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Hybrid Voltage Multiplier for RF Energy Harvesting Circuits

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ABSTRACT

Paper describes the design of an improved voltage multiplier for Radio Frequency (RF) energy harvesting circuits using a generic doubler circuit and the Dickson's charge pump, all these utilize the BAT63-02V Schottky diode. The design is based on using four narrowband antennas operating at 800MHz, 1800MHz 2100MHz and 2400MHz, the designs and simulations are performed by Keysight's ADS 2019 simulation software, the outputs observed show improved voltage levels that can be used to operate ultra-low powered devices such as sensor nodes and remotes.

Keywords: RF energy harvesting, Schottky Diode, Voltage multipliers.

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Ultra-low-power devices, have bought attention and attracted a significant interest in the expansion of Information and Communication Technology (ICT) research sector. Radio Frequency (RF) energy harvesting is a process of capturing readily available electromagnetic radiation from different transmitting sources transforming it to DC and storing the electrical energy. Among different means of energy harvesting such as wind, solar and vibration harnessing, which remain limited and unstable in practice. RF energy harvesting as a strong candidate against all, it has been identified as a reliable source for powering extremely low power electronic devices[1-6].

Harvesting this abundant resource has been under research since the beginning of 19th century [7]. However, the field is still the challenges facing harvesting RF energy are low voltages and currents that tend to limit direct utilization of this technology. RF abundance makes it suitable for providing power to a wide range of low power appliances in the emerging revolution of the Internet of Things (IoT).

There has been a considerable amount of work conducted on improving RF energy harvesters as previously done by 2,8 the authors designed a wideband antennas for harvesting ambient RF, after implementation, suggested the use of directional antennas and beam forming to increase efficiency. However, challenges experienced in 9, brought about authors proposing a MIMO based topology for energy harvesting for the convenience of analysis by adding power splitters between receive antenna and rectifier. However in [10-12], authors used simple matching networks, PN diodes and MOSFET's to increase switching capabilities but yielding low output voltages and currents.

The main objective of this paper is to improve the output voltage of RF energy harvester by using multi narrowband matched antennas, rectifying independent nodes to constantly power an LMC555 timer acting as an oscillator, driving a Dickson charge pump which is then charging a super-capacitor.

The reminder of this paper is organized as follows: Section II discusses the RF Energy Harvesting circuit blocks. Section III shows the proposed RF energy harvesting circuit. Section IV show simulation results and comparison discussion. Section V is dedicated for conclusions and recommendation.

I. RF ENERGY HARVESTING CIRCUITS

RF energy harvester is composed of an antenna, a well matched impedance network, a voltage multiplier and a power bank as illustrated on[13]

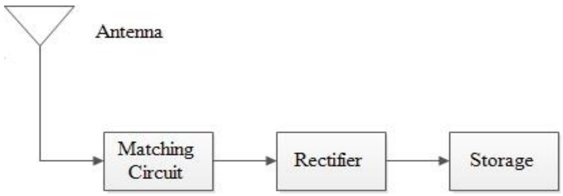

Figure 1: Basic block diagram for RF energy harvester[14]

Any RF harvesting circuit is made up of an antenna, impedance matching network, voltage multiplier and a storing unit 14. For a RF harvesting circuit to work effectively and efficiently the antenna must receive the designed frequency and matched appropriately to assure maximum power reception at the desired frequency with minimum signal reflections, the matching network balances the antenna's impedance to the overall circuit resistance and the voltage multiplier converts the received AC signal to DC then stored in batteries or capacitors for future use[5,15].

