Signal Optimization and Rectenna Design for Electromagnetic Energy Harvesting and Wireless Power Transfer

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Outline

- Introduction
- Rectenna design
  - Dual band
  - Load independent performance
- Signal design
  - Multi-sine
  - Chaotic
  - Mode locked oscillators
- Conclusion

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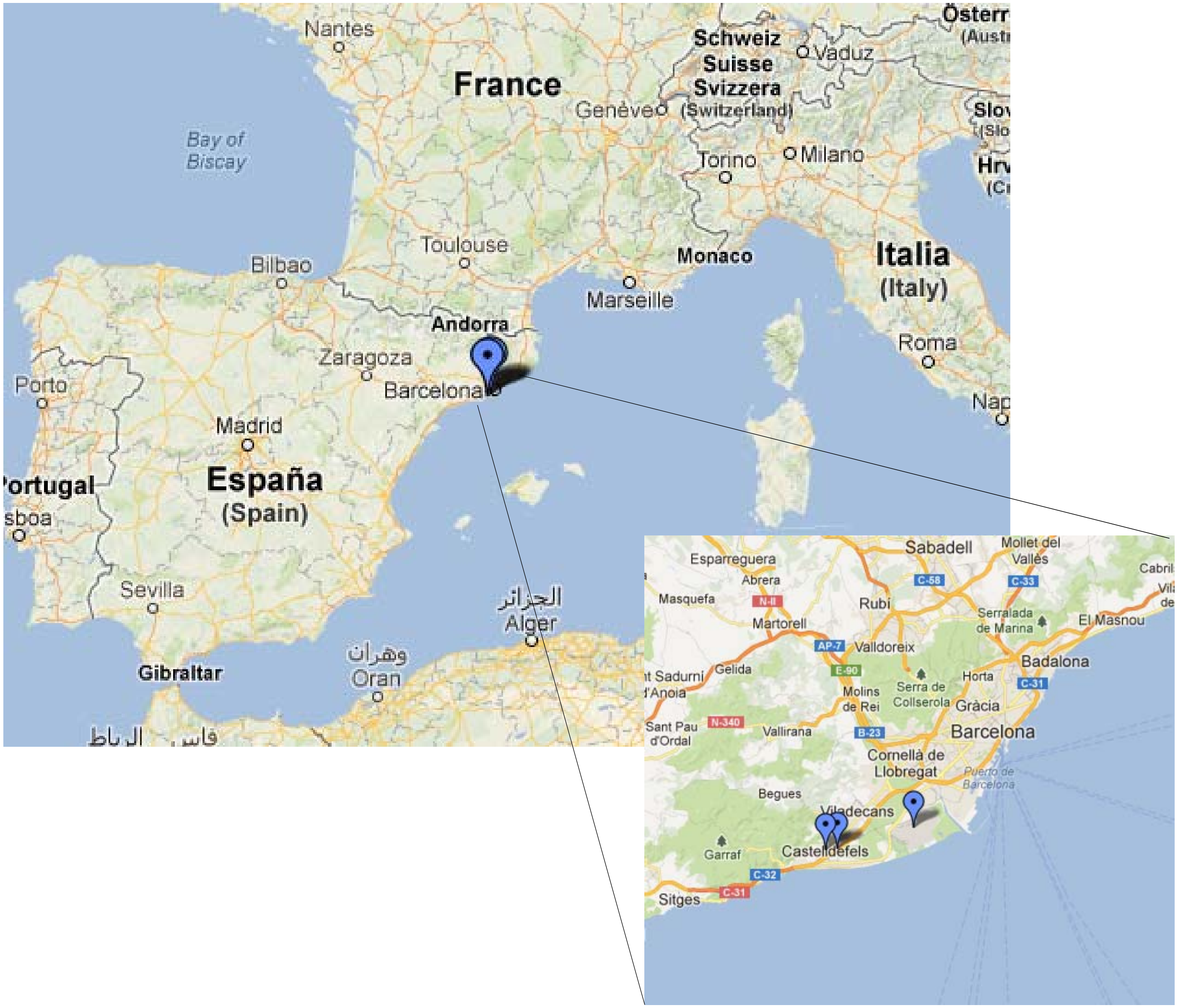
Founded in 2001



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- Research staff: 35 Ph.D., 20 M.Sc, 3500-m^2 building
- 3 Research Divisions: Comm. Systems, Comm. Networks, Comm. Technologies
- ***Department of Microwave Systems and Nanotechnology***

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Active microwave circuit design

- **Energy Harvesting and RFID**
- Oscillator design including integrated CMOS oscillators (Fig. 1)
- Active antennas, phased arrays (Fig. 2), retro-directive arrays (Fig. 3)
- Substrate Integrated Waveguide (SIW) (Fig. 4)
- Efficient Power Amplifier (Fig. 5)

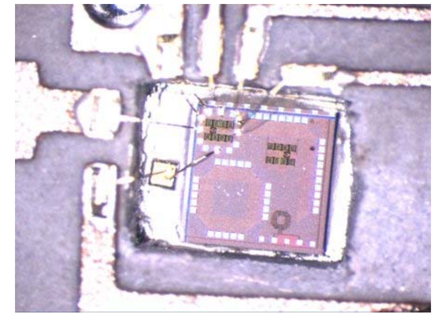

Fig. 1. CMOS VCO for UWB-FM

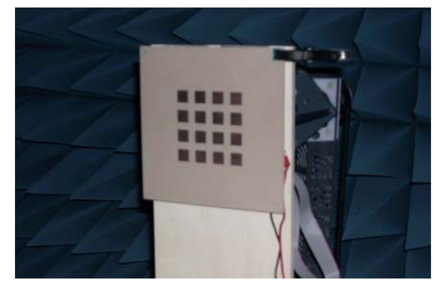

Fig. 2. C-band Coupled Oscillator Reflectrarray prototype

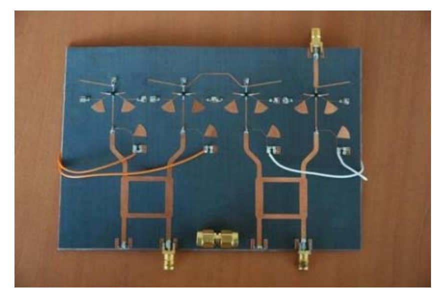

Fig. 3. S-band retro-directive array.

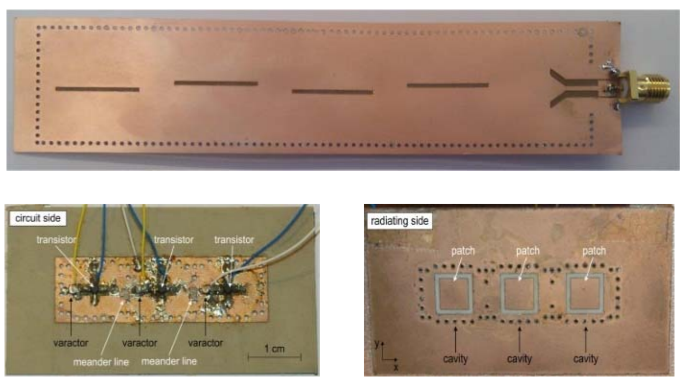

Fig. 4. SIW circuits.

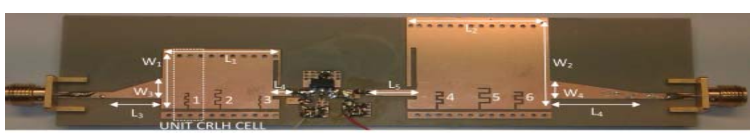

Fig. 5. Power Amplifier (SIW).

