# Radiative Wireless Power Transfer at Holst Centre / imec and TU/e: Past, Present and Future


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**April 2016**

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Where innovation starts

# Contents

# 1. Introduction

## Definitions

**Energy / Power Harvesting:** "The process by which power is obtained by a device from external sources in the environment of the device and converted into usable electric power".

**Radiative Wireless Power Transfer (RWPT):** "A special form of Radio Frequency (RF) Power Harvesting in which use is made of radiated fields".


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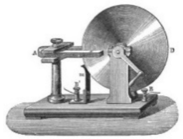
# 1. Introduction (ctd.)

## Energy Harvesting Sources

### Movement


1831 Faraday dynamo


WWII Philips dyno torch


Modern dyno torch

### Piezoelectricity

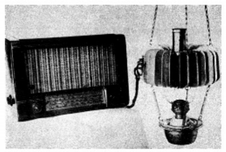

1880 Curie discovery of piezoelectricity

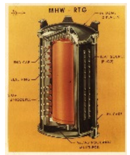

RPG7 fuse


Enocean wireless switch

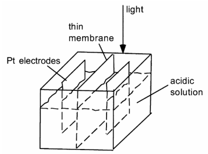
### Temperature


1821 Seebeck experiment

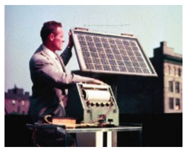

1948 USSR oil lamp powered radio


1977 Voyager 2 Radioisotope Thermoelectric Generator

### Light



1839 Becquerel experiment


1954 Bell Labs PV


Modern PV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# 1. Introduction (ctd.)

## Applications

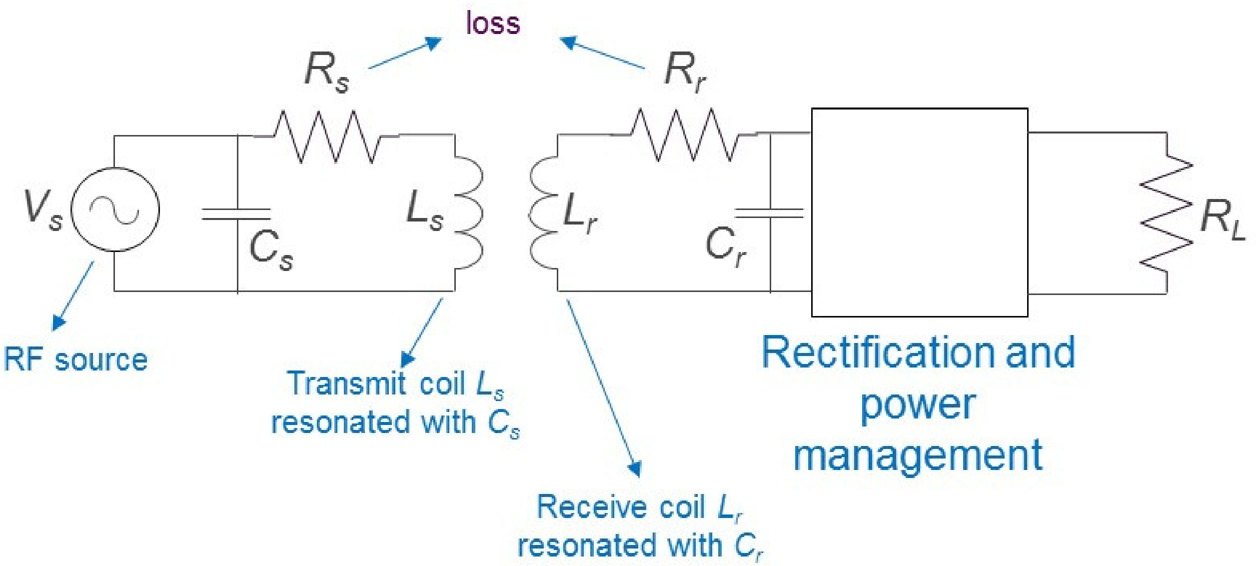
Replacing batteries in small, wireless, autonomous sensors

## Power Densities

| Source | Available Power Density | Typical Harvested Power Density |
|---|---|---|
| **Ambient Light** | | |
| Indoor | 0.1 mW/cm$^2$ | 10 $\mu$W/cm$^2$ |
| Outdoor | 100 mW/cm$^2$ | 10 mW/cm$^2$ |
| **Vibration/Motion** | | |
| Human | 0.5 m at 1 Hz<br>1 m/s$^2$ at 50 Hz | 4 $\mu$W/cm$^2$ |
| Industrial | 1 m at 5 Hz<br>10 m/s$^2$ at 1 kHz | 100 $\mu$W/cm$^2$ |
| **Thermal** | | |
| Human | 20 mW/cm$^2$ | 30 $\mu$W/cm$^2$ |
| Industrial | 100 mW/cm$^2$ | 1-10 mW/cm$^2$ |
| **RF** | | |
| GSM Base Station | 0.3 $\mu$W/cm$^2$ | 0.1 $\mu$W/cm$^2$ |

# 1. Introduction (ctd.)

## (Non-Radiative) Near-Field Wireless Power Transfer




- \+ High power
- \+ High efficiency
- \+ Standard

- \- Short distance
- \- Standard

Qi Wireless Power Consortium

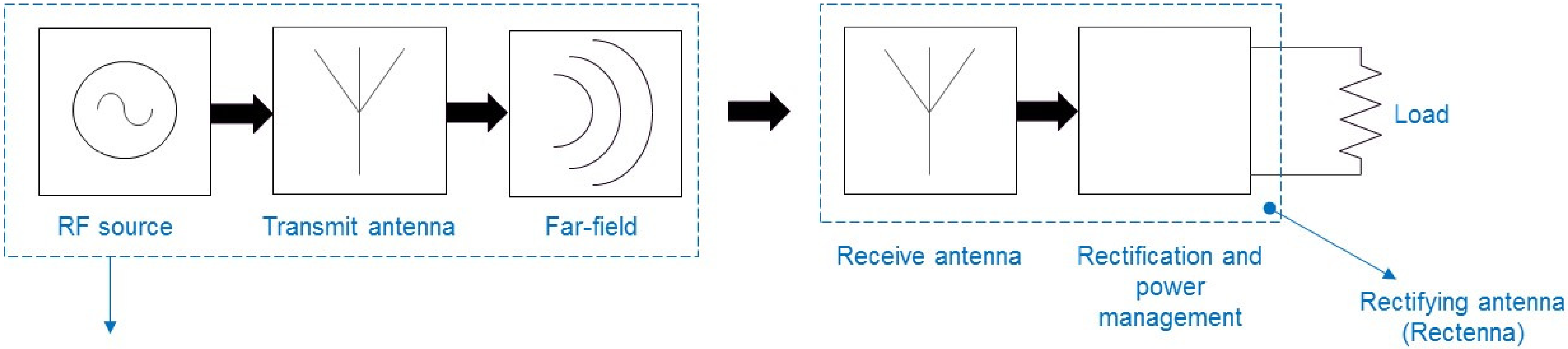
Asus, Blackberry, Broadcom, Dell, Fairchild, Freescale, Hama, Hitachi, HTC, Huawei, IKEA, Keysight, LG, Microsoft, Motorola, Nokia, NXP, Omron, Panasonic, Philips, Powercast, Qualcomm, Ricoh, Samsung, Sony, TDK, TI, Toshiba, Toyota, and others

PMA Power Matters Alliance & rezence Alliance for Wireless Power

Acer, Asus, AT&T, Broadcom, Canon, Deutsche Telekom, Dialog, Fairchild, Fujitsu, HP, Hitachi, HTC, Intel, Keysight, Lenovo, LG, Microsoft, Motorola, Nordic, NXP, Omron, Panasonic, P&G, Qualcomm, Renesas, Rohm, Samsung, Starbucks, Sandisk, Sharp, Sony, ST, TDK, TI, Toshiba, Witricity, and others

# 1. Introduction (ctd.)

## Radiative Far-Field Wireless Power Transfer




### Ambient RF Energy

- Unintentional WPT or harvesting
- No influence on source and transmit antenna

### Dedicated Transmit System

- Intentional WPT
- Access to source and transmit antenna
- Transmit power restrictions



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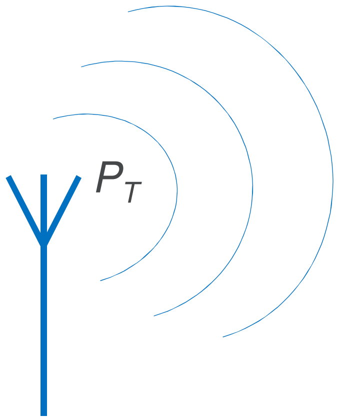
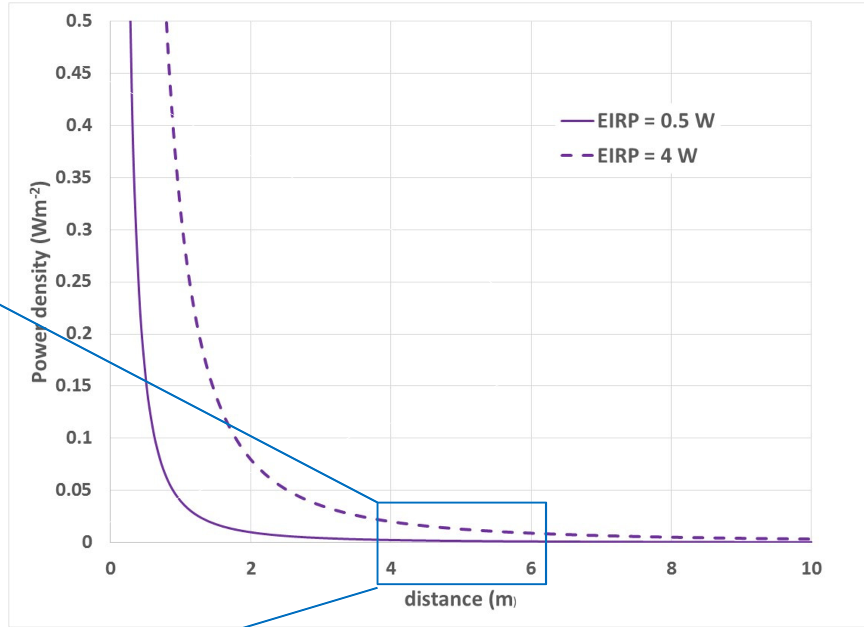
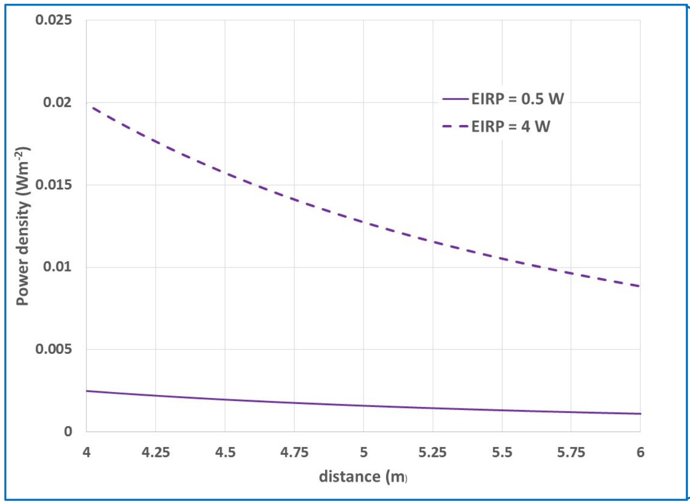
# Far-Field Wireless Power Transfer




Power density at distance $r$: $S = \dfrac{P_T G_T}{4\pi r^2} = \dfrac{EIRP}{4\pi r^2}$ Spherical spreading

$P_T$: Transmit power
$G_T$: Transmit antenna gain
*EIRP*: Effective Isotropic Radiated Power




Ambient (GSM900): 0.003 $Wm^{-2}$



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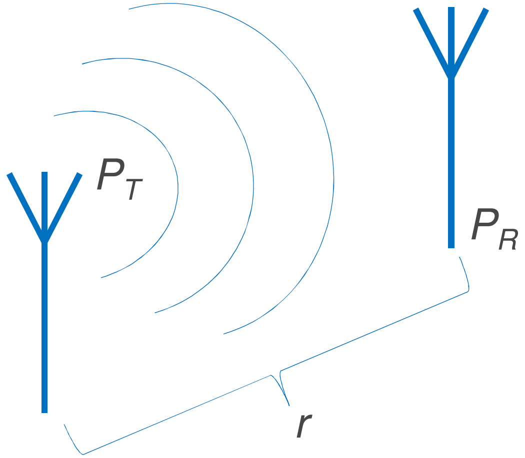
## Far-Field Wireless Power Transfer




Power density at distance $r$: $S = \dfrac{P_T G_T}{4\pi r^2} = \dfrac{EIRP}{4\pi r^2}$

Received power at distance $r$: $P_R = \dfrac{EIRP}{4\pi r^2} A_{eR}$

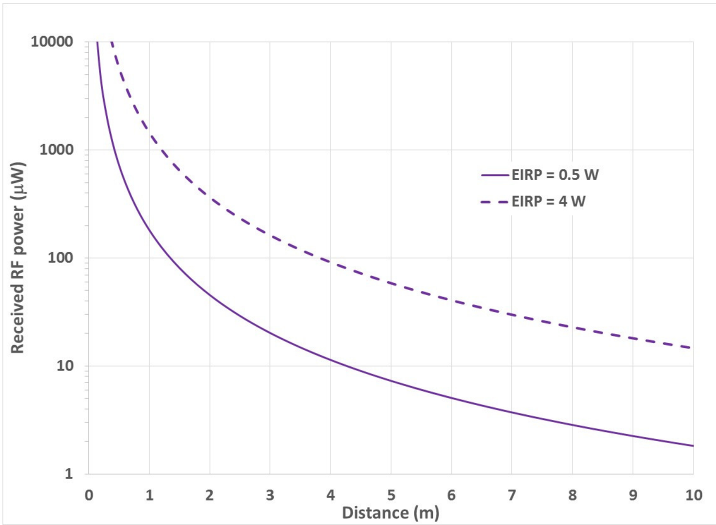
$A_{eR}$: Effective area receive antenna $A_{eR} = \dfrac{G_R \lambda^2}{4\pi}$

$$P_R = EIRP \frac{G_R \lambda^2}{(4\pi)^2 r^2}$$

*Friis transmission equation*

Example: 2.4 GHz ($\lambda$ = 12 cm)
antenna 6 cm x 6 cm: $G_R \approx 4$ ⇒ $P_R = \dfrac{3.65 \cdot 10^{-4} EIRP}{r^2}$ ⇒

