Introduction to energy harvesting from electromagnetic radiation sources

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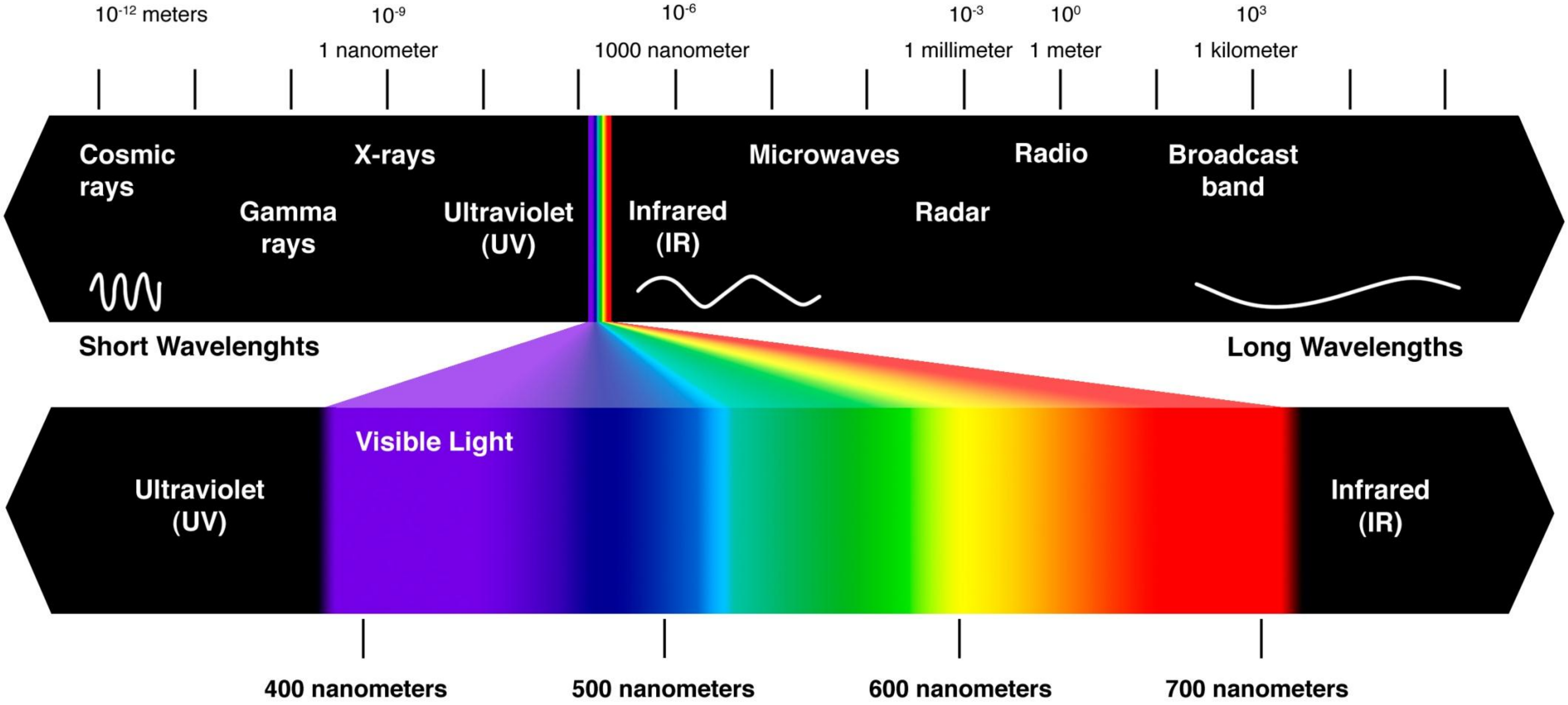
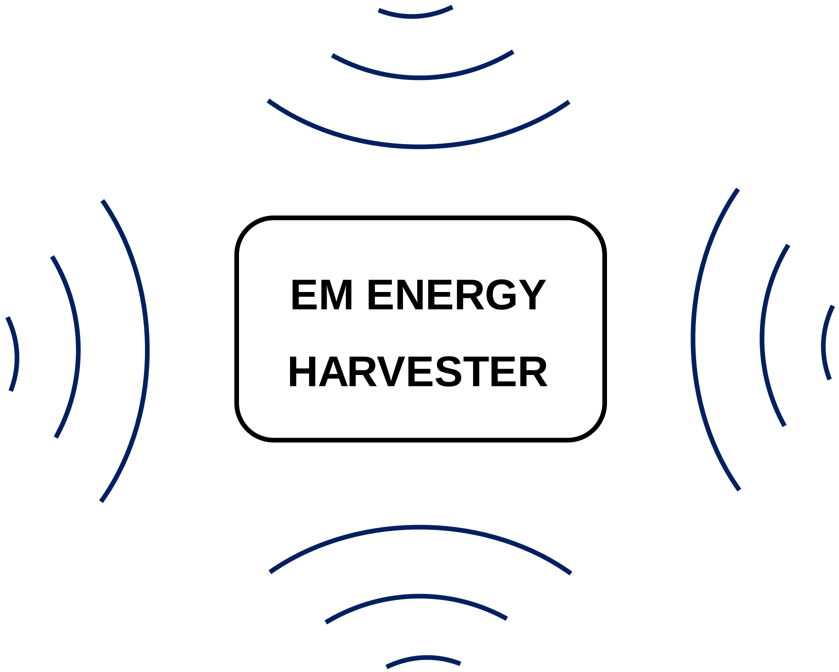
The electromagnetic spectrum



