Multiple Energy Harvesting for Highly Efficient Wireless Power Receiver

Kee Hoon Yang[1], Yeong Hun Kim, Hyoung Jun Na, Ho Won Kim, Tae Seob Oh, Jae Bin Kim, Jong Wan Jo, and Kang Yoon Lee[a]

Department of Electrical and Computer Engineering, Sungkyunkwan University

E-mail : [1]yangghmail@skku.edu

***Abstract* - This paper shows an efficient wireless power receiver (WPR) based on multiple energy harvesting (EH) methodology. The proposed WPR structure consists of a high and low power route holding power conversion efficiency (PCE) high in a broad scope input. Solar/Thermoelectric/ Triboelectric/Vibration/RF energies are proposed as multiple hybrid energy sources. Thermal and solar energy harvester is proposed with Maximum Power Point Tracking (MPPT) in time-domain. For triboelectric/vibration EH and high-power path energy harvesting, highly efficient rectifier in full wave (FWR) and RF-DC converter operating at 5.8 GHz are presented to increase the input power range. A 0.18 µm Bipolar-CMOS-DMOS process is used for the chip fabrication. The RF-DC operating at 5.8 GHz attains 76.9% PCE at 30 dBm input. A PCE of 69.85% is achieved using the harvester of solar energy as a peak point. The RF-DC converters of low power path in 900 MHz and 2.4 GHz frequency attain 73% and 71.9% PCE results at 0 dBm in 1 mW as a peak.**

***Keywords*—Energy Harvesting, MPPT, Multiple Energy, WPR**

I. INTRODUCTION

In recently, energy harvesting has been developing increasingly and selected as a replaceable device for a battery to make wearable devices charged in wireless network and Internet of Things. [1-2] For instance, a battery which is used for a supply of power input has lots of limits for changing and charging operation in specific circumstances [3−5]. To get rid of the supply, especially battery, various EH methods have been suggested to get the energies from the surrounding environments effectively and change them into available power [1−6]. However, there is a restriction for harvesting the energies from various kinds of sources for lots of reasons. In this paper, we propose the multiple hybrid EH based high efficiency WPR.

a. Corresponding author; klee@skku.edu

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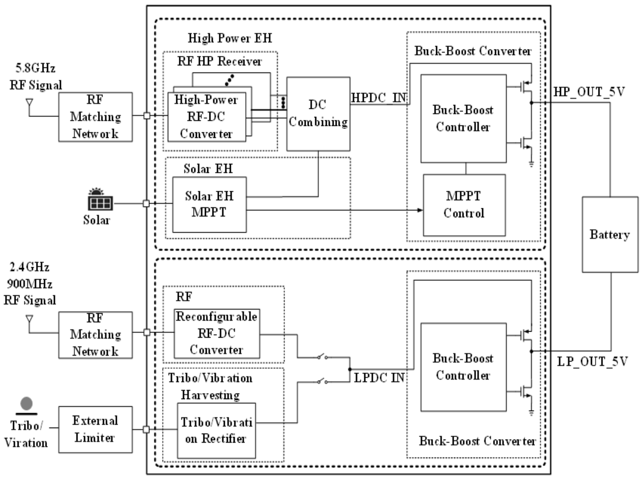


Fig. 1. Diagram of the block for the designed high efficiency WPR based on the Multiple hybrid EH.

II. DESIGN METHODOLOGY

The block diagram of the designed highly efficient WPR based on multiple hybrid energy harvesting is shown through Fig. 1. This proposed structure has 4 paths to gain the energy during a high condition of PCE in a wide scope of input. The high-power path output is connected to a solar EH path, and the output from them is used for source of power supply in Buck-Boost converter, giving 5V stored in a battery eventually. In similar method, the low power course is connected to the vibration/triboelectric course output, and the output of them is used to supply the voltage to the Buck-Boost converter giving regulated 5V, which is stored in a load battery. Therefore, it keeps load battery charged with a high PCE by tetra-path energy harvesting simultaneously.

