RF and microwave energy harvesting for space applications

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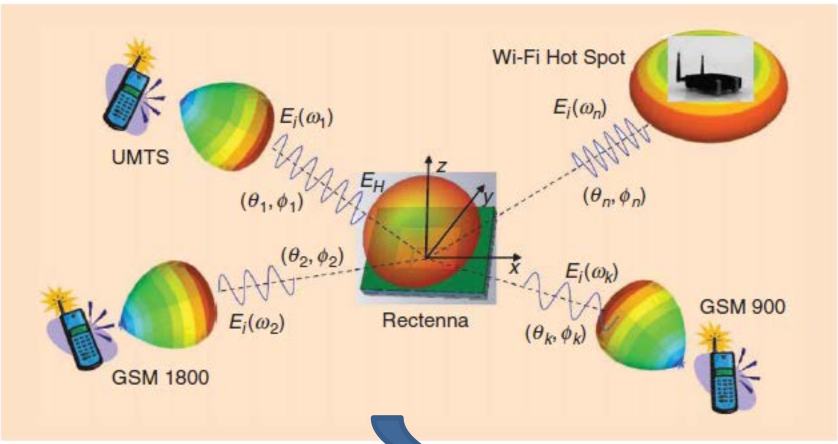
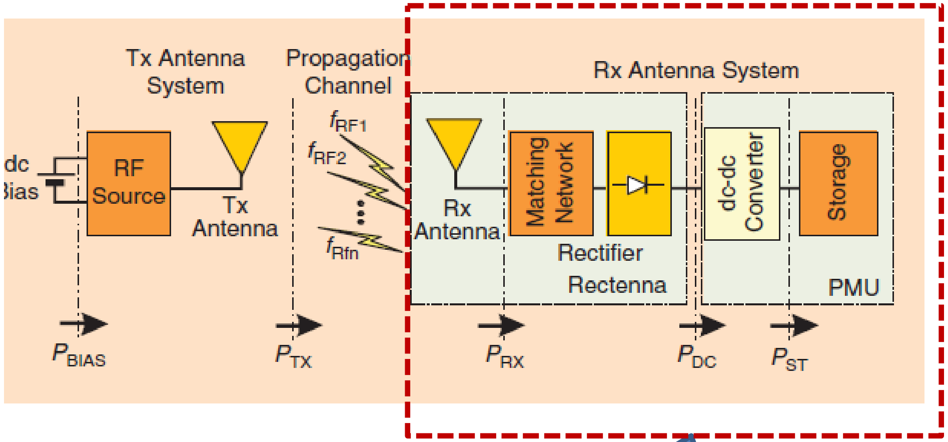
Outline

- Concepts :
  - RF & Microwave energy harvesting
  - Wireless power transmission
- Targeted application
- Electromagnetic environment
- Design requirements
- RF & Microwave rectenna:
  - Topologies & Design
  - Experimental results
- Conclusion and perspective

Energy harvesting & wireless power transmission





EH (left) & WPT* by using RF waves (right)*

** from '**Smart Solution in Smart Places**', IEEE Microwave Magazine (May 2016)*

$$P_{Rx} = P_{Tx} + G_{Tx} + G_{Rx} - P_L - M_{Ant} \quad \text{(dB)}$$

$$P_{DC} = \eta \cdot P^{EH}{}_{RF} = \eta \cdot P^{WPT}{}_{Rx}$$

Targeted application: SHM

- Structural health monitoring (thermal, mechanical, material damage, etc.) of satellite panels
- Requires the use of the sensors
- The sensors should be *interrogated wirelessly and energetically autonomous* (battery not recommended due to weight, harsh environment and lifetime issues)

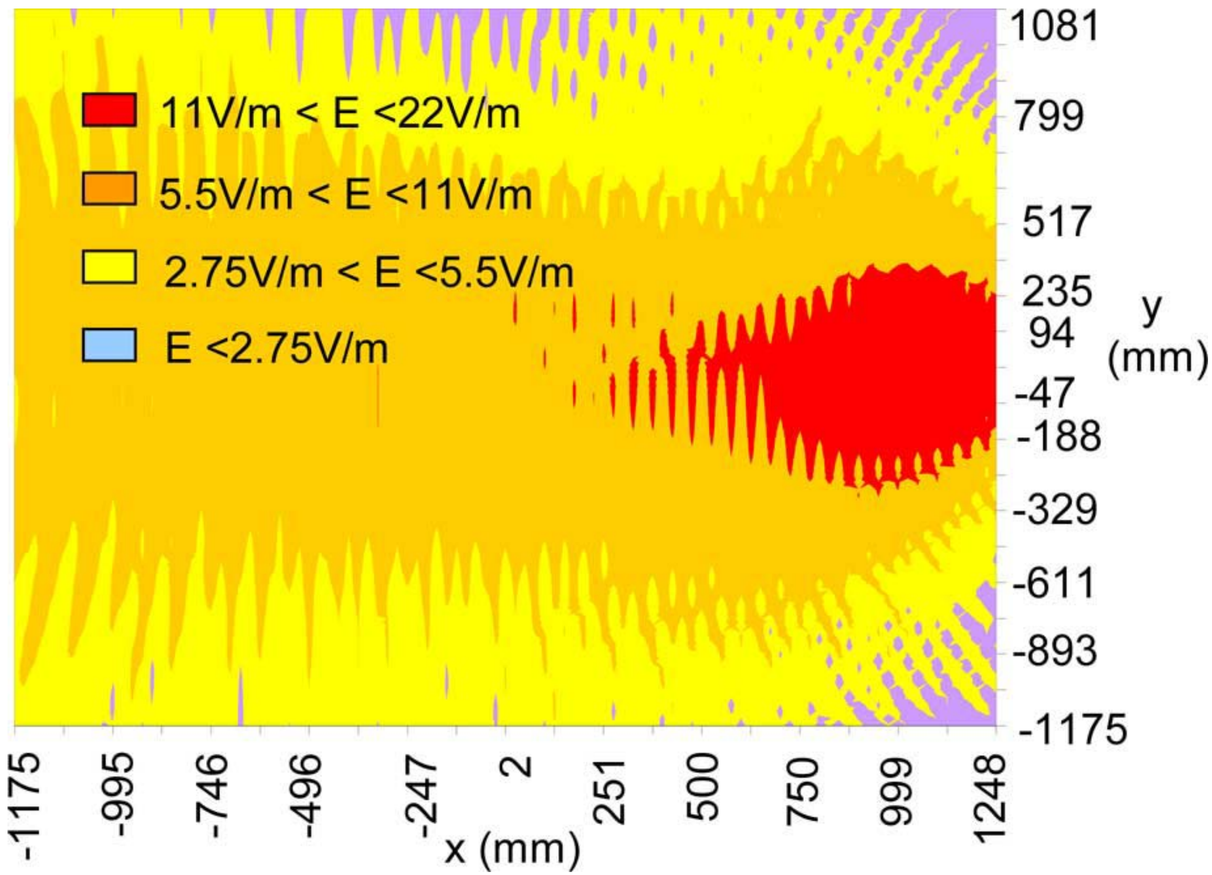
Electromagnetic environment

Spacebus Class C satellite

Satellite Antennas :