$$c = \lambda \cdot \nu$$

$$E = h \cdot \nu$$

Electromagnetic radiation energy harvesting



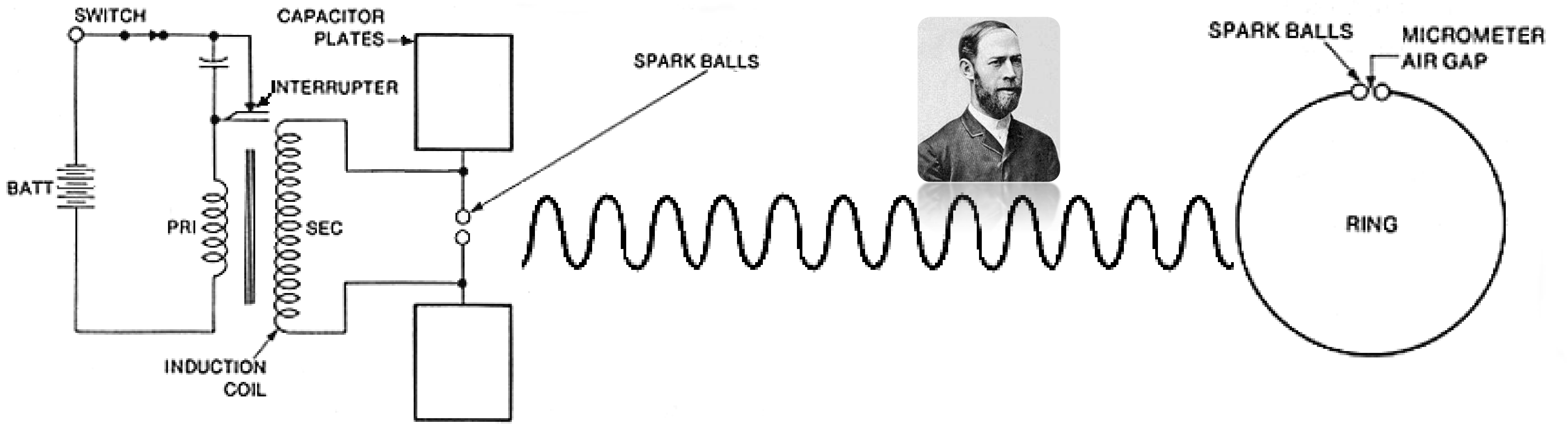
Energy is harvested from **"natural"** EM radiation sources

Wireless power transmission or RF power transmission

Energy is harvested from **"artificial"** specially designed EM radiation sources

History of RF wireless power transmission

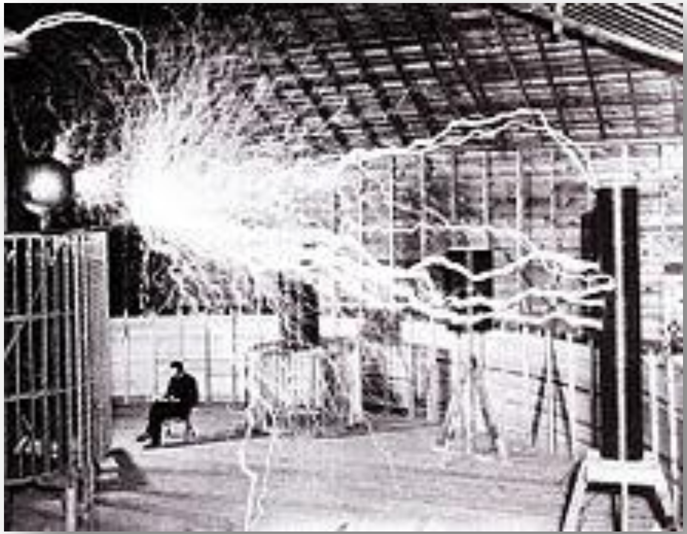
H. Hertz (1857-1894)

