APSYM

A Highly Efficient Energy Harvesting Circuit Using Luneburg Lens

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***Abstract*—This paper presents the design and analysis of a highly efficient energy harvesting circuit using a modified Greinacher rectifier and Luneburg lens at 2.4 GHz. The circuit is optimized for low power levels ranging from -30 dBm to -5 dBm. For 10 kΩ load, the rectifier provides an output voltage of 310 mV with a Power Conversion Efficiency (PCE) of 30.36 % for -15 dBm input power. RF power combining topology is used to combine power from multiple antennas. The use of Luneburg lens leads to an increase in received power because of its directional characteristics.**

***Keywords*—RF energy harvesting, rectifier, power combining circuit, Luneburg lens, patch antenna**

I. Introduction

The growth of systems like GSM, 3G, 4G, WiFi, Bluetooth etc. has led to ambient amount of RF electromagnetic energy available in the environment which makes it a very likely source for energy harvesting applications. Microwave energy harvesting from electromagnetic sources is being considered as one of the most favourable technologies for the continuous power supply of standalone sensors for smart applications. In this paper, the WiFi band at 2.4 GHz is selected for energy harvesting. The basic elements of RF energy harvesting system consists of receiving antenna to collect the ambient RF power, rectifier to rectify input RF power to DC power, matching network to enable maximum power transfer between receiving antenna and rectifier and the DC pass filter to reduce the ripples present due to the fundamental frequency component and any other higher order harmonic components remaining after rectification. The block diagram is shown in Fig. 1. The performance

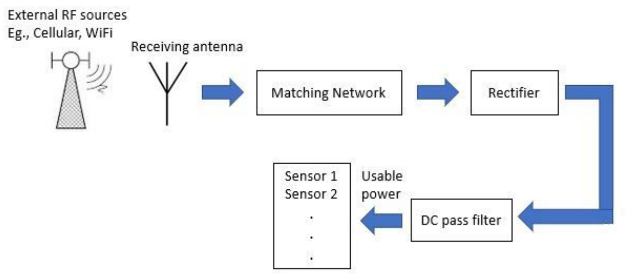


Fig. 1: Block diagram of RF energy harvesting system

comparison of various topologies of rectifier circuits namely series, Greinacher rectifier and voltage doubler have been reported in [1]. The antennas generally used for harvesting can be broadly classified as either omnidirectional or directional antennas. Omnidirectional antennas are used for getting better coverage at the cost of reduced gain [2]. In this paper, the idea of using a 3D Luneburg lens with the antenna is proposed as it provides wide spatial coverage, as well as, high gain. The rest of the paper is organized as follows: Sections II and III describe the design process and results of the rectifier and antenna respectively, Section IV presents the simulation setup for rectenna and its performance analysis and lastly, the conclusions are reported in Section V.

II. Rectifier design

Voltage multipliers are found to give the best performance among various topologies of rectifiers, hence a modified Greinacher rectifier [3] is used in this work. The complete rectifier is designed in Agilent ADS 2014 and is shown in Fig. 2.

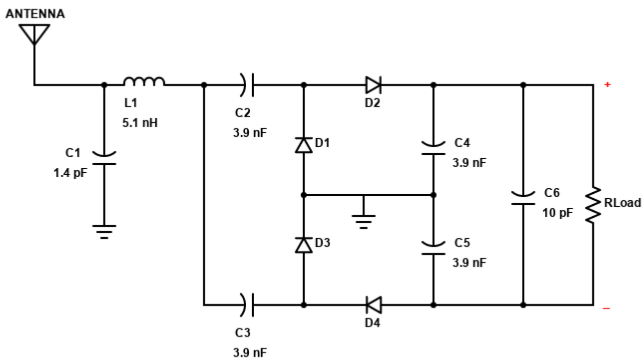


Fig. 2: Complete rectifier circuit

Schottky diode SMS7630 (V_F = 60-120 mV (I_F = 0.1 mA), V_R = 1V) is selected because of its best performance in low power regions due to its low threshold voltage. The capacitor value in the modified Greinacher rectifier is chosen as 3.9 nF for optimal performance. The Large Signal S-Parameters (LSSP) simulation of the modified Greinacher rectifier circuit with varying input power and load resistance is performed to find the input impedance of the circuit for designing the matching network. The load resistance of the practical applications generally varies between 5 kΩ and 75 kΩ [4]. In energy harvesting systems from WiFi, the power range is generally between -30 dBm to -5 dBm [4], in which the input impedance remains almost constant. Hence, the input impedance at reference input power of -15 dBm and reference load resistance of 10 kΩ is used for designing the matching network.