900 MHz ($\lambda$ = 33 cm)
antenna 4 cm x 3 cm: $G_R \approx 1$ ⇒ $P_R = \dfrac{6.90 \cdot 10^{-4} EIRP}{r^2}$



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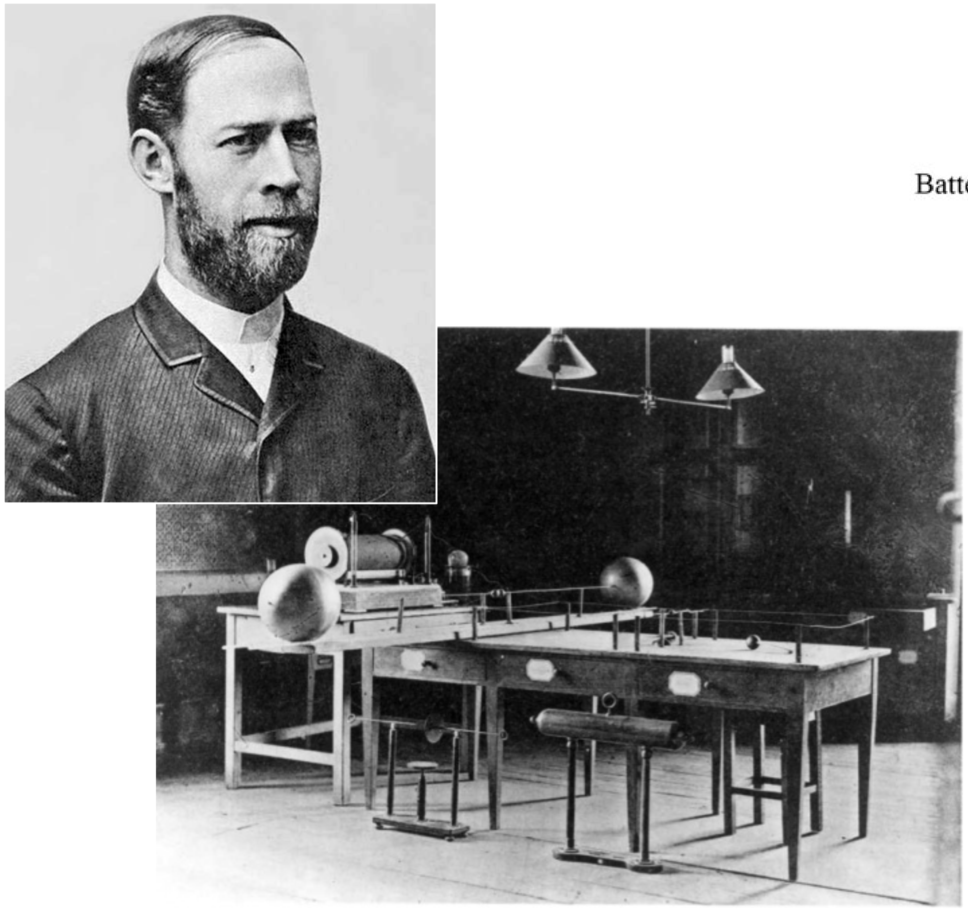
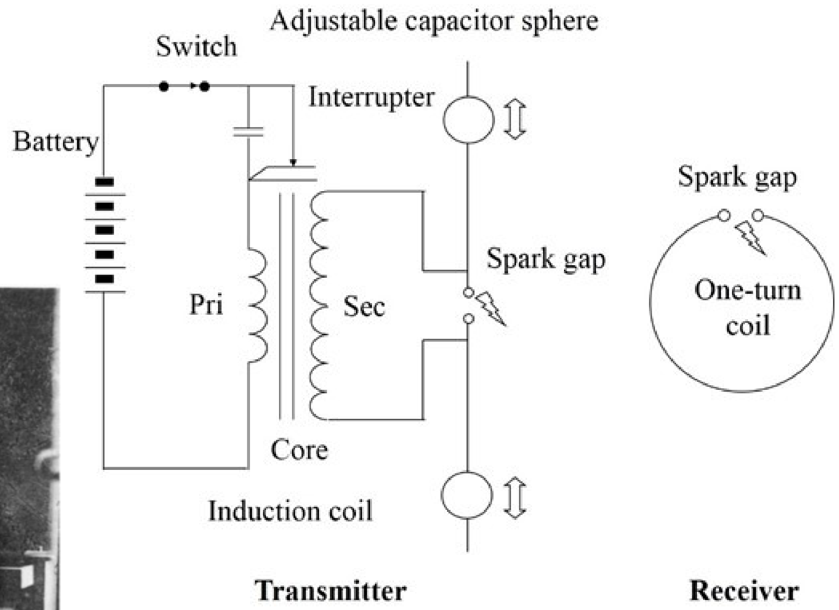
# 2. The Early History of RWPT

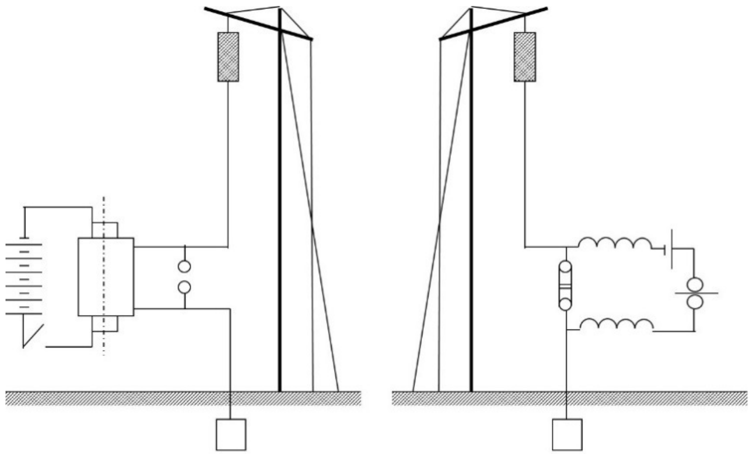
<u>1886:</u> *Heinrich Hertz*, in proving the Maxwell equations, constructs the first radio





# 2. The Early History of RWPT (ctd.)

1894: *Guglielmo Marconi* develops practical radio, transmitting and receiving *data*



# 2. The Early History of RWPT (ctd.)

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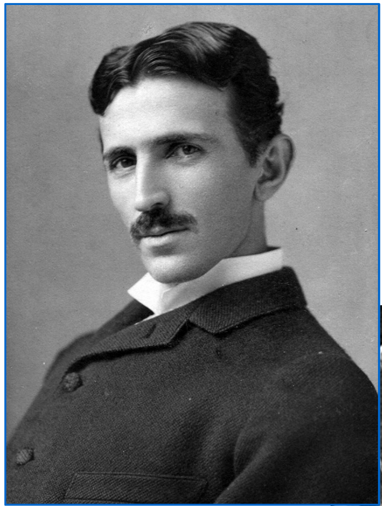
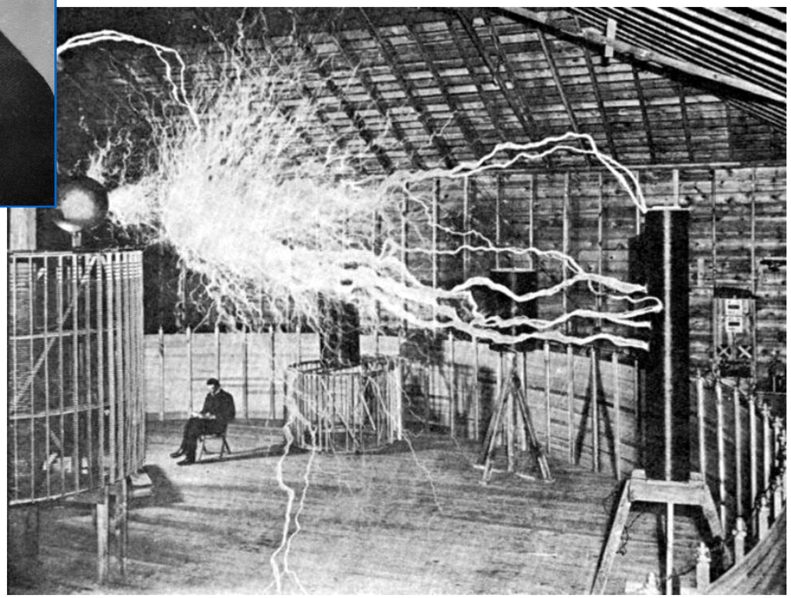
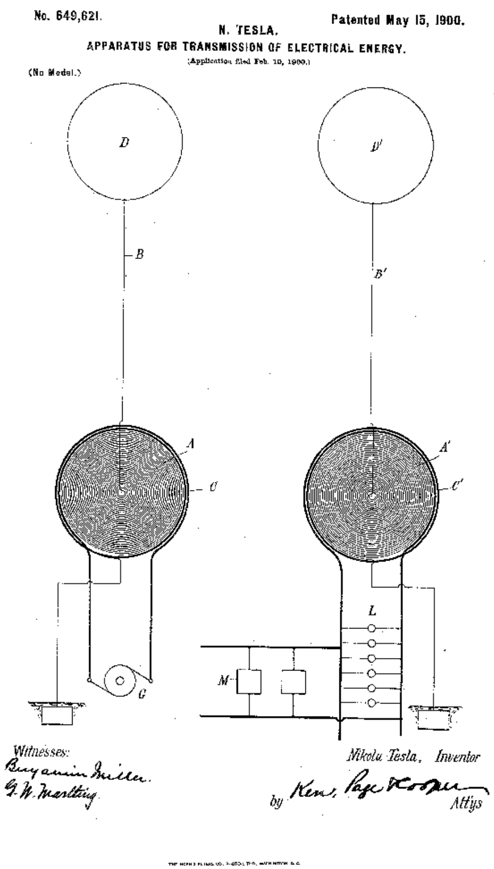
# 2. The Early History of RWPT (ctd.)

1901: *Nikola Tesla* creates the idea to wirelessly transmit and receive *power*







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# 2. The Early History of RWPT (ctd.)

<u>1931:</u> *Harrell Noble* demonstrates Wireless Power Transfer

- 100MHz half-wavelength dipoles
- Displaced 5 to 12 meters
- 15kW transmit power (!)

- Westinghouse laboratories
- Demonstrated at 1933-1934 Chicago World Fair

# 3. The Modern History of RWPT

<u>1964:</u> *William Brown* demonstrates a microwave powered model helicopter

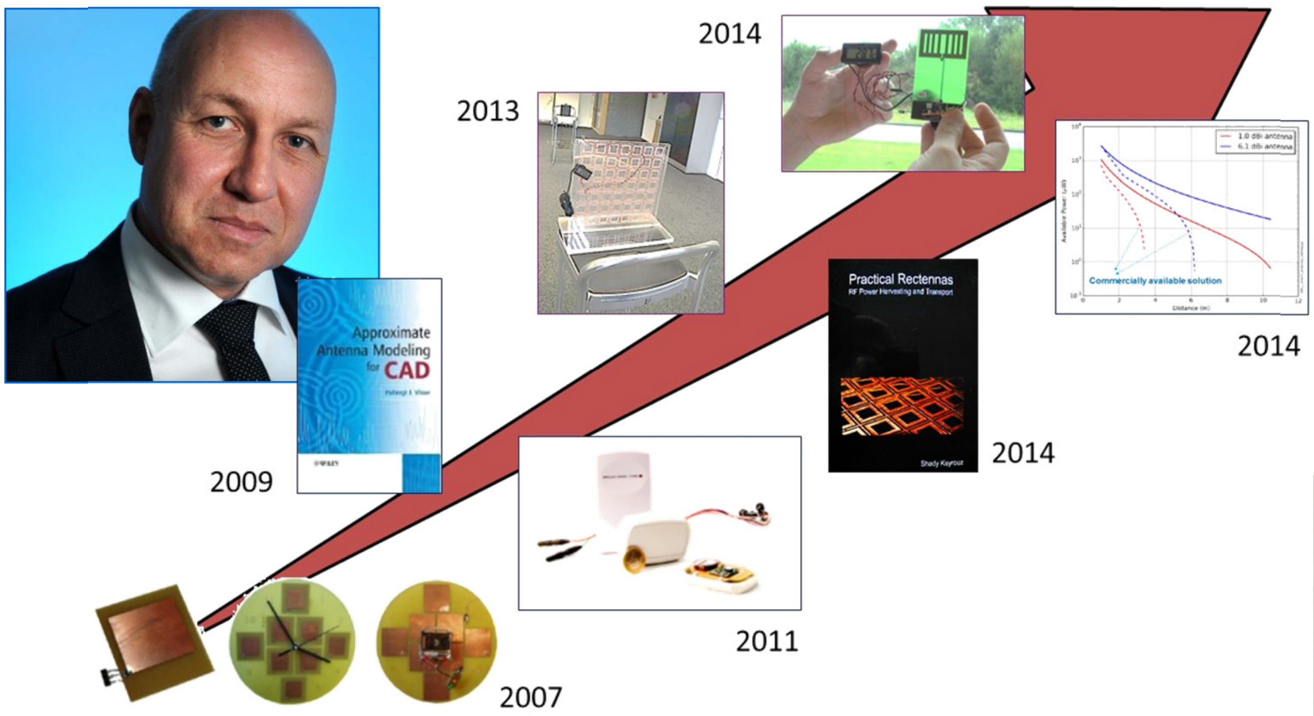
- 5kW, 2.45GHz magnetron
- 3m diameter parabolic reflector antenna
- 9m height

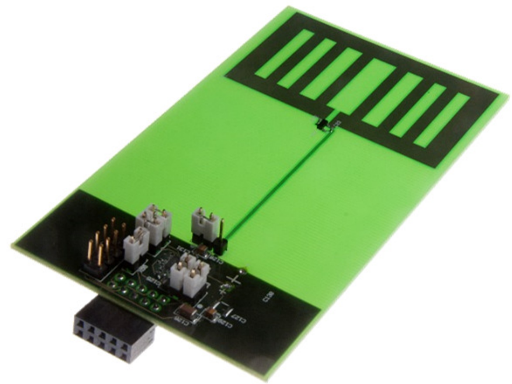
- 1.5m$^2$ receive antenna
- 4480 diodes
- 270W dc power

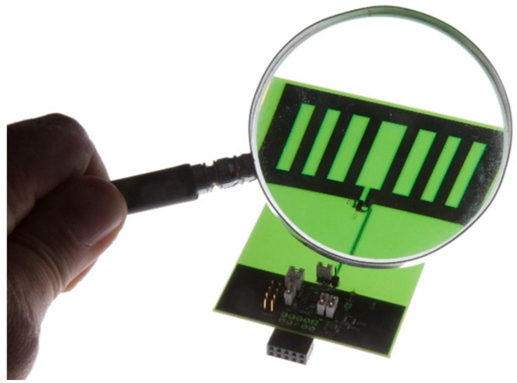
- Raytheon Airborne Microwave Platform (RAMP) project

# 3. The Modern History of RWPT (ctd.)

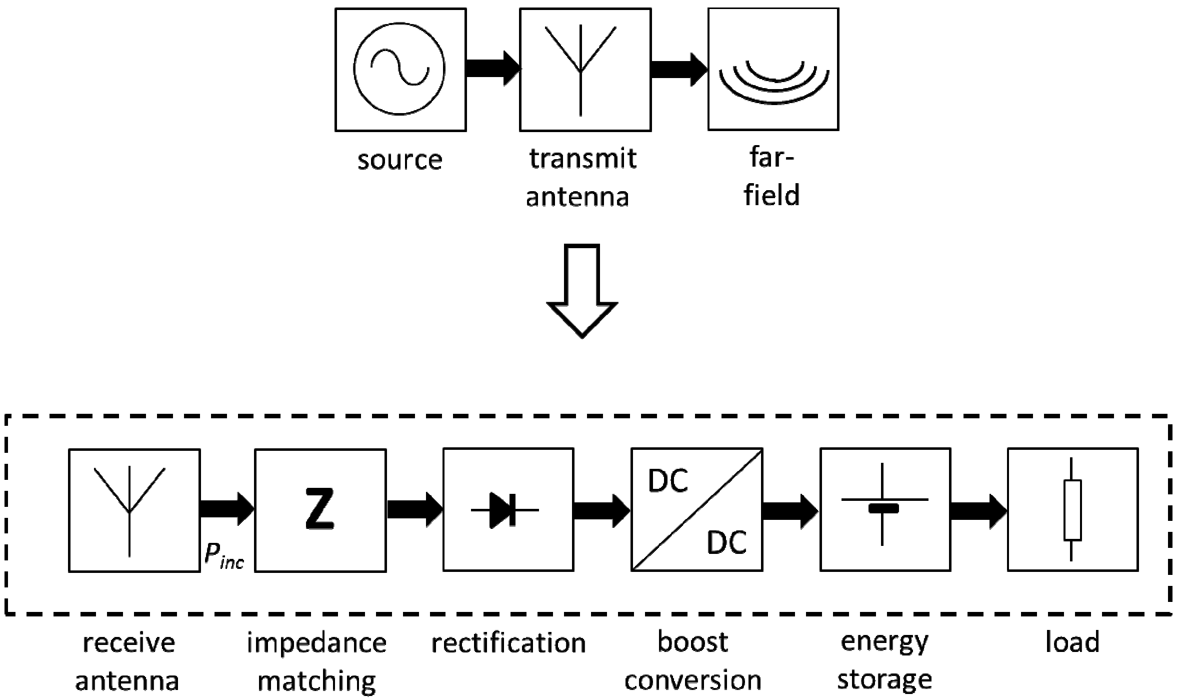
<u>2014:</u> *Visser et al.* demonstrate most compact, efficient 868/915MHz rectenna