A. Solar/Thermal Block using MPPT in Time-Domain

Fig. 2 depicts the diagram of block for energy harvesting of solar system using a time-domain MPPT. The MPPT controller selects the optimum available sets of three words; mode, duty, and core control word. The optimum choice is obtained by tracking and comparing V_{OUT}, and controlling Buck-Boost converter, and it improves the PCE of converter.

The actuation principle of the block is that, V_{OUT} is compared with decision levels, V_{REFL} and V_{REFH}, as shown in Fig. 3. Signal START or STOP goes high level when V_{OUT} becomes low level or high level. When START constant is high before STOP constant is high, the time between them is called charge time (T_{CH}). It can have a value which is not greater than 1 second. The V_{OUT} is discharged by the value of DISCTRL being high.

B. Vibration / Triboelectric Block

The designed rectifier of Vibration/Triboelectric EH is shown in Fig. 4. Design of Vibration/Triboelectric rectifier uses two methods for high path and low path; two schottky diodes and NMOS for high and low side respectively. To make the power loss minimized due to low side NMOS of the core, sensing the input voltage makes self-reset generated to make the reset pulse. Voltage limiter is used in front of input path to make core input voltage clipped because of input which can go up by 100V. Triboelectric can maximize the output effect while having a spark discharge effect. This has the effect of inducing output and current rise by about tens of times or more.

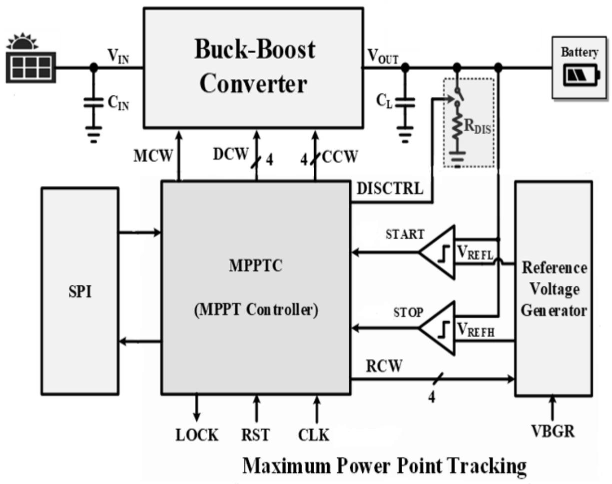


Fig. 2. Solar/Thermal EH block diagram using MPPT controller.

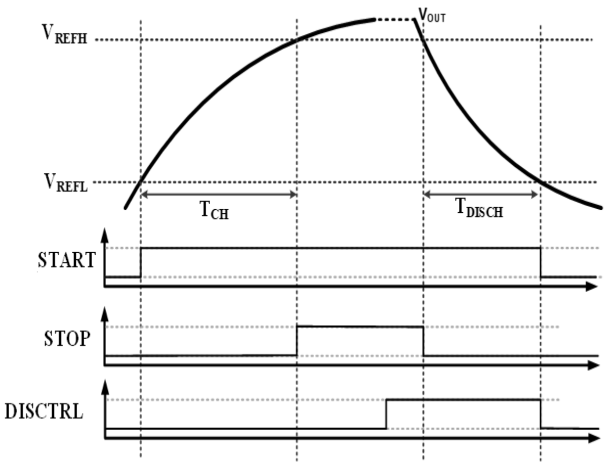


Fig. 3. Time-Domain MPPT algorithm timing diagram.

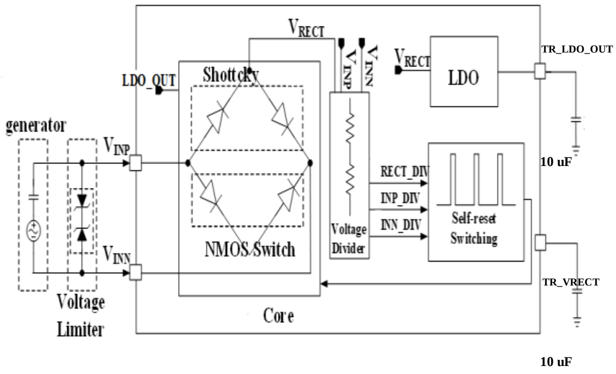


Fig. 4. A Vibration/Triboelectric EH block diagram.

