Optimal Signal Selection and Rectenna Design for Electromagnetic Energy Harvesting and Wireless Power Transfer

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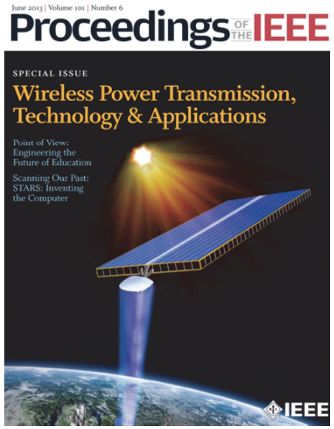
Outline

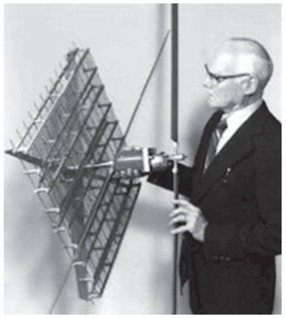
- Introduction
  - Motivation
  - Wireless power transfer
- Energy harvesting and Wireless Power Transfer
  - Rectenna design and optimization
  - Signal optimization
  - Energy harvesting assisted RFID and WSN
- Conclusion

Motivation

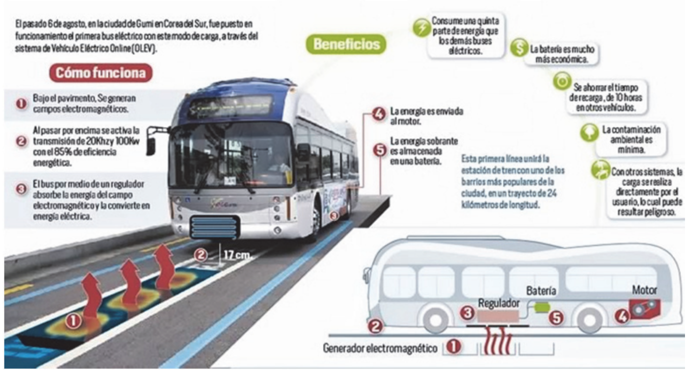
- Wireless Power Transfer
  (Selected historical milestones)
- Nikola Tesla (1899)
- William Brown (1964)
  (Microwave powered helicopter)
- Kyoto Univ. (1992)
- MIT (2007)(Resonant magnetic coupling)
- KAIST (2009)(On-line electric vehicle – OLEV))



Tesla, Colorado Springs



W.C. Brown



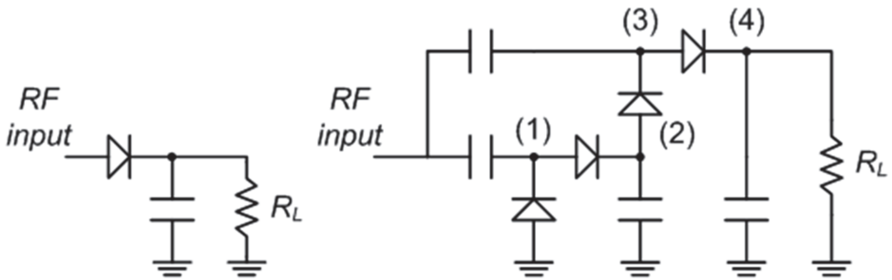
MILAX (1992) Kyoto Univ., Kobe Univ., etc.

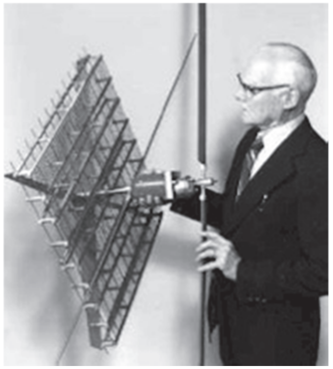
Motivation

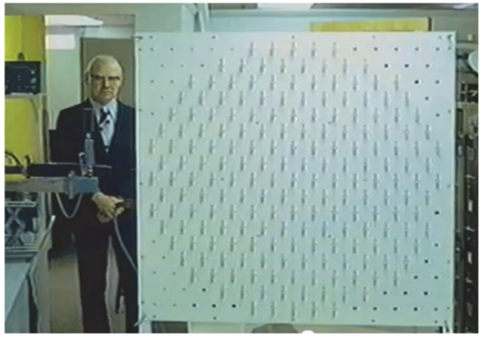
- Choice of harvesting module(s) is application dependent
- Transducer efficiency depends on available power density and load variation
- Transducer efficiency depends on signal and nonlinear device characteristics

Rectenna Design and Optimization

- Key element: Rectenna (Brown US3434678, 1969).
- Rectifier circuits: envelope detector, charge pump circuits Schottky diodes, low / zero barrier diodes







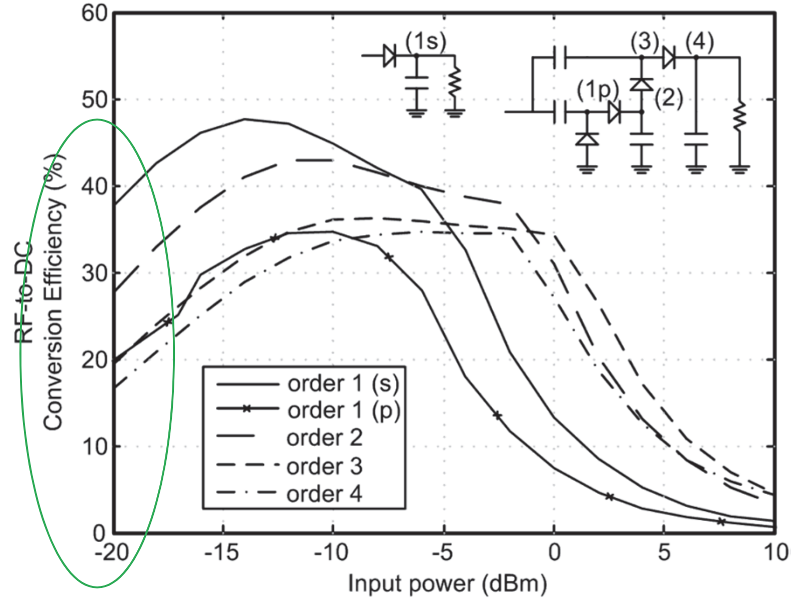
Reported UHF rectifier efficiencies for available input power levels in the order of 10 µW are approximately 20 %, and increase to > 50 % for available power levels of 100 µW.

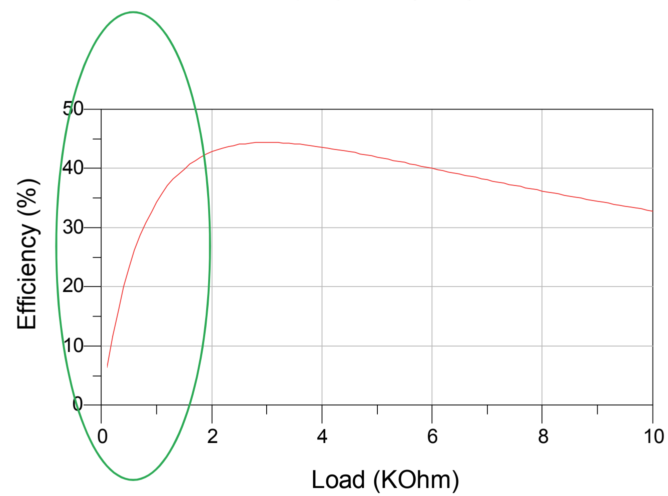
Rectenna Design and Optimization

- Circuit topology important
  in low available power conditions

- Trade-off between efficiency
  and output voltage

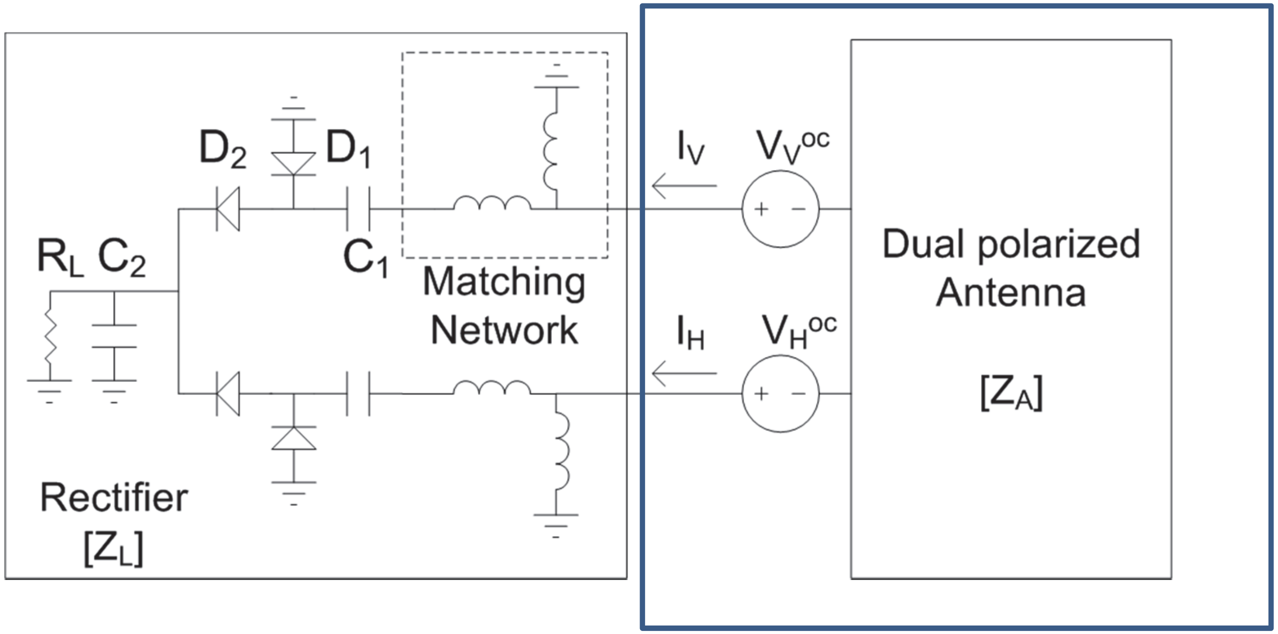
- Efficiency varies with input power and
  load variation





Rectenna Design and Optimization

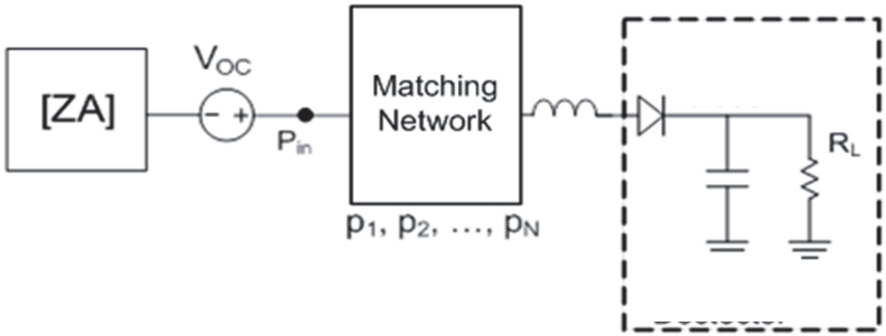
- Rectenna optimization using Thevenin (below) or Norton equivalent of antenna/coil in receive mode.



N-port loaded scatterer
(see e.g. Mautz and Harrington)

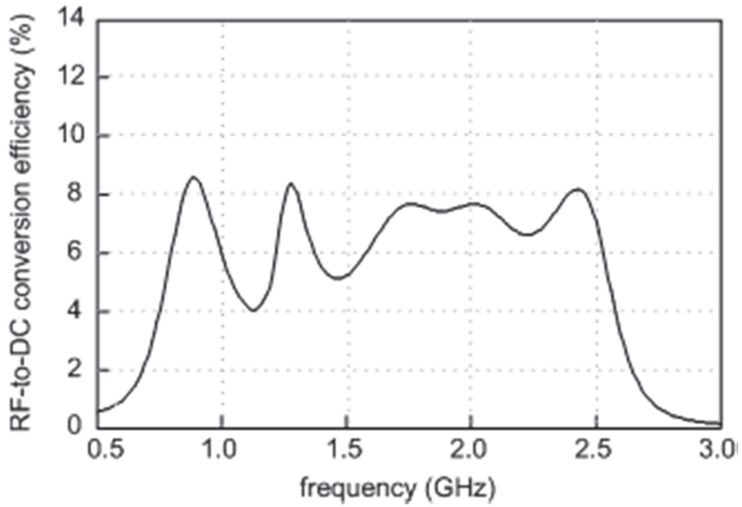
A.Georgiadis, G. Andia-Vera, A. Collado "Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (EM) energy harvesting," IEEE Antennas and Wireless Propagation Letters, vol. 9, pp. 444-446, 2010.