- Parabolic
- Gregorien/Cassegrain
- High radiated power (~100 W)
- Subject to spill-over losses

Electromagnetic environment

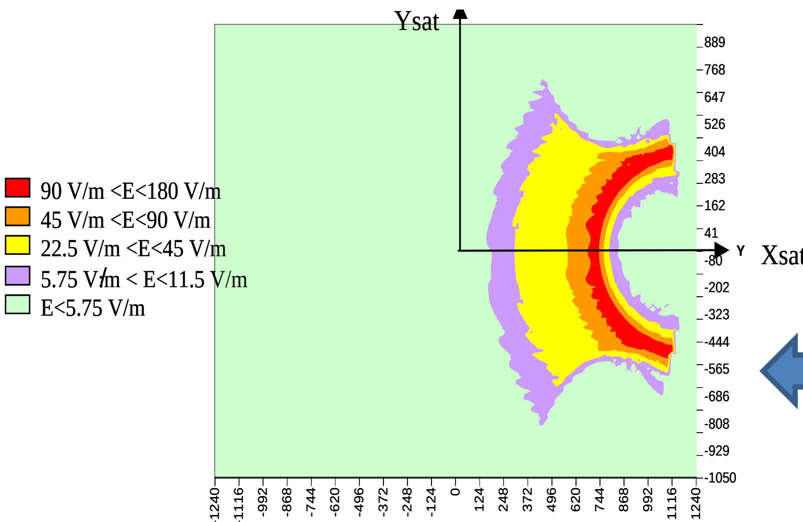


E-field distribution (peak value) on a lateral panel at 3.5 GHz (**C-band**).

Radiated power: 90 W

Electromagnetic simulation using GRASP software from TICRA*
Near field refraction/diffraction are taken into account (curtesy of TAS & CNES)

Electromagnetic environment



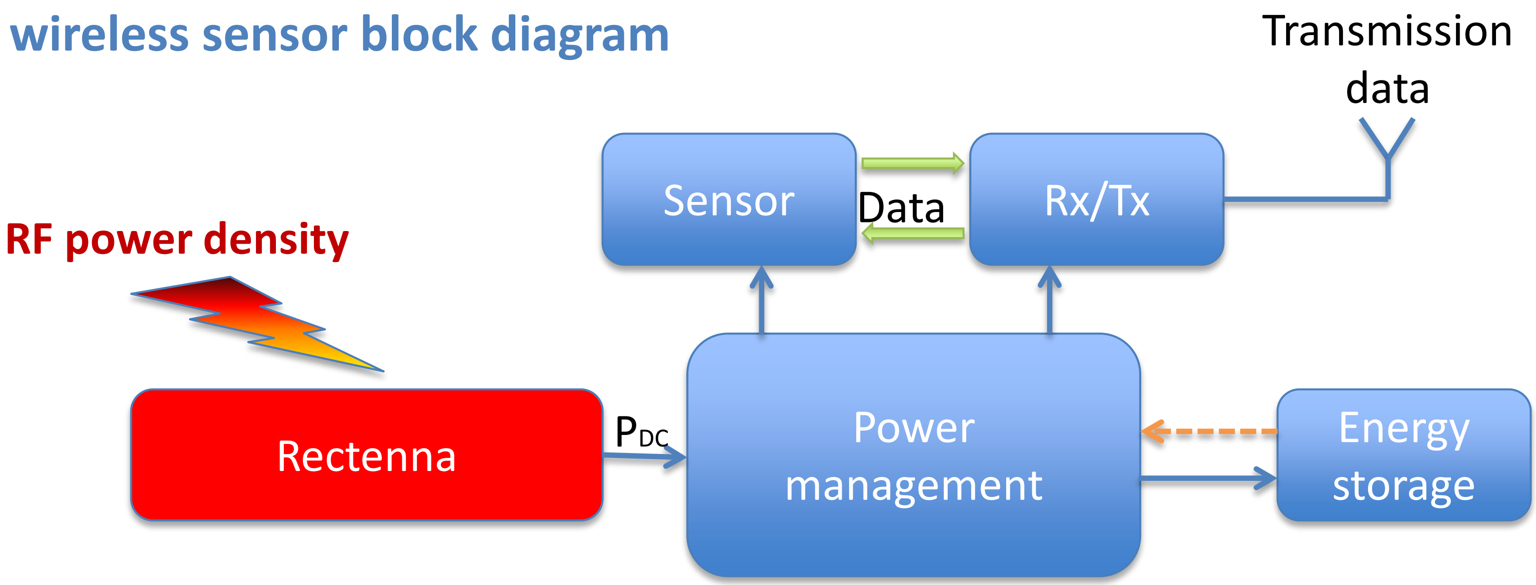
A. Takacs, H. Aubert, S. Fredon, L. Despoisse, H. Blondeaux, "Microwave power harvesting for satellite health monitoring," *IEEE Trans. on Microwave Theory Tech*, Vol.: 62, Issue: 4 , April 2014

		Niveau max	
Lieu	Bande	V/m	V/m RMS
Lateral panels Panneaux latéraux	C (cas 1)	16	11,3
	C (cas 2)	22	15,5
	Ku (cas 1)	12	8,5
	Ku (cas 2)	20	14,1
	Ka (cas 1)	12	8,5
	Ka (cas 2)	12	8,5
Earth panel Panneaux Terre	C	56	40
	X	70	49,5
	Ku (cas 1)	150	106
	Ku (cas 2)	26	18,5
	K (cas 1)	180	127
	K (cas 2)	130	92
Panneaux Solaires	C	< 1	< 1
	Ku	< 1,5	< 1,5

