A Survey of RF Energy Harvesting Circuits

C. Achille Fumtchum, Pierre Tsafack, Florin Hutu, Guillaume Villemaud, Emmanuel Tanyi

Abstract: The aim of this work is, on one hand, to review the state of the art of the architectures and diodes used in radio-frequency energy harvesting systems, the idea here is to review the most recent works, as well as their characteristics, which include frequency, type of diode used, topology, maximum efficiency and corresponding power, and on the other hand to carry out simulations to determine the most appropriate case for any further work in the field. After having determined the most common topologies, we used the main known radio-frequency diodes to characterize them in a first step, clearly a process of comparing the results of the simulations of the different topologies is done by initially considering an identical frequency. and afterward determine the effect of frequency band on their conversion efficiency.

Keywords: RF Energy Harvesting Topologies; Conversion Efficiency; Wireless Power Transfer; Telecommunications; Circuits And Systems.

I. INTRODUCTION

From 2005 to present, there has been intense research activity on RF energy harvesting. Those works have allowed their authors to focus on the harvesting of very low energies such as the ambient RF energy radiated by telecommunication sources succinctly described in [1], or on the RF energy transmitted in a technology commonly call wireless power transfer (WPT) [2]. Whether we are dealing with the harvesting of ambient energy or radiated energy, the topology of the harvesters remains unchanged.

The key features of RF energy harvesters are the simplicity of the circuit, the size, the operating frequency, the technology (here referring to discrete components circuits, CMOS circuits and microstrip technology circuits), and the conversion efficiency. Although all of these characteristics are important, on this work we will focus on the conversion efficiency.

The conversion efficiency of a rectifier circuit is the ratio between the output DC power at its load to the input RF power. It is expressed by the following equation:

$$\eta = \frac{P_{DC}}{P_{RF}} \qquad (1)$$

where η: Conversion efficiency

P_{DC} : Direct current power at the output of the converter

P_{RF} : RF input power

The conversion efficiency of a rectifier circuit is a fundamental characteristic in the sense that it determines the rate of energy capture. The higher the efficiency, the better the circuit. An efficiency close to 100% is therefore required, which would mean in this case that all the energy that reaches the rectifier is converted into DC energy. It is therefore necessary to design energy conversion circuits to achieve the best conversion efficiency, that will require proper optimization of the impedance matching circuits, as well as the load resistance at the output of the system

RF energy harvesting, while using the same mechanism and circuitry as the conversion of AC current and voltage to DC current and voltage at low frequencies, does not use similar diode types or circuit design techniques. The RF signal, being by nature radiated, is highly dispersive and therefore calls for the use of impedance matching techniques to allow the transmission of the maximum available power from the source to the conversion system. In addition, in order to expect the output energy of the rectifier to be as low as possible, diodes with very low thresholds must be considered. This requirement for low threshold diodes is dictated by the fact that for WPT the power to be radiated in nature is limited or the ambient energy to be recovered is very low, ranging from a few nano-watts to a few tens of micro-watts. For this above reason, there are mainly two families of diodes used, namely the HSMS28xx family from Avago technology and the SMS76xx family from Skyworks, and also the use of CMOS technology. As will be seen in the following sections, these above two families of diodes were used in each of the topologies that we used for the investigation. As per the state of art, the work done so far is performed on a variety of frequencies, topologies, diodes and technologies with results that do not measure or determine the impact of frequency, topology and diode choice on the circuits.

