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

Apostolos Georgiadis
Department of Microwave Systems and Nanotechnology
Centre Tecnologic de Telecomunicacions de Catalunya
(CTTC)
Barcelona - Spain

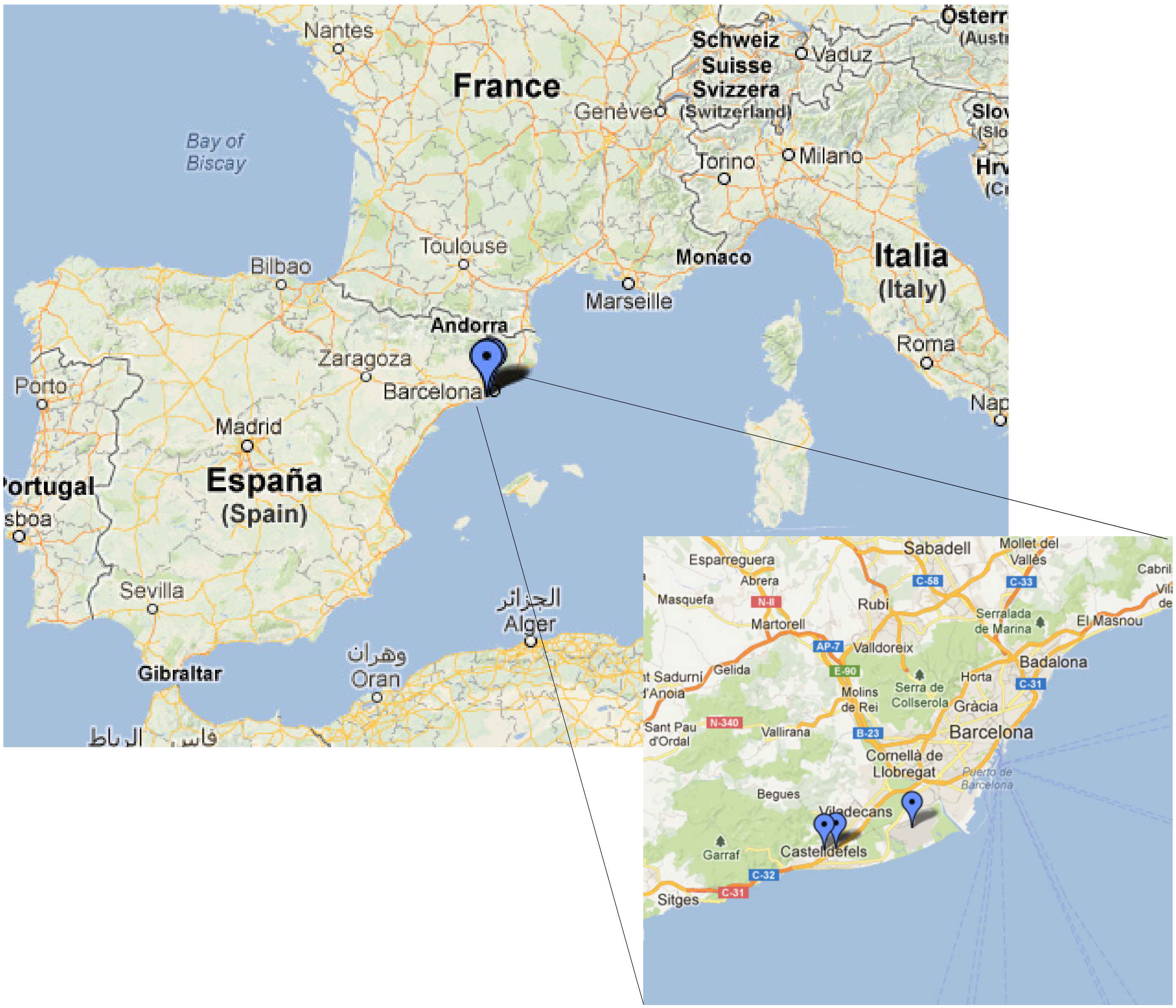
CTTC
Centre Tecnològic de Telecomunicacions de Catalunya

Outline

- Introduction
- Rectenna design
  - Dual band
  - Load independent performance
- Signal design
  - Random modulation, noise, chaotic signals
  - Mode locked oscillators
- Some circuits…!
  - Solar powered RF circuits
  - Multi-technology harvesters
- Conclusion

CTTC, Castelldefels – Barcelona

Founded in 2001



Centre Tecnològic de Telecomunicacions de Catalunya

Centre Tecnològic de Telecomunicacions de Catalunya

CTTC, Castelldefels – Barcelona

- 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***

Centre Tecnològic de Telecomunicacions de Catalunya

CTTC, Castelldefels – Barcelona, SPAIN

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)

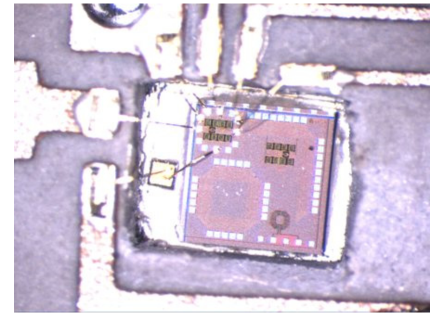


Fig. 1. CMOS VCO for UWB-FM

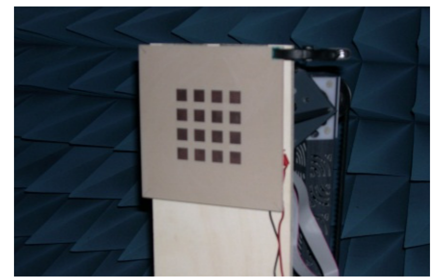


Fig. 2. C-band Coupled Oscillator Reflectrarray prototype

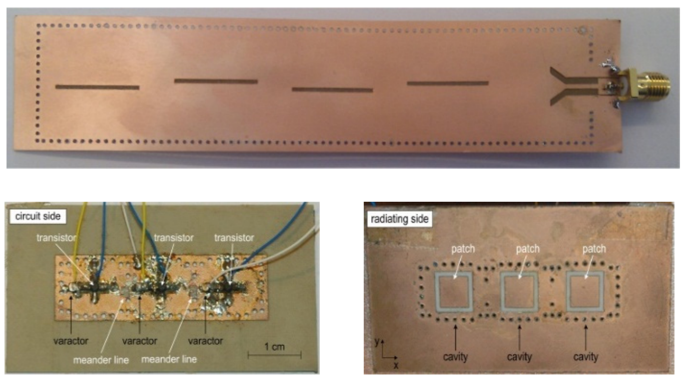


Fig. 4. SIW circuits.

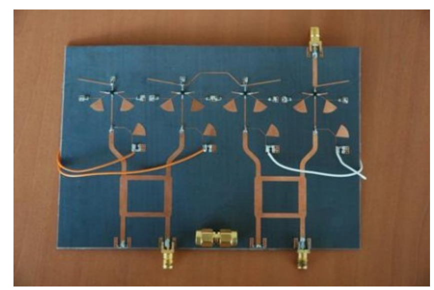


Fig. 3. S-band retro-directive array.

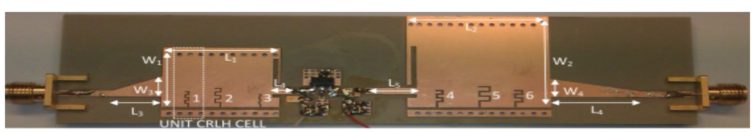


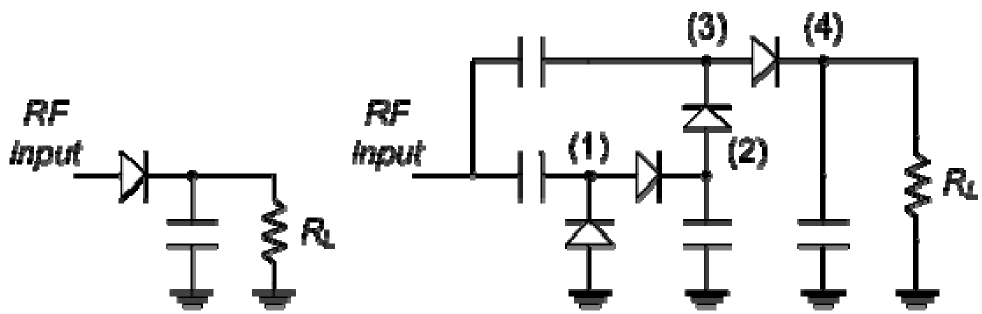
Fig. 5. Power Amplifier (SIW).

Centre Tecnològic de Telecomunicacions de Catalunya

CTTC
Centre Tecnològic de Telecomunicacions de Catalunya

Rectenna Design

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

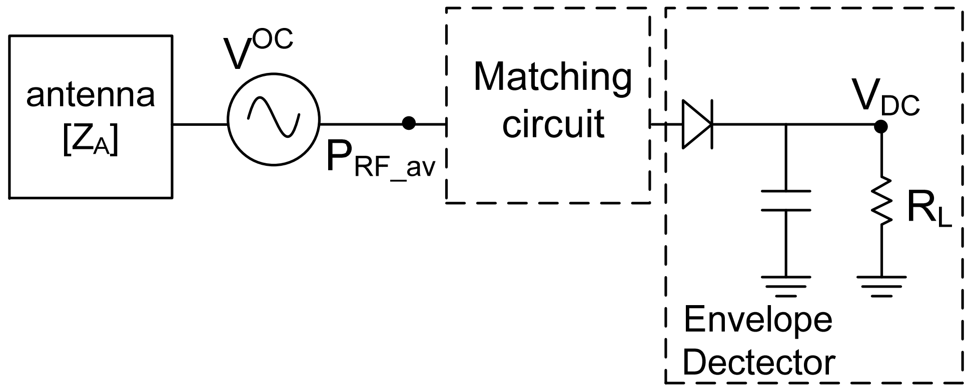


Reported UHF rectifier efficiencies for available input power levels in the order of 10 uW are near 20%, and increase to >50% for available power levels of 100uW.

CTTC
Centre Tecnològic de Telecomunicacions de Catalunya

Rectenna Design

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



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

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

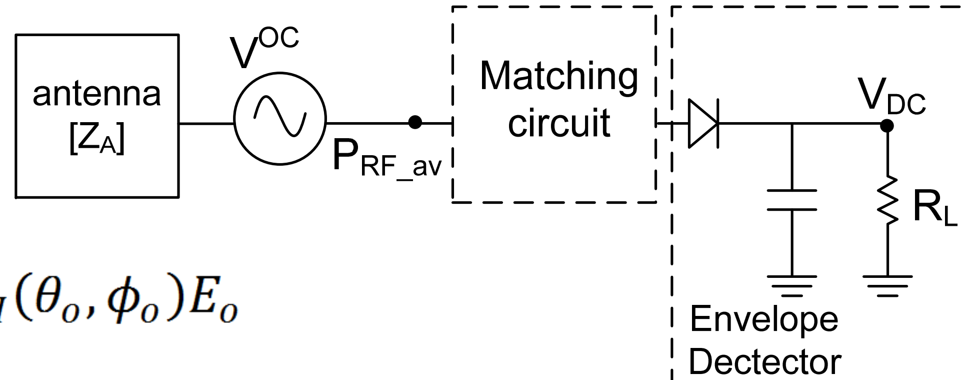
Georgiadis, A.; Andia Vera, G.; Collado, A., "Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (EM) energy harvesting," *Antennas and Wireless Propagation Letters, IEEE* , vol.9, no., pp.444,446, 2010

Centre Tecnològic de Telecomunicacions de Catalunya

Rectenna Design

- Open circuit voltage maybe calculated using reciprocity theory

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



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

$$E_o = \sqrt{2\eta_o S}$$

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

$$\eta_o = 120\pi$$

- 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

CTTC
Centre Tecnològic de Telecomunicacions de Catalunya

Rectenna Design

- The open circuit voltage *MAGNITUDE* can also be calculated using the antenna effective area

$$E_o = \sqrt{2\eta_o S}$$

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

$$A_e = \frac{\lambda^2}{4\pi} G$$

$$P_{av} = A_e S$$

$$P_{av} = A_e S = \frac{\lambda^2}{8\pi\eta_o} G(\theta_o, \phi_o) E_o^2$$

HOW DO THEY COMPARE ?

$$V_{oc} = \sqrt{8 P_{av} R_A} = \sqrt{\frac{G(\theta_o, \phi_o) R_A}{\pi \eta_o}} \lambda E_o$$

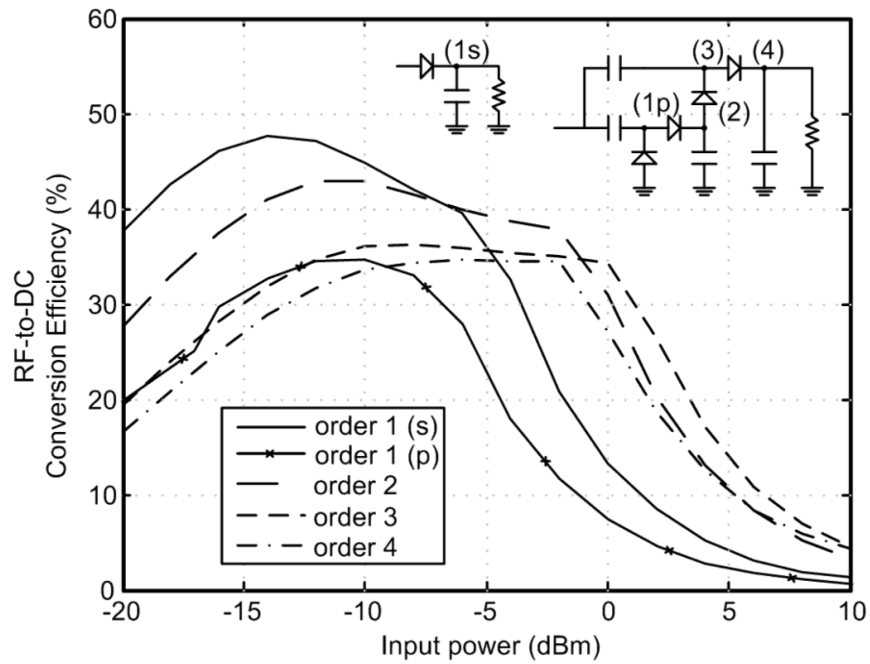
C. A. Balanis, Antenna Theory: Analysis and Design, 3rd Ed., Wiley,2005