Solar panels

Autonomous wireless sensor

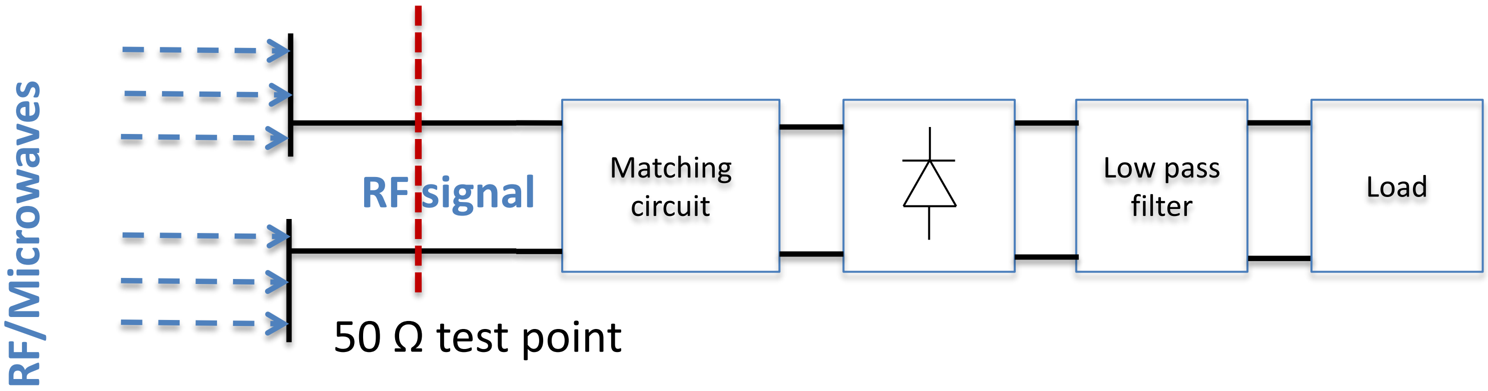
- **wireless sensor block diagram**



- RF power constantly available
- Sensor consumption : few µW
- Power management (consumption/losses) : few µW
- Transceiver : ~1mW(ultra low power) or more

Rectenna topology

- Rectenna : Antenna + Rectifier



- Antenna

  Convert the electromagnetic energy to RF signal

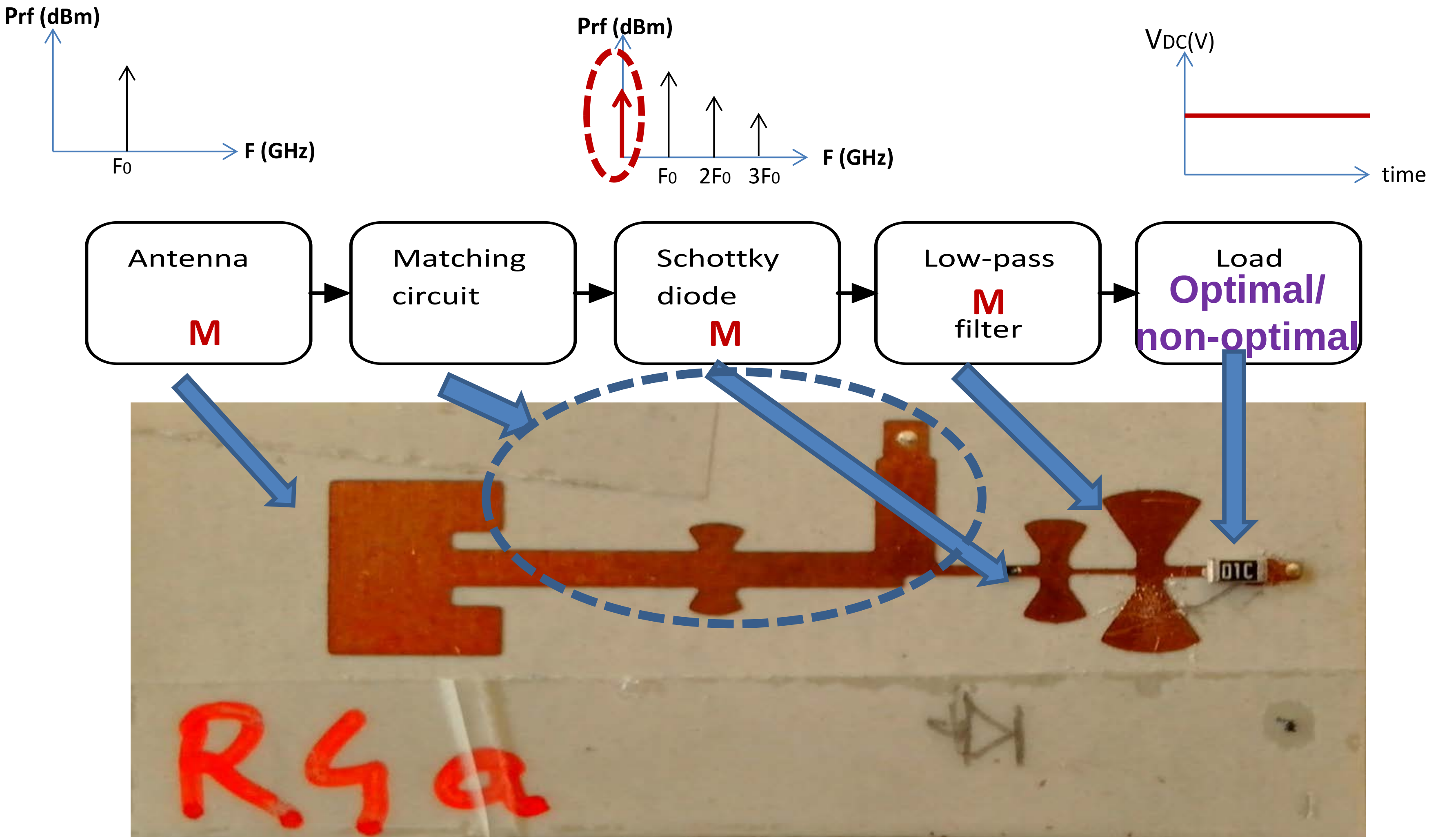
- Rectifier

  Convert the RF signal to DC signal

- Goals :
  - **DC voltage > threshold**
  - **Increase the RF-to-DC conversion efficiency**
  - **Increase the available DC power**

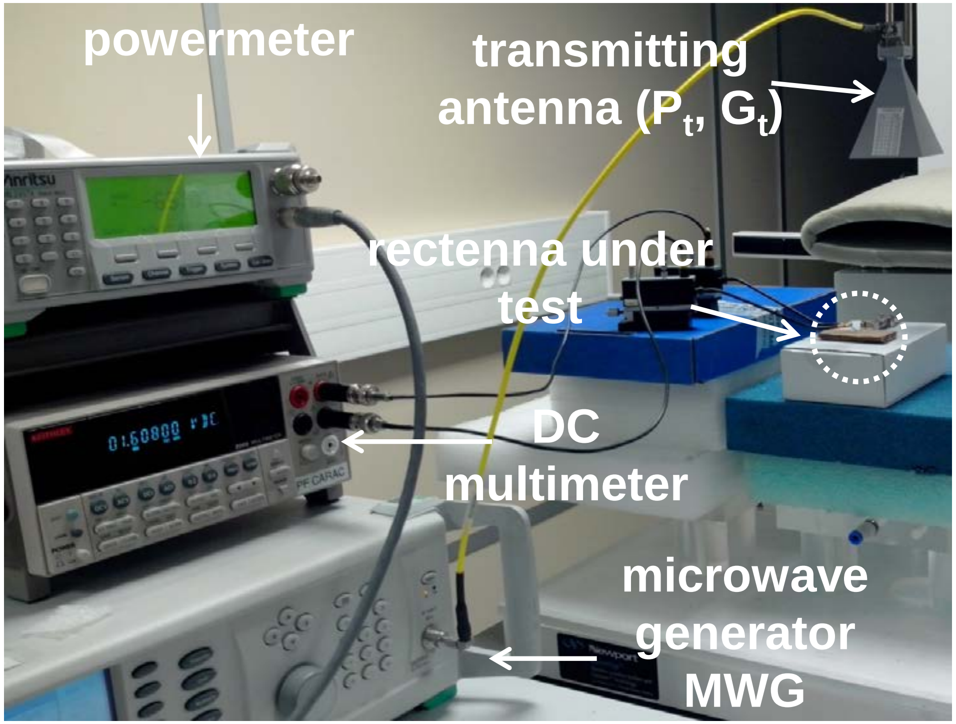
$$\eta(\%) = 100 \cdot \frac{P_{DC}}{P_{RF}}$$