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Table I: characteristics of some recent energy harvesting circuits							
Ref	**Year**	**Frequency (GHz)**	**Max. Efficiency / Input Power**	**Topologies**	**Diodes**	**Substrate**	**Load (kOhms)**
[4]	2020	2.2	50% / 0 dBm	Series	SMS7621	RO5880	0.2
[5]	2020	0.9 / 1.8 / 2.45	52%, 50%, 46.5% / 0 dBm	Series	HSMS2852	FR4	3.8
[6]	2020	2.4	69.3% / 5.5 dBm	Voltage doubler	SMS7630	RO4003C	2
[7]	2020	2.4 / 5.2	63.38%, 65.4% / 13 dBm	Series	HSMS2860	FR4	0.15
[8]	2020	5.8	81% / 15 dBm	Shunt	HSMS286F	RO4350B	0.45
[9]	2019	5.8	66% / 20 dBm	Shunt	HSMS2860	F4B	0.12
[10]	2019	1.4	74.8% / 10 dBm	Voltage doubler	SMS7630	FR4	1
[11]	2019	2.4 / 5.8	63%, 54.8% / 12.3 dBm	Series	HSMS2860	FR4	0.6
[12]	2019	0.9 / 1.8	57.5%, 52.6% / - 5 dBm	Series	HSMS2850	RO5880	7
[13]	2019	0.920	24% / - 4 dBm	Dickson	SMS7630	FR4	0.050
[14]	2018	2.45	17% / 0 dBm	Greinacher	HSMS2862	Textile	10
[15]	2018	1.1 - 1.35	63% / 10 dBm	Voltage doubler	SMS7630	FR4	2
[16]	2018	2.45	68% / 5 dBm	Cockcroft-Walton	HSMS2850	FR4	5
[17]	2018	2.5	69 % / 3.5 dBm	Voltage doubler	HSMS2850	RO3003	1
[18]	2018	2.45	27 % / 10 dBm	Shunt	HSMS2850	RO350B	0.68
[19]	2018	0.9 / 1.8	20.2%, 22.59% / - 11.8 dBm	Greinacher	-----	CMOS	70
[20]	2017	0.93	12.6 % / - 15.4 dBm	Dickson	-----	CMOS	500
[21]	2017	2.45 / 5.8	57.1 %, 39.2% / - 0 dBm	Voltage doubler	SMS7630	RO5880	5
[22]	2017	2.45	57 % / 0 dBm	Shunt	SMS7630	RO3203	2.47
[23]	2017	2.45	37 % / 0 dBm.	Voltage doubler	SMS7630	FR4	2.4

One of the objectives of this work is to support the reader who wishes to design an energy harvester circuit for an application with topologies analysis as well as the impact of the frequency bands and environment on their conversion efficiency. To achieve this, a state-of-the-art analysis was carried out to determine the most commonly used topologies and diodes, afterward a simulation analysis and evaluation of the efficiency of each topology with those main diodes commonly used.

The rest of this paper is organized as follow: in section II, the state of the art of energy recovery circuits is described together with some of the most recent ones presented with their characteristics. In section III the different rectifier topologies are presented; simulations and comparative analysis to determine the conversion efficiencies are also performed. Subsequently, we repeat the simulations on a second frequency band in order to determine the influence of frequencies on the circuits. Then follows a conclusion in section IV which gives the perspective of this work.

II. STATE OF THE ART OF ENERGY HARVESTING CIRCUITS

In this section, some of the most recent and important related works will be presented on the subject with their characteristics; we must not lose sight of the fact that the ultimate aim of these circuits is to harvest radio energy for a contribution to the energy consumption of various systems.

To the best of our knowledge, the harvesting of radio energy as it stands today really began in 2005 with the work presented in [3]. In this pioneering work, a series of 4 passive antennas made of transmission lines (Engraved on the FR4 PCB) interlaced in a square spiral was used. Each of the antenna was matched in impedance with a rectifier using a double diode bridge HSMS2820. The interlacing of antennas in that work aimed at collecting the maximum of energy on a physical surface different from the effective surface of an antenna at the considered frequency (915 MHz). The result

obtained was a power of 80 milliwatts harvested at a distance from 20 cm from a 5 W emission.

The most commonly used radio frequency energy harvesting circuits are essentially the one listed in Table I. These are the series, shunt, voltage doubler, Dickson, Greinacher and Cockcroft-Walton topologies. These different topologies are employed in the design of rectifiers that operate in several frequency bands as can be seen in Table I. These topologies that are represented in Figure 1 will be used later as case studies for the following demonstration. The Cockcroft-Walton topology is not used in the next steps and will not be depicted since it is a multiple diode version of the voltage doubler topology which uses two diodes.