C. RF-DC Converter of Low-Power Path

The RF-DC block diagram in low power path is shown in Fig. 5. For executing the dual frequency operation, impedance network with the different input power and frequency is controlled by a tunable cap bank. A 2 Dickson charge pump design is used for making the structure of the circuit. Diode connected MOS structure is used to accomplish the high efficiency and integration

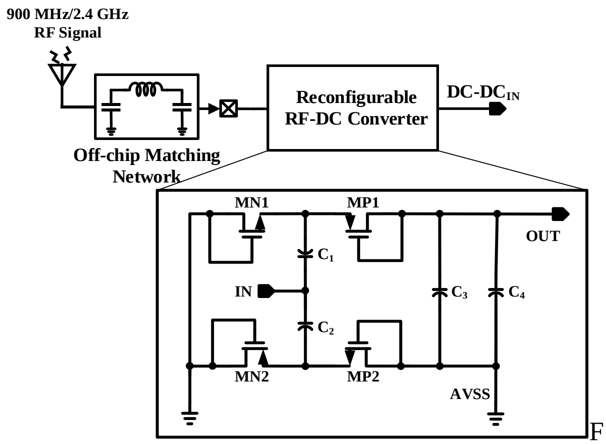


Fig. 5. A block diagram of Low Power RF-DC.

D. RF-DC Converter of High-Power Path

The diagram of the designed RF-DC with Schottky diodes is shown in Fig 6. In this RF-DC scheme, it includes six parallel converters to change RF_{IN} signal efficiently, and contains the adaptive matching network to make input range wide and PCE high. If the input bias voltage RF_{IN} is too low to operate the circuit, the PCE and output voltage value are decreased. Therefore, the shunt diodes are used to control input bias voltage so that circuit functions accurately at input range of high power.

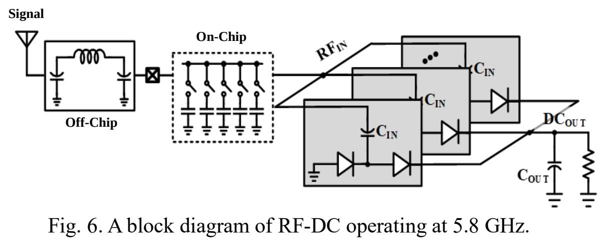


Fig. 6. A block diagram of RF-DC operating at 5.8 GHz.

E. DC-DC Converter

DC-DC Converter block diagram is shown in Fig. 7. A hysteresis triple-mode selector is used in DC-DC converter to control the converter effectively during choosing as operation mode in three modes according to input: buck, boost or buck-boost mode. This technique gets rid of the unstable condition while changing the mode. This converter generates a regulated output of 5V.

The principles of operating this converter is shown in Fig. 8. In a mode of buck, each switch M3 and M4 is OFF and ON. SA, SB signals can make the switch M1, M2 on and off. In a mode of boost, each switch M1 and M2 is ON and OFF. SC and SD signals can make M3 and M4 on and off. In a mode of buck-boost, signals SA, SC and SB, SD operate as switches of high and low path. The output is generated to 5 V through switching two pairs, M2-M4 and M1-M3.