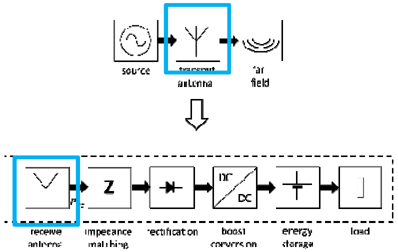





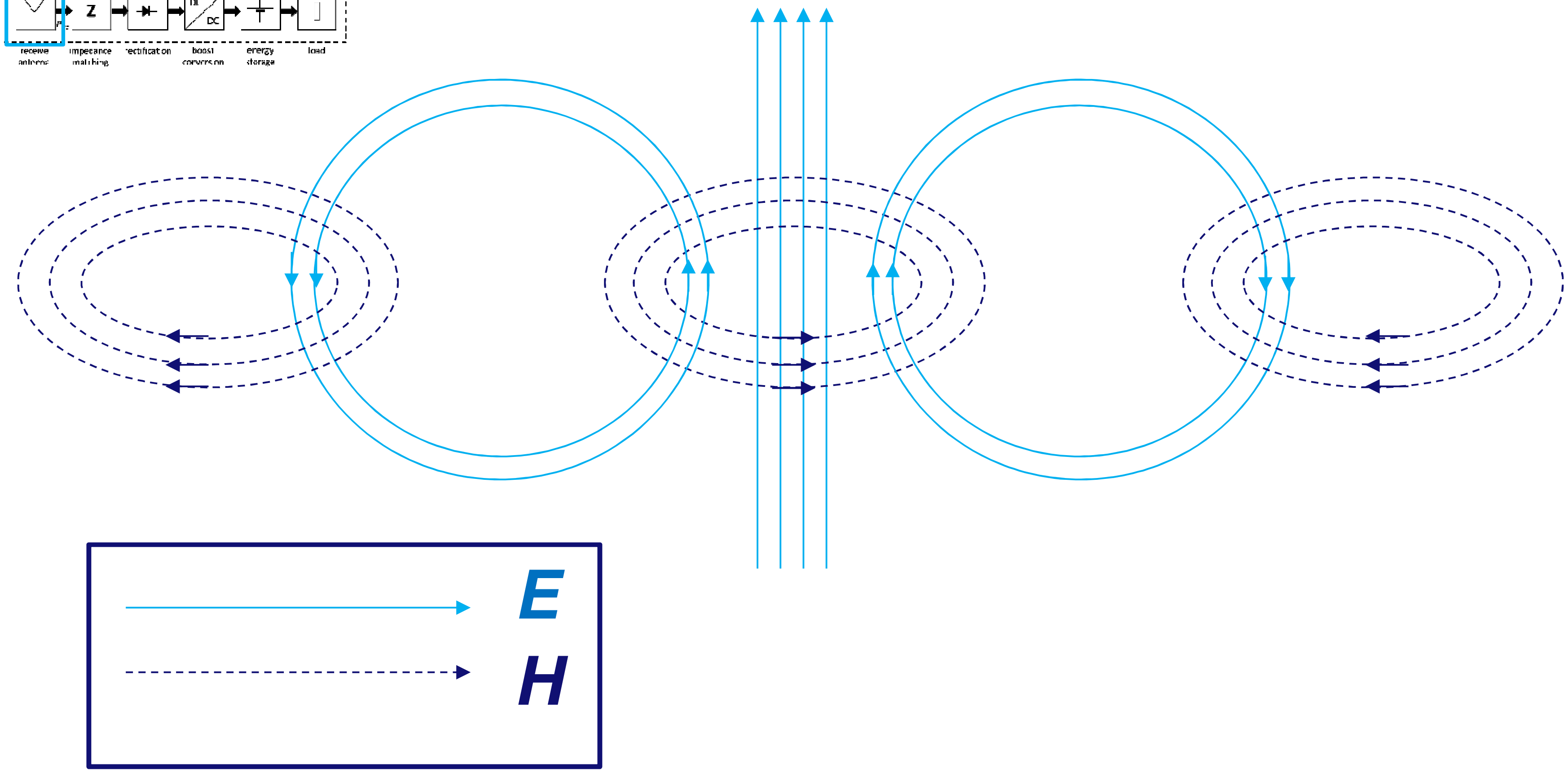
# 4. RWPT Basics



# 4. RWPT Basics (ctd.)




## Antenna Radiation



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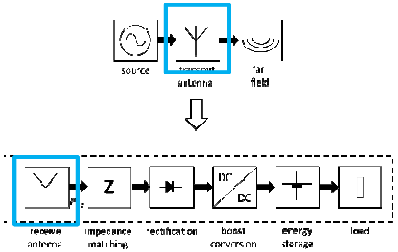
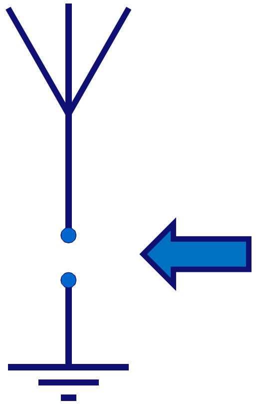
# Antenna Input Impedance





$$Z_A = R_A + jX_A$$

Reactive near field, energy storage

$$R_A = R_R + R_L$$

Desired, radiation

Undesired, loss (heat)

Tuned antenna: $X_A = 0$. Low-loss materials: $R_L \approx 0$.

Maximum power delivered to load $R_r$ if $R_r = R_A$: $$P = \frac{1}{8}\left|V_A\right|^2 \frac{1}{R_A}$$

Maximum power delivered to load $R_r$ if $R_r \neq R_A$: $$P = \frac{1}{2}\left|V_A\right|^2 \left|\frac{R_A}{R_A + R_r}\right|^2 \frac{1}{R_A}$$

Voltage reflection coefficient, looking into load: $$\Gamma = \frac{R_r - R_A}{R_r + R_A}$$



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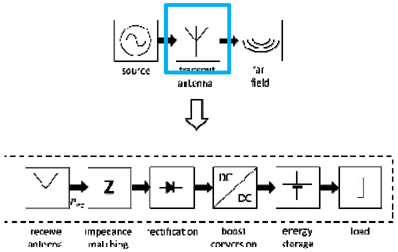
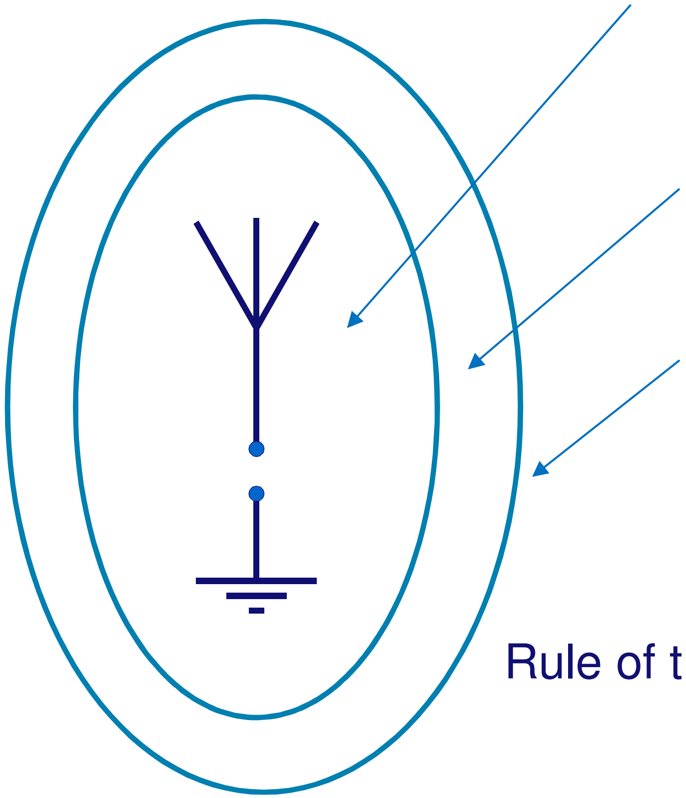
# 4. RWPT Basics (ctd.)

## Antenna Far-Field Distance



*Reactive near-field region*: emitted energy is dominantly stored and returned to the antenna

*Radiating near-field or Fresnel region*: radiated fields dominate reactive fields

*Far-field region*: radiated fields dominate, angular distribution independent from the distance

Rule of thumb: $r_{ff} \geq \dfrac{2L^2}{\lambda}$

*L*: largest dimension antenna
$\lambda$: wavelength used



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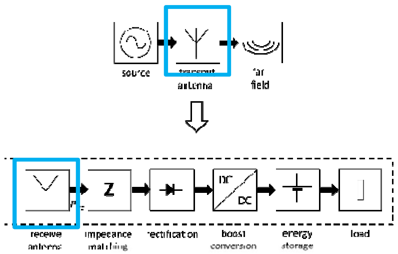
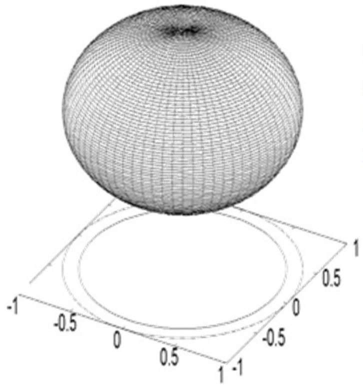
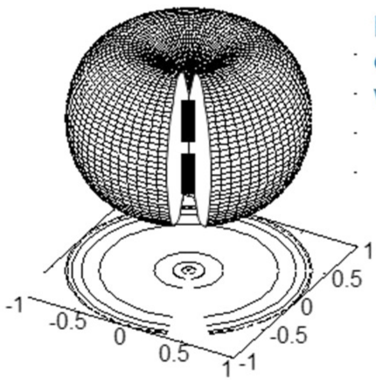
## Antenna Directivity and Gain

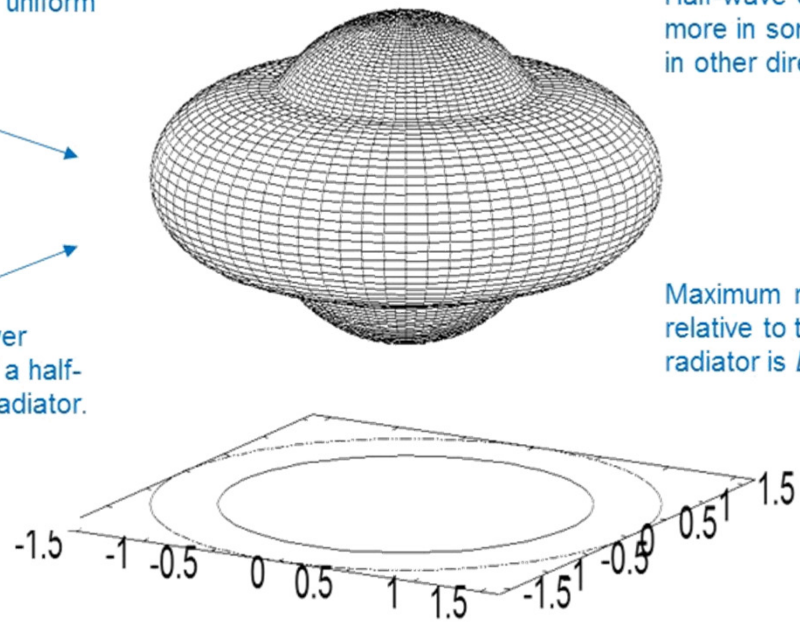



Radiated power distribution of a (hypothetical) uniform radiator.




Radiated power distribution of a half-wave dipole radiator.




Same total radiated power

Half-wave dipole radiates more in some direction, less in other directions.

Maximum radiated power relative to that of a uniform radiator is *Directivity*.

$$\eta = \frac{G}{D}$$



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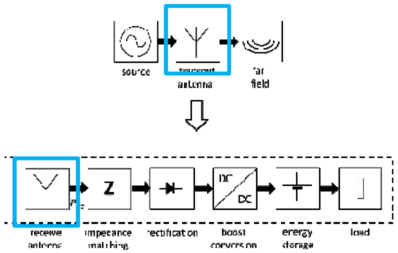
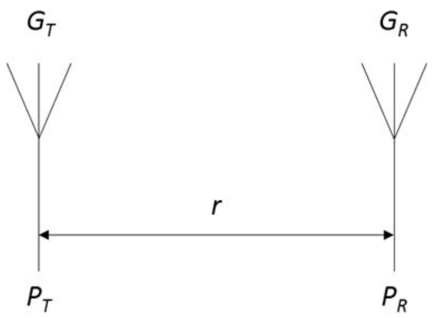
# 4. RWPT Basics (ctd.)

## Friis Equation






Assume transmit antenna to be uniform radiator. Then power density at distance *r*:

$$S(r) = \frac{P_T}{4\pi r^2}$$

spherical spreading

In reality antenna has gain $G_T$: $S(r) = \frac{P_T G_T}{4\pi r^2}$

Receive antenna intercepts power equal to the power density times the *effective aperture* $A_e$:

$$P_R(r) = S(r)A_e = \frac{P_T G_T A_e}{4\pi r^2}$$

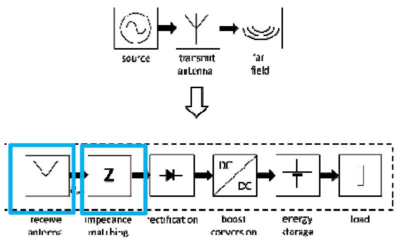
With: $A_e = \frac{G_R \lambda^2}{4\pi}$

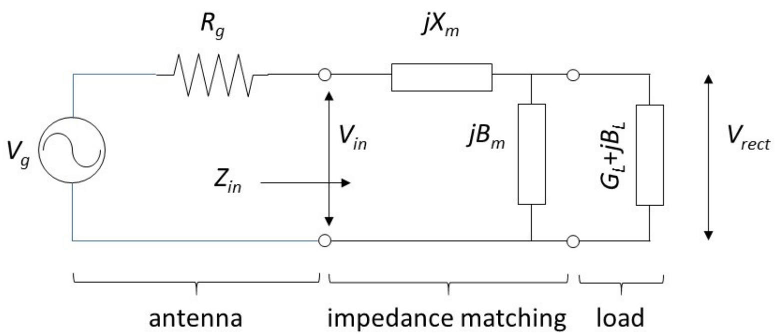
$$P_R(r,\lambda) = P_T G_T \frac{G_R \lambda^2}{(4\pi)^2 r^2}$$

$P_T G_T$ is Effective Isotropic Radiated Power

# 4. RWPT Basics (ctd.)

## Antenna Matching






$$P_{in} = \frac{1}{2} v_{in}^2 \Re\{Y_{in}\} \quad \xrightarrow[Y_{in} = \frac{1}{Z_{in}}]{v_g - IR_g = v_{in} = \frac{I}{Y_{in}}} \quad P_{in} = \frac{1}{2}\left|\frac{1}{1+Y_{in}R_g}\right|^2 v_g^2 \Re\{Y_{in}\}$$

$$P_{out} = \frac{1}{2} v_{rect}^2 \Re\{Y_L\}$$

no losses:

$$P_{in} = P_{out} \quad \xrightarrow[Y_L = \Re\{Y_L\} + j\Im\{Y_L\} = G_L + jB_L]{Y_{in} = \Re\{Y_{in}\} + j\Im\{Y_{in}\} = G_{in} + jB_{in}} \quad v_{rect}^2 = v_g^2 \frac{1}{(1+G_{in}R_g)^2 + B_{in}^2 R_g^2} \frac{G_{in}}{G_L}$$

also:

$$P_{in} = \frac{v_g^2}{8R_g} \quad \longrightarrow \quad \boxed{v_{rect} = \sqrt{\frac{2P_{in}}{G_L}} \cdot 2\sqrt{\frac{G_{in}R_g}{(1+G_{in}R_g)^2 + B_{in}^2 R_g^2}}}$$

maximize $v_{rect}$ for maximum sensitivity



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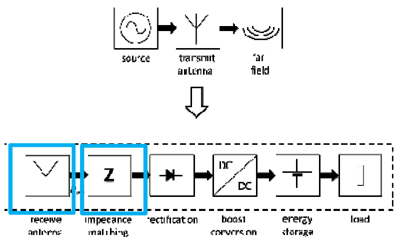
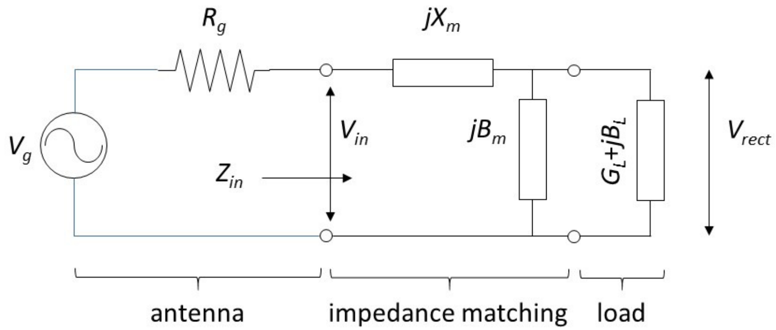
# 4. RWPT Basics (ctd.)

