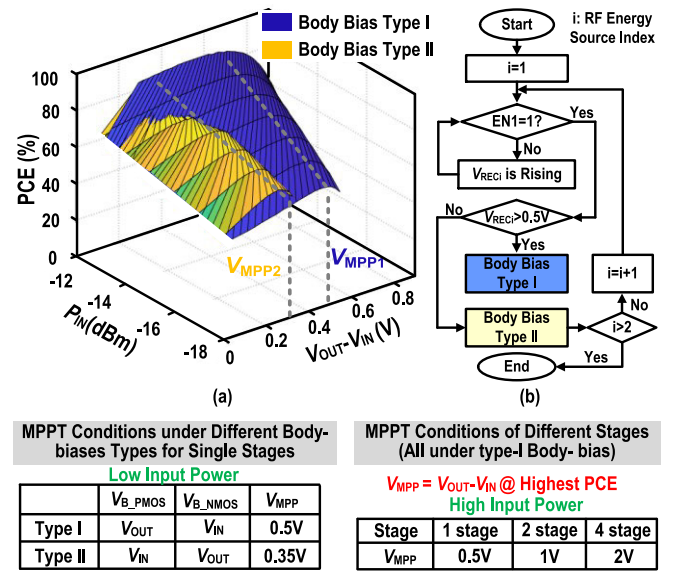


Fig. 7. (a) MPPT operating conditions of the RF-DC rectifier as a function of body-bias configurations and the number of stages. (b) Flowchart of rectifying transistor body-bias selection under different input power levels.

power level, an optimal load resistance and a corresponding rectifier output voltage (V_{REC}) exist, which jointly minimize the series conduction loss and the reverse leakage loss.

This work investigates the fundamental conditions and mechanisms governing maximum power transfer in an RF-DC rectifier, with a focus on single-stage cross-coupled topologies. In the absence of MPPT control, the PCE of the rectifier is highly dependent on the relationship between the input and output voltages, typically exhibiting a convex dependence. As a result, there exists a distinct peak-PCE point, and the corresponding high-PCE input power range is relatively narrow. As illustrated in Fig. 7(a), the PCE peaks consistently occur when the output-input voltage difference is approximately equal to the PMOS threshold voltage (V_{TH_PMOS}). This is because at this point, conduction loss due to insufficient gate overdrive and loss from increased reverse current are optimally balanced: a lower V_{OUT} results in higher ON-resistance and increased conduction loss, while a higher V_{OUT} increases reverse current during switching, also degrading the PCE. Furthermore, this optimal voltage difference V_{MPP} increases proportionally with the number of rectifier stages, as the net accumulated forward charge reaches its maximum, thereby maximizing PCE.

These observations provide a theoretical foundation for implementing accurate MPPT in the RF-DC rectifier. By dynamically adjusting the rectifier's output load under varying input conditions, the output voltage can be regulated to remain near the maximum power point (MPP), enabling high PCE over a wider input power range. Moreover, since the V_{MPP} is closely correlated with the V_{TH} of the rectifying transistors, it can be effectively modulated by tuning the body bias. This technique is particularly beneficial under extremely low input power conditions. Fig. 7(a) further illustrates the impact of different body-biasing schemes on V_{MPP} , while Fig. 7(b) depicts the flowchart for rectifying transistor body-bias selection across different input power levels.