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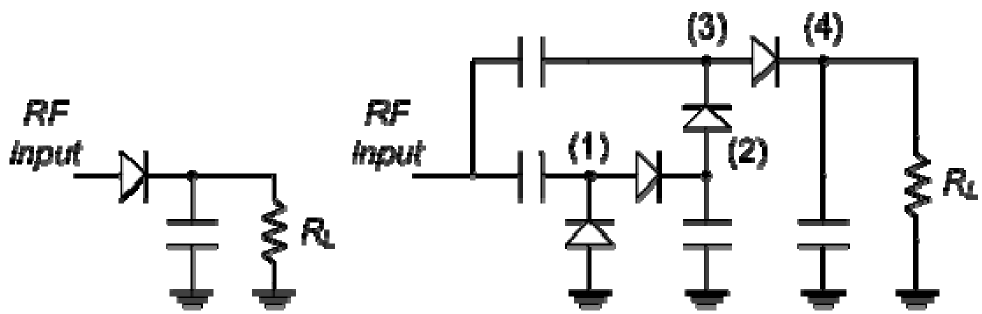
Rectenna Design

- 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 uW are near 20%, and increase to >50% for available power levels of 100uW.

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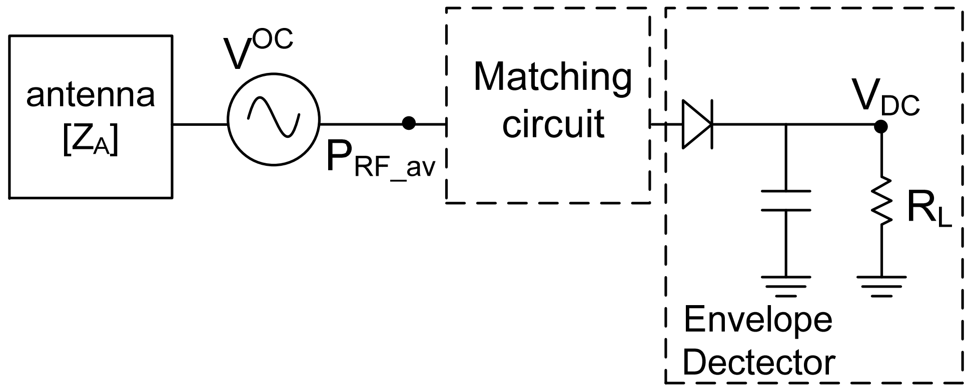
Rectenna Design

- Rectenna optimization using the RECEIVE antenna Thevenin (or Norton) equivalent circuit



- Multiple goal harmonic balance for optimizing the RF-DC conversion efficiency

$$\eta = \frac{P_{DC}}{P_{RF,av}} = \frac{V_{DC}^2}{P_{RF,av} R_L}$$

Georgiadis, A.; Andia Vera, G.; Collado, A., "Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (EM) energy harvesting," *Antennas and Wireless Propagation Letters, IEEE* , vol.9, no., pp.444,446, 2010

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Rectenna Design

- Open circuit voltage maybe calculated using reciprocity theory

$$\eta = \frac{P_{DC}}{P_{RF,av}} = \frac{V_{DC}^2}{P_{RF,av} R_L}$$

$$V_{V,H}^{oc}(\theta_o, \phi_o, S) = \frac{4\pi}{jk\eta_o} F_{V,H}(\theta_o, \phi_o) E_o$$

$$P_{av} = \frac{1}{4} V^{oc\,*} [Z_A + Z_A^*]^{-1} V^{oc}$$

$$E_o = \sqrt{2\eta_o S} \qquad \eta_o = 120\pi$$

- Harmonic balance for the optimization of the RF-DC conversion efficiency

Georgiadis, A.; Andia Vera, G.; Collado, A., "Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (EM) energy harvesting," *Antennas and Wireless Propagation Letters, IEEE* , vol.9, no., pp.444,446, 2010

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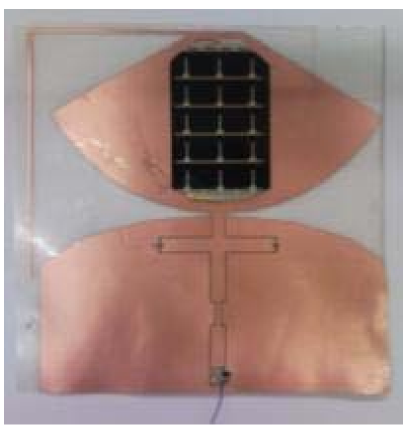
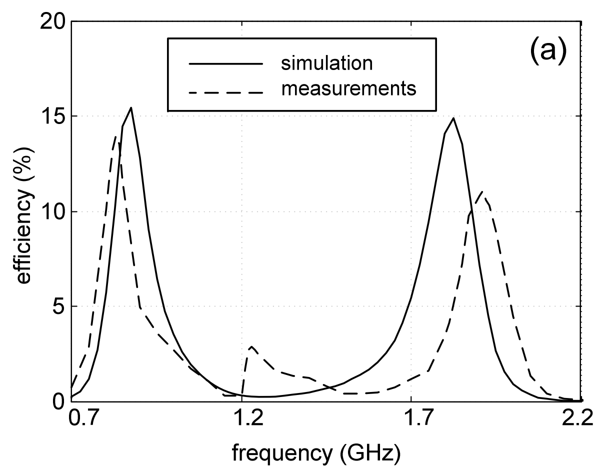
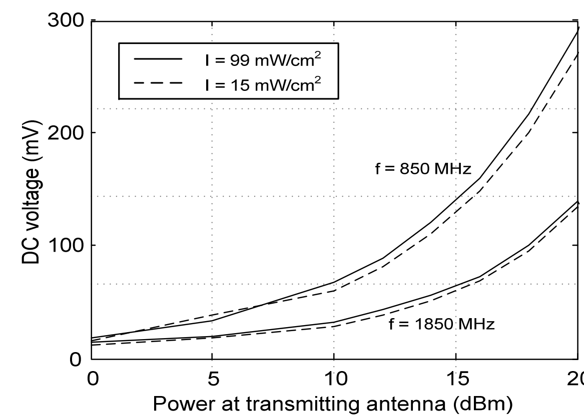
Rectenna Design

850 MHz/1850 MHz Dual Band Rectenna

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

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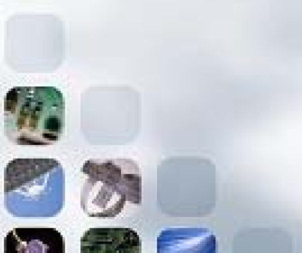
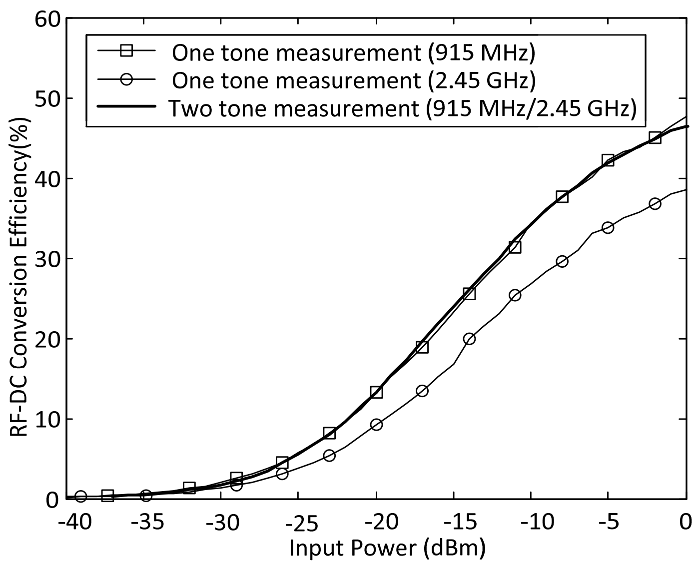


