Staggered pattern charge collector design and optimization

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***Abstract*— This paper outlines an innovative antenna configuration called a staggered pattern charge collector (SPCC) to increase microwave wireless energy harvested from an antenna at 5.8 GHz. The two-by-two staggered pattern charge collector (SPCC) uses a pair of two-element linear arrays to increase gain and effective aggregate "beamwidth" to capture more wireless energy than a single patch antenna. Also, a new array parameter called integrated power conversion gain (IPCG) is introduced as a metric to compare how effective antenna systems are at energy harvesting. Finally, the SPCC is optimized to maximize IPCG and the optimized, fabricated SPCC's DC voltage output data is measured.**

I. Introduction

Completely passive (batteryless) sensors and radio frequency identification (RFID) tags have many benefits, including the reduction of production costs and environmental impact by eliminating battery replacement. Current far-field microwave energy harvesting RFID tags use UHF such as 915 MHz due to low path loss through the air, but by using 5.8 GHz, the tag antenna footprint can be reduced and high-gain antenna arrays can be used to overcome higher path loss [1].

Completely passive tags have three main components: an antenna, an energy harvesting circuit, and load modulator circuitry. The antenna translates the wireless electrical energy into an AC signal to feed an energy-harvesting circuit, which then converts the AC signal to a DC voltage that powers the load [2]. While all parts of the tag are important, this paper focuses on the antenna and energy harvesting portion.

The staggered pattern charge collector (SPCC) is a novel topology of antenna arrays and charge pump connectivity to create two separate antenna array beams steered in opposite directions. The SPCC is composed of a pair of two-element linear patch antenna arrays with a pair of 4-stage Dickson charge pumps to create a DC voltage output. Fig. 1 shows the top and bottom arrays of the SPCC with charge pumps that terminate on a single common stage capacitor. The top array steers from the +z axis towards the -x axis, while the bottom array steers a beam from the +z towards the +x axis. The benefit of a SPCC over a single patch as predominately used is that each array steers its beam in equal and opposite directions from the reader to create a larger effective aggregate "beamwidth" for the antenna system. This does not violate any concepts of antenna theory because *two* arrays are connected to a pair of non-linear charge pumps terminated on a single capacitor [2].

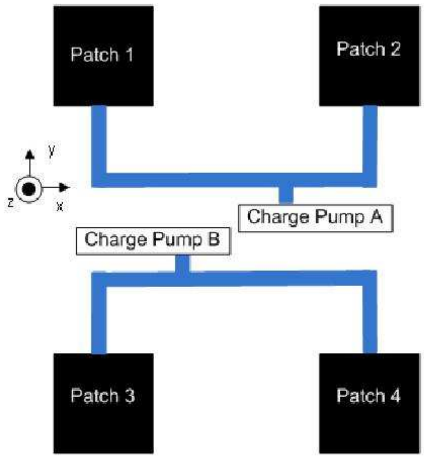

Fig. 1. Overview of SPCC layout

This paper focuses on the design and optimization of the SPCC antenna system at 5.8 GHz and not on the charge pump optimization. Matching to a charge pump is a difficult problem because traditional matching techniques do not apply to non-linear loads. Range of operation can be dramatically affected by the antennas and charge pump matching, but it is difficult to get high efficiency levels [3]. By the end of this paper, the reader should be able to design a basic SPCC array that harvests wireless 5.8 GHz energy and understand its benefits compared to traditional single antenna RF harvesting.

II. SPCC Theory and Design

A. SPCC Antenna Theory

As previously stated, the SPCC antenna system is a pair of two-element arrays connected to two charge pumps terminated on a common capacitor. Each array contains two 5.8 GHz patches that are separated by a half wavelength for a maximum broadside lobe with a phase offset to steer the beam to either side of the +z direction. Fig. 2 shows one of the two arrays which is steered by an angle θ to the left due to the offset between x_1 and x_2.