R. E. Collin , Antennas and Radiowave Propagation . New York: Mc-Graw-Hill, 1985.

CTTC
Centre Tecnològic de Telecomunicacions de Catalunya

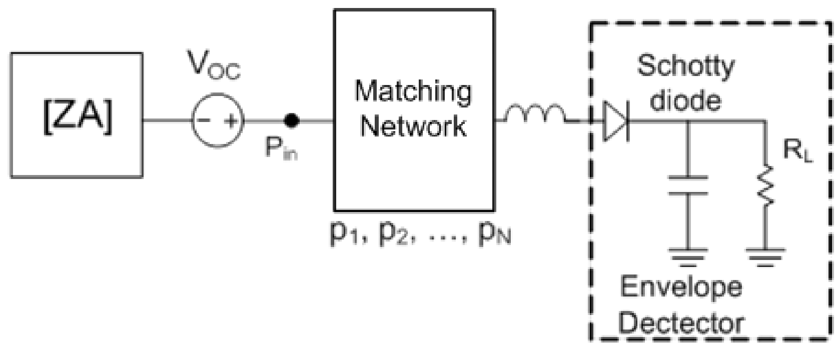
Rectenna Design

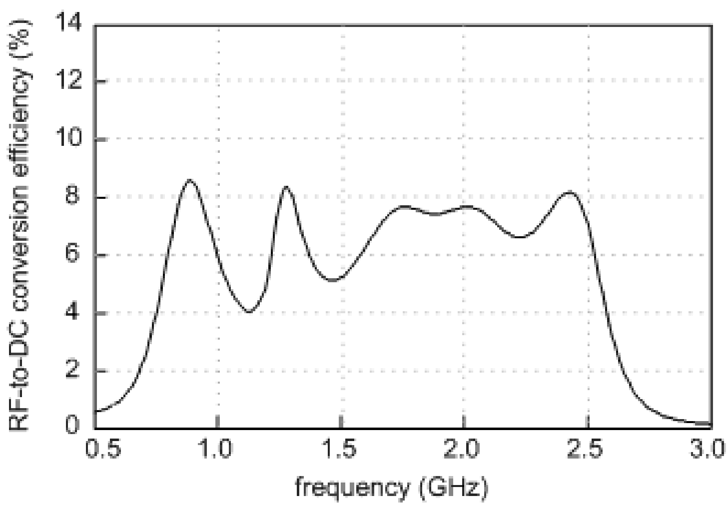
- Circuit topology important in low available power conditions
- Trade-off between efficiency and output voltage



Centre Tecnològic de Telecomunicacions de Catalunya

RF to DC conversion efficiency optimization: Broadband Case



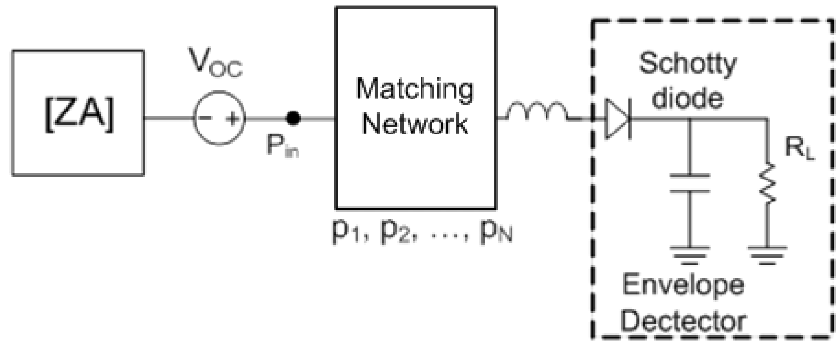


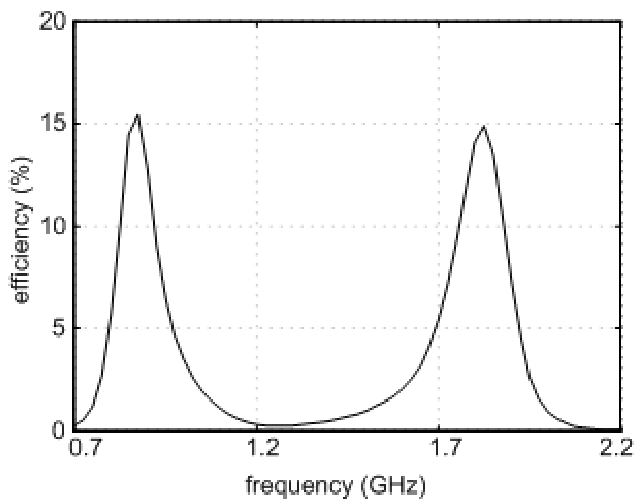
OPTIMIZATION PARAMETERS:

$p_1, \ldots, p_N$

R_L

RF to DC conversion efficiency optimization: Dual-Band Case





OPTIMIZATION PARAMETERS:

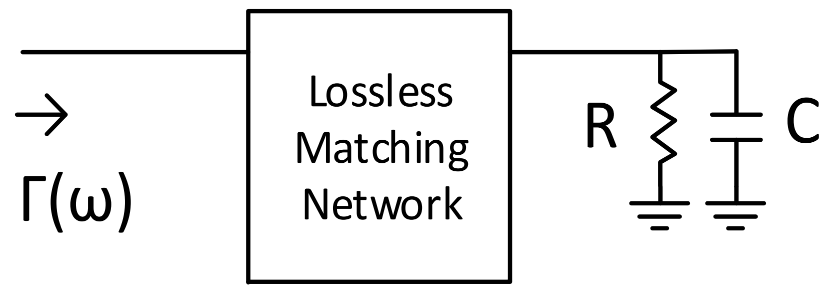
$p_1,\ldots,p_N$
R_L

Theoretical limits: impedance bandwidth

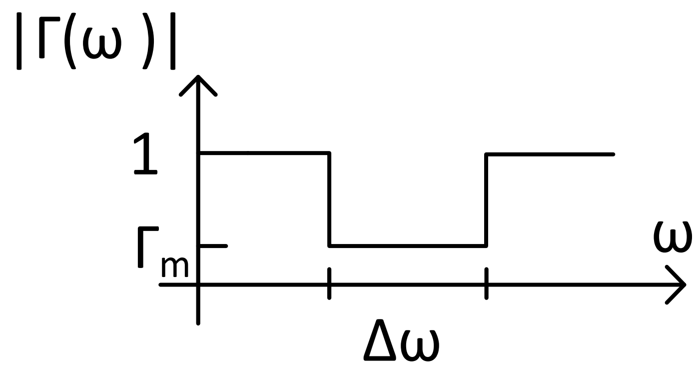
Centre Tecnològic de Telecomunicacions de Catalunya

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

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



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



Let R = 1.5 KOhm, and C = 0.9 pF

What is the miminum reflection coefficient if one wants to cover a freq. band from 800 MHz to 2.6 GHz ?

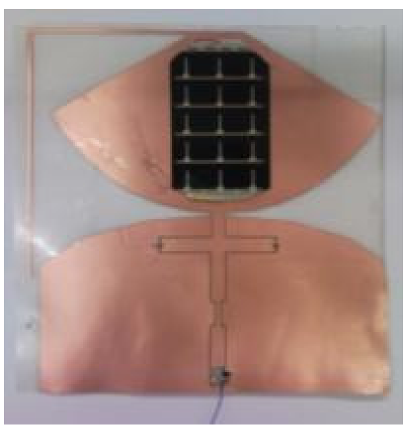
Centre Tecnològic de Telecomunicacions de Catalunya

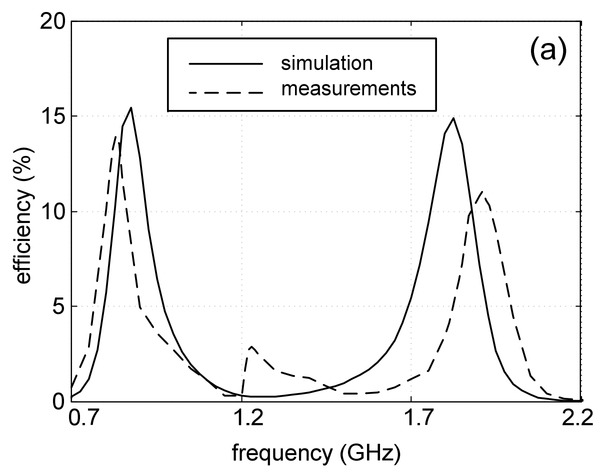
Centre Tecnològic de Telecomunicacions de Catalunya

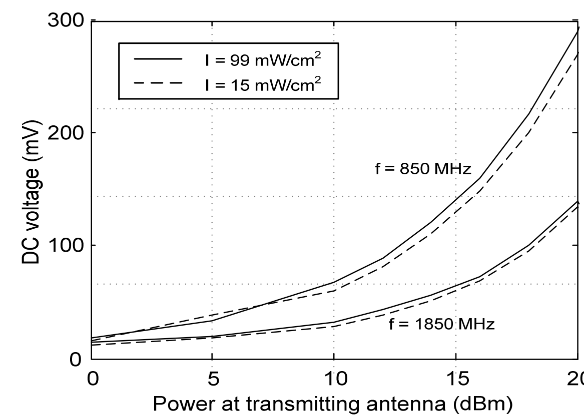
Rectenna Design

850 MHz/1850 MHz Dual Band Rectenna

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







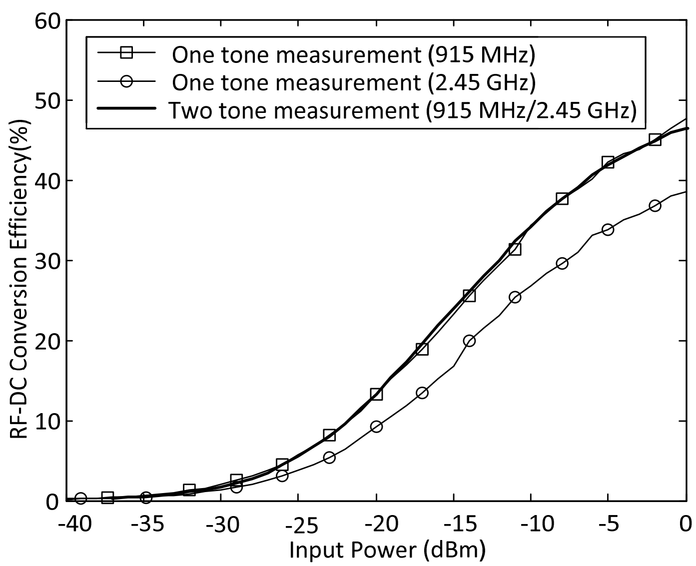
Collado, A.; Georgiadis, A., "Conformal Hybrid Solar and Electromagnetic (EM) Energy Harvesting Rectenna," *Circuits and Systems I: Regular Papers, IEEE Transactions on* , vol.60, no.8, pp.2225,2234, Aug. 2013

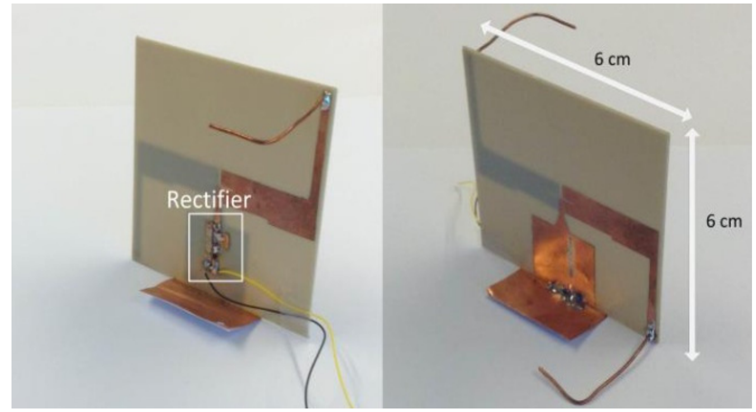
Rectenna Design

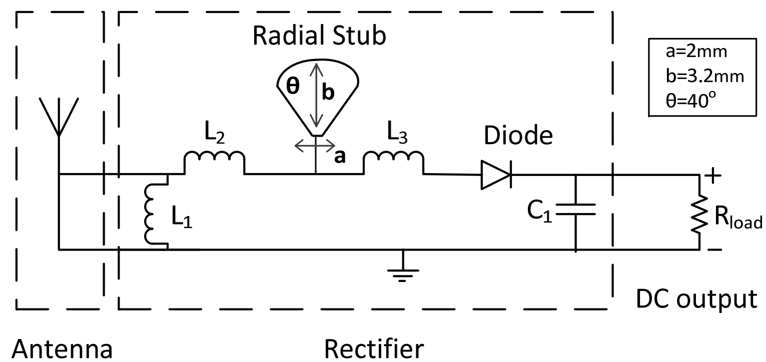
- Optimization goals are used to maximize the RF-DC conversion efficiency at 915 MHz and 2.45 GHz

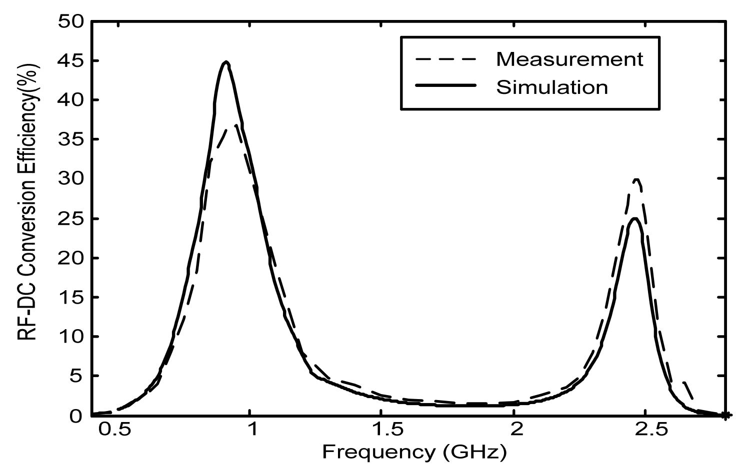
η = 48% and η = 39% at 915 MHz and 2.45 GHz, for P_{in}=0 dBm

η <1 % for P_{in}<-33 dBm







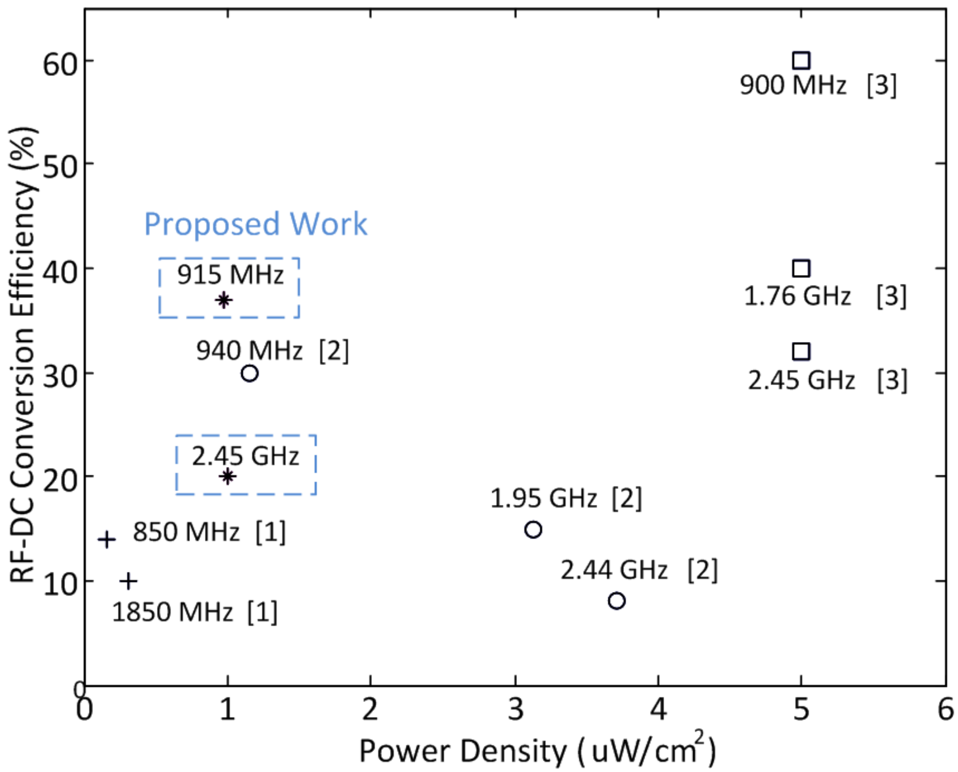


Niotaki, K.; Sangkil Kim; Seongheon Jeong; Collado, A.; Georgiadis, A.; Tentzeris, M.M., "A Compact Dual-Band Rectenna Using Slot-Loaded Dual Band Folded Dipole Antenna," *Antennas and Wireless Propagation Letters, IEEE* , vol.12, no., pp.1634,1637, 2013

Centre Tecnològic de Telecomunicacions de Catalunya

CTTC
Centre Tecnològic de Telecomunicacions de Catalunya

Rectenna Design



[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

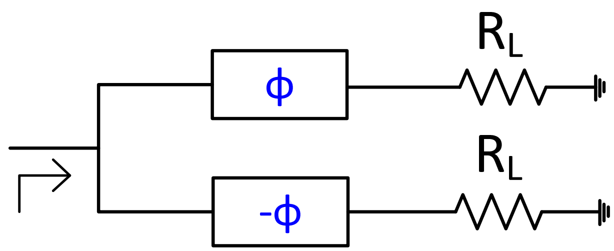
[2] B. L. Pham and A.-V. Pham, "Triple Bands Antenna and High Efficiency Rectifier Design for RF Energy Harvesting at 900, 1900 and 2400 MHz," in *Proc. IEEE MTT-S Int. Microwave Symp.*, Seattle, WA, 2–7 June 2013.