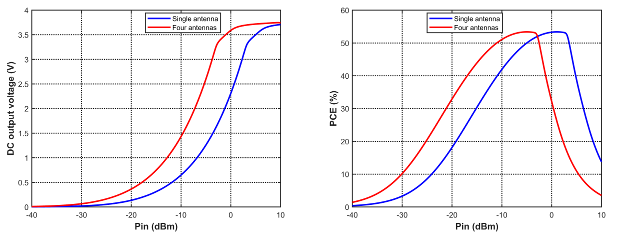
The input impedance of the antenna is taken as 50 Ω and input impedance of the rectifier is 19.741 - j117.209 Ω at the reference values. A LC matching network is designed to match the aforementioned input impedances. The inductor used is a ceramic chip inductor from Coilcraft and all the capacitors used in the circuit are high-Q ceramic chip capacitors from Murata. The power conversion efficiency (PCE) or RF-to-DC conversion efficiency of a rectifier is given by (1).

$$\text{PCE} = \frac{P_{DC}}{P_{RF}} = \frac{V_{DC}^2}{R_{Load}\, P_{RF}} \quad (1)$$

For a single antenna, the simulated DC output voltage and PCE obtained are 310 mV and 30.36 %, respectively at -15 dBm input power as shown in Fig. 3. The maximum PCE obtained is 53.36 % at 1 dBm input power. The output voltage saturates and PCE starts decreasing due to breakdown voltage of the diode.

A. *Power combining circuits*

In energy harvesting circuits, multiple antennas can be utilized to increase the input power and in turn, increases the output voltage obtained. There are two types of power combining circuits namely, DC power combining and RF power combining. It has been reported that RF power combining topology has better performance than DC power combining topology in low power input [5]. In RF power combiner, the RF power from multiple antennas is combined together, then passed through a single rectifier. In this work, a 4×1 Wilkinson power combiner is used to combine RF power from four antennas. All the components are replaced by their practical spice models and the harmonic balance analysis results are shown in Fig. 3. As expected, the output voltage, as well as, PCE considerably increase with power combining circuit.



(a) DC output voltage (b) Power conversion efficiency

Fig. 3: Harmonic balance analysis of single and four antenna system

III. Antenna Design

In order to increase the received power by the receiving antenna, concept of Luneburg lens has been proposed. Because of focusing nature of Luneburg lens and of infinite number of focal points on the spherical surface, the use of lens can substantially increase the received power. Hence, in this work, a Luneburg lens is used along with a patch antenna to function as receiving antenna.

A. *Microstrip patch antenna*

Rectangular inset-fed microstrip patch antenna is placed around Luneburg lens to receive the radiations that are focused by the Luneburg lens. The patch antenna is designed using FR-4 (ϵ_r = 4.3, tan δ = 0.025) to keep a balance between size of the antenna and loss incurred. The parameters of the patch antenna are calculated using design equations given in [6]. The antenna is simulated using CST Microwave Studio, and the simulated maximum directivity and gain obtained at 2.4 GHz are 6.655 dBi and 2.483 dBi, respectively. The S_{11} obtained at 2.4 GHz is -14.49 dB, which shows a good amount of impedance matching.

B. *Microstrip patch antenna with Luneburg lens*

The Luneburg lens has the property of focusing parallel incident radiations to their diametrically opposite side. It is a spherically symmetric gradient index (GRIN) lens with maximum refractive index n at the centre of the sphere and decreasing radially to the outer surface according to [7]

$$n(r) = \sqrt{\epsilon_r(r)} = \sqrt{2 - \left(\frac{r}{R}\right)^2}$$

where ϵ_r is the relative permittivity, R is the radius of the lens and r is the distance from the point to the center of the lens.

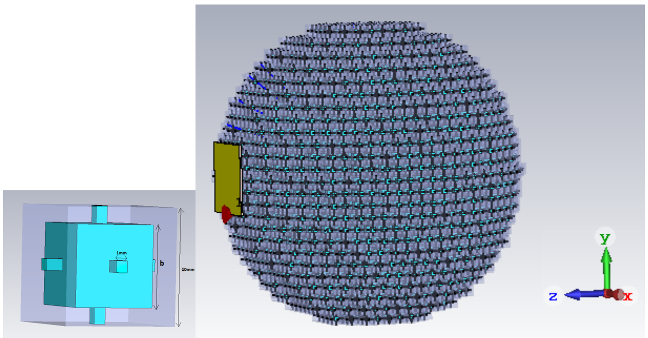
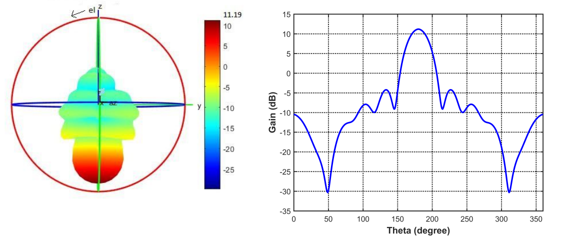