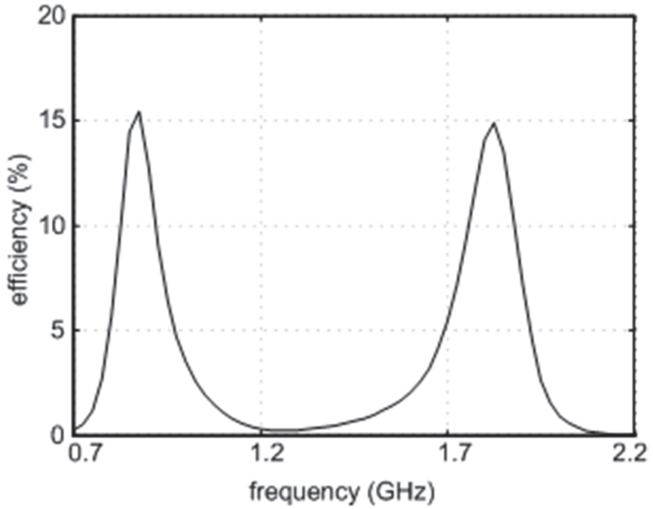
Rectenna Design and Optimization



OPTIMIZATION PARAMETERS:

$p_1,\ldots,p_N$
R_L



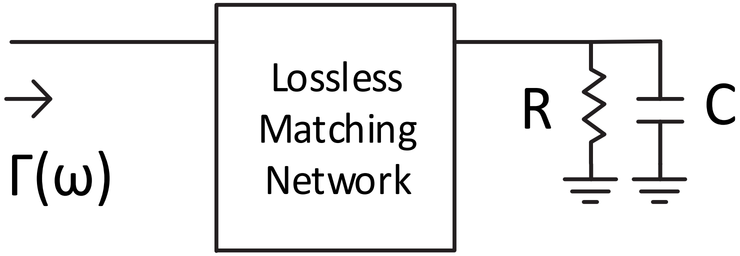


For a given wave receiving structure (antenna/coil) and nonlinear device (diode), optimize matching network and output load

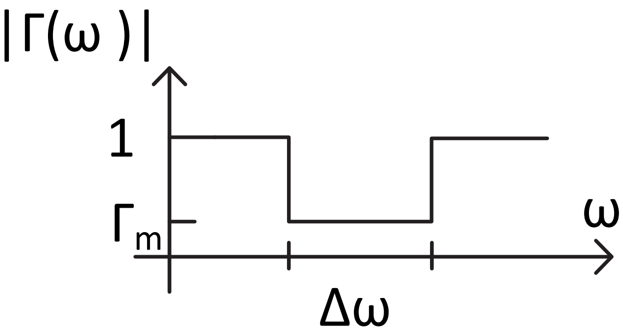
Rectenna Design and Optimization

Bode-Fano criteria (see e.g. D. Pozar, Microwave Eng.)

$$\int_0^{\infty} \ln \frac{1}{|\Gamma(\omega)|} d\omega \leq \frac{\pi}{RC}$$

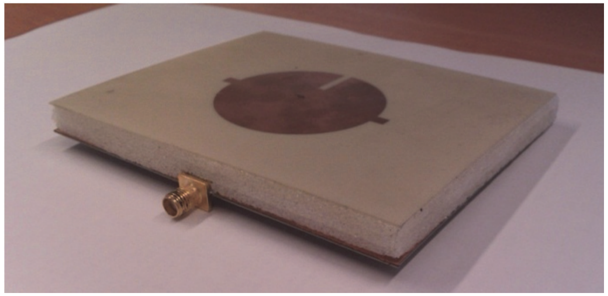


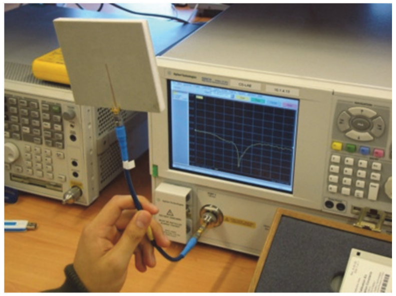
$$\Delta\omega \ln \frac{1}{\Gamma_m} \leq \frac{\pi}{RC}$$

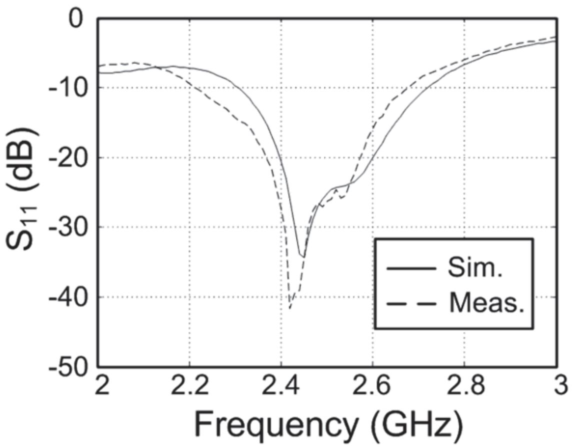


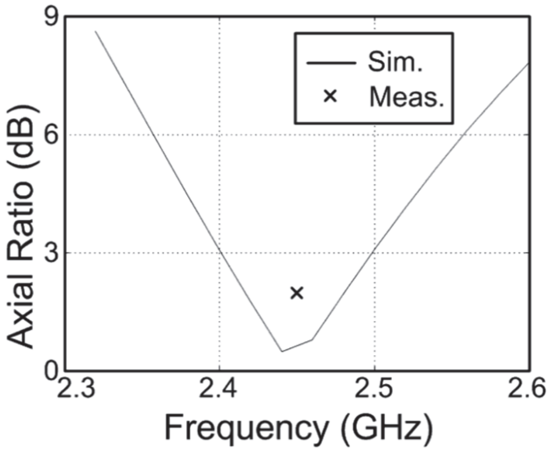
Rectenna Design and Optimization

Circularly polarized rectenna





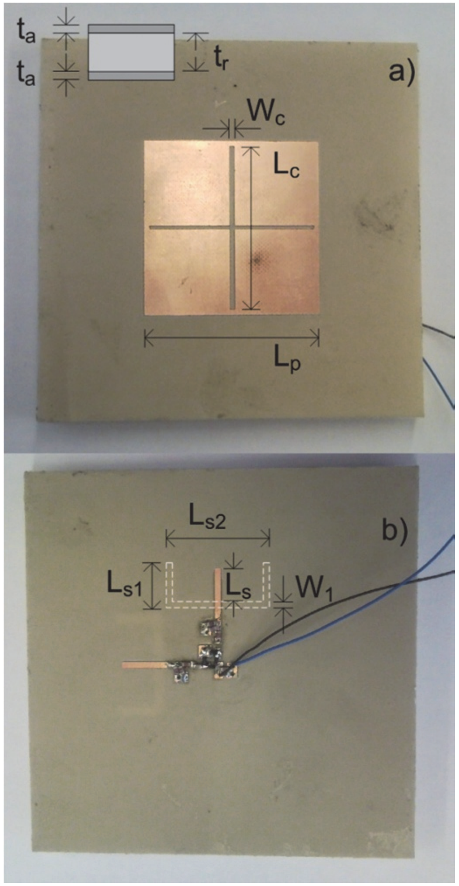




Rectenna Design and Optimization

Rectenna design example

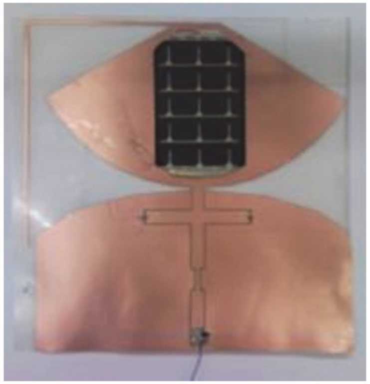
- 2.40 GHz - 2.48 GHz ISM band
- Aperture coupled patch topology:
- Circuit and radiator layers are made of Arlon A25N 20 mil thick
- Separated by a Rohacell51 layer of 6mm in order to achieve the desired bandwidth

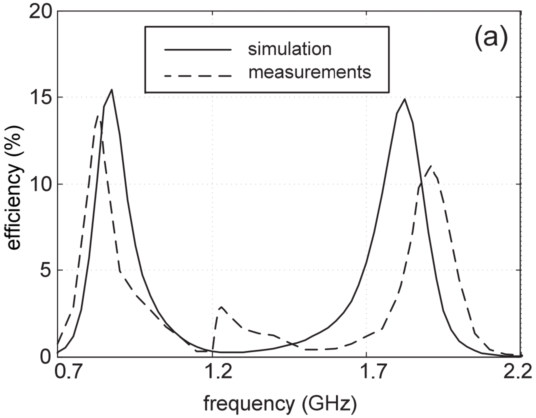


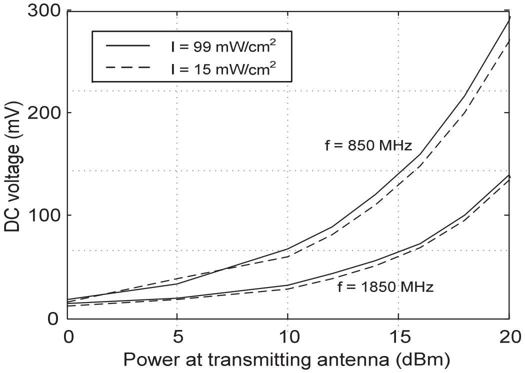
Rectenna Design and Optimization

850 MHz/1850 MHz Dual Band Rectenna

- Broadband monopole antenna (0.7GHz - 6 GHz)
- Akaflex PCL3-35/75 µm with εr = 3.3 and tanδ = 0.08
- Silicon Schottky diode (Skyworks SMS7630)
- Coplanar waveguide matching network
- Optimization for input power of -20 dBm and RL=2.2 kΩ







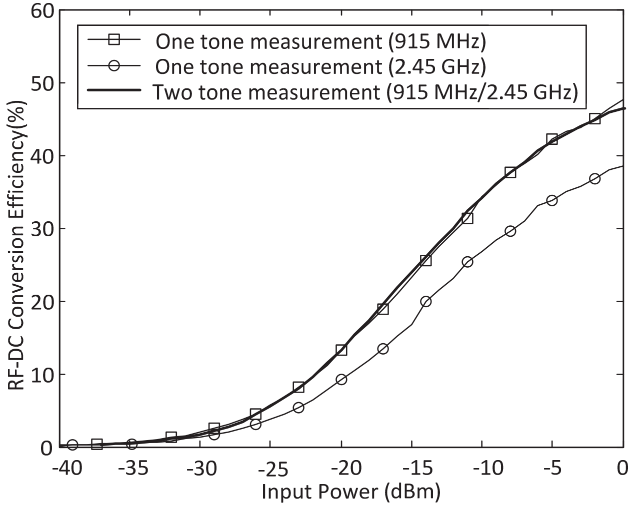
Collado, A.; Georgiadis, A., "Conformal Hybrid Solar and Electromagnetic (EM) Energy Harvesting Rectenna," *Circuits and Systems I: Regular Papers, IEEE Transactions on* , vol.60, no.8, pp.2225,2234, Aug. 2013

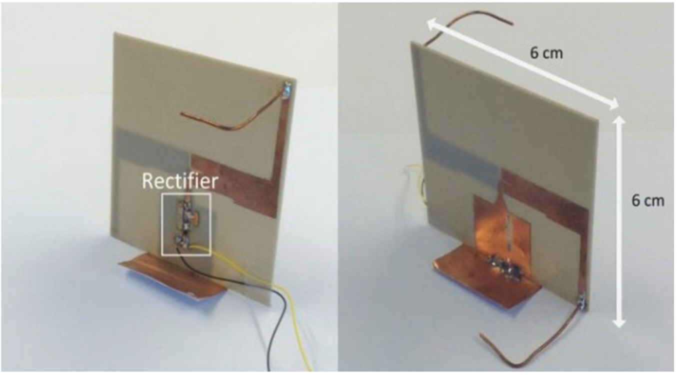
Rectenna Design and Optimization

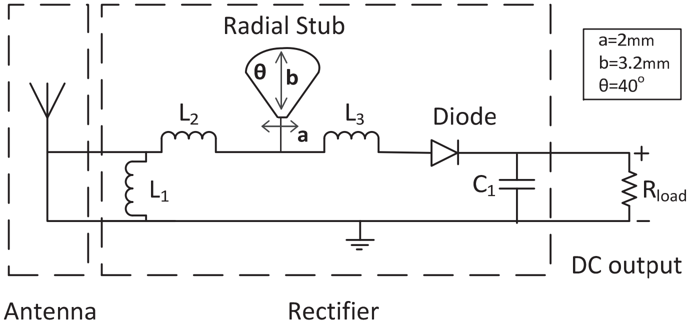
- ❑ Optimization goals are used to maximize the RF-DC conversion efficiency at 915 MHz and 2.45 GHz