Rectenna Design

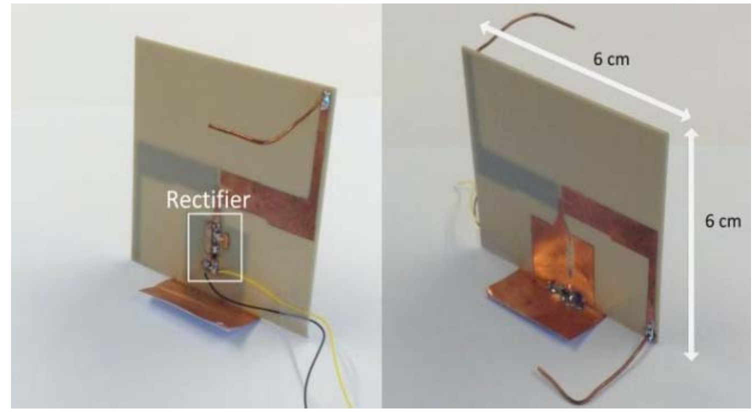
- Optimization goals are used to maximize the RF-DC conversion efficiency at 915 MHz and 2.45 GHz

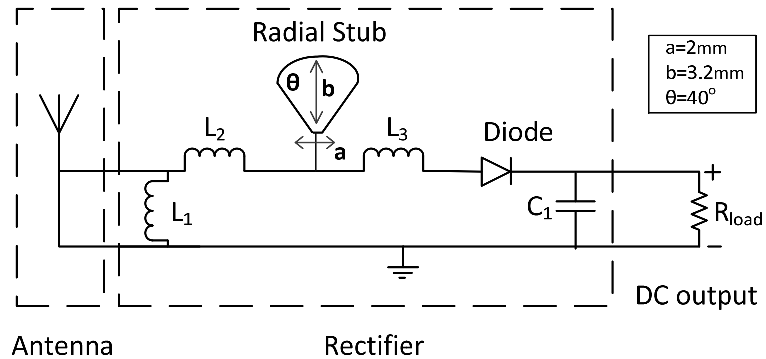
η = 48% and η = 39% at 915 MHz and 2.45 GHz, for P_{in}=0 dBm

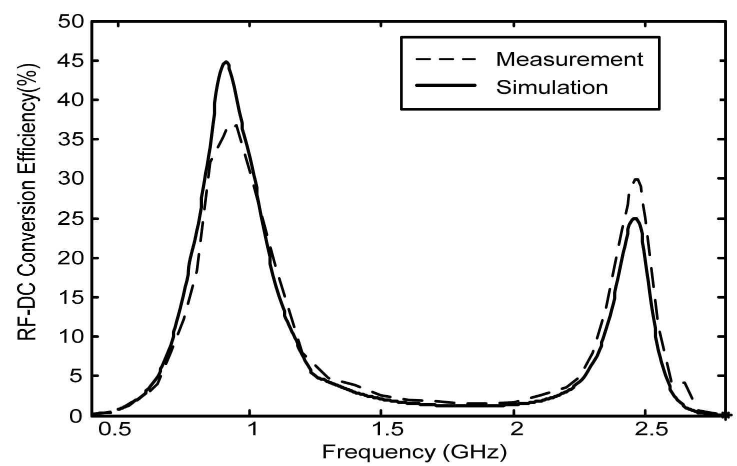
η <1 % for P_{in}<-33 dBm



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

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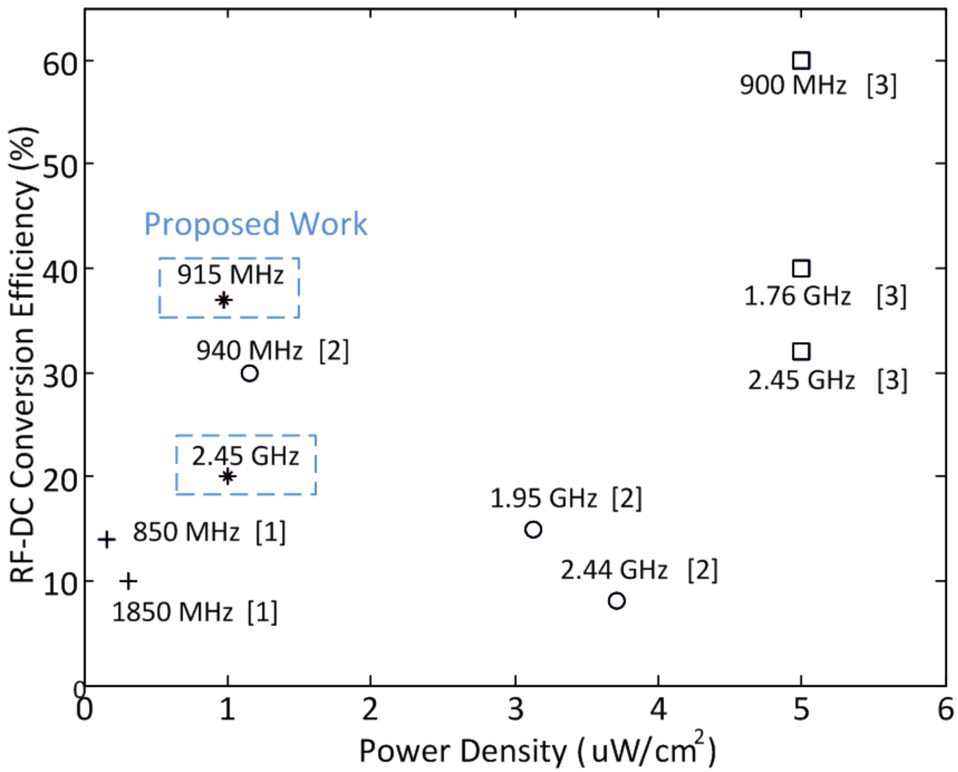


[1] A. Collado, and A. Georgiadis, "Conformal Hybrid Solar and Electromagnetic (EM) Energy Harvesting Rectenna," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 8, pp.2225,2234, Aug. 2013

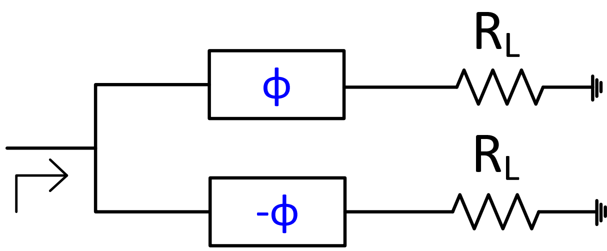
[2] B. L. Pham and A.-V. Pham, "Triple Bands Antenna and High Efficiency Rectifier Design for RF Energy Harvesting at 900, 1900 and 2400 MHz," in *Proc. IEEE MTT-S Int. Microwave Symp.*, Seattle, WA, 2–7 June 2013.

[3] 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.