III. SIMULATIONS AND COMPARATIVE ANALYSIS OF THE STRUCTURES
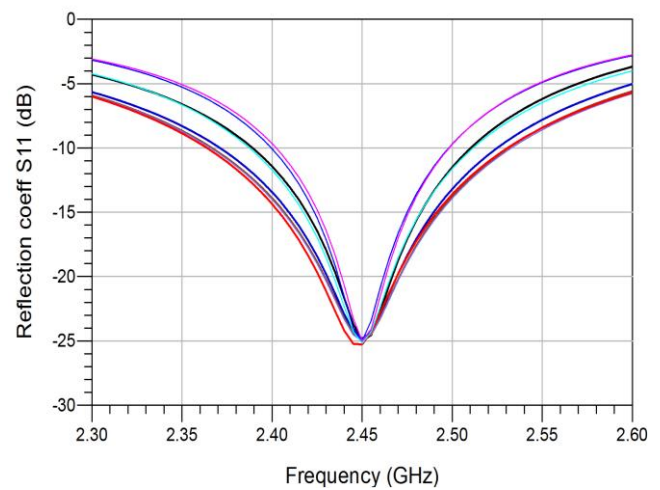
A. Energy Harvester Circuit Structures

Radio frequency energy harvesting circuits are usually designed around four functional blocks. The antenna, which represents the source to be placed at the input of the circuit, the impedance matching network that allows the source to transmit the maximum power to the next block, and then the rectifier block which is the rectification block in the strict sense. This includes a filtering capacitor and is followed by the last block which is the load for which the DC power from the rectification and filtering is intended.

Figure 1 presents the various topologies of circuits used for radio frequency energy harvesting.

(a) Series topology

(b) Voltage doubler topology

(c) Shunt topology

(d) Dickson topology
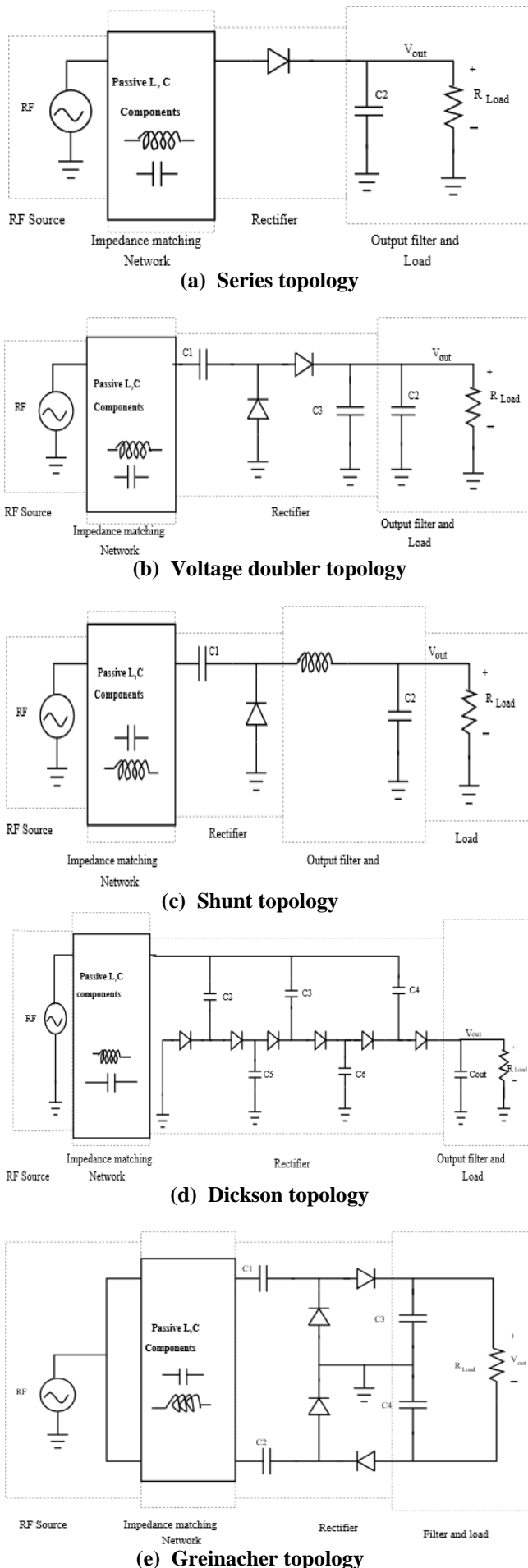
(e) Greinacher topology
**Fig. 1.Topologies of circuits used for radio frequency energy harvesting**