## Antenna Matching





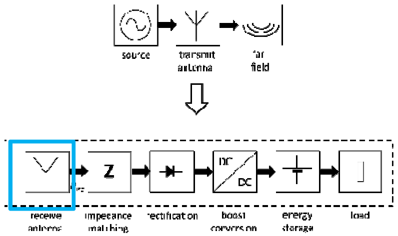

$$v_{rect} = \sqrt{\frac{2P_{in}}{G_L}} \cdot 2\sqrt{\frac{G_{in}R_g}{\left(1+G_{in}R_g\right)^2 + B_{in}^2 R_g^2}}$$

maximize $v_{rect}$ for maximum sensitivity

maximum for: $G_{in} = \frac{1}{R_g} \wedge B_{in} = 0$ (matched condition) → $v_{rect_{\max}} = \sqrt{\frac{2P_{in}}{G_L}}$

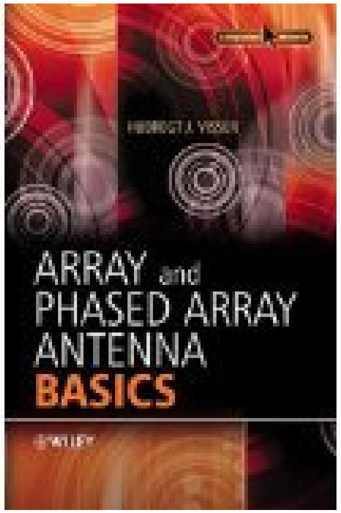
$$v_{rect_{\max}} = \sqrt{2P_{in}\frac{R_L^2 + X_L^2}{R_L}}$$

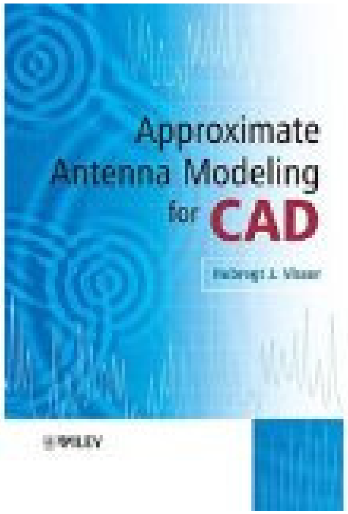
maximize $R_L$ and minimize $X_L$
or
maximize $X_L$ and minimize $R_L$

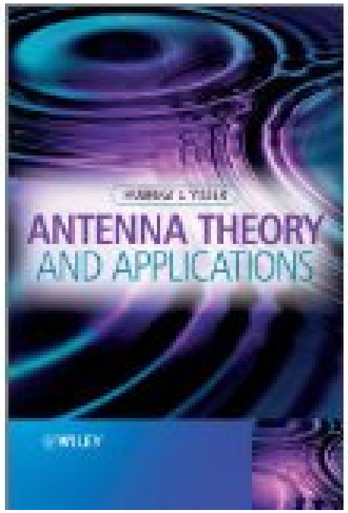



## Antenna Design

Any antenna textbook, but preferably:



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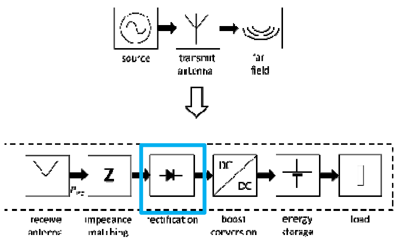
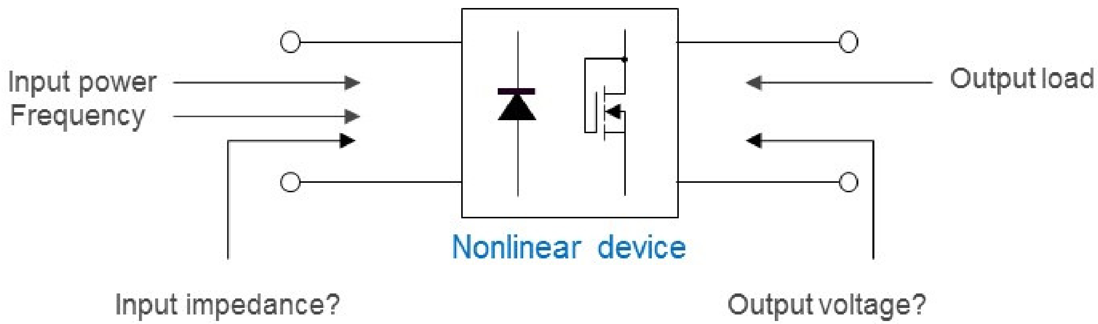
# 4. RWPT Basics (ctd.)



## Rectifier




### Output voltage

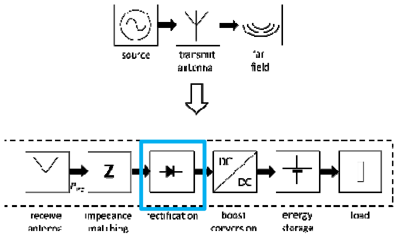
$$II_0\left(\frac{\Lambda}{n}\sqrt{8R_gP_{inc}}\right)=\left(1+\frac{V_{dc}}{R_LI_s}\right)e^{\left(1+\frac{R_g+R_s}{R_L}\right)\frac{\Lambda}{n}V_{dc}}$$

$$\Lambda=\frac{q}{kT}$$

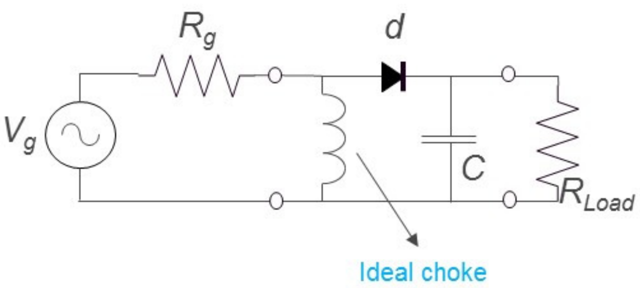
- $I_0$: Zero-order Bessel function of the first kind
- $n$: Diode ideality factor
- $R_g$: Generator resistance
- $P_{inc}$: Available RF input power
- $V_{dc}$: DC output voltage
- $R_L$: Load resistance
- $I_s$: Diode saturation current
- $R_s$: Diode series resistance
- $q$: Electron charge
- $k$: Boltzmann's constant
- $T$: Temperature

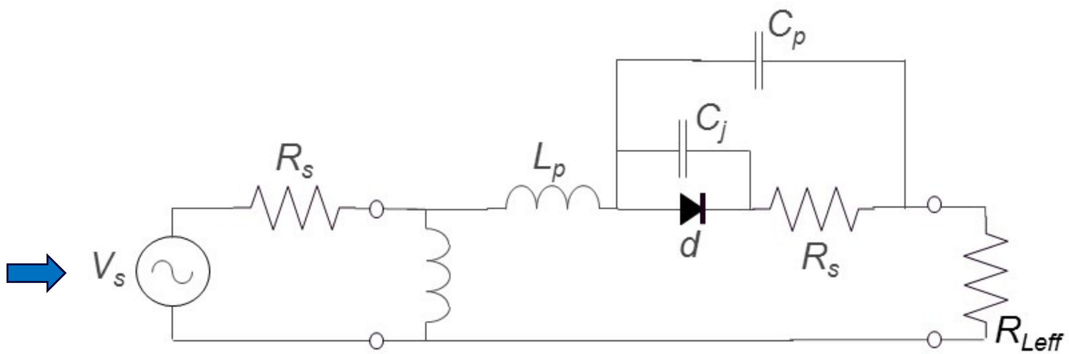

R.G. Harrison and X. Le Polozec, "Nonsquarelaw Behavior of Diode Detectors Analyzed by the Ritz-Galerkin method", IEEE Transactions on Microwave Theory and Techniques, Vol. 42, No. 5, pp. 840-846, May 1994.

# Rectifier




## Input Impedance




$R_{Load} = 2R_{Leff}$ ➡ Fundamental harmonic of diode's current is ~ twice dc load current



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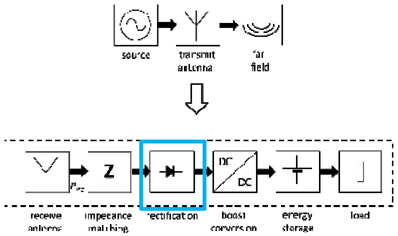
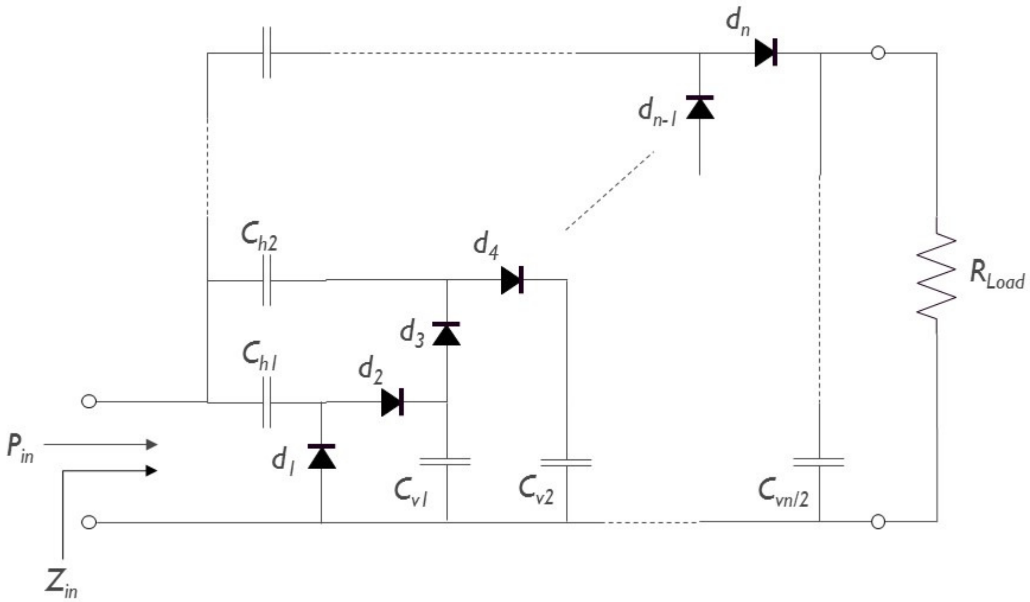
# 4. RWPT Basics (ctd.)

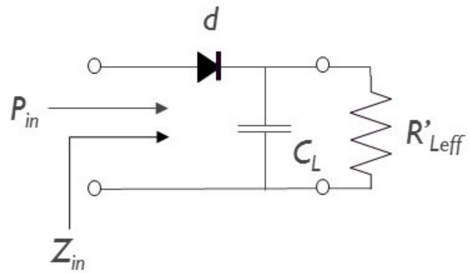



## Cascaded Rectifier

### Input Impedance



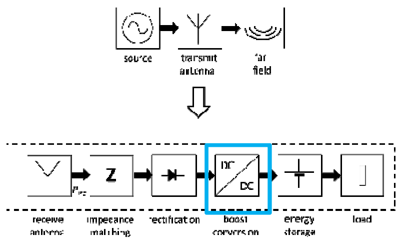

Equivalent circuit




$$R'_{Leff} = \frac{R_{Load}}{2n}$$

# 4. RWPT Basics (ctd.)

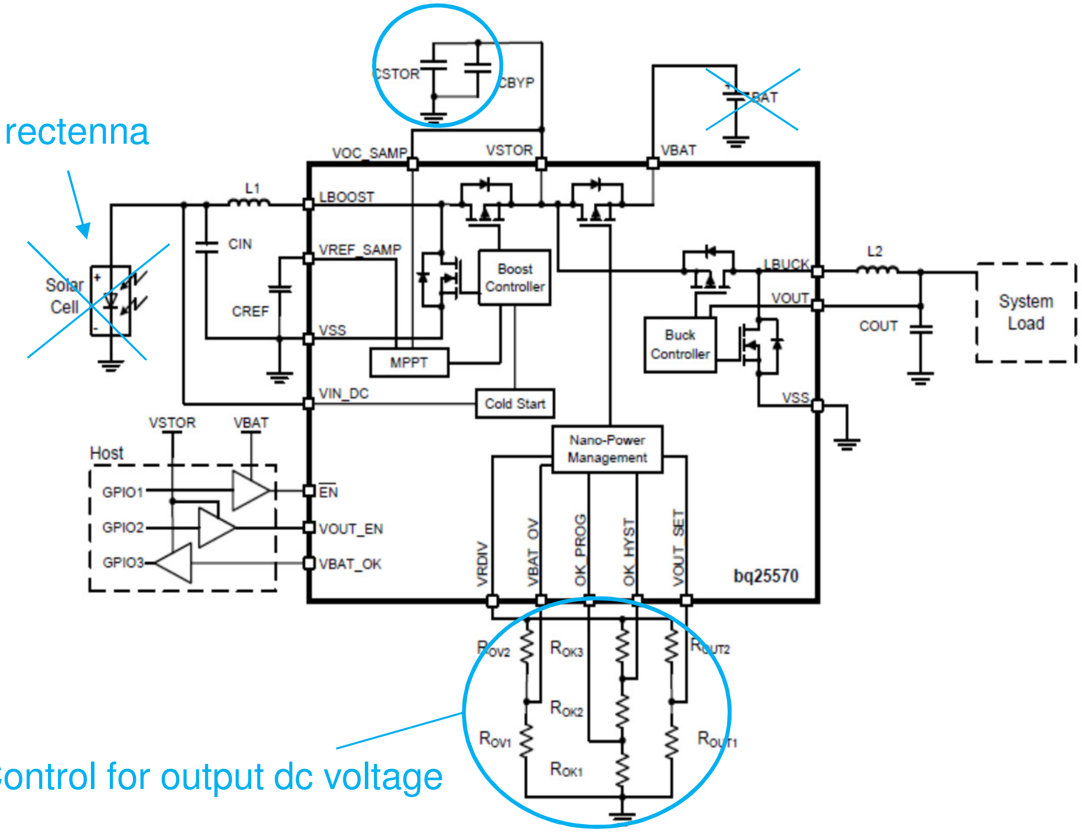
## Power Management




### TI BQ25570, including boost-buck-converter

- 330 mV in cold start
- 100 mV in after start
- $V_{out}$ 1.2 – 4.0 V

rectenna




Control for output dc voltage

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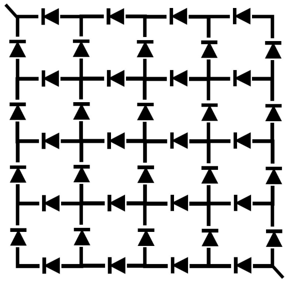
# Large Area Rectenna

## The Idea

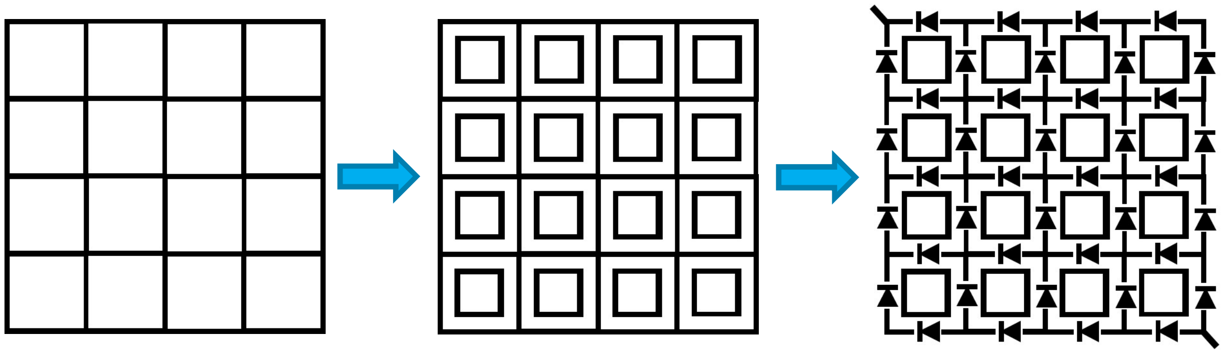


Diode loaded grid, after *

- Current is flowing upward and to the left;
- DC collection on lower-right and upper-left;
- *DC collection network integrated in receiving aperture*.

## The Improvement

- The above structure is recognized as being a diode-loaded Frequency Selective Surface (FSS);
- Therefore, the modeling and design may be based on FSS equivalent circuit models;
- The grid may be modified to improve performance.



- Scalable;
- May be positioned over an already existing antenna aperture;
- Carefully choose transmission and reflection bands;
- Reflection may be used for position determination.

* Hagerty, J.A. et al. (2000) Broadband Rectenna Arrays for Randomly Polarized Incident Waves. EuMC, 4pp.