- η = 37% and η = 20% at 915 MHz and 2.45 GHz for a power density of 1 uW/cm^2
  - 1 uW/cm^2 corresponds to P_{in}=-9 dBm and P_{in}=-15 dBm at 915 MHz and at 2.45 GHz

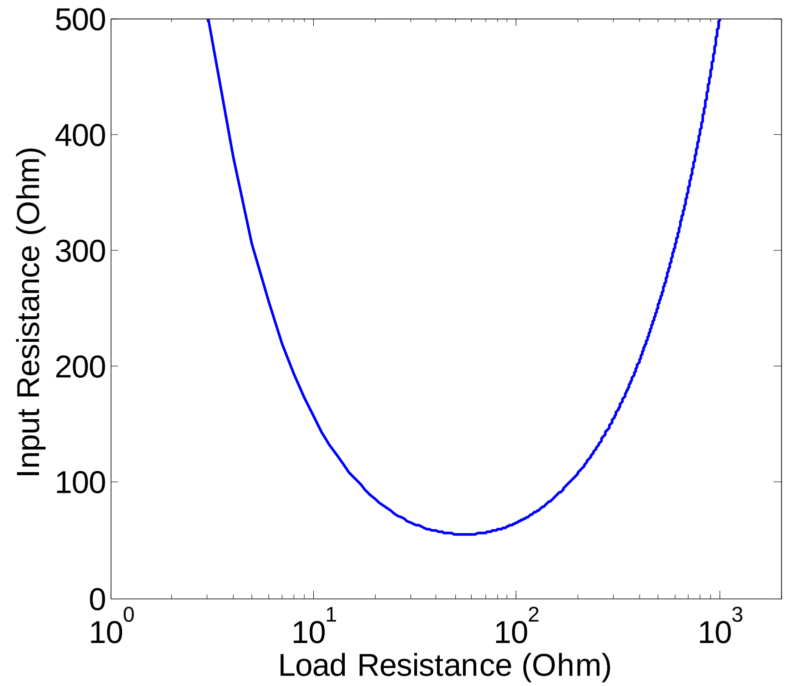
Rectenna Design

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



Load resistance variation: 3 Ohm – 1000 Ohm

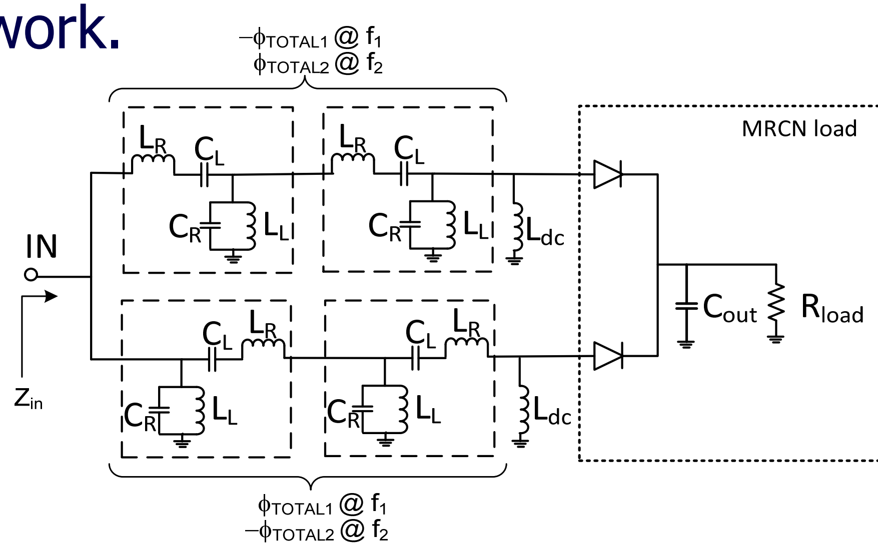
Input resistance variation: 55 Ohm – 500 Ohm

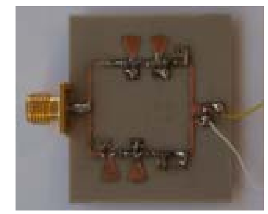


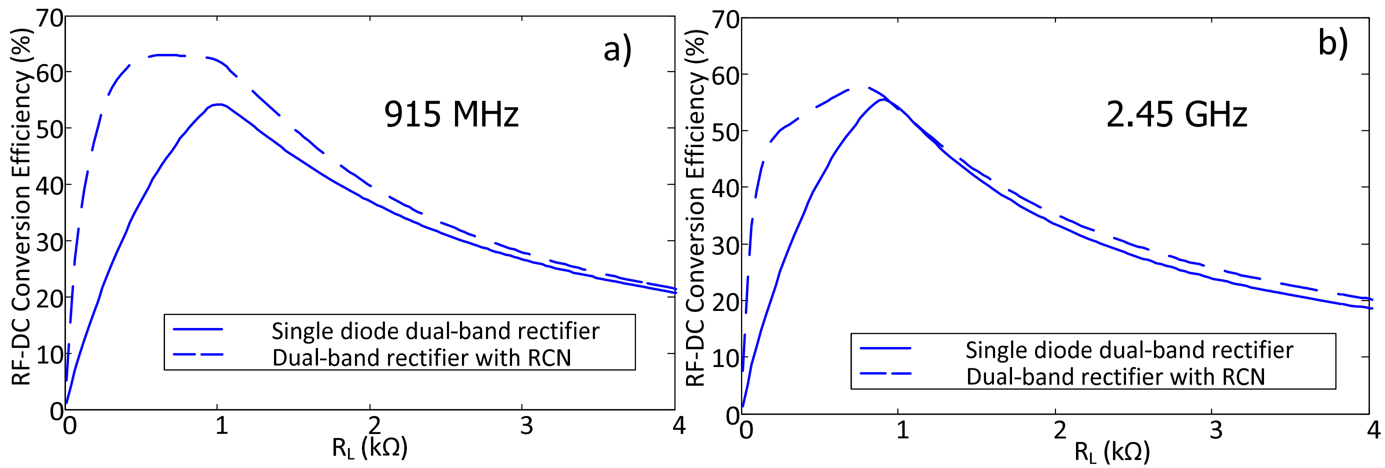
Y. Han, O. Leitermann, D.A. Jackson, J.M. Rivas, and D.J. Perreault, "Resistance Compression Networks for Radio-Frequency Power Conversion," *IEEE Trans. on Power Electronics*, vol. 22, no. 1, pp. 41-53, Jan. 2007.

Rectenna Design

- Dual band metamaterial based resistance compression network.







K. Niotaki, A. Collado, A. Georgiadis, “Dual band rectifier based on resistance compression networks,” in Proc. 2014 IEEE MTT-S IMS, Tampa, 1-6 June 2014.