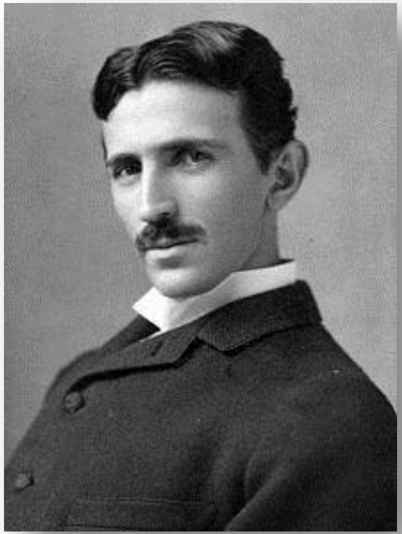


1887. Heinrich Hertz experiments to demonstrate the existence and propagation of electromagnetic waves in free space

History of RF wireless power transmission

Nikola Tesla (1856-1943)



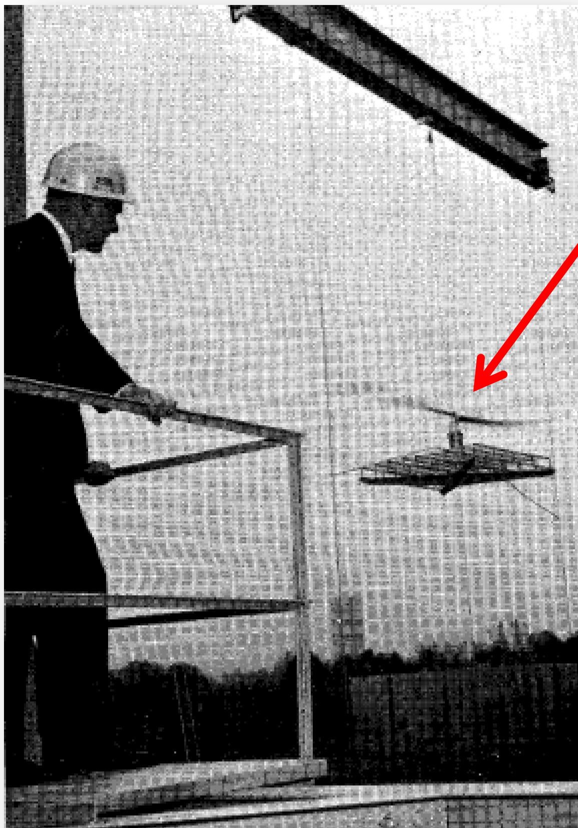


1899
Colorado Spring Laboratory
Antenna:
60m mast antenna with a
1m diameter Cu ball on top.
Generator:
coil connected to 300kW in resonance @ 150kHz
Antenna connected to coil: 100 MV of RF

1901
Wardenclyffe plant at Long Island
Wooden tower 46 m tall to place a 30 m in diameter doughnut-like copper electrode.
Transatlantic power transmission

History of RF wireless power transmission

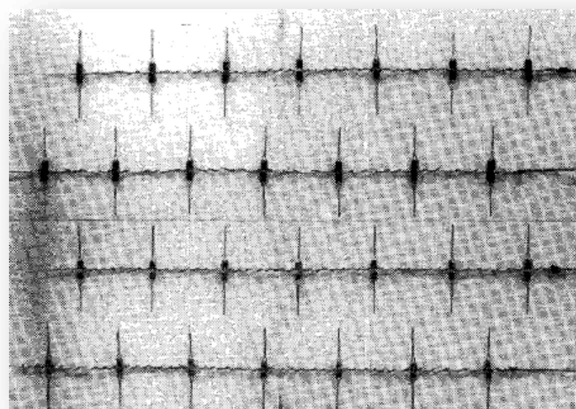
William C. Brown (1916-1999)



Achievements application driven:

* Raytheon Airborne Microwave Platform (RAMP) (Raytheon Company).