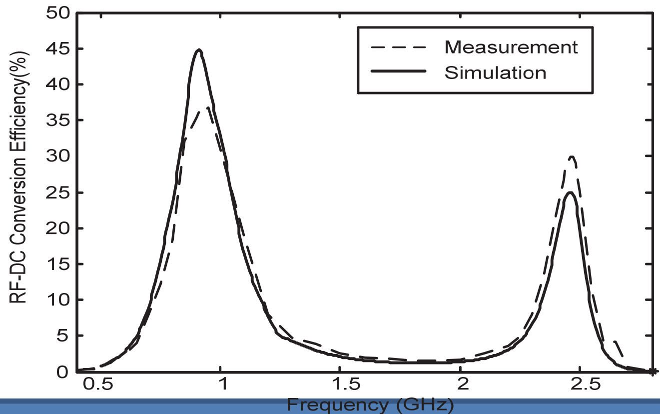
$\boldsymbol{\eta}$ = 48% and $\boldsymbol{\eta}$ = 39% at 915 MHz and 2.45 GHz, for P_{in}=0 dBm

$\boldsymbol{\eta}$ <1 % for P_{in}<-33 dBm



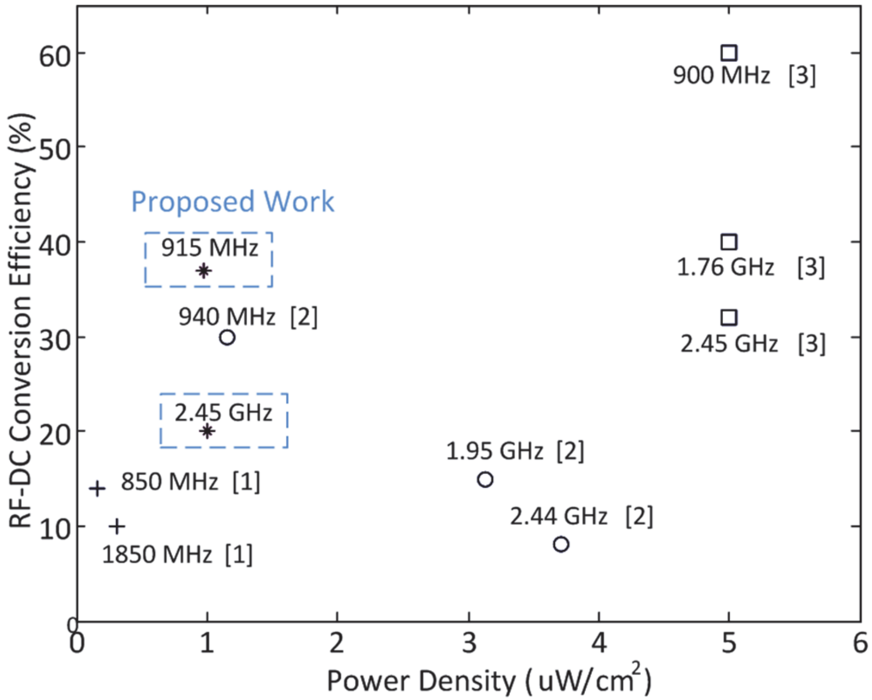


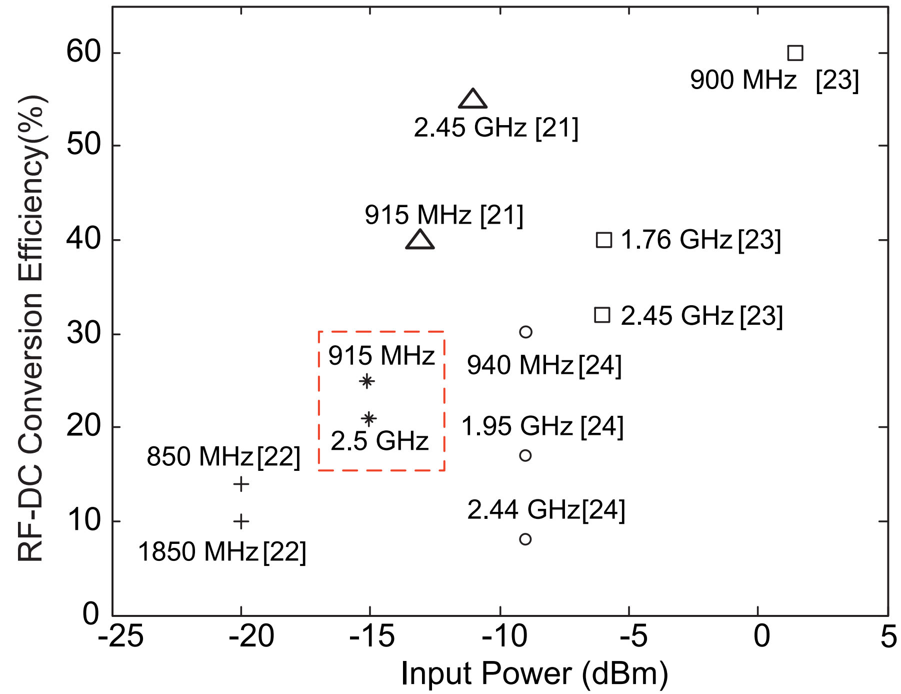




Niotaki, K.; Sangkil Kim; Seongheon Jeong; Collado, A.; Georgiadis, A.; Tentzeris, M.M., "A Compact Dual-Band Rectenna Using Slot-Loaded Dual Band Folded Dipole Antenna," *Antennas and Wireless Propagation Letters, IEEE* , vol.12, no., pp.1634,1637, 2013

Rectenna Design and Optimization





[1]([22]) A. Collado, and A. Georgiadis, "Conformal Hybrid Solar and Electromagnetic (EM) Energy Harvesting Rectenna," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 8, pp.2225,2234, Aug. 2013

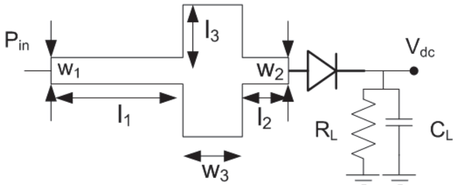
[2]([24]) B. L. Pham and A.-V. Pham, "Triple Bands Antenna and High Efficiency Rectifier Design for RF Energy Harvesting at 900, 1900 and 2400 MHz," in *Proc. IEEE MTT-S Int. Microwave Symp.*, Seattle, WA, 2–7 June 2013.

[3]([23]) V.Rizzoli, G. Bichicchi, A. Costanzo, F. Donzelli, and D. Masotti, "CAD of multi-resonator rectenna for micro-power generation," in *Proc. Microwave Integrated Circuits Conference (EuMIC 2009)*, 28-29 Sept. 2009, pp.331–334.

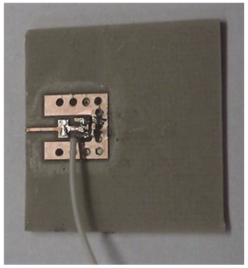
[21] R. Scheeler, S. Korhummel, Z. Popovic, "A Dual-Frequency Ultralow-Power Efficient 0.5-g Rectenna," Microwave Magazine, IEEE , vol.15, no.1, pp.109,114, Jan.-Feb. 2014

Rectenna Design and Optimization

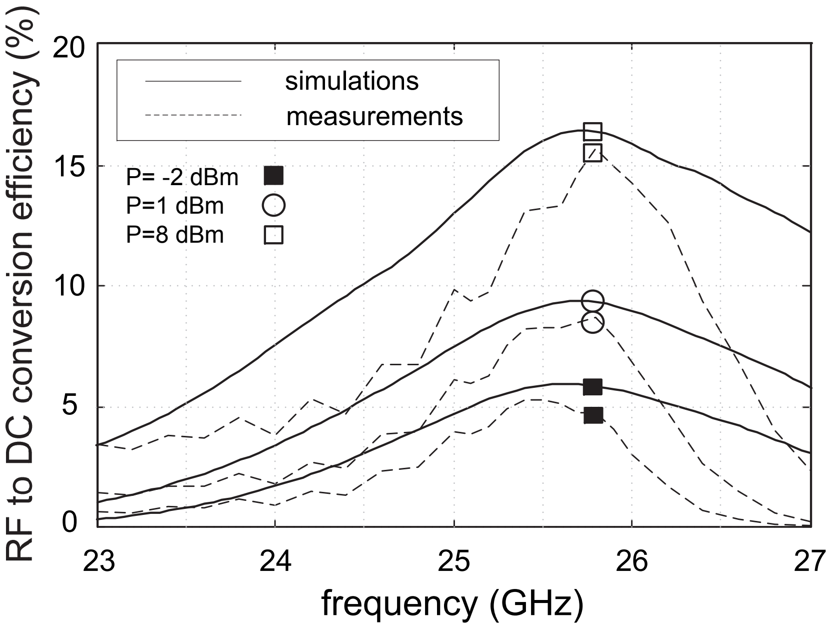
- SIW 24 GHz rectenna
- Compact rectenna inside substrate integrated cavity (SIW)

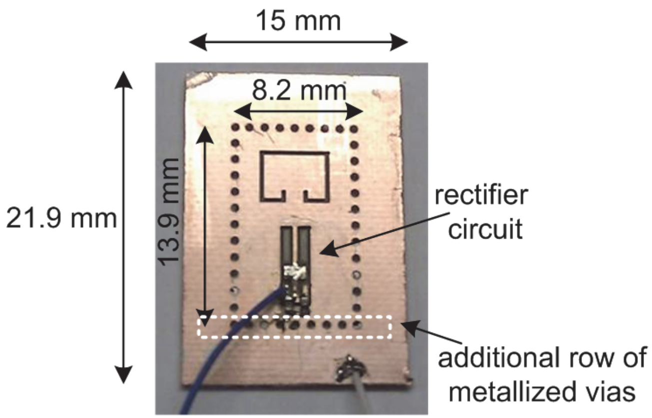


(a)



(b)

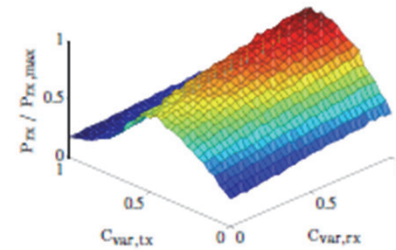




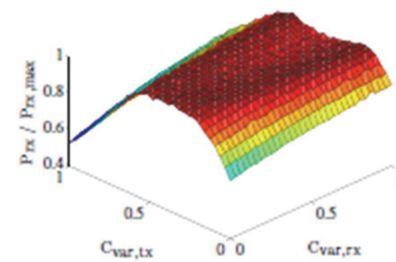
Rectenna Design and Optimization

- **Resonant magnetic transfer systems:**

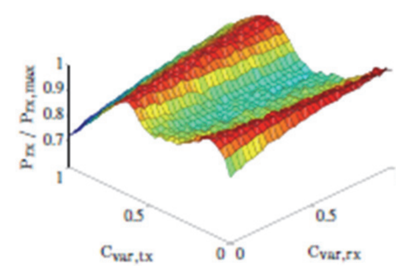
- RF-DC efficiency sensitive to misalignments and distance (due to power variation)
- Frequency splitting occurs at strong coupling conditions (short distance)
- Reconfigurable and/or adaptively tuned systems allow re-tuning resonance to maximum efficiency at the expense of additional complexity



(a) Weak coupling.



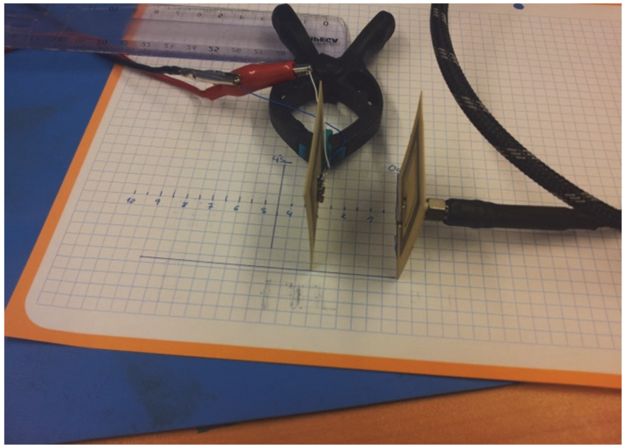
(b) Critical coupling.