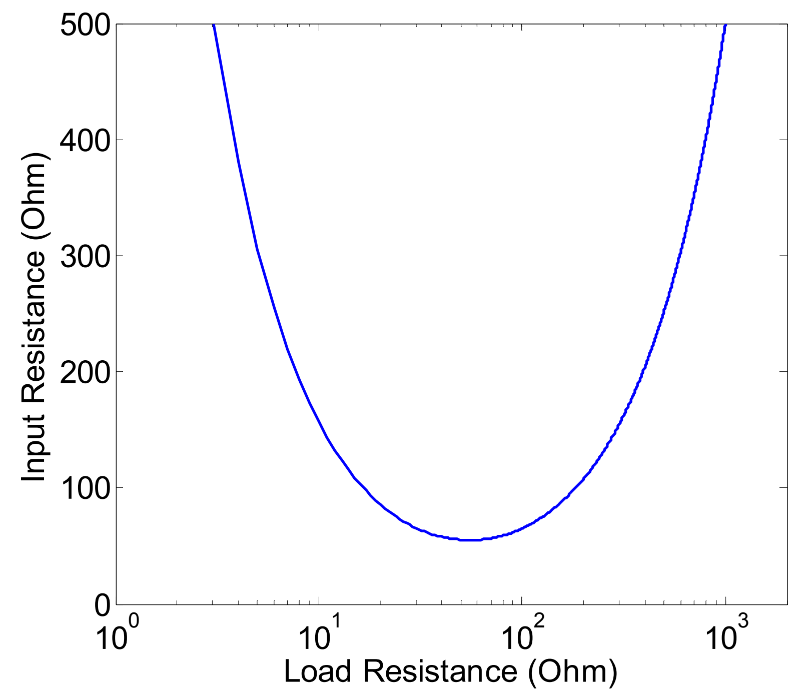
[3] V.Rizzoli, G. Bichicchi, A. Costanzo, F. Donzelli, and D. Masotti, "CAD of multi-resonator rectenna for micro-power generation," in *Proc. Microwave Integrated Circuits Conference (EuMIC 2009)*, 28-29 Sept. 2009, pp.331–334.

- 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





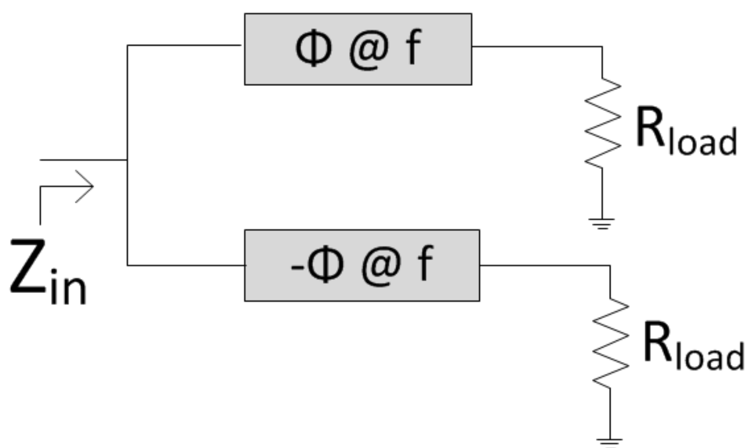
Load resistance variation: 3 Ohm – 1000 Ohm

Input resistance variation: 55 Ohm – 500 Ohm

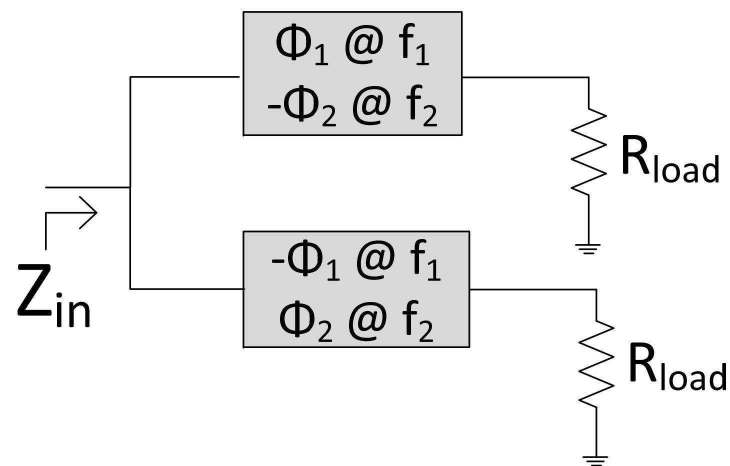
Y. Han, O. Leitermann, D.A. Jackson, J.M. Rivas, and D.J. Perreault, "Resistance Compression Networks for Radio-Frequency Power Conversion, " *IEEE Trans. on Power Electronics*, vol. 22, no. 1, pp. 41-53, Jan. 2007.

Dual-Band Resistance Compression Networks

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



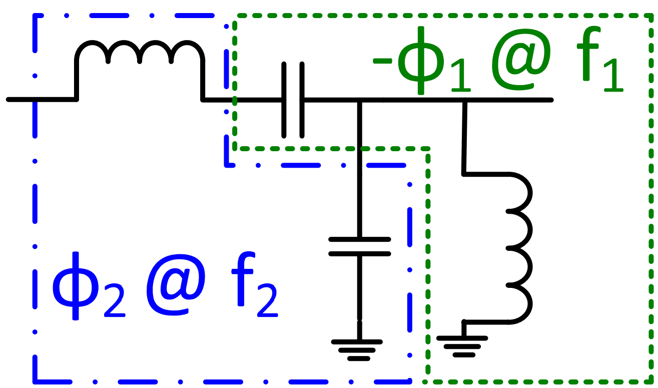
RCN operating at single frequency

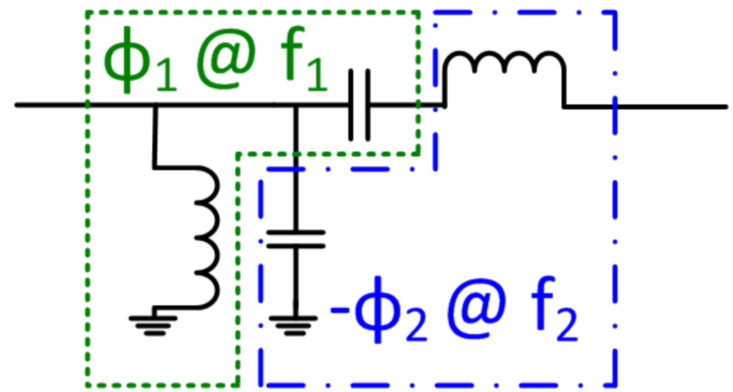


Dual-Band RCN

Dual-Band Resistance Compression Networks

- Dual-Band RCNs
  - **Opposite** phase response at f_1 and f_2 ($f_1 < f_2$)





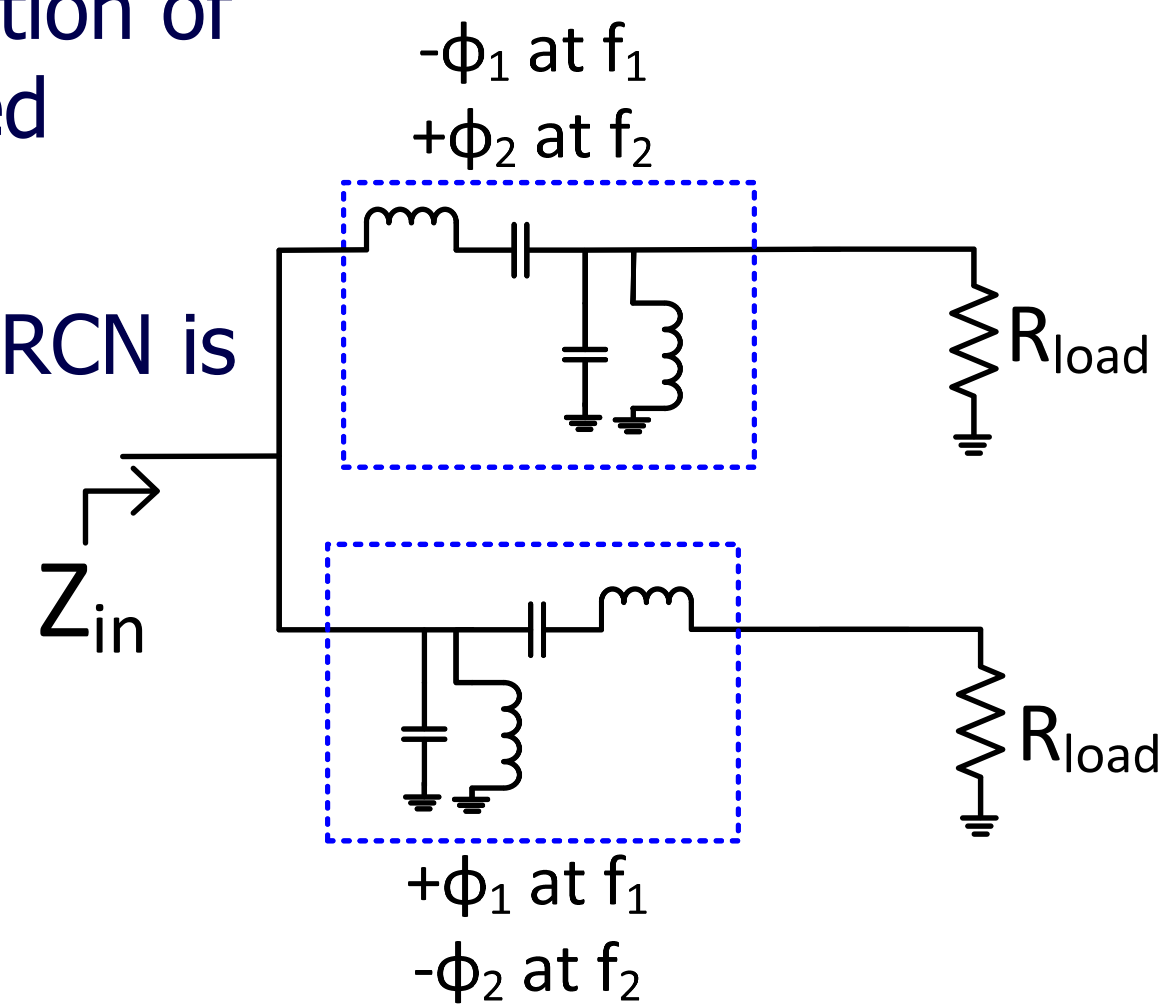
→ $-\varphi_1$ at f_1, $+\varphi_2$ at f_2

→ $+\varphi_1$ at f_1, $-\varphi_2$ at f_2

K. Niotaki, A. Georgiadis, A. Collado, 'Dual-Band Rectifier Based on Resistance Compression Networks,' in Proc. IEEE MTT-S IMS, Tampa, 1-6 June 2014

Dual-Band Resistance Compression Networks

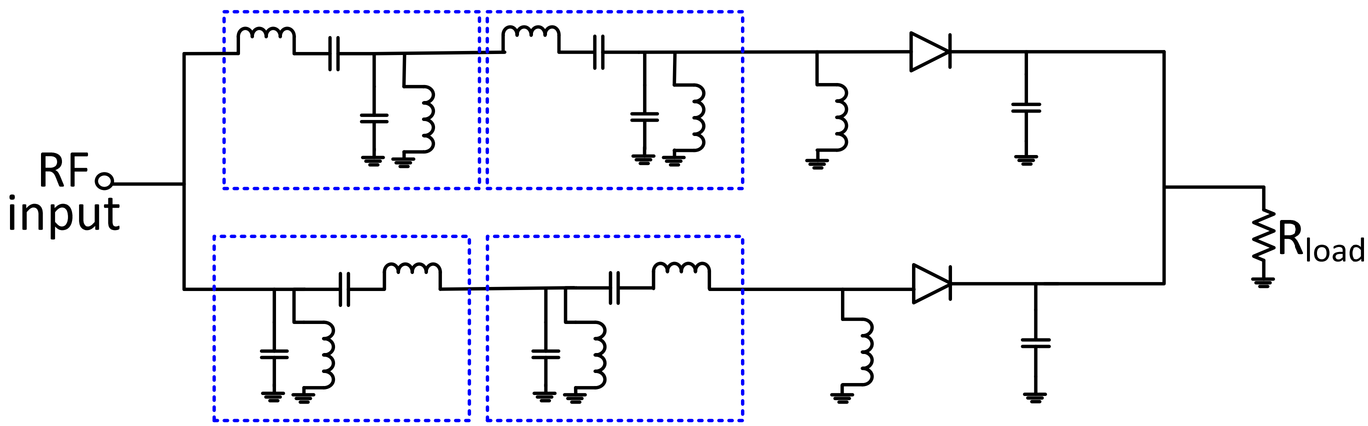
- A small variation of Z_{in} is achieved
- A dual-band RCN is obtained



K. Niotaki, A. Georgiadis, A. Collado, 'Dual-Band Rectifier Based on Resistance Compression Networks,' in Proc. IEEE MTT-S IMS, Tampa, 1-6 June 2014