Fig. 2.Reflection coefficient of all the rectifier topologies in simulation at frequency 2.45 GHz with input power – 30 dBm

**B. Survey of Energy Harvesting Topologies And Data Analysis**

This survey is conducted by simulations where a feasible impedance matching of - 25 dB at an input power of - 30 dBm was chosen as shown in Figure 2. For all the five structures submitted to study, the matching network is just after the source for both families of HSMS and SMS diodes. The choice of the HSMS 2850 diode is guided by a study carried out in [24], which shows that it offers an advantage over many other RF diodes and is commonly used for RF applications. The SMS 7630 diode is chosen because it is almost ubiquitous in rectifiers, as shown in the study we present in the state of the art in Table I. Furthermore, in [25], it was shown that for the specific case of the rectifier using the diode in series, the SMS 7630 diode was better than the HSMS 2850 diode. For these reasons, three diodes that are HSMS2850, HSMS2860 and SMS7630 will be used for the survey study.

Figure 3 presents simulation results of the conversion efficiency of the five topologies mentioned above. In order to achieve this, each topology was constructed using the three most commonly used diode types mentioned above.

As can be seen, this study was carried out on the power band from – 30 dBm to 30 dBm, corresponding to the power range from 1 microwatt to 1 Watt. This power band is the same one in which can be found the radiated energy in the case of wireless power transfer, and the ambient RF Energy. The result obtained on each graph was done by optimizing the load resistance using the "Optimization tool" of the Keysight's ADS software. In the above case, the working frequency is 2.45 GHz and all the results are summarized in Table II where is also presented a summary of the simulations of the different topologies with the optimized load values for each case. By varying the input power from – 30 dBm to 30 dBm, we determine the point of maximum efficiency.
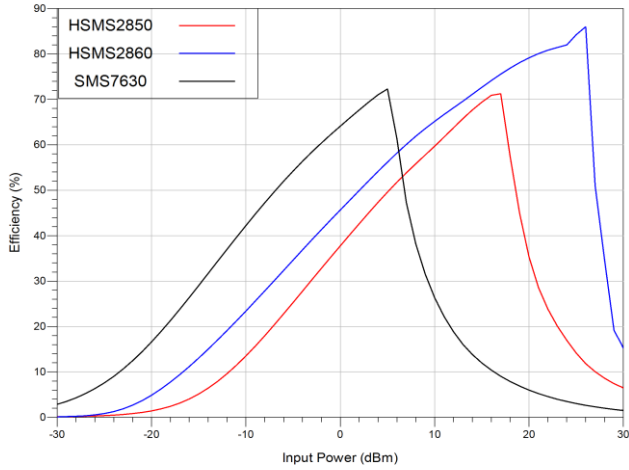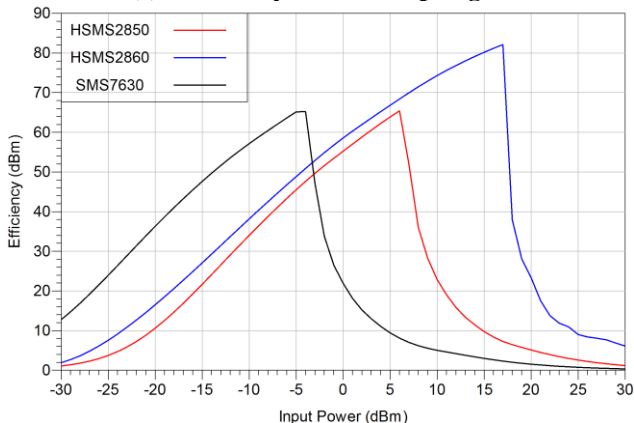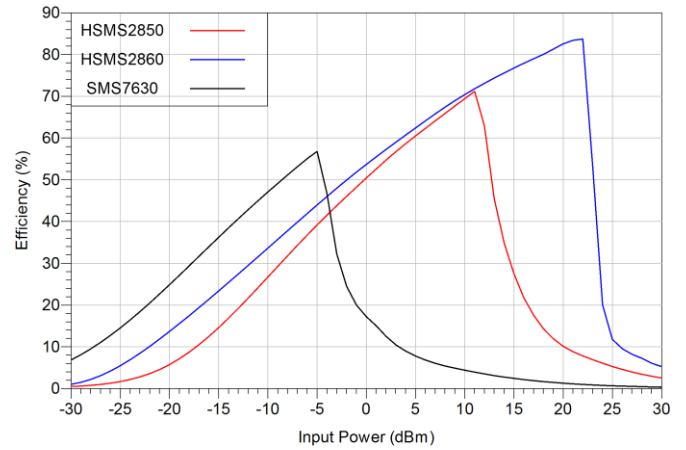
(a) Efficiency in Dickson topologies
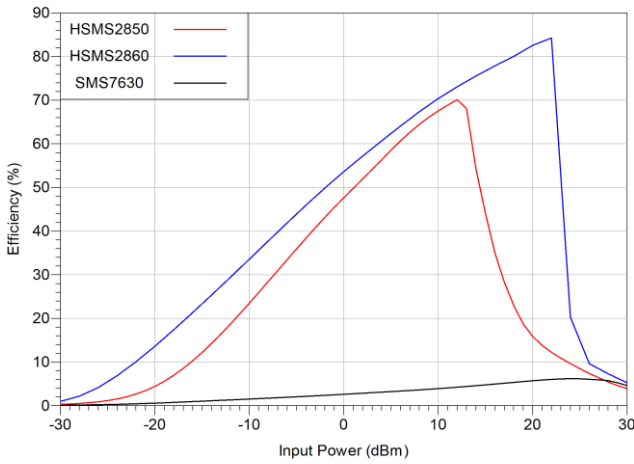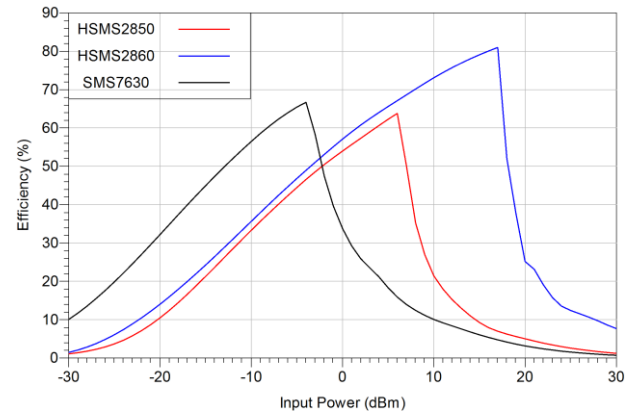
(b) Efficiency in Greinacher topologies