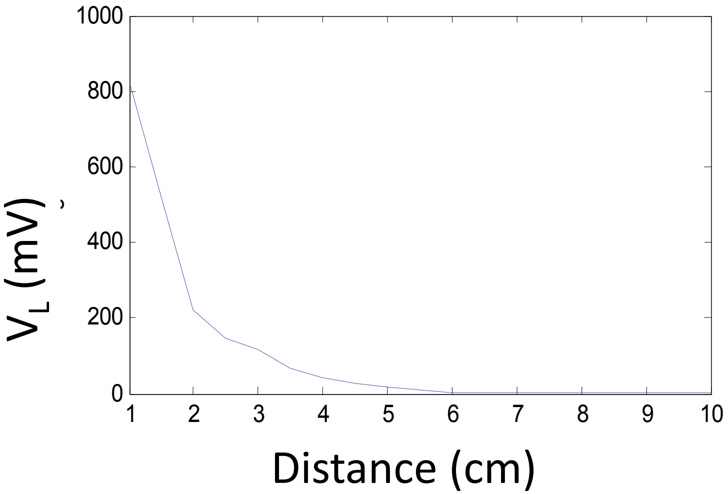


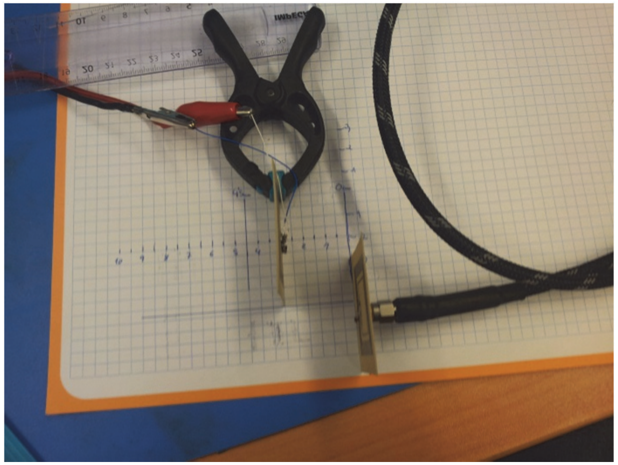
(c) Strong coupling.

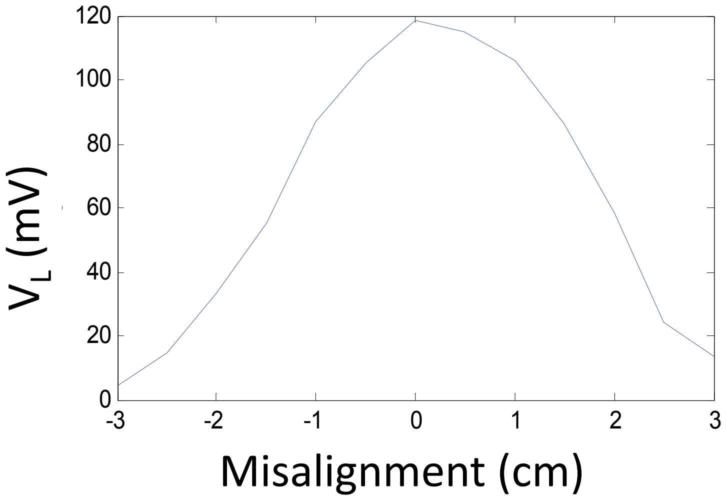
Rectenna Design and Optimization

- Near-field magnetic resonance wireless power transfer

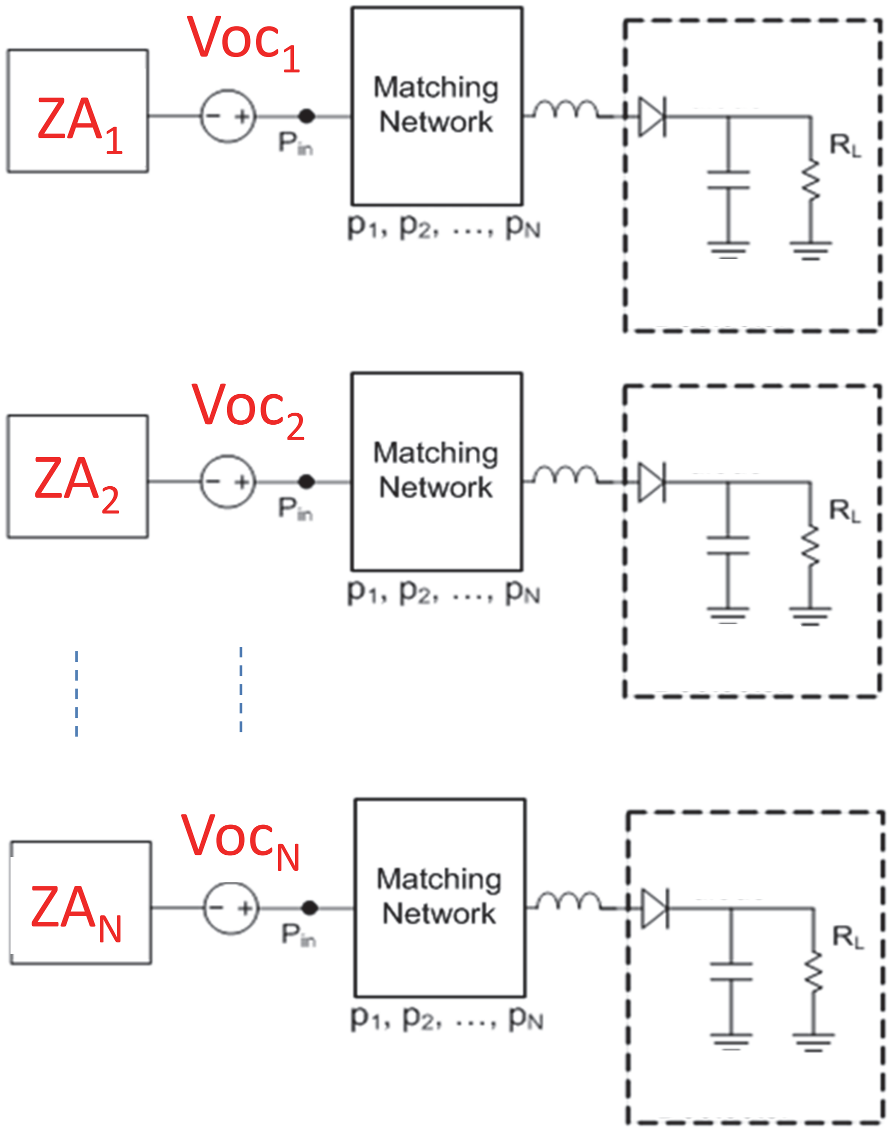








Rectenna Design and Optimization



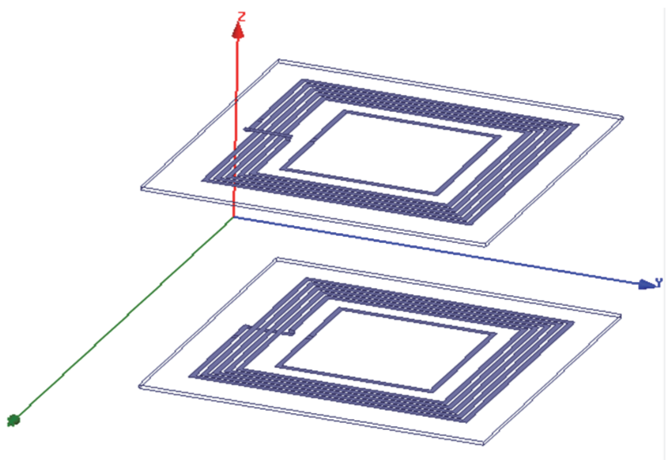
Jointly optimize multiple copies of the rectifier circuit,

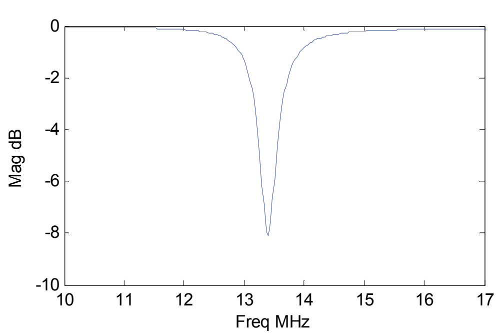
....from a set of desired TX-RX scenarios

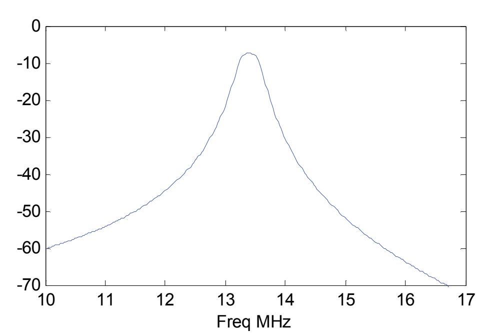
....corresponding to misalignments, varying orientation and / or distance

Rectenna Design and Optimization

- **Simulate desired set of TX-RX scenarios:**
- S-parameter simulation using 2 identical coils for different distance and misalignment (displacement and angular) conditions

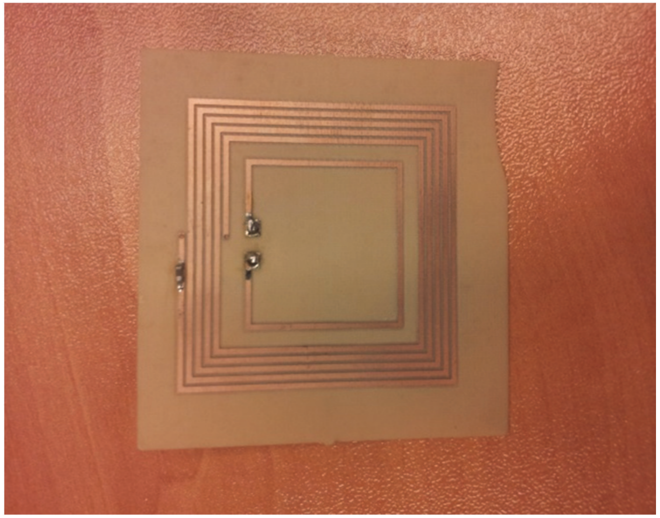




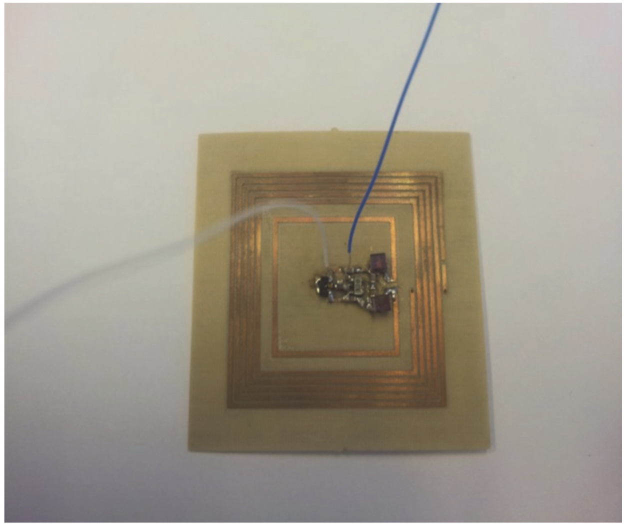


Rectenna Design and Optimization

- Prototype fabrication using Arlon A25N substrate 0.5mm thickness, er = 3.38, tand = 0.0025
  Trace thickness 0.7 mm, trace distance 0.4 mm



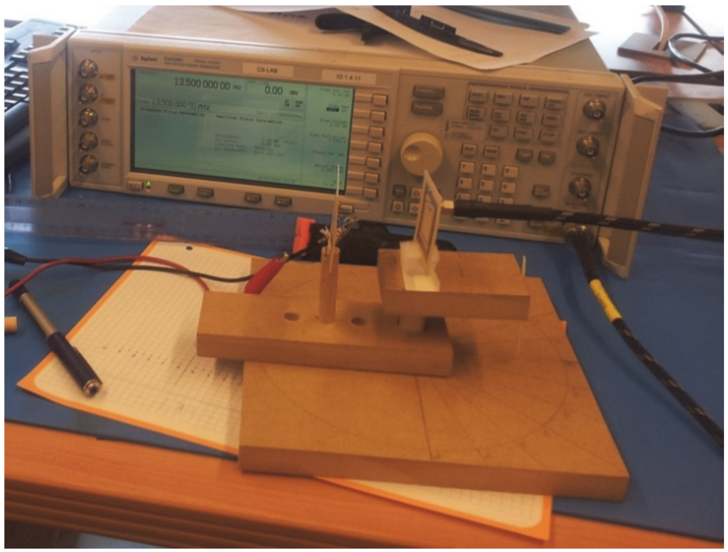
TX coil
(w/ resonating capacitor)

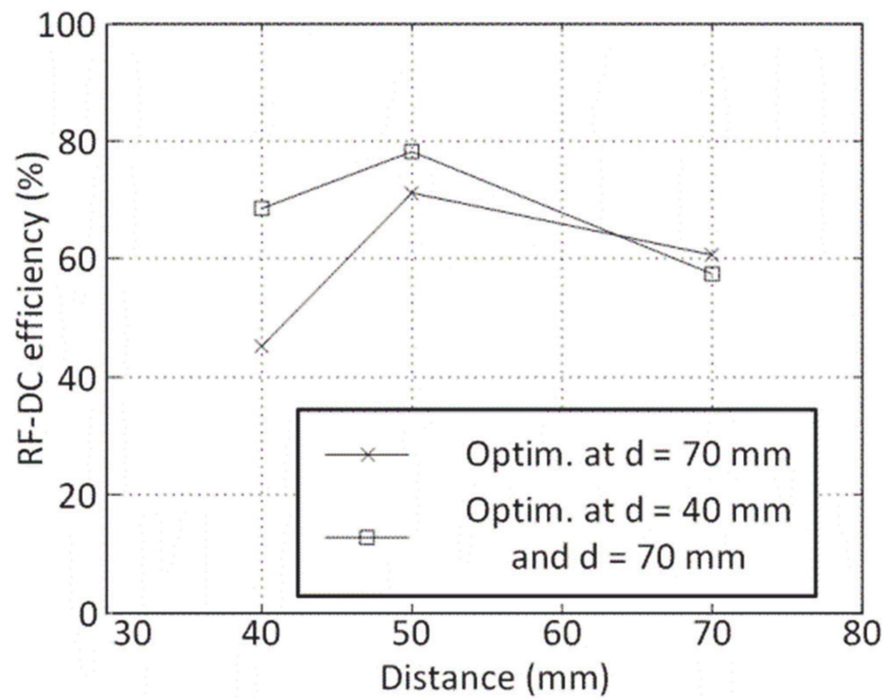


RX coil
(w/ rectifier)