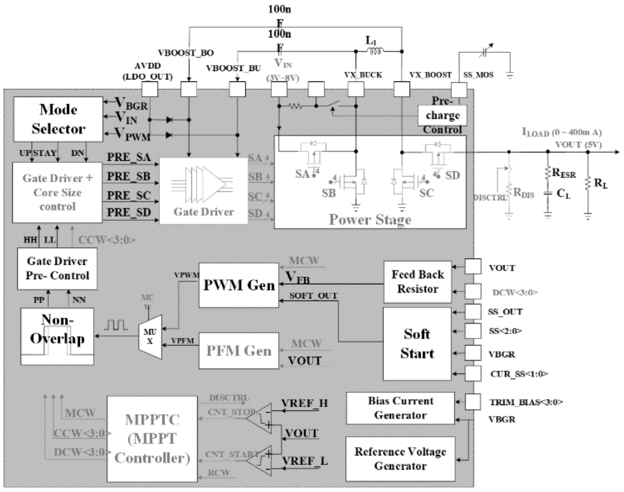


Fig. 7. The proposed DC-DC Converter block diagram

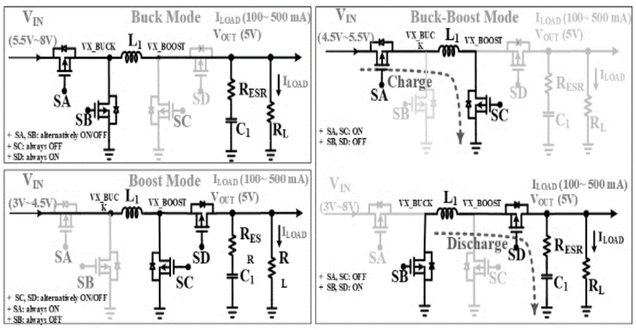


Fig. 8. DC-DC Converter operation principles in three modes.

III. RESULTS AND DISCUSSIONS

The layout of the proposed design chip including pads is shown in Fig. 9. The 0.18 μm BCD process is used to design the chip. The measurement result graph of settling time and PCE for Solar/Thermal EH. The measuring method and simulation result graph of the vibration/triboelectric EH block. Fig. 10 shows Energy Harvest.

The method of measuring the chip of RF-DC operating in 5.8 GHz is shown in Fig. 13. To measure PCE, load generator, RF generator, and power amplifier are employed. Through the power amplifier getting 10 dBm input by RF signal generator, the input power 30 dBm has been connected to the testing board. The appropriate value of load can be drawn during adjustment of load resistance. The RF-DC in 5.8 GHz gets 76% PCE result at 30 dBm input.

The PCE results of low-power RF-DC is shown in Fig. 14. The measurement shows results as 73% and 71.9% PCE at 0 dBm in each frequency.

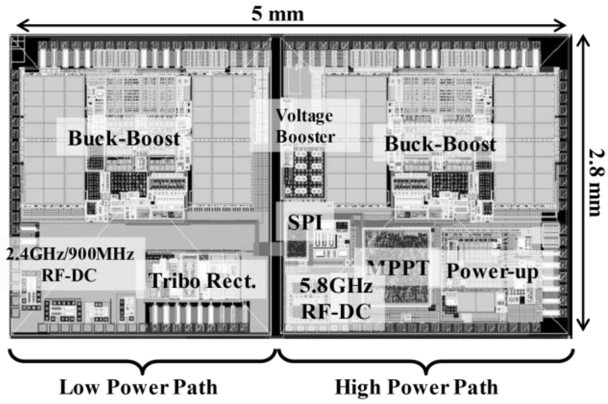


Fig. 9. Layout of the chip.

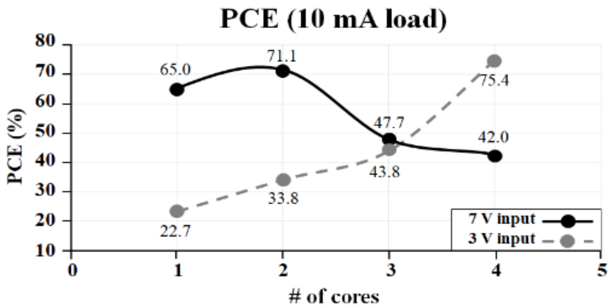


Fig. 10. Settling Time and PCE of the Solar/Thermoelectric EH.