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Signal Design

- Signals with time-varying envelope (PAPR > 0 dB) lead to higher rectifier RF-DC conversion efficiency
  - Multi-sines (Durgin, Carvalho, Popovic, …)
  - Chaotic signals
  - White noise
  - Random modulation (multi-carrier)

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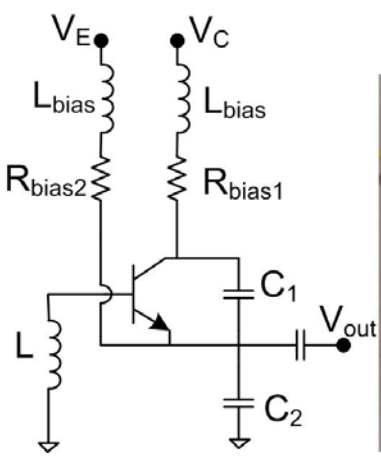
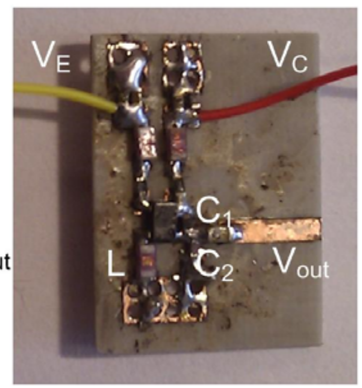
Signal Design

- First experiments: chaotic oscillator

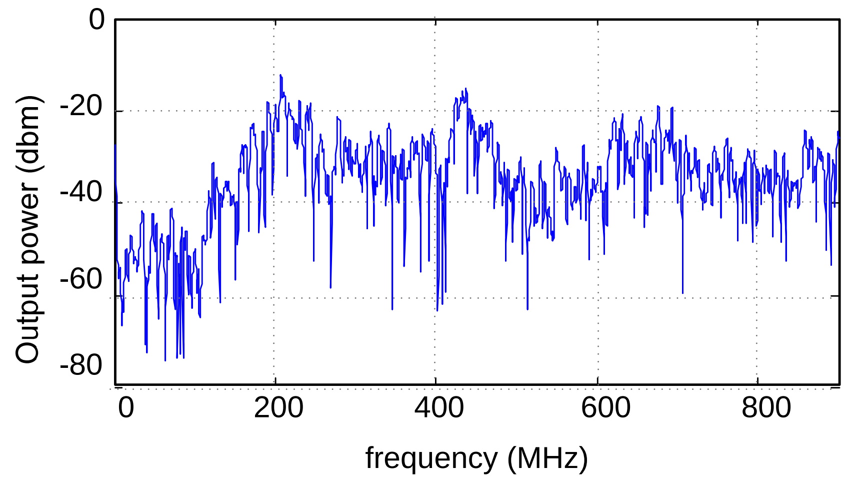
❑ Colpitts based chaotic generator

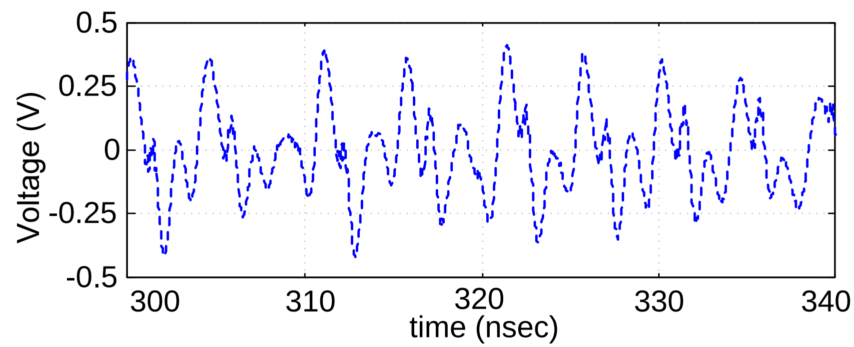
❑ Bipolar transistor BFP183w





433 MHz chaotic generator





A. Collado, A. Georgiadis, "Improving Wireless Power Transmission Efficiency Using Chaotic Waveforms," in Proc. IEEE MTT-S IMS 2012, Montreal, 17-22 June 2012.

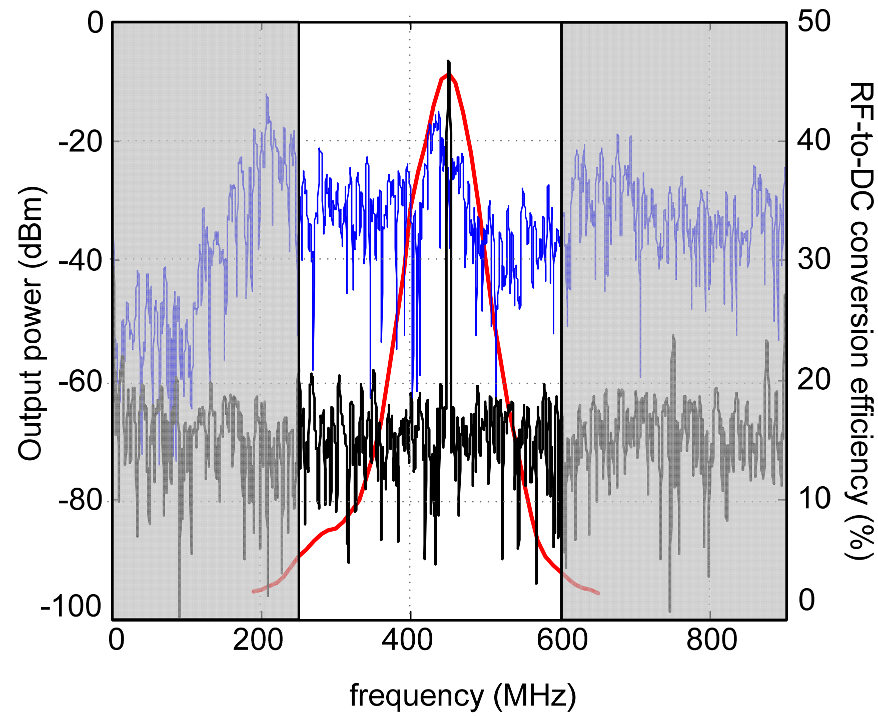
Signal Design

- Need to filter chaotic signal

chaotic signal power
[250 MHz – 600MHZ]

-6.5 dBm

One-tone signal power
[250MHz – 600MHZ]



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

A. Collado, A. Georgiadis, "Improving Wireless Power Transmission Efficiency Using Chaotic Waveforms," in Proc. IEEE MTT-S IMS 2012, Montreal, 17-22 June 2012.