Dual-Band Rectifiers

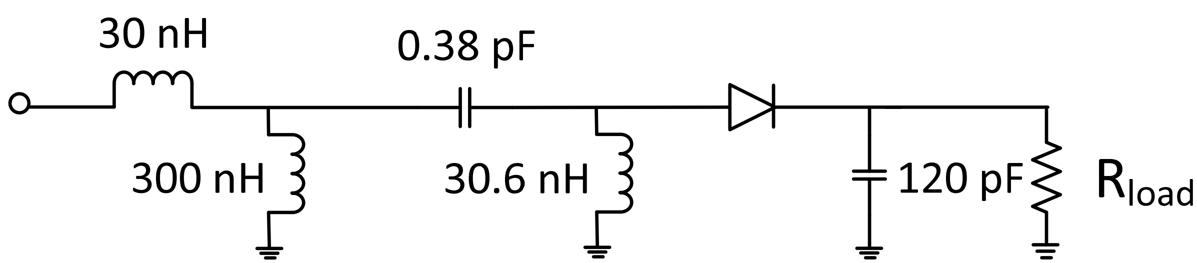
- Dual-Band Resistance Compressed Rectifier
  - 2 unit cells for each branch
  - 915 MHz and 2.45 GHz
  - Skyworks Schottky SMS7630 diode



Centre Tecnològic de Telecomunicacions de Catalunya

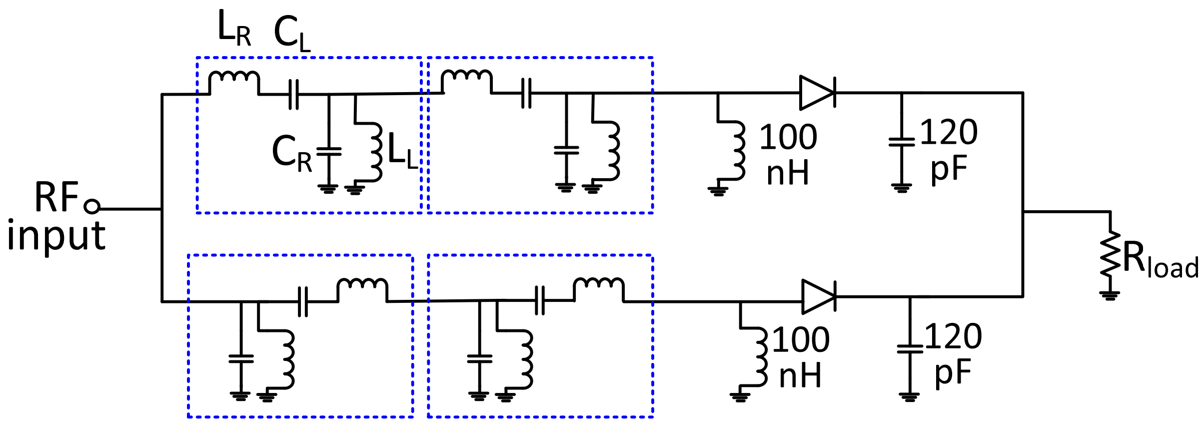
Dual-Band Rectifiers

- Performance comparison
  - Resistance compressed rectifier
  - Conventional envelope detector rectifier



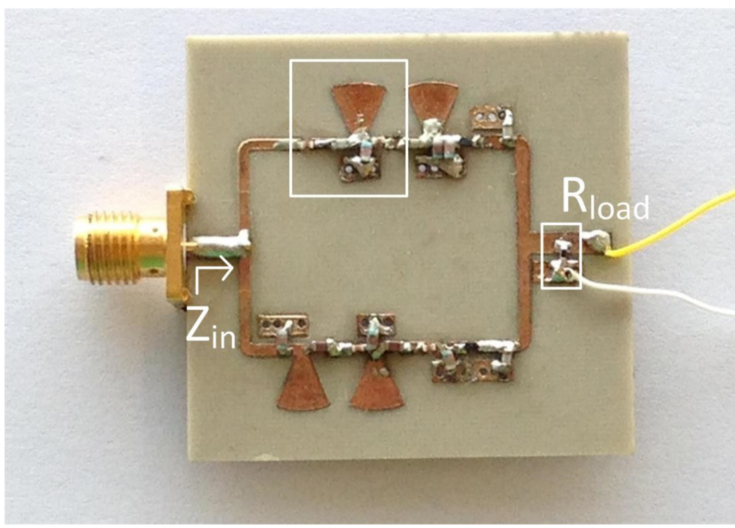
- Rectifier design
  - Harmonic balance analysis (*HB*)
  - Large signal Scattering parameters (*LSSP*)

Resistance Compressed Rectifier



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

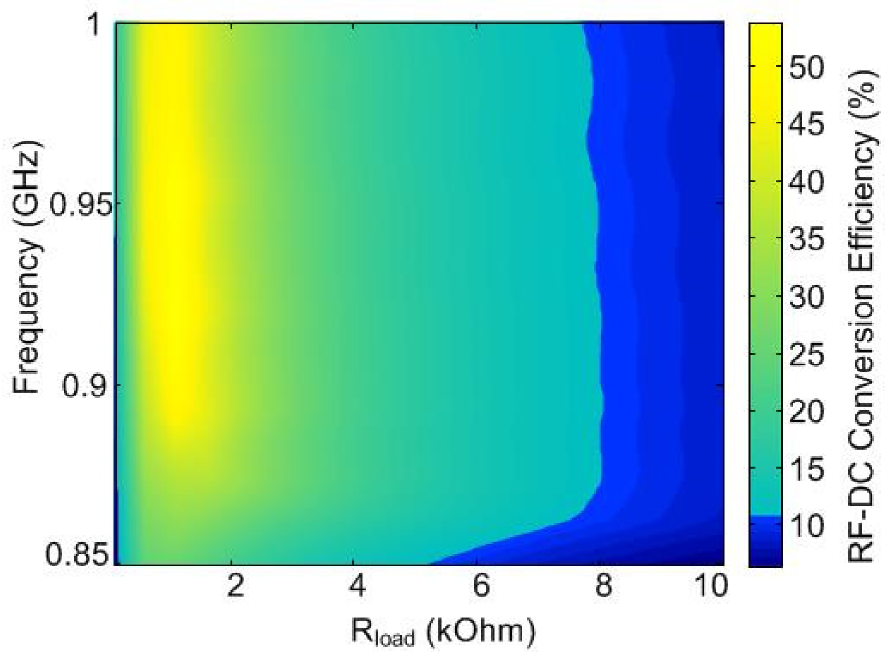
Centre Tecnològic de Telecomunicacions de Catalunya



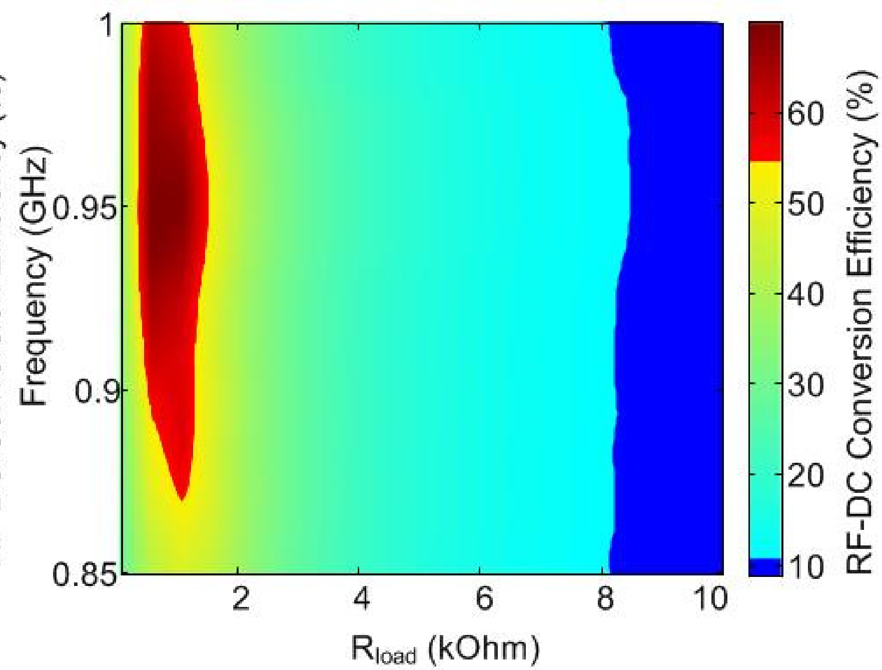
- Schottky diode
  - SMS7630
- Arlon 25N
  - 30 mil
  - ε_r=3.38

Dual-Band Rectifiers

- Efficiency Improvement of n
  - 37 % → 62.3 % for R_{load}=0.5 kOhm & Pin=0 dBm at 915 MHz



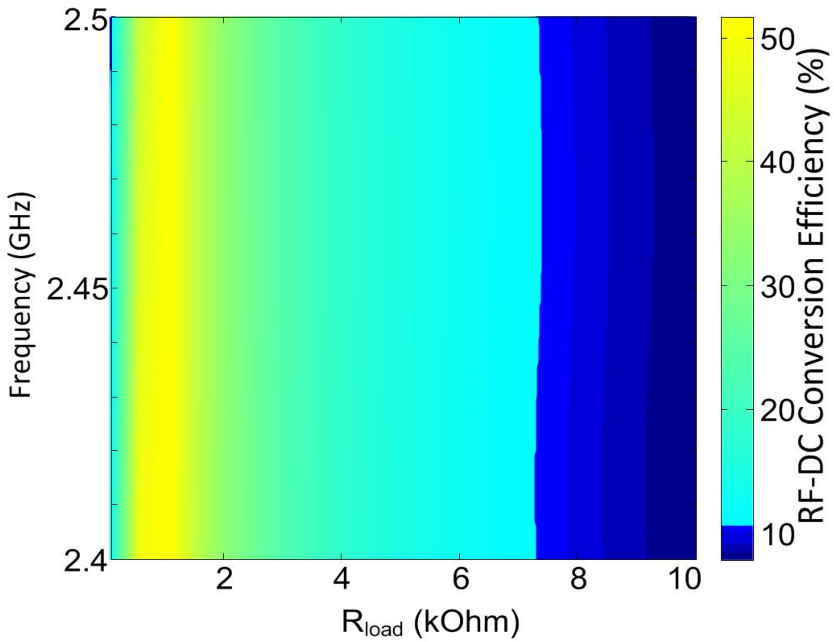
Conventional Rectifier



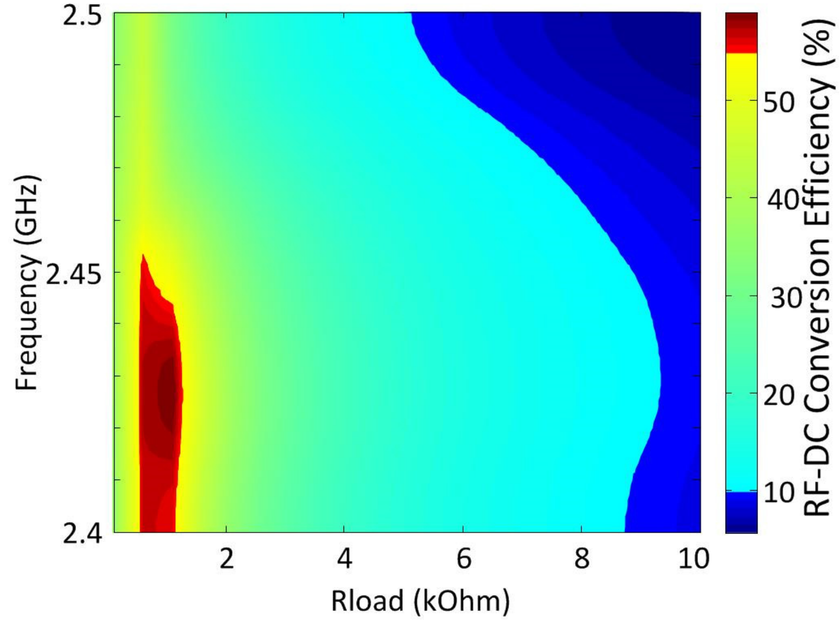
Resistance-Compressed Rectifier

Dual-Band Rectifiers

- Efficiency Improvement of n
  - 41.2 % → 54.4 % for R_{load}=0.5 kOhm & P_{in}=0 dBm at 2.45 GHz



