5.8GHz ISM Band Energy Harvester Utilizing Staggered Pattern Charge Collector (July 2010)

Minki Cho, Hoseon Lee, Michael J. Schork, Satyanarayana Telikepalli

Abstract— **This paper introduces a 5.725-5.850GHz ISM band energy harvester that utilizes a staggered pattern Dickson charge pump to harvest enough charge to light up an LED from 50cm away with less than 1W of transmitted power. The design utilizes two arrays of dual patch antennas with a staggered feed to enable a wider radiation gain pattern.**

***Index Terms*— Charge Collector, Energy Harvester, RF Schottky Diodes, Dickson Charge Pump**

I. INTRODUCTION

Advancements in RFID technology has made ultra low-power wireless communication possible in industrial and commercial enviornments. Building passive communication devices by utilizing charge pumps and rectifying circuits can greatly reduce the cost and complexity of wireless communication devices. In this project, the student team will produce an arrayed microwave charge pump that converts a 5.8 GHz continuous wave signal to a DC power supply to drive a low-powered light-emitting diode (LED). In addition, the design of 5.8 GHz patch antenna is also discussed.

II. CHARGE PUMP DESIGN

A. Charge Pump Overview

There are many methods available for rectifying an AC signal. One common method is to use a full-wave rectifier. However, the output voltage can be further increased by increasing the number of stages. The charge collector design presented here is based on a Dickson charge pump, a common nonlinear circuit used for boosting DC-to-DC voltage. The analysis of a Dickson-charge pump is fairly straightforward when considering a single stage. When the input signal from the antenna is negative, the series capacitor charges up, since the top diode is reversed-biased. However, when the input signal is positive, the top diode is forward-biased and the shunt capacitor charges up. The charge from the series capacitor is transferrred to the output node, so the two voltages are summed. This circuit is also referred to as a *voltage multiplier*, since the output voltage is multiplied by the number of stages.

$$V_{OUT} = (N+1)\cdot(V_A - V_T) \tag{1}$$

In Equation 1, V_A is the voltage available at the input of the antenna and V_T is the turn-on voltage of the diode. For this device, Avago HSMS-2862 schottkey diodes with a relatively low turn-on voltage of approximately 300mA. In addition, all capacitors have the same value, except for an output capacitor, which smoothes out the voltage ripple created by the recificication.

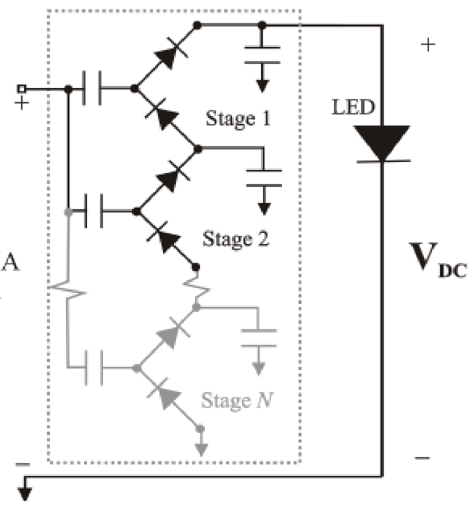

Fig. 1. General circuit diagram of an N-stage Dickson charge collector loaded with an LED.

B. Design Equations

While Equation 1 can be used to determine the output voltage, a more accurate output voltage, as presented by John F. Dickson, can be calculated by using Equation 2 below.

$$V_{OUT} = \frac{(N+1)\cdot(V_A - V_T)}{1 + \dfrac{N}{f\cdot C\cdot R_L}} \tag{2}$$

For the calculation and simulations, the CMD 28-21 LED is modeled by a load resistor. The typical forward voltage of the LED is 2.0V, and with test current of 20mA, the LED dissipates about 105mW. The load resistor can be approximated from Equation 3.

$$R_L = \frac{2\cdot P_{dis}}{I_{test}^2} \rightarrow \frac{2\cdot 105mW}{(20mA)^2} \rightarrow 525\Omega \tag{3}$$

In addition, the power at the input of the antenna can be approximated by using the Friis transmission equation.

