Smart Energy Harvesting System for IoT & Cyber Physical Devices

Московский институт электроники и математики НИУ ВШЭ

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Abstract

The modern IoT & cyber-physical systems often rely on wireless or independent energy sources that do not need battery change or manual recharging. Recharging of such systems is often delivered by rectifying antennas. In this paper we propose an energy harvesting system for IEEE 802.11 standard that can work within Wi-Fi frequency range (2412 - 2472 MHz and 5160-5825 MHz). The proposed system is based on phased patch-antennas with focusing and scanning of electron beam. The use of such a system increases the gain, power characteristics and, consequently, the productivity of a smart energy harvester compared to energy harvesting systems with a single antenna.

Introduction in Modern Cyber Physical Systems and IoT Devices

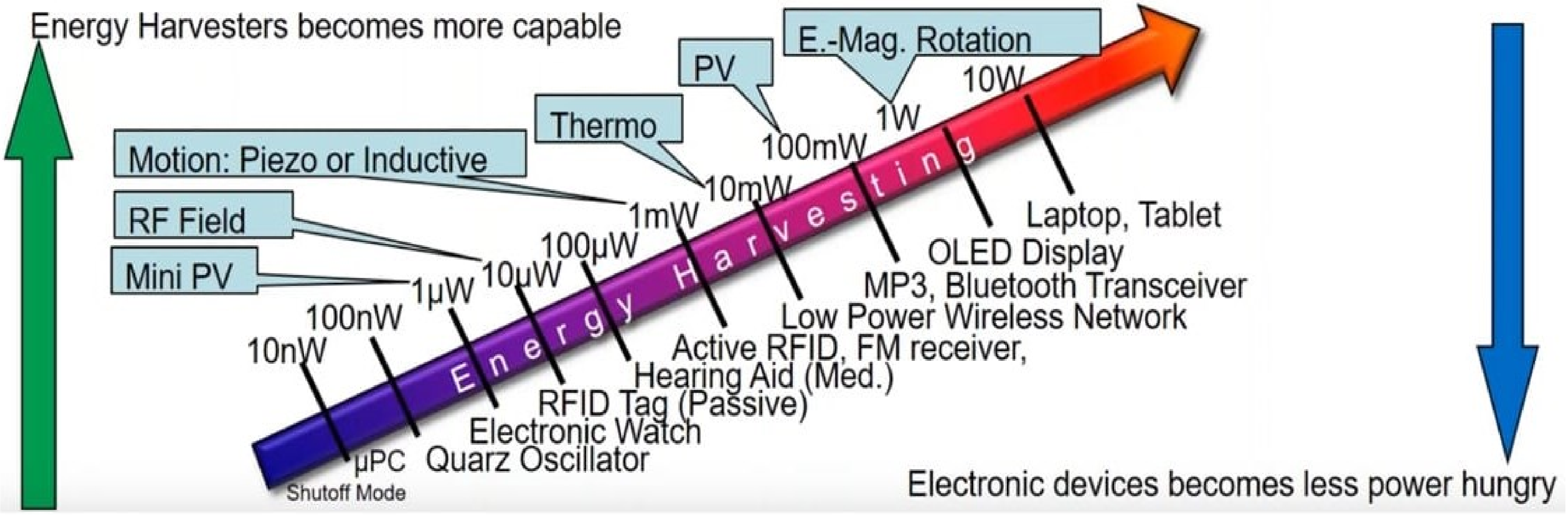
Microchip's TPWR001 Lifetime Power Energy Harvesting development kit.

Modern cyber physical systems and IoT devices consist of huge number of objects working in various bands and on different standards. Such systems require a lot of energy that is usually taken from batteries and accumulators. Regardless of their capacity, necessity of their replacement and recharging poses a significant inconvenience for a user. Therefore, a wireless recharging can become a promising way to develop new devices for IoT that can work autonomously longer, by harvesting energy from local electromagnetic fields.

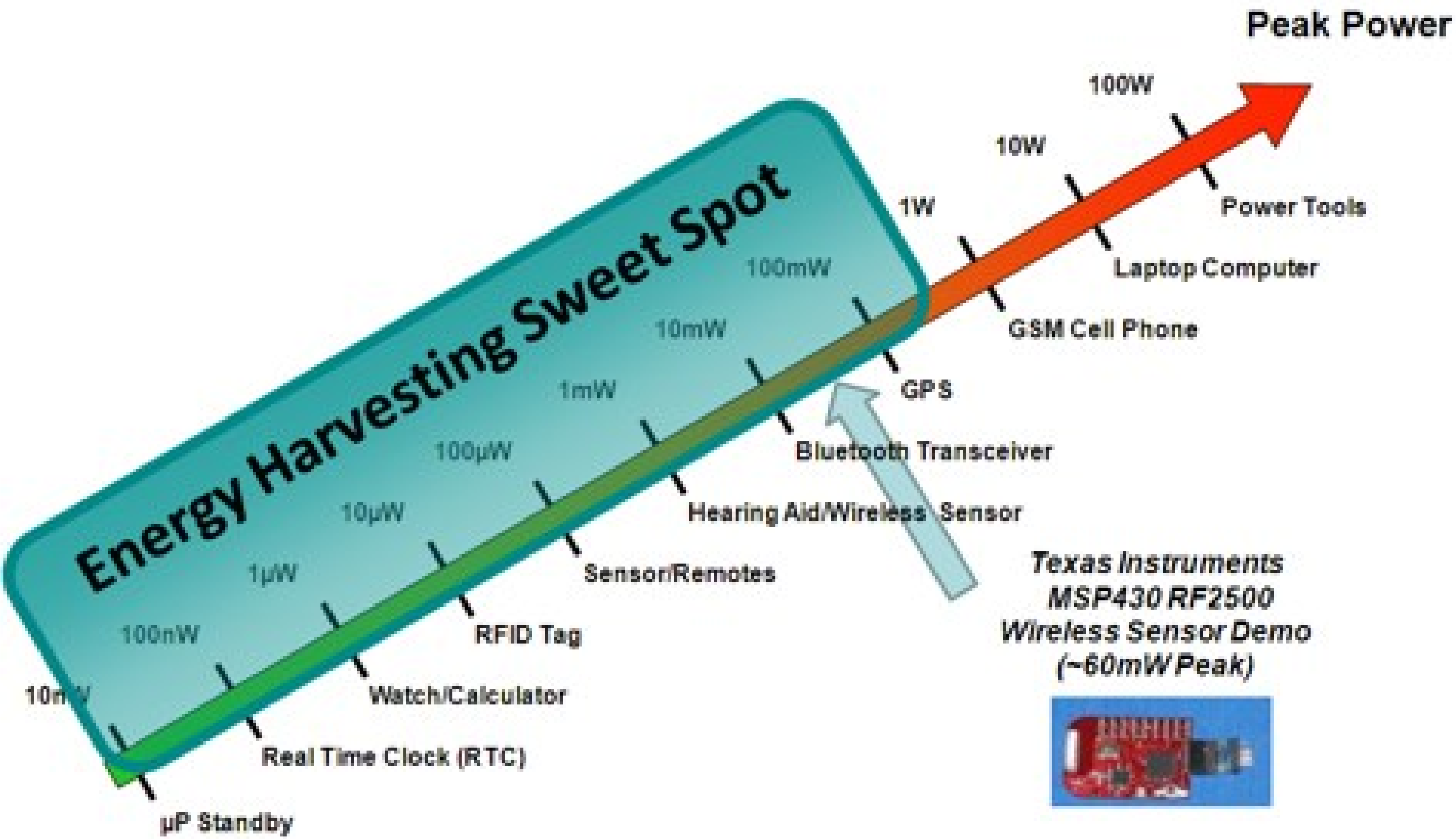
Energy harvesting resources versus requirements