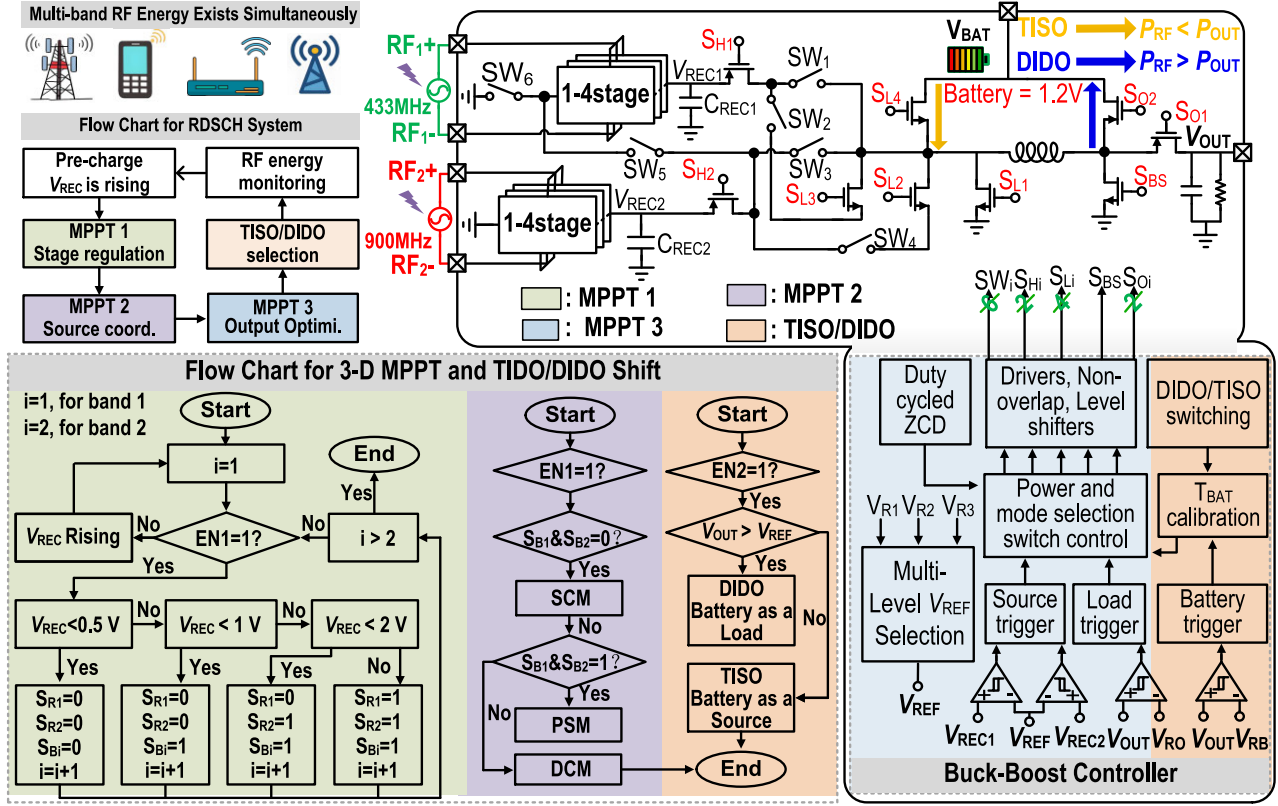


Fig. 8. Block diagram of the RDSCH system, including the flowcharts of the power stage with control modules.

By precisely regulating the rectifier's output, the system can maintain operation at the optimal power point, maximizing the harvested energy from each RF frequency band. The rectifier optimization process includes stage control and body-bias-type adjustment based on the input power level to ensure accurate tracking, minimize power loss, and improve overall conversion efficiency.

III. RECONFIGURABLE DUAL-BAND RF ENERGY COLLABORATIVE HARVESTING SYSTEM IMPLEMENTATION

A. 3-D MPPT RDSCH Architecture Overview

The proposed 3-D MPPT RDSCH system is illustrated in Fig. 8. It consists of two reconfigurable RF-DC rectifiers, a reconfigurable DC-DC converter with multi-input and multi-output capabilities, and an integrated control circuit. RF energy from two frequency bands is received through an off-chip antenna and matching network, and is subsequently processed by the RF-DC rectifiers. Each reconfigurable rectifier functions as an AC-DC converter and supports stage reconfiguration based on the input power level, thereby improving PCE under varying conditions. The DC-DC converter regulates both the rectifier output and the system output voltages by adaptively adjusting its operating frequency and duty cycle. In addition, the concept of synchronization-coordinated harvesting of multiple energy sources proposed in this article can be extended to any number and type of inputs or outputs by

simply adding switches to the source side or load side of the power stage, respectively.

In the initial operating phase, only the rectifier module is active, where all rectifier sub-units are connected in parallel to form a single-stage topology, and the rectifier output voltage V_{REC} gradually increases. Upon arrival of the first enable signal, the system adjusts the rectifier configuration based on the magnitude of V_{REC} . Depending on the voltage range in which V_{REC} resides, one-stage, two-stage, or four-stage configurations are selected, each corresponding to a different target V_{MPP} . Fig. 8, bottom, shows the proposed rectifier stage and dual-band RF source reconfiguration algorithms. Stage adjustment is realized through dynamic series-parallel reconfiguration of the rectifier sub-units, allowing full utilization of all modules. The switching control signal $S_{R1/2}$ determines whether each rectifier unit is connected in series or in parallel, thereby modifying the effective stage configuration of the rectifier.

Upon the arrival of the first enable signal, the reconfigurable buck-boost converter transfers the charge stored in C_{REC} to the load using pulse-frequency modulation (PFM) and dynamic ON-time control. During this process, the converter regulates its input impedance by adjusting the switching frequency and duty cycle of the inductor charging phase, thereby maintaining the rectifier output voltage within a defined hysteresis window.

The buck-boost converter also supports mode switching based on the input power level. From the perspective of dual-band RF source coordination, the system dynamically

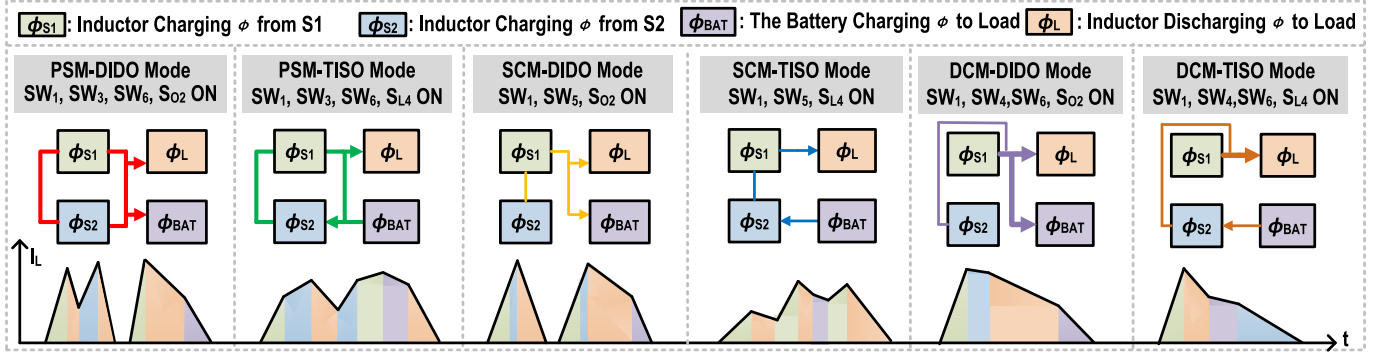


Fig. 9. Six operating modes of the RDSCH system.

reconfigures the source connections under varying input power conditions to operate in three distinct modes (PSM, SCM, and DCM), thereby satisfying global MPPT conditions and improving overall efficiency. In PSM, switches SW_1 , SW_3 , and SW_6 are turned on, connecting the two rectifiers in parallel to the buck–boost converter. In SCM, switches SW_1 and SW_5 are turned on, enabling a series connection of the rectifiers before feeding into the converter. In DCM, switches SW_1 , SW_4 , and SW_6 are turned on, allowing the two rectifiers to alternately drive the converter during the inductor charging and freewheeling phases, respectively.