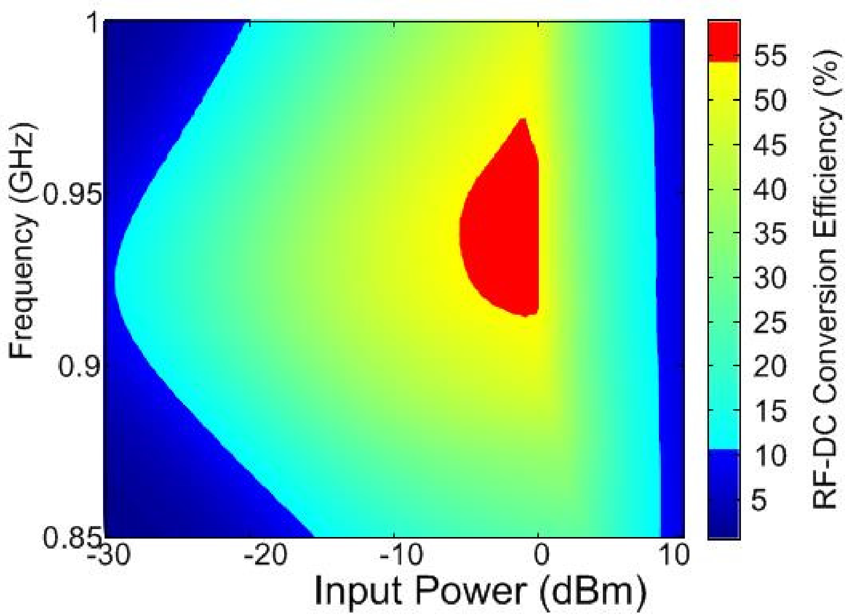
Conventional Rectifier



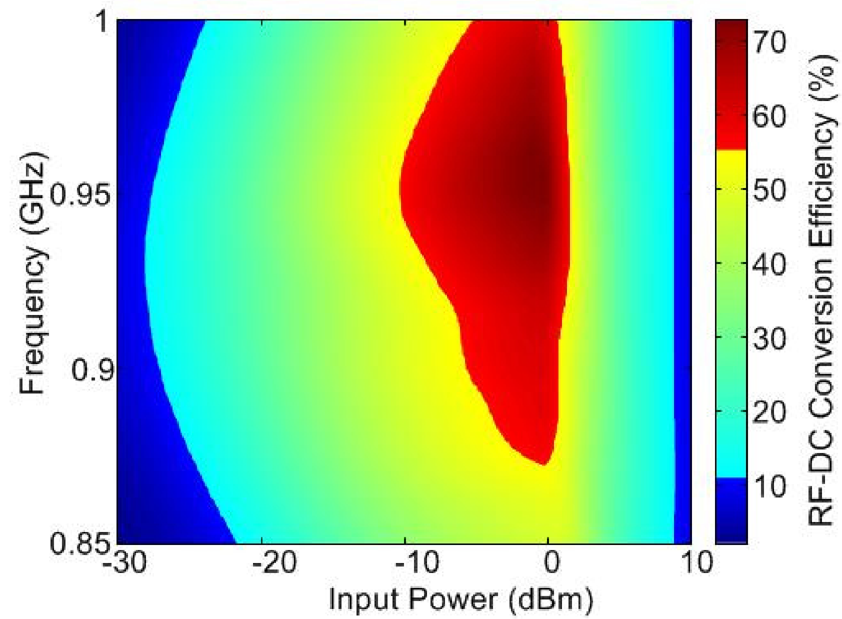
Resistance-Compressed Rectifier

Dual-Band Rectifiers

- RF-DC conversion efficiency at 915 MHz
  - R_{load}=1 kOhm



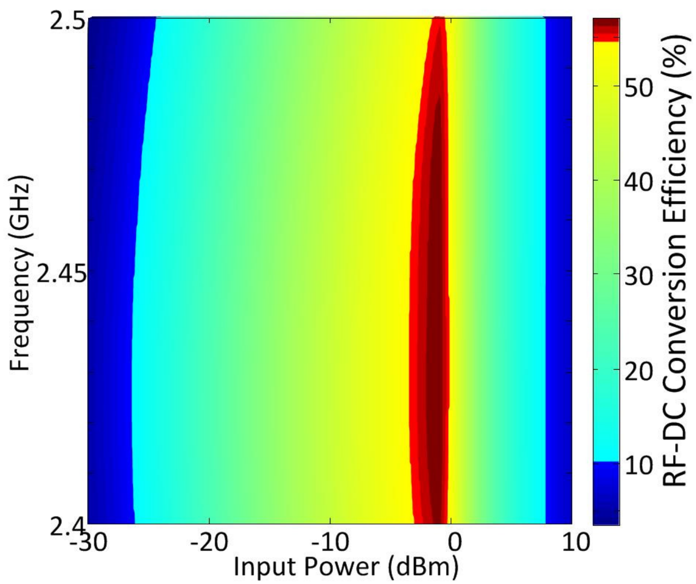
Conventional Rectifier

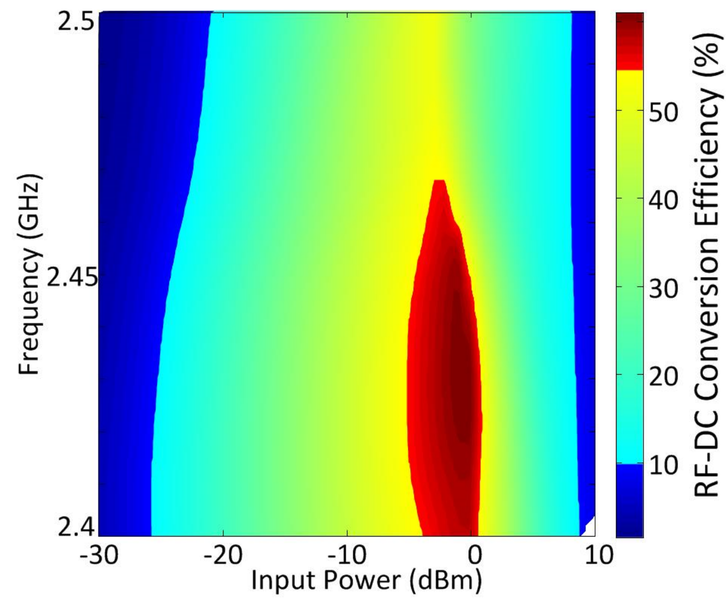


Resistance-Compressed Rectifier

Dual-Band Rectifiers

- RF-DC conversion efficiency at 2.45 GHz
  - R_{load}=1 kOhm





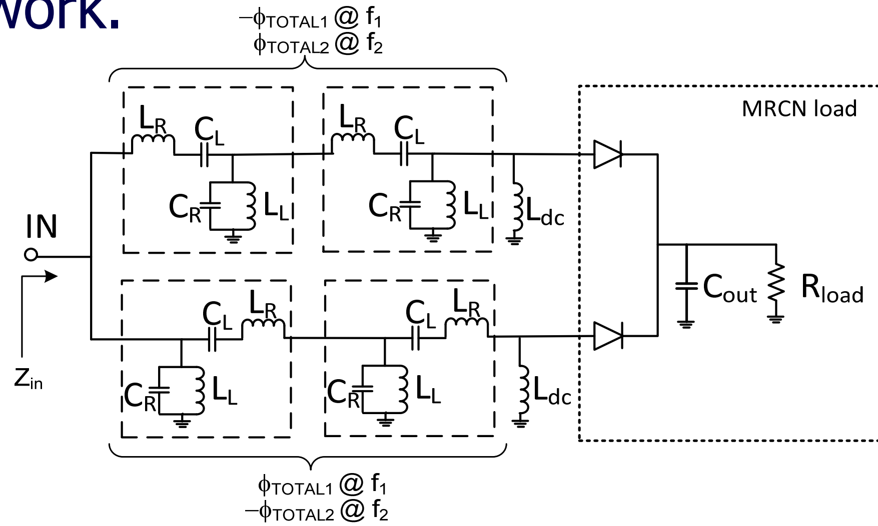
Conventional Rectifier

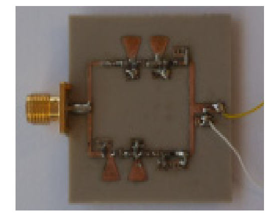
Resistance-Compressed Rectifier

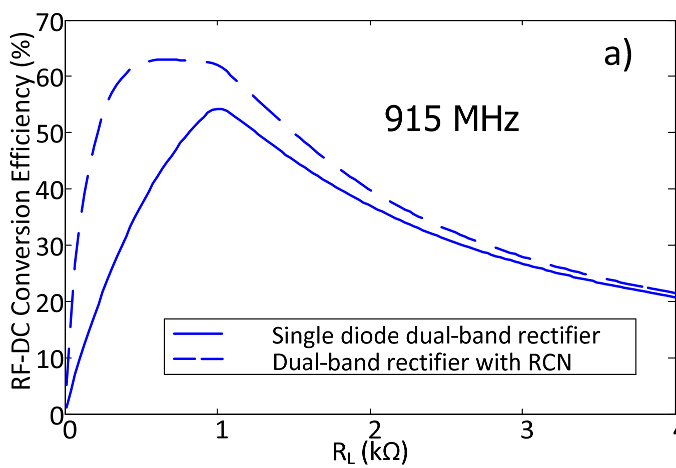
Centre Tecnològic de Telecomunicacions de Catalunya

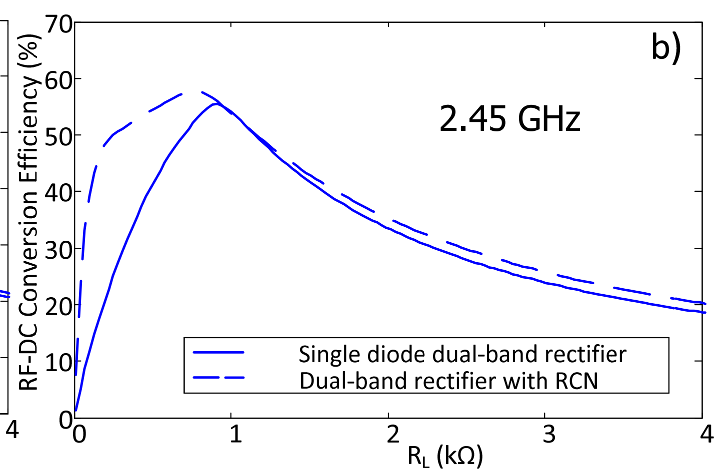
Rectenna Design

- 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.

CTTC
Centre Tecnològic de Telecomunicacions de Catalunya

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)

CTTC

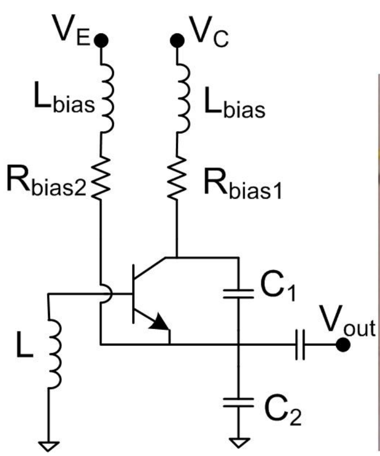
Centre Tecnològic de Telecomunicacions de Catalunya

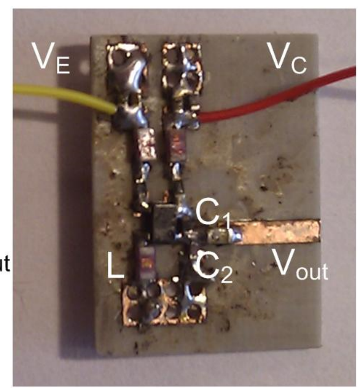
Signal Design

- First experiments: chaotic oscillator

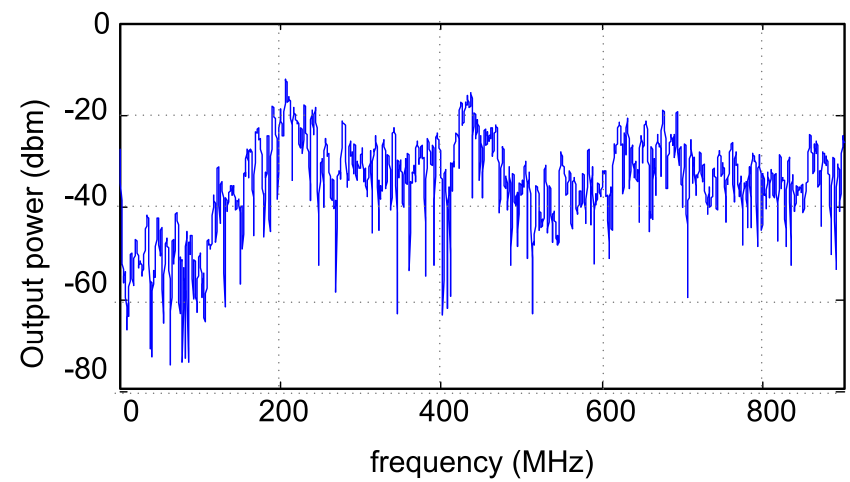
❑ Colpitts based chaotic generator

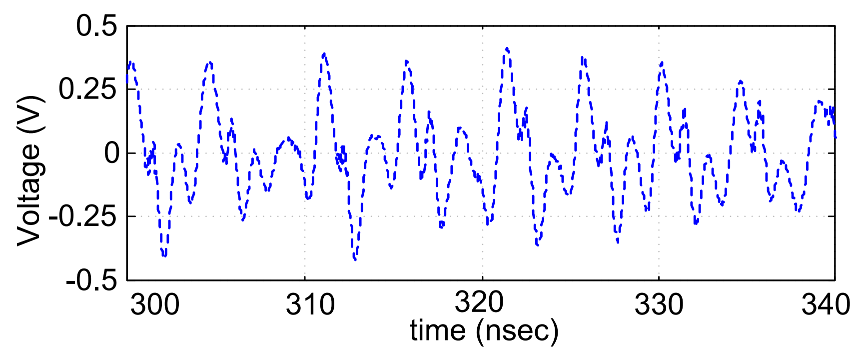
❑ Bipolar transistor BFP183w





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.

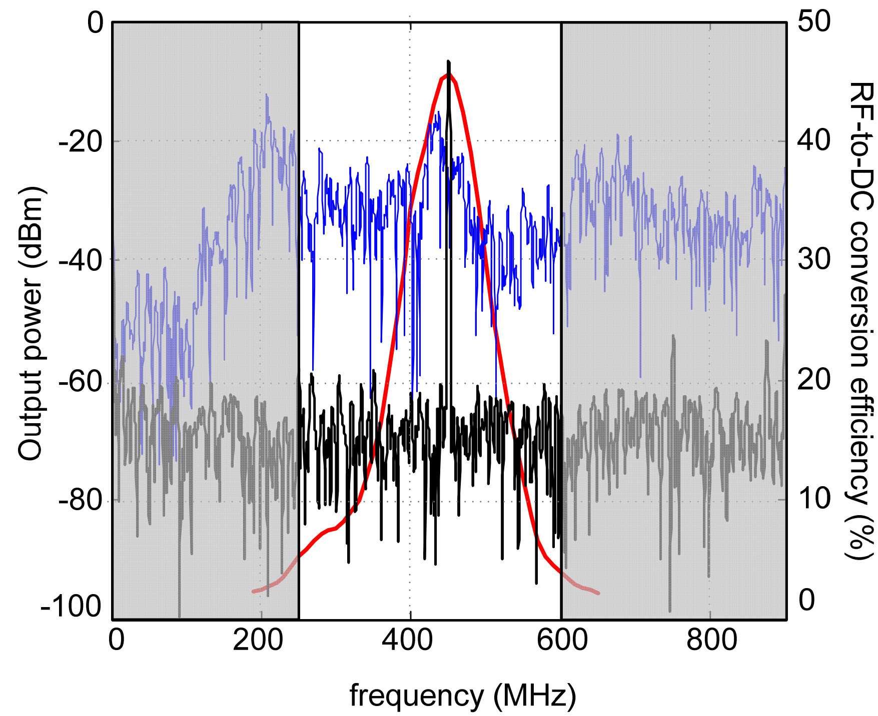
Signal Design

- ❑ 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

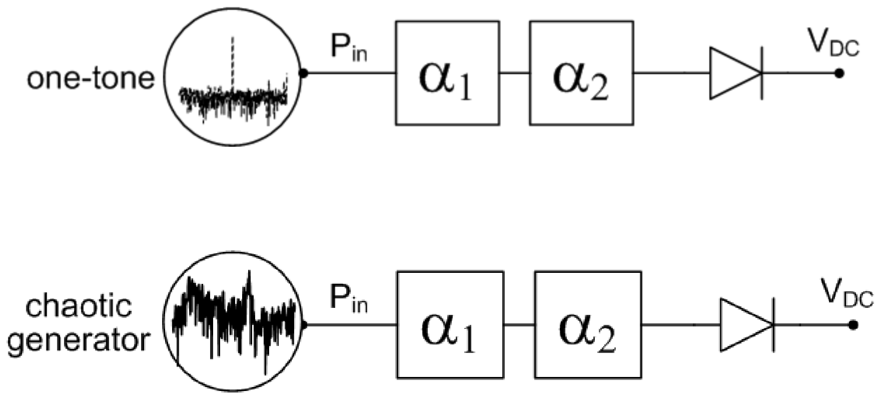
A. Collado, A. Georgiadis, "Improving Wireless Power Transmission Efficiency Using Chaotic Waveforms," in Proc. IEEE MTT-S IMS 2012, Montreal, 17-22 June 2012.