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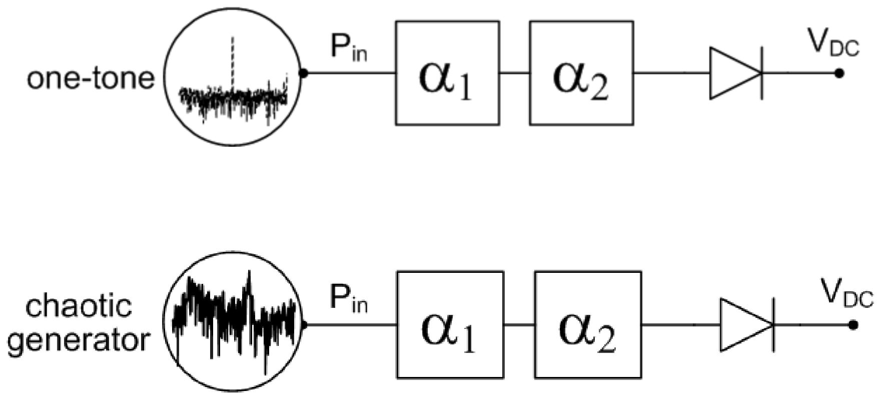
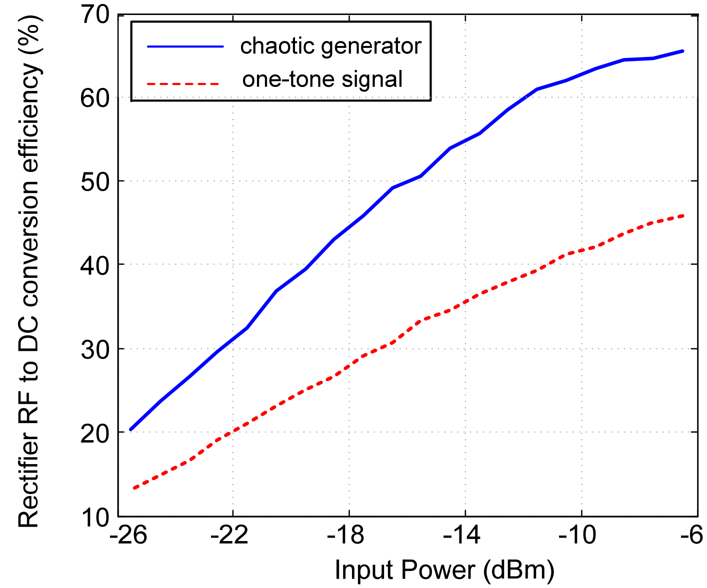
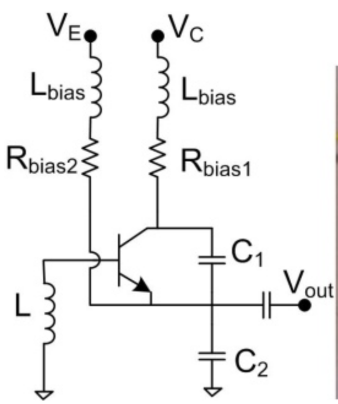
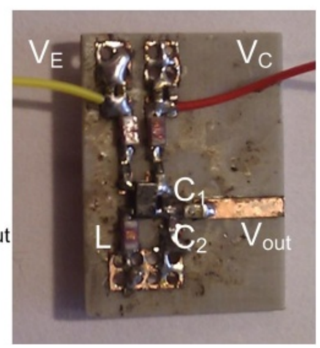
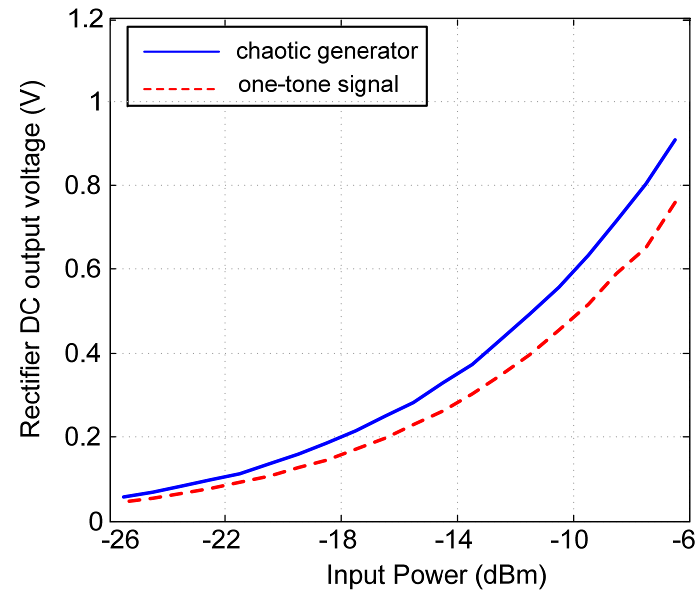
Signal Design







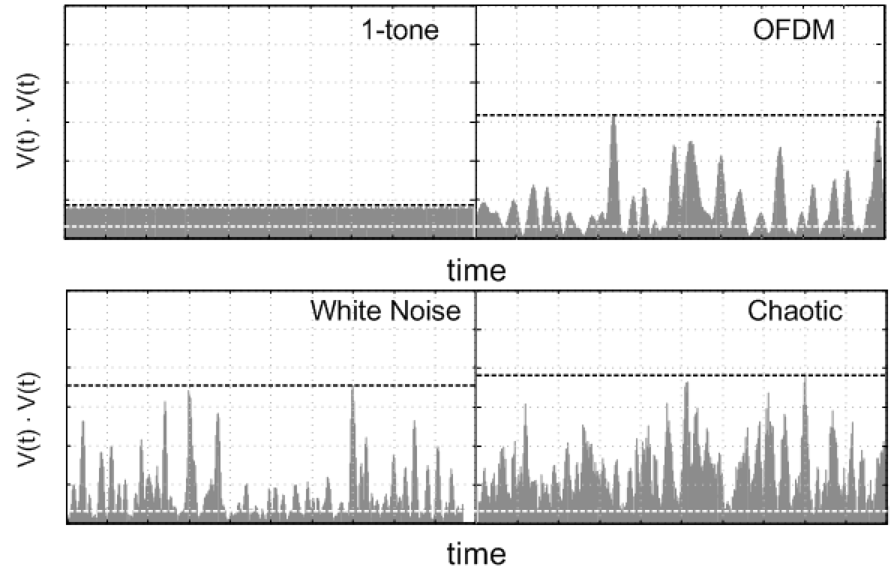




A. Collado, A. Georgiadis, "Improving Wireless Power Transmission Efficiency Using Chaotic Waveforms," in Proc. IEEE MTT-S IMS 2012, Montreal, 17-22 June 2012.

Signal Design

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



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

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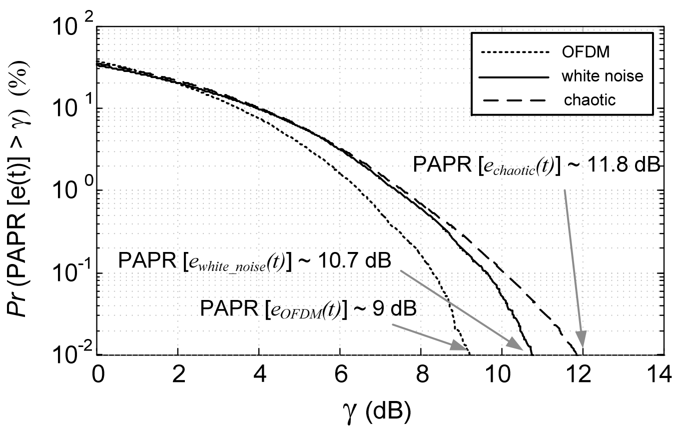
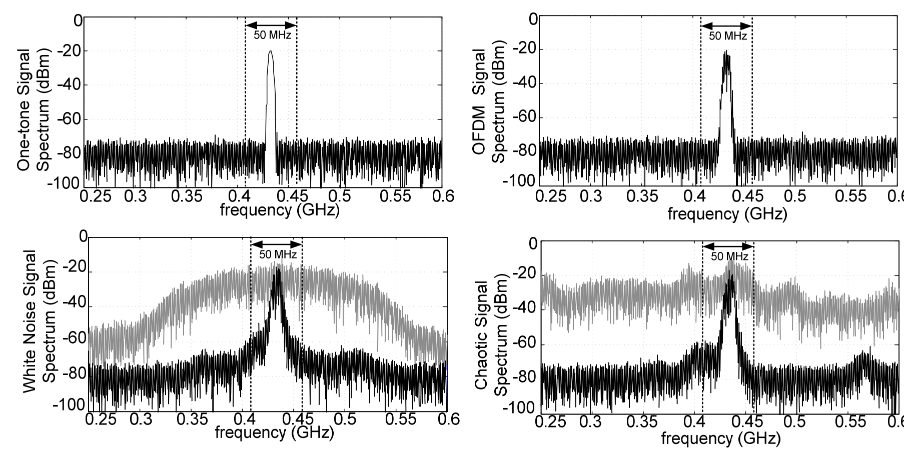
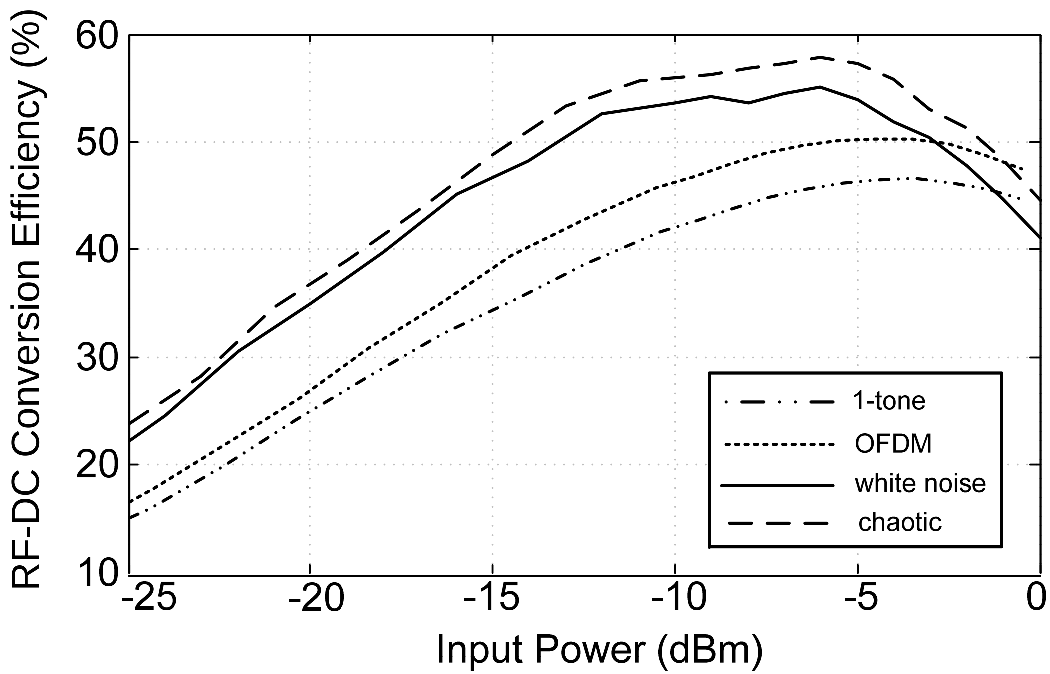