In addition, due to the time- and location-dependent variability of RF energy sources, a rechargeable battery is incorporated to compensate for the inherent intermittency of ambient energy under specific load requirements. Depending on the relative magnitudes of the harvested input power (P_{RF}) and the load power consumption (P_{Load}), the system dynamically switches between tri-input single-output (TISO) and dual-input dual-output (DIDO) operating modes. This mode transition enables both energy supplementation when $P_{RF} < P_{Load}$ and energy recovery when $P_{RF} > P_{Load}$.

Specifically, at the arrival of the second enable signal, the system compares the output voltage of the buck–boost converter to the reference voltage to determine the power balance condition. If the converter output exceeds the reference, indicating $P_{RF} > P_{Load}$, the battery is configured as a secondary load to store the surplus energy. Conversely, when $P_{RF} < P_{Load}$, the battery supplies supplemental power by connecting to the input of the buck–boost converter. To achieve this bidirectional power flow, a single-inductor buck–boost converter is employed to decouple input-side energy regulation from output-side voltage control. This configuration enables simultaneous MPPT and regulated output voltage delivery, enhancing the system's adaptability to variable operating conditions. The six operating modes of the proposed RDSCH system are shown in Fig. 9.

B. Event-Driven Control Circuits

The proposed RDSCH platform is controlled by an asynchronous event-driven digital controller designed to support low quiescent power. There are four trigger sources for the digital controller: 1) source hysteresis comparator outputs

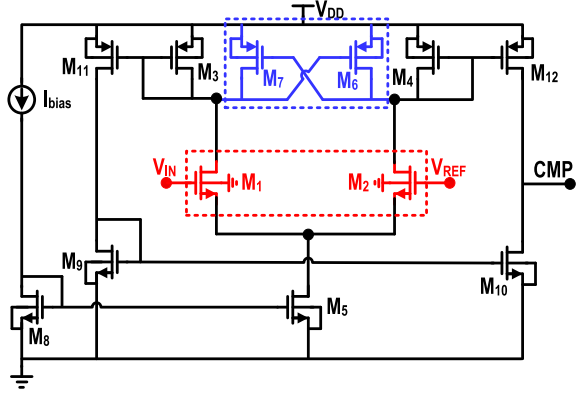


Fig. 10. Schematics of the hysteresis comparator.

trigger the controller whenever there is available energy at the source side to harvest; 2) load hysteresis comparator outputs trigger the controller if the load does not have sufficient energy; 3) the ZCD output triggers the end of the inductor switching cycle and the start of a new cycle; and 4) the TISO/DIDO mode monitor triggers the controller when the RF input power is insufficient to maintain load operation.

The source-side controller is triggered only if any of the load has an energy deficit, or if harvester energy is available. Otherwise, the converter is in the freewheeling phase, and the source-side controller is disabled to save power. For the load-side controller, it checks the output of the load hysteresis comparator and charges the load until its comparator output is high. If the load is charged and there is still current in the inductor, extra charge is recycled back to the battery at the end of the cycle. The following describes the operation of the converter for the dual-side regulating in one cycle. When $V_{REC1/2} < V_{MPP}$, all PMOS switches connected to C_{REC} of the buck–boost converter are turned off, allowing the rectifier to charge C_{REC} and raise $V_{REC1/2}$. Once V_{REC} exceeds V_{MPP} , the PMOS switch at the output of the rectifier turns on to discharge C_{REC} and charge the inductor. When the capacitors C_{REC} at the output ends of the two rectifiers do not need to be discharged, the inductor enters the discharge phase to charge the load and V_{OUT} rises.

Fig. 10 shows the detailed schematics of the hysteresis comparator used for source-side and load-side voltage regulations [18]. The hysteresis window is determined by the ratio

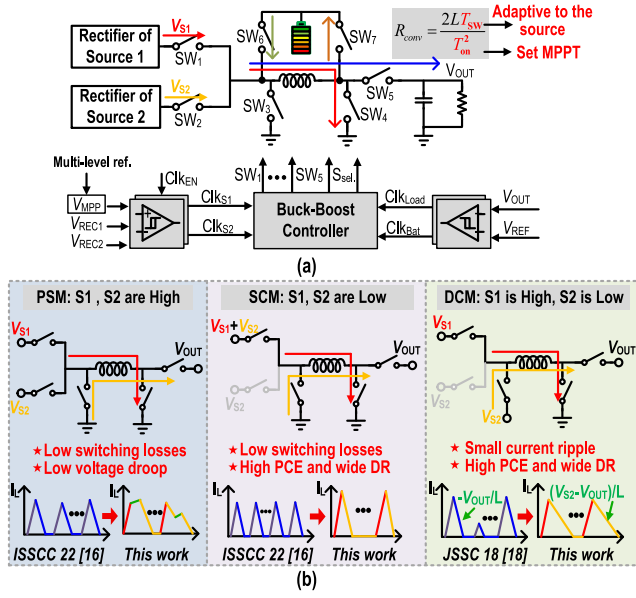


Fig. 11. (a) Implemented SIDRR buck-boost converter and (b) inductor current waveforms in different modes.

between the width of the cross-coupled transistors (M_6 and M_7) and the diode-connected transistors (M_3 and M_4). The hysteresis window, ΔV , can be described by the following equation:

$$\Delta V = \pm \frac{1 - \sqrt{(W/L)_{6,7} / (W/L)_{3,4}}}{1 + \sqrt{(W/L)_{6,7} / (W/L)_{3,4}}} V_{OV1,2}. \quad (3)$$

C. SIDRR Buck-Boost Converter

The proposed single-inductor dual-side regulated reconfigurable (SIDRR) buck-boost converter uses hysteretic control to optimize the rectifier output nodes by regulating each rectifier at its respective MPP through PFM and adaptive inductor ON-time, all managed by a low-power, event-driven controller. It combines both multi-input energy harvesting and load regulation, all in a single-stage topology using a single inductor.