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2 \tag{4}$$

P_T, the transmitted power, is 1W, and G_T and G_R are 10 and 2.5, respectively. The charge pump is designed to work at a distance of 50cm. Another parameter that is very important to the design of the charge pump is the power conversion efficiency, η.

$$\eta = \frac{\left(1 - \frac{Vt}{Vin}\right)}{1 + \frac{N}{f \cdot C \cdot R_L}} \tag{5}$$

The efficiency can be maximized by selecting an appropriate capacitor value. In addition, the charge pump in this design is chosen to have 4-stages. In order to ensure a positive capacitance, the efficiency has a cieling.

$$\eta_{\max} = 1 - \frac{Vt}{Vin} \tag{6}$$

In addition, the approximate input resistance can be determined by Equation 7.

$$R_{in} = \frac{R_L}{\eta (N+1)^2} \tag{7}$$

By combining Equations 2, 5, and 7, an appropriate capacitor value can be determined to ensure good efficiency, this is shown in Figure 2.

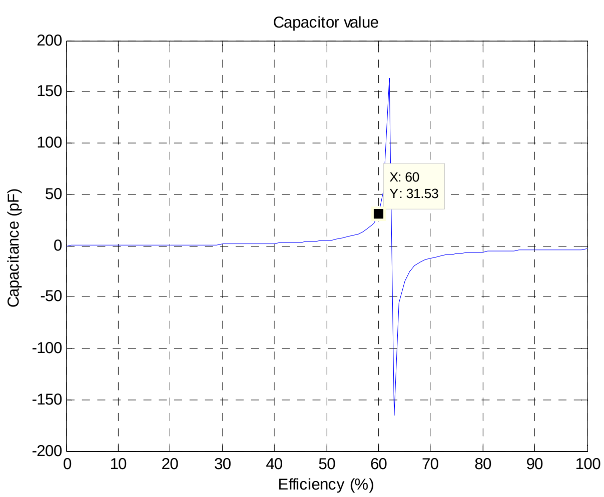

Fig. 2. Capacitance plotted versus efficiency to determine optimum capacitor value.

With a capacitor value of 31.5 pF, the efficiency is approximately 60% and the input resistance, from Equation 7, becomes 35Ω.

Using the input resistance of 35Ω, the patch antennas can be matched to the charge pump circuit by placing a quarter-wave transformer in between. Since the patch antennas are matched to 50Ω, the characteristic impedance of the transformer can be determined from Equation 8.

$$Z_l = \sqrt{Z_{in,A} \cdot Z_{in,C}} \tag{8}$$

Z_l is determined to be 41.83Ω.

C. Simulation

The charge pump design and the element values were simulated in ADS.

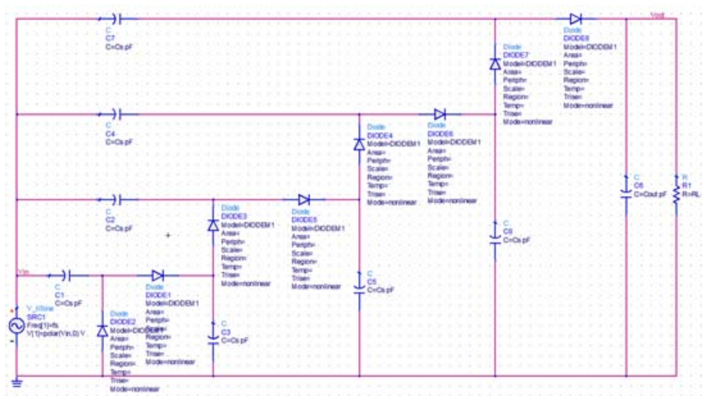

Fig. 2. ADS circuit schematic.

The value of the output capacitor C_{out} was tuned in order to keep the voltage ripple as small. The value of C_{out} that was eventually used was 10pF. The output voltage produced by this circuit is show below.