A. Collado, A. Georgiadis, 'Optimal Waveforms for Efficient Wireless Power Transmission,' IEEE Microwave and Wireless Components Letters, 2014, to appear.

Signal Design

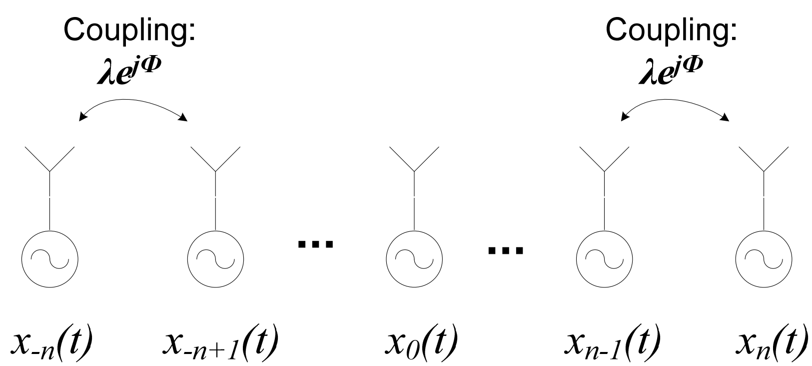
- ❑rectifier operates at 433 MHz
- ❑Skyworks SMS7630-02LF diode
- ❑output load of 5.6 KOhm



A. Collado, A. Georgiadis, 'Optimal Waveforms for Efficient Wireless Power Transmission,' IEEE Microwave and Wireless Components Letters, 2014, to appear.

Signal Design

- High PAPR signals saturate the PAs
- Spatial power combining – each tone amplified independently and then combined in free space
- Mode-locked coupled oscillators – establish phase reference and control phase shift among elements



A. Georgiadis, A. Collado "Mode Locked Oscillator Arrays for Efficient Wireless Power Transmission," 2013 IEEE Wireless Power Transfer Conference (WPT), Perugia, May 15-16, 2013.

A. Boaventura, A. Collado, A. Georgiadis, N.B. Carvalho, 'Spatial Power Combining of Multi-sine Signals for Wireless Power Transmission Applications,' IEEE Transactions on Microwave Theory and Techniques, Special Issue on Wireless Power Transfer, 2014, accepted for publication

Signal Design

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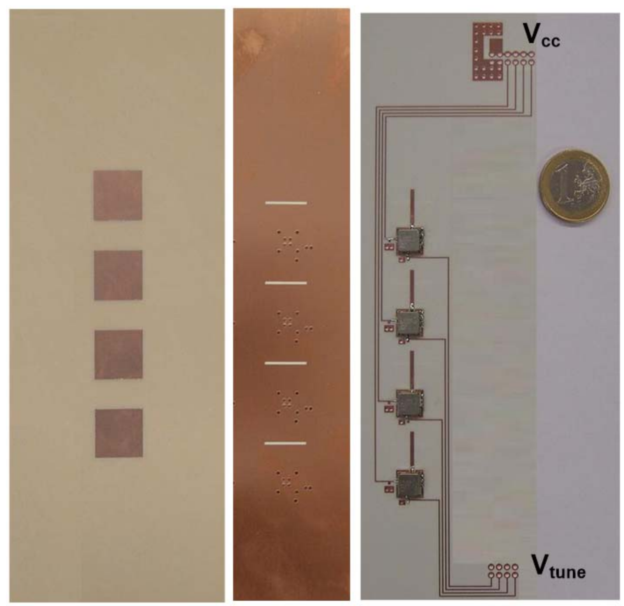
- 4x1 active antenna oscillator array at 6 GHz
- Patch antenna aperture coupled to a VCO



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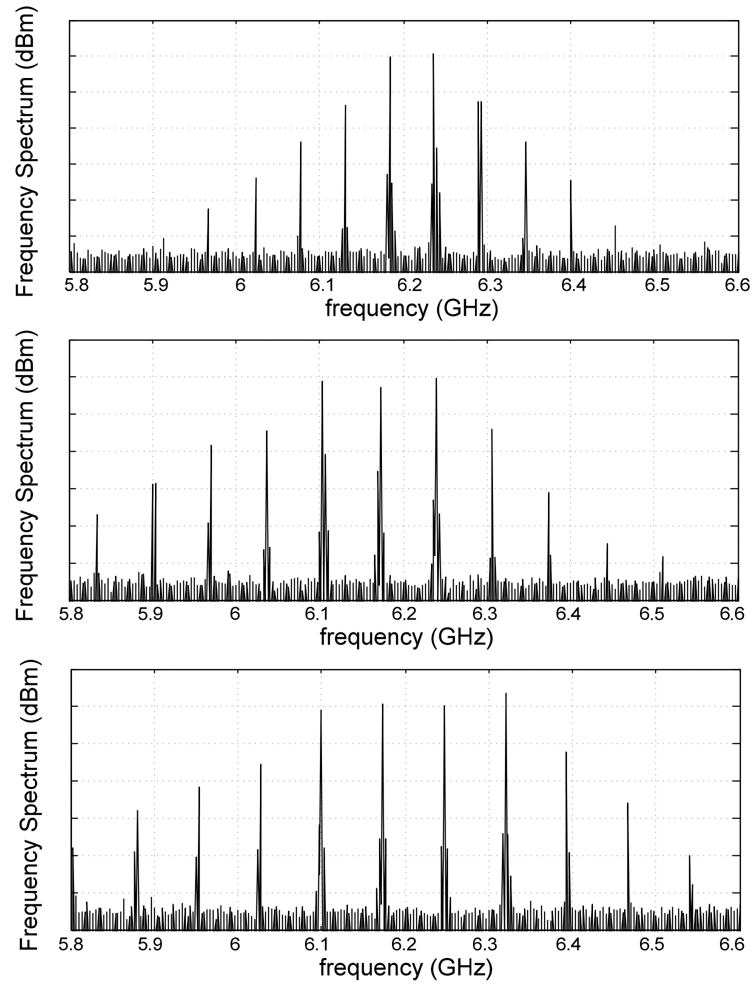
Signal Design