Rectenna Design and Optimization

- Near-field magnetic resonance wireless power transfer



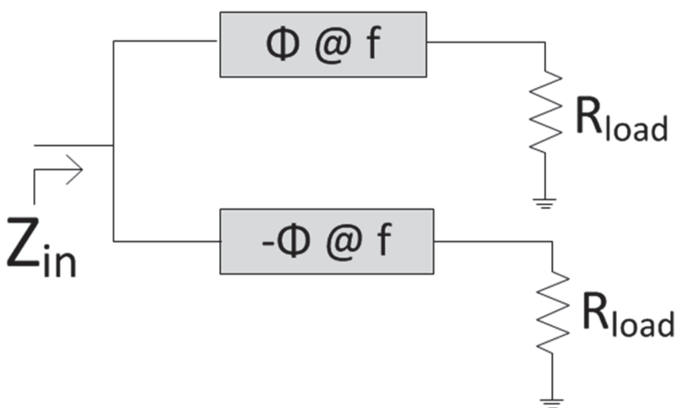


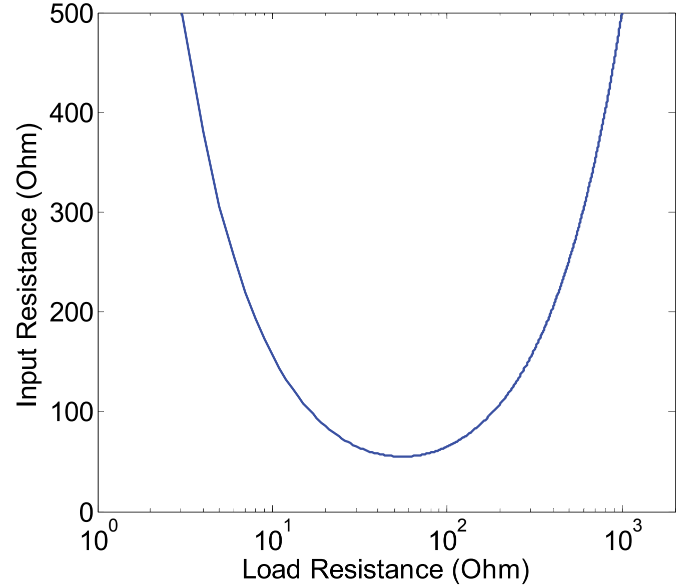
60.8 % RF-DC efficiency at d = 70 mm, drops to 45.1 % at 40 mm distance.

When the system is optimized simultaneously at d = 40 mm and d = 70 mm:
57.4 % RF-DC efficiency at d = 70 mm and 68.6 % at d = 40 mm

Rectenna Design and Optimization

- Challenge: load and input power variation
- Resistance compression networks





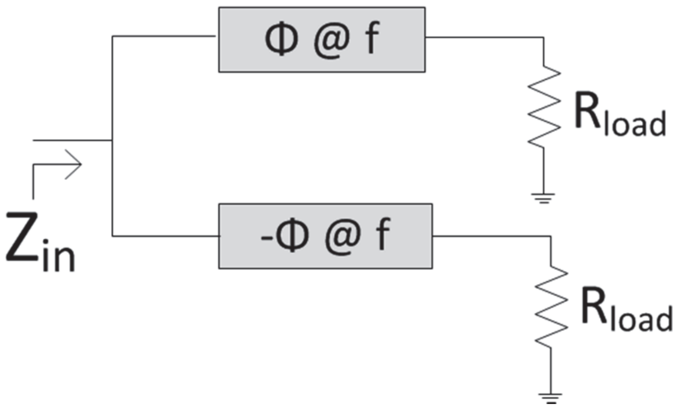
Load resistance variation: 3 Ohm – 1000 Ohm

Input resistance variation: 55 Ohm – 500 Ohm

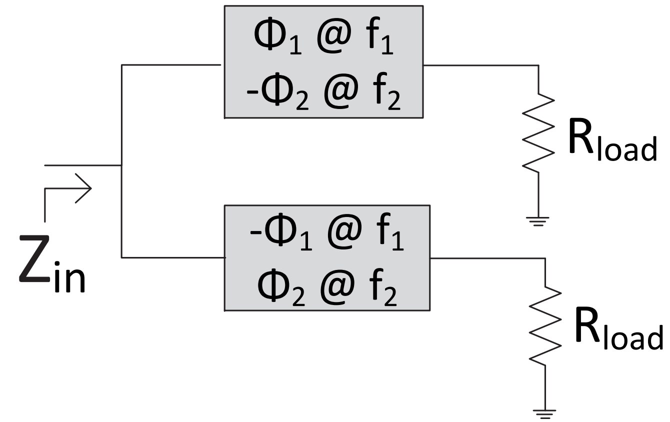
Y. Han, O. Leitermann, D.A. Jackson, J.M. Rivas, and D.J. Perreault, “Resistance Compression Networks for Radio-Frequency Power Conversion, ” *IEEE Trans. on Power Electronics*, vol. 22, no. 1, pp. 41-53, Jan. 2007.

Rectenna Design and Optimization

- Resistance Compression Networks
  - Identical R_{load} variation
  - Opposite phase response

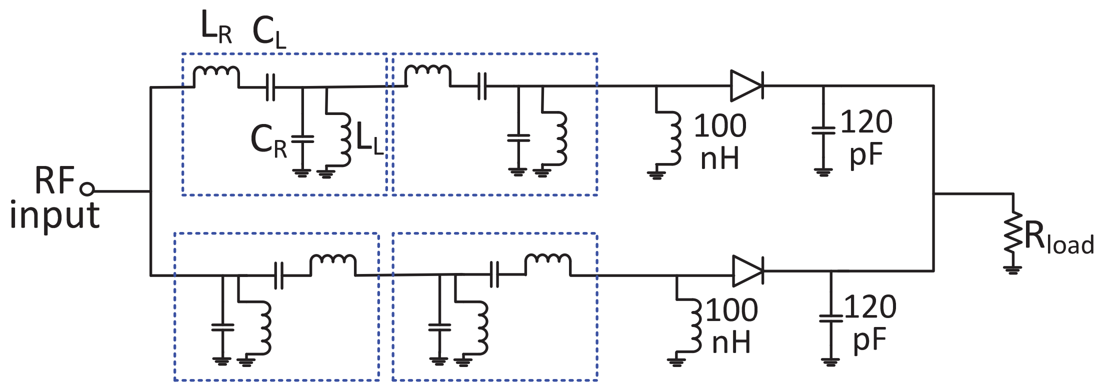


RCN operating at single frequency

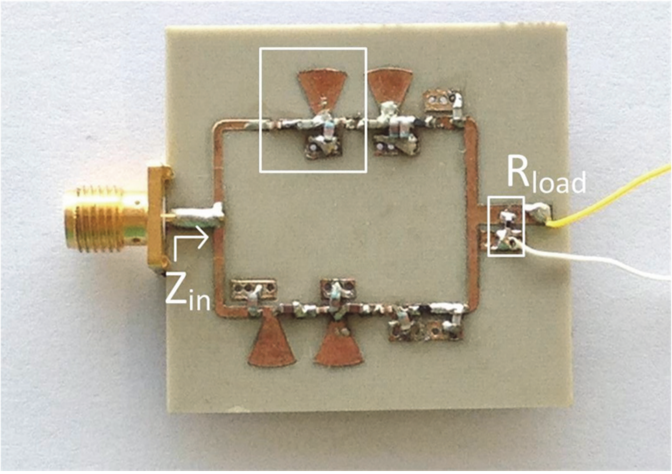


Dual-Band RCN

Rectenna Design and Optimization



L_R	8.7 nH
L_L	100 nH
C_R	0.8 pF
C_L	2.7 pF

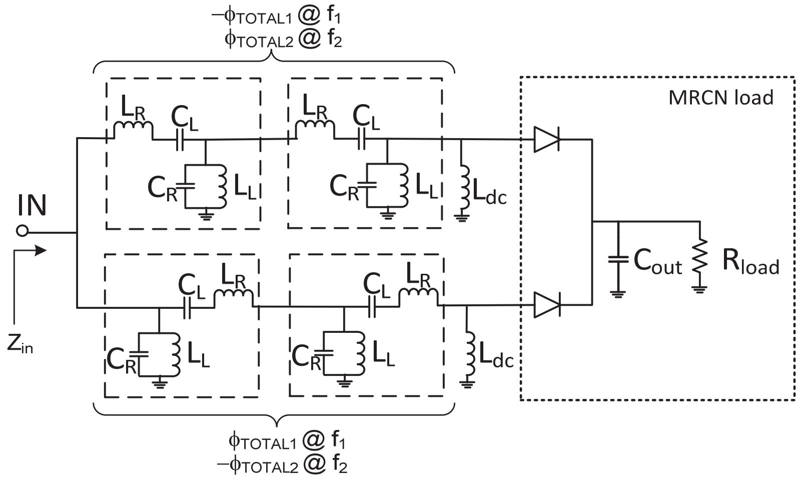


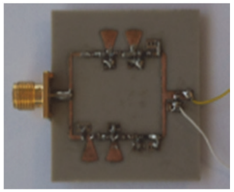
- Schottky diode
  - SMS7630
- Arlon 25N
  - 30 mil
  - $\varepsilon_r = 3.38$

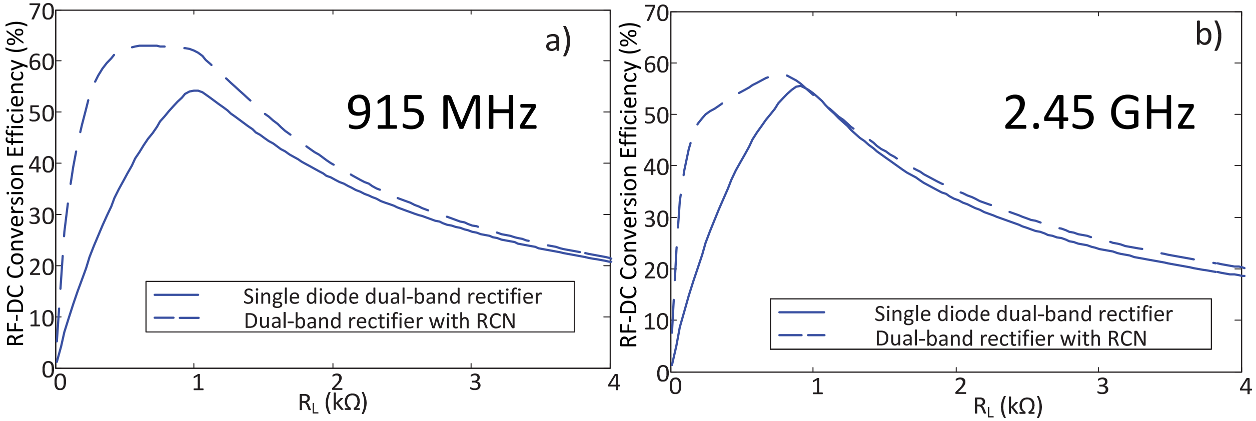
K. Niotaki. A. Georgiadis, A. Collado, 'Dual-Band Resistance Compression Networks for Improved Rectifier Performance,' IEEE Transactions on Microwave Theory and Techniques, accepted for publication, Dec. 2014.

Rectenna Design and Optimization

- Dual band resistance compression network.