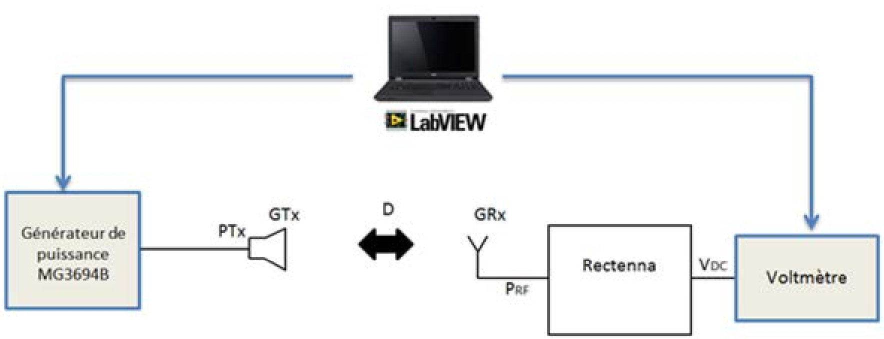
Microwave rectenna topology



M: mandatory

Rectenna: experimental setup





- DC power

$$P_{DC} = \frac{V_{DC}^2}{R}$$

- E : Electric field

$$E = \frac{\sqrt{30.P_t.G_t}}{d}$$

- S : power density

$$S = \frac{E^2}{120.\pi} = \frac{30.P_t.G_t}{d^2.120.\pi}$$

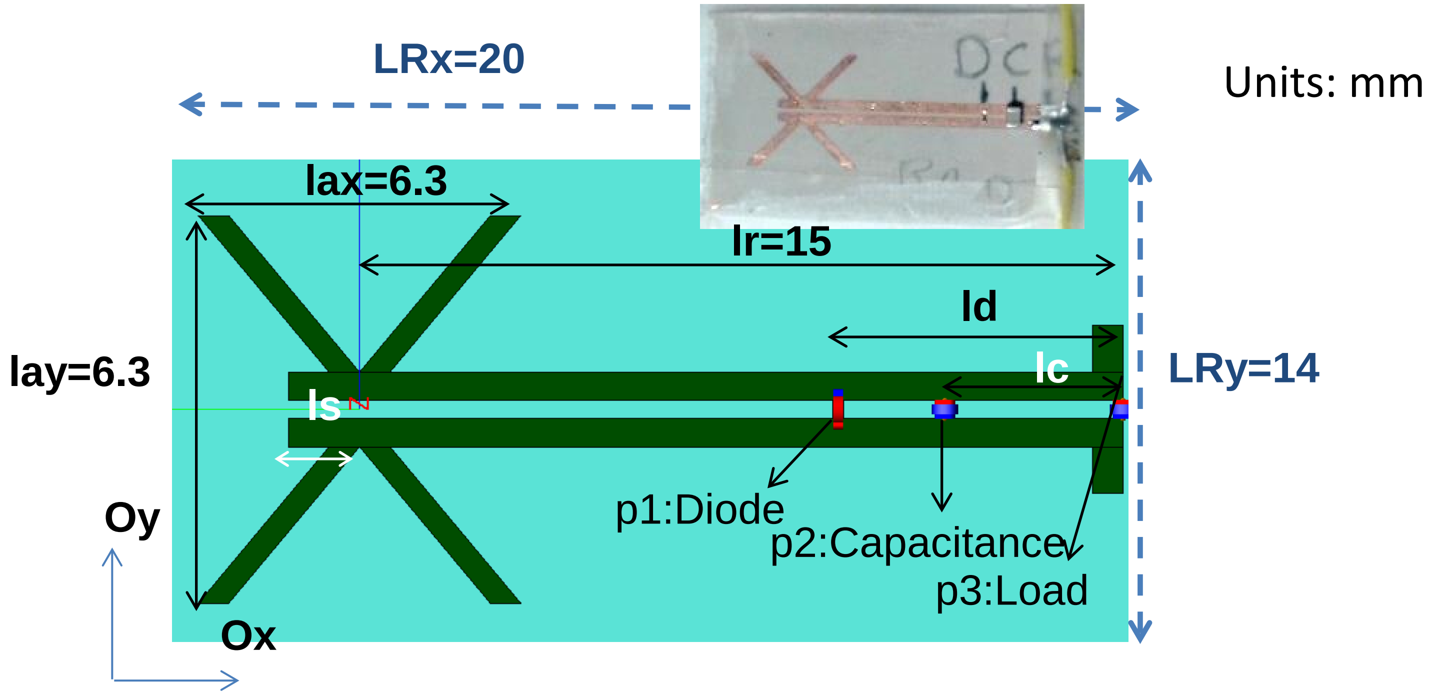
- Aeff : effective area

$$Aeff = Gr\frac{\lambda^2}{4\pi}$$

- η : efficiency

$$\eta\ (\%) = 100\frac{P_{DC}}{P_{RF}} = 100\frac{P_{DC}}{S.A_{eff}}$$

Rectenna: CDA topology

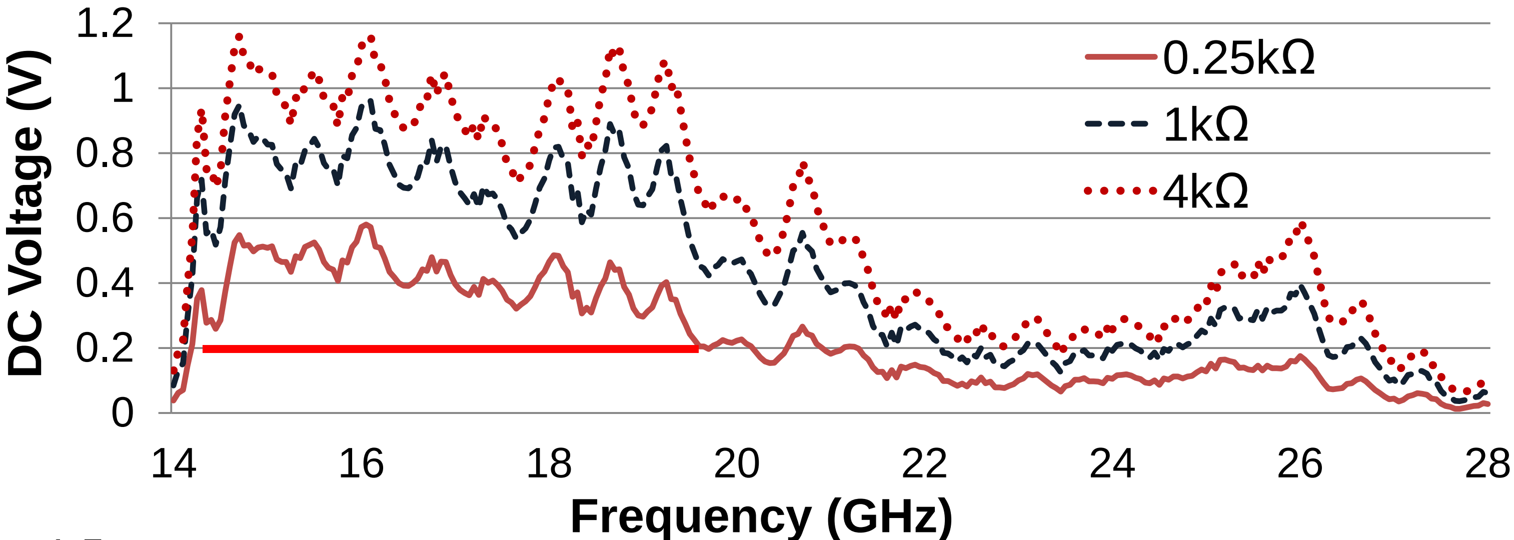


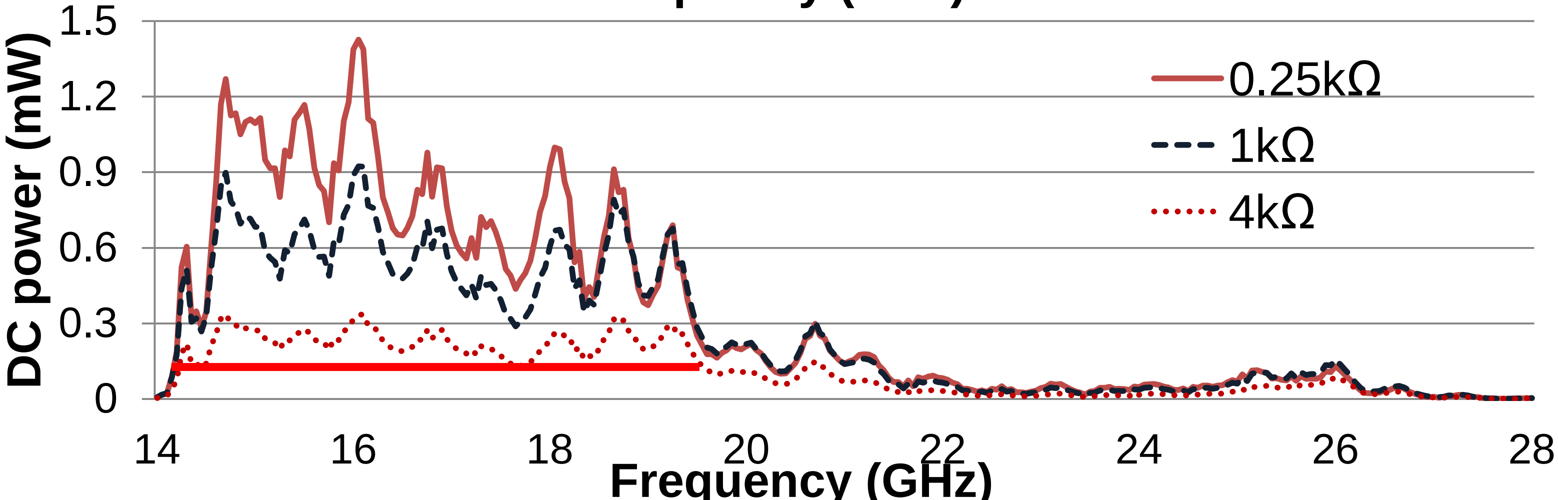
