A Dual-Mode Nested Rectifier for Ambient Wireless Powering in CMOS Technology

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Abstract— This paper proposes a dual-mode nested RF rectifier for ambient wireless powering. The proposed architecture utilizes a dual-mode nested feedback circuit to enhance the conductivity of the rectifier at low-power while reducing the reverse leakage current at high-power by generating supply voltages at the gates of the PMOS rectifying transistors. The proposed rectifier is fabricated in 65 nm CMOS technology and occupies an area of $6480 \mu\text{m}^2$. The measurement results show a peak power conversion efficiency of 86%, 10.1 dB dynamic range, and -19.2 dBm 1-V sensitivity when operating with a 100 k Ω load at the industrial, scientific and medical band 433 MHz. Moreover, the enhanced low-power performance is achieved by reducing the effective threshold voltage of the rectifier by about 37%, compared to a low-threshold transistor in 65 nm technology. This reduction in the threshold voltage allows the rectifier to operate with efficiency exceeding 10% for input power ≥ -40 dBm.

Index Terms— Ambient wireless powering, dual-mode, energy harvesting, nested rectifier, RF-DC converter, self-bias, rectifier, wireless power transfer, wireless powering.

I. INTRODUCTION

OVER THE past two decades, we witnessed the revolution of wireless sensor network (WSN) and the associated fields, including, Internet of Things (IoT), wearable and implantable biomonitors, machine to machine communication and cyber-physical systems [1]-[3]. One of the visions of WSN is to autonomously monitor the environmental parameters such as temperature, moisture, and dissolved oxygen [4], [5]. The WSN market was valued at USD 29.06 Billion at 2016, and it is expected to reach USD 93.86 Billion by 2023 [6]. Powering such a considerable number of WSN devices using conventional methods (*i.e.*, using wireline connections or batteries) can be very challenging or even impossible [2], [7]. Thus, wireless power transfer (WPT) has been heavily investigated as a practical approach for powering battery-free WSN [7]-[16]. With the recent enhancement in WPT techniques and the efficiency of the integrated circuits, the vision of having a truly WSN is becoming a reality [17]-[28].

WPT can be classified into near-field WPT that delivers tens of watts for a short distance (*i.e.*, less than one meter); and microwave WPT that delivers RF power over large distances (*i.e.*, as long as within the range of an RF transmitter).

Depending on the distance between the RF transmitter and the microwave WPT receiver, the power level at the receiver can vary from milliwatts to microwatts [15]. The microwave WPT utilizes a wide range of frequencies including high frequency (HF) band and ultra-high frequency (UHF) band [29]. One of which is the industrial, scientific and medical 433 MHz band that is used for license-free communication, automotive applications [30] and underwater wireless-sensor networks [31].

Fig. 1 shows a schematic of a wireless power receiver (WPR) for wireless powering. It consists of an antenna, a matching network, a radio frequency (RF) rectifier, and a storage element. The RF rectifier is a critical component as it is responsible for converting the limited RF power into a dc voltage. In fact, it determines the sensitivity of the WPR defined as the required input power to generate a certain amount of dc output voltage; the dynamic range (DR) which is the range of input power where the WPR operates efficiently; and a significant portion of the overall power conversion efficiency (PCE) [32]. The efficient operation range of the WPR is determined by 1) the threshold voltage of the rectifier and 2) the reverse leakage current (I_{REV}) in which some amount of the harvested energy leaks back the RF input. Ideally, to extended the efficient operating range of the WPR there is a need to minimize both of the threshold voltage and the I_{REV} .

Many works have been proposed to improve the overall performance of the RF rectifier. Traditionally, rectifiers have been realized using diode-based architectures, such as Dickson [33], half-wave and full-wave rectifiers [34]. In CMOS technology, diodes are realized using diode-connected

Fig. 1. Efficient operation region of the wireless power receiver. Inset is a block diagram of a wireless power receiver.