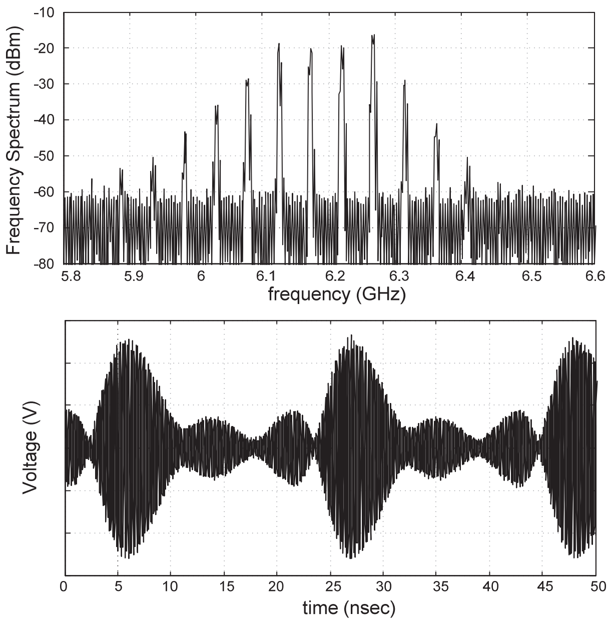
Signal Optimization

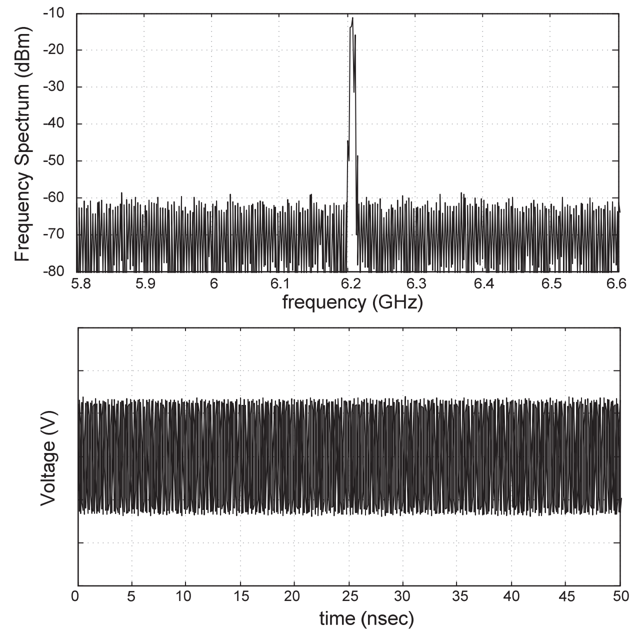
- Signals with time-varying envelope (peak-to-average power ratio PAPR > 0 dB) lead to higher rectifier RF-DC conversion efficiency

  - Multi-sines
  - Chaotic signals
  - White noise
  - Random modulation (multi-carrier)

Signal Optimization

- Comparison of obtained DC voltage by a rectifier when using:
  - generated mode-locked signal with high PAPR
  - single carrier signal
- Same average power for both signals

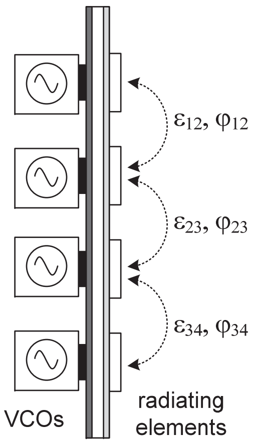


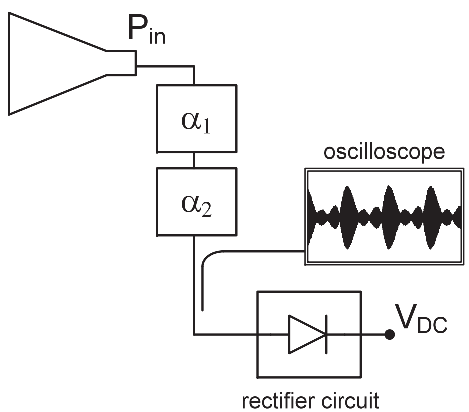


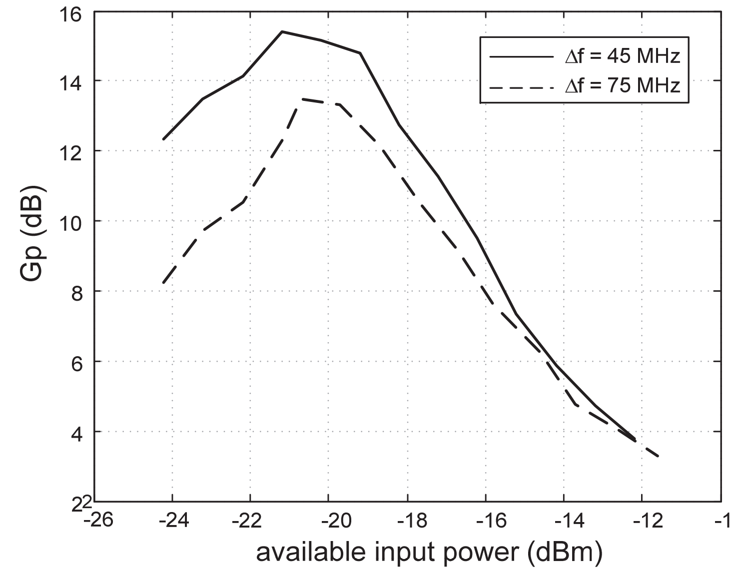
Signal Optimization

- Power gain compares the obtained DC voltage by a rectifier when using the high PAPR signal in comparison with a one-tone signal
- Improved performance when using the high PAPR mode-locked signal

$$G_{P1}(dB) = 10 \cdot log10\left(\frac{P_{DC\,(N)}}{P_{DC\,(1)}}\right) = 10 \cdot log10\left(\frac{V_{DC\,(N)}^2}{V_{DC\,(1)}^2}\right)$$

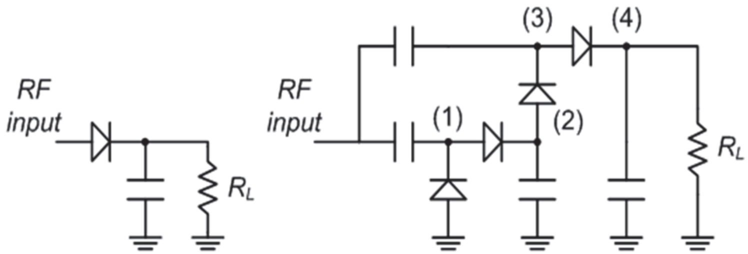






Signal Waveform Design for Improved Efficiency

- Rectifier circuits: envelope detector, charge pump circuits
- Schottky diodes, low / zero barrier diodes



- Schottky diode model approximated by a polynomial series expansion

$$I_D = I_S\left(e^{\frac{V_b}{nV_t}} - 1\right) \Rightarrow y(t) = \sum_{n=0}^{N} k_n \cdot x(t)^n \Rightarrow y(t) = k_2 x(t)^2 + k_4 x(t)^4$$

Signal Waveform Design for Improved Efficiency

- Single tone excitation of the diode

$$x(t) = A\cos(\omega_1 t + \varphi_1) \qquad y_{DC} = \frac{A^2 k_2}{2} + \frac{3A^4 k_4}{8}$$

- Multi-tone excitation
  DC output depends on the phase distribution

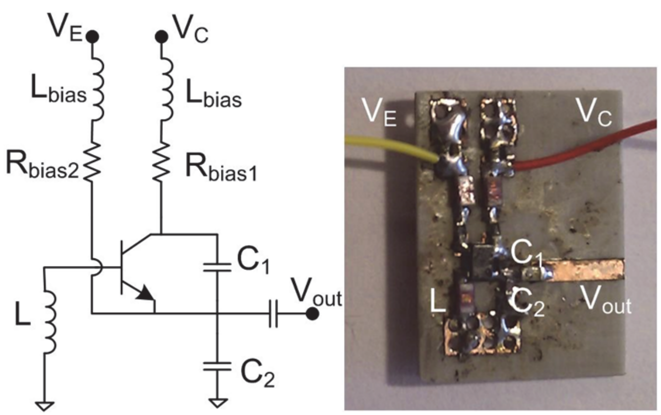
$$x(t) = A\cos(\omega_1 t + \varphi_1) + A\cos(\omega_2 t + \varphi_2) + A\cos(\omega_3 t + \varphi_3) + A\cos(\omega_4 t + \varphi_4)$$

$$y_{DC} = \frac{4A^2 k_2}{2} + \frac{21A^4 k_4}{2} + \frac{3A^4 k_4}{2}\cos(2\varphi_3 - \varphi_2 - \varphi_4) + \frac{3A^4 k_4}{2}\cos(-2\varphi_2 + \varphi_1 + \varphi_3) + 3A^4 k_4 \cos(\varphi_1 - \varphi_2 - \varphi_3 + \varphi_4)$$

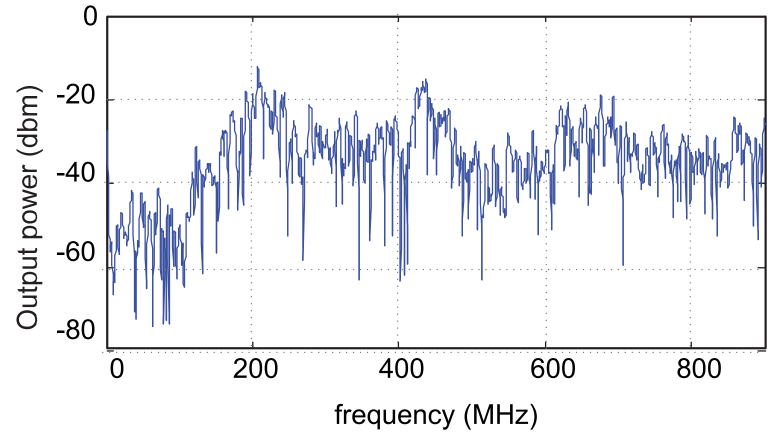
A.S. Boaventura and N. B. Carvalho, “Maximizing dc power in energy harvesting circuits using multi-sine excitation,” in IEEE MTT-S Int. Dig. , Jun. 5–10, 2011.
C. R. Valenta and G. D. Durgin, “Rectenna performance under power-optimized waveform excitation,” in Proc. IEEE Int. Conf. RFID (RFID) , Apr. 30–May 2 2013, pp. 237–244.

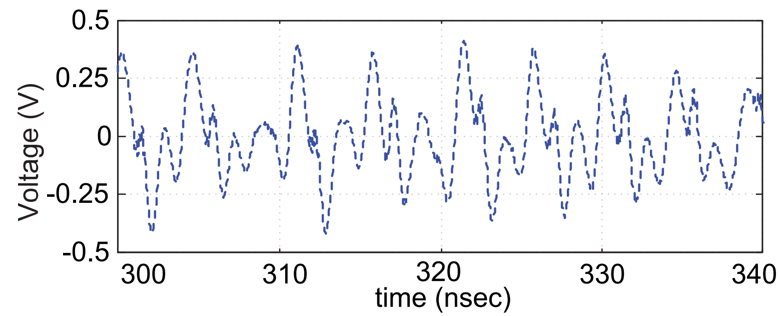
Signal Optimization

- First experiments: chaotic oscillator
  - Colpitts based chaotic generator
  - Bipolar transistor BFP183w



433 MHz chaotic generator





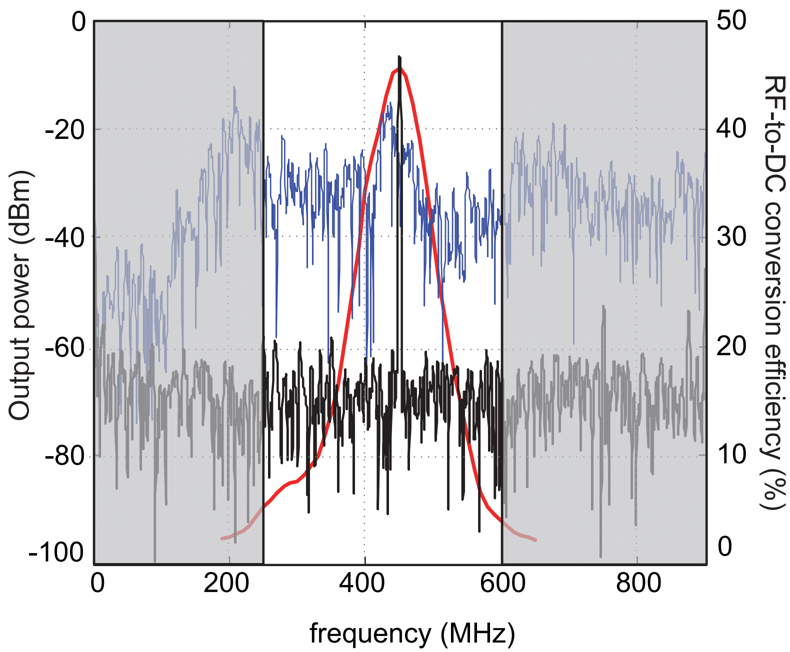
Signal Optimization

- Need to filter chaotic signal

Chaotic signal power
[250 MHz – 600 MHz]