As discussed in Section II-C, the RF-DC rectifier must satisfy the MPPT condition by maintaining a stable output voltage across a wide range of input power levels. To achieve MPPT operation, the input resistance of the buck-boost converter, R_{IN_DC-DC} , must adaptively match the equivalent resistance seen at the rectifier output, R_{REC} , at the optimal operating point, as illustrated in Fig. 11. This impedance matching ensures that the rectifier operates at its MPP, i.e., $V_{REC} = V_{MPP}$. By basic derivation, R_{IN_DC-DC} can be expressed as a function of the inductor charging time T_{ON} and the switching period T_{SW} , as follows:

$$R_{IN_DC-DC} = \frac{2 \times L \times T_{SW}}{T_{ON}^2}. \quad (4)$$

In order to achieve simultaneous output voltage regulation of two rectifiers in the SIDRR converter, each rectifier output is controlled around its respective V_{MPP} using adaptive T_{ON} modulation and PFM, implemented within a hysteretic control

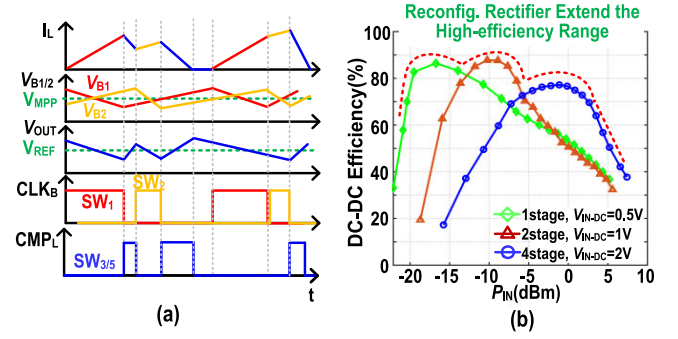


Fig. 12. (a) DC-DC converter node waveforms and (b) its simulated efficiency versus P_{IN} with different configurations of the rectifier.

framework. Specifically, a source-side hysteresis comparator maintains V_{REC} within a defined hysteresis window centered at V_{MPP} , as illustrated in Fig. 12. Once $V_{REC1/2}$ reaches the lower hysteric limit, the negative edge of the comparator output triggers, thereby defining T_{ON} . When $V_{REC1/2}$ reaches the upper hysteric limit, the positive edge of the comparator output triggers the start of a new inductor switching phase, thereby defining T_{SW} . Therefore, there is no need for a clock: unlike conventional approaches, the hysteresis comparator output, CMP, becomes an asynchronous clock.

To enable dynamic reconfiguration of the source-to-DC-DC interface and adapt to varying input power conditions, a reconfigurable DC-DC converter is proposed. The operating mode of the converter is determined by the power levels of the two RF sources, as well as the relationship between the total harvested power and the load demand.

As described in Section II-C, the output voltage of the two rectifier units to reach the minimum required V_{MPP} during the pre-charging phase is used to evaluate the input power levels of the two RF sources. Based on this assessment, the optimal connection configuration between the sources is dynamically determined. Fig. 11, bottom, illustrates the operation concept and the inductor current waveforms in different modes. In the PSM, both rectifier outputs meet the V_{MPP} requirement and are connected in parallel to the DC-DC converter, which operates in a dual-input configuration. In the SCM, the two rectifier units are connected in series, and the converter functions as a single-input configuration. In the DCM, the weaker source is selectively connected during the inductor freewheeling phase, enabling time-division dual-phase energy extraction.

On the other hand, as shown in the right of Fig. 12, the proposed system dynamically adjusts the number of rectifier stages in response to varying input power levels. This adjustment effectively modifies the input voltage of the DC-DC converter, thereby broadening its high-efficiency operating range and further enhancing the overall system efficiency, achieving global optimization.

From a system-level perspective, the proposed design introduces a rechargeable battery to address both energy shortage and surplus conditions, depending on the relationship between the total input RF power and the power required by the load. The rechargeable battery is emulated by a power source and a resistor for circuit verification. The battery enables

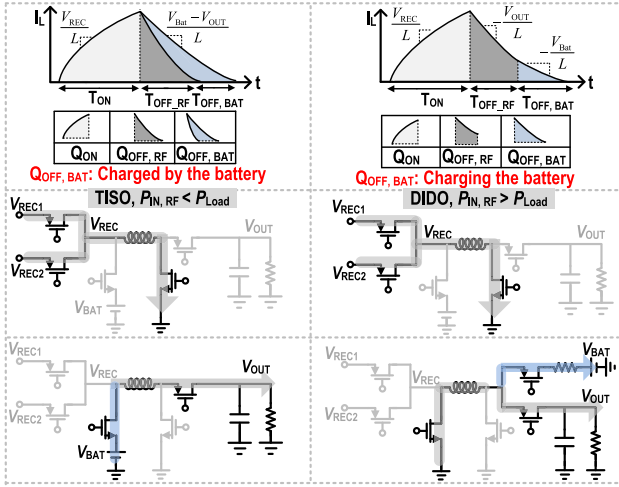
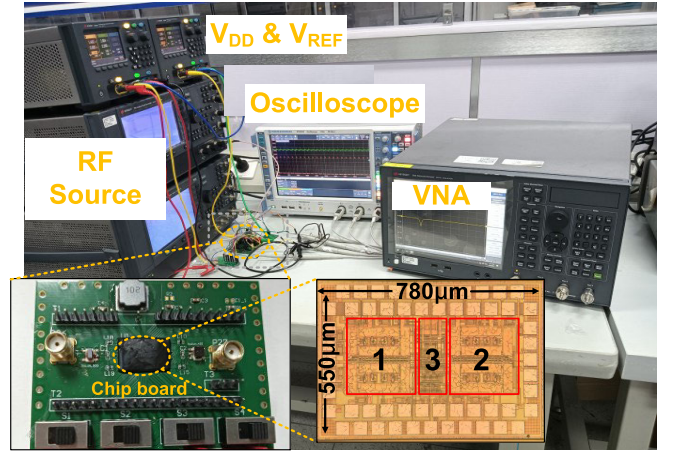