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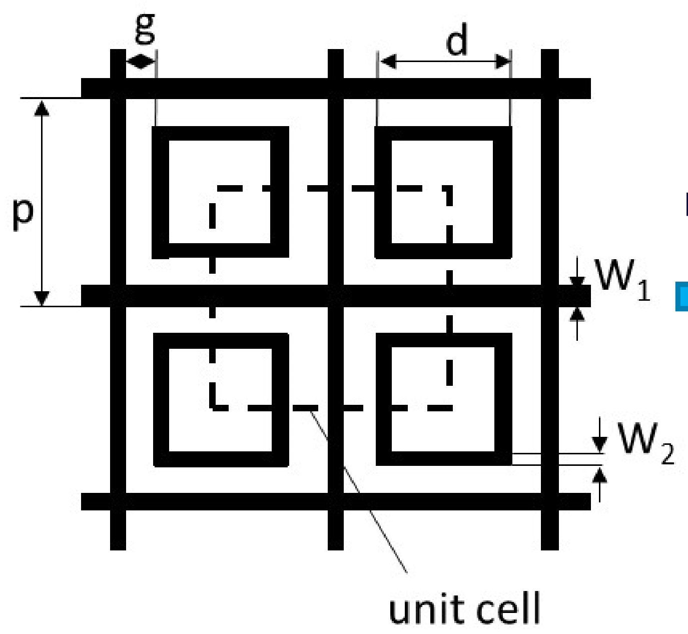
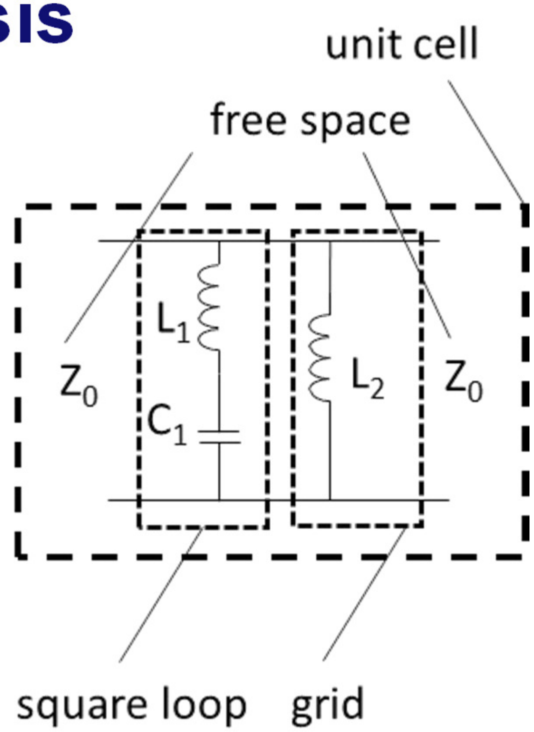
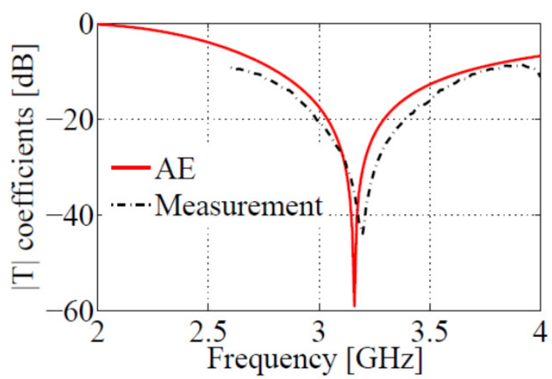
# 5. Examples (ctd.)

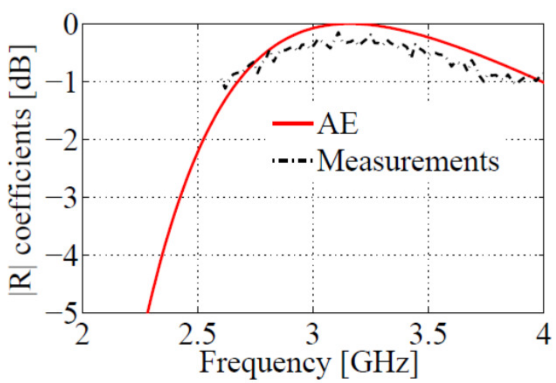
## FSS Analysis

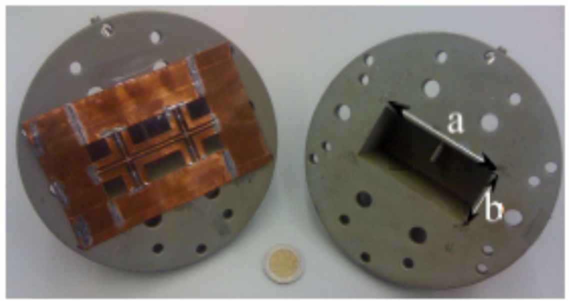



**Equivalent electric circuit**



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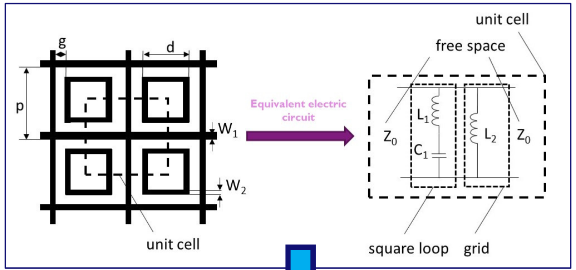
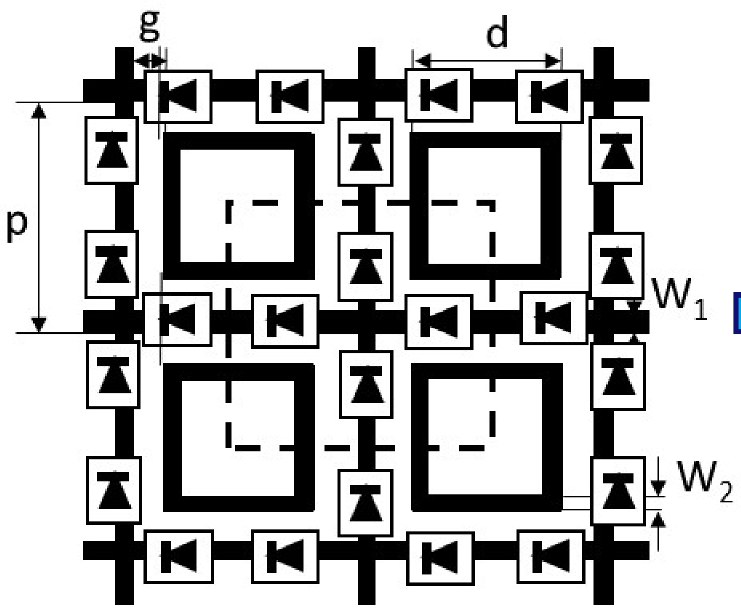
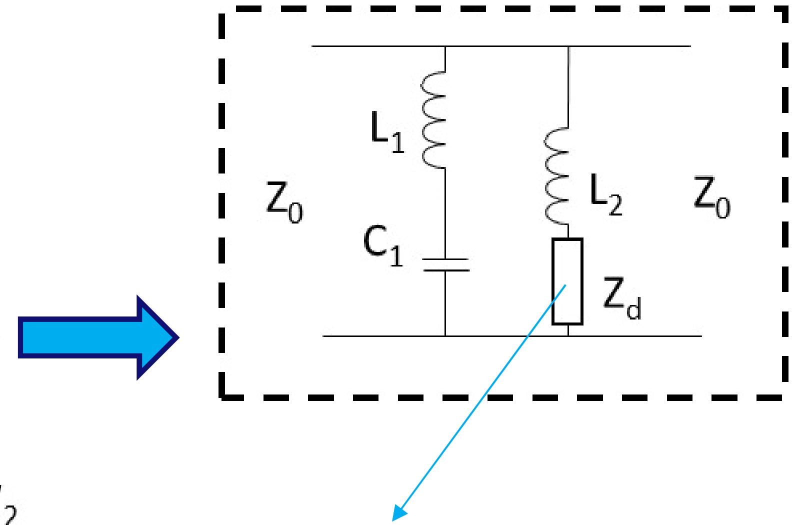
# RF Energy Harvesting FSS Analysis



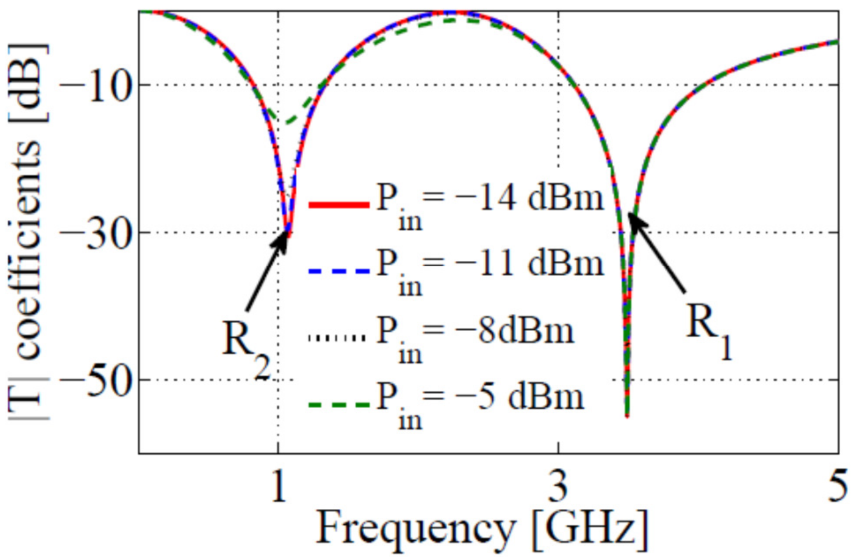

Diode impedance

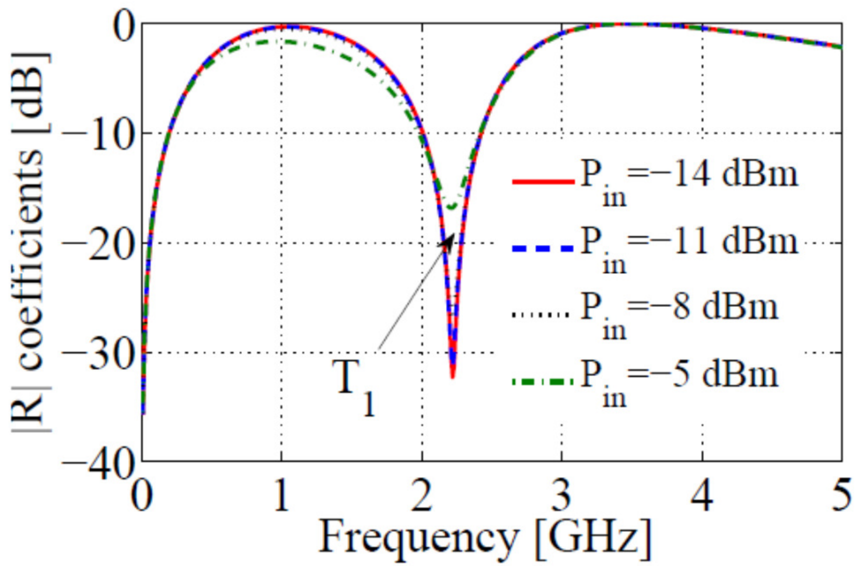
# 5. Examples (ctd.)

## 1 GHz Design

Considerations:

- HSMS-2820 Schottky diode impedance analyzed: Reactive part invariant with input power → resonance invariant with input power;
- Through full-wave simulation it is verified that 1GHz resonance is in the grid → optimum RF-to-dc power conversion efficiency



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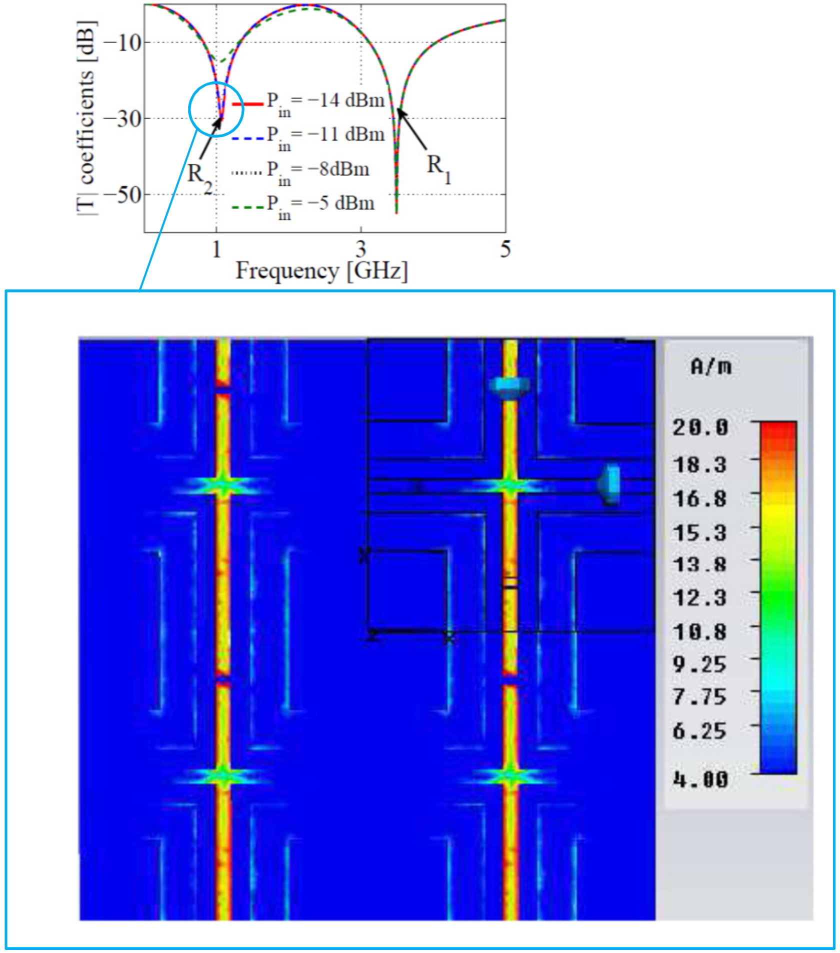
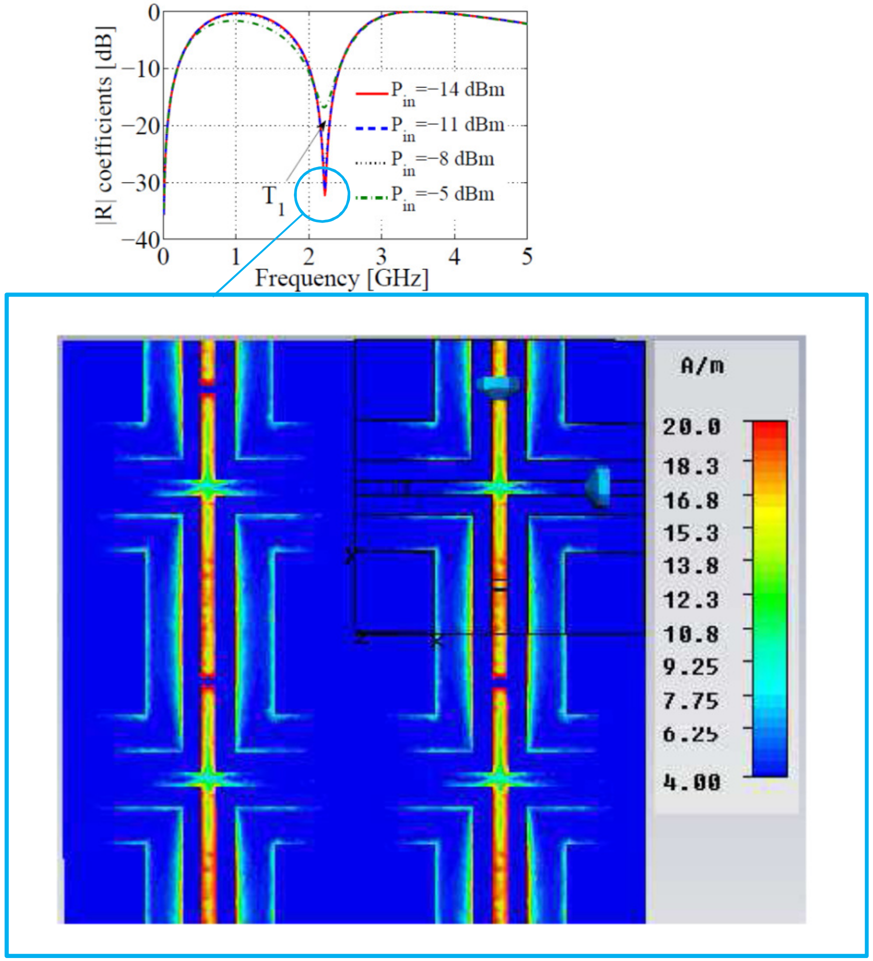
# 5. Examples (ctd.)