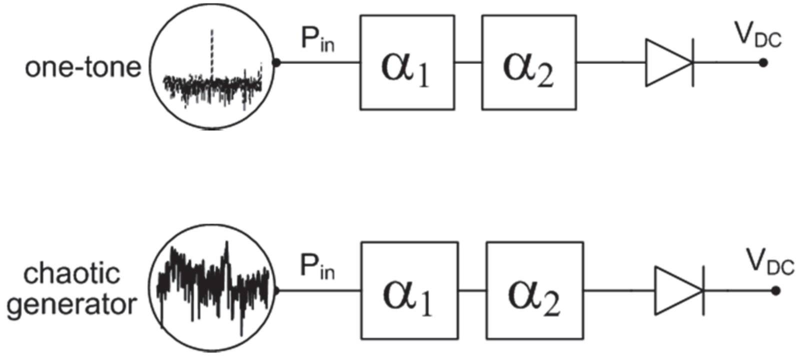
-6.5 dBm

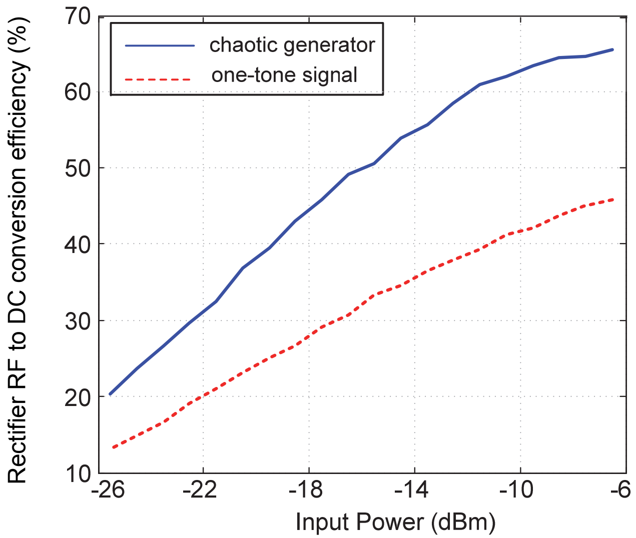
CW signal power
[250 MHz – 600 MHz]

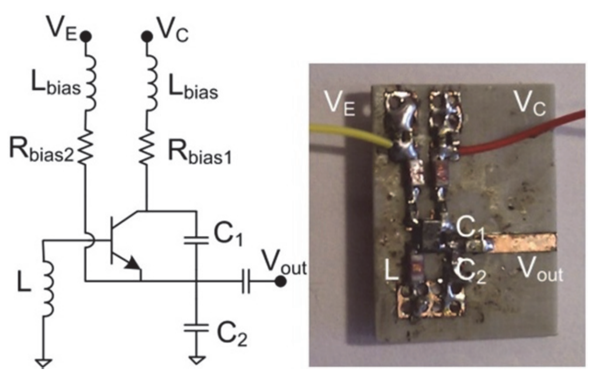


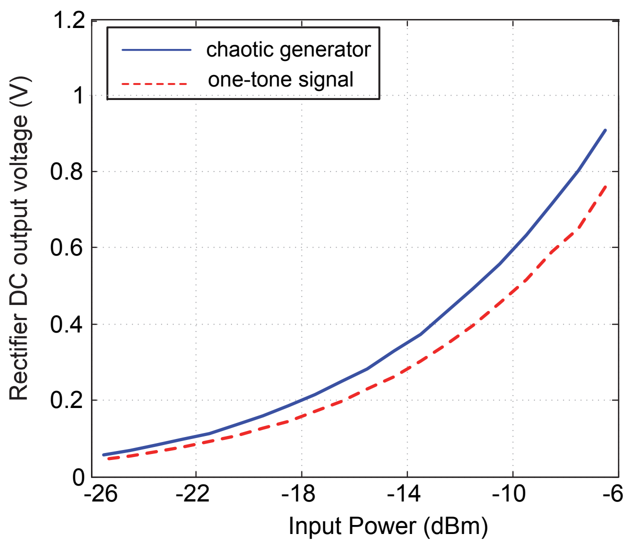
- Total power of 1-tone signal selected to be equal to the chaotic signal total power in the bandwidth of the rectifier

Signal Optimization





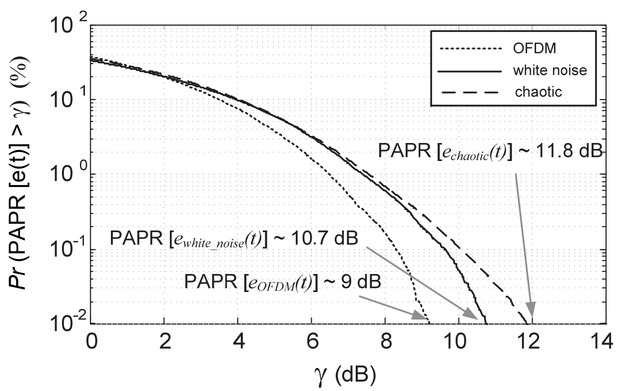


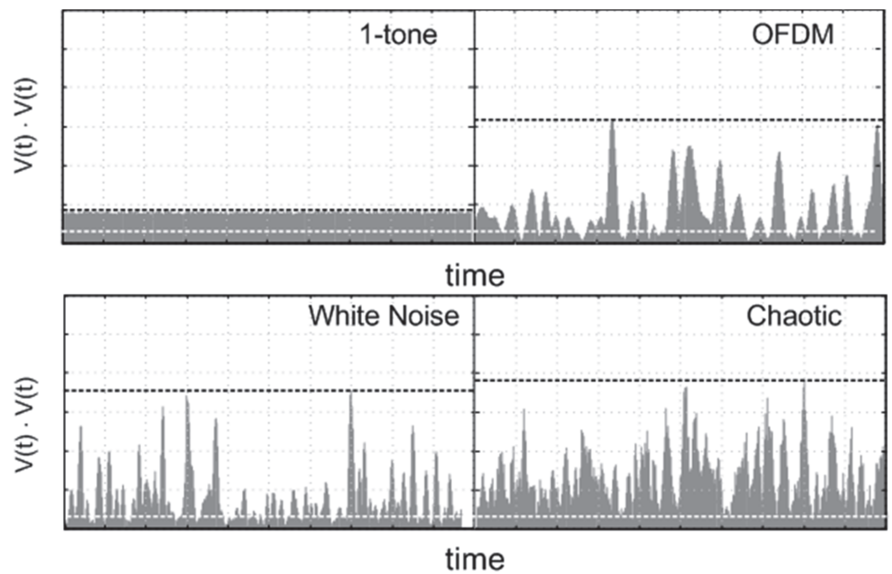


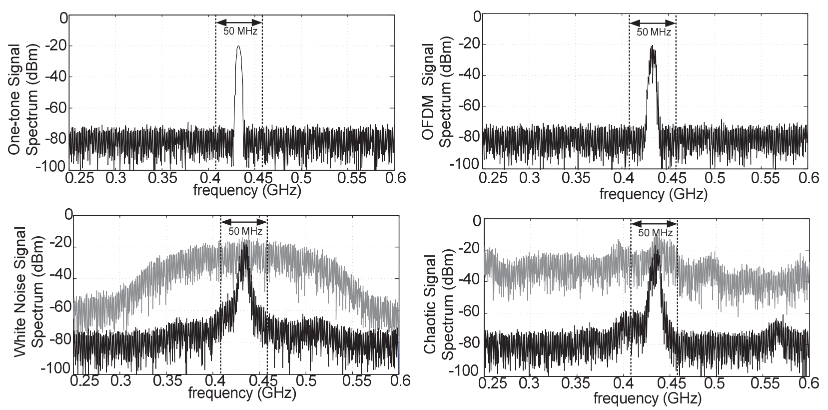
Signal Optimization

Signal	PAPR (dB)
1-tone	3
OFDM	12
White noise	13.7
Chaotic	14.8

PAPR[x(t)] ~ PAPR[e(t)] + 3 dB

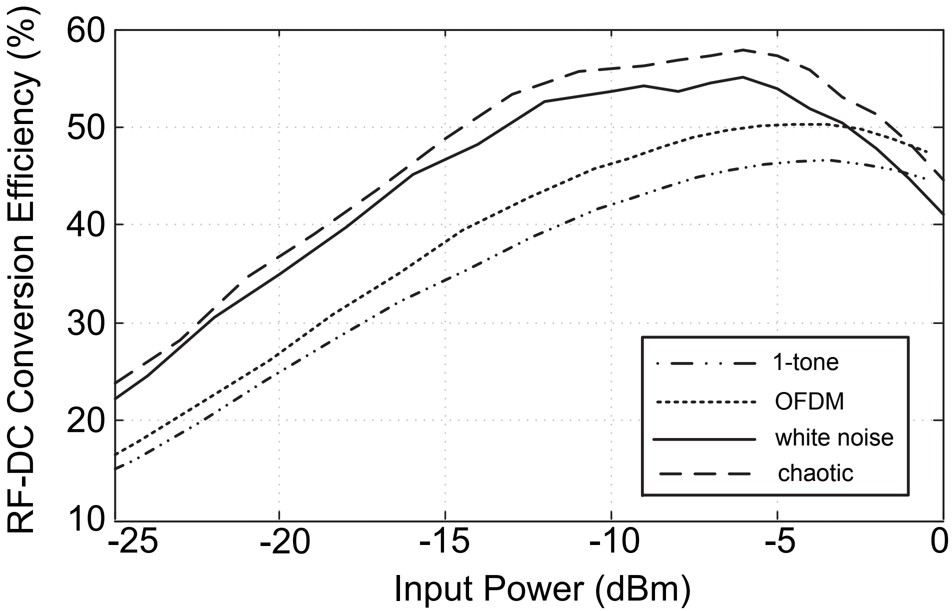






Signal Optimization

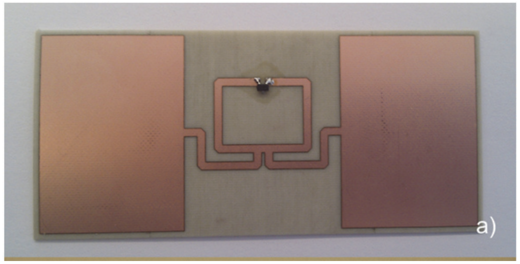
- Rectifier operates at 433 MHz
- Skyworks SMS7630-02LF diode
- Output load of 5.6 KOhm

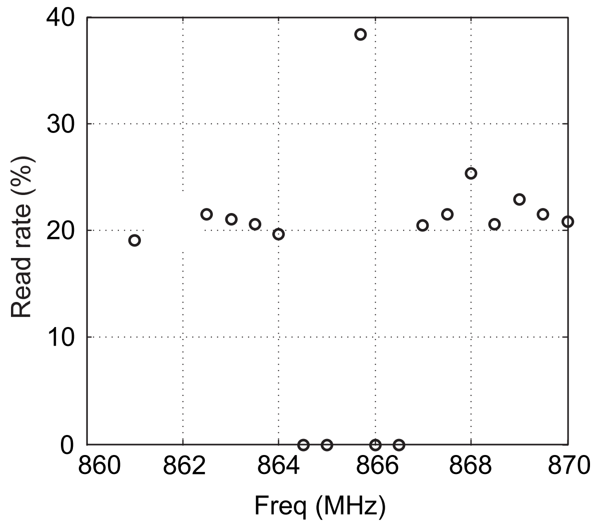


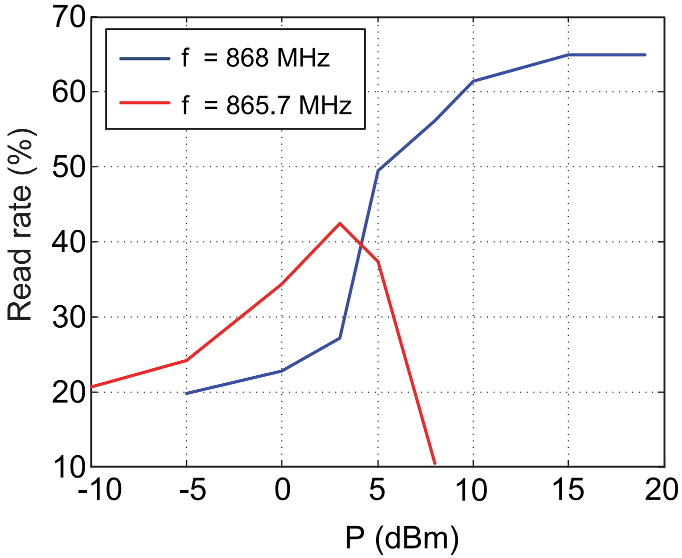
A. Collado, A. Georgiadis, 'Optimal Waveforms for Efficient Wireless Power Transmission,' IEEE Microwave and Wireless Components Letters, vol. 24, no. 5, pp. 354-356, May 2014.