- Step1: 2 VCOs with 50 MHz spacing. Mixing products are created
- Step2: 3 VCOs. The third one with a free running frequency corresponding to one of the mixing products
- Step3: 4 VCOs. The fourth one with a free running frequency corresponding to one of the mixing products



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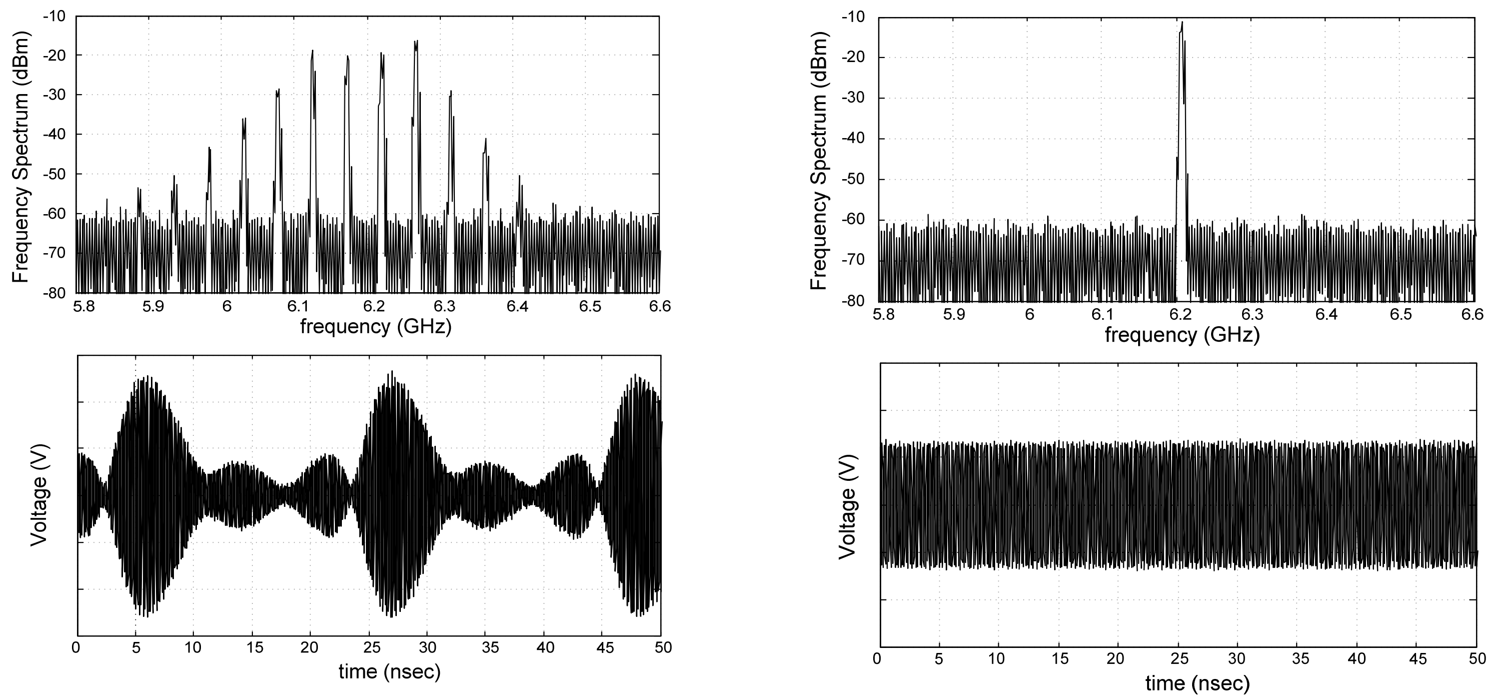
Signal Design

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



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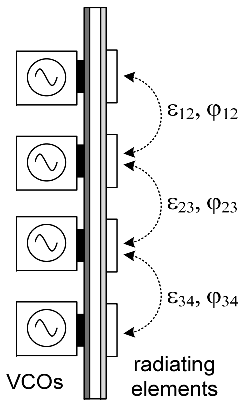
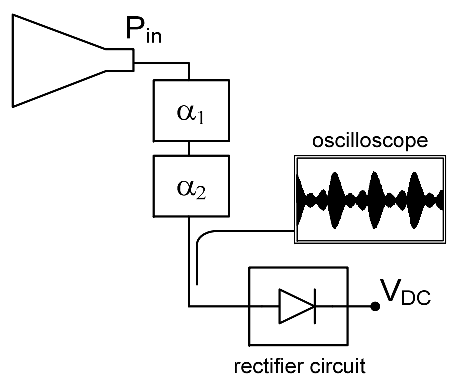
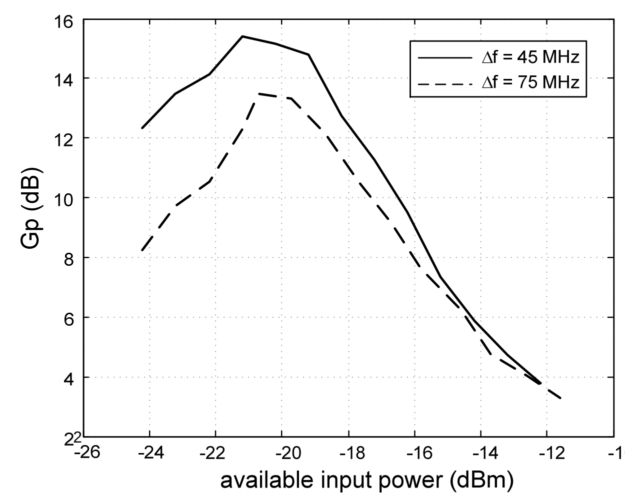
Signal Design

- 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





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



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Conclusion

- Multi-band rectennas allow wider application
- Reactive networks capable of minimizing rectenna efficiency sensitivity to load variation
- High PAPR leads to higher efficiency
- Spatial power combining for WPT transmitters

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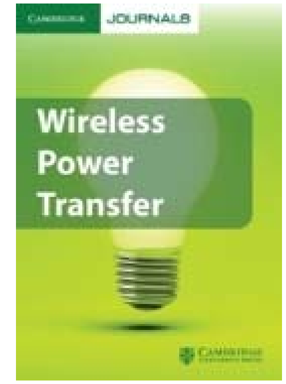
Cambridge Journal on Wireless Power Transfer



http://journals.cambridge.org/action/displayJournal?jid=WPT

Wireless Power Transfer (WPT) is the first journal dedicated to publishing original research and industrial developments relating to wireless power.

Kick-off issue to appear APRIL 2014

WPT will cover all methods of wireless power transfer and articles will reflect the full diversity of applications for this technology, including mobile communications, medical implants, automotive technology, and spacecraft engineering.

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