(c) Efficiency in Series topologies

(d) Efficiency in Shunt topologies

(e) Efficiency in Voltage doubler topologies

Fig. 3.Rectification efficiency simulation survey of different topologies (Dickson, Greinacher, Series, Shunt and voltage doubler) using diodes HSMS2850, HSMS2860 and SMS7630. Here the simulations are done at frequency 2.45 GHz; for each topology, the color code are red for HSMS2850, blue for HSMS2860 and black for SMS7630

A simple analysis shows that Dickson diode structure HSMS2860 which has an efficiency of 85.71 % at 25 dBm input power is the best structure for RF energy harvesting. If, on the contrary, we are in an environment where the power that arrives at the antenna is very low, around - 4 dBm, then the SMS7630 diode series topology, which reaches its maximum efficiency at 66.66 %, is the best. At this power (– 4 dBm), the Dickson topology has an efficiency of only 34 %.

As shown in this same Table II, there is a wide range of loads to be placed at the output of the rectifier circuit to achieve maximum efficiency. These loads are varying depending on the topology and the diode used, from a few tens of ohms to a few tens of kilo ohms.

Table II. Simulation of efficiency at frequency 2.45 GHz

Architecture	Diode Type	Max Eff. (%)	Power of Max. Eff. (dBm)	Inp. Pwr. at 10% Eff. (dBm)	Load Res. (kΩ)
Dickson	HSMS 2850	71.13	17	– 12	7
	HSMS 2860	85.71	25	– 17	30
	SMS 7630	71.56	5	– 23	20
Greinacher	HSMS 2850	70.1	12	– 16	2
	HSMS 2860	84.2	16	– 22	15
	SMS 7630	6.15	23	– –	0.1
Series	HSMS 2850	63.97	7	– 20	2
	HSMS 2860	81.03	16	– 22	3
	SMS 7630	66.66	– 4	– 30	2

|					
Shunt	HSMS 2850	65.36	6	– 20	2
	HSMS 2860	82.09	16	– 23	4
	SMS 7630	65.46	– 5	– 31	5
Voltage Doubler	HSMS 2850	71.20	11	– 17	3.3
	HSMS 2860	84.58	20	– 22	15
	SMS 7630	56.78	– 5	– 28	5

It should be noted that during the simulations, whatever the value of the load resistance, it does not influence the reflection coefficient (S11) that is used for impedance matching. This is due to the fact that S11 is and RF parameter and the load is in the DC part, and its value depends on the overall impedance of the system. However, this value of the load resistance has a great influence on the efficiency of the whole system. Therefore, to determine the optimum load, it must be varied by measuring the efficiency of the system; this is done in simulation using the Parameter Sweep tool of the ADS software.

From the discussion above, it can be deduced that the choice of topology and diode of the energy harvesting circuit to achieve maximum efficiency must depend on the input power available to be captured. If, for example, 0 dBm of power is to be harvested in the 2.45 GHz band, it can be seen from graphical analysis that we have an efficiency of 60 % for the shunt topology with HSMS2860 diode and HSMS2850 diode series topology. For the same power, the Dickson topology with the SMS7630 diode has an efficiency of 63 %. These last three circuits are therefore the ones to be considered since they have the highest efficiencies at 0 dBm input power.

With this obtained result, it can be said that the choice of diode for an energy harvester depends on the power source available and the related topology to be considered. This means that one diode is only better than the other if a specific situation is considered.

C. Energy Harvesting Topologies and Frequency Impact Investigation

To evaluate the influence of frequency on the radio frequency energy harvesting circuits, the five previous topologies have
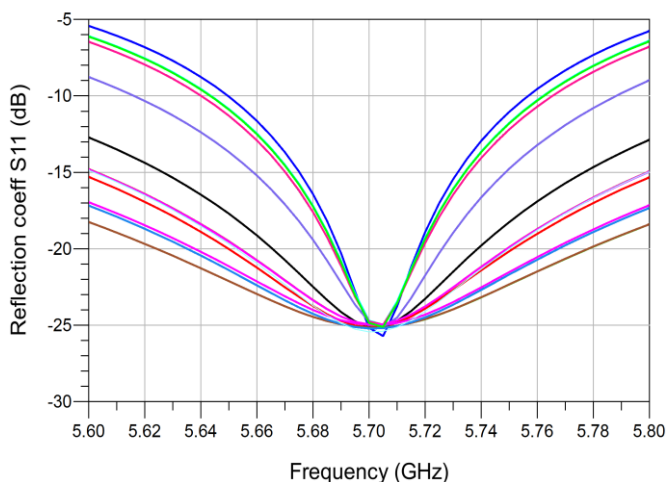
Fig. 4. Reflection coefficient of all the rectifier topologies in simulation at frequency 5.7 GHz with input power of – 30 dBm

been taken up again and matched in impedance at 5.7 GHz frequency, with a realizable reflection coefficient S11 of – 25 dB, as in the previous cases. The reflection coefficient plots can be seen in Figure 4 where graphs represent the impedance matching for all the five topologies with the three most commonly used diode types highlighted. In this Figure 4 there are 15 plots, some of which overlap with the others and make them invisible.

This frequency is chosen for the same reason as the 2.45 GHz, that is Wireless Local Area Network (WLAN) frequency band most often used for Wi-Fi and likely to have radio frequency energy.

In the following, we present in Figure 5, the curves corresponding to the simulations of the above studied topologies at the 5.7 GHz frequency band. In this Figure 5, as in the case of Figure 3, there are 15 graphs, which represent the five topologies, each of which uses the 3 identified diodes.