Energy Harvesting Assisted RFID and WSN

- RFID tag and wireless power transmission
- Using Impinj reader
  and RF signal generator
  - Read rate improvement
  - Saturation

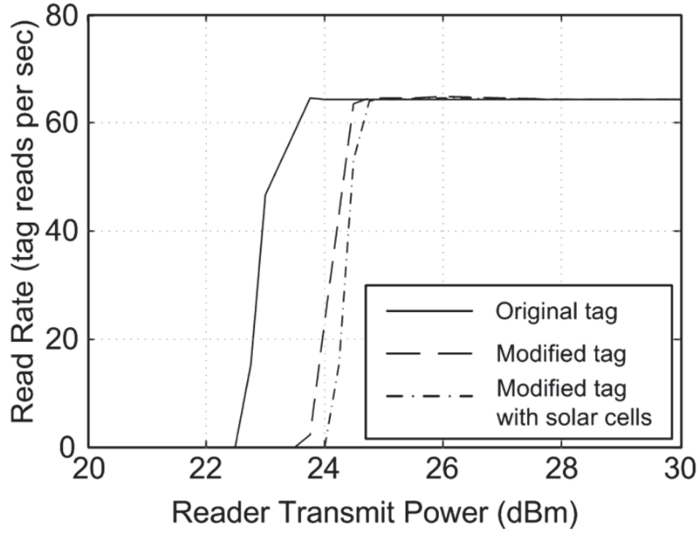


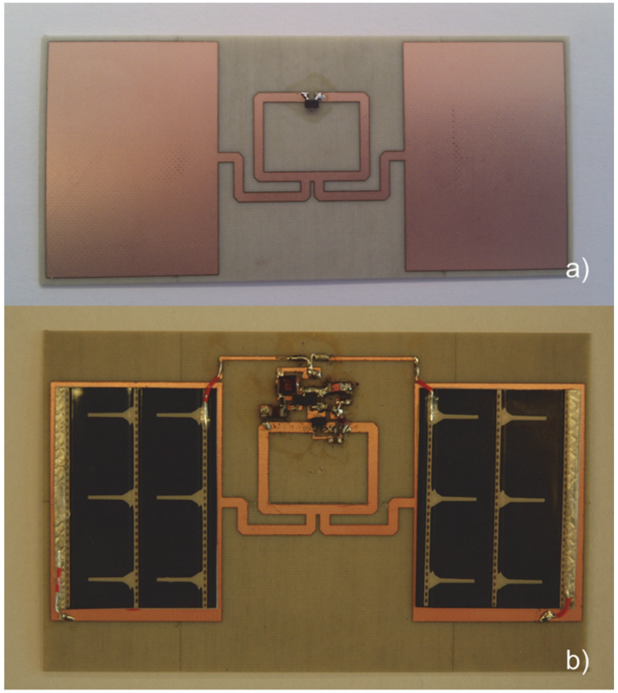




Energy Harvesting Assisted RFID and WSN

- Solar tag with high efficiency
  DC-to-RF converter: Class-E oscillator

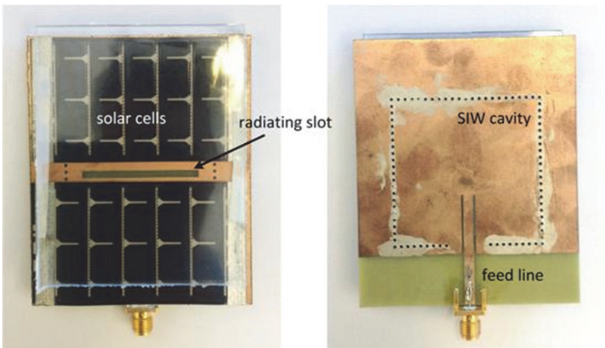


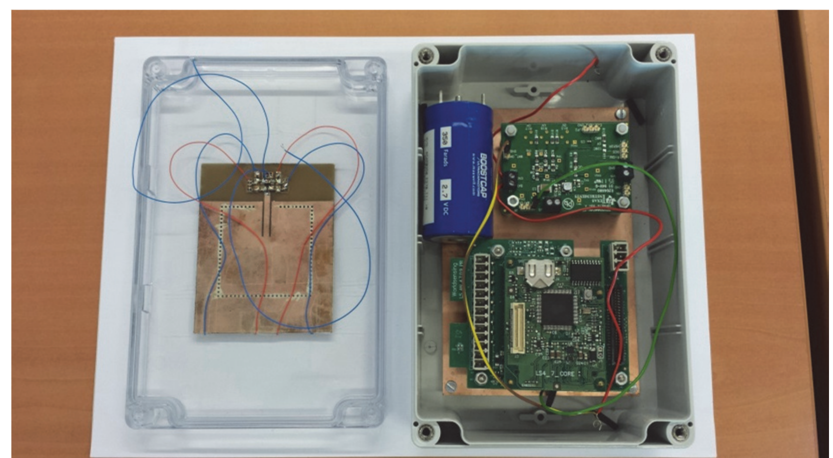


Georgiadis, A.; Collado, A., "Improving range of passive RFID tags utilizing energy harvesting and high efficiency class-E oscillators," *Antennas and Propagation (EUCAP), 2012 6th European Conference on* , vol., no., pp.3455,3458, 26-30 March 2012

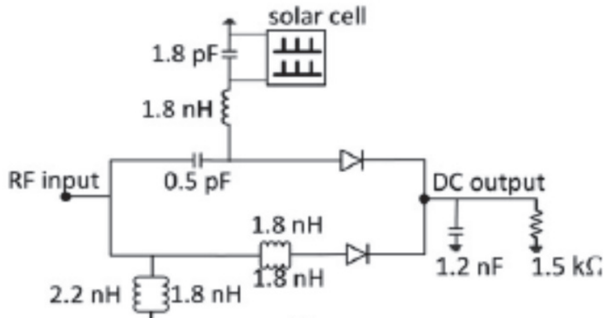
Energy Harvesting Assisted RFID and WSN

- Solar powered data logger (SWAP project)

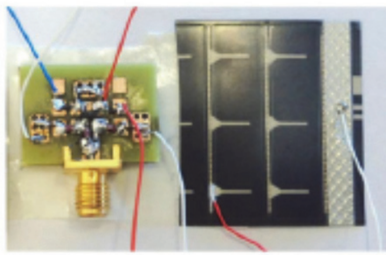




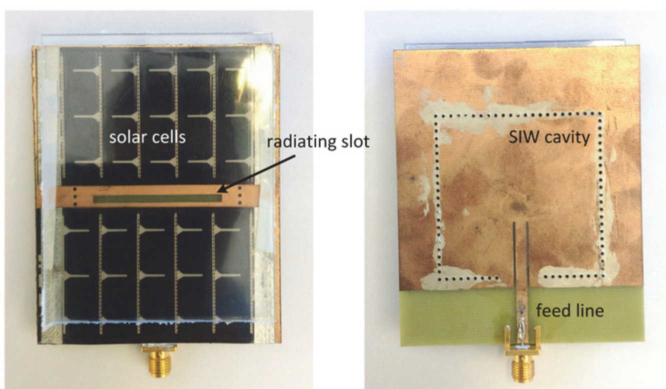
Energy Harvesting Assisted RFID and WSN

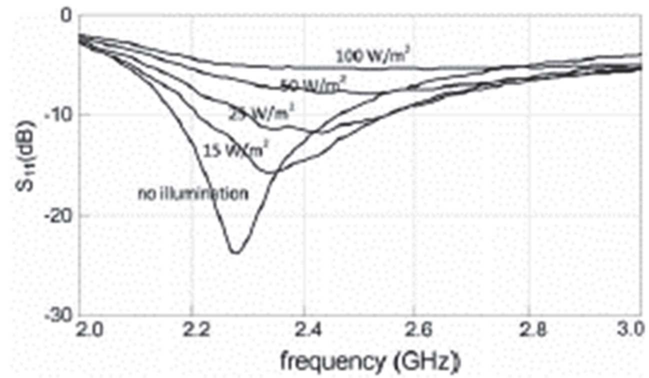


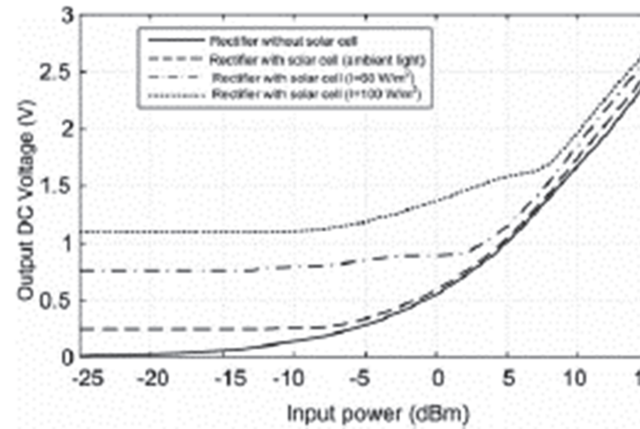
(a)



(b)

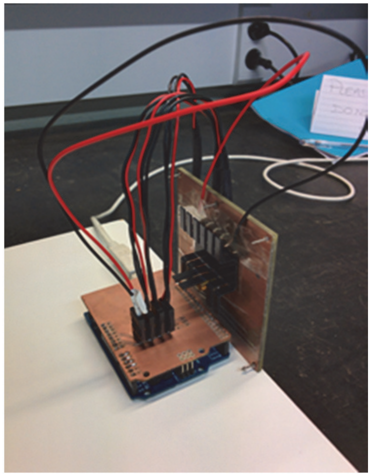


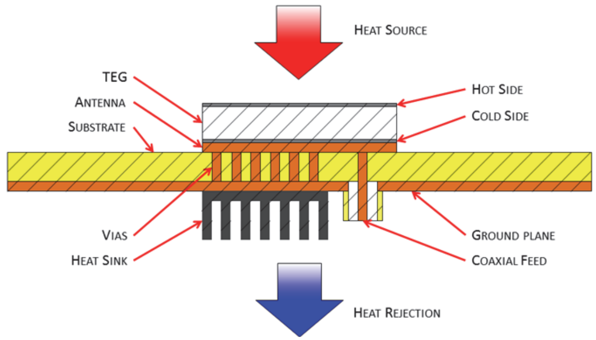


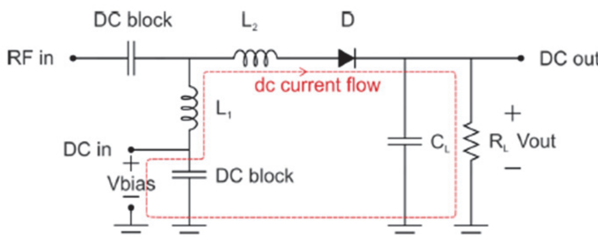


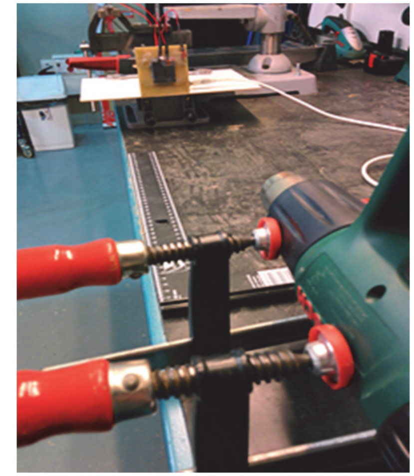
K. Niotaki, F. Giuppi, A. Georgiadis and A. Collado. Solar/EM energy harvester for autonomous operation of a monitoring sensor platform . Wireless Power Transfer, vol. 1, no. 1, pp. 44-50, Mar 2014.

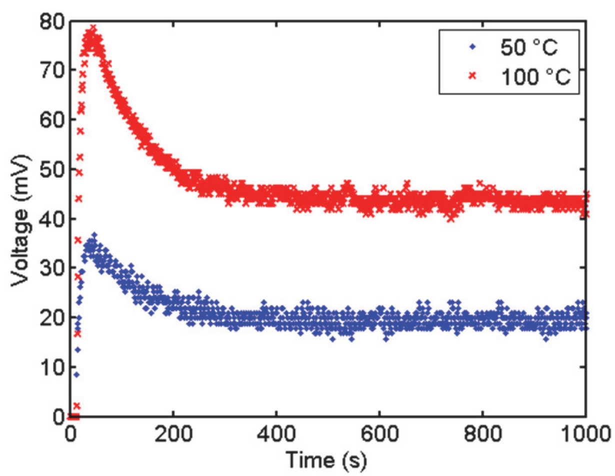
Energy Harvesting Assisted RFID and WSN

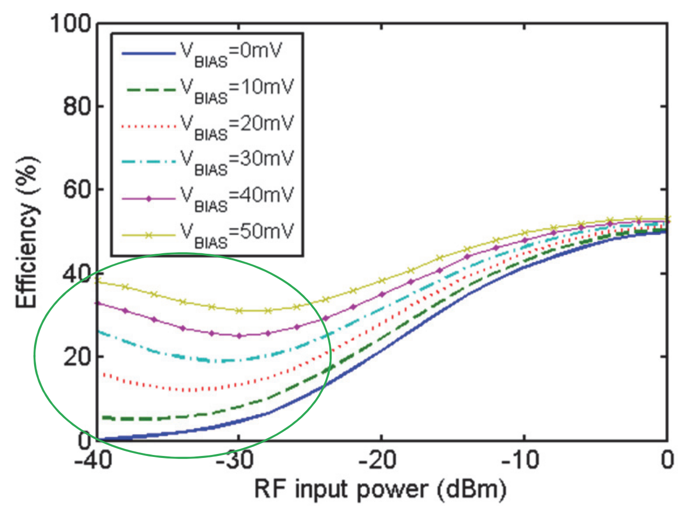












Thank you for your attention !

Questions

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