Energy Harvesting and Wireless Power Transfer Towards Autonomous Wireless Sensors and RFIDs

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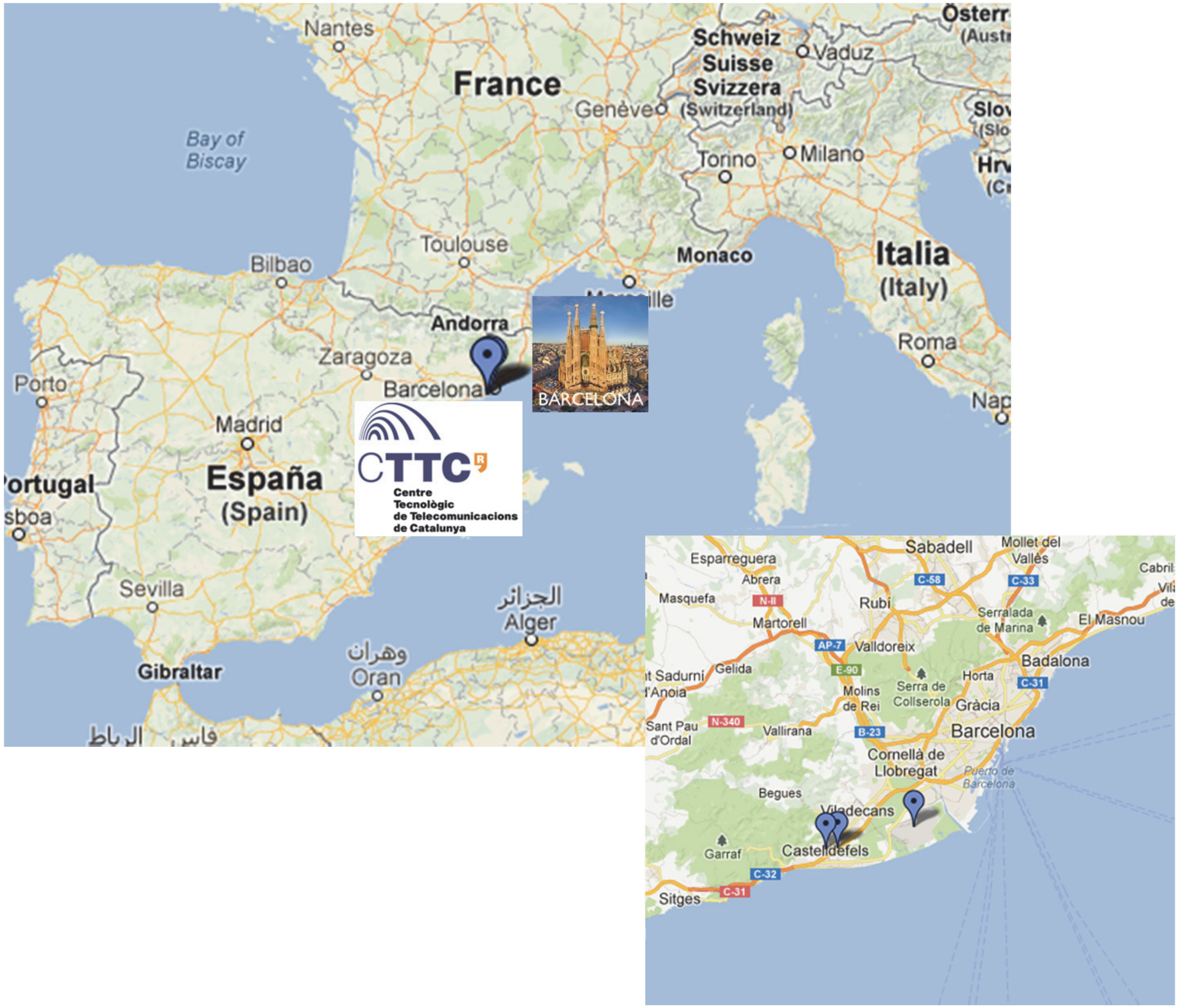
Outline

- Introduction
- Motivation
- Energy harvesting solutions and challenges
    - Solar, Mechanical,
      Thermal, Electromagnetic
- Energy harvesting and Wireless Power Transfer
    - Integration of Harvesting Modules
    - RF energy harvesting challenges
- Conclusion

Introduction



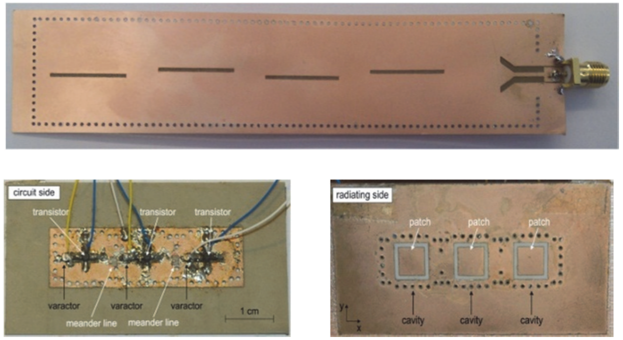
Introduction

- Centre Tecnologic de Telecomunicacions de Catalunya
  - Founded in 2001
  - Research Staff: 45 Ph.D. and 25 M.Sc.
- Four Research Divisions
  - Communication Networks, Systems, Technologies & Geomatics
- Communication Technologies
  - Department of Microwave Systems and Nanotechnology

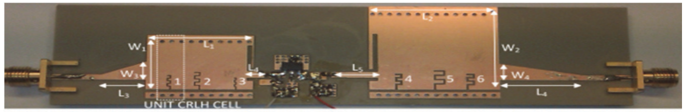
Introduction

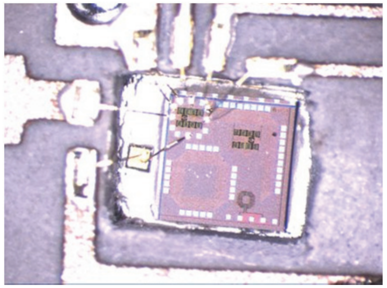
Active microwave circuit design

- **Energy Harvesting and RFID**
- Inkjet printed RF circuits and sensors
- Oscillator design including integrated CMOS oscillators
- Active antennas, phased arrays retro-directive arrays
- Substrate Integrated Waveguide (SIW)

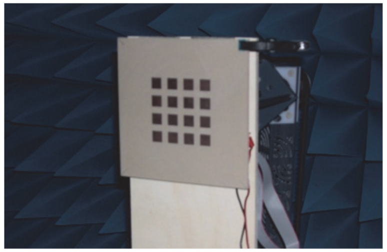


SIW circuits.

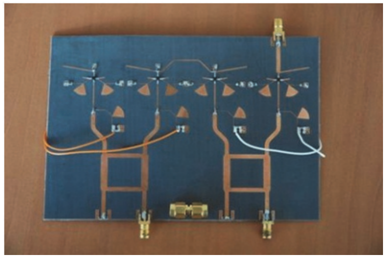




CMOS VCO for UWB-FM



C-band Coupled Oscillator Reflectrarray prototype



S-band retro-directive array

Motivation

- Ubiquitous sensor networks
  - Monitoring (environment, wild-life), security, health…
    - Low power, conformal and low profile circuit topologies
    - Low cost (manufacturing, material and maintenance)
- Autonomous operation
    - Operating with high efficiency
    - Minimize dissipated power / maximize harvested power
- “Green” networks
    - Environmental friendly materials and fabrication (Spent batteries pose a waste management concern)

Motivation

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

Motivation

Energy Sources	**Harvested power examples**	**Conditions**
Light / Solar	60 mW	6.3 cm x 3.8 cm Flexible solar cell AM1.5G Sunlight (100 mWcm^{-2}) [1]
Kinetic Mechanical	20 mW	PMG-FSH Electromagnetic transducer [2]
Thermal	0.52 mW	Thermoelectric Generator TEG [3]
Electromagnetic	0.0015 mW	Ambient power density 0.15 μWcm^{-2} [4]

[1] Silicon Solar Inc., Flexible Solar Panels 3V, http://www.siliconsolar.com/flexible-solar-panels-3v-051282-p-500992.html.

[2] Perpetuum, http://www.perpetuum.com/.

[3] MicroPelt Inc., TEG MPG-D751. http://www.micropelt.com.

[4] A. Georgiadis, G. Andia, and 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, July 2010.

Motivation

Human Body Sources	**Total available power from body**	**Available power for harvesting**
Body heat	2.8W - 4.8 W	0.2-0.32 W (neck brace)
Breathing band	0.83 W	0.42 W
Walking	67 W	5.0-8.3 W

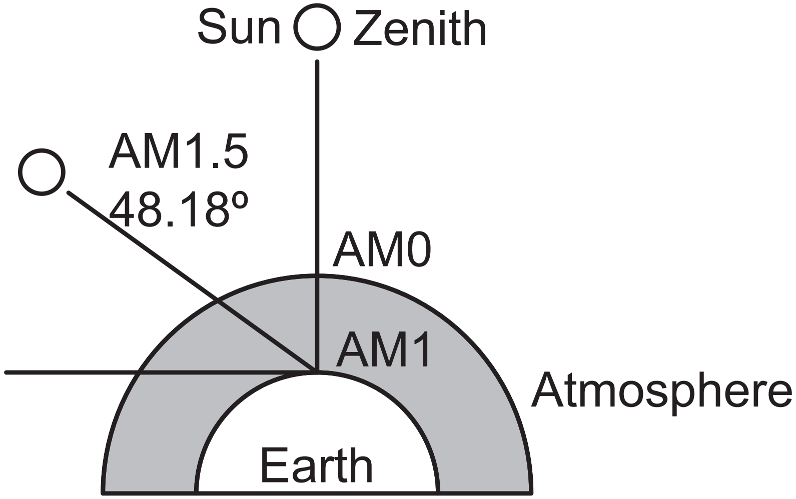
Thad Starner, 'Human powered wearable computing', IBM systems journal, vol. 35, no. 3-4, 1996

Solar energy harvesting

- ***Photovoltaic Effect (Observed by Becquerel 1839)***
- ***Photoelectric Effect (Mathematical Description by Einstein 1905, Nobel Prize in Physics 1921)***
- Ubiquitous Solar Energy
- *Irradiance* (W/m^2) versus *Illuminance* (1 lux)
- *Illuminance* measures the perceived power density of light weighted by the sensitivity of the human eye using a luminocity function.
- *Spectral Irradiance* (W/m^2/nm)
- ***1 sun = 1000 W/m^2 = 100 mW/cm^2***

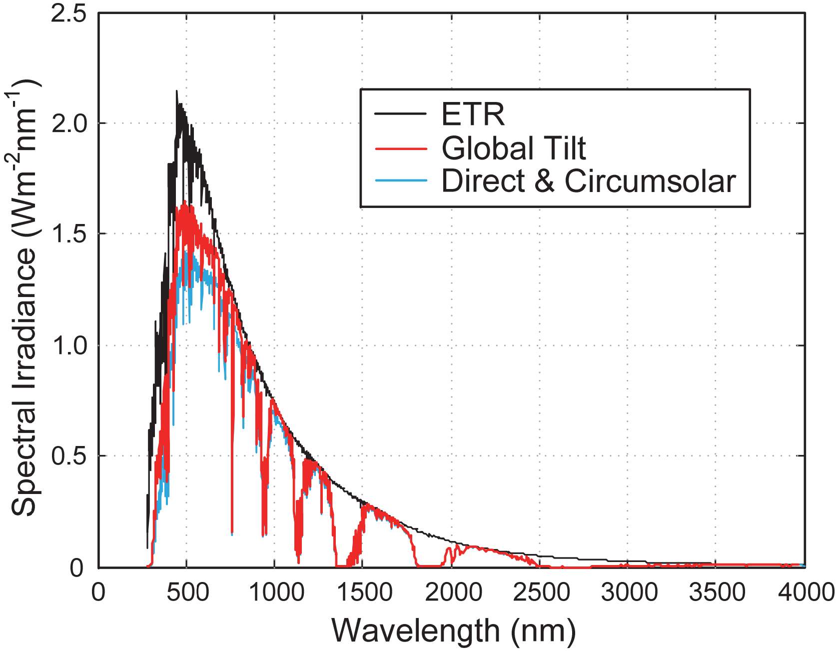
Solar energy harvesting

- American Society for Testing and Materials (ASTM) ***Reference Solar Spectra***
- AM0 or ETR (Solar constant = 1.366 KW/m^2)
- AM1.5G (1 sun = 1 KW/m^2) (includes direct and diffuse radiation)
- AM1.5D (0.9 KW/m^2) (concentrator systems)
- Average solar irradiance on earth much lower than 1 sun (~1/6 of AM1.5G Irradiance)



Solar Energy Harvesting

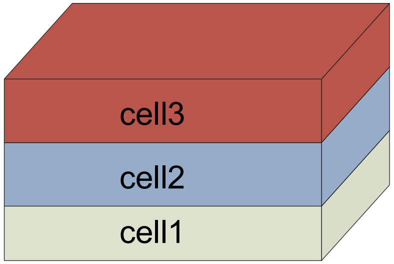
- *ETR Spectral Irradiance Distribution is modeled as black-body radiation with T= 5800 K*
- *Atmosphere Absorption bands visible*

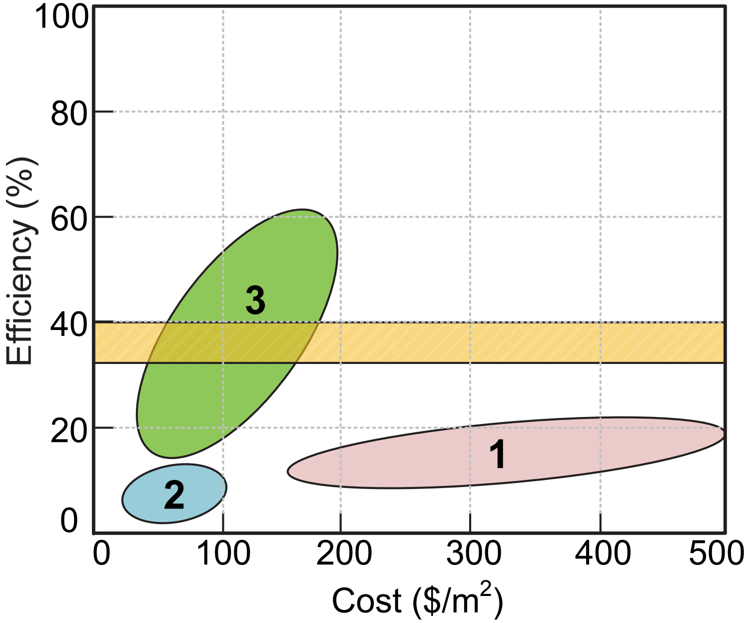


- *Principles of thermodynamics and black-body radiation allow estimating performance limits of solar cells (**Shockley-Queisser Limit 1961**)*
- The maximum theoretical efficiency of an ideal (single energy gap) solar cell was estimated by William Schockley and Hans S. Queisser in 1961 to be approximately 31%.