The results shown in Figure 5 are summarized in Table III. From these results, in addition to the general observations already made in the case of 2.45 GHz frequency, it can be said that whatever the topology and diode used for RF energy harvesting, better results are obtained in the 2.45 GHz band than in the 5.7 GHz band. It is important to mention that, the considered diodes are working on the frequency bands considered and above. This leads to the conclusion that the higher the frequency, the lower the energy harvested with this known circuits. This overall drop in conversion efficiency is not subject to a general rule of proportionality; for example, the conversion efficiency of the voltage doubler topology with the HSMS2860 diode drops from 84.58 % to 72.88 %, which is a relative loss of 11.7 % when moving from the 2.45 GHz to the 5.7 GHz bands, whereas this relative loss is 35.61 % for the Dickson topology with the HSMS2860 diode in both bands.

Table III. Simulation of efficiency at frequency 5.7 GHz

Architecture	Diode Type	Max Eff. (%)	Pwr of Max. Eff. (dBm)	Inp. Pwr. at 10% Eff. (dBm)	Load Res. (kΩ)
Dickson	HSMS 2850	41.73	17	0	1.5
	HSMS 2860	50.10	24	– 7	30
	SMS 7630	57.28	9	– 14	10
Greinacher	HSMS 2850	41.58	12	– 5	0.5
	HSMS 2860	0.25	30	– –	0.5
	SMS 7630	6.08	16	– –	0.3
Series	HSMS 2850	47.16	9	– 9	0.7
	HSMS 2860	71.98	16	– 15	1
	SMS 7630	52.23	0	– 21	0.9
Shunt	HSMS 2850	50.88	9	– 9	0.6
	HSMS 2860	75.12	17	– 16	1.5