Fig. 13. Operation concept and inductor current waveforms of buck-boost converter.

energy supplementation when the input power is insufficient and stores excess energy when the input exceeds the load demand. The proposed DC-DC converter operates in two distinct modes depending on the power conditions. During the DIDO mode, when the total harvested RF power (P_{RF}) from the two inputs (P_{B1} and P_{B2}) exceeds the load demand (P_{Load}), the system performs time-multiplexed power management, in which energy is alternately delivered to the load and stored in the battery. This operation is orchestrated by non-overlapping output-side control clocks, ensuring stable load regulation while enabling surplus energy storage. During the TISO mode, when the harvested RF power becomes insufficient to sustain P_{Load} , the battery is activated as an auxiliary energy source. The battery, with a nominal voltage of 1.2 V, is coupled to the DC-DC converter during the inductor freewheeling phase, thereby contributing additional energy to the load. Importantly, this assistance is realized without modifying the charging and discharging dynamics of the rectifier output capacitors (C_{REC}) during the inductor energizing phase, allowing the rectifier and MPPT operation to remain unaffected. As a result, the overall system-level efficiency of the DC-DC converter is improved under low harvested power conditions. The converter structure in different modes is shown in Fig. 13.

IV. MEASUREMENT RESULTS

The proposed system was fabricated using a 0.18- μm CMOS process. Fig. 14 shows the chip microphotograph, with a total silicon area of 0.43 mm², including the pads. The die is attached and bonded to the two-layer FR-4 printed circuit board (PCB). Two 50- Ω RF generators are employed as RF sources to independently inject 433- and 900-MHz signals into the power paths of the respective frequency bands. A 50- Ω off-chip balun is used to convert the single-ended input into a differential signal, which is then fed into the matching network. The matching network is implemented using discrete components, offering higher quality factors compared to their on-chip counterparts. In addition, two off-chip capacitors C_{REC} of 100 pF are placed at the outputs of the two reconfigurable rectifiers.



1. Reconfigurable rectifier for 900MHz; 2. Reconfigurable rectifier for 433MHz; 3. Control block for source configuration.

Fig. 14. Measurement setup and chip microphotograph.

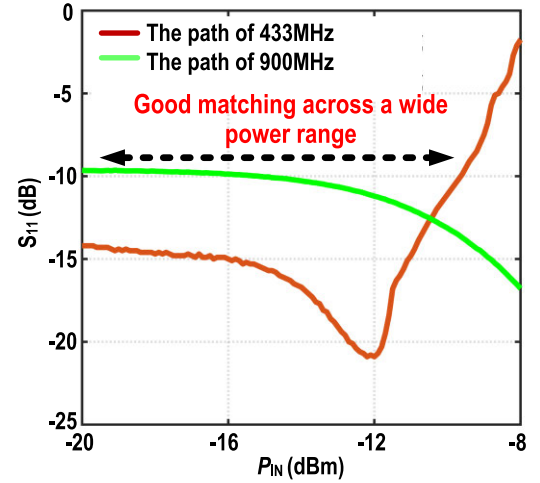


Fig. 15. Measured reflection coefficient S_{11} versus available input power for two frequency bands.

The reflection coefficient (S_{11}) of the system was obtained through a vector network analyzer (VNA), with the condition that S_{11} should be less than -10 dB to represent a matched state at the desired frequencies. Fig. 15 presents the measured S-parameter curves for the two power paths with the rectifier configured in the two-stage topology. The results indicate that both paths achieve good impedance matching at 433 and 900 MHz with a wide input power range, respectively. As the matching characteristics of the rectifier deteriorate with increasing input power, works from [10], [11], and [12] precluded the non-ideal S_{11} by calculating the instantaneous input power delivered to the rectifier's input, which is calculated by the following equation:

$$P_{IN} = P_S * (1 - |S_{11}|^2) \quad (5)$$

where P_S is the output RF power of the RF signal generator, and S_{11} is the measured S-parameters of the rectifier input.

The measured waveforms, including both system start-up and steady-state operation, are shown in Figs. 16–18. The

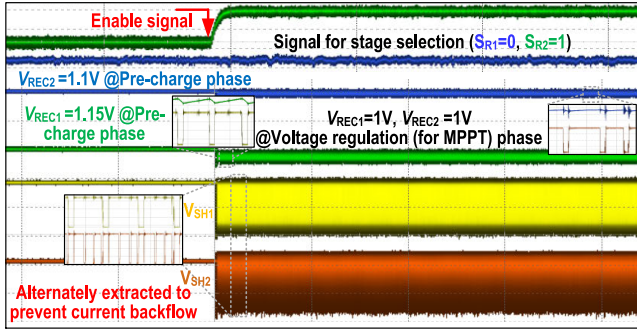


Fig. 16. Measured voltage waveforms of start and steady-state operation in PSM.