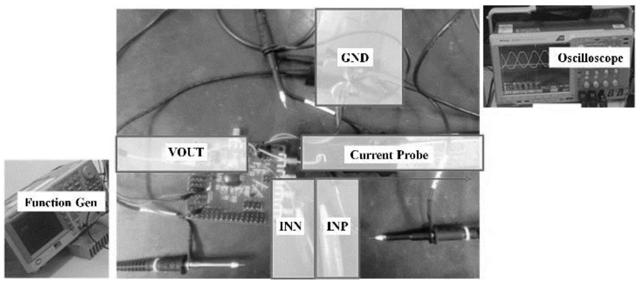


Fig. 11. Method of Measuring Vibration/Triboelectric chip.

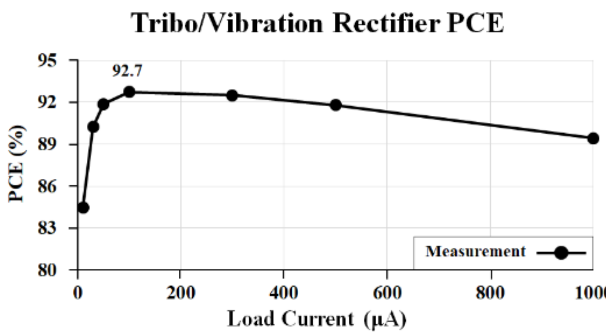
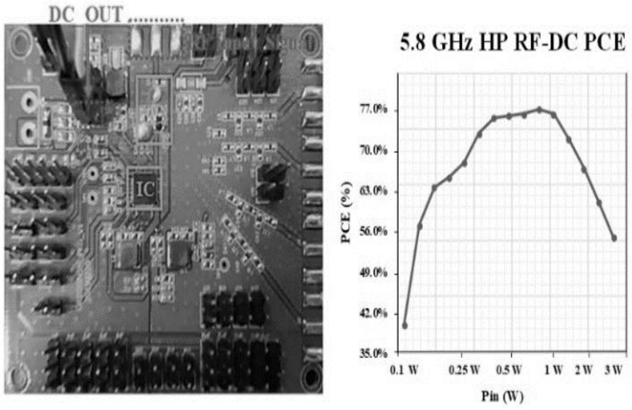


Fig. 12. PCE of Vibration/Triboelectric EH.



(a) (b)

Fig. 13. (a) The measurement chip and (b) PCE results of RF-DC converter in 5.8 GHz

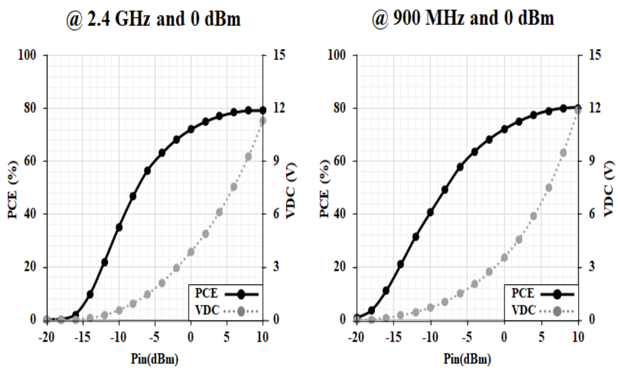


Fig. 14. PCE results of RF-DC operating in each frequency.