Fig. 2. Impact of changing the threshold voltage of the rectifying transistors (M1-4) on the performance of the FX rectifier. Inset is schematic of the FX architecture

transistors where the gate and the drain of a transistor are connected together. However, these rectifiers suffer from poor low-power performance and poor PCE due to the high dropout voltage across the diodes [35]. Non-CMOS technologies such as Schottky diodes can enhance the low-power performance of the diode-based rectifiers [3], [36]. However, it is seldom offered in conventional CMOS processes; hence, it cannot be used in low-cost applications where high integration level is needed [3], [35]. Fully cross-coupled (FX) architecture came to solve this problem by applying the input power differentially over a cross-couple bridge, as shown in Fig. 2 inset [37]. Such a configuration offers relatively good low-power performance and peak PCE in standard CMOS technology. However, the FX architecture suffers from poor high-power performance and poor DR due to the presence of the I_{REV} which leaks part of the harvested energy back to the RF input [38], [39]. Many self-biased architectures were proposed to reduce the I_{REV} by lowering the driving voltage of the rectifying transistors at high input power [35], [38], [40]. As a consequence, the self-biased based architectures extended the efficient operating range of the rectifier by offering a wider DR.

Depending on the input power, the rectifiers might not be able to generate sufficient dc voltage for the proper operation of the WPR [41]. For such cases, some of these architectures (*i.e.*, Dickson, FX, self-biased) are arranged in a way to act as a voltage multiplier [33], [37], [41]. For example, voltage multiplier using the FX architecture is achieved by several FX stages connected in series for the dc path where the V_{DD} terminal of the first stage is connected to the V_{SS} of the next stage, and in parallel for the RF input [37]. Still, the minimum operating input power of a rectifier is limited by the threshold voltage of the transistors. One way to solve this problem is by using a low-threshold transistor for the FX architecture. However, by using low threshold transistors the I_{REV} increases, hence, worsening the high-power performance, as shown in Fig. 2. Lowering the threshold voltage of the FX architecture shifts the efficient operating region toward the lower input power range by sacrificing the high-power PCE performance. To this end, Schottky diode-based architectures perform better at very low input power due to their low threshold voltage [3], [18], [41], and there is a need to reduce the effective threshold voltage of

the CMOS-based architectures without sacrificing the PCE at high input power.

This work proposes a highly efficient dual-mode nested RF-to-DC converter for ambient wireless powering. The proposed rectifier is based on the FX architecture and extends the concept of self-bias to enhance both the low- and high- power performance. The proposed design lowers the effective threshold voltage of the rectifier, offers higher PCE at low and high input power, a wider DR and higher 1-V sensitivity, compared to both the FX and the self-biased architectures. This paper is organized as follows: Section II introduces the dual-mode nested feedback circuit and explains the working methodology, Section III shows the measurement results, and Section IV presents conclusions.

II. PROPOSED DESIGN

A. Concept

Conceptually, to improve the performance of the FX rectifier at low input power, there is a need to enhance the conductivity of the rectifying transistors (*i.e.*, by increasing the overdrive voltage of the rectifying transistors). On the other hand, to enhance the performance of the FX rectifier at high input power (*i.e.*, when the instantaneous RF voltage at the source of the rectifying transistors $\leq V_{DD} - V_{th}$), there is a need to reduce the I_{REV} (*i.e.*, by decreasing the overdrive voltage of the rectifying transistors). To achieve such performance, there is a need for a dual-mode (DM) feedback circuit that dynamically changes the dc operating points of the rectifying transistors, hence, changing the effective threshold voltage of the rectifier. Note that, the effective threshold voltage is defined as the minimum voltage required to turn the rectifier ON. The DM functionality is achieved by generating a V_{SS} or V_{DD} biasing voltage at the gates of the rectifying transistors (M2,4) depending on the input power, as shown in Fig. 3. For example, to enhance the performance of the PMOS transistors (M2,4) at low input power, V_{SS} dc voltage is applied at the gates; and to enhance the performance of the rectifier at high input power, V_{dd} dc voltage is applied at the gates.

The real challenge in realizing the DM concept is the lack of sufficient supply voltage at low input power for powering the feedback circuit. As a consequence, the use of inverters, switches or comparators is not appropriate for enhancing the

Fig. 3. Block diagram of the proposed dual-mode feedback circuit

low-power performance of an RF rectifier. Therefore, the DM feedback circuit should be independent and self-sustained by harvesting its own energy. At the same time, the DM feedback circuit should consume minimum energy across the full range of input power to conserve the overall PCE. To overcome these challenges, a novel nesting scheme is proposed and discussed in depth in section IIB. Basically, the nested DM rectifier is achieved by utilizing two rectifiers acting as the DM feedback circuit and connected to the gates of M2 and M4. For such a configuration the output dc voltages of the nested rectifiers are used to bias the rectifying transistors of the main rectifier.