- ✓ Rectenna uses a cross dipole antenna* (CDA)
- ✓ The matching between rectifier & antennas is realized by properly controlling the input impedance of the antenna and the distance 'lr-ld' between antenna & diode

A. Takacs, H. Aubert, S. Charlot, S. Fredon, L. Despoisse, "Compact Rectenna for Space Application", in Proc. of IEEE IMS'2014, Tampa, USA, 1-6 June, 2014

CDA rectenna: results

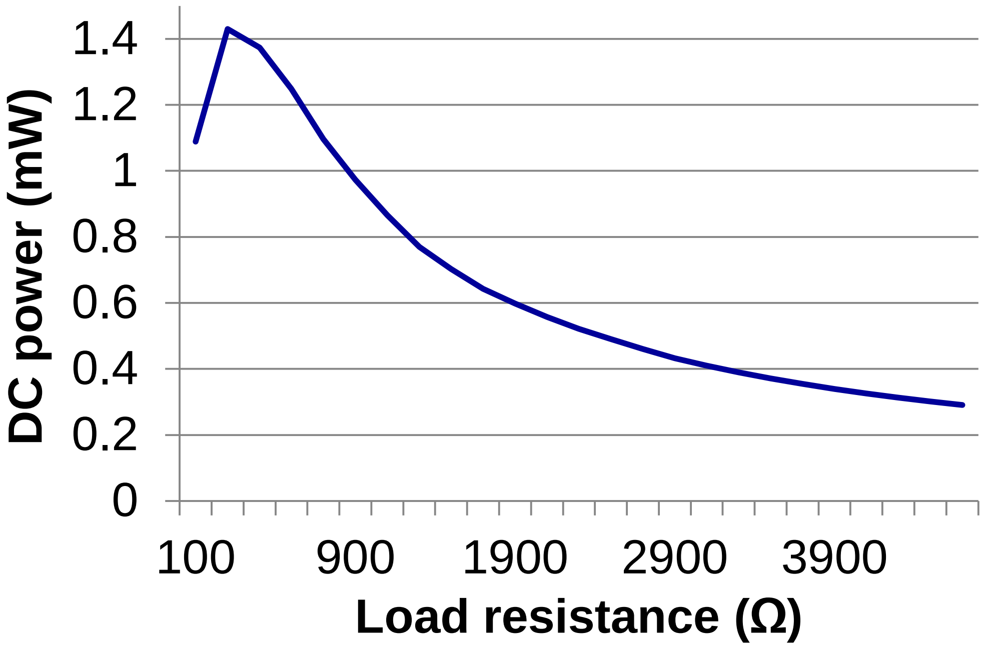
E~69.28 V/m





CDA rectenna: results

Optimum load



The maximum DC power (1.43mW) is obtained for RL=250Ω at f=16.05GHz efficiency: 55.3%.