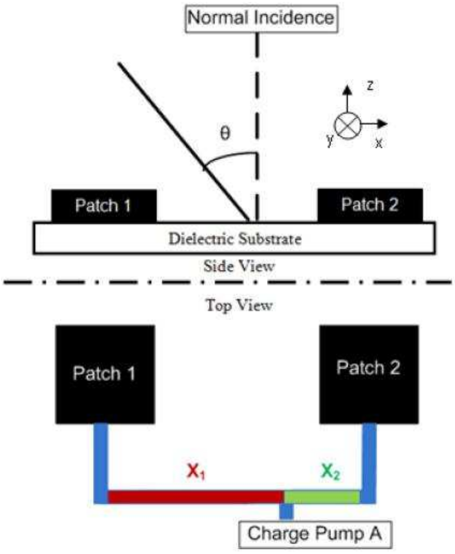

Fig. 2. Single array of SPCC with steered beam

By using an intuitive antenna analysis, the delay in the difference in the lengths cause the waves to constructively interfere at an angle of θ to create one of the main beams. This phenomenon is characterized by (1) and the antennas must be separated by half a wavelength of maximum broadside lobe as in (2). Both these equations can be used to find x_1 and x_2 for a desired phase offset, frequency, and dielectric constant [4]. Note that each array has a phase difference of ϕ, so the phase difference between arrays is 2ϕ. Also note, although the angle of incidence (θ) and phase difference (ϕ) are related, they are definitely not the same value.

$$\Delta\phi = \frac{2\pi f}{v_p}(x_1 - x_2) \tag{1}$$

$$x_1 + x_2 = \frac{\lambda}{2} \tag{2}$$

With a closed-expression for the required length offset and a given phase difference (ϕ), the x_1 and x_2 can be found. If the optimal phase difference for energy harvesting from an SPCC is known, the x_1 and x_2 are set.

B. SPCC Optimization

In order to optimize the two-by-two SPCC with patch antennas at 5.8 GHz, the radiation patterns and a quantifiable energy harvesting metric must be defined. The array factor for a two-element linear array is shown in (3) and an antenna factor for a patch antenna is shown in (4) [5]. By squaring the magnitude of their product, the gain pattern for one array of the SPCC is found, and, by symmetry, the other array can be assumed with the opposite phase difference to cause the second array to steer in the other direction (-θ).

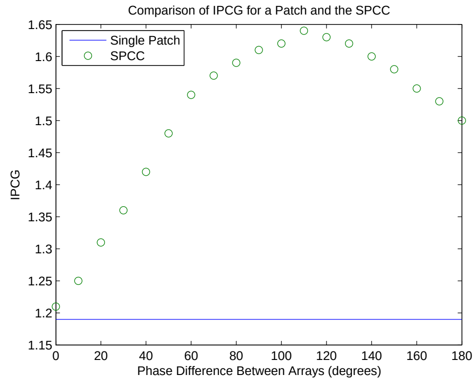

Fig. 3. Comparison of IPCG of a single patch and the SPCC

$$AF = \sum a_n e^{j(n-1)(kd\cos(\theta)+\beta)} \tag{3}$$

$$f(\theta) = \cos(\theta)\frac{\sin(\frac{\beta W}{2}\sin(\theta))}{\frac{\beta W}{2}\sin(\theta)} \tag{4}$$

For the quantifiable energy harvesting metric, the gain of the antennas and the aperture for receiving wireless energy should both be maximized. The ideal wireless energy harvester must have a high gain to create large received voltage and a large beamwidth to receive energy from any direction. The gain and beamwidth are a traditional tradeoff for a single array [5]. As the peak gain of an antenna array increases, the beamwidth reduces which limits the aperture of the receiving antennas reducing the amount of power that can be received. In order to quantify both of these values into one metric, the integrated power conversion gain (IPCG) is defined as in (5) as the integration of the gain pattern over the effective half-power "beamwidth" [2].

$$IPCG = \int_{BW} G(\theta)d\theta \tag{5}$$

To optimize the amount of wireless RF energy harvested, the IPCG should be maximized. Since a closed-form expression for maximization is difficult and assumption based, a simulation is used to find an empirical solution of optimization. The simulation was performed in CST and the data exported to Matlab for analysis to calculate IPCG. Note that during this analysis only the array with highest power excitation is assumed to be collecting energy while the other is assumed to be "off."