Where to find „free energy“

- **Typical energy harvester output power**
  - RF: 0.1µW/cm²
  - Vibration: 1mW/cm²
  - Thermal: 10mW/cm²
  - Photovoltaic: 100mW/cm²
- **Typical energy harvester voltages**
  - RF: 0.01mV
  - Vibration: 0.1 ~ 0.4 V
  - Thermal: 0.02 ~ 1.0 V
  - Photovoltaic: 0.5 ~ 0.7 V typ./cell



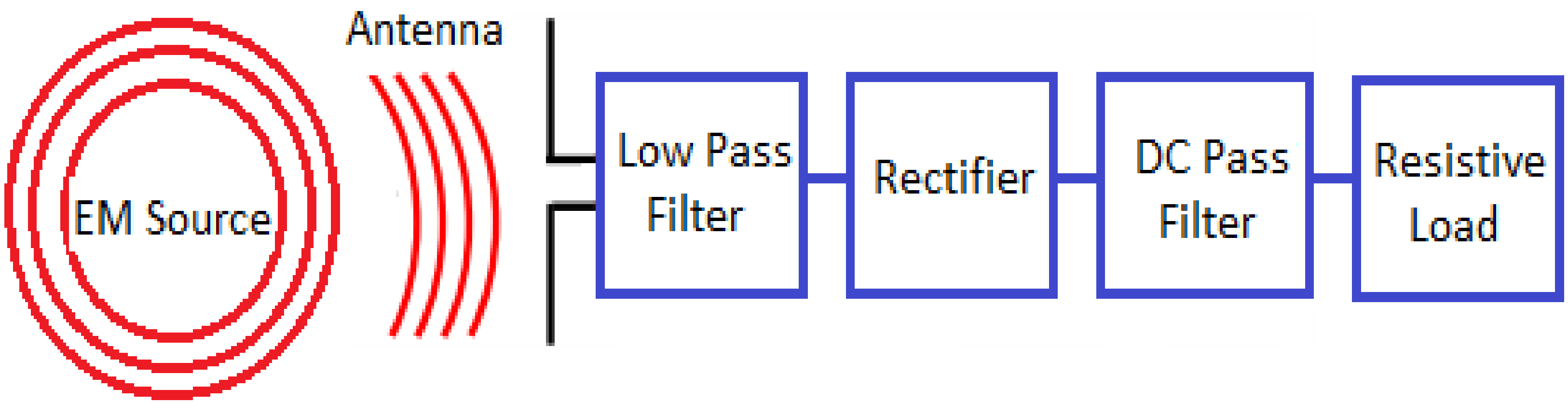
Energy Harvesting Transducer Comparisons



(https://www.psma.com/HTML/newsletter/Q2_2012/page8.html)

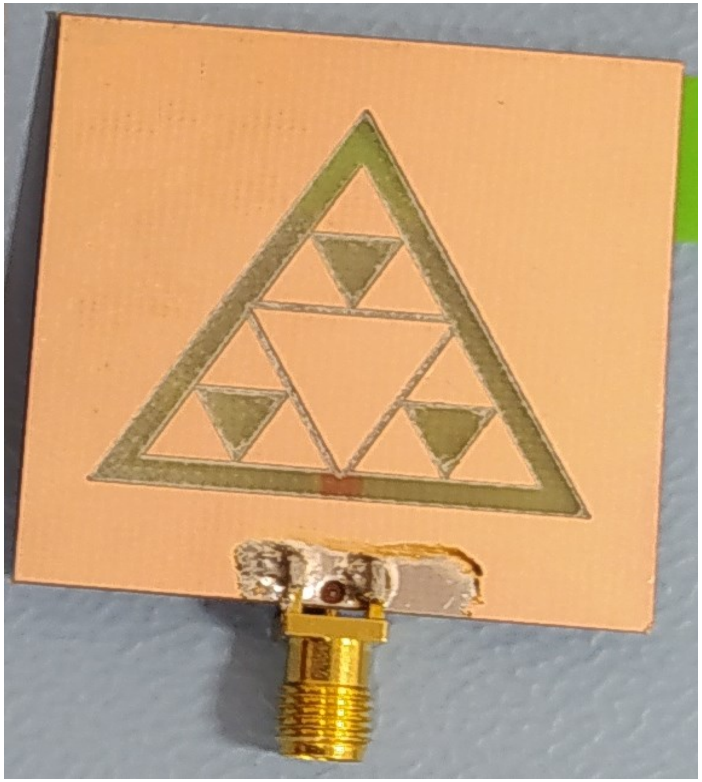
Rectifying Antenna (Rectenna) flowchart

The dual-band rectenna can be used with wireless devices based on IEEE 802.11 standards in the Wi-Fi bands 2.4 GHz (2412-2472 MHz) and 5 GHz (5160-5825 MHz). A modified fractal patch antenna detects electromagnetic waves in surrounding space.