A. *Impedance matching network*

From the antenna to voltage multiplier, impedances should match so as to assure maximum energy capturing and transfer to the voltage multiplier, for matching to be achieved successfully, the impedance matching circuitry should be as simple as possible so as to avoid unnecessary signal losses, the mostly preferred topologies are the T and Π Type impedance matching topologies, their selection criteria was based on their most responsive frequency acceptance[15-16]

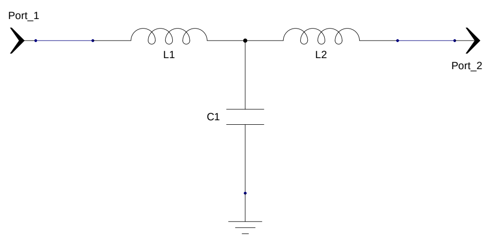

Figure 2: T- Type Impedance match network

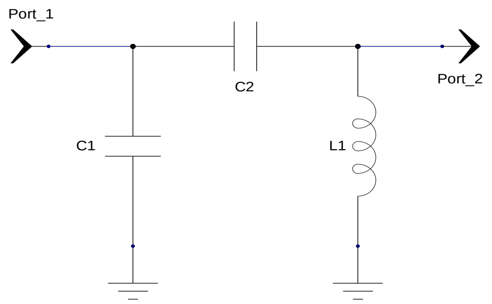

Figure 3: Π - Type Impedance match network

To achieve maximum power transfer the load impedance needs to match to source impedance and for this case a conjugate match is obtained,

$Z_S = Z_L{}^*$ (1)

Equation 1 condition for conjugate match

$R_S = R_L$ And $X_S = -X_L$ (2)

Equation 2 Conditions for maximum power

B. Voltage Multipliers

There are several types of voltage multipliers as described by [7] and [12], but the most common types used in low power boosting are; the Dickson charge pump and Greinacher voltage multiplier. These two will be considered as it has been mostly recommended in literature [12], [17], [18]. A voltage multiplier is made from a series of diodes and capacitors to get high DC voltages, extended to n stages in which each stage contributes to a higher value than the initial stage [7], [14] and [19].

A voltage multiplier performs the task of converting AC signal voltage to twice, thrice and so forth, based on the topology and the peak amplitude of the signal to DC. Figure 4 shows a generic concept for a voltage doubler.

The conversion of RF signal to DC requires some n-stages of voltage multiplications, the received RF power can be described by the Friss transmission equation below,

$$P_R = P_T G_T G_R \left(\frac{C}{4\pi r f}\right)^2$$

The received power and transmitted power in dBm are expressed by P_R and P_T respectively, the antenna gain, and speed of light are also expressed as G_R and C respectively, the r lastly represents the distance in-between the receiver and transmitter.

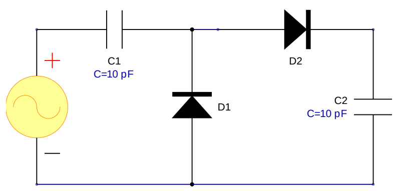

Figure 4: Generic voltage doubler [17]

1.1. The Dickson's charge pump:

The Dickson's charge pump is a revolution that overcame the deficiencies of stray capacitance in Cockcroft – Walton voltage multiplier 20. The output voltage of Dickson charge pump for n – multiplying stages can be expressed by Equation 3 and circuit wise on Figure 5.

$$V_{out} = N(V_p - V_d) \qquad (3)$$

Equation 3: N stage output voltage

Whereas;

V_{out}= Output voltage

N = Number of Stages

V_p = Input voltage

V_d = Diode threshold voltage

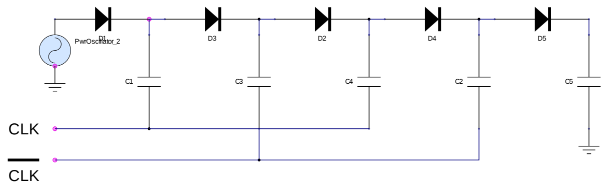

Figure 5: Dickson's charge pump 21

1.2. Greinacher voltage multiplier:

The Greinacher voltage multiplier overcomes the shortcomings of the Villard voltage doubler by having an additional diode placed at the output as described by [20], extending it to n stages is possible but limits its output as there is a great efficiency loss described by [22], current improvements to this is overcome by choosing a very sensitive diode [11].

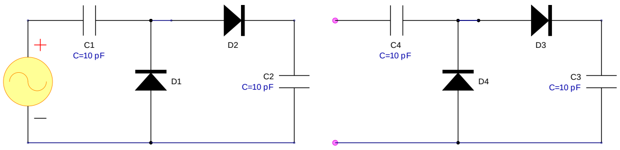

Figure 6: Dual stage Greinacher voltage multiplier [22]

The Dickson's charge pump as seen in [10, 18, 23, 24] and Greinacher voltage multipliers demonstrated in [23, 25, 26] were taken into account due to their wide applicability on various energy harvesting systems. For that reason it was taken into account.