B. Architecture

Fig. 4(a) shows a schematic of the proposed DM rectifier for the enhanced performance. It consists of four low-threshold (V_{th_L}) rectifying transistors (M1-4), a DM feedback circuit that encloses two identical nested rectifying circuits connected to the gates of M2,4, six diode-connected transistors (D1-6), and eight coupling capacitors.

The DM feedback circuit consists of a weak-conduction low-threshold voltage transistor (M5,6) connected in parallel with a high-threshold (V_{th_H}) diode (D7,8). Note that, the weak-conduction of M5,6 and D7,8 is achieved using transistors with a small width to length ratio (W/L) to reduce the current flow. In such a configuration, M5,6 produces a V_{SS} dc signal at the gate of M2,4 at low input power, while D7,8 produces a V_{dd} dc voltage signal at high input power. The DM feedback circuit by itself acts as a special type of a rectifier where the positive terminal (the cathode of D7,8) and the negative terminal (the drain of M5,6) are shorted together and connected the gates of M2,4. Note that, M5,6 is indeed inherited and equivalent to M1,3 in the FX design, and D7,8 is inherited and equivalent to the diode in the half-bridge rectifier. Since D7,8 is a high-threshold diode, its operation is limited to relatively high input power level (*i.e.*, when the instantaneous RF voltage becomes

larger than V_{th_H}). On the other hand, the low threshold voltage of M5,6 results in a pronounced operation at low input power. For such a configuration, the proposed DM feedback circuit is able to generate a V_{SS} dc voltage at low input power and a V_{DD} voltage at high input power.

To reduce the short-circuit current between D7,8 and M5,6 at high input power (*i.e.*, when both M5,6 and D7,8 are ON), D5,6 is connected to the gate of M5,6. D5,6 acts as a switch to reduce the conduction of M5,6 by lowering the dc voltage at the gate of M5,6 at high power levels. In general, this concept is presented in [40]. In short, at low input power, the voltage-drop across D5,6 is relatively low (less than the threshold voltage of the diode); hence, the diode remains OFF and acts as an open-circuit. However, at relatively high input power, the voltage-drop across D5,6 exceeds the threshold voltage of the diodes. As a consequence, the diode is ON and drains current from the gate of M5,6, hence, lowering the dc voltage at M5,6's gate. Note that, D5,6 is a weak-conduction diode to reduce the leakage DC current from the DM feedback circuit to the load (*i.e.*, V_{SS} terminal). Similarly, the high-threshold diode D1,2 is connected to the gate of M1,3 to lower the dc voltage, hence, reducing I_{REV} in M1,3 at high input power. On the other hand, D2,4 enhances the I_{FWD} of M1,3 by draining more current from the negative terminal of the load (V_{SS}).

Fig. 4(b) shows the steady-state operating points of M2 (similarly M4). At low input power, M6 is active, and D8 is OFF. For such case, the driving voltage (V_{SG}) of M2 is:

$$V_{SG\_low\ power\_M2,4} = V_{RF} - V_{SS} \quad (1)$$

where V_{RF} is the instantaneous RF voltage, and V_{SS} is the negative dc voltage supplied by the DM feedback circuit. Such high driving voltage is important at low input power where I_{REV} is negligible and the need to enhance I_{FWD} is critical. On the other hand, at high input power, D8 is active and M6 is OFF, as shown in Fig. 4(c). For such case, the driving voltage (V_{SG}) of

Fig. 4. (a) Proposed dual-mode (DM) rectifier, and corresponding steady-state operating points at (b) low and (c) high input power.

TABLE I.
DRIVING VOLTAGE FOR THE DIFFERENT SELF-BIASED BASED ARCHITECTURES AT LOW AND HIGH INPUT POWER

At low input power	At high input power	At low input power	At high input power
Fully cross-coupled [37] $V_{SG,M2} = V_{RF}$ Moderate I_{FWD} at low power	$*R_{RF} \propto V_{RF} \propto V_{DD}$ $V_{SG,M2} = V_{RF}$ High I_{REV} at high power	Double-sided diode [40] $V_{SG,M2} = V_{RF}$ Moderate I_{FWD} at low power	$V_{SG,M2} = V_{RF} - V_{DD}$ Low I_{REV} at high power
Self-biased [35] $V_{SG,M2} = V_{RF} - V_{DD}$ Poor I_{FWD} at low power	$V_{SG,M2} = V_{RF} - V_{DD}$ Low I_{REV} at high power	This work $V_{SG,M2} = V_{RF} - V_{SS}$ High I_{FWD} at low power	$V_{SG,M2} = V_{RF} - V_{DD}$ Low I_{REV} at high power