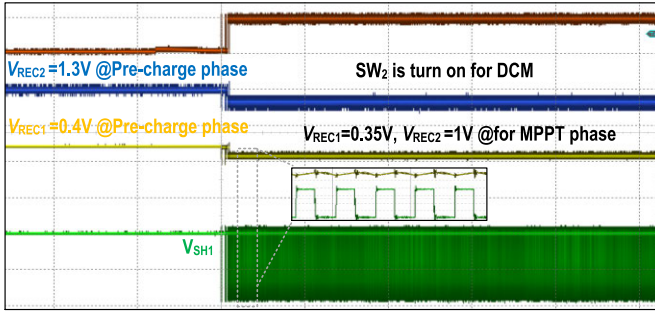


Fig. 17. Measured voltage waveforms of start and steady-state operation in DCM.

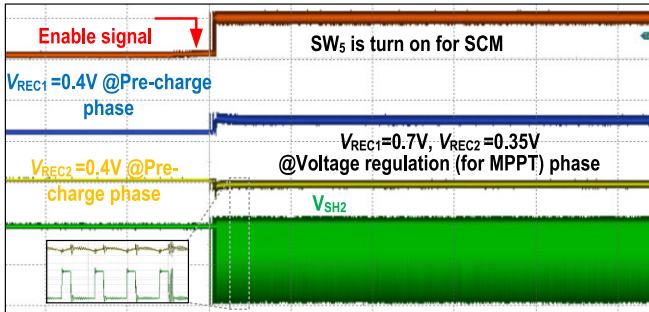


Fig. 18. Measured voltage waveforms of start and steady-state operation in SCM.

externally applied enable signals ensure that, under varying input power conditions, each rectifier unit for the respective RF band is provided with sufficient charging time to evaluate the input power level and determine the appropriate operating mode. Before the enable signal is activated, the rectifier operates in a single-stage mode, charging the C_{REC} . Once the enable signal is received, the input power is determined according to the V_{REC} , and the number of stages and source configuration mode are selected. Depending on the input power level, the system transitions into one of the following operational modes.

PSM (Fig. 16): In this mode, both energy sources are capable of meeting their respective minimum MPPT voltage requirements. A parallel synchronous harvesting configuration is employed, where PFM is used to regulate the voltages at

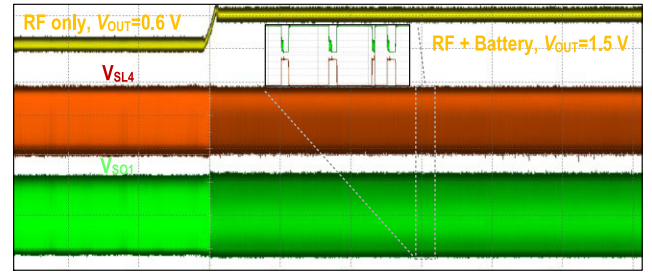


Fig. 19. Measured voltage waveforms of start and steady-state operation in TISO.

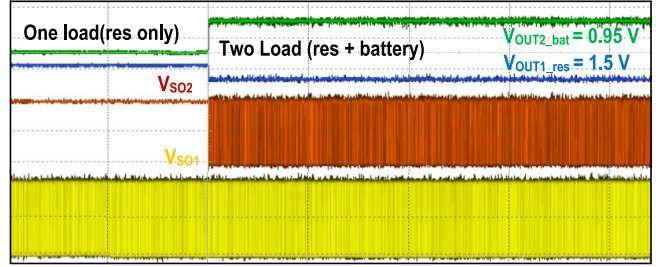


Fig. 20. Measured voltage waveforms of start and steady-state operation in DIDO.

both the rectifier output and the load. Under this condition, the input powers of the two sources are -14.5 and -14 dBm, respectively. Each power path utilizes a two-stage rectifier, and the switching frequency of the subsequent DC–DC converter is dynamically adjusted to maintain the rectifier output at 1 V, thereby ensuring effective MPPT.

DCM (Fig. 17): In this mode, the two RF energy sources exhibit asymmetric input power levels, where one source fails to meet the minimum voltage requirement for MPPT operation. To address this, a two-phase cooperative harvesting strategy is employed. The weaker source is stabilized at approximately 0.35 V and is connected to the ground terminal of the inductor during the freewheeling phase of the DC–DC converter. As illustrated in the figure, the input powers of the two sources are -18 and -13 dBm, respectively.

SCM (Fig. 18): In this mode, both energy sources operate at low input power levels of -17 and -18 dBm, respectively. The corresponding rectifier units are configured as single-stage structures and connected in series. The output voltages of the first and second energy sources are stabilized at 0.7 and 0.35 V, respectively. The resulting input–output voltage difference of 0.35 V across each rectifier unit satisfies the MPPT requirement.

Figs. 19 and 20 present the measured performance of the DC–DC converter under two distinct operating modes. In the TISO mode (Fig. 19), when the received RF power (P_{RF}) is lower than the load power (P_{Load}), the output voltage is regulated to 1.5 V through cooperative energy contribution from both the rechargeable battery and the energy harvester. In the DIDO mode (Fig. 20), when P_{RF} exceeds P_{Load} , the system emulates a rechargeable battery at the auxiliary output using a parallel RC network. Under this condition, once the primary output is regulated at 1.5 V, the auxiliary output, representing the emulated battery, is charged to 0.95 V.