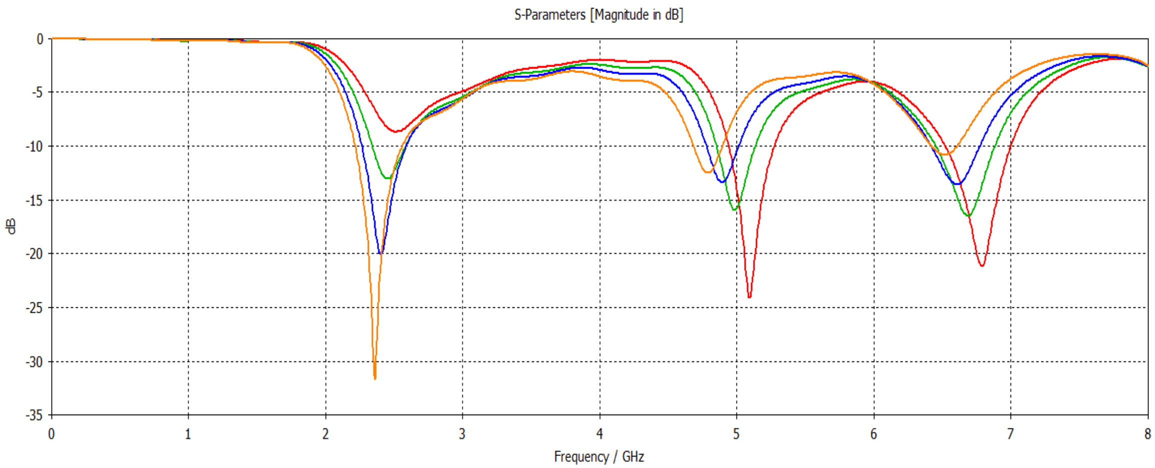
The basic elements of the rectenna are a receiving antenna, a low-pass filter, a matching device, a rectifier, and a DC filter, followed by a resistive load.

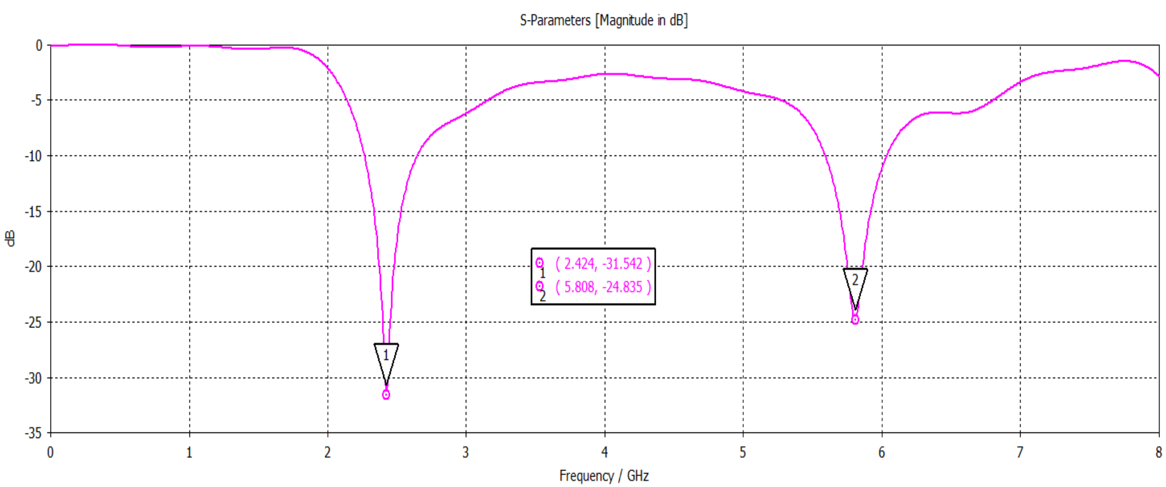
Antenna Design



The proposed receiving patch antenna is made on a square substrate of FR4 fiberglass with overall dimensions of 40×40 mm, a dielectric constant of 4.4, a loss angle tangent of 0.02, and a thickness of 1.5 mm. The antenna is powered by a microstrip conductor with a 50 Ohms wave resistance, located on the opposite side of the substrate and exciting the main triangular resonator. To achieve dual-band operation of the proposed antenna, smaller triangular resonators are also used, located on each side of the main resonator and separated from it by a capacitive gap.

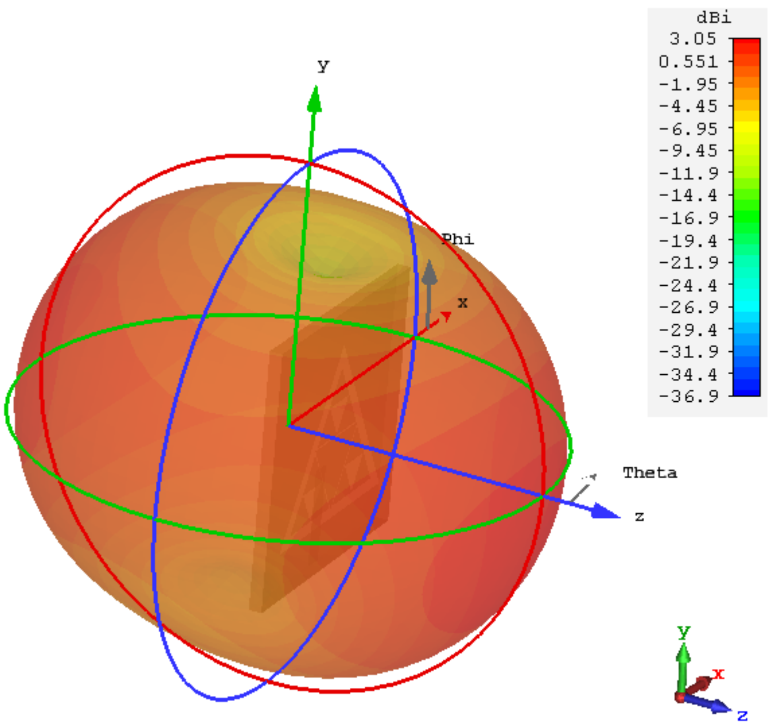
Simulation results in the CST Studio Suite program