M2 is:

$$V_{SG\_high\ power\_M2,4} = V_{RF} - V_{dd} \approx V_{RF} - V_{DD} \quad (2)$$

where V_{dd} is the positive dc voltage supplied by the DM feedback circuit. Such small driving voltage is essential at high input power where reducing I_{REV} is critical. Table I compares the driving voltages of the different self-biased based architectures. As shown, the proposed DM feedback circuit is the only architecture with a high driving voltage at low input power allowing for high I_{FWD} . It also maintains the enhanced performance at high input power levels by reducing I_{REV} . Fig. 5 shows the simulation results of the output voltage and the normalized output voltage from the DM feedback circuit at both low- and high- input power. At low input power, the DM

Fig. 5. Simulation results of the feedback voltage and the input RF voltage, and the feedback voltage normalized to the input RF voltage versus the input power for the proposed DM rectifier, operating at 433 MHz with a 100 kΩ load.

feedback circuit is capable of generating a low dc voltage to enhance the conductivity of M2,4. On the other hand, the DM feedback circuit is capable of generating a high dc voltage at high input power to reduce the reverse leakage current in M2,4.

Fig. 6 shows the performance for different types of rectifiers including the proposed DM rectifier, FX, half-wave and full wave rectifiers, simulated in 65 nm CMOS technology, 433 MHz frequency and with a 100 kΩ load. The simulation results indicate that the proposed DM rectifier has a significantly lower effective threshold voltage of about 170 mV, compared to the other architectures, as indicated in Fig. 6(a). Note that the reduction of the effective threshold voltage of the proposed DM rectifier below the actual threshold-voltage (*i.e.*, about 270 mV for a low threshold NMOS transistor in 65 nm technology, as anticipated from the performance of the half bridge rectifier) is due to the subthreshold conduction ($I_{subthreshold}$) of M5,6, which is described by:

$$\begin{aligned}
 I_{subthreshold} &= I_{ds0} e^{\frac{V_{gs}-V_{th}}{n v_T}} \left(1 - e^{\frac{-V_{ds}}{v_T}} \right) \\
 &= I_{ds0} e^{\frac{V_{RF}-V_{th}}{n v_T}} \left(1 - e^{\frac{0.5V_{RF}-V_{g,M2,4}}{v_T}} \right) \quad (3)
 \end{aligned}$$

where n and I_{ds0} are process dependent parameters, v_T is the thermal voltage, $V_{g,M2,4}$ is the dc voltage at the gate of M2,4, and V_{th} is the threshold voltage of M5,6 [42]. $I_{subthreshold}$ results in the charging the equivalent capacitance at the gates of M2,4, hence, changing the dc operating points of M2,4 even when the RF voltage is below the threshold voltage. For such case, the dc voltage at the gates of M2,4 is equal to:

Fig. 6. Simulation results of (a) the output voltage versus the input voltage and (b) the output voltage versus the input power for different architectures, operating at 433 MHz with a 100 kΩ load.

$$V_{sub} = \frac{1}{C_{total}} \int I_{subthreshold} dt \quad (4)$$

where C_{total} is the total equivalent capacitance seen at the node connected the gate of M2,4, and approximated as:

$$C_{total} \approx C_{g,M2,4} // C_{D7,8} // C_{coupling} \quad (5)$$

where $C_{g,M2,4}$ is the gate capacitance of M2,4, and $C_{D7,8}$ is the equivalent capacitance looking at the cathode of D7,8. As a consequence, the effective threshold voltage of the rectifier is lowered by V_{sub} , and it equals:

$$V_{th,eff} = |V_{th}| - |V_{dc,g,M2,4}| = |V_{th}| - |V_{sub}| \quad (6)$$

This reduction in the effective threshold voltage is reflected in the overall performance of the rectifier at low input power, as shown in Fig. 6(b) and Fig. 7(a). In fact, the dual-mode capability of the proposed architecture allows for consistently efficient performance across an extended range of the input power, resulting in higher output voltage and PCE at low- and high- input power levels, compared to the other architectures. Note, the PCE results for the DM rectifier include the losses in the feedback circuit and the leakage current. The simulation results in Fig. 7(a) indicates more than 100% PCE enhancement compared to the FX when the input power is less than -30 dBm. This enhanced performance of the DM rectifier is maintained

Fig. 7. Simulation results of (a) the PCE and the enhancement in the PCE versus the input power for the proposed DM and the FX rectifiers operating with a 100 kΩ load, and (b) the PCE of the proposed DM rectifier for different loads. Operating frequency is 433 MHz.

for different loads (*i.e.*, $R_{Load} = 30, 50, 70$ and 100 kΩ), as shown in Fig. 7(b).