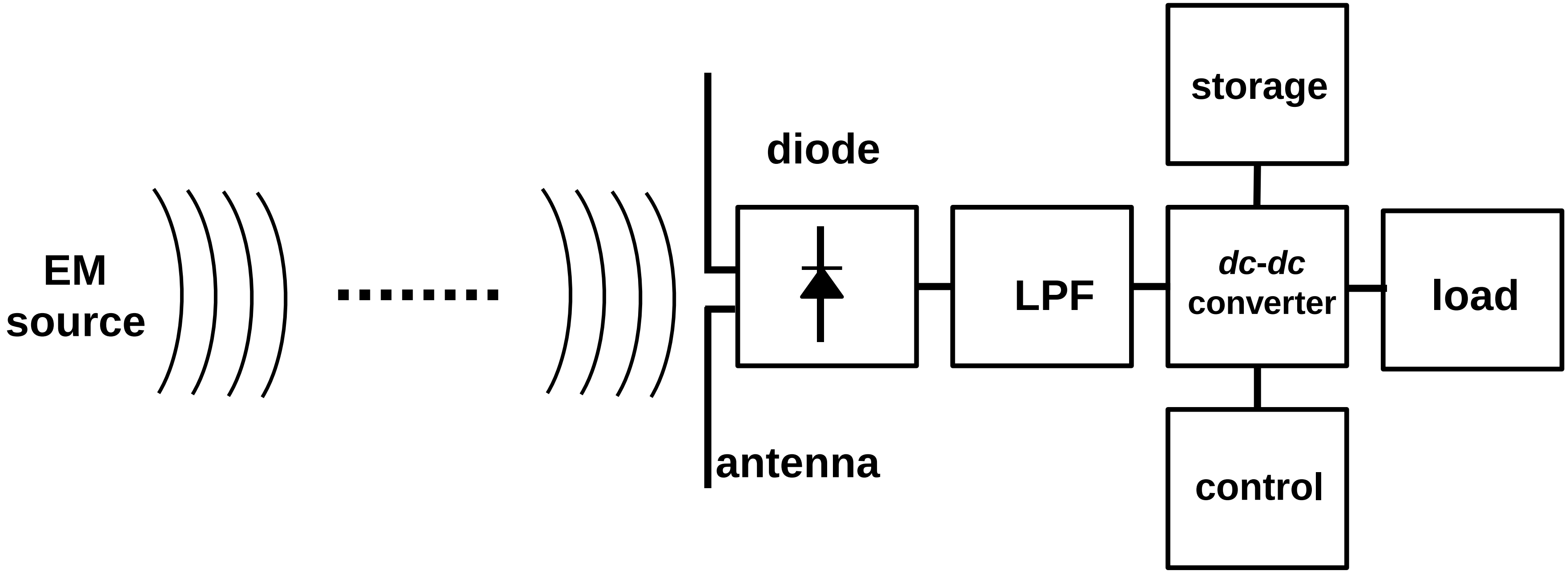
* Solar-power satellite (SPS) (JPL. NASA)



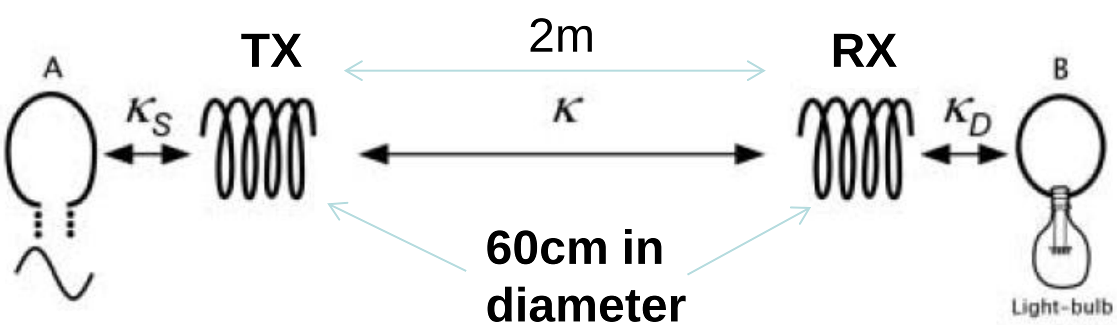
First rectenna (1963):
28 half-wave dipoles connected to bridge rectifiers 1N82G.
7W produced. 40% efficiency