TABLE I. Performing Table Compared with Other Papers

Parameter	[5]	[6]	This Work	
Technology	130nm	150nm	180nm BCD	
Energy Source	Thermoelectric, RF	Magnetic, Solar, Wind, PZ	Thermoelectric, Triboelectric, Vibration, Solar, RF	
Input Power	100 µW ~	200 µW ~ 50 mW	100 µW ~ 1 W	
PCE (peak)	RF: 38% @14.8 dBm	Solar: 72.5% @V_{IN}=3V	RF	76% @ 30dBm & 5.8GHz 71.9% @ 0dBm & 2.4GHz 73% @ 0dBm & 900MHz
			Solar	75.4% @ V_{IN}=3V
			Tribo	92.7%@ 1.2dBm
Die Area	8.25 mm^2	1.69 mm^2	14 mm^2	

IV. CONCLUSION

A Multiple hybrid EH based high efficiency WPR is designed in this paper. The structure of the designed WPR includes a large power and small power course keeping PCE high through a wide input range. Time domain MPPT is used for Solar/Thermoelectric EH. Highly efficient FWR is proposed for Vibration/Triboelectric EH. Using adaptive matching network about large power of RF-DC Converter at 5.8 GHz is used to extend input power. In addition, the PCE improves higher by reconfigurable cores. This chip of proposed circuit is made in BCD 180nm process. The length by length of the die is 2.8 mm by 5.0mm containing pads. The solar/thermoelectric EH gets 69.85% PCE value as a peak. The high-power RF-DC retains measurement result about 77% PCE at 30dBm. Other RF-DC converters with low power operating at 0.9 GHz and 2.4 GHz retain 73% and 71.9% as peak efficiency at 0 dBm. The proposed WPR architecture using Buck-Boost DC-DC converter attains measured PCE of 94.5% as a peak.

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Kee Hoon Yang received his B.S. degree from the Department of Electrical and Electronic Engineering at Sungkyunkwan University, Suwon, Korea, in 2021, He is currently working toward the M.S. course in Electronics and Computer Engineering from Sungkyunkwan University, Suwon, Korea. His research interests include CMOS RF Energy Harvesting.

Hyoung Jun Na received his B.S. degree from the Department of Electronic Engineering at Kyonggi University, Suwon, Korea, in 2020, where he is currently working toward the M.S degree in School of Information and Communication Engineering, Sungkyunkwan University. His research interests include ADC/Mixed circuit.

Yeong Hun Kim received his B.S. degree from the Department of Electronic Engineering at Suwon University, Hwaseong, Korea, in 2021, He is currently working toward the M.S. course in Electorinics and Computer Engineering from Sungkyunkwan University, Suwon, Korea. His research interests include AI and Neuromorphic.

Tae Seob Oh received his B.S. degree from the Department of Mathematics at Sungkyunkwan University, Suwon, Korea, in 2020, He is currently working toward the M.S. course in Electronics and Computer Engineering from Sungkyunkwan University, Suwon, Korea. His research interests include DAC and Analog filter.

Jae Bin Kim. received his B.S. degree from the Department of Electrical Engineering at Myongji University, Suwon, Korea, in 2019, Since then he has been working toward the combined Ph.D. & M.S. Course in electronics and computer engineering from Sungkyunkwan University, Suwon, Korea. His research interests include RF Energy Harvesting and Wireless Power Transfer System.

Jong Wan Jo received his B.S. degree from the Department of Electronic Engineering at Cheongju University, Cheongju, Korea, in 2018, where he is currently working toward the M.S degree in School of Information and Communication Engineering, Sungkyunkwan University His research interests include Wireless Power Transfer systems and Power Management IC.

Kang Yoon Lee received the B.S., M.S. and Ph.D. degrees in the School of Electrical Engineering from Seoul National University, Seoul, Korea, in 1996, 1998, and 2003, respectively

From 2003 to 2005, he was with GCT Semiconductor Inc., San Jose, CA, where he was a Manager of the Analog Division and worked on the design of CMOS frequency synthesizer for CDMA/PCS/PDC and single-chip CMOS RF chip sets for W-CDMA, WLAN, and PHS. From 2005 to 2011, he was with the Department of Electronics Engineering, Konkuk University as an Associate Professor. Since 2012, he has been with College of Information and Communication Engineering, Sungkyunkwan University, where he is currently a Professor. His research interests include implementation of power integrated circuits, CMOS RF transceiver, analog integrated circuits, and analog/digital mixed-mode VLSI system design.