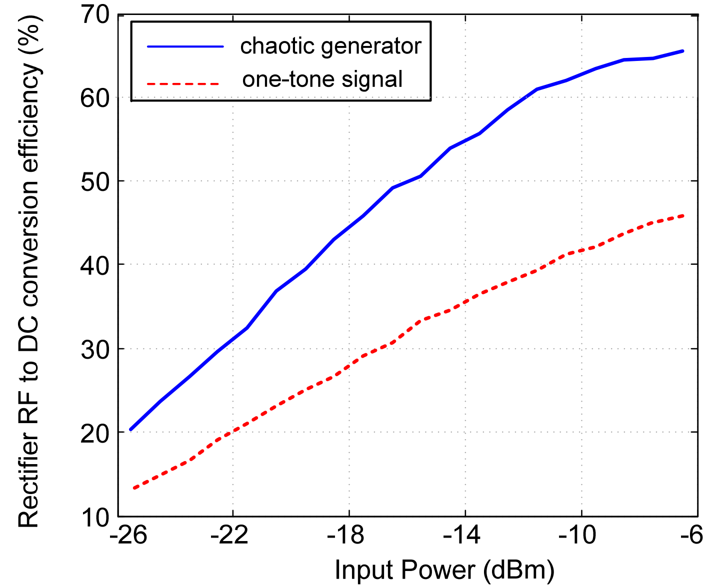
Centre Tecnològic de Telecomunicacions de Catalunya

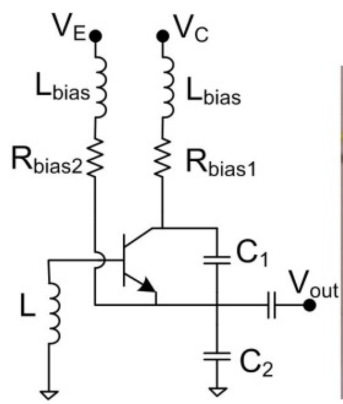
CTTC

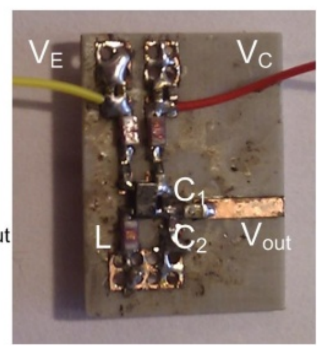
Centre Tecnològic de Telecomunicacions de Catalunya

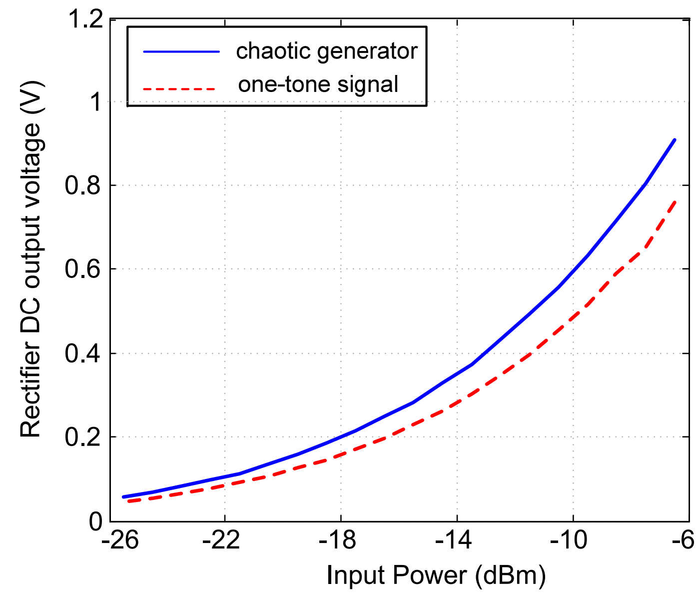
Signal Design









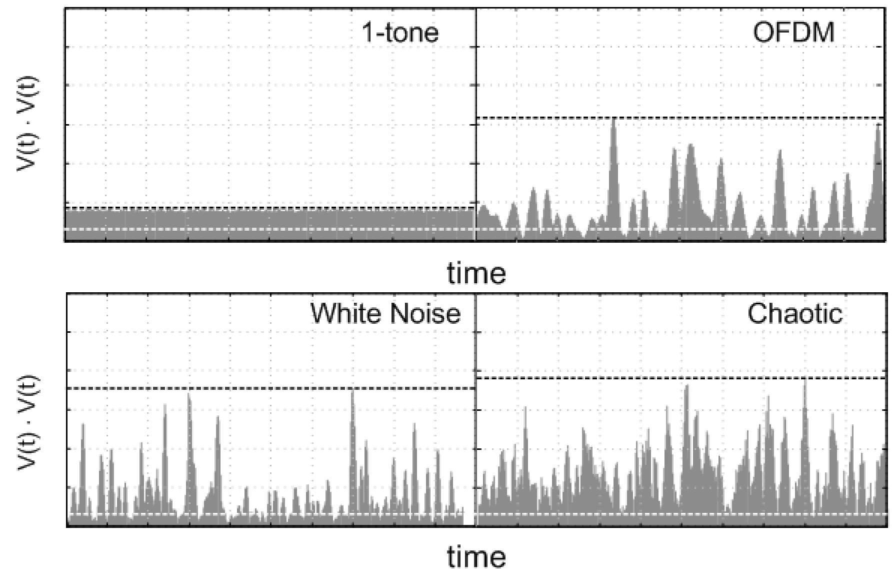


A. Collado, A. Georgiadis, "Improving Wireless Power Transmission Efficiency Using Chaotic Waveforms," in Proc. IEEE MTT-S IMS 2012, Montreal, 17-22 June 2012.

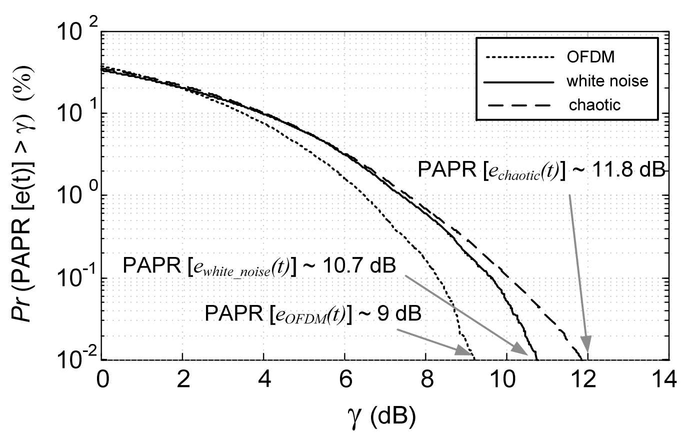
Centre Tecnològic de Telecomunicacions de Catalunya

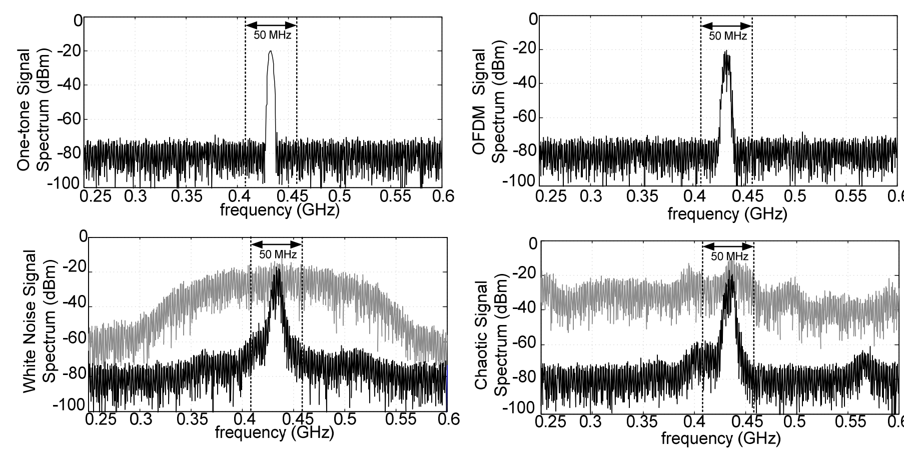
Signal Design

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



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

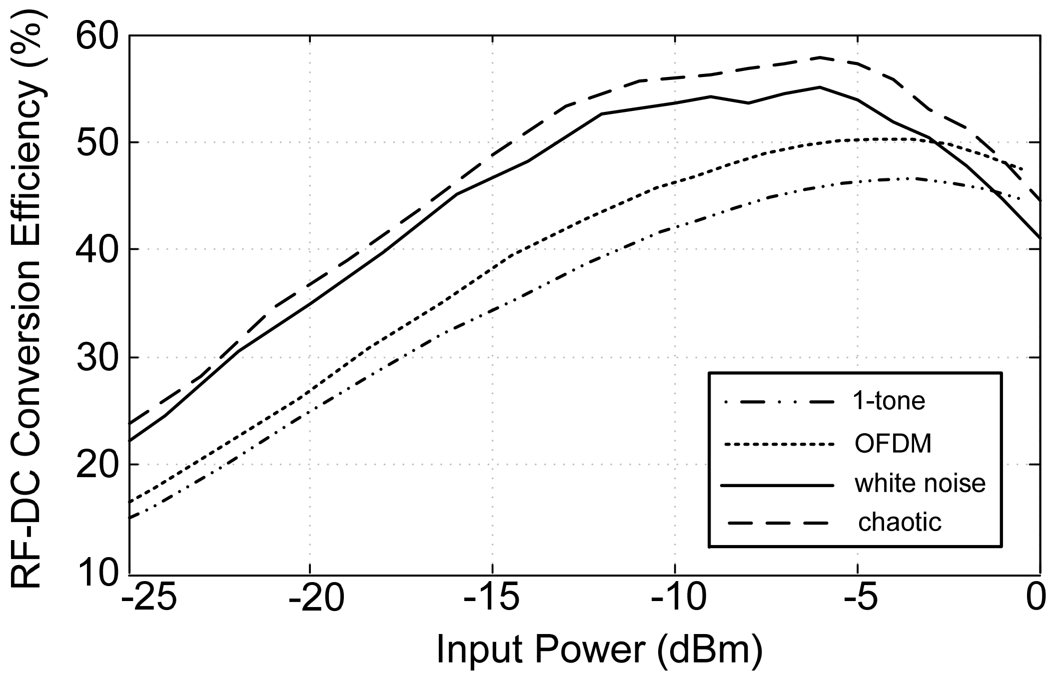




A. Collado, A. Georgiadis, 'Optimal Waveforms for Efficient Wireless Power Transmission,' IEEE Microwave and Wireless Components Letters, 2014, to appear.

Signal Design

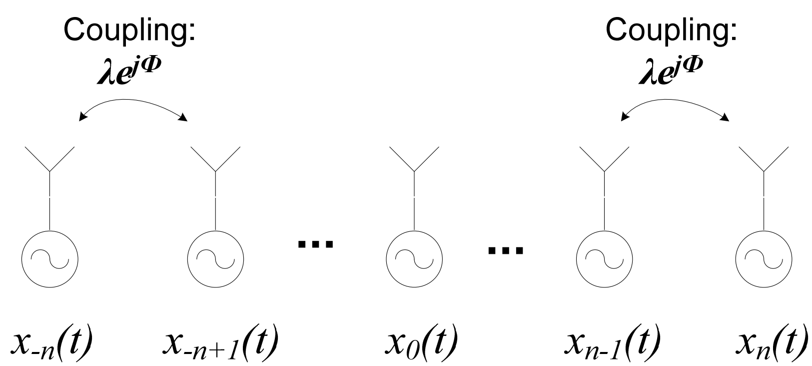
- ❑rectifier operates at 433 MHz
- ❑Skyworks SMS7630-02LF diode
- ❑output load of 5.6 KOhm



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.

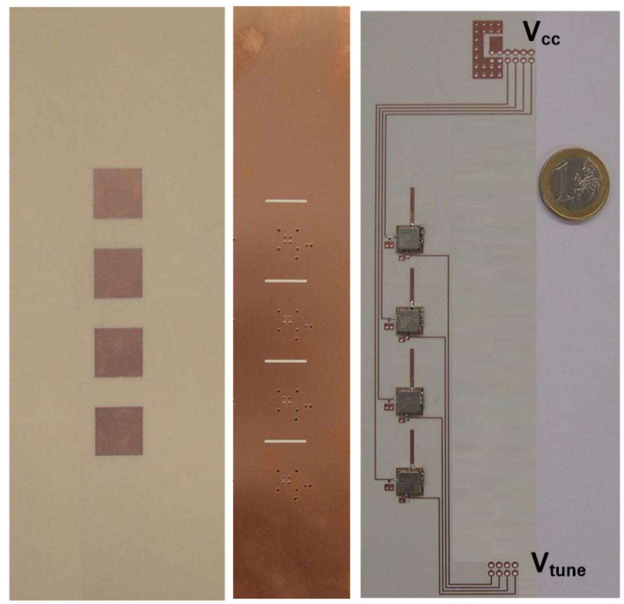
A. Boaventura, A. Collado, A. Georgiadis, N.B. Carvalho, 'Spatial Power Combining of Multi-sine Signals for Wireless Power Transmission Applications,' IEEE Transactions on Microwave Theory and Techniques, Special Issue on Wireless Power Transfer, 2014, accepted for publication

CTTC

Centre Tecnològic de Telecomunicacions de Catalunya

Signal Design

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

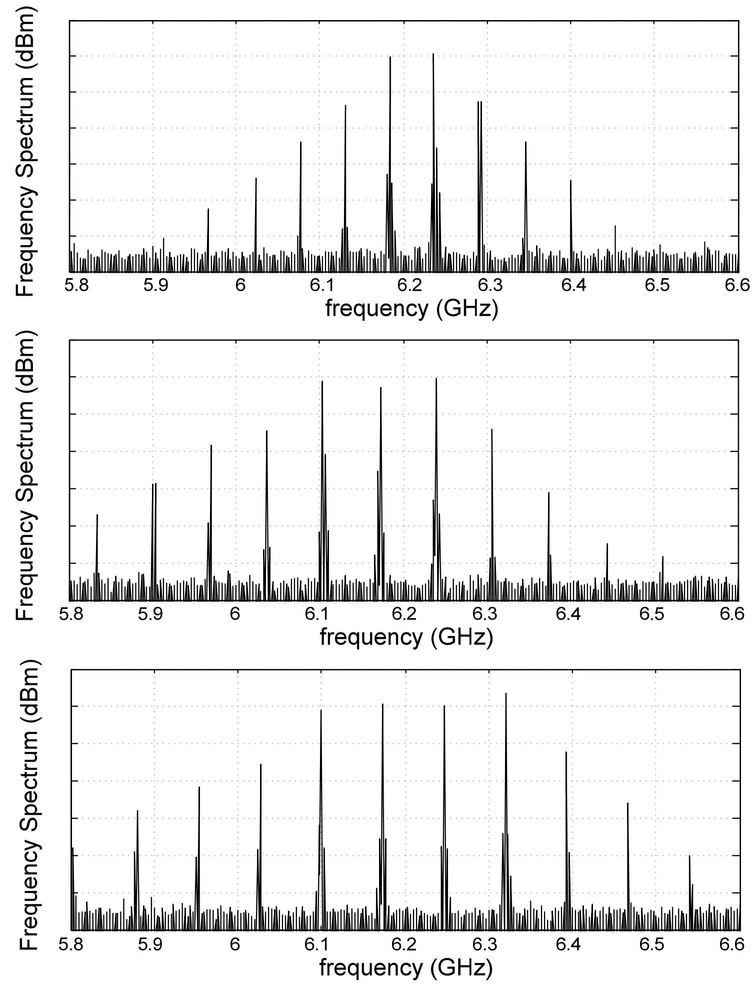


A. Boaventura, A. Collado, A. Georgiadis, N.B. Carvalho, 'Spatial Power Combining of Multi-sine Signals for Wireless Power Transmission Applications,' IEEE Transactions on Microwave Theory and Techniques, Special Issue on Wireless Power Transfer, 2014, accepted for publication