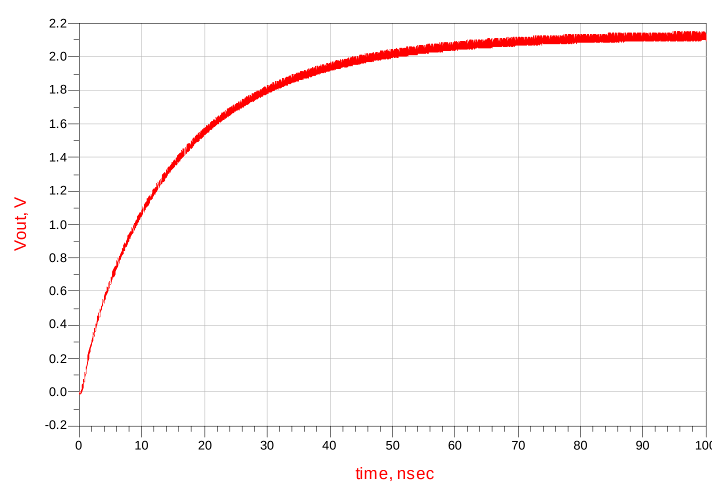

Fig. 3. Output voltage simulation from ADS.

D. Layout & Fabrication

After simulation, the fabrication layout of the charge pump circuit was designed using CadSoft's Eagle Layout software. In order to increase the circuit's sensitivity to the incoming signal, two separate charge collectors were implemented, each with two antennas.

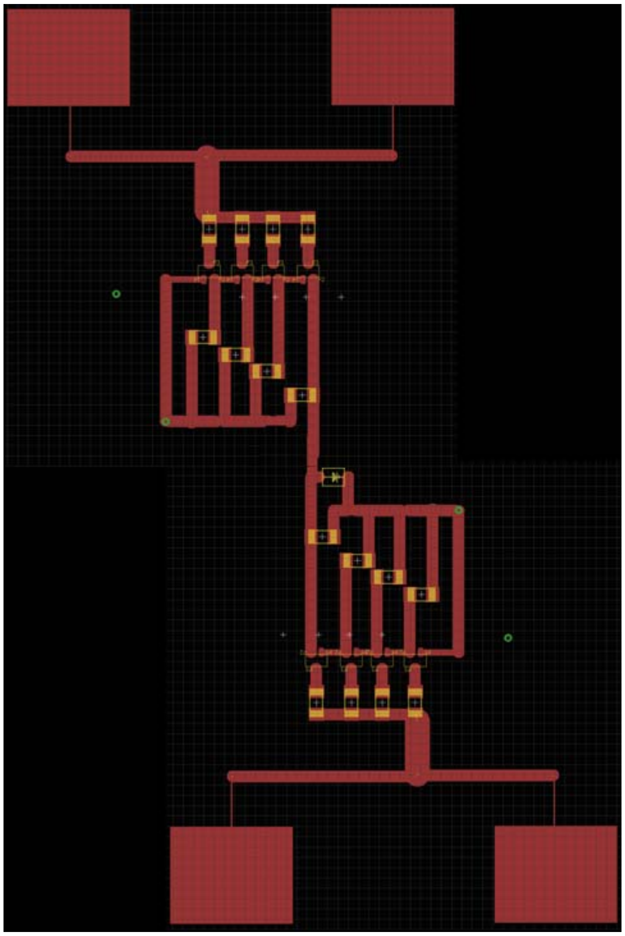

Fig. 4. Charge pump layout with patch antennas.

The charge pump circuits and the antennas were placed in a staggered fashion. This gives the circuit a larger effective radiation pattern at which to receive the input signal. In addition, two separate antennas were connected to each charge pump for diversity as well as slightly higher antenna gain at the expense of more area.

III. Patch Antenna Design

In addition to the charge pump, the four patch antennas were also designed to operate at 5.8GHz using Ansoft's High Frequency Structural Simulator (HFSS) software. Using the substrate parameters, the patch antenna was construted and then optimized in HFSS in order to get the desired resonance frequency.

Table 1. Patch antenna dimensions	
Width	15.1867 mm
Length	11.804 mm

Simulation results gave with a 10% bandwidth and S11 of -26.33dB at 5.79GHz.