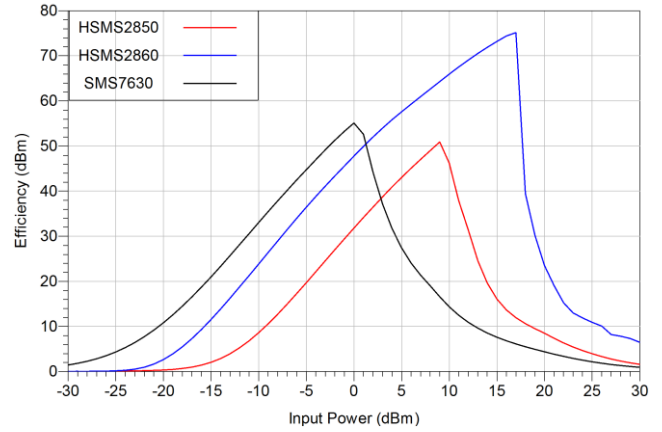|					
	SMS 7630	55.07	0	− 21	0.8
Voltage Doubler	HSMS 2850	42.30	12	− 5	0.6
	HSMS 2860	72.88	19	− 10	1
	SMS 7630	41.73	− 1	− 15	1
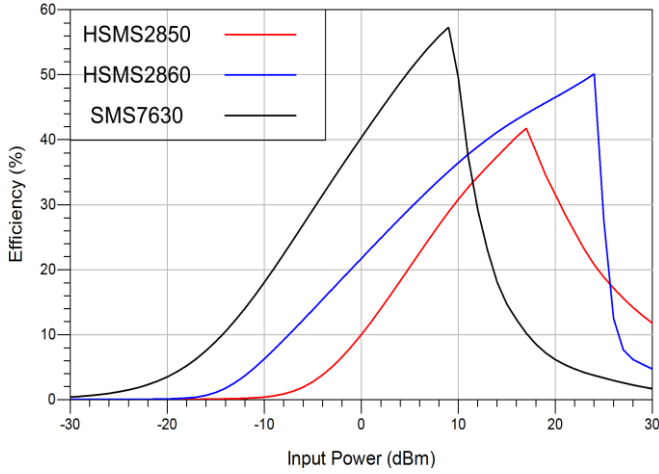
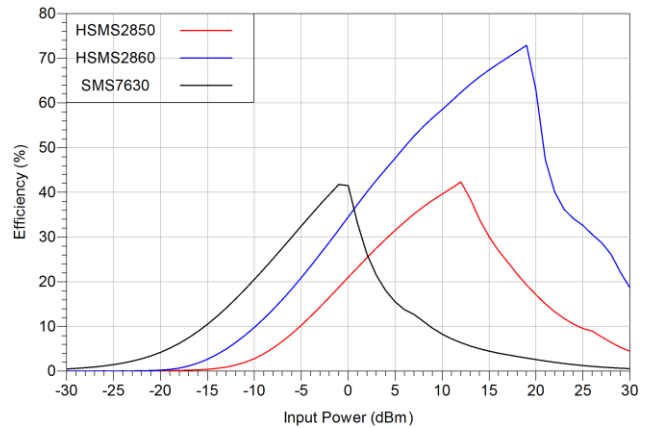**(a) Efficiency in Dickson topologies**
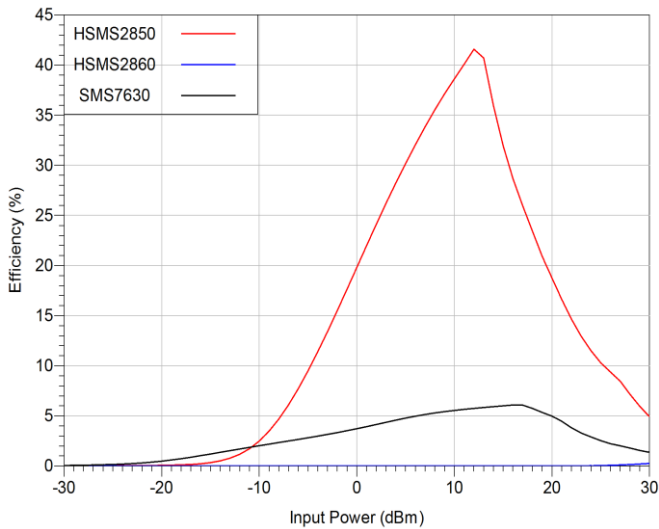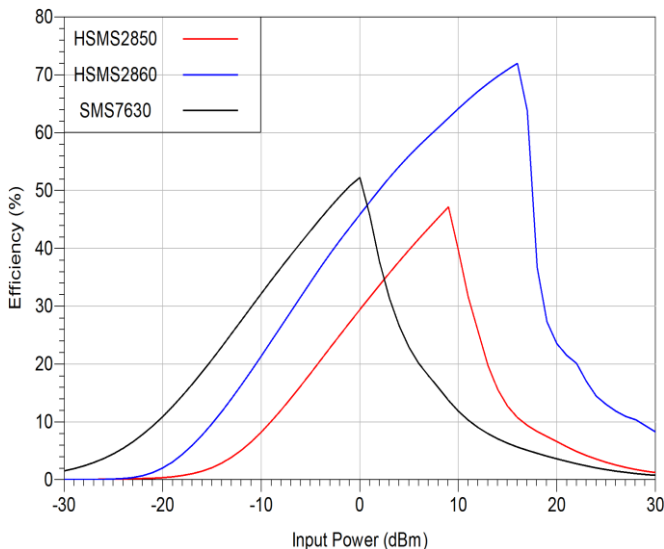
(b) Efficiency in Greinacher topologies

(c) Efficiency in Series topologies

(d) Efficiency in Shunt topologies

(e) Efficiency in Voltage doubler topologies

Fig. 5.Rectification efficiency simulation survey of different topologies (Dickson, Greinacher, Series, Shunt and voltage doubler) using diodes HSMS2850, HSMS2860 and SMS7630. Here the simulations are done at frequency 5.7 GHz; for each topology, the color code are red for HSMS2850, blue for HSMS2860 and black for SMS7630

Furthermore, it is observed that the input power at which the maximum conversion efficiency is achieved can change in some cases from one frequency band to another. The same observation is true for load resistances when the operating frequency is varied.

IV. CONCLUSION

This work on RF energy harvesting circuits studied the most employed circuit topologies and three of the main employed diodes. After a work done on the state of the art, we proceeded to simulations which allow to establish that the choice of the circuit as well as the diode to be used depends mainly on the available input power as well as on the topology. We also observe that better results are obtained with one diode compare to the other only at particular power and topology circumstance. In addition, we established that the higher the frequency, the lower the energy harvested. This work, although simulations, may be a guide in the future design of RF energy harvesting circuits.

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