Centre Tecnològic de Telecomunicacions de Catalunya

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

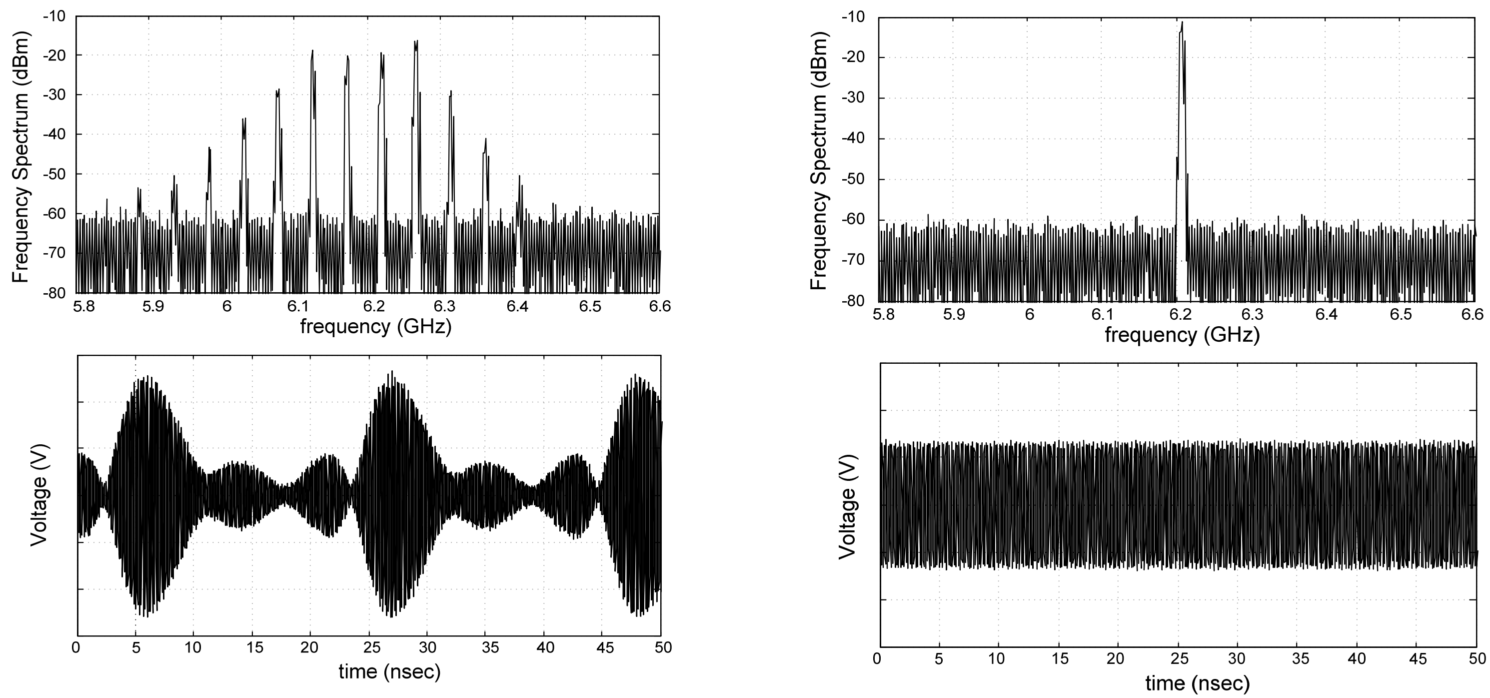


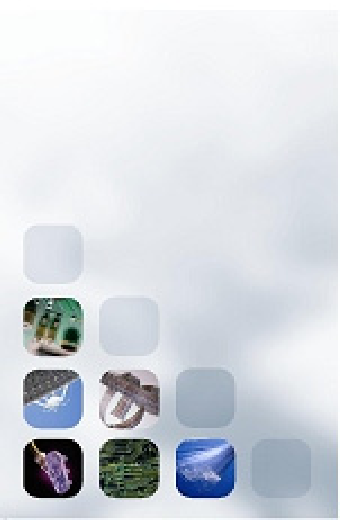
A. Boaventura, A. Collado, A. Georgiadis, N.B. Carvalho, 'Spatial Power Combining of Multi-sine Signals for Wireless Power Transmission Applications,' IEEE Transactions on Microwave Theory and Techniques, Special Issue on Wireless Power Transfer, 2014, accepted for publication

Centre
Tecnològic
de Telecomunicacions
de Catalunya

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





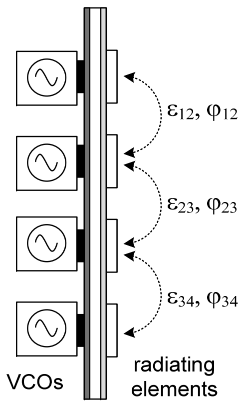
A. Boaventura, A. Collado, A. Georgiadis, N.B. Carvalho, 'Spatial Power Combining of Multi-sine Signals for Wireless Power Transmission Applications,' IEEE Transactions on Microwave Theory and Techniques, Special Issue on Wireless Power Transfer, 2014, accepted for publication

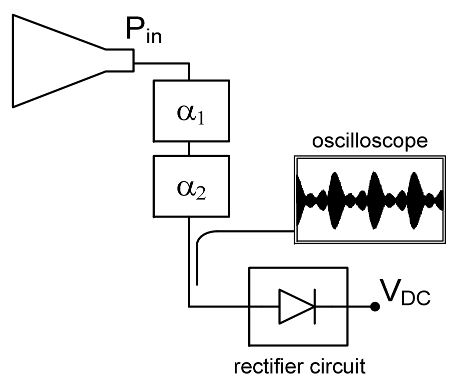
CTTC

Centre Tecnològic de Telecomunicacions de Catalunya

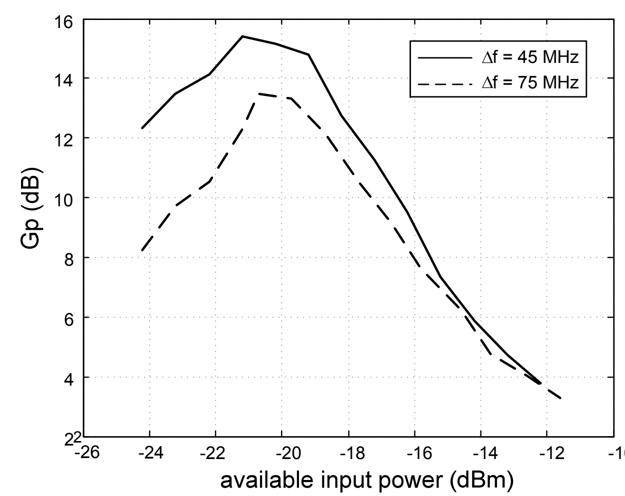
Signal Design

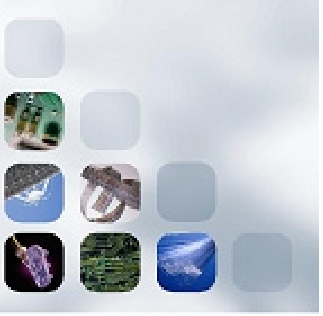
- Power gain compares the obtained DC voltage by a rectifier when using the high PAPR signal in comparison with a one-tone signal
- Improved performance when using the high PAPR mode-locked signal





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





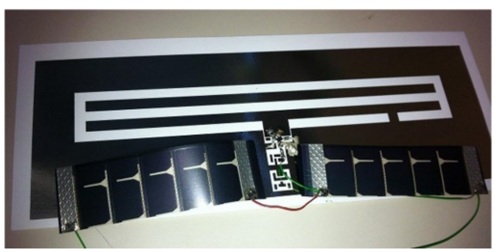
A. Boaventura, A. Collado, A. Georgiadis, N.B. Carvalho, 'Spatial Power Combining of Multi-sine Signals for Wireless Power Transmission Applications,' IEEE Transactions on Microwave Theory and Techniques, Special Issue on Wireless Power Transfer, 2014, accepted for publication

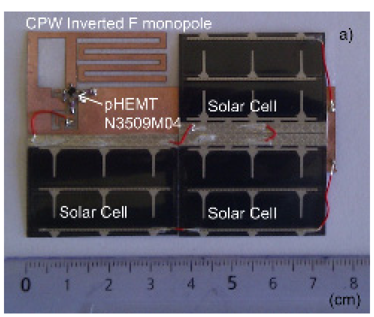
CTTC

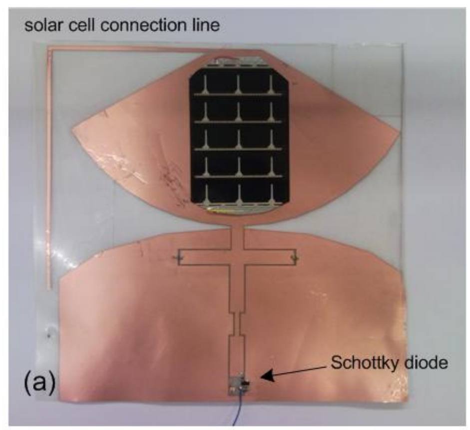
Centre Tecnològic de Telecomunicacions de Catalunya

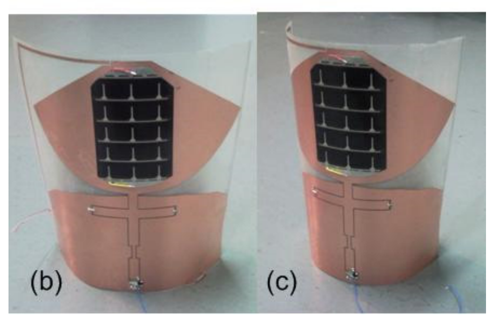
Challenges - Applications

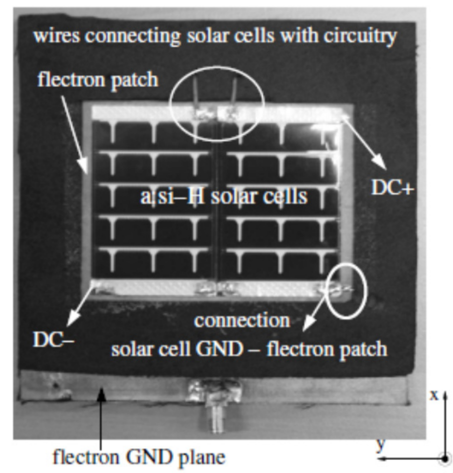
- **Multi-technology harvesters**
  - Solar antennas and rectennas
- **Flexible electronics**
  - Paper - Textile – Plastic substrates
- **Solar powered batteryless circuits**

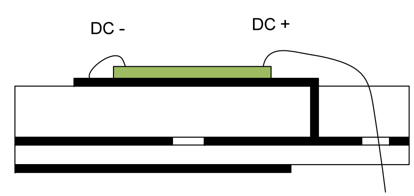






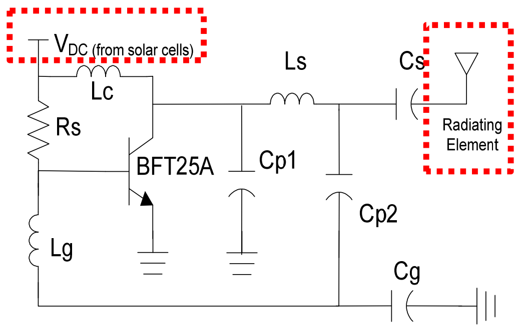


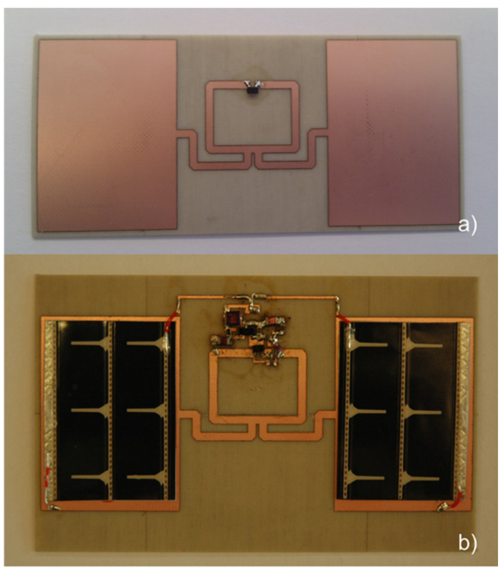




Challenges - Applications

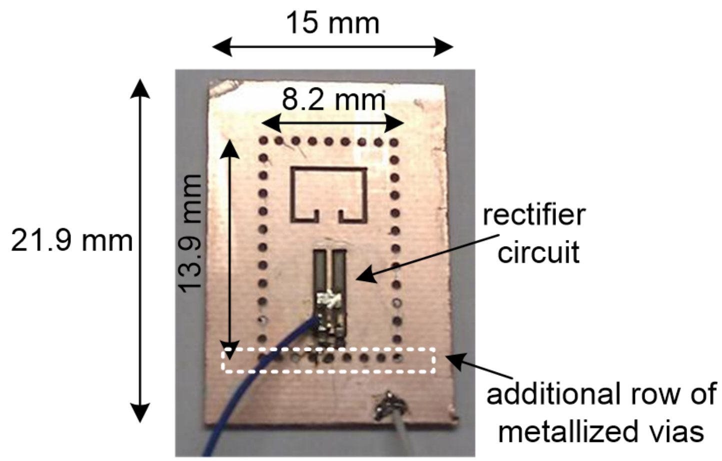
- **Solar RFID tag**
  - Solar => DC => RF
  - UHF Class-E oscillator
  - Solar antenna

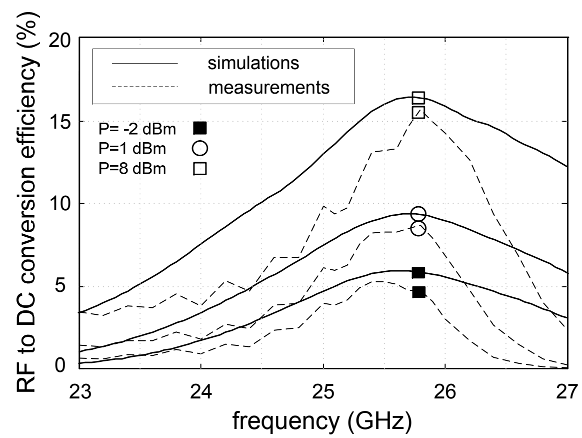




•A. Georgiadis and A. Collado, "Improving Range of Passive RFID Tags Utilizing Energy Harvesting
•and High Efficiency Class-E Oscillators," in Proc. EuCAP 2012, Prague, 26-30 March 2012.