TABLE I
COMPARISON OF THE PROPOSED RECTIFIER WITH PREVIOUS WORKS

Ref.	This work	JSSC'19 [2]	TCAS I'23 [1]	JSSC'25 [3]	JSSC'21 [6]	JSSC'22[5]
Technology	180nm	180nm	65nm	65nm	65nm	65nm
Freq. (GHz)	0.43, 0.9	0.915	0.9, 1.9, 2.4	2.4	2.45	1.07
Energy Source	Dual-band RF & Battery	RF	Tri-band RF	RF	RF	RF
Harvesting Technique	Collab. Source +3-D MPPT	Reconfig. Rectifier	Tri-band Network + Rectifier	3-D MPPT	High-PAPR Self-gating	Self-Biased Rectifier
Sync. & Collab. Extraction	Yes	No	No	No	No	No
Sensitivity (dBm) @ V_{OUT}	-24.1 @ 1 V	-17.8 @ 1V	-20, -16, -19 @ 1V	-28.5 @ 1.2V	-26.7 @ 400mV	-13.8 @ 1 V
High PCE Range (PR) ^a	15.5dB@430 20.5dB@900	13 dB	<10dB @ 900 <10dB @ 1.9 <7.5dB @ 2.4	18.5 dB	12dB**	12 dB
Peak E2E PCE	71%	34.4%	42.8%, 37.1%, 30.4%	18.4%	32.3%	30%
MPPT Mechanism	3-D MPPT	Stage Reconfig.	No MPPT	3-D MPPT	Off-chip MPPT PMU	No MPPT
Output Voltage	1.5V Regulated	0.4-2.8V No Regulated	0 - 3.3V No Regulated	1.2V	0.4-1.4V ^b No Regulated	0-9.3V No Regulated
FoM ^c	32.8	10.12	9.7	9.13	10.39	8.39

a. PCE above 20%, b. Estimated from the figure, c. $FoM = Max.PCE \times PR \times \log_{10}(f/f_0)$, $f_0 = 5\text{MHz}$

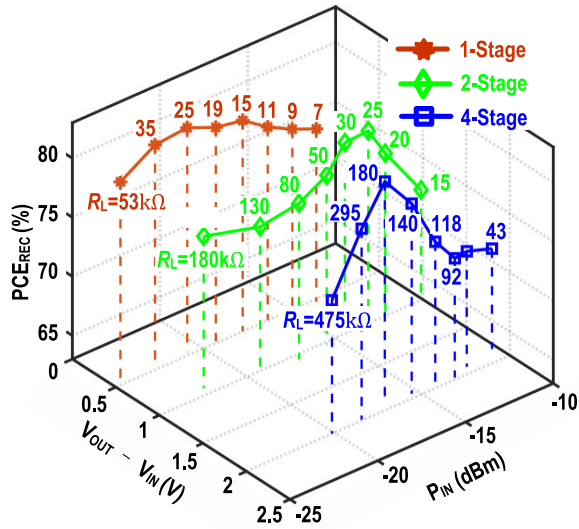


Fig. 21. Measured results of rectifier-only PCE_{REC} at optimum load (kΩ).

Fig. 21 illustrates the optimized PCE characteristics of the rectifier, obtained by sweeping the load resistance across various input power levels and rectifier stage configurations. For each condition, the load resistance is tuned such that the rectifier output voltage aligns with the corresponding MPP voltage V_{MPP} . These results validate the effectiveness of maximizing rectifier efficiency through adaptive optimal load matching in this design. This matching is realized by dynamically adjusting the switching frequency of the DC-DC converter to align

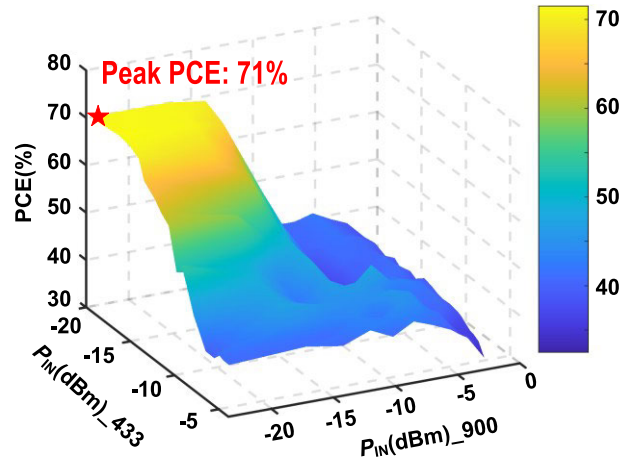


Fig. 22. Measured end-to-end PCE of the system when the two-RF source power change.

its input impedance with the optimal operating point of the rectifier. Fig. 22 presents the overall system-level PCE under a 30-kΩ load across different input power combinations from the two RF energy sources, demonstrating a peak end-to-end efficiency of 71%, together with an ultra-wide input power range of 15.5 and 20.5 dB for the two sources, respectively.

To provide a comprehensive evaluation between different RF energy harvesting techniques, a figure of merit (FoM) is formulated to better reflect the performance of the energy harvesting system after deriving it from the equation reported

in [7] and [8]. The RF energy harvesting system's FoM can be expressed as

$$\text{FoM} = \text{Max.PCE} \times \text{PR} \times \log_{10} \left(\frac{f}{f_0} \right) \quad (6)$$

where FoM is the system's figure of merit, f is the frequency of operation, and $f_0 = 5$ MHz is the frequency normalization factor to uniformly evaluate the performance of the state-of-the-art rectifiers, which operate at different frequencies [7], [8].

Table I summarizes the performance comparison between this work and prior art. Compared to single-path or single-dimension MPPT systems in [1] and [2], the proposed design achieves the highest sensitivity of -24.1 dBm. For a fair comparison, the reported sensitivity in the comparison table is all measured under RF-only operating conditions, without assistance from the battery. Unlike [3], this work introduces, for the first time, a source-coordinated MPPT dimension, which substantially enhances the PCE, achieving a peak PCE of 71%. Moreover, the system supports an ultra-wide input power range of 15.5 to 20.5 dB under dual-source conditions, respectively.