III. MEASUREMENT RESULTS AND DISCUSSION

The proposed DM rectifier is implemented in 65 nm standard CMOS technology. For a fair comparison, the FX architecture is also fabricated on the same die. Note that, the rectifying transistors (M1-4) for both architectures are low-threshold transistors. Also, the FX architecture was optimized separately for its optimum performance (FX sizing: M1,3 = $1480 \mu\text{m}/0.18 \mu\text{m}$ and M2,4 = $4 \mu\text{m}/0.1 \mu\text{m}$). Fig. 8 shows a microphotograph of both architectures. The proposed DM rectifier occupies an area of $6.48 \times 10^3 \mu\text{m}^2$, compared to $0.43 \times 10^3 \mu\text{m}^2$. This increase in the area for the DM architecture is mostly due to the extra coupling capacitors introduced in the DM architectures.

Fig. 8. Die microphotograph of (a) the FX and (b) the proposed DM architectures. Insets show pictures of the layouts.

The measurement setup consists of a vector network analyzer (VNA) (Agilent N5225A), a digital multimeter (Keysight 34420A), and a 100 kΩ load. The test is achieved by RF probing the chip using a GSGSG differential probe with a reference plane set to the on-chip pads of the rectifier's input. After that, the RF power of the VNA is swept, and the corresponding S-parameters and the output voltage at the load are recorded. The instantaneous input power delivered to the rectifier is calculated by de-embedding the transmission and the reflection losses, as described by the following equation:

$$P_{in} = P_{source}(dBm) - L_{cable}(dB) - 10\log|S_{11rect}|^2 \quad (7)$$

where P_{source} is the output RF power supplied by the VNA, L_{cable} is the losses of the RF cable, and S_{11rect} is the measured S-parameters of the rectifier's input. Finally, the PCE of the rectifier is calculated as follow:

$$PCE = \frac{P_{out}}{P_{in}} = \frac{v_{out}^2 / R_{Load}}{P_{in}} \quad (8)$$

where P_{out} is the output power delivered to the load, v_{out} is the output voltage, and R_{Load} is the 100 kΩ load [38], [35]. Note, the complete design of the WPT receivers (*i.e.*, including the matching network and the antenna) using FX-based architectures are discussed in [43]-[45].

Fig. 9(a) shows the measured PCE for both the proposed DM and the FX architectures which is in good agreement with the simulation results. In general, the proposed design offers an

enhanced performance across the full range of the input power with a peak PCE of 86%, compared to 72% for the FX architecture. The enhanced performance at low input power (*i.e.*, input power less than -30 dBm) is exclusive for the DM architecture. For example, at -35dBm input power, the PCE of the proposed DM rectifier is 38% which is more than two times the efficiency of the FX architecture. The superb performance at both the low and the high input power is reflected in the extended DR of the proposed rectifier. Note that, the DR is defined as the range where the performance of the rectifier exceeds 80% of the peak PCE. The DR is influenced by both the low and the high power performance of the rectifier and is calculated by:

$$DR(dB) = P_{max}(dBm) - P_{min}(dBm) \quad (9)$$

where P_{max} and P_{min} are the range where the $PCE \geq 0.8 \times \text{peak PCE}$. Fig. 9(b) compares the peak PCE and the DR of the DM and the FX architectures for different loads. In general, the proposed design consistently offers improved performance compared to the FX architecture, with up to 19% enhancement in the peak PCE and 53% in the DR.

Fig. 10 shows the measured output dc versus the input power. The proposed rectifier offers a boosted output voltage across the full range of the input power. This improvement in the output voltage is reflected in the sensitivity of the rectifier defined as the input power required to generate a 1-V output voltage at the load. The sensitivity of the proposed DM rectifier is -19.2 dBm which is more than 13 dB better than the FX

Fig. 9. (a) Measured PCE versus the input power with a 100 kΩ load, and (b) the measured enhancement in the dynamic range and the peak PCE for different loads.