Solar Energy Harvesting

- wafer based solar cells (150 \$/m2 – efficiency 20%)
- thin film solar cells
  (30 \$/m2 – efficiency 5-10%)
- third generation solar cells
  (high efficiency, low cost)





M. Green, Third Generation Photovoltaics,
Advanced Solar Energy Conversion,
Berlin Heidelberg: Springer-Verlag, 2006.

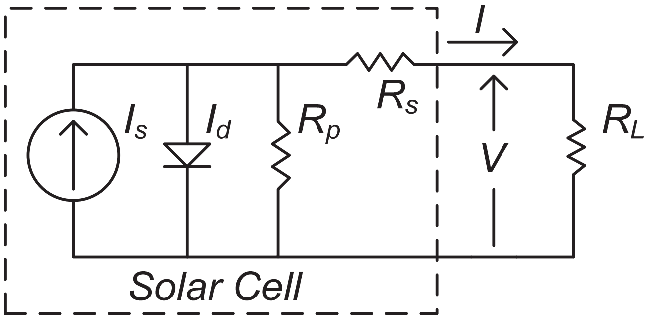
Challenges

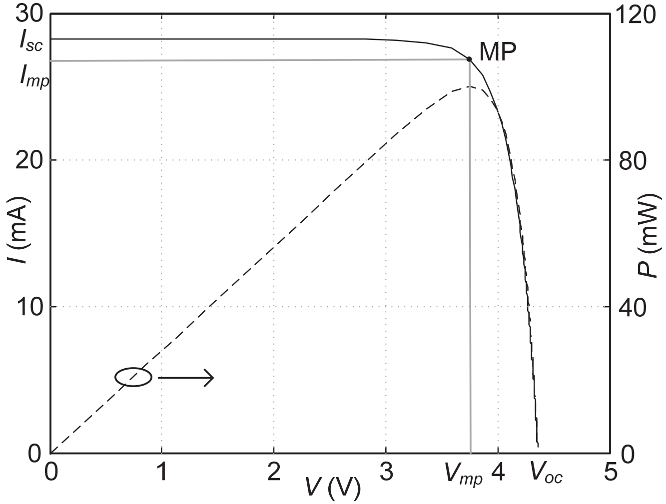
High efficiency and low cost

Integration with other circuitry

Indoor conditions?

Solar Energy Harvesting





$$I = I_s - I_o\left(e^{\frac{V+IR_s}{nkT}} - 1\right) - \frac{V + IR_s}{R_p}$$

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}}$$

Fill Factor

$$\eta = \frac{FFV_{oc}I_{sc}}{P_i}$$

Conversion Efficiency

Integration of Harvesting Modules

- Solar cell efficiency, measured under AM1.5G at T = 25 C

Classification	**Efficiency (%)**	**V_{oc} (V)**	**J_s ($mAcm^{-2}$)**	**FF (%)**	**Description**
c-Si	25.6	0.74	41.8	82.7	Panasonic HIT
mc-Si	20.4	0.664	38	80.9	FhG-ISE
GaAs (thin film)	28.8	1.122	29.68	86.5	Alta Devices
CIGS	20.5	0.752	35.3	77.2	Solibro
CdTe	19.6	0.857	28.59	80	GE Global Res.
a-Si	10.1	0.886	16.75	67.8	Oerlikon Solar Lab
Dye Sensitised	11.9	0.744	22.47	71.2	Sharp
Organic polymer	10.7	0.872	17.75	68.9	Mitsubishi Chemical

M.A. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop, ‘Solar cell efficiency tables (version 44),’ Progress in Photovoltaics: Research and Applications, vol. 22, no. 7, pp. 701-710, June 2014

Kinetic/Vibration Energy Harvesting

- *Conversion of mechanical movements to electrical energy*
    - Vibrations
    - Displacements
    - Forces or pressures
- *Sources*
    - Traffic
    - Human movement
    - Heating, Ventilating and AC (HVAC)
    - Air currents
    - Water movement

Kinetic/Vibration Energy Harvesting

- Transducer types:

  Electromagnetic (inductive)

  - Faraday's law

  Electrostatic (capacitive)

  - Vary the capacitance or charge of a variable capacitor

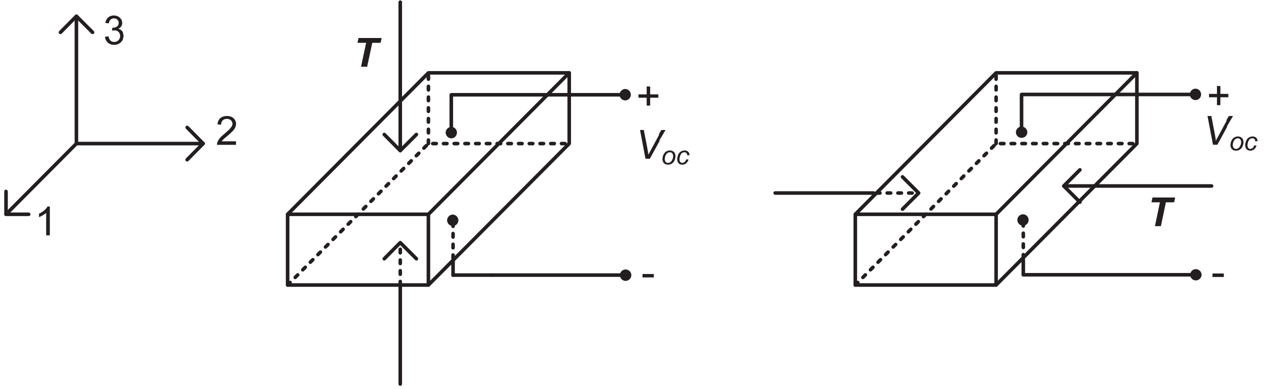
  Piezoelectric

  - Piezoelectric strain **d** tensor relating Mechanical Stress **T** to Electric Displacement **D**

Kinetic / vibration energy harvesting

- Piezoelectric Transducers:
  Piezoelectric strain d tensor relating Mechanical Stress **T** to Electric Displacement **D**

$$\mathbf{D} = d\mathbf{T} + \varepsilon \mathbf{E}$$

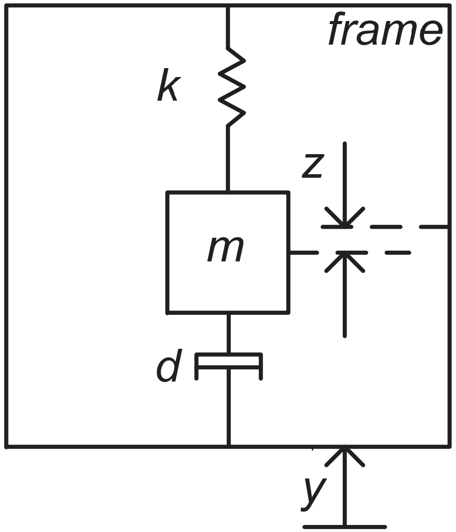


d_{33} d_{31}

- Anisotropic behavior:
  direction of Strain relative to Polarization

Kinetic/Vibration Energy Harvesting

- Vibration transducers modeled by mass m, attached to a frame using a spring k [*].
- Mechanical to electric conversion losses included in d.



$$m\ddot{z} + d\dot{z} + kz = -m\ddot{y}$$

$y(t) = Y_o \sin(wt)$ $A = w^2 Y_o$ $P_{emax} = m^2A^2/(4d)$

[*] C.B. Williams and R.B. Yates, 'Analysis of a Micro-Electric Generator for Microsystems,' in *Proc. 8th International Conference on Solid-state Sensors and Actuators and Eurosensors IX,* Stockholm, Sweden, pp. 369-372, June 25-29, 1995.

Kinetic/Vibration Energy Harvesting

- Require low frequency high-Q resonators
- Application dependent

Application / Vibration source	**Vibration frequency (Hz)**	**Acceleration amplitude (ms^{-2})**
Door Frame (after door closes)	125	3
Clothes Dryer	121	3.5
Washing Machine	109	0.5
HVAC vents in office building	60	0.2-1.5
Refrigerator	240	0.1
Small microwave over	121	2.25
External windows next to busy street	100	0.7

S. Roundy, "On the Effectiveness of Vibration-based Energy Harvesting,"
Journal of Intelligent Material Systems and Structures, vol. 16 no. 10, pp. 809-823, Oct. 2005.

Kinetic/Vibration Energy Harvesting

Challenges:

Self-tuning / Adaptive tuning, Wideband / Multiband

Description	**Frequency (Hz)**	**Power (mW)**	**REF**
MEMS AlN Piezoelectric	325	0.085	[*]
JouleThief Piezoelectric	50, 60, 100, 120	1.2	[**]
PMG-FSH Electromagnetic	50, 60, 100, 120	20	[***]

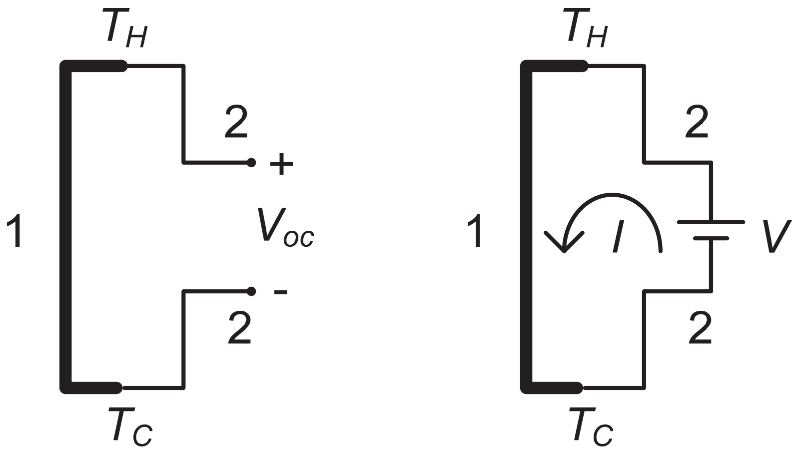
[*] R. Elfrink, et al., "First autonomous wireless sensor node powered by a vacuum-packaged piezoelectric MEMS energy harvester," in Proc. *IEEE International Electron Devices Meeting (IEDM)*, pp.1-4, 7-9 Dec. 2009.

[**] JouleThief, AdaptivEnergy.

[***] PMG FSH, Perpetuum.

Thermal Energy Harvesting

- *Conversion of temperature differences to electrical energy.*
- *Sources*
- Waste heat from industrial plants
- Heating systems
- Automobiles, other vehicles
- Human body



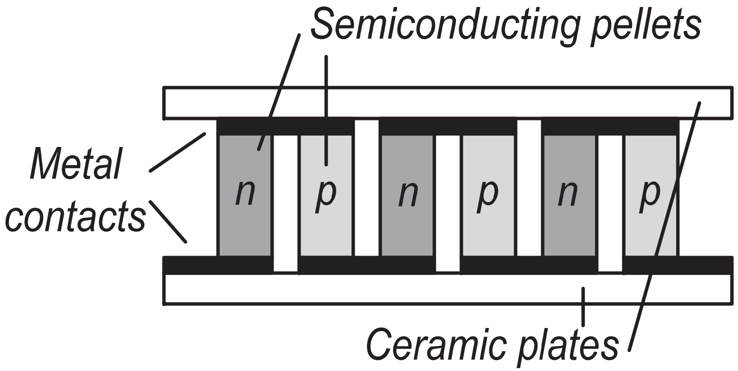
Seebeck Effect

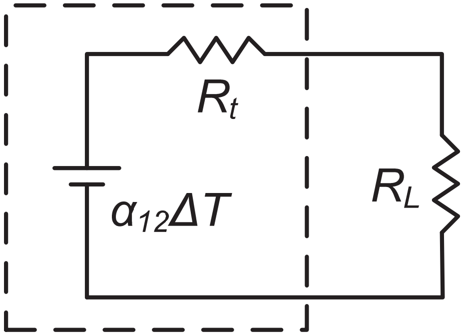
Peltier Effect

- Seebeck

Thermal Energy Harvesting

- The Seebeck coefficient is much higher for semiconductor materials rather than metals and metal alloys, where it can reach magnitudes of 1mV/K.
- Thermoelectric generators (TEGs) are formed by pairs of coupled of N-doped and P-doped semiconductor pellets connected electrically in series and placed between two thermally conductive plates.