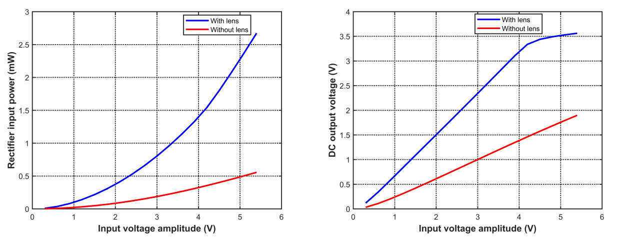
Fig. 4: Left picture shows a unit cell (b=7mm). Right picture shows the constructed Luneburg lens of 250 mm diameter excited by patch antenna

In this work, polymer-filled air cubes are used as unit cell for constructing the 3D Luneburg lens [8] as shown in Fig. 4. Each unit cell consists of an air cube with fixed dimension 10 mm. The polymer cube size (b) is varied accordingly to realize the required relative permittivity and 0.8 mm side cuboid on each face for supporting the adjacent unit cells is used. The polymer used for the unit cells is Acrylonitrile Butadiene Styrene (ABS) (ϵ_r = 2.7, tan δ = 0.005). The 250 mm diameter Luneburg lens is constructed in CST Microwave Studio and excited with patch antenna. The time domain analysis of the lens is performed to obtain the farfield characteristics at 2.4 GHz as shown in Fig. 5. The maximum directivity and gain obtained are 15.32 dBi and 11.19 dBi, respectively. The side lobe level and HPBW obtained are -15.4 dB and 29.6 degree, respectively.



(a) 3D farfield gain (b) 2D farfield gain

Fig. 5: Farfield radiation pattern of patch antenna placed on a Luneburg lens



(a) Received power at the rectifier input (node A) (b) DC output voltage

Fig. 7: Performance comparison of rectifier with and without Luneburg lens

IV. Simulation Results

In order to demonstrate the effect of lens on energy harvesting circuit performance, the antenna and rectifier circuit with components replaced by SPICE models are integrated in CST Circuits & Systems and the simulation setup is shown in Fig. 6. A receiving and transmitting antenna block is designed in CST Microwave Studio for this purpose in which a transmitting patch antenna (same specifications as the receiving antenna) is kept at a distance of 320 mm from the receiving patch antenna with and without Luneburg lens.

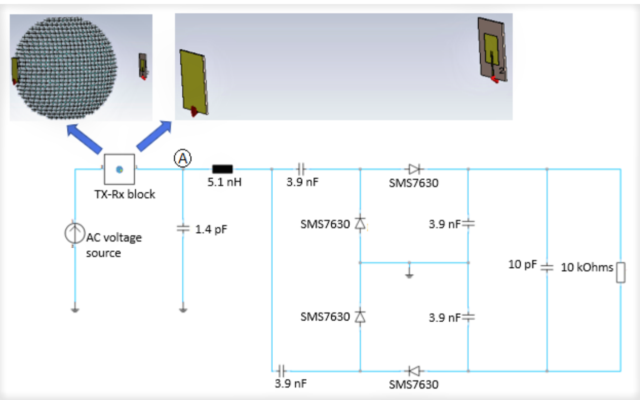


Fig. 6: Simulation setup for rectifier integrated with antenna

The transmitting antenna in both the cases is excited by AC signal source and the amplitude is swept between 0.3 V to 5.4 V. It can be observed from Fig. 7 that the received power at the rectifier input while using Luneburg lens is much higher than that received without Luneburg lens. Due to the increased input power to the rectifier, the output voltage obtained is much higher using a Luneburg lens. The proposed concept is demonstrated with a single patch antenna over the lens. As the lens has infinite focal points, the use of multiple antennas on the lens surface will result in larger output voltage, as the antennas will efficiently receive more power available in any direction.

V. Conclusion

The design and analysis of modified Greinacher rectifier and Luneburg lens are discussed in this paper. The DC output voltage and PCE obtained for -15 dBm power and 10 kΩ load resistance is 310 mV and 30.36 % respectively, with maximum efficiency obtained as 53.36 % at 1 dBm power. RF power combining topology is used for combining power from multiple antennas. The simulation results show that the use of Luneburg lens has led to increase in received power to the rectifier which resulted in increase in output voltage. The simulated results need to be verified by measurement results and the analysis will be further carried forward with more number of patch antennas placed on the lens surface to practically demonstrate the usefulness of lens.

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