1964: First flight of a helicopter prototype.
270W *dc* provided by a 1.4 kg array-like rectenna (=4480 1N82G semiconductor diodes in 0.4 m^2).
Power to mass ratio of 5 kg/kW → 1983: 1kg/kW (85% efficiency)

History of RF wireless power transmission



History of RF wireless power transmission



WiTricity Corp. (2007)

Non-radiative power transfer between two self-resonant coils operating in the strong coupling regime

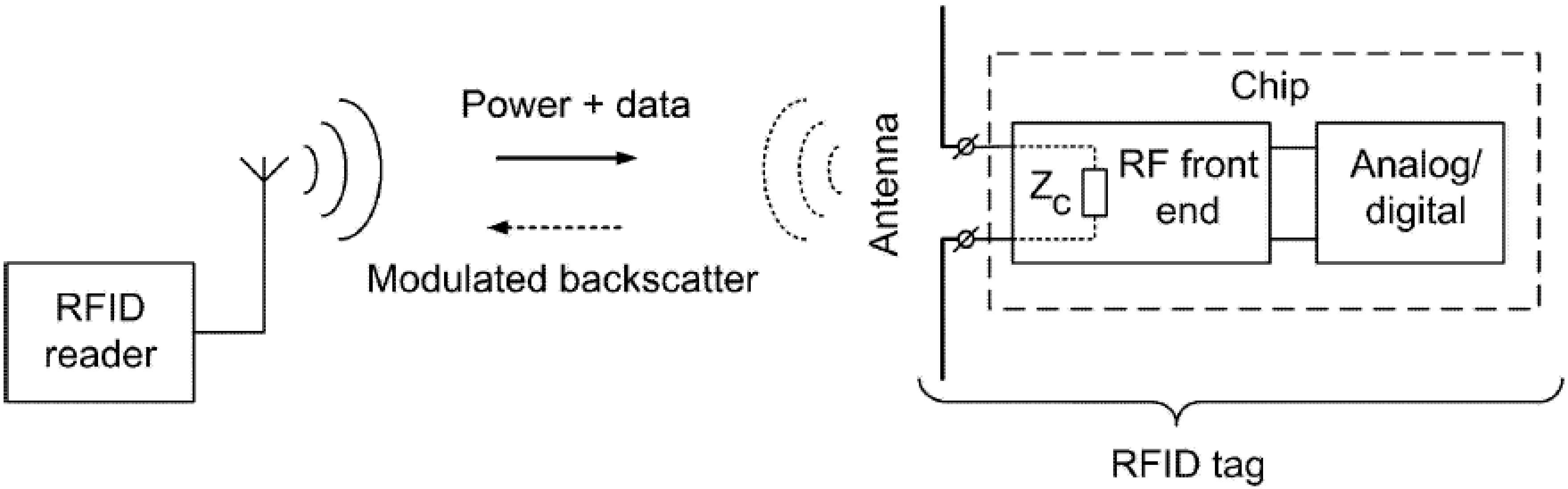
9 MHz resonance

60W power

2m: 45% efficiency
0.9m: 90% efficiency

History of RF wireless power transmission

Passive RFID technology

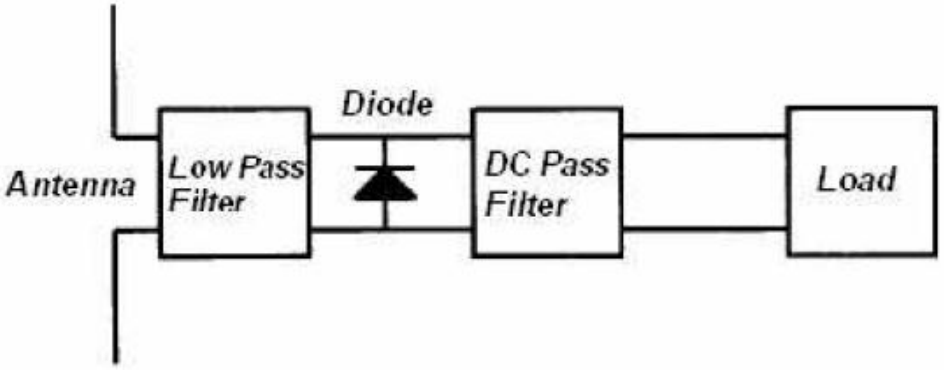


Power transmitted by the reader during the unmodulated periods is converted in a dc power at the input of a passive circuitry of the tag to supply the rest of the active ASIC chip