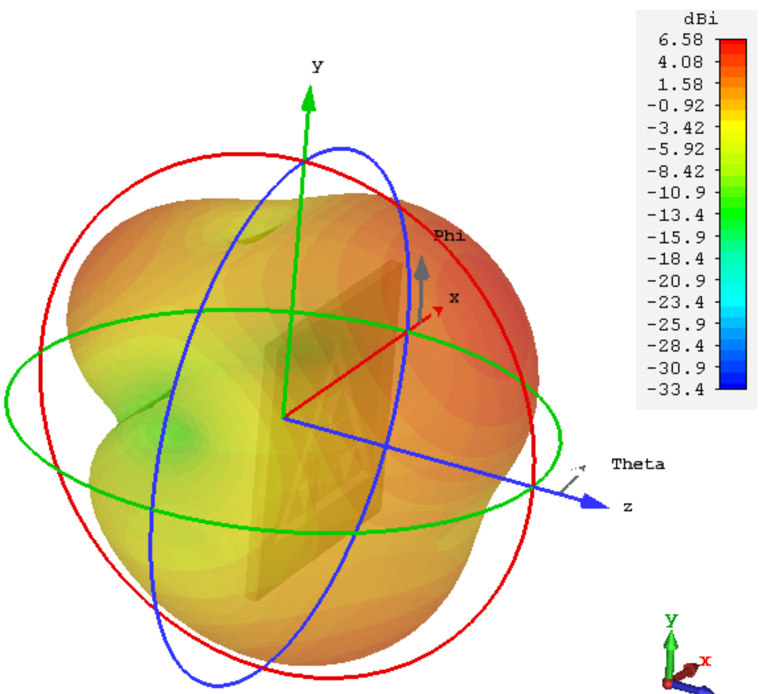


Simulation results obtained demonstrate that the proposed antenna has three resonances at frequencies of 2.4, 5.1, and 6.8 GHz with maximum attenuation coefficients of -32, -24, and -22 dB, respectively. It can be seen that with increasing length of the microstrip feed, the Q-factor of the first resonance at a frequency of 2.4 GHz increases. By varying geometry of the triangular resonators, it is possible to achieve resonances in required bands with central frequencies at 2.4 GHz and 5.8 GHz.

Simulation results in the CST Studio Suite program

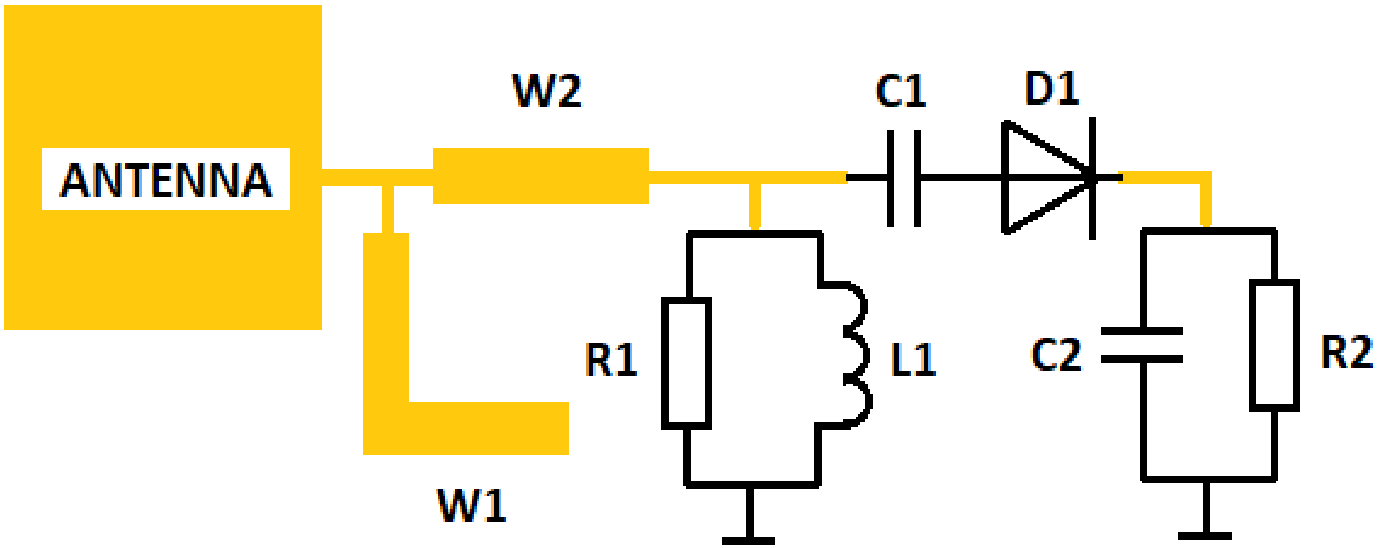


Volumetric radiation pattern of a single antenna at 2.4 GHz



Volumetric radiation pattern of a single antenna at 5.8 GHz

The block diagram of the rectenna



A single-half-period rectifier is used to convert the RF power received by the antenna into DC power. The rectifier circuit consists of two matching loops and a Schottky diode connected in series through a blocking capacitor separating the RF path from the DC power supply circuit.

Calculated ratios

The DC output voltage and the overall efficiency of converting the RF signal to DC are calculated as a function of the power density (mW/m^2) from the Friis equation:

$$P_r = \left(\frac{\lambda}{4\pi r}\right)^2 P_t G_t G_r$$

there *Pt* , *Gt* , *Gr* , *r* and λ - transmitted or input power, the gain of the transmitting antenna, the gain of the receiving antenna, the distance between the two antennas, and the wavelength, respectively.