## 1 GHz Design




Peak current density at 1GHz: Concentrated in the grid




Peak current density at 2.2GHz: Resonance in square loops

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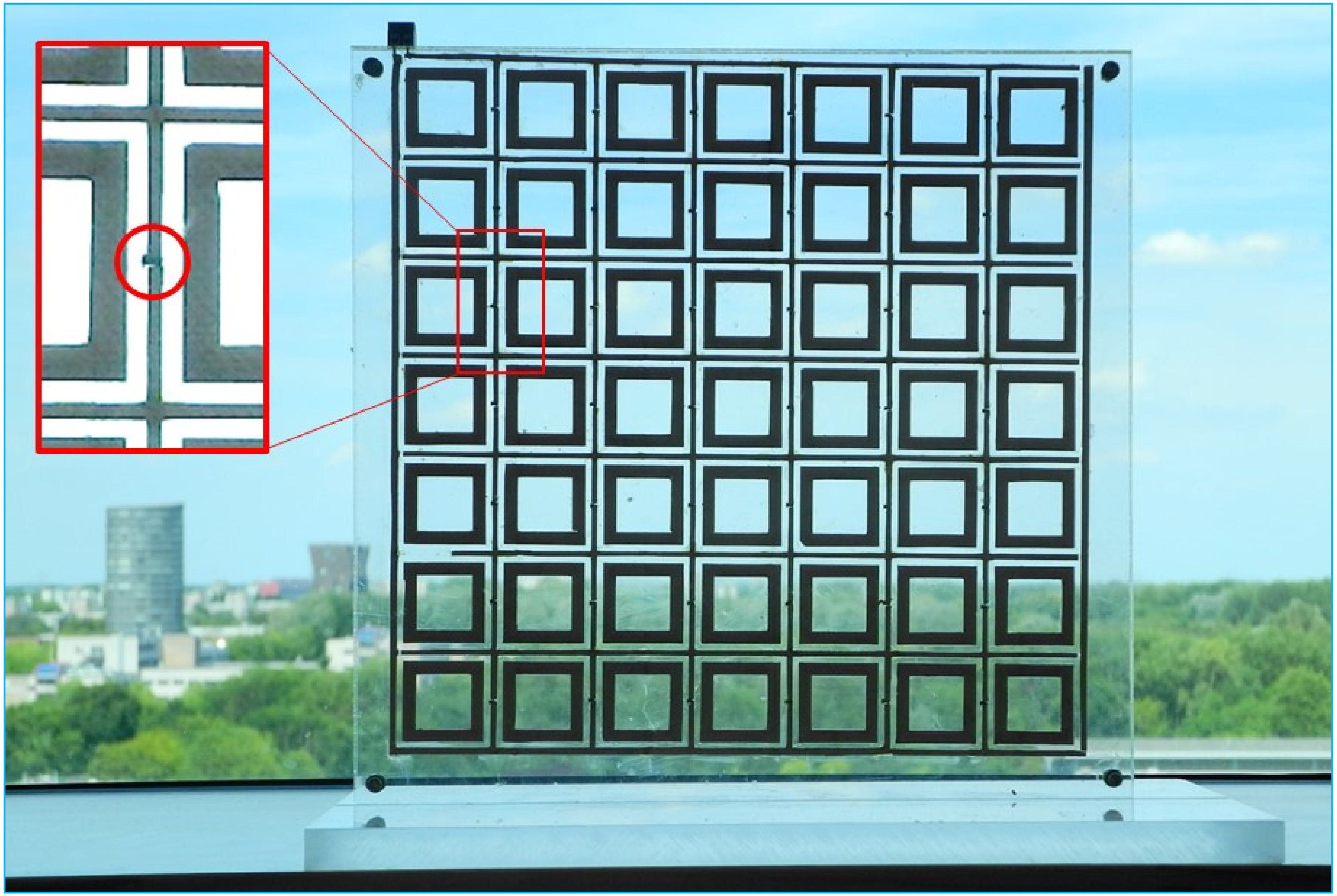
# 5. Examples (ctd.)

## Prototype



# Demonstration



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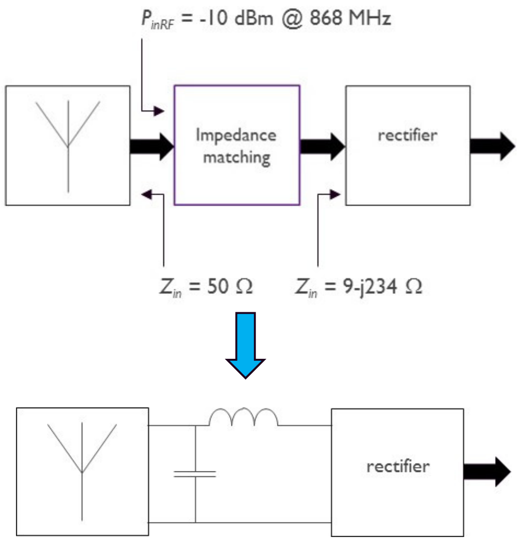
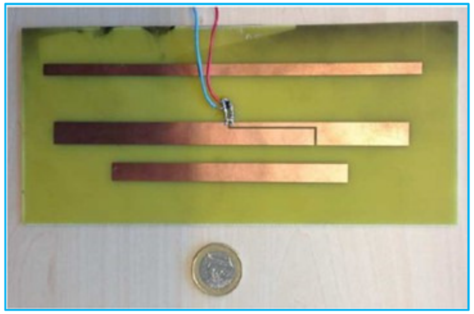
# 5. Examples (ctd.)

## Small Area Rectenna



$$PCE = \frac{P_{dc}}{P_{inRF}}$$

| State of the art | $P_{in}$ (dBm) | Freq. (MHz) | Load (kΩ) | Diode(s) | PCE (%) |
|---|---|---|---|---|---|
| [61] | -10 | 866.5 | 3 | HSMS285C | 24 |
| [62] | 4.3 | 870 | 1 | HSMS285X | 50 |
| [63] | -10 | 830 | $10^4$ | HSMS286Y | 44 |
| [64] | -20 | 850 | - | Skyworks SMS7630 | 15 |
| [65] | -10 | 950 | 0.13 | Toshiba 1SS315 | 40 |
| [66] | -9 | 915 | 2.2 | Skyworks SMS7630 | 37 |
| This work | -10 | 868 | 10 | HSMS2852 | 50 |
| | -20 | 868 | 10 | HSMS2852 | 32 |


[61] D. De Donno, L. Catarinucci and L. Tarricone, 'An UHF RFID Energy-Harvesting System Enhanced by a DC-DC Charge Pump in Silicon-On-Insulator Technology', *IEEE Microwave Wireless Components Letters,* Vol. 23, pp. 315-317, 2013.

[62] G. Monti, L. Corchia and L. Tarricone, 'UHF Wearable Rectenna on Textile Materials', *IEEE Transactions on Antennas and Propagation*, Vol. 61, pp. 3869-3873, 2013.

[63] H. Kanaya, S. Tsukamaoto, T. Hirabaru and D. Kanemoto, 'Energy Harvesting Circuit on a One-Sided Directional Flexible Antenna', *IEEE Microwave Wireless Components Letters,* Vol. 23, pp. 164-166, 2013.

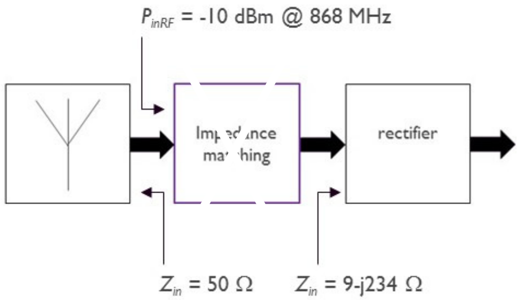
[64] A. Georgiadis, A. Collado, S. Via and C. Menses, 'Flexible Hybrid Solar/EM Energy Harvester for Autonomous Sensors', *IEEE MTT-S International Microwave Symposium*, Baltimore, USA, 2011.

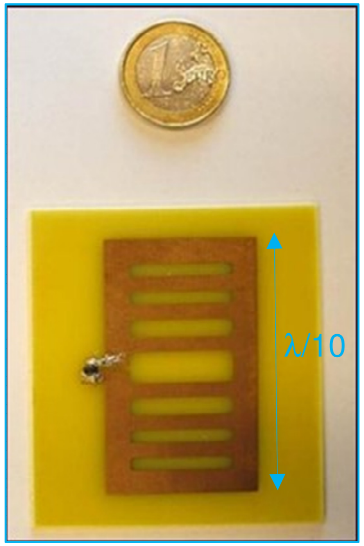
[65] K. Ogawa, K. Ozaki, M. Yamada and K. Honda, 'High Efficiency Small-Sized Rectenna Using a High-Q LC Resonator for Long Distance WPT at 950 MHz', *IEEE MTT-S International Microwave Symposium*, Nanjing, China, 2012.

[66] K. Niotaki, S. Kim, S. Jeong, A. Collado, A. Georgiadis and M. Tentzeris, 'A Compact Dual-Band Rectenna Using Slot-Loaded Dual Band Folded Dipole Antenna', *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, pp. 1634-1637, 2013.

# 5. Examples (ctd.)

## Small Area Rectenna




$Z_{rectifier}$ = 9 – j234 Ω

Capacitive

Compensate with inductance

**Small antenna** **Loop antenna**

| State of the art | $P_{in}$ (dBm) | Freq. (MHz) | Load (kΩ) | Size ($\lambda^2$) | PCE (%) |
|---|---|---|---|---|---|
| [63] | -10 | 830 | $10^4$ | 0.028 | 44 |
| [67] | -20 | 550 | 2 | 0.036 | 18 |
| [68] | 0 | 900 | 1 | 0.66 | 49 |
| This work | -10 | 868 | 10 | 0.028 | 55 |
| | -20 | 868 | 10 | 0.028 | 34 |

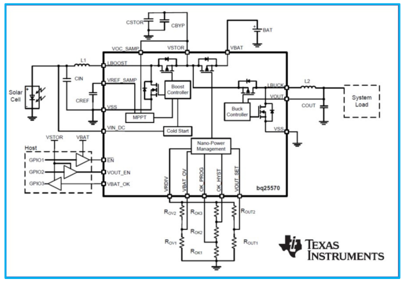

[63] H. Kanaya, S. Tsukamaoto, T. Hirabaru and D. Kanemoto, ‘Energy Harvesting Circuit on a One-Sided Directional Flexible Antenna’, *IEEE Microwave Wireless Components Letters,* Vol. 23, pp. 164-166, 2013.

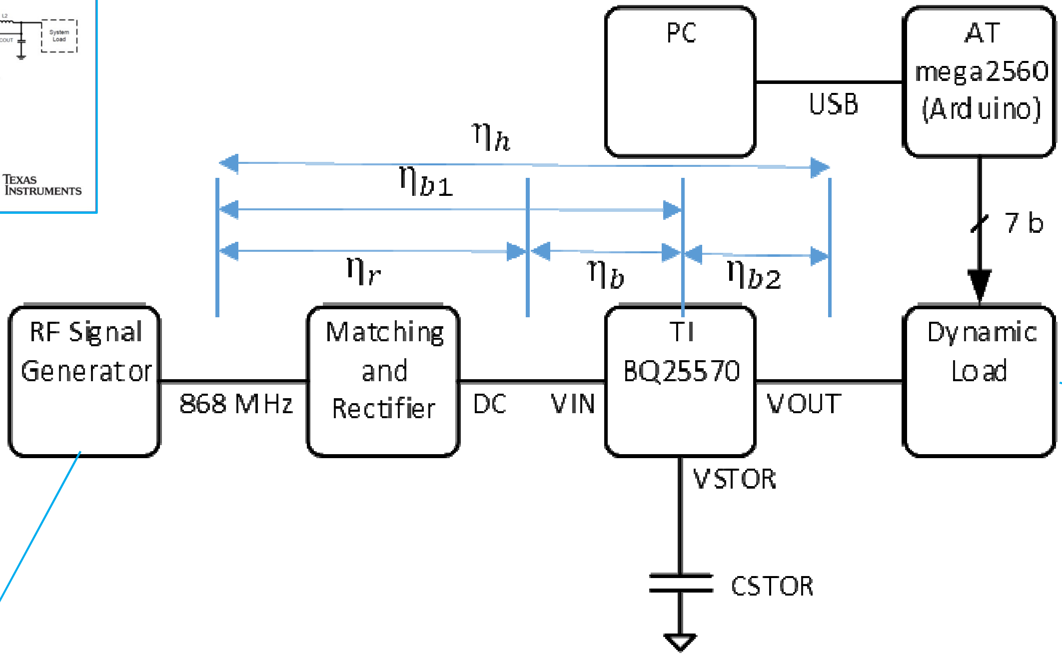
[67] C. Mikeka, H. Arai, A. Georgiadis and A. Collado, ‘DTV Band Micropower RF Energy Harvesting Circuit Architecture and Performance Analysis’, *RFID-TA*, Barcelona, Spain, 2011.

[68] S. Korhummel, D.G. Kuester and Z. Popovic, ‘A Harmonically-Terminated Two-Gram Low-Power Rectenna on a Flexible Substrate’, *USNC-URSI Radio Science Meeting*, Boulder, USA, 2013.

# 5. Examples (ctd.)

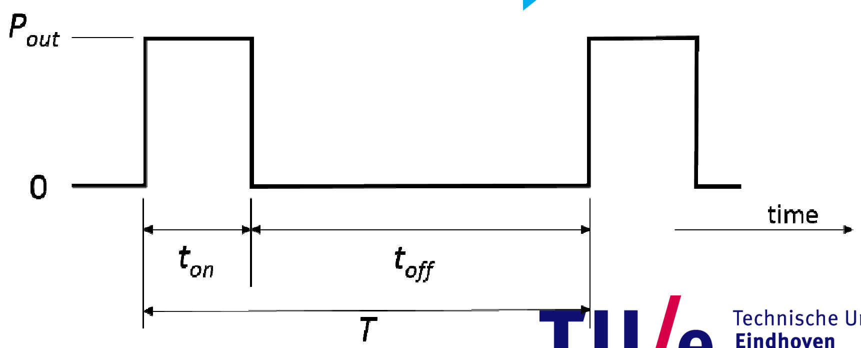
## Circuit Test



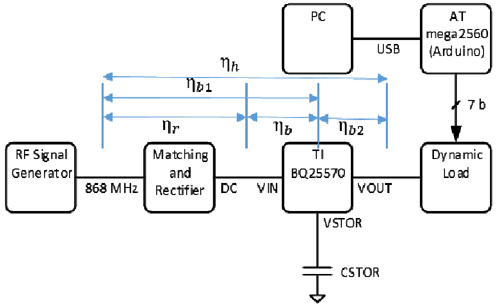

Array of load resistors connected to BJTs that are operated as switches

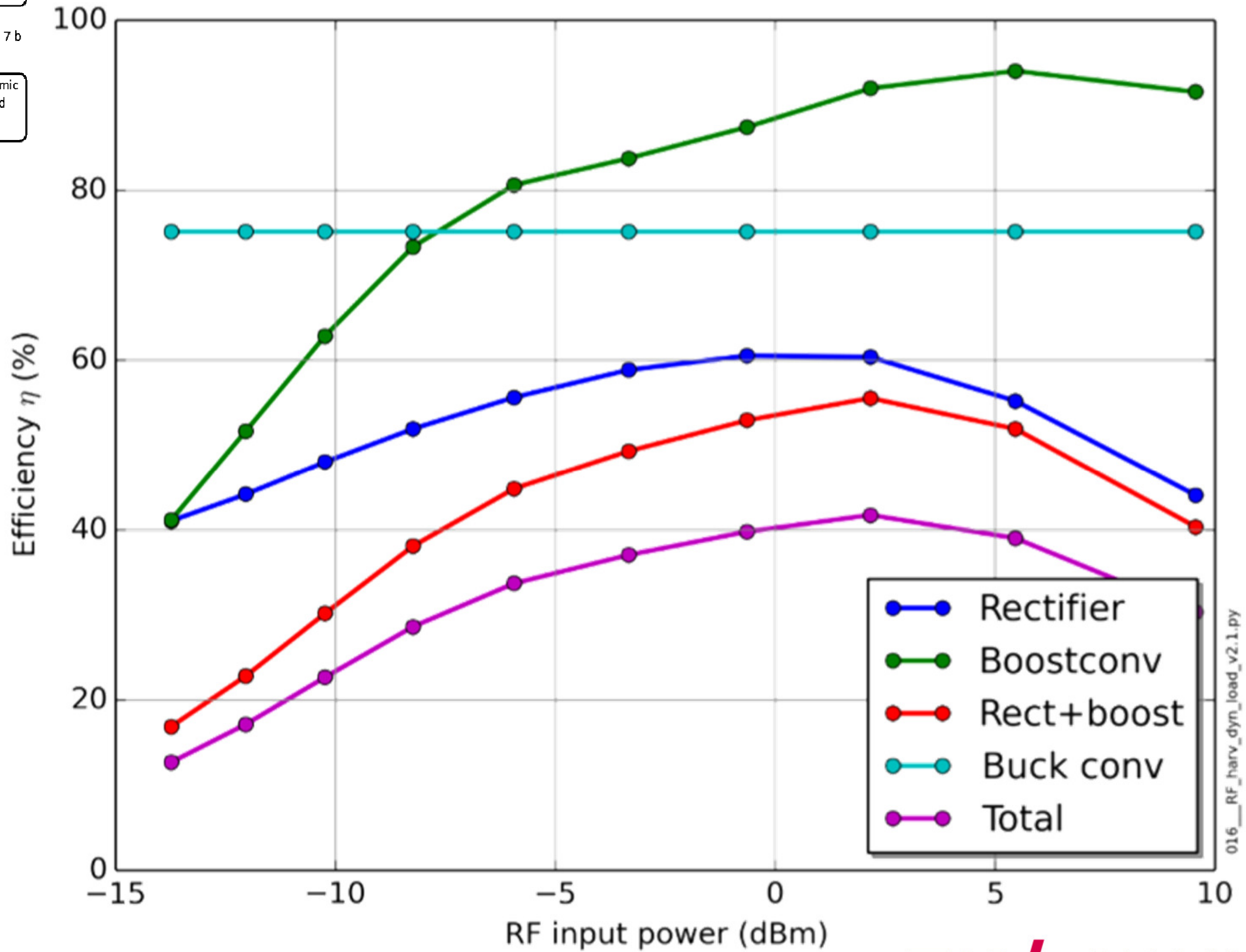
Replacing antenna during tests for ensuring a stable signal