Fig. 10. Measured output voltage versus the input power with a 100 kΩ load.

Fig. 11. Measured output voltage versus for different loads and input power.

TABLE II
PERFORMANCE COMPARISON

Architecture	Load (k Ω)	Frequency (MHz)	Technology (nm)	Number of stages	Area ($\times 10^3 \mu\text{m}^2$)	Sensitivity ^a (dBm)	PCE ^b at -35 dBm (%)	Peak PCE ^b (%)	Dynamic Range ^c (dB)
Proposed design	100	433	65	1	6.48	-19.2	38	86	10.1
Fully cross-coupled (FX) using low threshold transistors [37] ^d	100	433	65	1	0.43	-6.1	14	72	6.6
Self-biased [35]	100	433	180	1	17	-17	< 3	52	7.9
Diodes, double sided [40]	100	433	180	1	8.8	-19.2	< 18	86	6.7
Fully cross-couple with inter-stage RF injection [47]	100	433	180	3	88	-4.1	N.A.	10	4.8
Threshold Compensated [48]	100	433	180	4	150	-13.5	< 7	34	8.2
Dynamic Threshold Reduction using PMOS [49]	10	402	180	1	24	> -1	< 1	86	4.2
Adaptive Threshold Voltage Compensation [46]	30	402	180	3	1440	-8.8	N.A.	31.9	10
Proposed design ^e	100	900	65	1	6.48	-14.9	19	80	6.5
Fully cross-coupled (FX) [37]	100	953	180	1	13.4	-12.9	< 18	86.2	5.1
Adaptive [38]	100	900	180	1	8.4	-18	< 10	65	8.7
Diodes, double sided [40]	100	900	180	1	8.8	-18.2	< 8	66	4
Self-biased [50]	50	850	180	1	17	-N.A.	< 2	40	6.48
Adaptive Vth compensated [51]	130	915	130	12	250	-17	N.A.	33	7.5

^a. Input RF power for 1-V output voltage; ^b. Power Conversion Efficiency (PCE); ^c. input power range of $\text{PCE} \geq 0.8 \times \text{peak PCE}$; ^d. measurement results are reproduced in this work; ^e. simulation results.

architecture. Fig. 11 shows the measured output voltage for different loads (ranging from 30 k Ω to 100 k Ω) and input power levels (ranging from -35 dBm to -15 dBm). In general, the proposed DM rectifier maintains the enhanced performance for

the large range of the input power and the resistive loads.

Table II compares the performance of the proposed DM rectifier with the state-of-the-art rectifiers designed in CMOS technology and operating at similar frequency range. The proposed design offers the best sensitivity, peak PCE and DR. Moreover, the proposed design offers the best low-power performance with a PCE of 57% at -30 dBm. The double-sided architecture [40] offers a similar peak PCE and sensitivity, yet, the proposed design offers 3.4 dB wider DR and 37% higher PCE at -30 dBm input power due to the superb low power performance of the proposed architecture. The adaptive threshold voltage compensation [46] offers similar DR to the proposed design, yet, the proposed design offers more than double the peak PCE. Fig. 12 compares the performances of many recent architectures including the peak PCE and the sensitivity versus the DR operating at similar frequency range (i.e., 400 to 500 MHz). In general, the proposed DM rectifier offers consistently the highest PCE and the best sensitivity for a wide range of RF power levels.

IV. CONCLUSION

The proposed dual-mode nested feedback circuit enhances the low- and high- power performance of the fully cross-coupled architecture by dynamically changing the dc operating points of the rectifying transistors. At low input power, it applies a V_{SS} dc voltage at the gates of the PMOS rectifying transistors to enhance their conductivity. On the other hand, the reverse leakage current at high input power is reduced by applying a V_{DD} dc voltage at the gates of the PMOS rectifying transistors. The proposed DM rectifier is implemented in 65 nm CMOS technology using low- and high- threshold transistors. Nevertheless, this topology is scalable to other CMOS

Fig. 12. (a) Peak PCE and (b) sensitivity versus DR for different architectures operating at the UHF band.

technologies that support low-threshold transistors. The proposed dual-mode rectifier offers a high peak power conversion efficiency of 86% with exceptionally low-power performance exceeding 10% for input power greater than -40 dBm. Such a design enables ambient wireless powering and energy harvesting using standard CMOS technology.

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