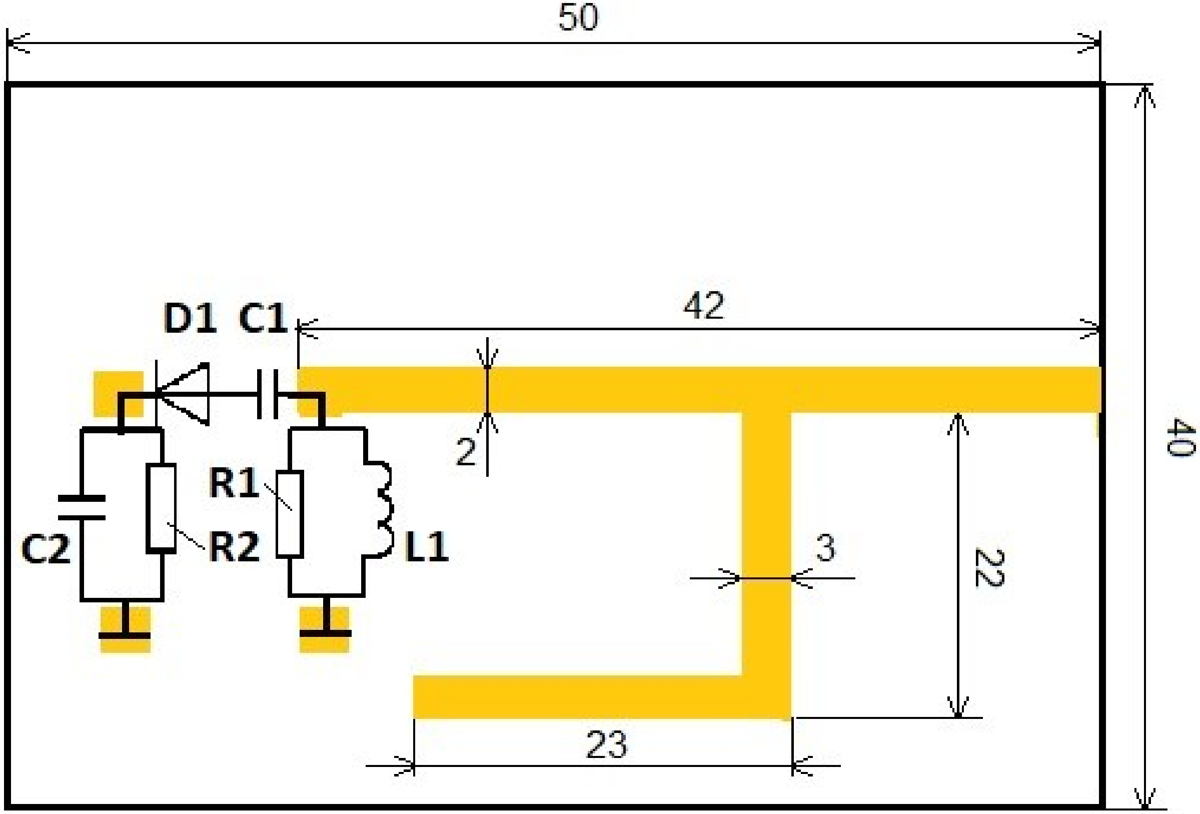
If the DC output voltage is measured through the load resistance R_L, the efficiency of converting the RF power of the rectifier circuit to DC is calculated using the following formula:

$$\eta_{CE}\% = \frac{P_{DC}}{P_{in}} \times 100\% = \frac{V_{DC}^2}{R_L \cdot P_{in}} \times 100\%$$

there P_{in} is the input power of the diode.

Experimental layout

According to the results of the rectenna simulation, the characteristic resistance of the diode is (74-j58.1) and (82-j18.1) for a given input power of 30 mW and a resistive load of 1 kOhm, at frequencies of 2.4 GHz and 5.8 GHz, respectively.

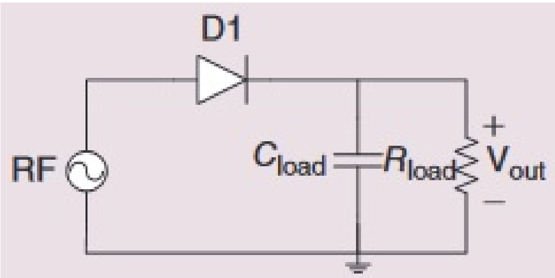


Experimental layout

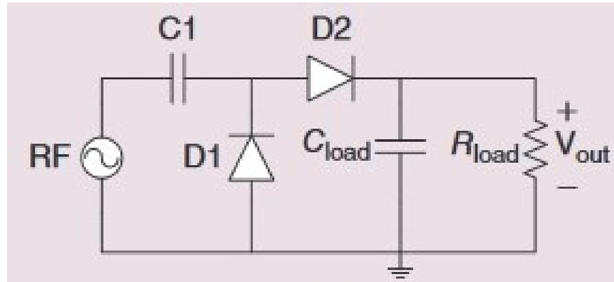
The maximum DC output voltage with an applied input power not exceeding 30 mW and a resistive load of 1 kOhm is 653 mV at 5.8 GHz and 432 mV at 2.4 GHz. At the same time, it should be noted that the useful output power is not affected by losses in the form of harmonic distortion introduced through the rectifier circuit.

The efficiency of converting the RF signal to direct current calculated for this rectenna is 76% and 82% at the frequencies of 2.4 GHz and 5.8 GHz, respectively.