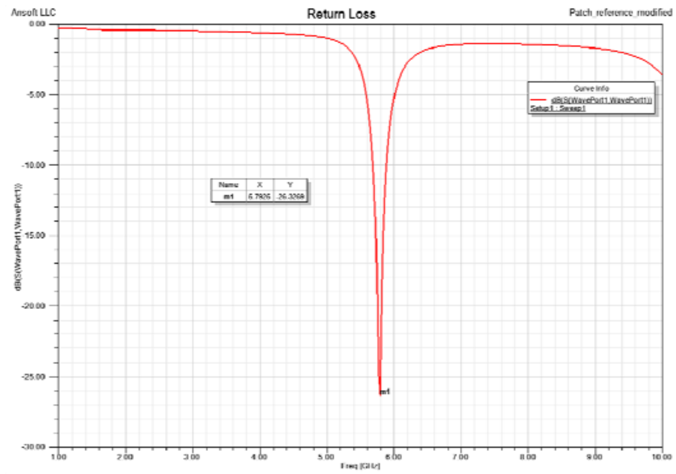

Fig. 5. Simulated return loss shows that the antenna is well matched at the desired frequency of 5.8 GHz.

The radiation and electric field pattern are shown in Figures 6 and 7, respectively. The radiation gain is approximately 3.94dB at 5.8 GHz. The gain can be further improved by increasing the size of the ground plane, but this was not chosen since the board size would have been too large.

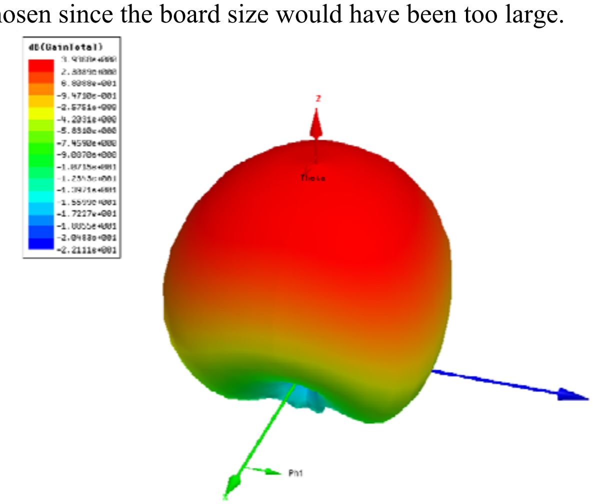

Fig. 6. Radiation gain pattern as simulated in HFSS.

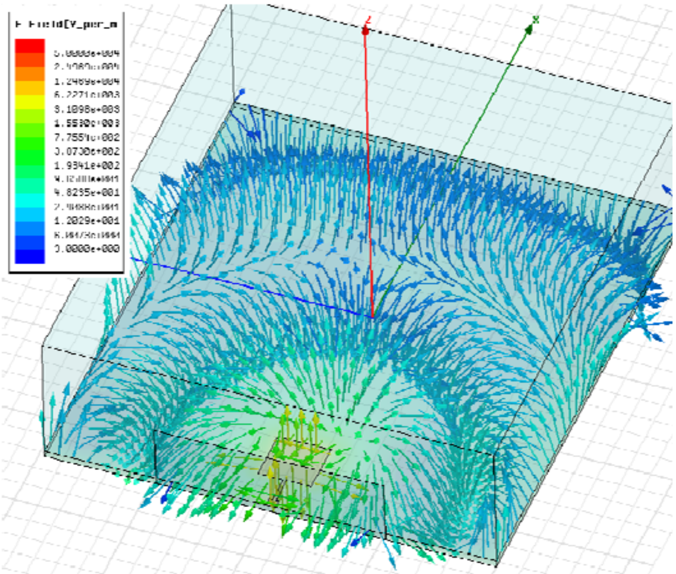

Fig. 7. This figure shows good electric field patterns of close to 6kV/m from the patch antenna.