Thermal Energy Harvesting

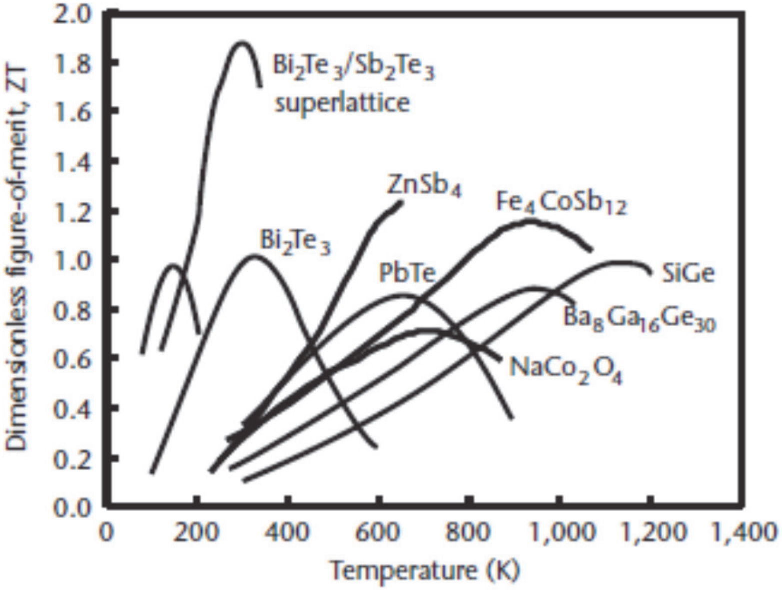
- Gulielmo Marconi
- ~ 1895
- Villa Griffone, Bologna, Italy

Thermal Energy Harvesting

- Thermoelectric Figure Of Merit:

$$ZT = \frac{\alpha^2 \sigma T}{\lambda}$$

- High Seebeck Coefficient (α)
- High Electrical Conductivity (σ)
- Low Thermal Conductivity (λ)



S. Beeby and N. White, *Energy Harvesting for Autonomous Sensors*, Artech House 2010.

Thermal Energy Harvesting

Challenge:

Increase conversion efficiency and maintain temperature gradient

Carnot efficiency: $n_c = (T_{hot}-T_{cold})/T_{hot}$

Conversion efficiency: $\varphi = n_c\left(2 - 0.5n_c + (4/ZT_{hot})\right)^{-1}$

Conversion Efficiency limited by Carnot Efficiency

Example:

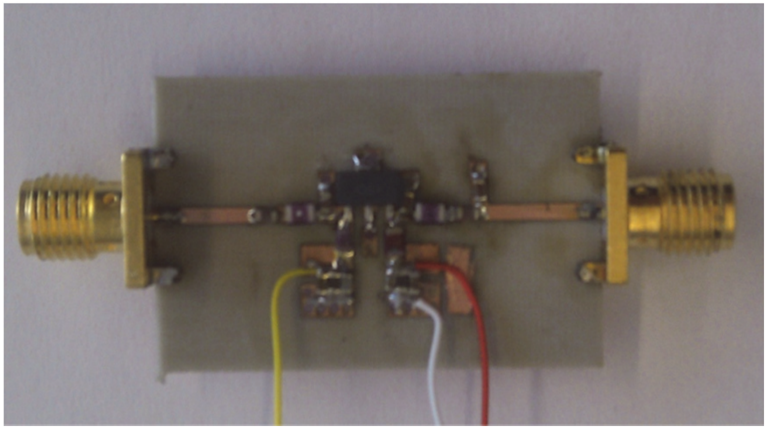
T_{cold} = 293 K (20 C) and T_{hot} = 303 K (30 C) => n < 3,3 %

T_{cold} = 233 K (-40 C) and T_{hot} = 293 K (20 C) => n < 20,48 %

Thermal Energy Harvesting

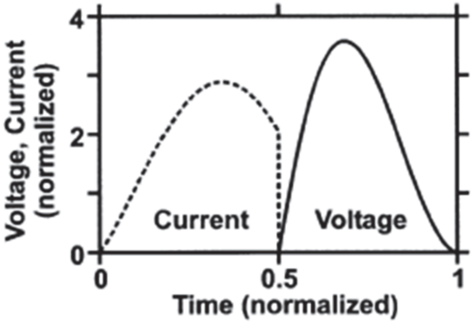
- Power amplifiers are fundamental blocks in every transmitter circuit.
- Linearity requirements and technology limitations result in a significant amount of wasted heat.
- Challenge: Recover DC electrical power from the generated heat:
  - thermoelectric generators
  - principles of heat transfer and Seebeck effect

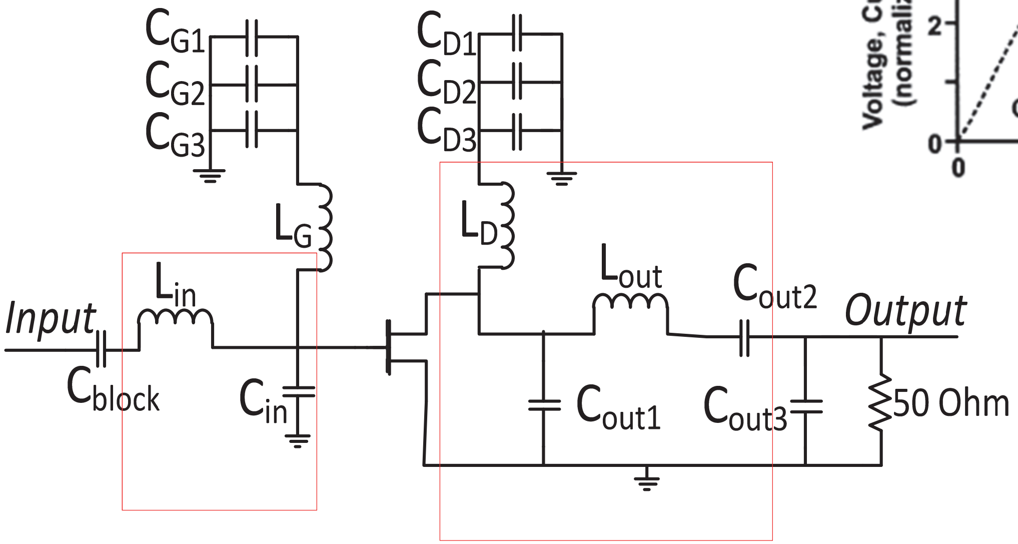
Thermal Energy Harvesting



Power amplifier used as heat generating mechanism:

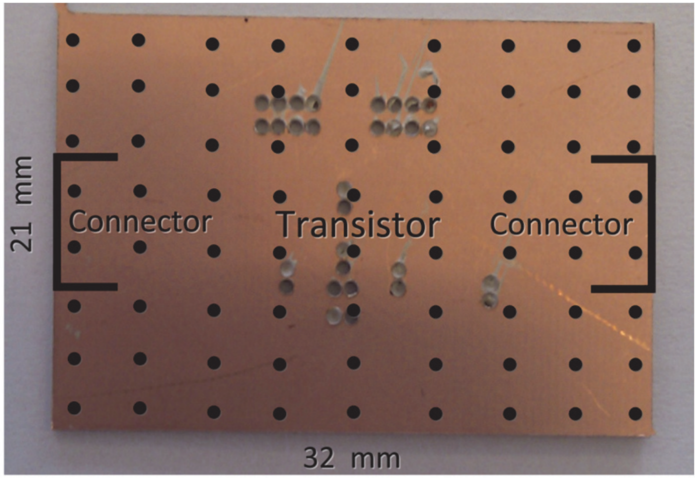
- freq=2.45 GHz
- P_{diss}=1.37 W

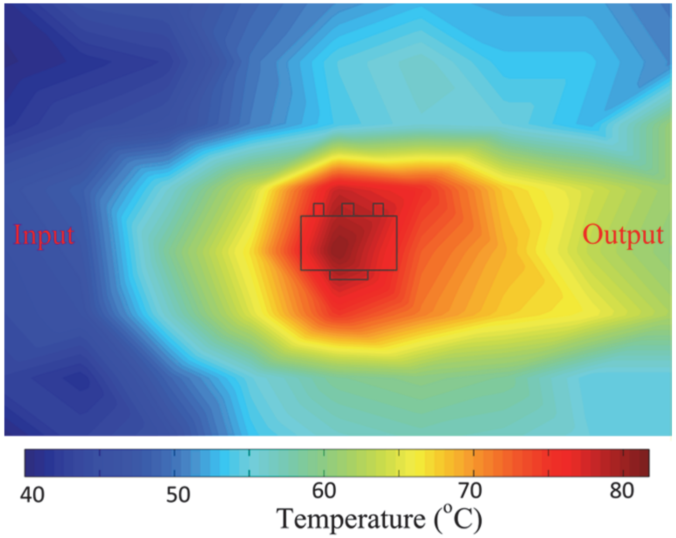




Thermal Energy Harvesting

Measurement of the temperature along the ground plane of the PCB, 72 points

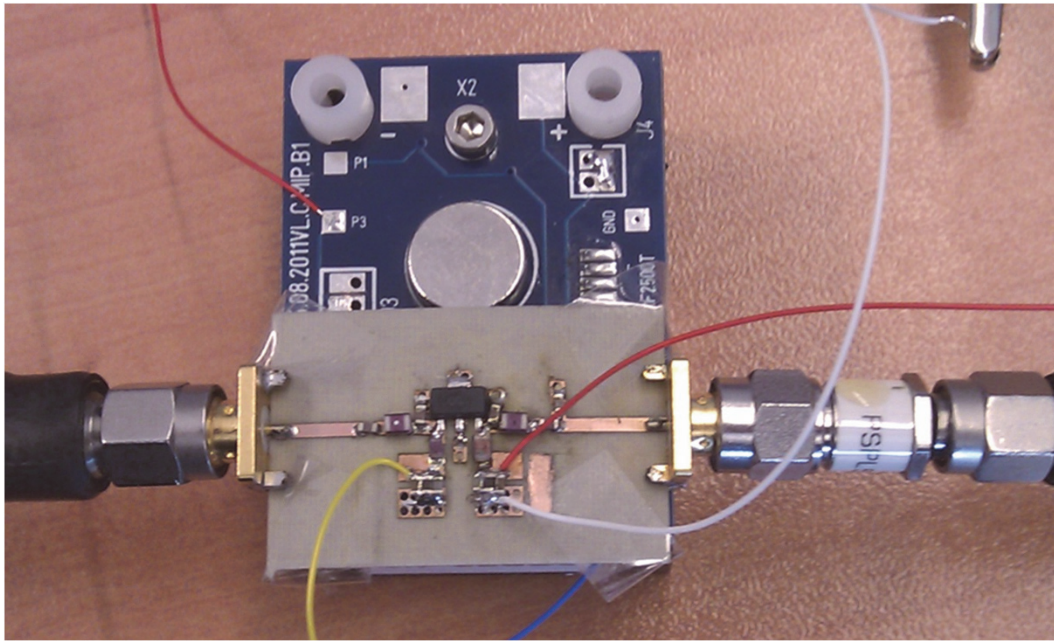




Measured Results
Max Temperature 82.4 ^{o}C (355.4 K)
Room Temperature 25.7 ^{o}C (298.7 K)

n_c=15.95%

Thermal Energy Harvesting



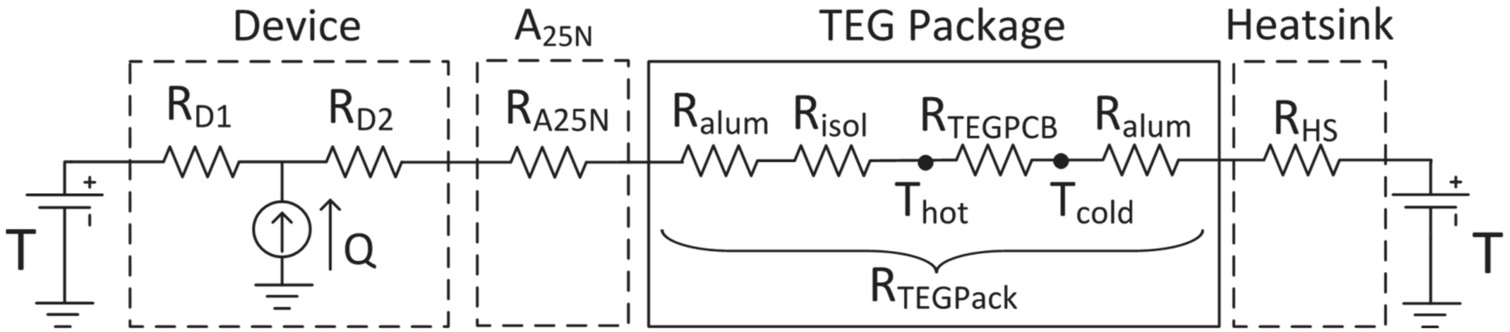
Experimental setup:

- Thermoelectric Generator (thermoelectric material Bi_2Te_3).
- Power amplifier circuit on Arlon 25N substrate.