Initially, with the phase difference between the arrays (2ϕ) of 0 degrees, the SPCC is essentially a two-element array resulting in an IPCG that is approximately the same as a single patch since the beamwidth decreases but the gain increases. As the phase difference between the two arrays is increased, the IPCG increases as the gain remains about the same but the effective beamwidth is increased as

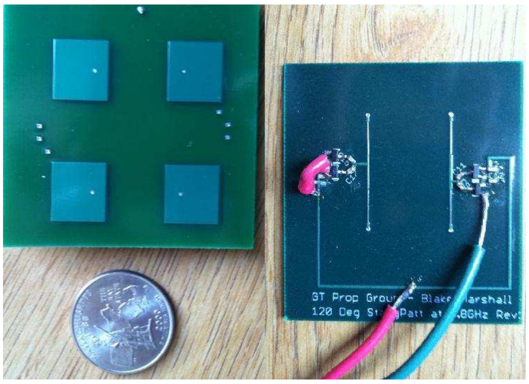

Fig. 4. 2x2 SPCC hardware with 120 degree phase difference between two subarrays

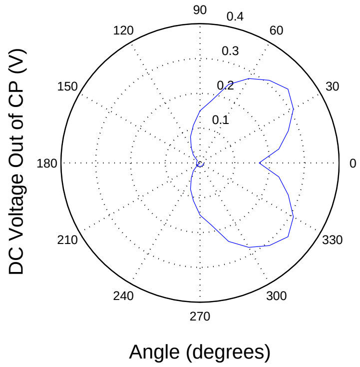

Fig. 5. DC voltage output at 1 m away from 36 dBm EIRP

the beam from each array is angled away from the other. After a certain point, the beams are spread too far apart resulting in a gap in coverage and slightly reducing the IPCG. The optimal phase difference between the arrays is between 100 and 140 degrees as shown on Fig. 3 [2].

III. SPCC Hardware

A. PCB Layout

The board is fabricated on a 4-layer board with three sections of FR-4 dielectric. The bottom layer of the board has the SPCC array and the top layer of the board contains the charge pump components. The SPCC hardware top layer is shown on the right of Fig. 4 with the two 4-stage charge pumps and the bottom side is shown on the left with the SPCC antenna system. Each array used a 4-stage charge pump with 1 pF capacitors and HSMS-2962 diodes. The output of each charge pump is tied to a common capacitor to store the DC voltage output.

B. Lab Results

For data collection, a 36 dBm EIRP transmitter produced a continuous wave wireless signal at 5.8 GHz from approximately 1 m away. The optimized SPCC has a 120 degree phase difference between arrays (2ϕ). The output DC voltage was measured at the output capacitor as a function of angle as the SPCC was rotated with stepper motor.

The results are shown in Fig. 5 with the maximum voltage of 0.325 V. Although the voltage did not meet expectations of 3 to 5 V, the low voltage can be attributed to the mismatch between the charge pump and SPCC. The non-linear impedance of the charge pump is difficult to match to 50 Ohms creating reflections. The large beamwidth shows that the beams were successfully steered in equal and opposite directions. Each beam can clearly be seen from each array, but the gap in the middle seems to show that the 60 degree phase shift on each antenna array.

The IPCG of a non-linear array cannot be calculated for this experimental data to show its improvement over a single patch antenna. The SPCC must be measured over its entire azimuth on an antenna range to find these results. The large beamwidth of over 100 degrees shows that SPCC is an improvement over a simple patch antenna for energy harvesting technology.

IV. Conclusions

A. Summary of Results

In conclusion, the SPCC is optimized for microwave energy harvesting between 100 and 140 degrees phase difference between arrays, since IPCG is maximized. IPCG combines both the gain and beamwidth of a radiation pattern into one concise comparison for all antenna energy harvesting systems. The SPCC increases IPCG by about 33 percent from a single patch antenna in simulation. The first optimized SPCC fabricated showed that the SPCC harvested RF energy over a much broader gain region than a basic patch, but improvements must be made to matching the antenna sub-arrays to the charge pumps.

B. Future Plans

As for future plans, the SPCC needs to be spun in an anechoic chamber to compare experimental IPCG. The next revision should improve matching of the SPCC to the charge pump to increase the output voltage. A load should be used in a test to find the total efficiency of the SPCC. For theoretical study, the larger N x N case of the SPCC can be analyzed to further improve IPCG and create a better RF energy harvesting antenna array.

References

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