Recycling Ambient Microwave Energy With Broad-Band Rectenna Arrays

Joseph A. Hagerty, *Student Member, IEEE*, Florian B. Helmbrecht, *Student Member, IEEE*, William H. McCalpin, *Student Member, IEEE*, Regan Zane, *Member, IEEE*, and Zoya B. Popović, *Fellow, IEEE*

Abstract—**This paper presents a study of reception and rectification of broad-band statistically time-varying low-power-density microwave radiation. The applications are in wireless powering of industrial sensors and recycling of ambient RF energy. A 64-element dual-circularly-polarized spiral rectenna array is designed and characterized over a frequency range of 2–18 GHz with single-tone and multitone incident waves. The integrated design of the antenna and rectifier, using a combination of full-wave electromagnetic field analysis and harmonic balance nonlinear circuit analysis, eliminates matching and filtering circuits, allowing for a compact element design. The rectified dc power and efficiency is characterized as a function of dc load and dc circuit topology, RF frequency, polarization, and incidence angle for power densities between 10^{-5}–10^{-1} mW/cm^2. In addition, the increase in rectenna efficiency for multitone input waves is presented.**



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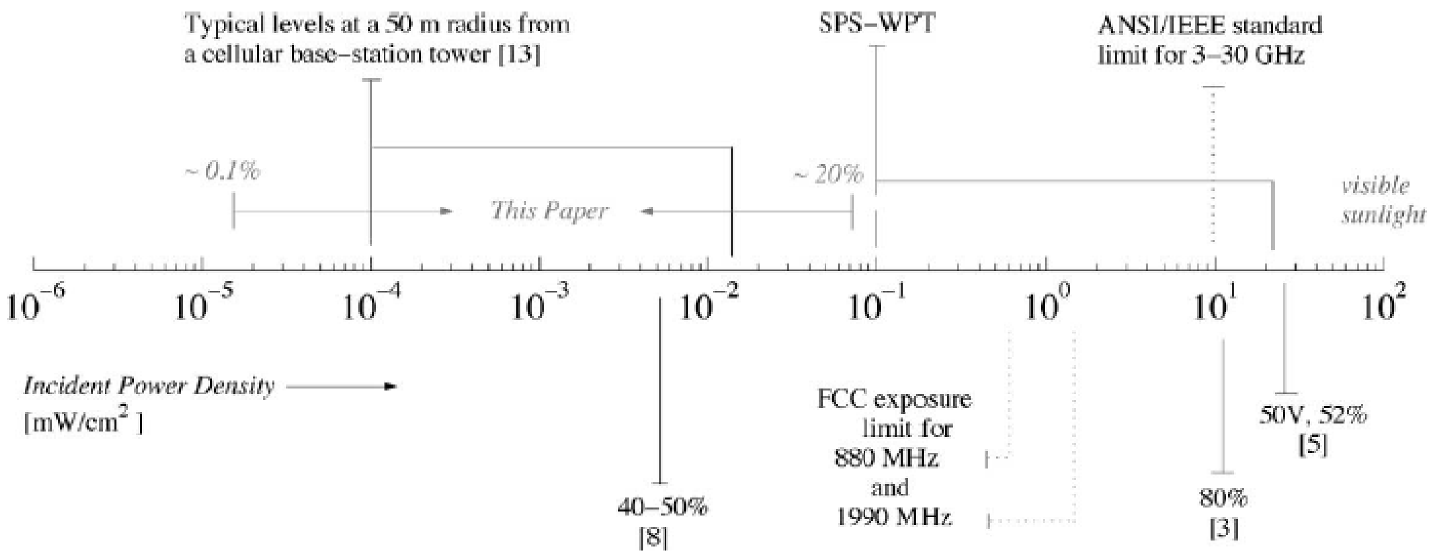
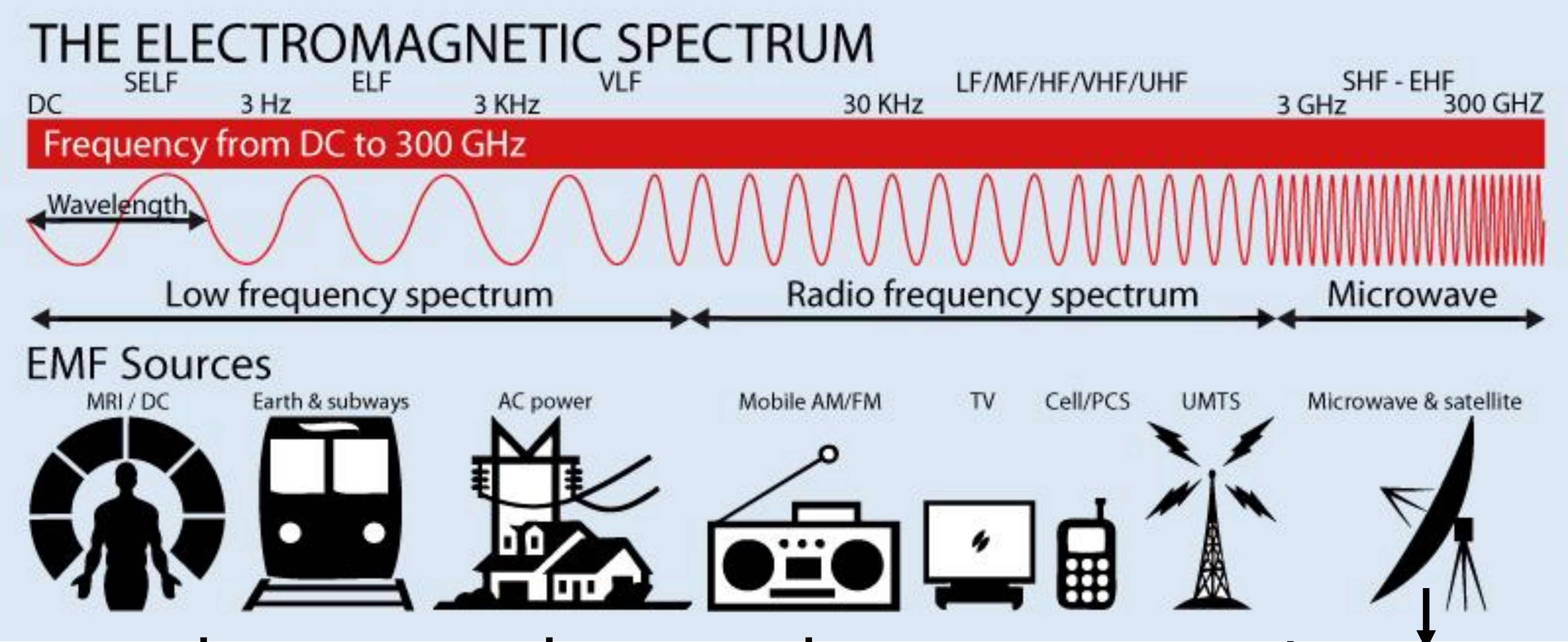