Thermal Energy Harvesting

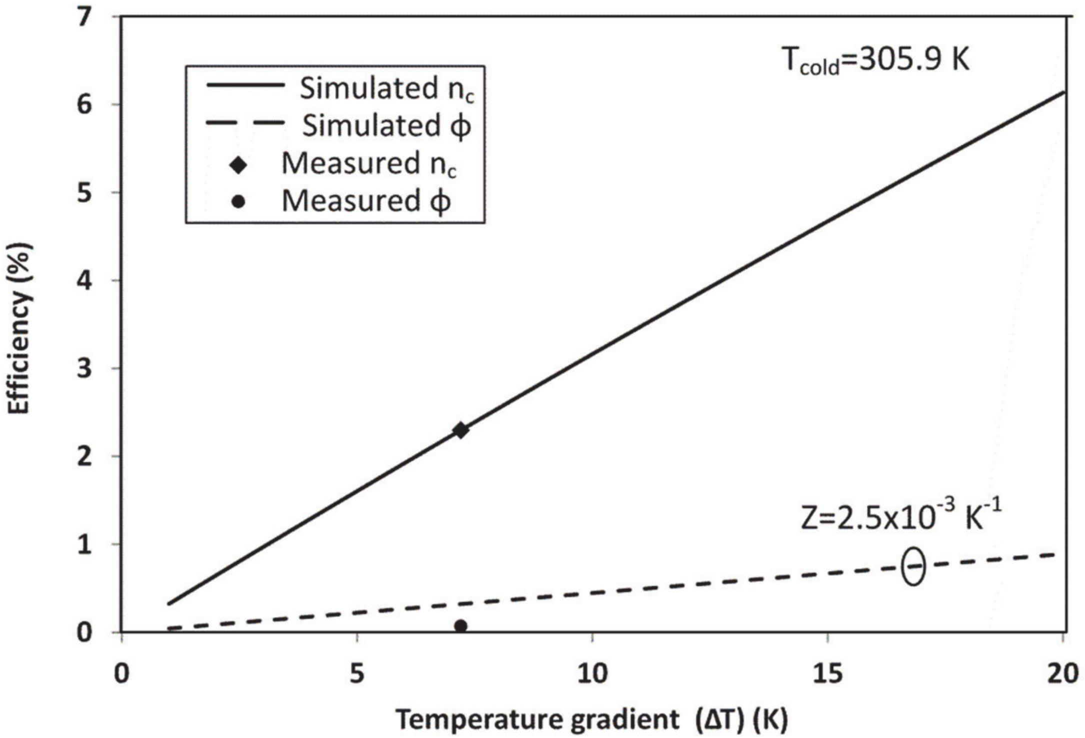
Thermal Model

- **analogy between the electrical and heat charge**.
- only steady state conditions are considered.



Quantity	Symbol	VALUE (K/W)
R_{th} for device (junction-ambient)	R_{D1}	125
R_{th} for device (junction-substrate)	R_{D2}	29
R_{th} for substrate and contact	R_{A25N}	10
Total R_{th} for TEG package	$R_{TEGPack}$	18
R_{th} for TEG PCB	R_{TEGPCB}	12.5
R_{th} for heatsink	R_{HS}	5.8

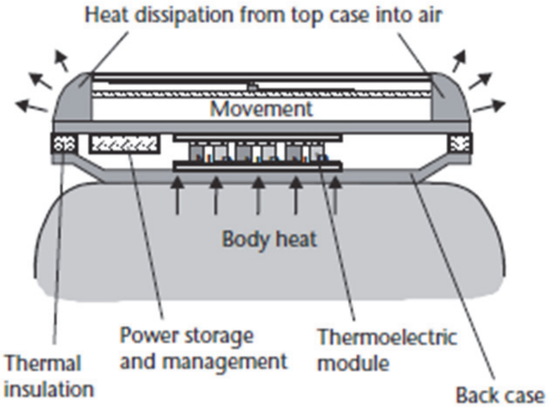
Electrical Power Generation



P_{diss}=1.37 W

	T_{hot} (K)	T_{cold} (K)	ΔT (K)	n_c (%)	φ (%)	P_{MAX}(mW)
Sim	318.1	306.7	11.4	3.58	0.51	2.1
Meas	313.1	305.9	7.2	2.3	0.074	1.015

Motivation



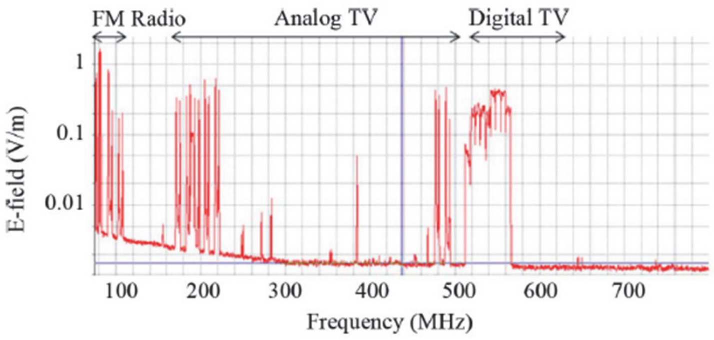
Wrist watch: *SEIKO thermic*

~ 20-40 μW required to power a quartz digital wrist-watch

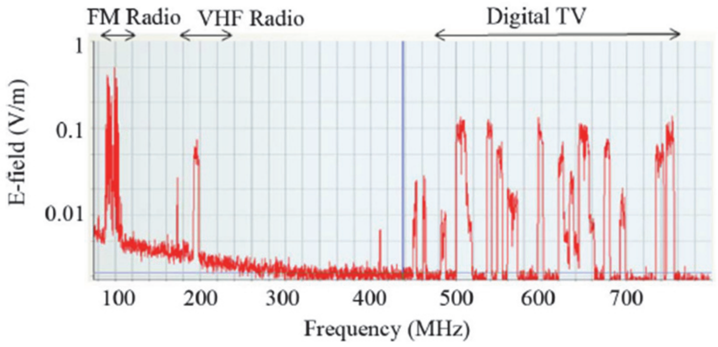
S. Beeby and N. White, Energy Harvesting for Autonomous Systems, Norwood: Artech House, 2010.
S. Kotanagi, et al., "Watch Provided with Thermoelectric Generation Unit," Patent No. WO/1999/019775.

RF energy harvesting

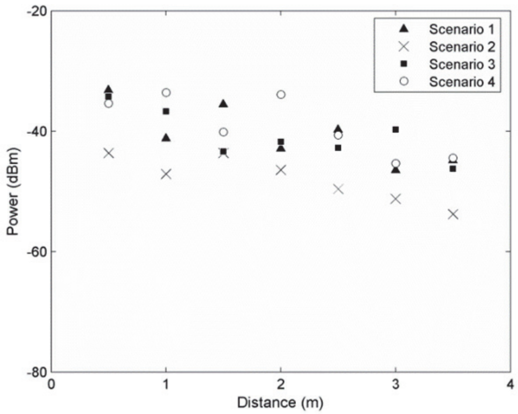
- Challenge: determine available power

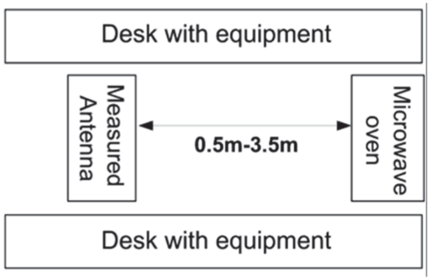


(a)



(b)





Desk with equipment

Measured Antenna

0.5m-3.5m

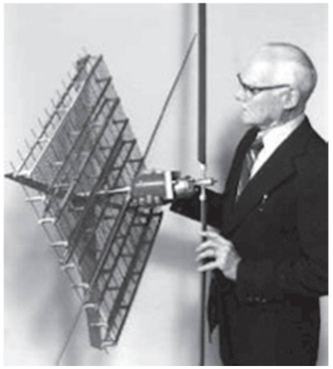
Microwave oven

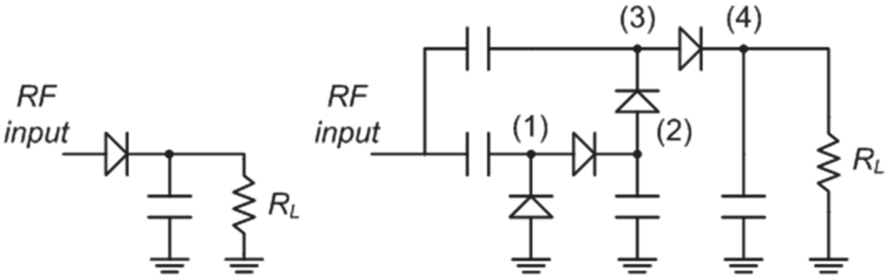
Desk with equipment

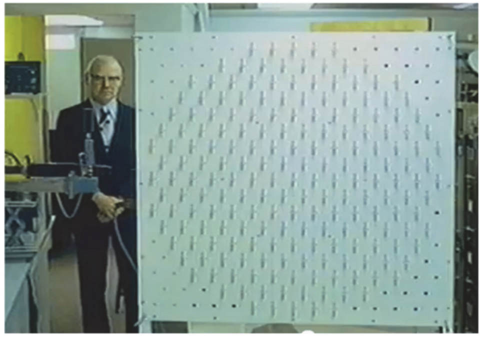
R. Vyas, B.S. Cook, Y. Kawahara and M. M Tentzeris, "E-WEHP: A Battery less Embedded Sensor-Platform Wirelessly Powered From Ambient Digital-TV Signals," Microwave Theory and Techniques, IEEE Transactions on , vol.61, no.6, pp.2491,2505, June 2013

RF energy harvesting

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

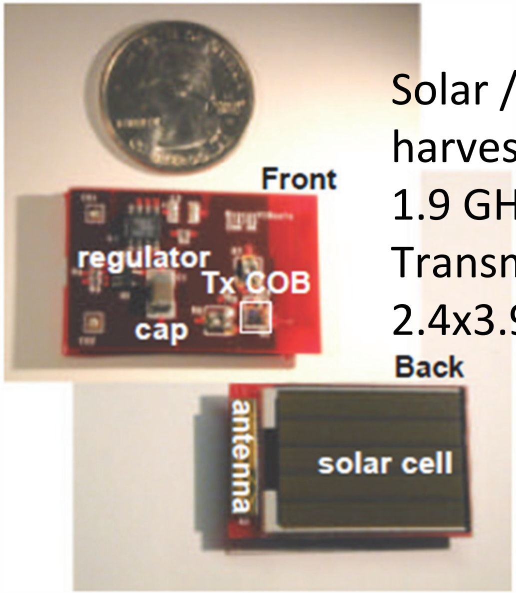




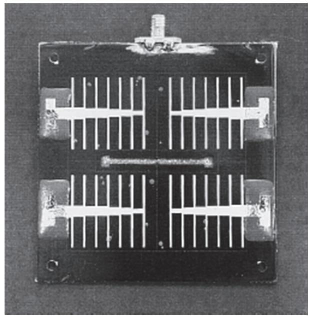


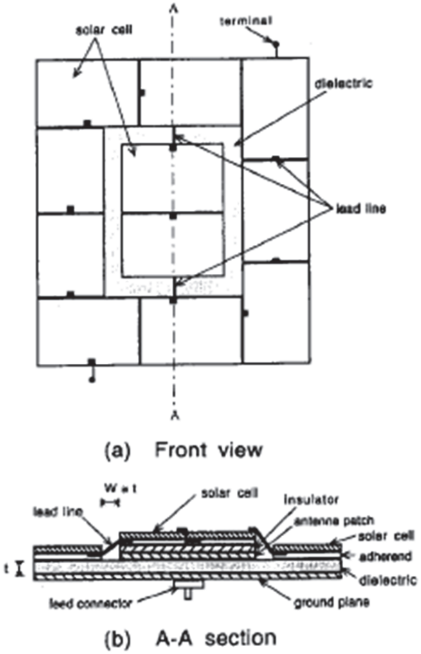
Reported UHF rectifier efficiencies for available input power levels in the order of 10 µW are approximately 20 %, and increase to > 50 % for available power levels of 100 µW.