# 5. Examples (ctd.)

## Circuit Test



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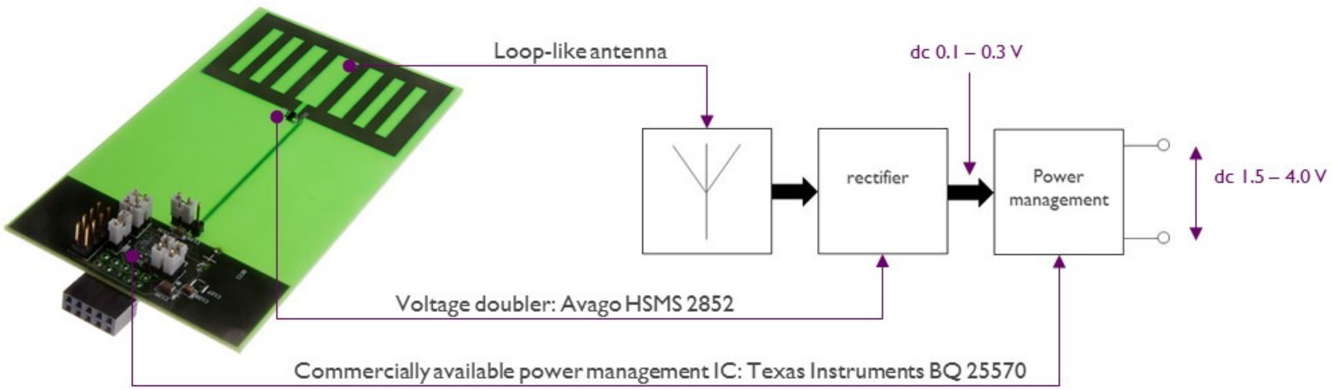
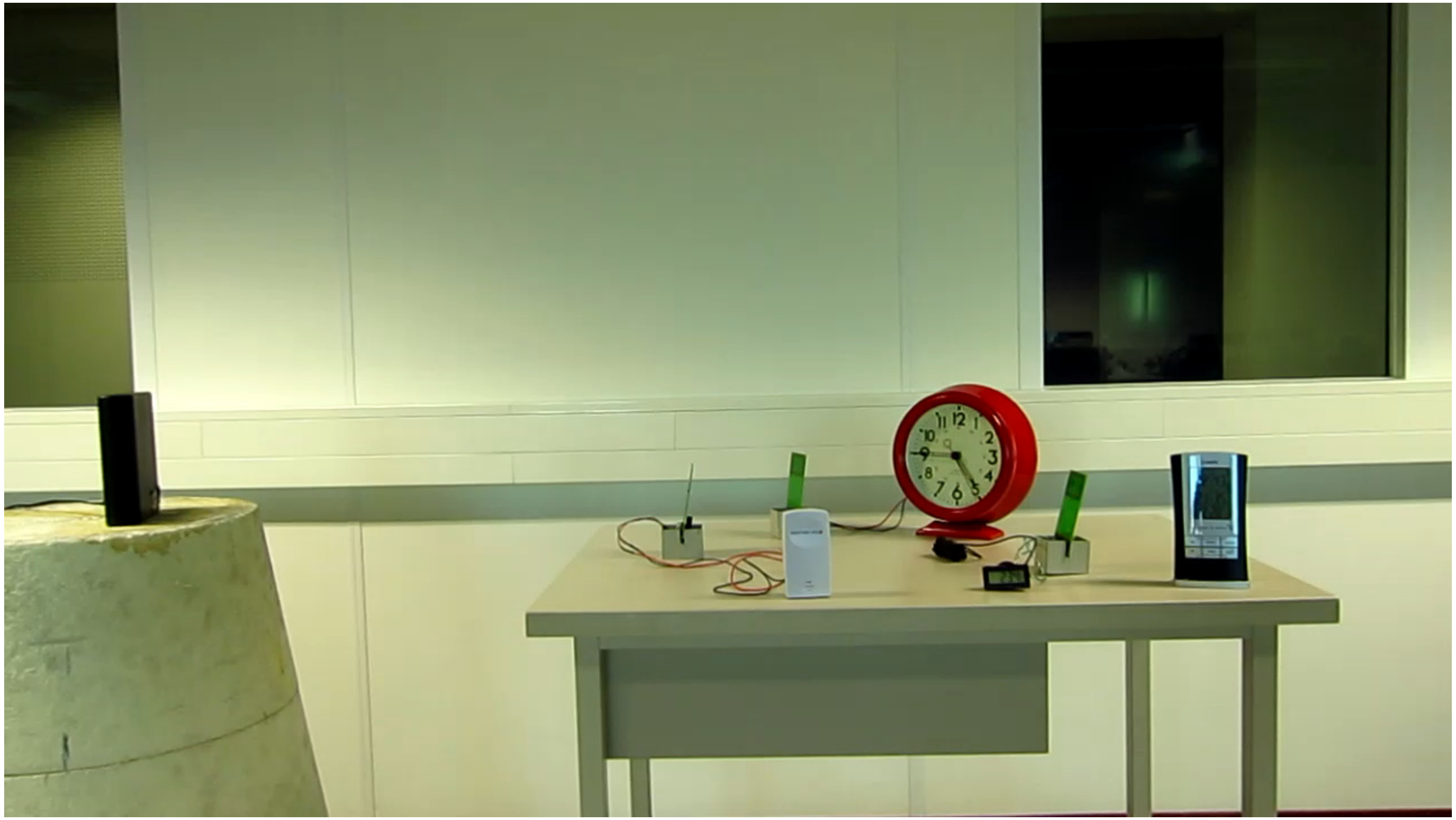
# 5. Examples (ctd.)