Efficiency:

$$\eta = \frac{P_{DC}}{S \cdot A_G} \cdot 100$$

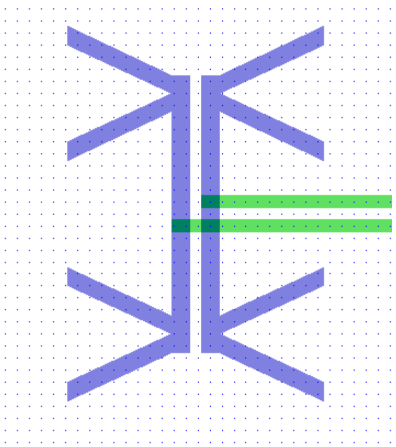
$$S = \frac{E^2}{120 \cdot \pi} \cdot 100 = \frac{30 \cdot P_t \cdot G}{d^2 \cdot 120 \cdot \pi} \cdot 100$$

E~69.28 V/m

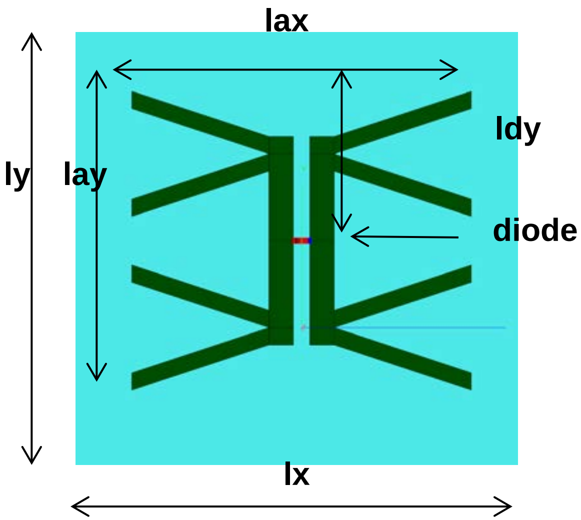
A_G~0.523 cm²

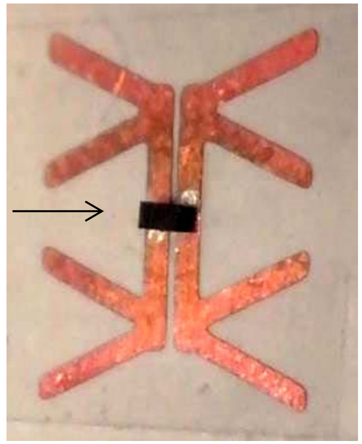
Rectenna surface : 2.8 cm²

Rectenna: 2CDAA topology



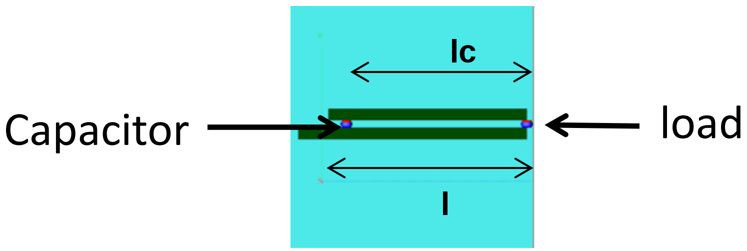
Top side





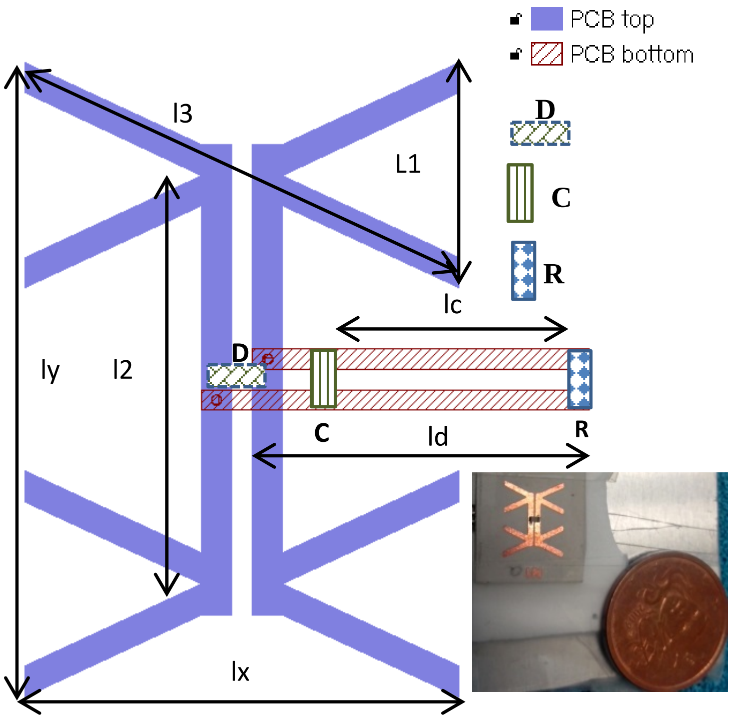
Schottky diode:
SMS201 from Aeroflex Metelics

Back side

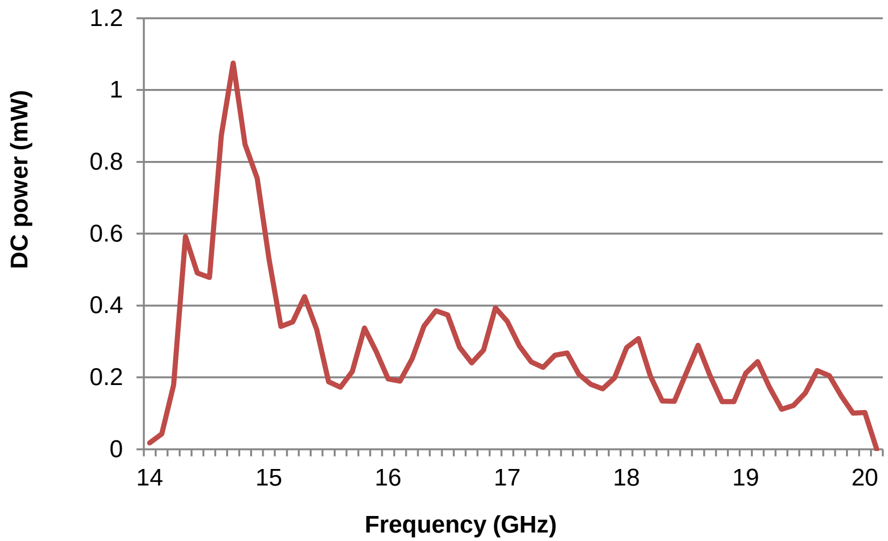


- ✓ Rectenna uses a **C**ross **D**ipole **A**ntenna **A**rray (**CDAA**)
- ✓ We adopt a non-resonant matching technique to provide a wideband behavior to the rectenna : matching implemented by properly controlling the input impedance of the antenna and the distances ‘lc’ and ‘l’