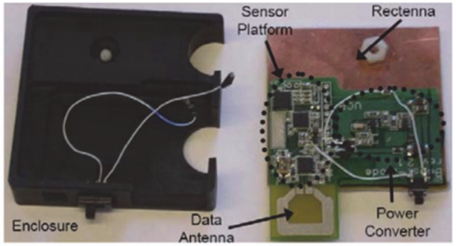
Integration of Harvesting Modules



Solar / Electromagnetic harvester
1.9 GHz / -1.5 dBm Transmitter
2.4x3.9 cm^2







Shad Roundy, Brian P. Otis, Yuen-Hui Chee, Jan M. Rabaey, Paul Wright, A 1.9GHz RF Transmit Beacon using Environmentally Scavenged Energy *IEEE Int. Symposium on Low Power Elec. and Devices*, 2003, Seoul, Korea.
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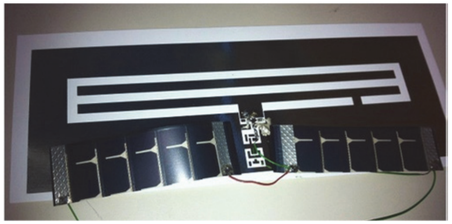
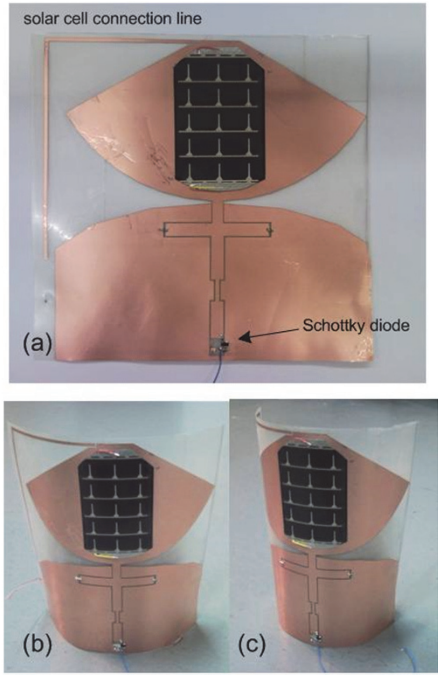
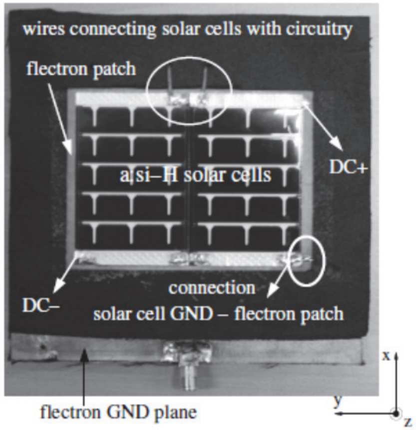
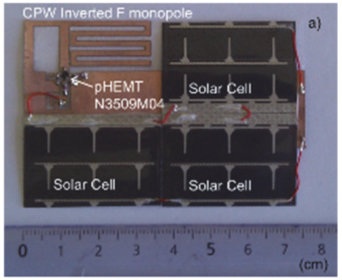
Integration of Harvesting Modules

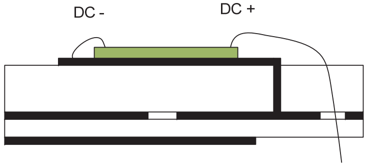
- Multi-technology harvesters
  - Solar antennas and rectennas
- Flexible electronics
  - Paper / Textile / Plastic Substrates
- Solar powered batteryless circuits





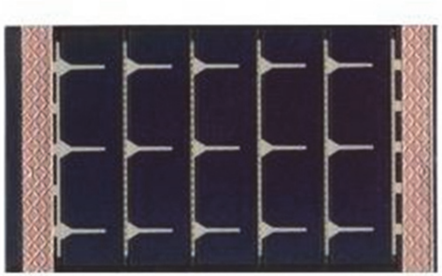


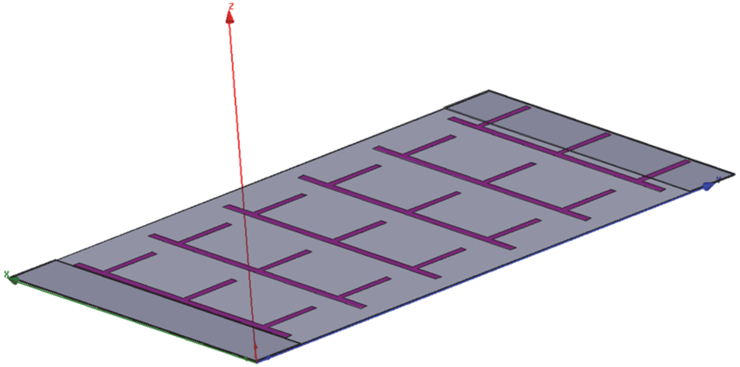


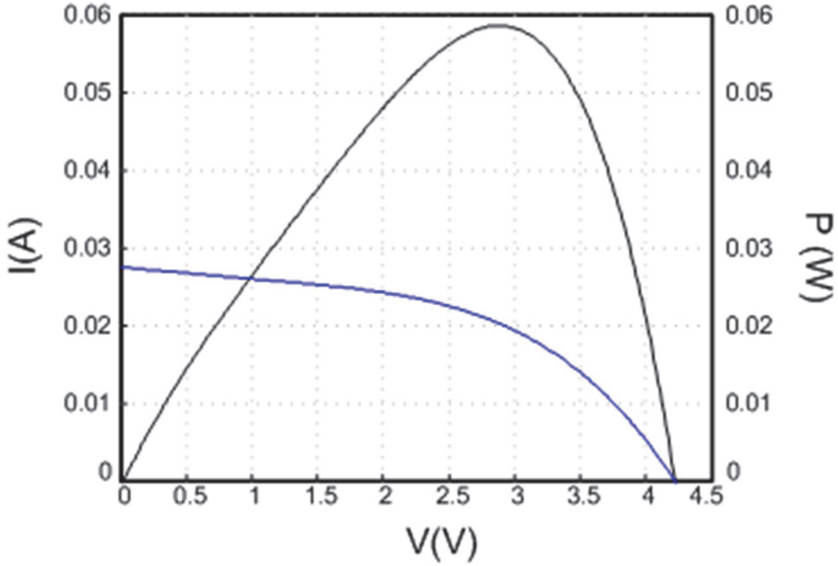


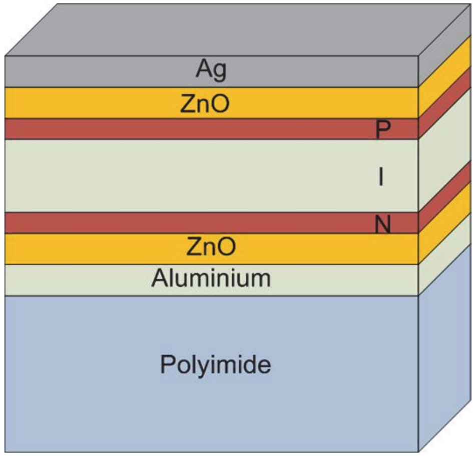
Integration of Harvesting Modules

Flexible amorphous silicon (a-Si) solar cell



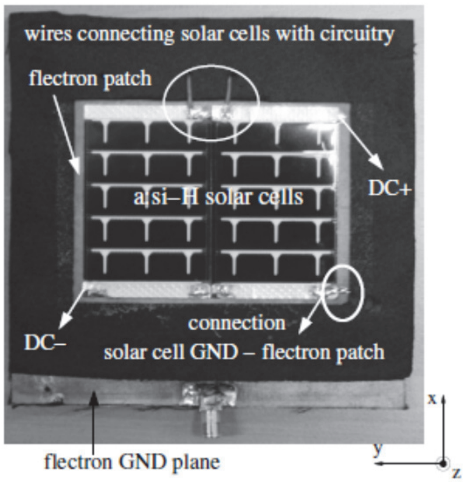


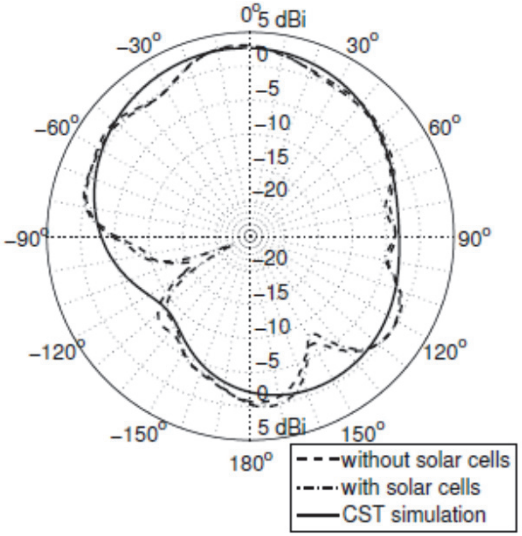


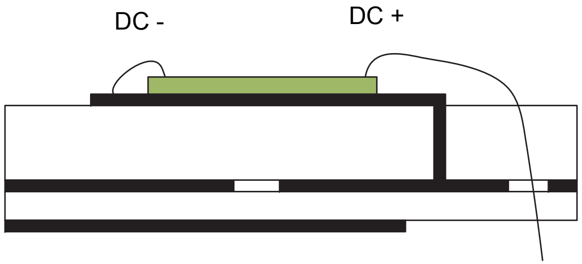


Integration of Harvesting Modules

- Textile /flexible foam passive and active circuit integration.
- Wearable smart fabric with sensing and communication (transmission) capabilities.





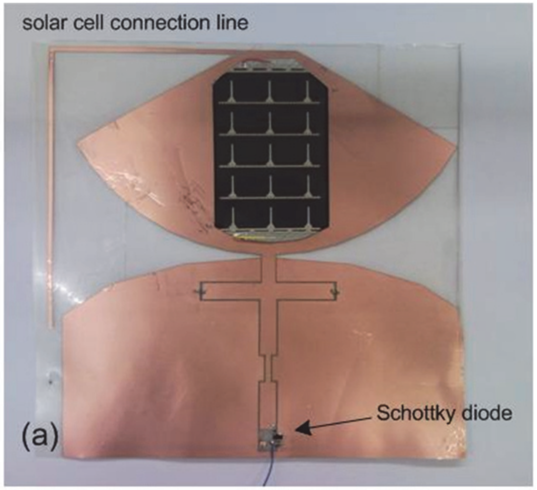


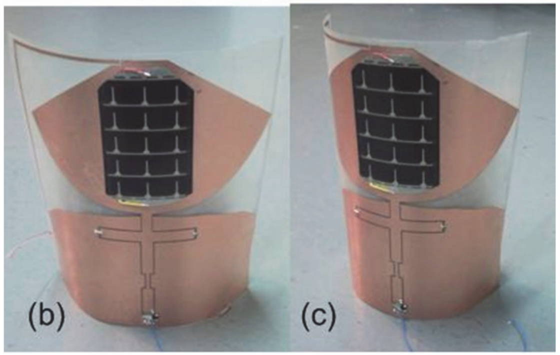
Flexible polyurethane (h=11mm /ε=1.16 /tanδ=0.01

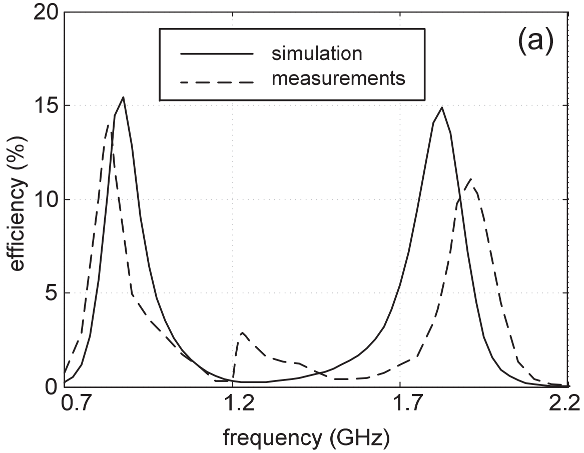
Aramid textile layer (h=0.95 mm /ε=1.97 / tanδ=0.02)