V. CONCLUSION

This article presents a dual-band RF energy harvesting system featuring 3-D MPPT and collaborative source reconfiguration. The MPPT principle of the single-stage rectifier is systematically analyzed and experimentally verified, introducing the concept of multi-dimensional optimization for the first time. Global efficiency optimization is achieved along three dimensions: energy-source coordination control, rectifier output optimization, and rectifier stage regulation. Furthermore, the concept of collaborative harvesting from multiple energy sources is proposed, and an SIDRR buck-boost converter is developed to enable synchronous and coordinated dual-band energy harvesting. Measurement results verify the superiority of the proposed system, achieving high peak PCE, a wide input power range, and enhanced sensitivity across dual-band operation compared with state-of-the-art designs.

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Xianguang Li received the B.S. degree from Shanghai Maritime University, Shanghai, China, in 2020, and the M.E. degree from Tianjin University, Tianjin, China, in 2023. He is currently pursuing the Ph.D. degree with the State Key Laboratory of Integrated Chips and Systems, College of Integrated Circuits and Micro-Nano Electronics, Fudan University, Shanghai.

His current research interests include RF energy harvesting systems and ultralow power management systems.



Qing Miao (Member, IEEE) received the M.Sc. degree in physics from North China Electric Power University, Beijing, China, in 2017, and the Ph.D. degree in optical engineering from Beijing Jiaotong University, Beijing.

Since 2022, he has been with Beijing Smart-Chip Microelectronics Technology Company Ltd., Beijing, where he currently holds the position of Assistant to the Design Department Manager. He has been involved in multiple key power electronics development projects. He has contributed to the development and successful implementation of several power management solutions aimed at improving efficiency and integration for various applications. His research focuses on AC–DC rectifiers, DC–DC converters, and energy harvesting systems.



Shiheng Yang (Member, IEEE) received the B.Sc. degree in electrical and electronics engineering and the Ph.D. degree in electronic and computer engineering from the University of Macau (UM), Macau, China, in 2014 and 2019, respectively.

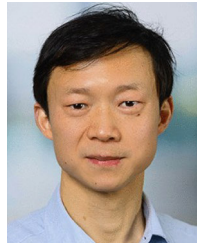
From 2019 to 2020, he was with the State Key Laboratory of Analog and Mixed-Signal VLSI, UM. Since 2020, he has been a Faculty Member with the University of Electronic Science and Technology of China, Chengdu, China. His research interests include analog/mixed IC designs and RF circuits, specializing in frequency synthesizers.

Dr. Yang currently serves as an Associate Editor for IEEE SOLID-STATE CIRCUITS LETTERS, a Reviewer for IEEE JOURNAL OF SOLID-STATE CIRCUITS, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—I: REGULAR PAPERS, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—II: EXPRESS BRIEFS, and a TPC Member for IEEE ICTA.



Tianting Zhao (Member, IEEE) received the B.Sc. and M.Sc. degrees in electronic engineering and microelectronics from Nankai University, Tianjin, China, in 2001 and 2004, respectively.

He is currently the Research and Development Director with Beijing Smart-Chip Microelectronics Technology Company Ltd., Beijing, China. With over 18 years of experience in analog and isolation technology, he has led the development and mass production of multiple key integrated circuits, including digital isolators, isolated DC–DC converters, and gate drivers. He holds several U.S. patents and has published articles at leading conferences such as ISSCC and CICC. His expertise lies in microelectronics, analog chip design, and isolated power solutions.



Sijun Du (Senior Member, IEEE) received the B.Eng. degree (Hons.) in electrical engineering from the University Pierre and Marie Curie (UPMC), Paris, France, in 2011, the M.Sc. degree (Hons.) in electrical and electronic engineering from the Imperial College, London, U.K., in 2012, and the Ph.D. degree in electrical engineering from the University of Cambridge, Cambridge, U.K., in January 2018.

He was with the Laboratoire d'Informatique de Paris 6 (LIP6), UPMC, and then was an IC Engineer at Shanghai, China, from 2012 to 2014. He was a Summer Engineer Intern with Qualcomm Technology Inc., San Diego, CA, USA, in 2016. He was a Post-Doctoral Researcher with the Department of Electrical Engineering and Computer Sciences (EECS), University of California, Berkeley, Berkeley, CA, USA, from 2018 to 2020. He joined the Department of Microelectronics, Delft University of Technology (TU Delft), Delft, The Netherlands, as an Assistant Professor, in 2020. His current research interests include energy-efficient integrated circuits and systems, including power management integrated circuits (PMICs), energy harvesting, wireless power transfer, and DC/DC converters.



Xiaoyang Zeng (Senior Member, IEEE) received the Ph.D. degree from Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Beijing, China, in 2001.

He performed his post-doctoral research at Fudan University, Shanghai, China, from 2001 to 2003. He joined Fudan University, as an Associate Professor, in 2003, and became a Full Professor in 2007. He has authored or co-authored over 100 articles and has applied for over 30 patents. His research interests include high-performance and energy-efficient

SOC integration, especially VLSI designs for wireless communication ICs, information security ICs, and mixed-signal ICs.



Zhiyuan Chen (Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees from the University of Macau (UM), Macau, China, in 2011, 2013, and 2018, respectively.

Since 2018, he has been with Fudan University, Shanghai, China, where he is currently an Associate Professor. His research interests include AC–DC rectifiers, DC–DC converters, and energy harvesting systems.

Dr. Chen serves as a member of the Technical Committee on Power and Energy Circuits and Systems in the IEEE Circuits and Systems Society and has been a Review Committee Member of the IEEE International Symposium on Circuits and Systems since 2021. He was a recipient of Macau Science and Technology Development Fund (FDCT) Postgraduate Award and Shanghai Super Post-doctoral Award.