II. Proposed RF Energy Harvesting Circuit

The proposed RF energy harvesting circuit is made up of 4 narrowband receiving antennas at the frequencies of 800MHz, 1800MHz, 2100MHz and 2400MHz having independent impedance matching and a dual stage voltage multiplier, the energy flows aggregating together to constantly power a LMC555 timer from Texas instruments acting as a pulse generator in astable mode. The timer provides clocking signals to the Dickson's charge pump in which it multiplies the clock pulses respect to the number of stages as revised from Equation 3.

In achieving this proposed topology, the circuit was designed on Keysight's ADS 2019, simulated and optimized to attain practical values. The source impedance is assumed to be a nominal value (50Ω).

A. Fixed source impedance matching.

A multi narrowband antenna array is proposed for the simplicity and effectiveness on signal selection and reception, these are designed to operate at specific frequency as described by [27], this accounts for the design of 800MHz, 1800MHz, 2100MHz and 2400MHz narrowband antennas.

1.0 800MHz and 1800MHz narrowband antenna

These antennas required a T- type impedance match so as to deliver maximum power transfer to the load (Greinacher voltage multiplier), the optimum values at 800MHz to adhere to maximum power transfer is by having C_1=234.95pF, L_1=293.73nH and L_2=18.27nH as described on Figure 7

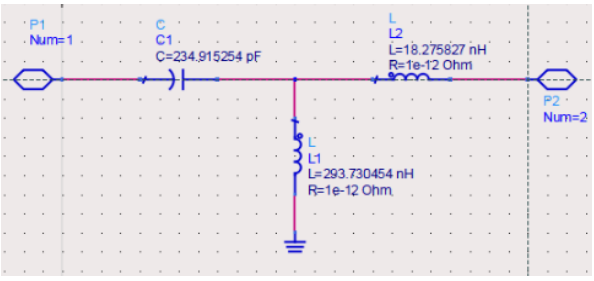

Figure 7: 800MHz matching network

Similarly to the 1800MHz antenna matching, C_1=24.20pF, L_1=19.36fH and L_2=6.84nH as described by Figure 7

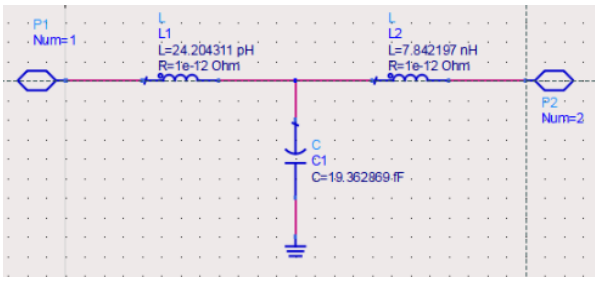

Figure 8: 1800MHz matching network

As the frequency increases, matching complexities increase aswell, the matching topology has to be keen so as to maintain optimum efficiency. The optimum values observed at 2100MHz is by having C_1=4.5pF, L_1=1.27nH and L_2=4.75nH as described by Figure 9

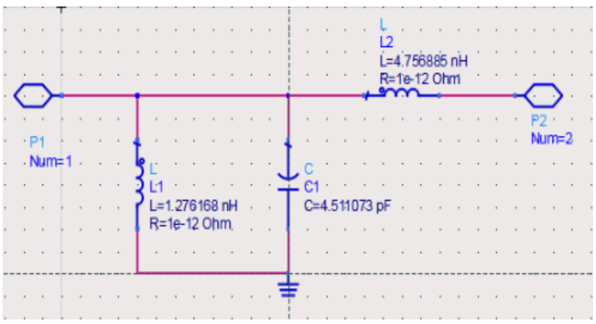

Figure 9: 2100MHz matching network

The optimum values observed at 2400MHz is by having C_1=1.74pF, L_1=2.53nH and L_2=3.40nH as described by Figure 10