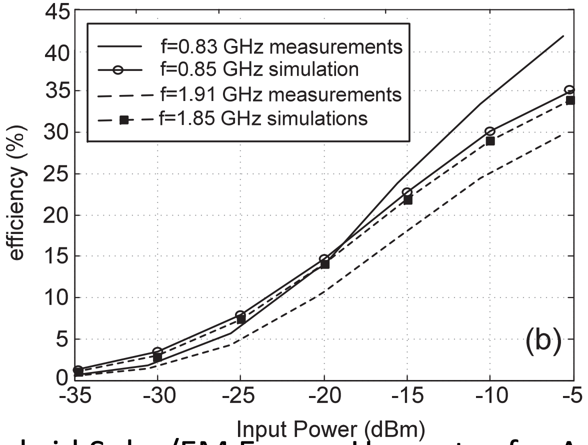
Integration of Harvesting Modules

- Multi-band rectenna / Solar energy harvester









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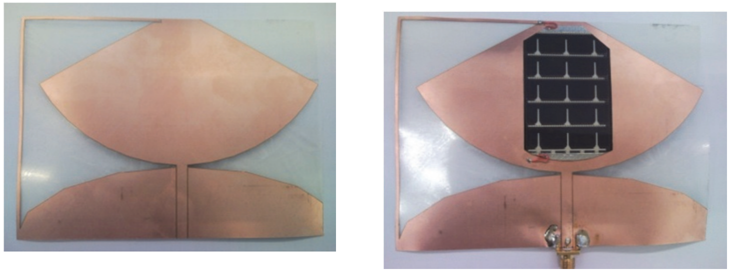
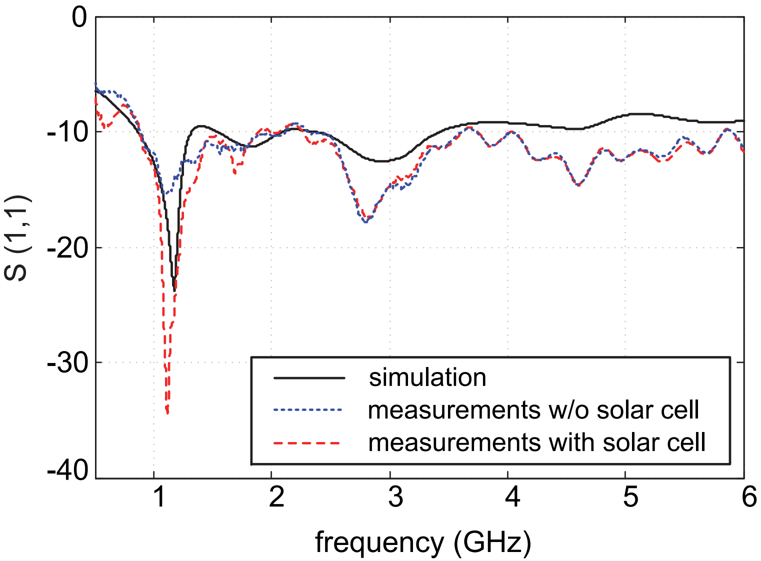
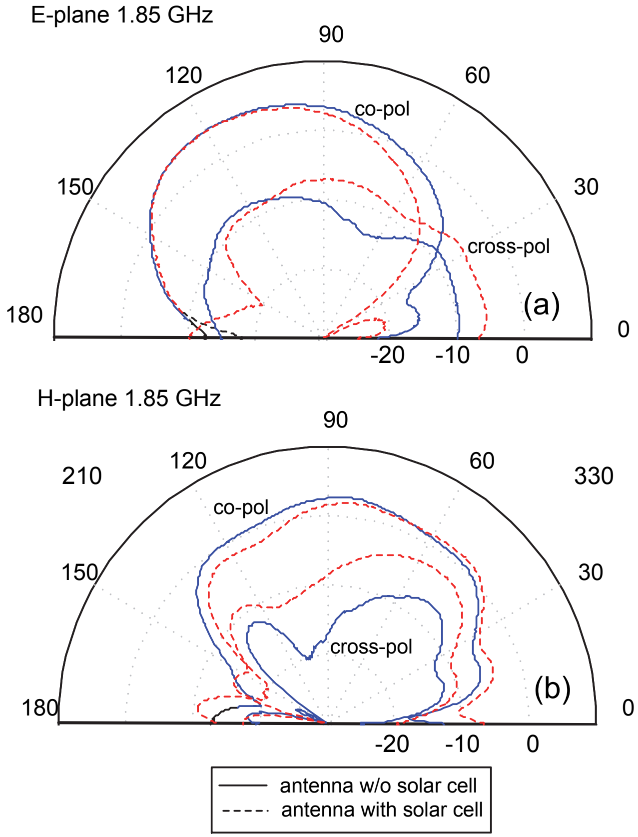
Integration of Harvesting Modules

Radiating element size minimized by eliminating areas of a semicircle monopole where field distribution are weaker

DC interconnect line for solar cell integration place for minimum effect on antenna performance

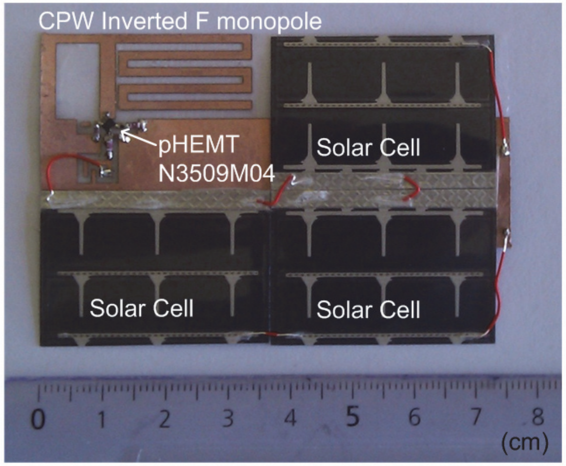


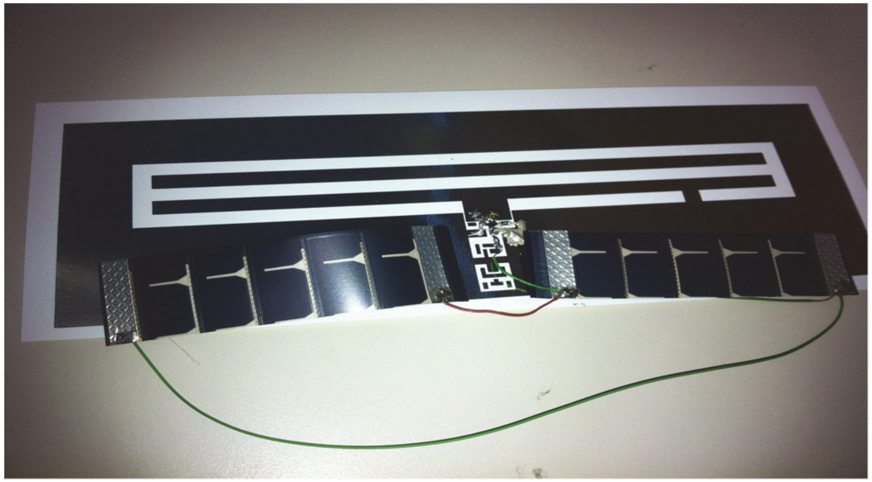




Integration of Harvesting Modules

- Compact design: Meander (PET) or Slot (Paper)
- Antenna surface shared with solar cell





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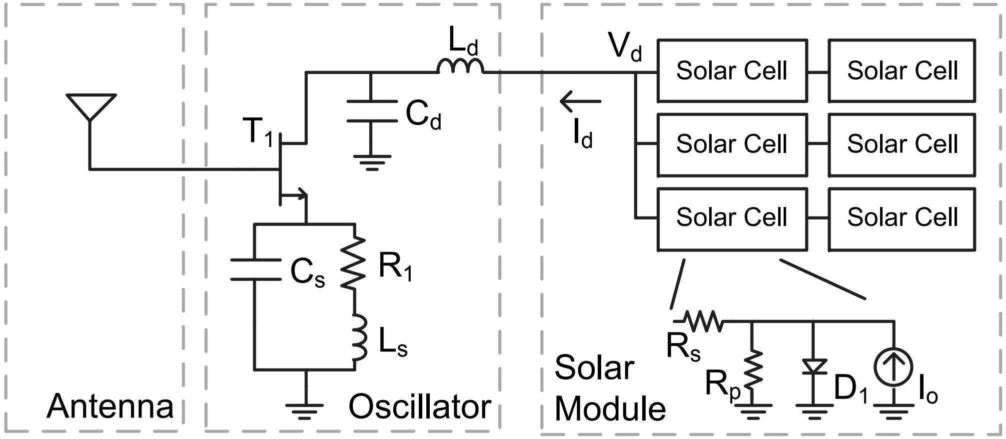
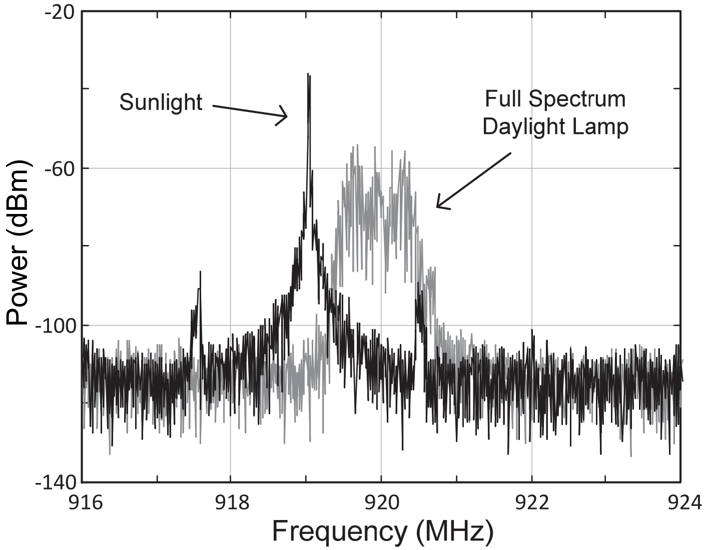
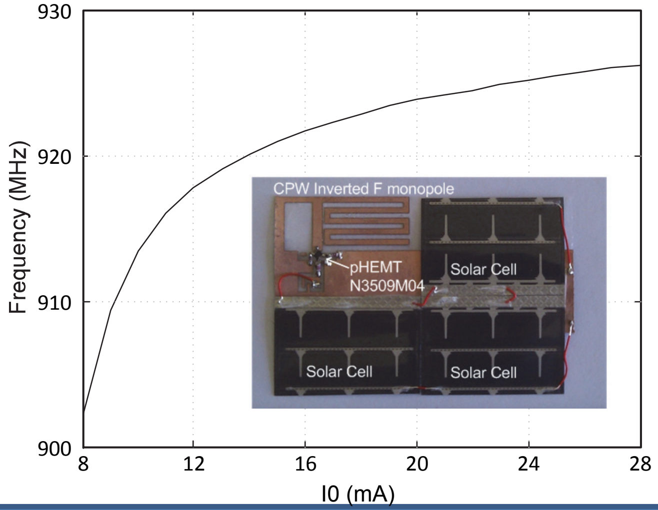
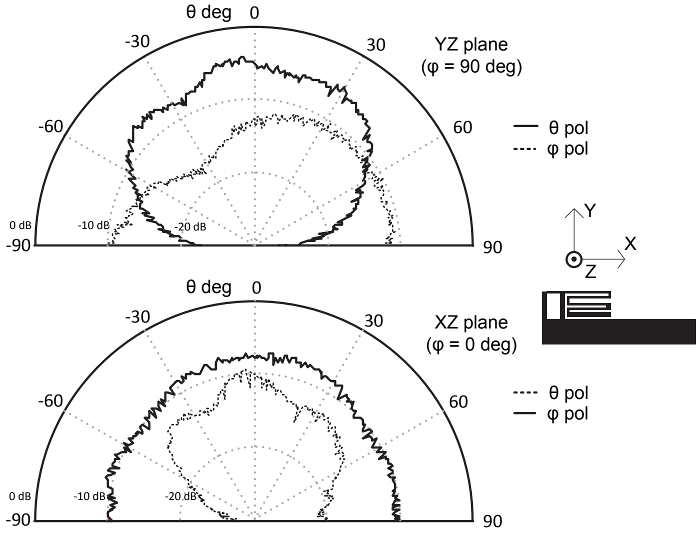
Integration of Harvesting Modules

Harmonic Balance
Oscillator Simulation

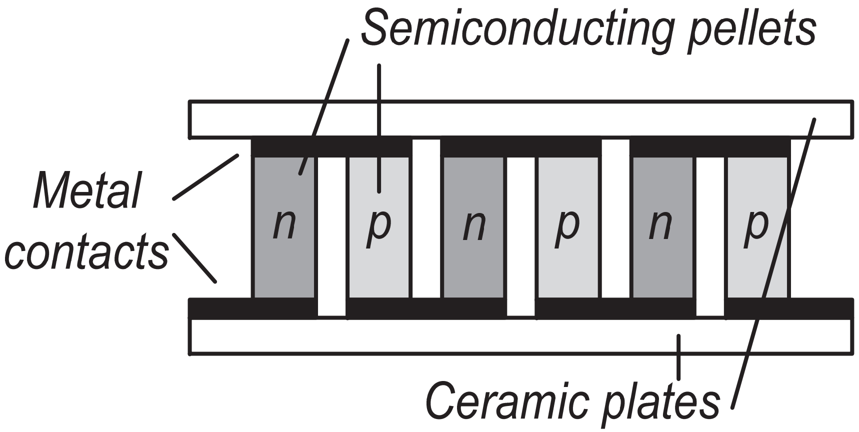


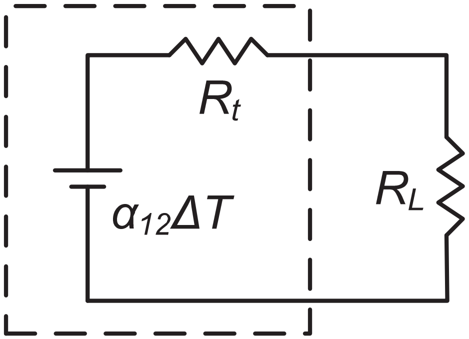






Integration of Harvesting Modules

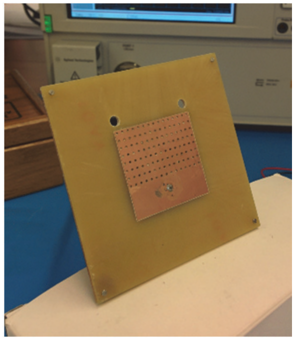


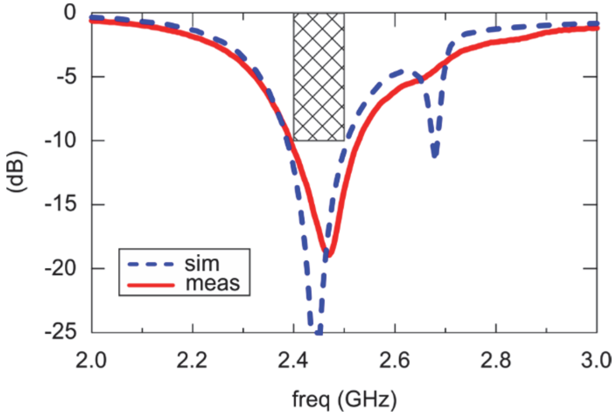


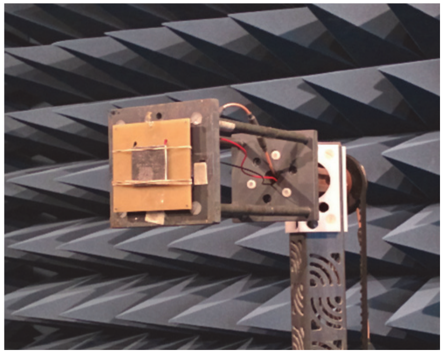
Carnot efficiency: $n_c = (T_{hot}-T_{cold})/T_{hot}$