Figure 8 shows the current distribution throughout the antenna as well as the matching transformer. The performance of the antenna is somewhat limited by the matching transformer. Due to the input impedance of the antenna, the transformer's characteristic impedance is large, so it is thin. Because it is thin, the amount current delivered to the antenna is decreased. An improved design would be to keep the transformer larger to allow more current flow.

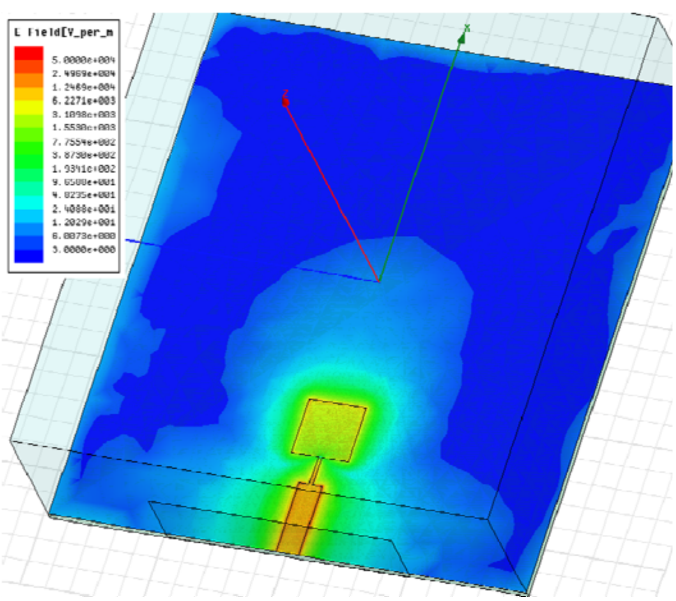

Fig. 8. The magnetic current is fed uniformly into the patch through the quarter wave transformer.

IV. Fabrication & Measurement

The charge pump and patch antennas were fabricated on a 30mil FR4 substrate with 1.4mil thick copper. Due to the unavailability of components, however, only one charge pump was fabricated.

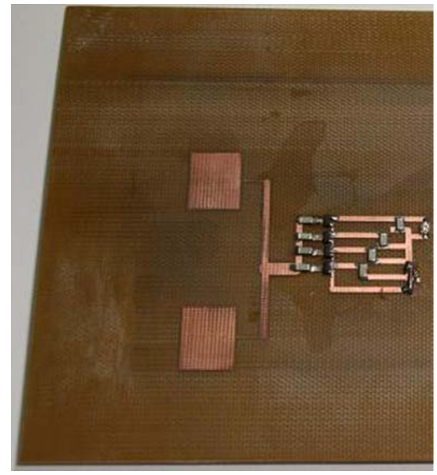

Fig. 10. Fabricated charge pump circuit.

The charge collector was tested by holding the charge collector board in parallel to the plane of a horn antenna fed by a vector network analyzer at varying distances away from the horn antenna. The LED lit up around 20cm away from the horn antenna. The linear polarization of the patch antenna could also be observed by rotating the energy harvester.

V. Conclusion

The measurement results indicated that enough charge could be collected with this energy harvester to light up a single LED at close to 15cm away. However, this range can be increased to 50cm through several different methods. The first method is using two charge pumps instead of one. Another charge pump of the same design can be added to the existing charge pump by joining the outputs of both charge pumps with a power divider. A second method is to use a five stage charge pump instead of a four stage to give an incremental voltage boost. Another method is to design the dual patch array to maximize gain, by optimizing the spacing between the two antennas. With too little spacing, the radiation pattern is too narrow band, whereas too much spacing will give a null in the pattern. Lastly, not only can the detection distance be increased by the above methods, but also the range in the phi direction can be wider by off-setting the feeds to the dual array patch antenna. This shifts the radiation pattern directivity 45 degrees, allowing the LED to light up even when the board is not directly in front of the horn antenna.

References

[1] Dickson, J.F., "On-chip high-voltage generation in NMOS integrated circuits using an improved voltage multiplier technique," *IEEE Journal of Solid-State Circuits*, vol. SC-11, pp.374-378, June 1976.

[2] D.M Pozar, *Microwave Engineering*, 3rd ed. Wiley, 2005