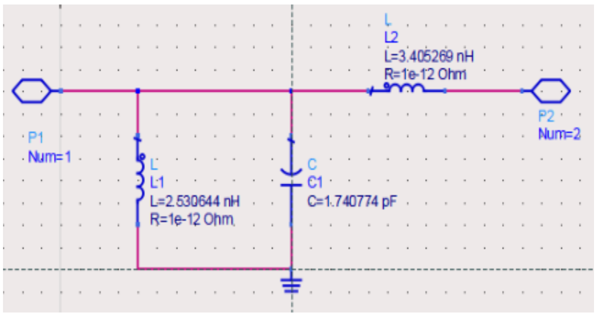

Figure 10: 24MHz matching network

The basis of determining the values for C and L are from the generic equation for parallel tank circuit

$$f = \frac{1}{2\Pi\sqrt{LC}} \qquad (4)$$

Equation 4 Resonant frequency determination of L and C

B. Voltage multiplication

A voltage multiplier is made from a series of diodes and capacitors to get high DC voltages, extended to n stages in which each stage contributes to a higher value than the initial stage. The important factors considered on the selection designing voltage multipliers are diode properties, leakage currents and stray capacitance [28]. Diode properties will be described by different comparison criteria, from Table 1. The BAT63-02V schottky diode is the proposed choice and will be used throughout this paper, as it complies with the smallest acceptable forward voltage.

Table 1: List of common Schottky diodes and their characteristics

Diode	**V_F (V)**	**V_R (V)**	**R_S (Ω)**	**I_F (mA)**	**J_C (pF)**
MA-40417	0.65	11	4.9	90	0.04
HSMS 2860	0.6	4	10	350	0.18
HSMS 2850	0.35	4	25	30	0.18
HSMS 2822	0.7	15	12	30	1.0
HSMS 8202	0.35	4	14	75	0.26
SMS 7630	0.34	2	20	50	0.14
SMS 7621	0.55	3	12	50	0.1
HP2800	0.34	50	25	15	2
BAT15-02EL	0.25	4	22k	110	0.2
BAT63-02V	**0.19**	**3**	**33k**	**100**	**0.65**

C. Clock generator

A low power timer was used during simulation, the LMC555 was set into astable mode so as to produce continuous clock pulses to the Dickson's charge pump, just as a normal 555 timer it is, the main advantage is that the LMC555 is capable of operating from a VCC = 1.5V [29]

Based on the equations, the values of R_A, R_B and C were obtained.

$$t_1 = 0.693(R_A + R_B)C \qquad (4)$$

$$t_2 = 0.693(R_B)C \qquad (5)$$

Total period

$$T = t_1 + t_2 = 0.693(R_A + 2R_B)C \qquad (6)$$

The frequency of oscillation is:

$$f = \frac{1}{T} = \frac{1.44}{(R_A+2R_B)C} \qquad (7)$$

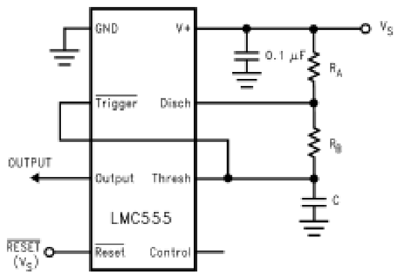

Figure 11: Astable mode LMC555

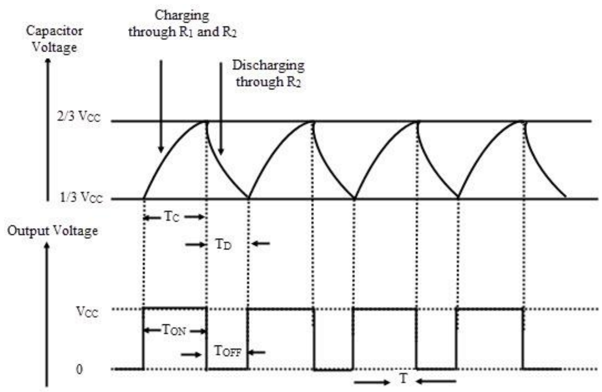

Figure 12: Astable Output waveform 30

III. SIMULATION RESULTS AND DISCUSSION

Circuit setup and simulation was performed using Keysight's ADS 2019, the simulation tool was used as it is the current most innovative and powerful RF simulator, It has also been seen used in a number of research such as [10, 31, 32]. After the setup and simulation as observed on Figure 13, the output power contributed by each node sum up to power the LMC555 timer. The clock cycles released are then synchronized to the 5 stage Dickson's charge pump as on Figure 14. The aftermath energy is then stored in a Supercapacitor for future use.