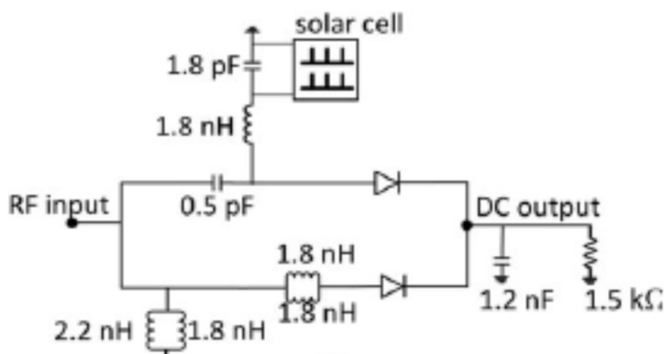
- **MMID (SIW)**
  - SIW 24 GHz rectenna
  - Integrate rectifier inside SIW cavity



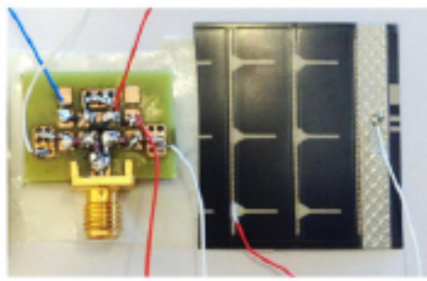


A. Collado, A. Georgiadis, "24 GHz Substrate Integrated Waveguide (SIW) Rectenna for Energy Harvesting and Wireless Power Transmission", 2013 IEEE MTT-S IMS, Seattle 2-7 June 2013.

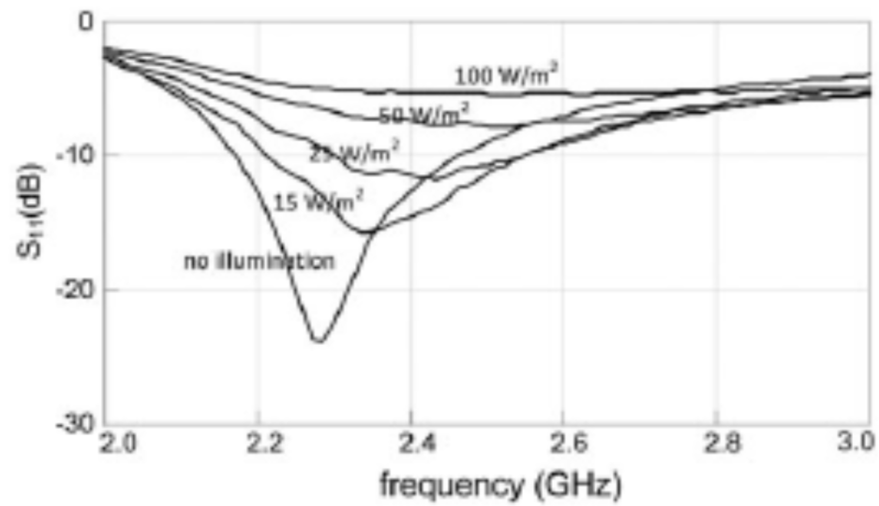
Multiple Technology Harvesters
Solar / EM

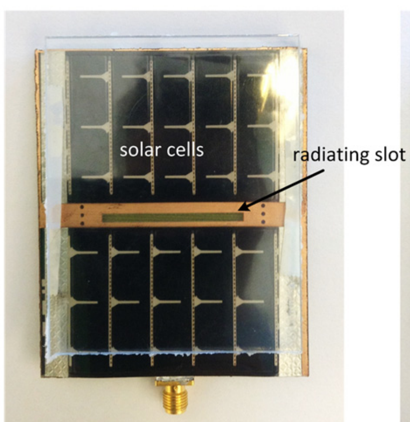


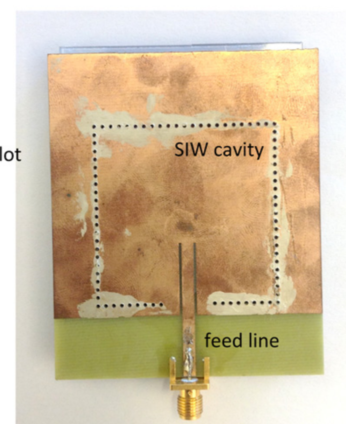
(a)

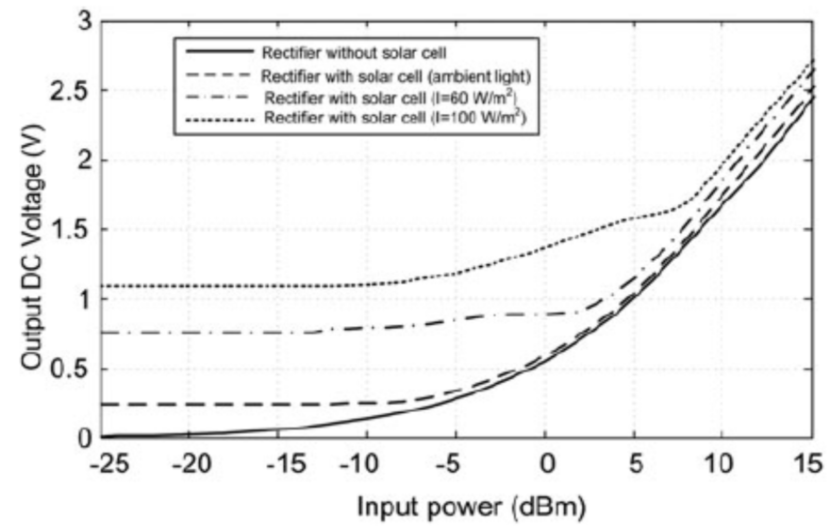


(b)





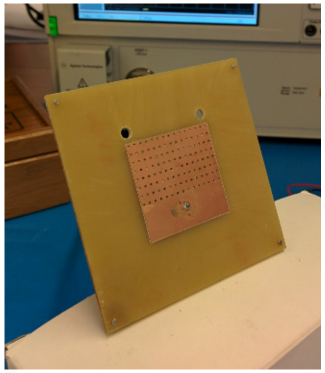


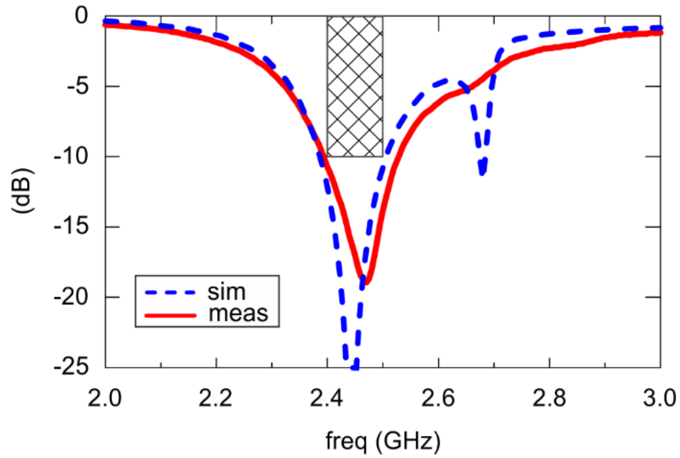


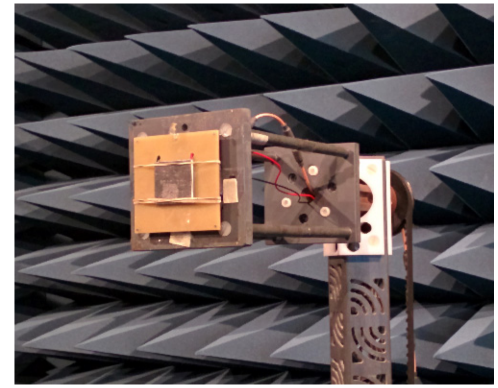
K. Niotaki, F. Giuppi, A. Georgiadis and A. Collado. Solar/EM energy harvester for autonomous operation of a monitoring sensor platform . Wireless Power Transfer, vol. 1, no. 1, pp. 44-50, Mar 2014.

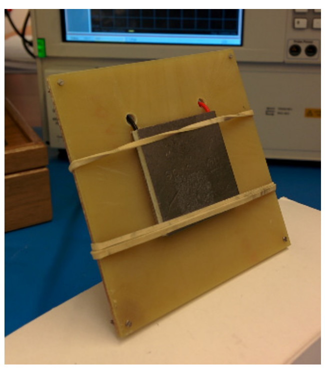
Centre Tecnològic de Telecomunicacions de Catalunya

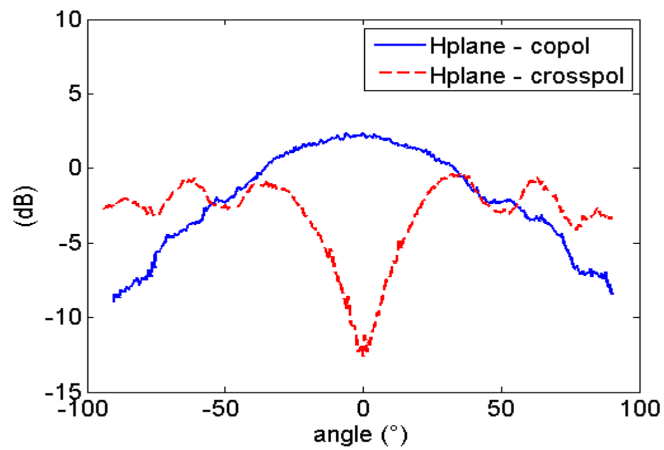
Multiple Technology Harvesters Thermal / EM

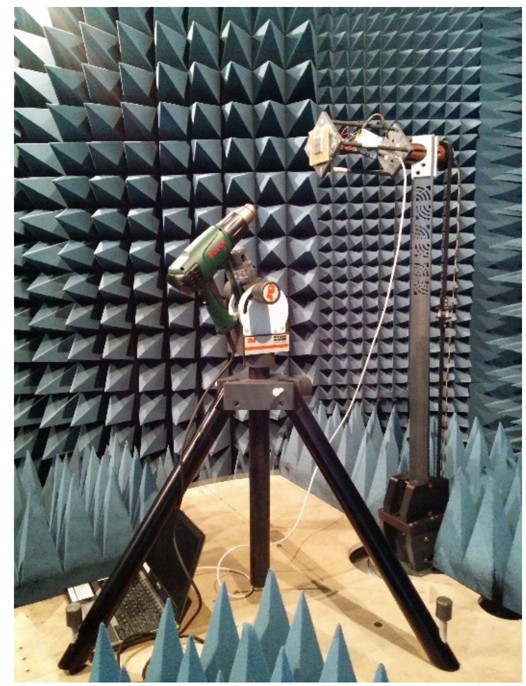












Centre Tecnològic de Telecomunicacions de Catalunya

M. Virili, A. Georgiadis, K. Niotaki, A. Collado, F. Alimenti, P. Mezzanotte, L. Roselli, N.B. Carvalho, 'Design and Optimization of an Antenna with Thermo-Electric Generator (TEG) for Autonomous Wireless Nodes,' in Proc. 2014 IEEE RFID-TA, Tampere, Finland, 8-9 Sep 2014

CTTC

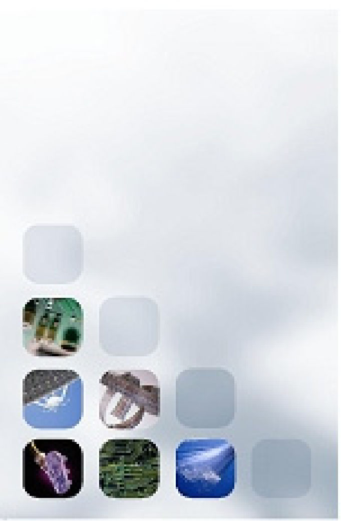
Centre Tecnològic de Telecomunicacions de Catalunya

Conclusion

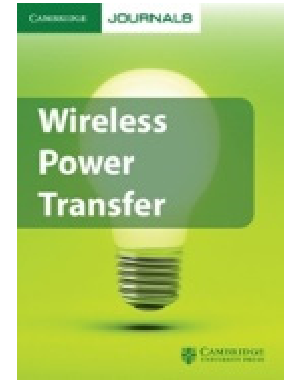
- Multi-band rectennas allow wider application
- Reactive networks capable of minimizing rectenna efficiency sensitivity to load variation
- High PAPR leads to higher efficiency
- Spatial power combining for WPT transmitters

CTTC

Centre
Tecnològic
de Telecomunicacions
de Catalunya



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.

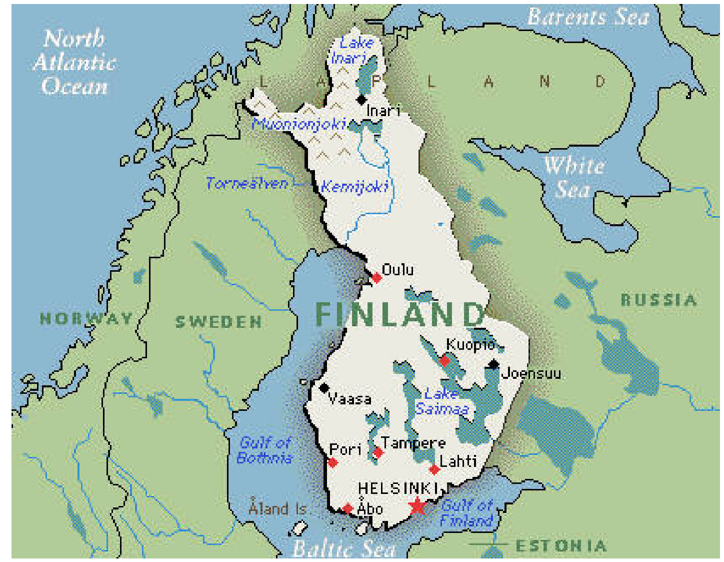
Vol. 1. No. 1. March 2014

Vol. 1. No. 2. Accepting contributions .....

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.

2014 IEEE RFID-TA Conference
8-9 Sep 2014, Tampere, Finland

http://www.rfid-ta2014.fi/



CTTC

Centre Tecnològic de Telecomunicacions de Catalunya

Acknowledgement

IEEE MTT Society

EU Marie Curie project
SWAP, FP7 251557
http://www.fp7-swap.eu/

Acknowledgment:

K. Niotaki, A. Collado,	CTTC
A. Boaventura, N. Carvalho,	Univ. of Aveiro
S. Kim, M.M. Tentzeris	Georgia Tech.

Apostolos Georgiadis
Department of Microwave Systems and Nanotechnology
Senior Researcher
Centre Tecnologic de Telecomunicacions de Catalunya (CTTC)
Avda Carl Friedrich Gauss 7
08860 Castelldefels - Barcelona Spain

Email: ageorgiadis@cttc.es
Google: https://sites.google.com/site/apostolosgeorgiadis1/home

Centre Tecnològic de Telecomunicacions de Catalunya