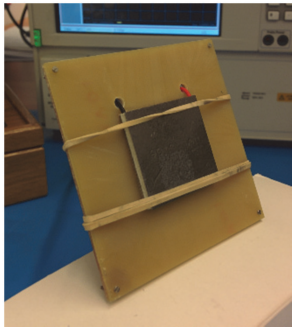
Conversion efficiency: $\varphi = n_c\left(2 - 0.5n_c + (4/ZT_{hot})\right)^{-1}$

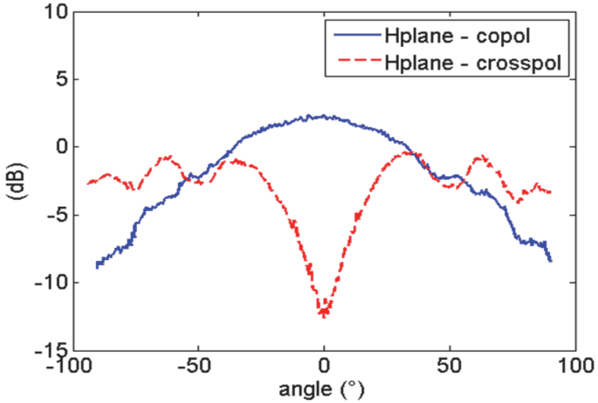
Integration of Harvesting Modules

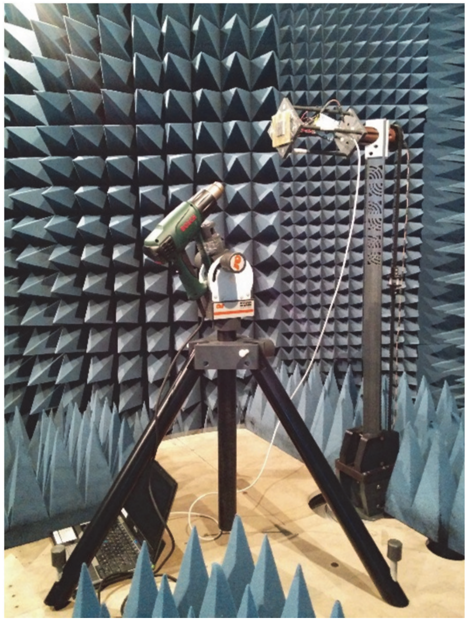












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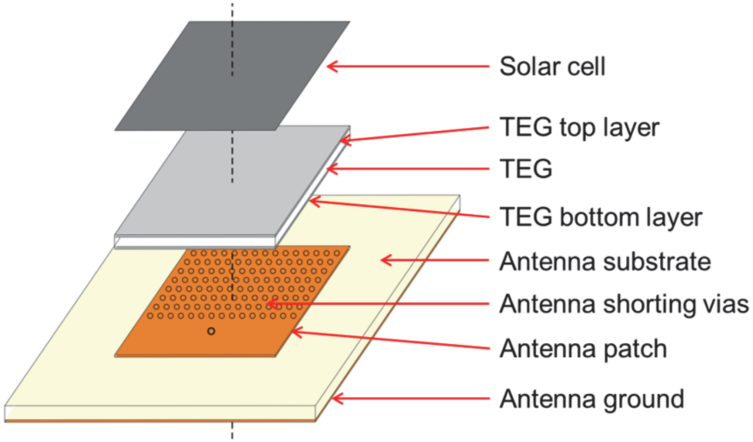
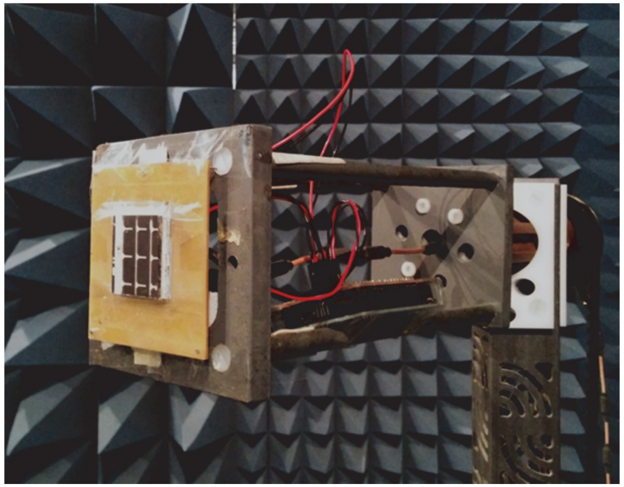
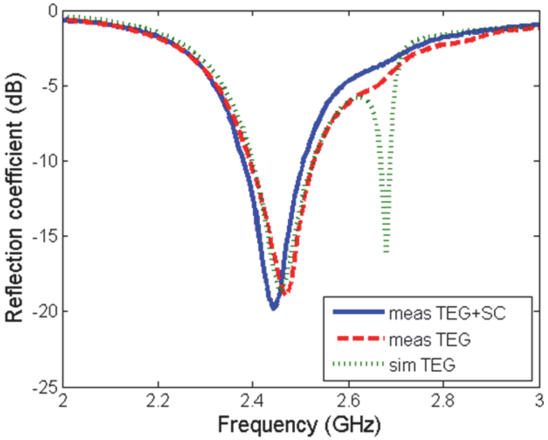
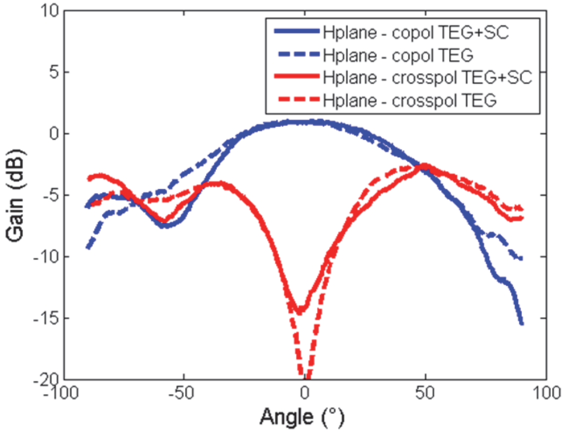






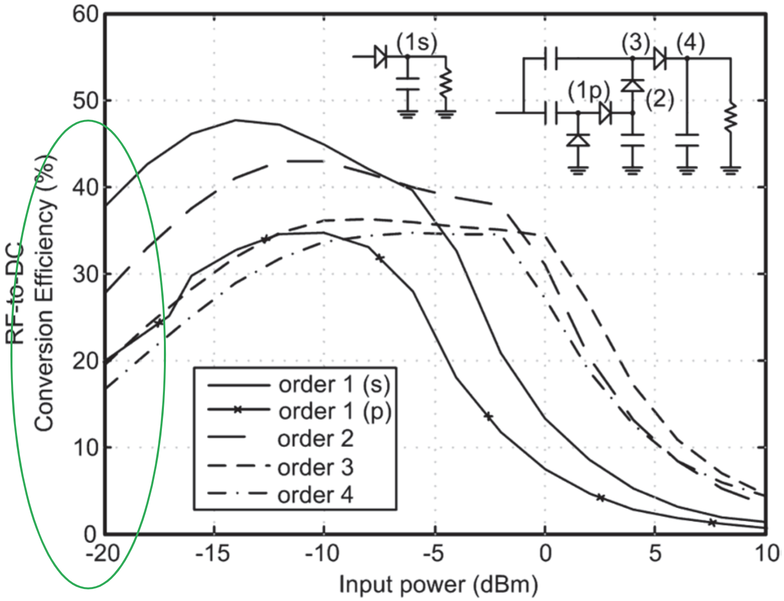


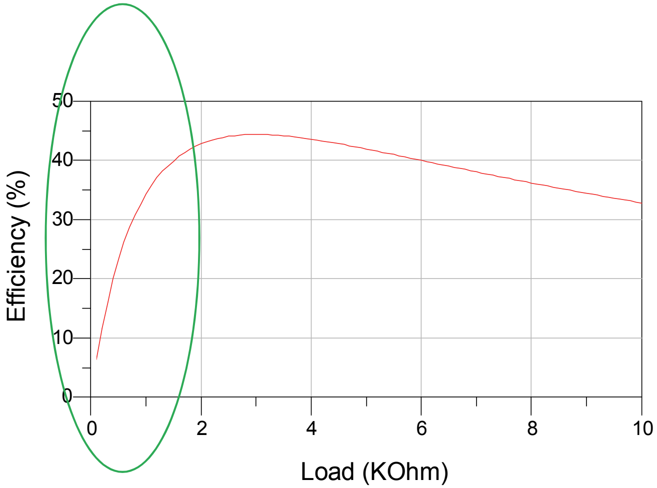
Rectenna Design and Optimization

- Circuit topology important in low available power conditions

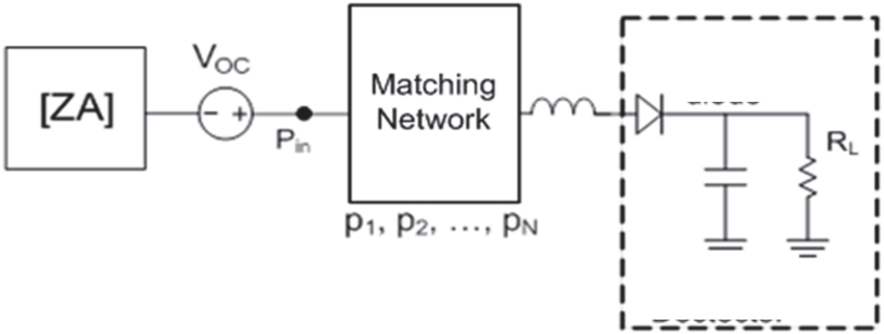
- Trade-off between efficiency and output voltage

- Efficiency varies with load



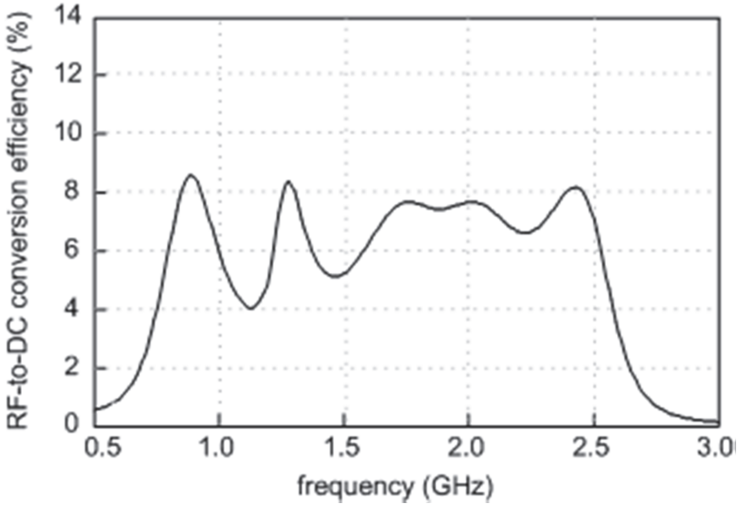


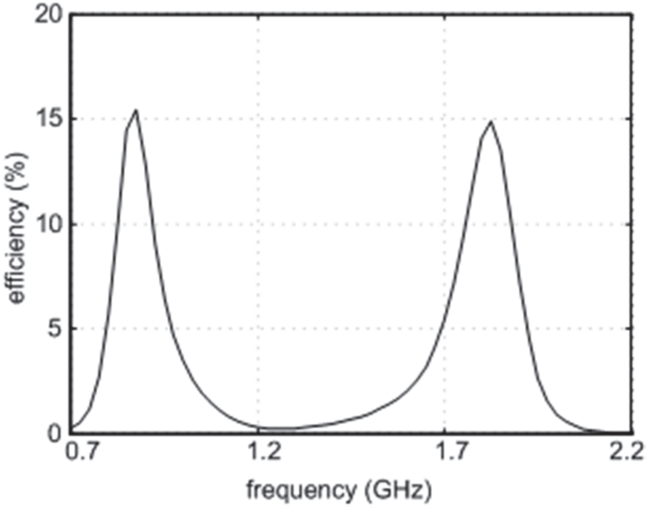
Rectenna Design and Optimization



OPTIMIZATION PARAMETERS:

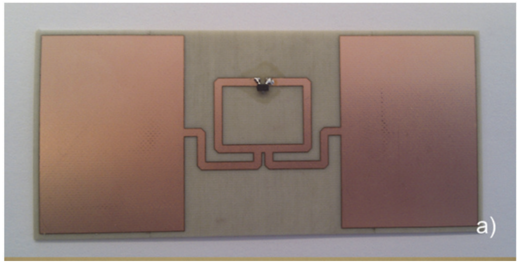
$p_1,\ldots,p_N$
R_L

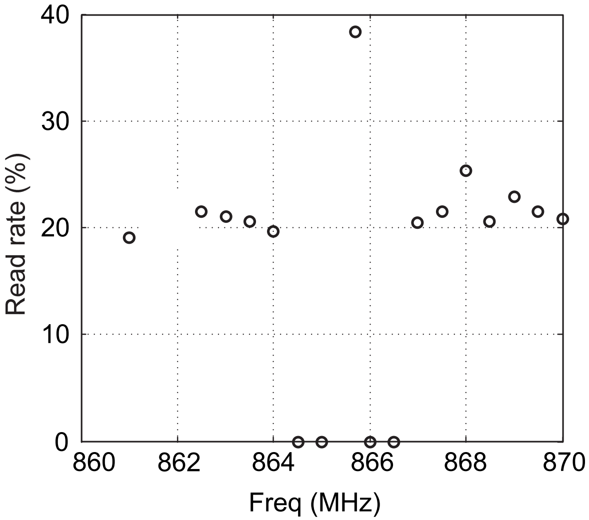


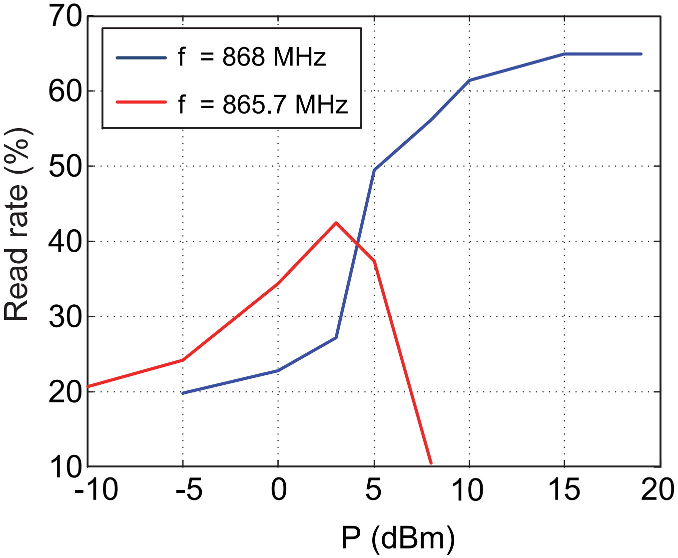


Energy Harvesting Assisted RFID and WSN

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

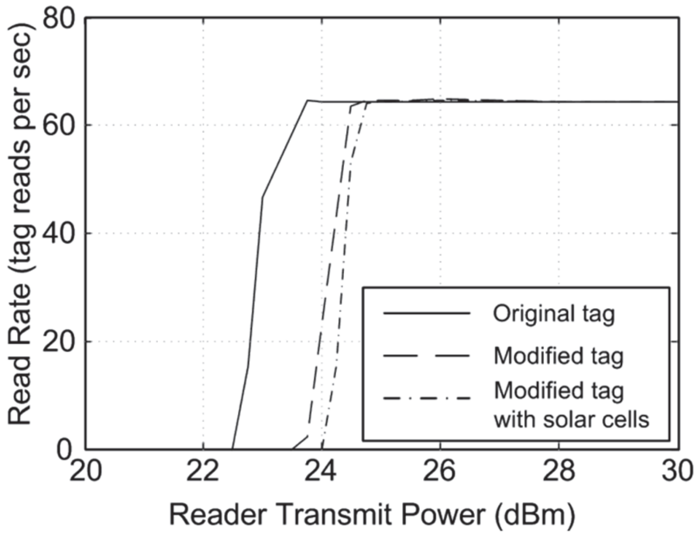


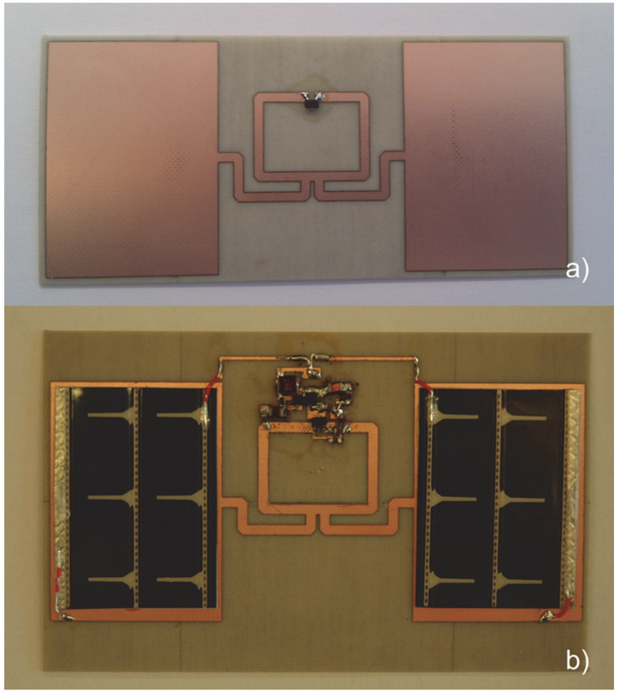




Energy Harvesting Assisted RFID and WSN

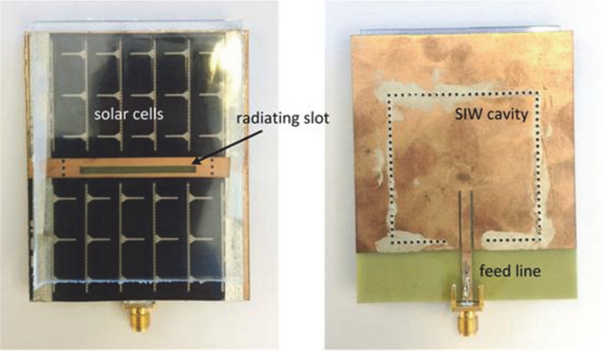
- Solar tag with high efficiency
  DC-to-RF converter: Class-E oscillator

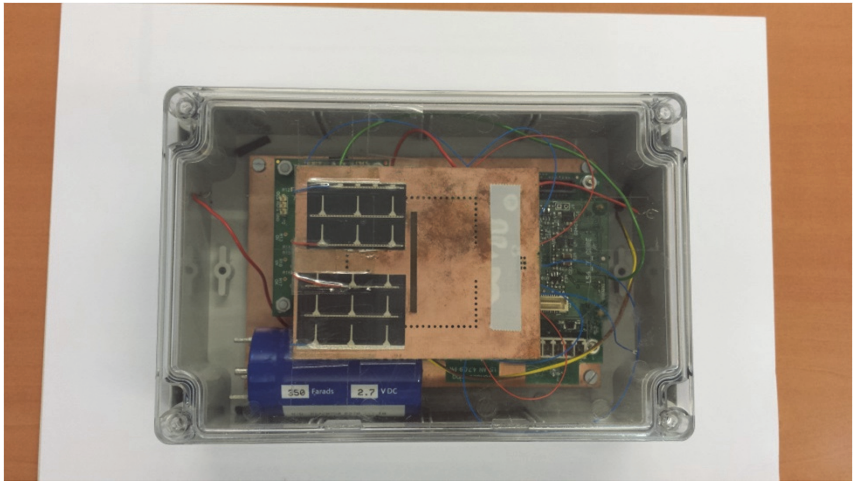


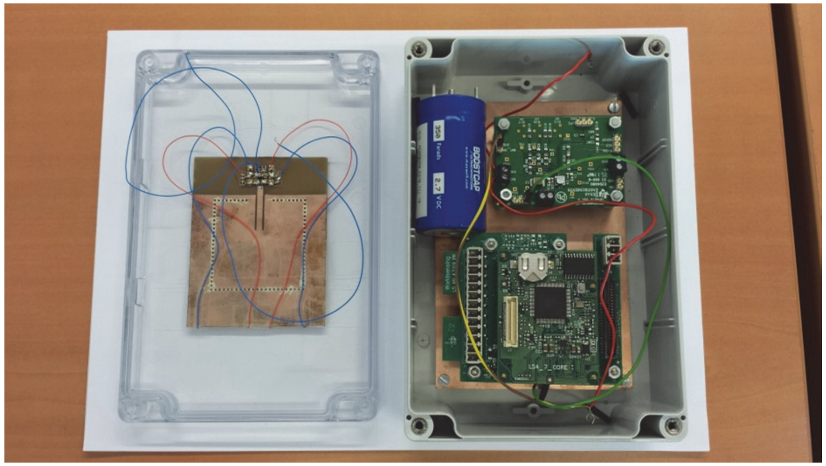


Energy Harvesting Assisted RFID and WSN

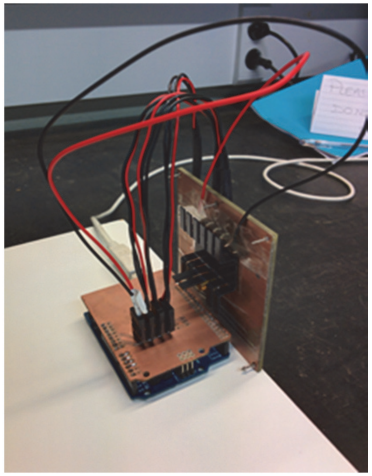
- Solar powered data logger (SWAP project)

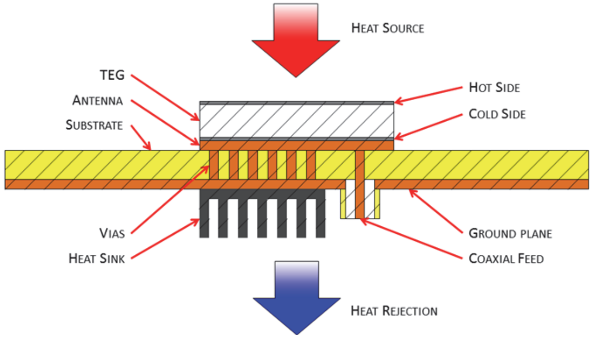


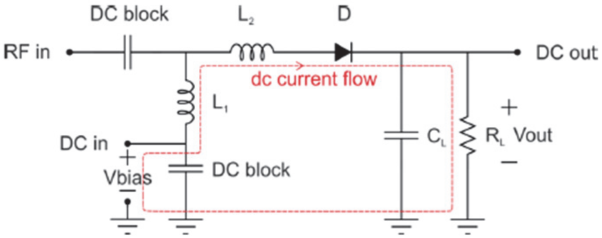


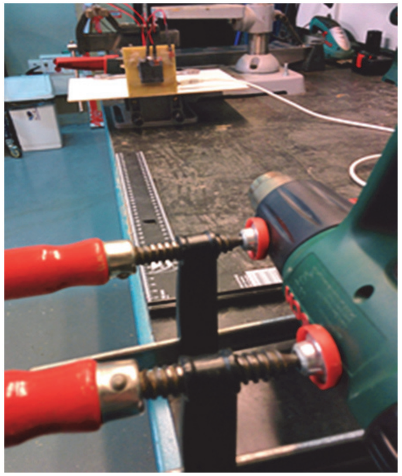


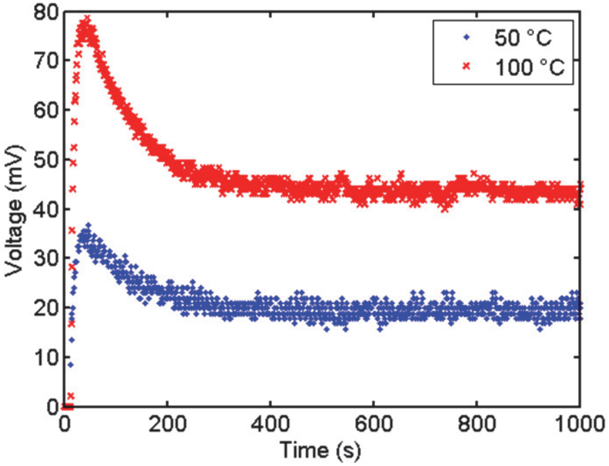
Energy Harvesting Assisted RFID and WSN

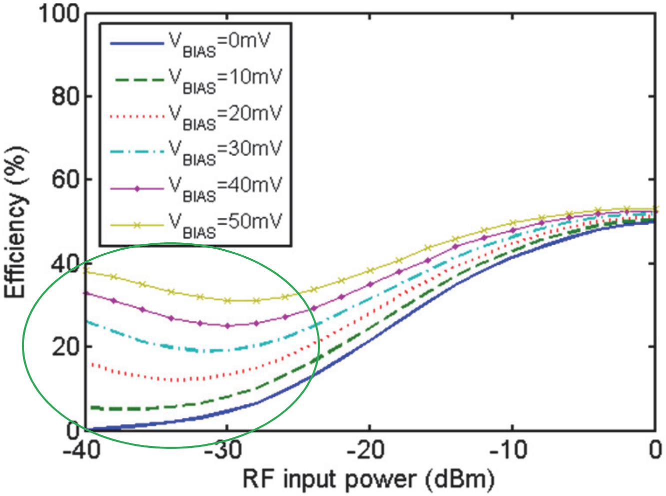












Thank you for your attention !

Questions

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