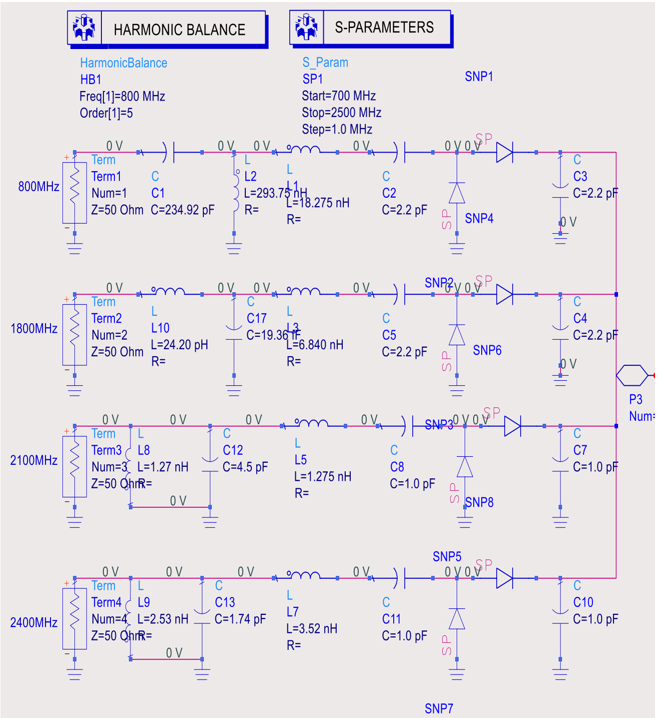

Figure 13: Multi narrowband matched aggregator circuit

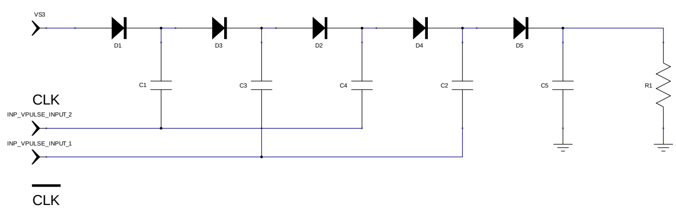

Figure 14: The Dickson's charge pump

The output power observed was plotted on the graph Figure 15, the power levels obtained are showing much improvements from previous research[10, 11] whereas the number of multiplier stages were increased as suggested by [11].

IV. Conclusions

It is observed that by independently receiving a desired set of frequencies and combining them provides a higher output voltage a factor of 0.2mV to 1.2 mV at 800MHz to 1800MHz respectively and 1.0mV to 1.1mV at 2100MHz to 2400MHz. Future work include prototyping this paper to take actual measurements.

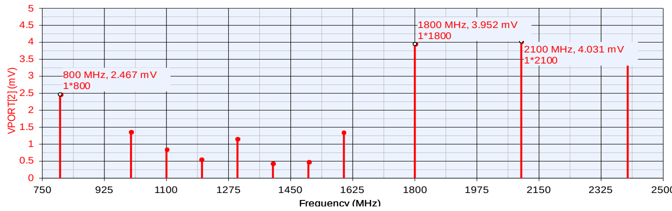

Figure 15: Output voltage (mV) against Frequency (MHz)

Table 2: DC output voltage comparison under similar conditions

Ref	Operating Frequency (MHz)	Pre Voltage boost	Number of Voltage multipliers	Avg. Output (V)
10	900	N/A	5	1.02
11	1800,2400, 5000	N/A	10	0.0000099
This Work	800,900, 1800,2100, 2400	1	5	3.95

Table 2 provides detailed comparisons on the output acquired from this work based on the input power

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