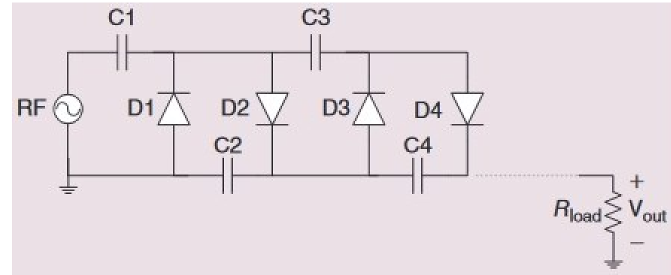
Rectifier Design



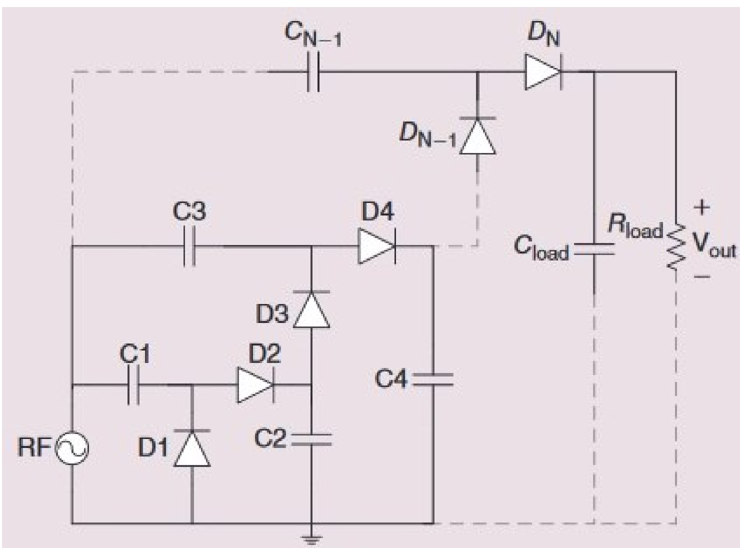
Half-wave rectifier



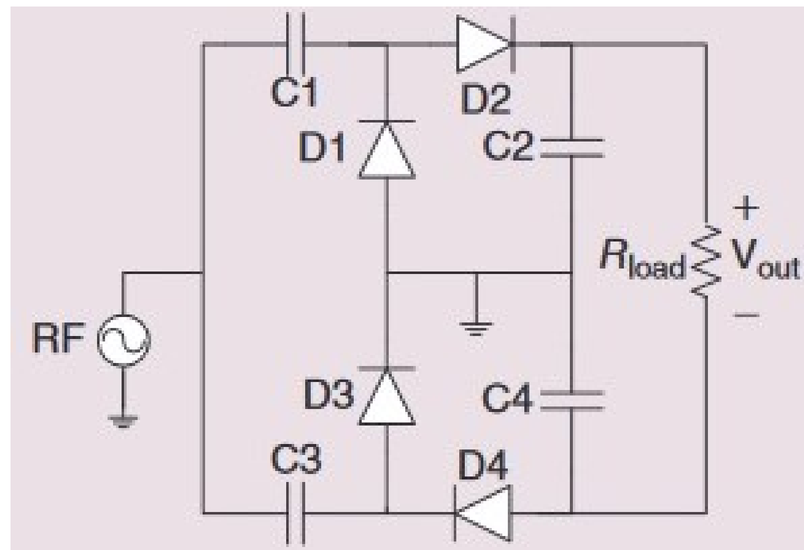
Greinacher single stage voltage multiplier