2CDAA rectenna: results



use a low cost SMS201 diode



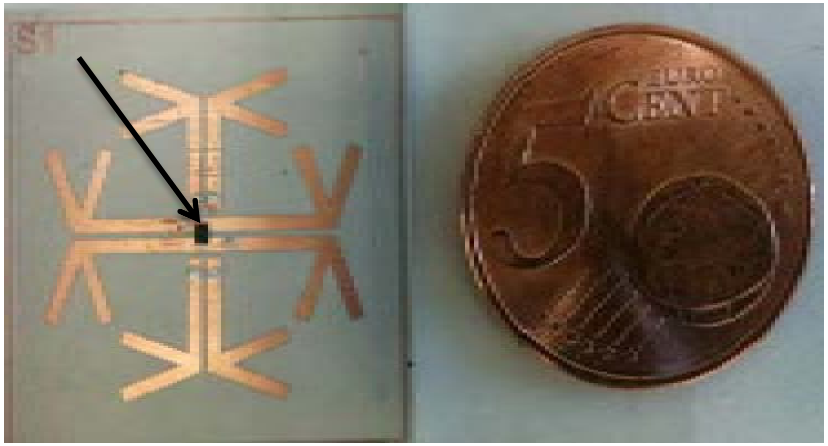
DC power as function of frequency for E≈60 V/m (S~955 µW/cm^2)

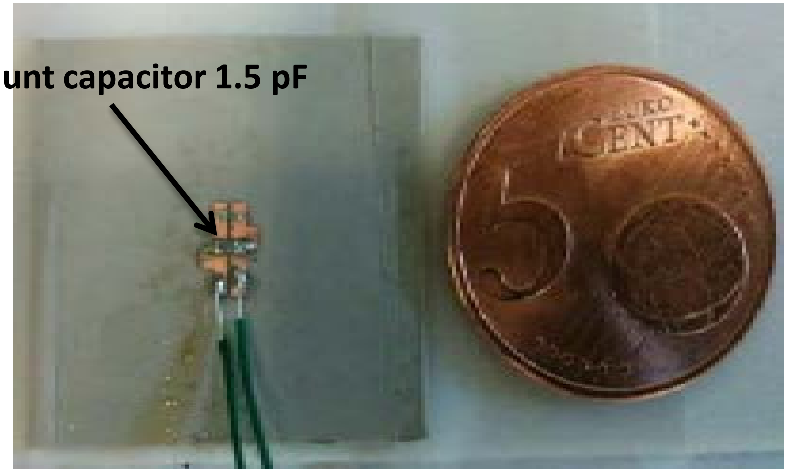
η_2=66% by taking into account the simulated gain of G_R=7.4 dBi

A. Takacs & al, "Ultra-Compact Ku band Rectenna", IMS'2015

4CDAA rectenna: results

SMS7630 diode





PCB top

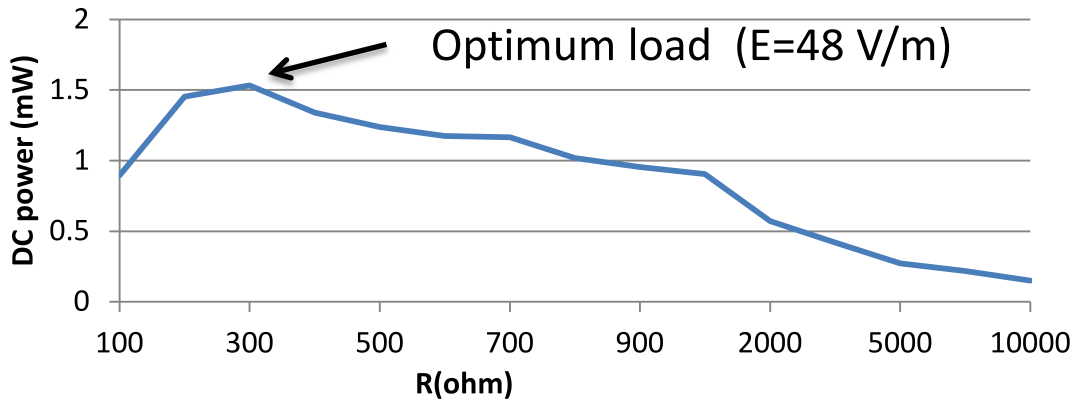
PCB botom

A. Okba, S. Charlot, P-F Calmon, A. Takacs, H. Aubert, Multiband Rectenna for microwave applications, IEEE Wireless Power Transfer Conference, Aveiro, Portugal, 5-6 May 2016

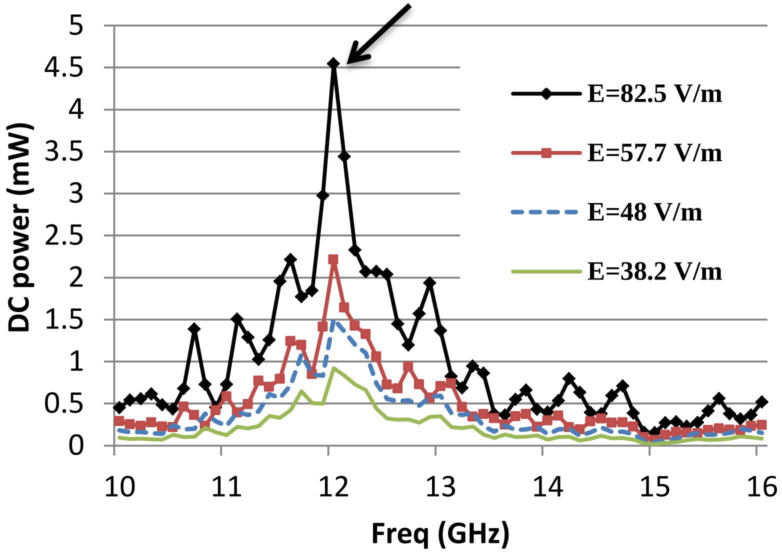
A. Okba, S. Charlot, P-F Calmon, A. Takacs, H. Aubert, Cross dipoles rectenna for microwave applications, European Microwave Conference, London, UK, 3-7 October 2016

A. Okba, A. Takacs, H. Aubert, S. Charlot, P-F. Calmon, "Multiband rectenna for microwave applications", Comptes Rendus Physique, Vol. 18, Issue 2, pp 107-117, Feb. 2017