## Prototype

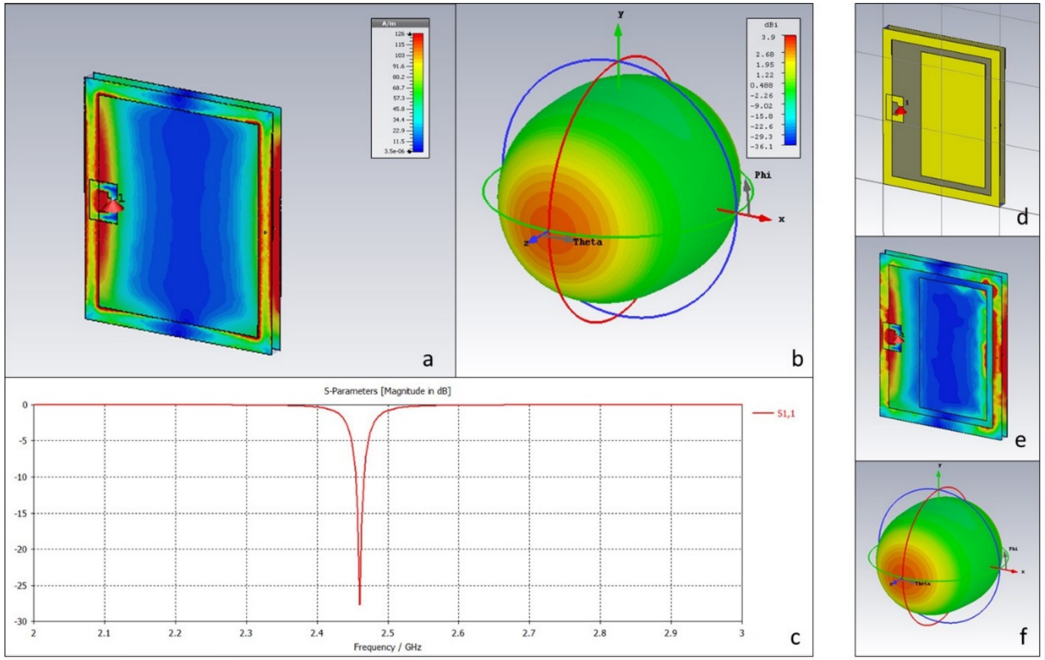


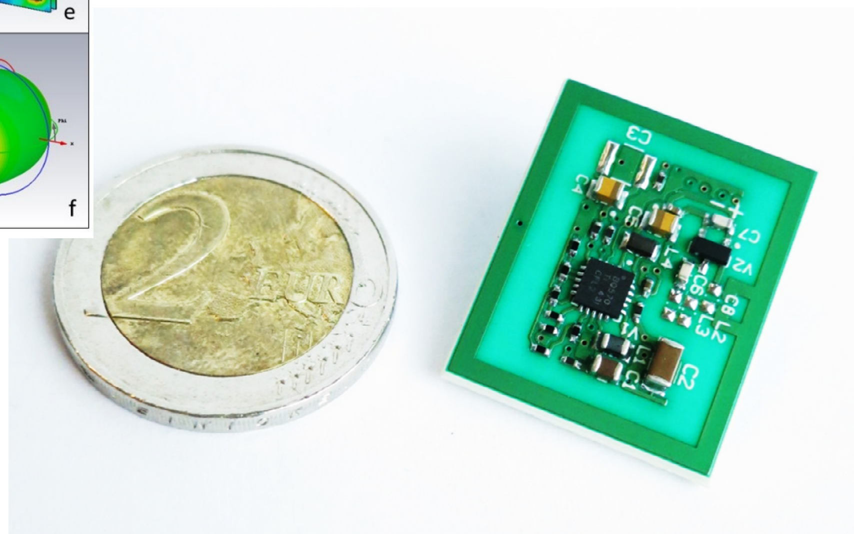

# 5. Examples (ctd.)

## Demonstration



## Smaller Rectenna

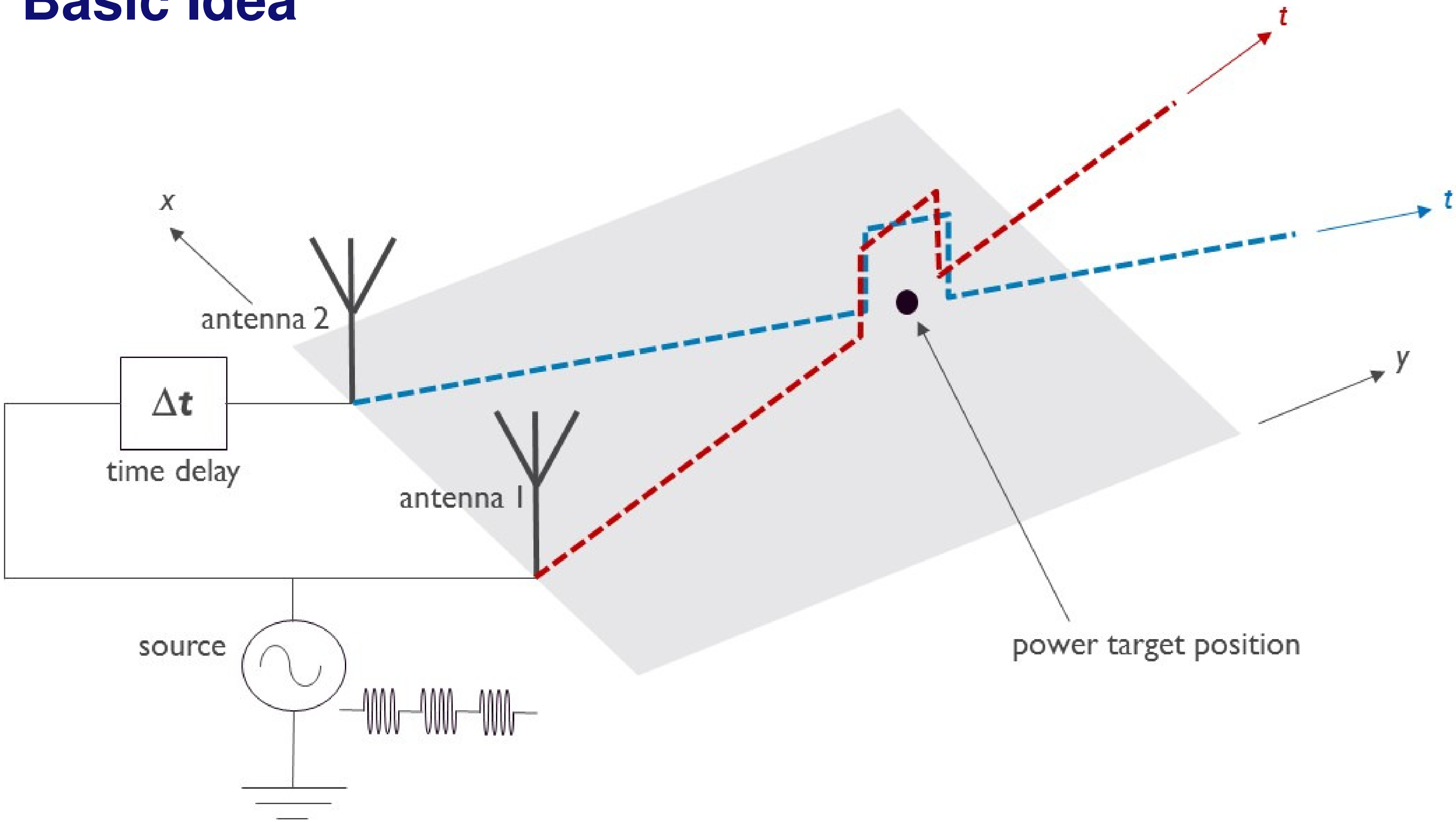


# 6. Future Perspectives (Ctd)

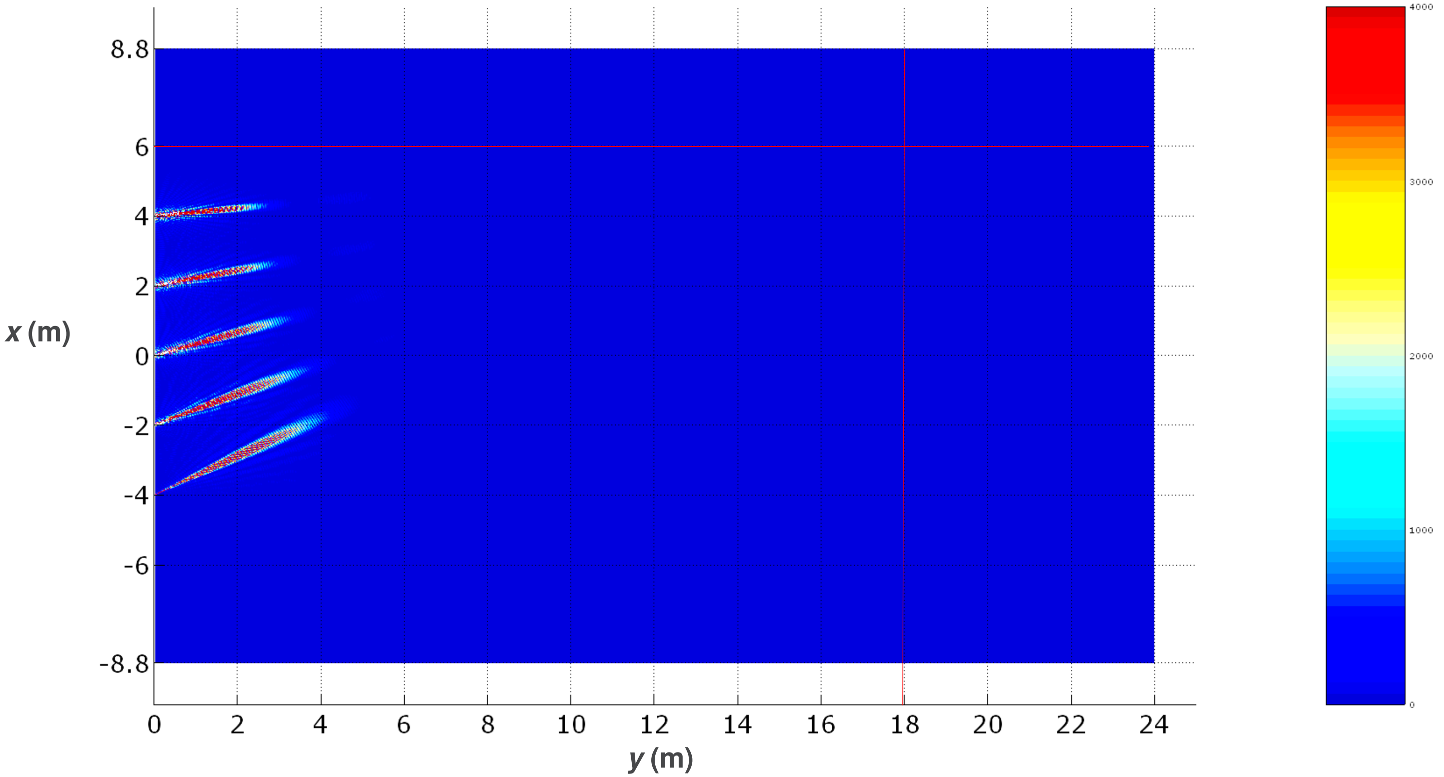
## More Power

### Basic Idea



# 6. Future Perspectives (Ctd)

## Test




$t = t_0 + 10\text{ns}$



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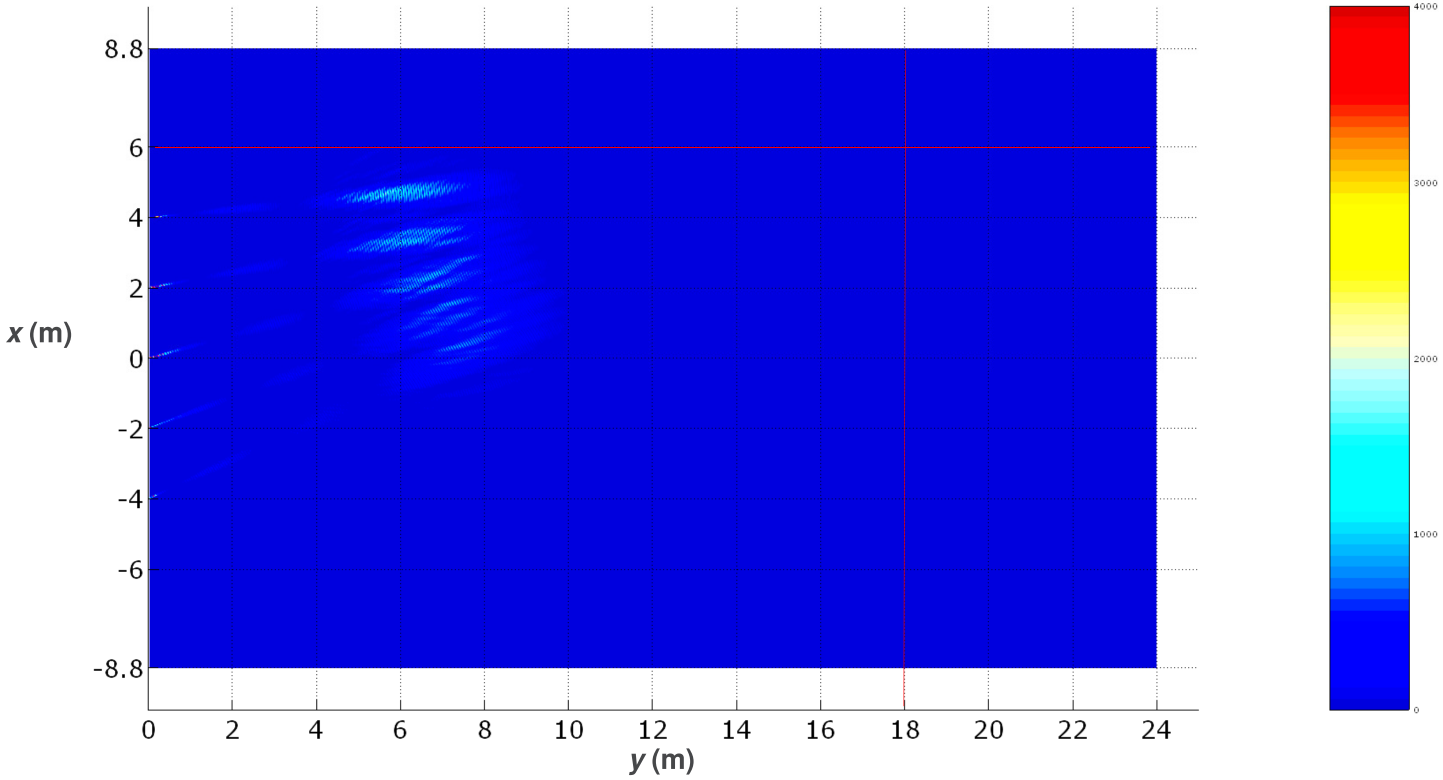
# 6. Future Perspectives (Ctd)

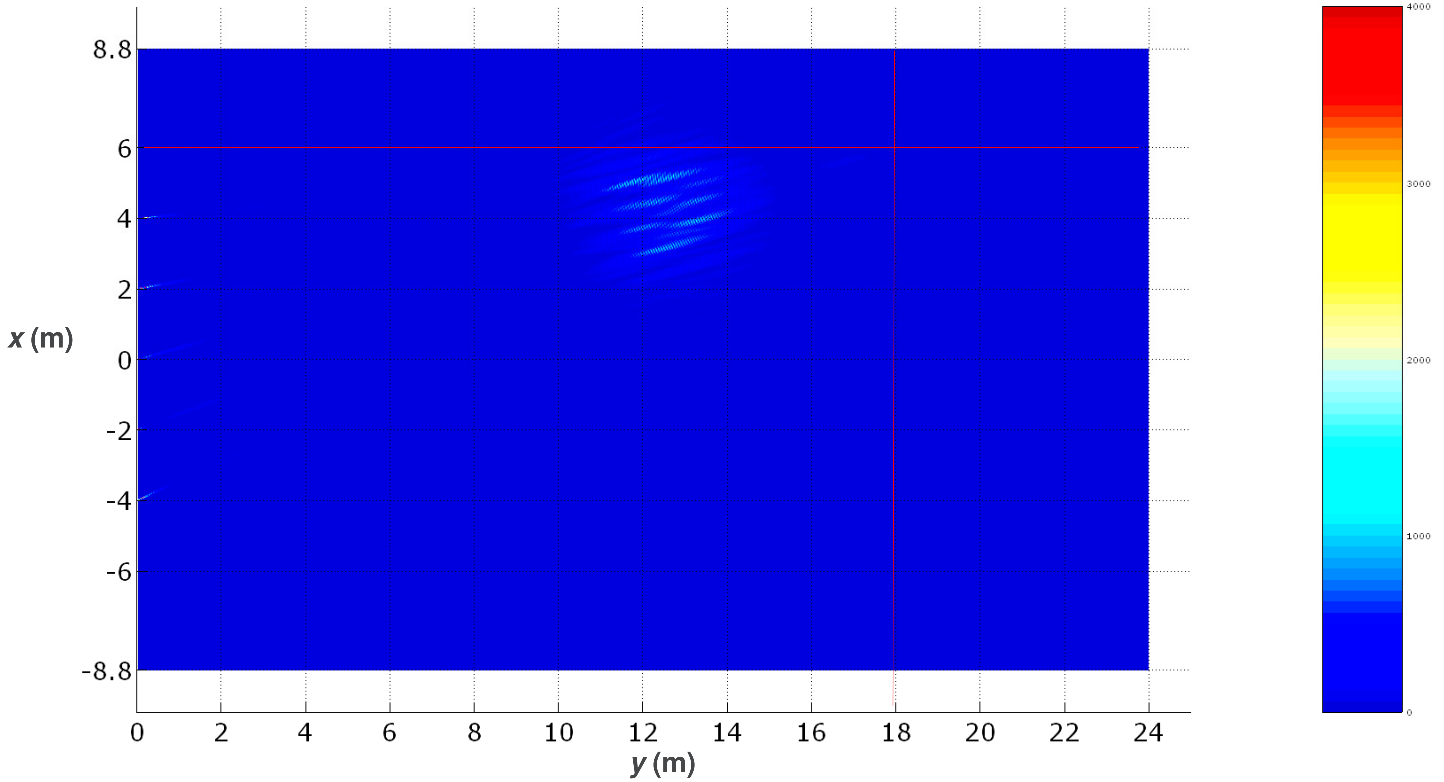
## Test




$t = t_0 + 30\text{ns}$

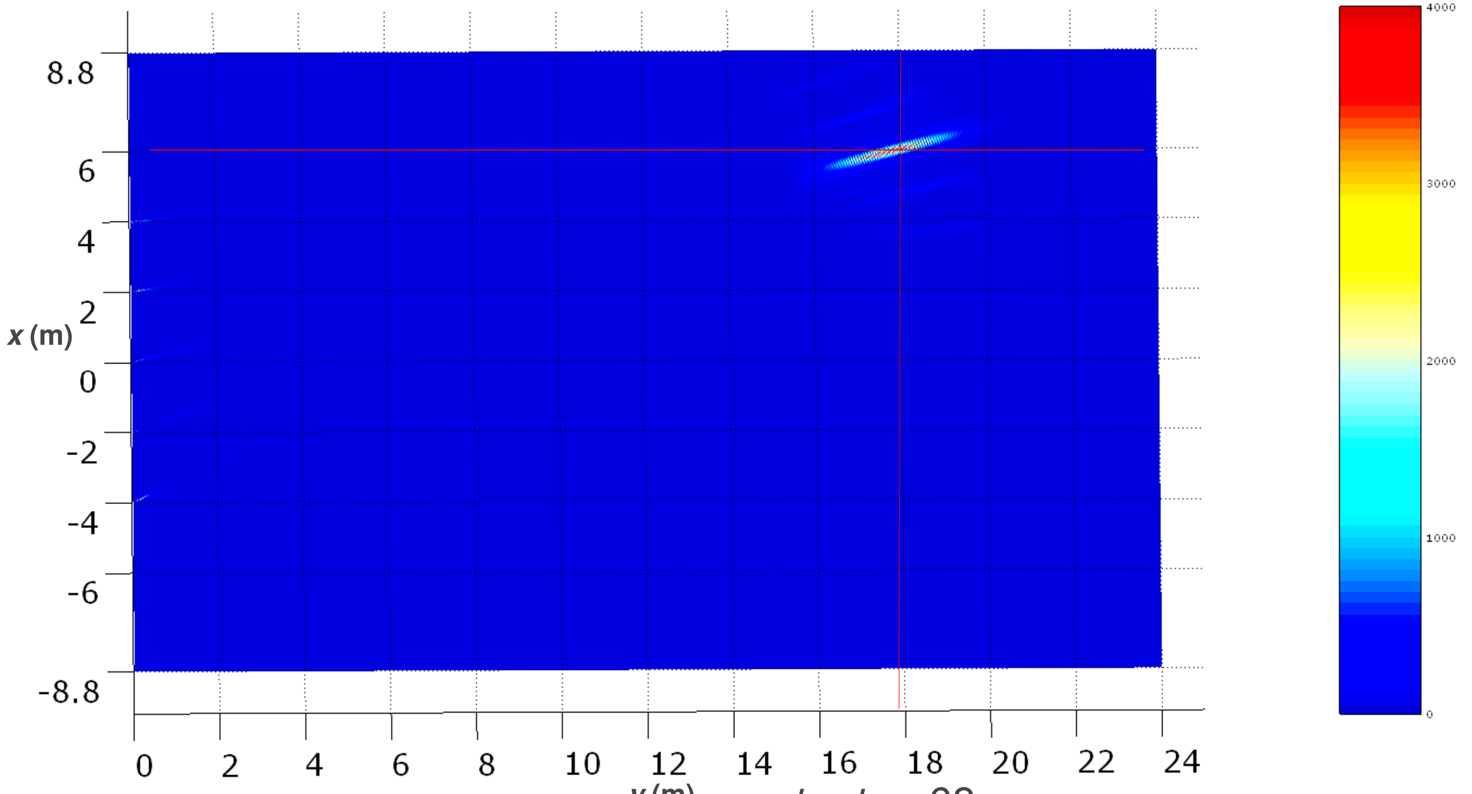
# 6. Future Perspectives (Ctd)

## Test




$t = t_0 + 50\text{ns}$

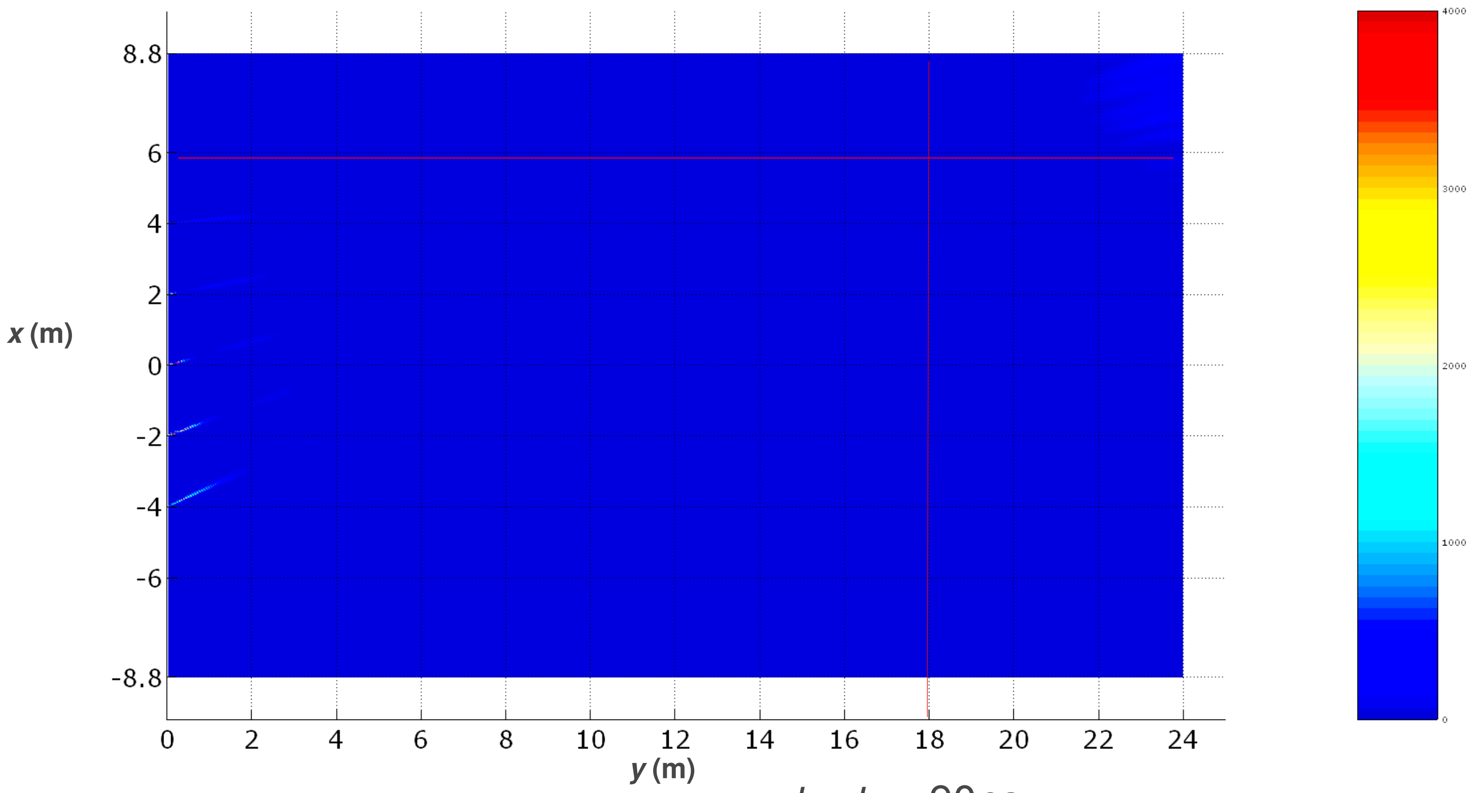
## Test




$t = t_0 + 68\text{ns}$

# 6. Future Perspectives (Ctd)

## Test




$t = t_0 + 90\text{ns}$

# Conclusion

- For practical far-field WPT dc voltage is a challenge;
- Sufficient voltage may be created by enlarging the receiving aperture;
- For small sensors, application of a voltage boost and power management circuit is advised;
- Through careful co-design of rectifier, antenna, matching circuits and power management circuit practical WPT becomes feasible;
- Periodic loading will make WPT over distances in excess of 10m possible;
- Transient WPT will make large power WPT



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