Cockcroft-Walton/Greinacher/Villard charge pump

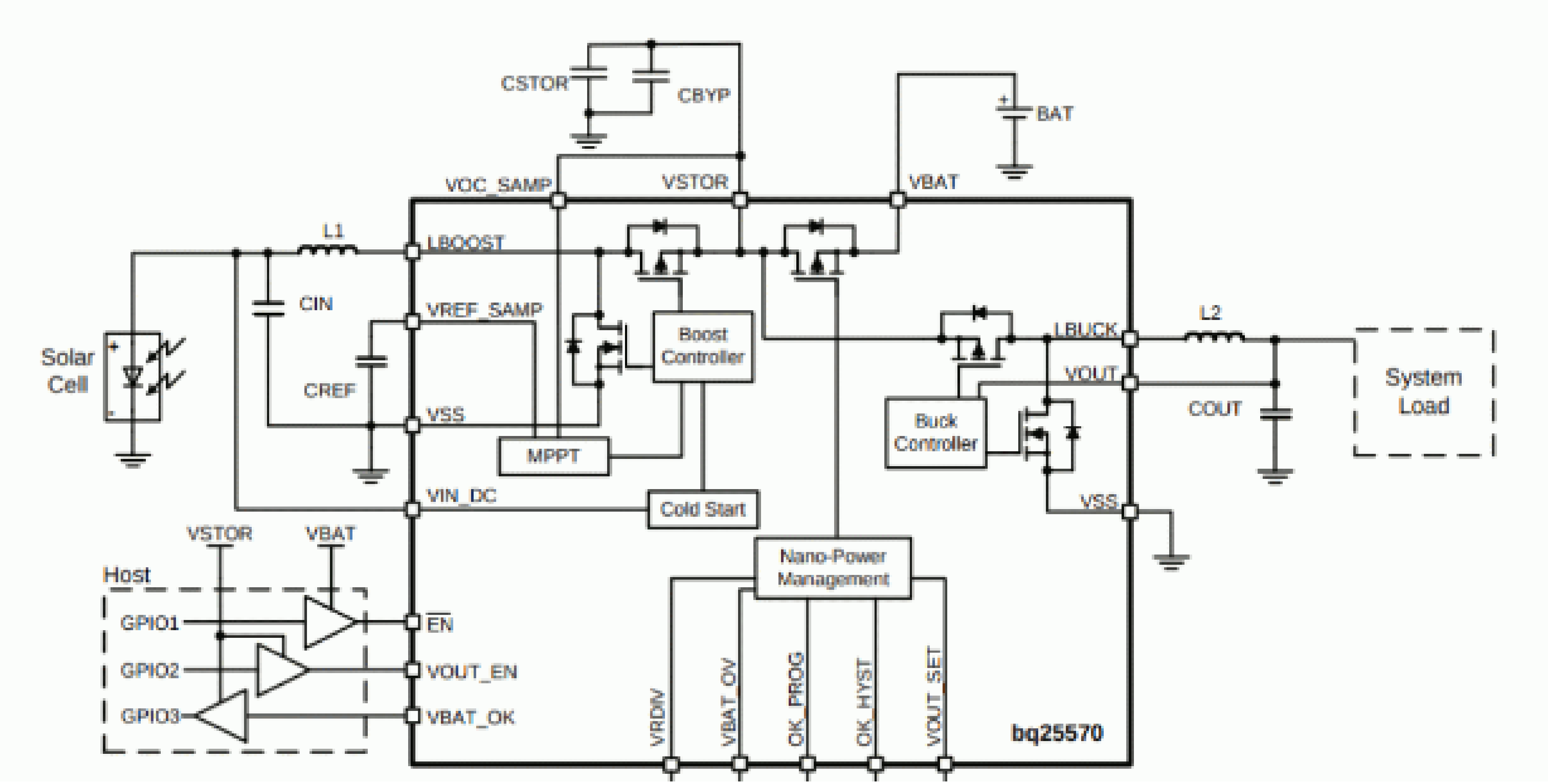


Charge pump of Dickson



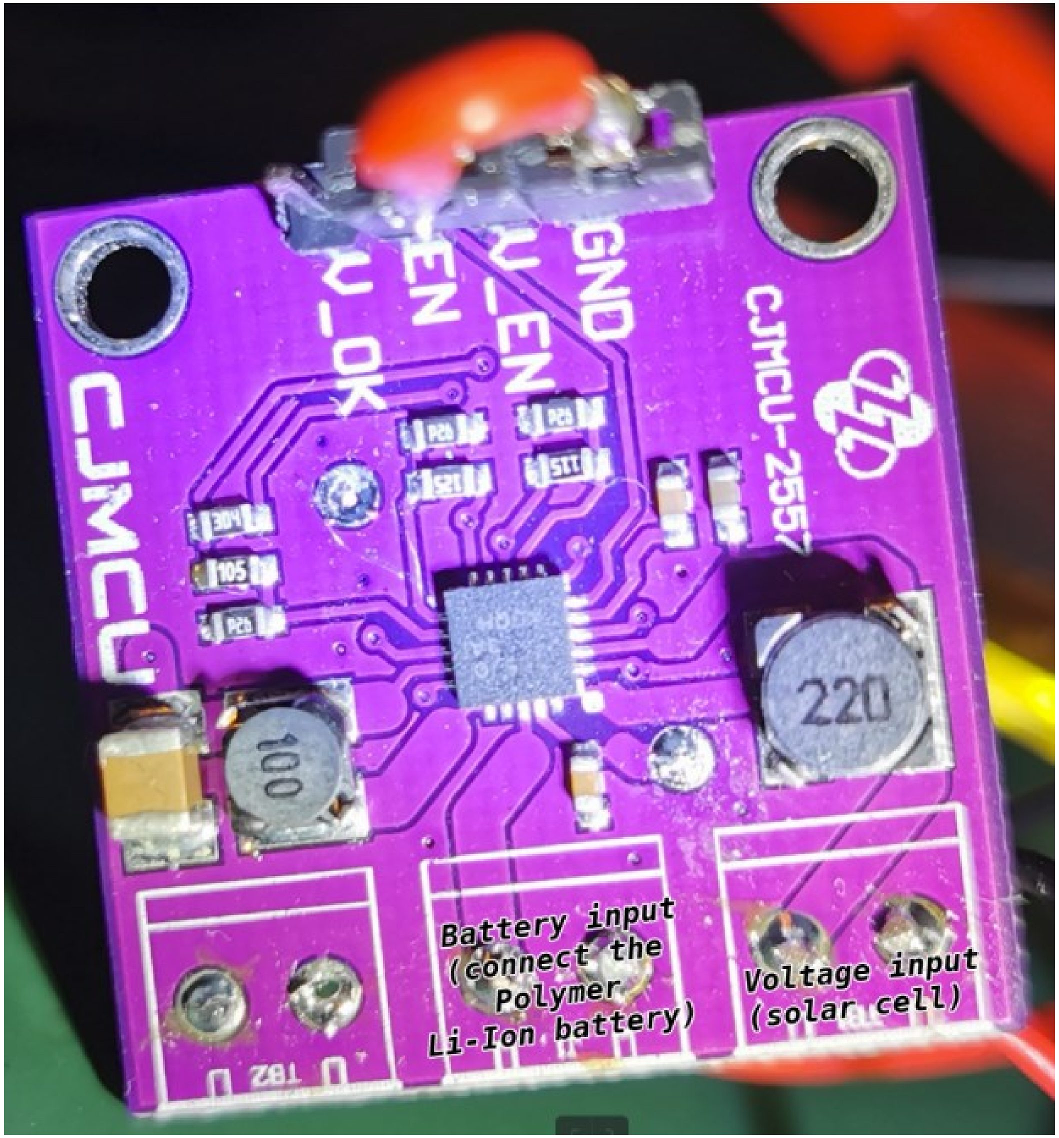
Modified Cockcroft-Walton/Greinacher charge pump

Rectifier Design – BQ 25570 (Texas Instruments)

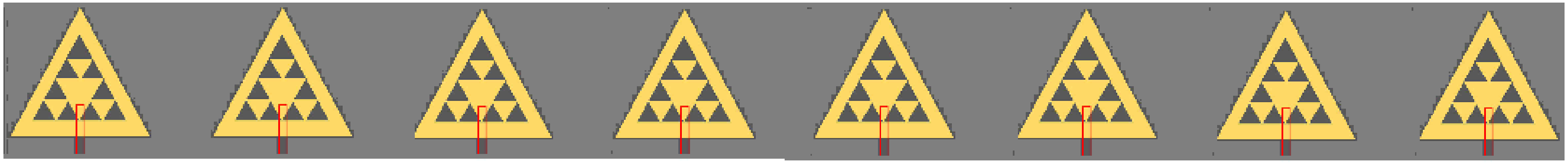


	Spreadsheet voltage	Measured voltage	Error percentage
VBAT_OV	4.066 V	4.160 V	+2.31%
VOUT	2.574 V	2.589 V	+0.58%

Rectifier Design – BQ 25570 (Texas Instruments)



Antenna Array Design



If we assume that the phase of the first element of the lattice is chosen as the reference phase, then the phase of the *n*th element can be defined as:

$$phase_n = k(n-1)d\sin\theta$$

where *k* is the wave number, *d* is the distance between the lattice elements.

A plane wave in exponential form describes the superposition of the discrete signal transmitted by every phased array element. It can be presented as:

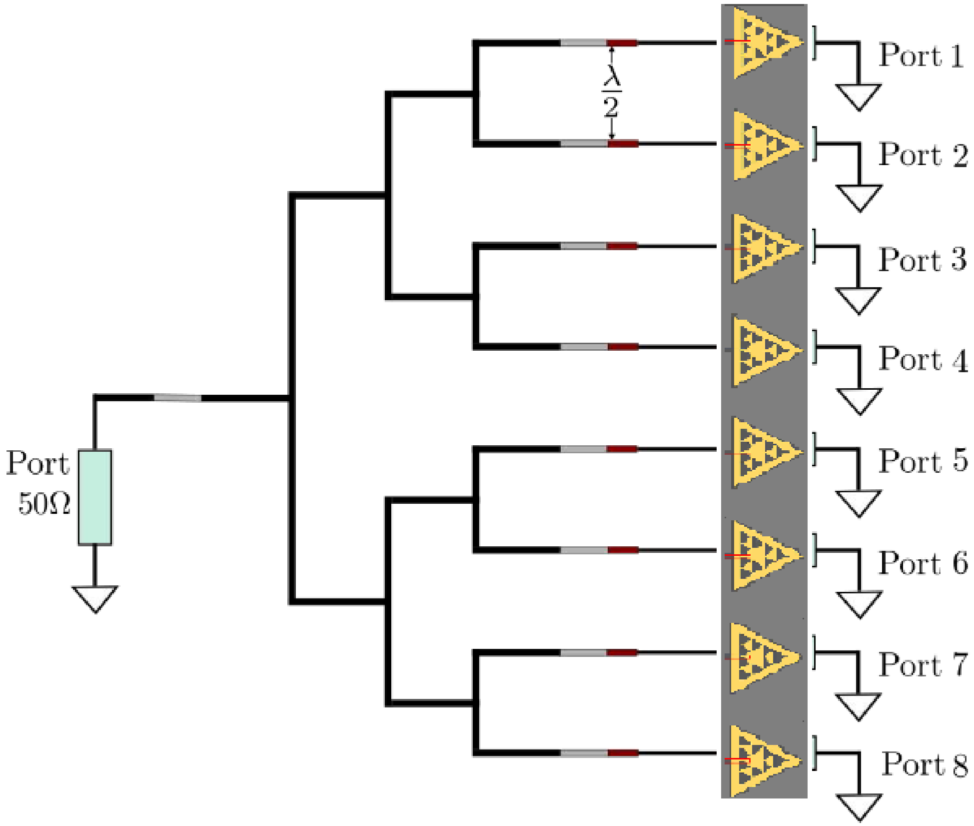
$$AF(\theta,\varphi) = \sum_{n=0}^{N-1} w_n e^{j(k(n-1)d\sin\theta\cos\phi - \delta_n)}$$

where w_n – is the amplitude coefficient of the nth –element.

The following formula that describes an additional phase shift of the n-element in the direction of the main lobe of radiation, set by the angles θ and ϕ :

$$\delta_n = k \cdot n \cdot d\sin\theta\cos\phi$$

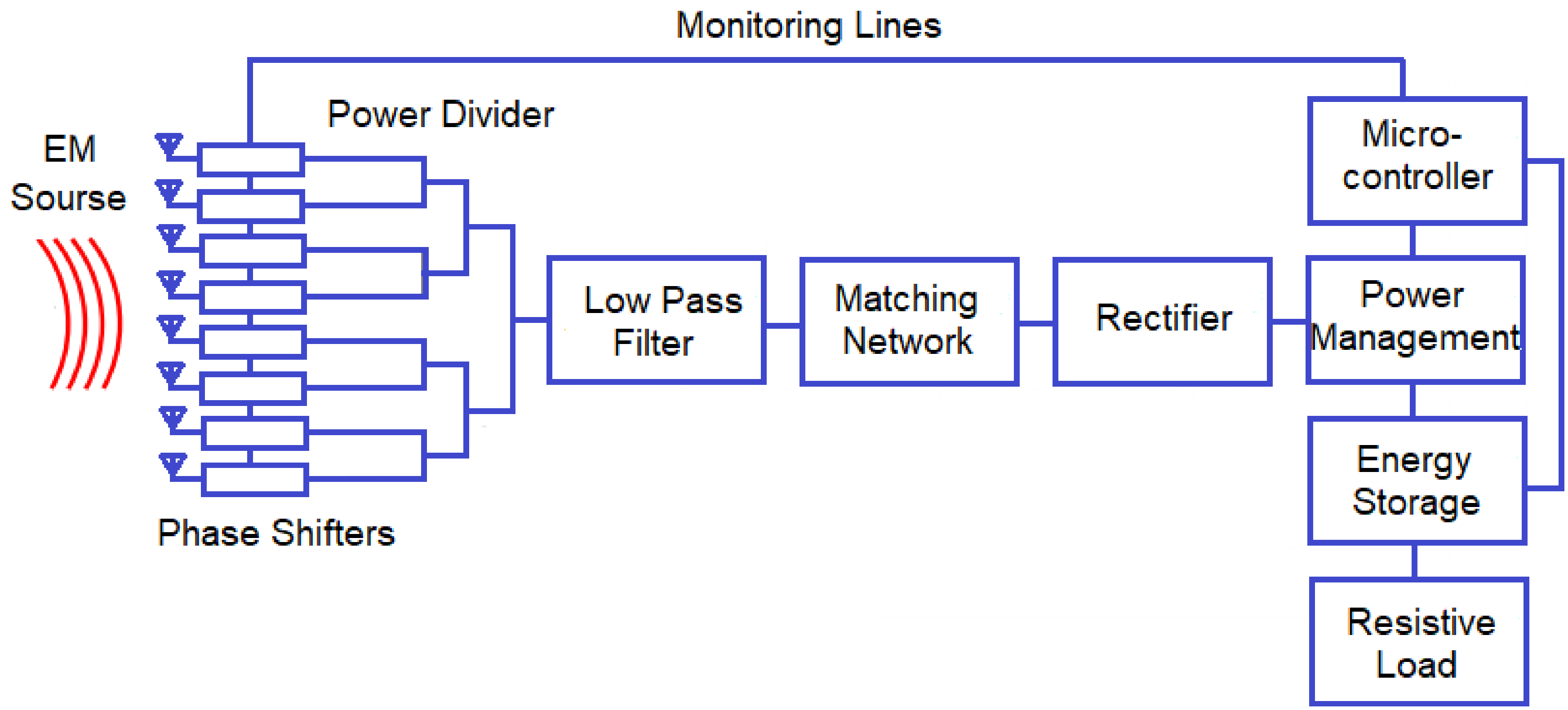
Feed Network Design



The phased array antenna is powered by a microstrip splitter made on the basis of T-shaped power dividers. The splitter contains one input and eight outputs at an frequency of 5.8 GHz.

To reduce the side lobes of the antenna array directional pattern, it is necessary to provide a transient attenuation of at least 20 dB. All ports are matched to 50 Ohms using quarter-wave transformers.

Project Smart RF- Harvesting System



Conclusion

A smart energy harvesting system of IEEE 802.11 standard with operating frequencies of 2.4 GHz and 5.8 GHz has been proposed and developed.

It features an eight-element phased patch antenna array with the ability to electronically scan and focus the beam. The system is designed for alternative power supply for wireless Internet of Things (IoT) & cyber-physical devices. The possibilities of further modernization of such an "energy combine" by integrating a microcontroller, digital phase shifters and a power amplifier into the system are considered.

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Thank you for your attention !