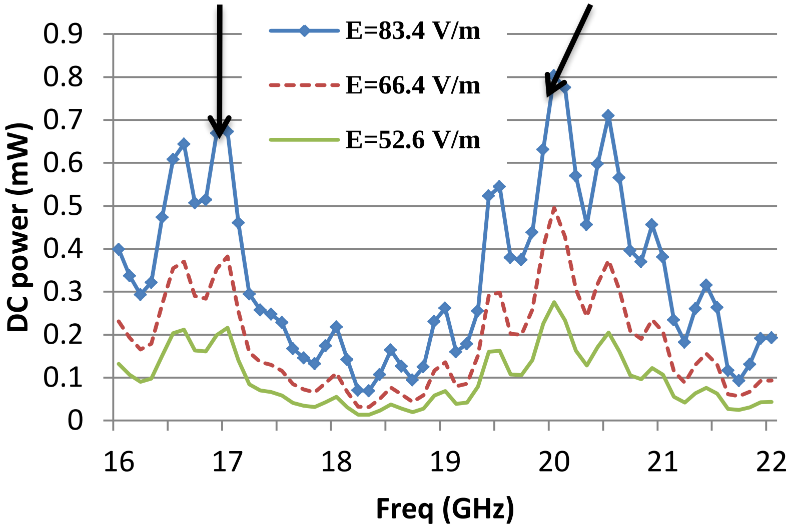
4CDAA rectenna: results



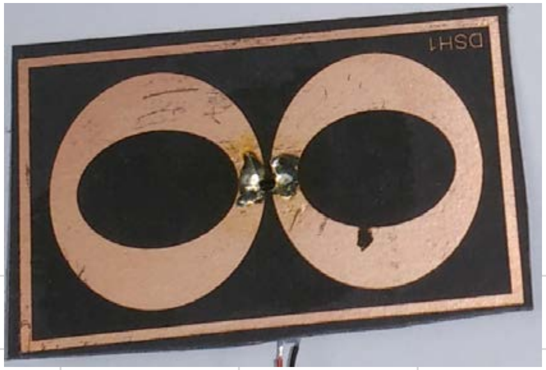
Efficiency : 40%



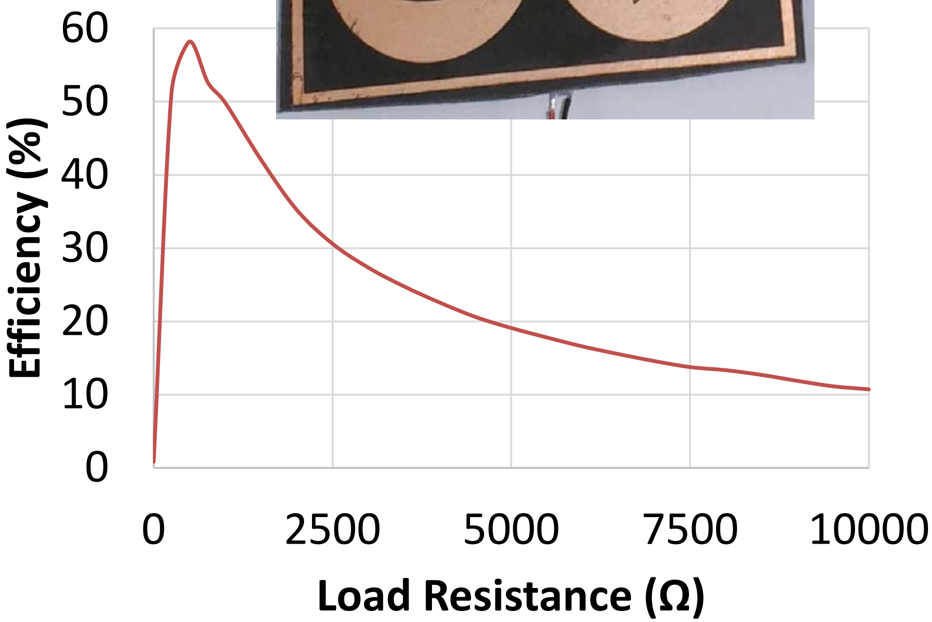
Efficiency : 11.7% Efficiency : 20%



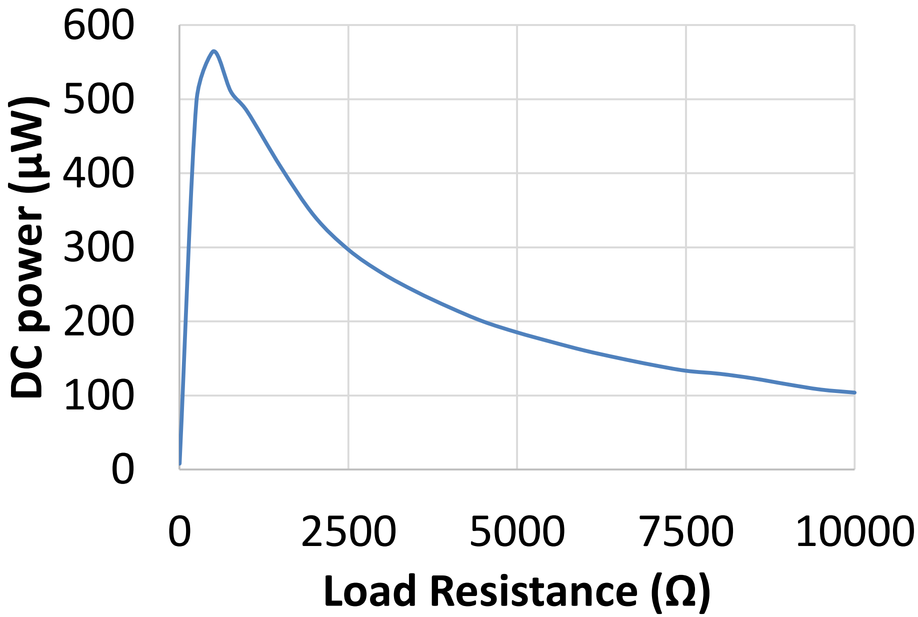
C-band rectenna:



Compact structure:
Surface is 16% of the square wavelength at 3.25 GHz



RF-to-DC conversion efficiency in % (incident power density: S=33.9 µW/cm^2, frequency: f=3.25 GHz)



Measured harvested DC power (incident power density: S=33.9 µW/cm^2, frequency: f=3.25 GHz)

A. Takacs, A. Okba, H. Aubert, D. Granena, M. Romier, A. Bellion, 'Compact C-band Rectenna for Satellite Applications', IEEE WPTC'2018, June 2018 Montreal, Canada

Conclusion

- using compact rectennas and COTS components we can harvest powers in the range of the mW (/used diode)
- design of the microwave rectenna is not an easy task despite of the ‘simplicity’ of the topology
- intensive simulations (electromagnetic & circuital) are needed
- prototyping and testing is mandatory at such frequencies

Perspective

- (fully) qualify our rectenna for space applications
- design and test a 'complete' autonomous wireless sensors powered by our rectenna
- use the wireless power transmission concept to power deep space probe & robots operating in dark areas
- use the wireless power transmission concept for flying (nano and cube) satellite constellation

Thanks you for your feedback