Fig. 1. Diagram of various microwave power sources and their typical power density levels. The power density operating points of several rectenna designs found in the literature and their corresponding efficiencies [3], [6], [8] are given. Also shown is the range of expected power densities used in the solar power satellite (SPS) and wireless power transmission (WPT) applications. The range of power densities measured in this paper is indicated for comparison. Measured ambient levels in our laboratory (no high-power equipment) are in the 10^{-6}–10^{-5}-mW/cm^2 range.



GPS: **10-100 aW**

GSM, UMTS -> 3G: **100mW-2W**

70 dBuV/m = **3.2mV/m** old UHF TV band

FM radio: **100kW** to achieve good reception at 50km

50 Hz, **100W-10kW**

ISM bands (900MHz-2.4GHz):
WIFI (**100mW**), Bluetooth (**2.5mW**), ZigBee (**<1mW**)

DC (no radiation)

Power density (W/cm^2)

GSM, UMTS -> 3G: **100mW-2W** → [1] **8-160 nW/cm^2 (10m distance)**

70 dBuV/m = **3.2mV/m** old UHF TV band → [2] **1.3 pW/cm^2**

FM radio: **100kW** to achieve good reception at 50km → [1] **0.3 nW/cm^2 (50km distance)**

ISM bands (900MHz-2.4GHz):
WIFI (**100mW**), Bluetooth (**2.5mW**), ZigBee (**<1mW**) → [1] **8 , 0.2 nW/cm^2 , <80pW/cm^2 (10m distance)**

[1]

$$P_r = \frac{P_i}{S_{esfera}} = \frac{P_i}{4\pi r^2} \quad [W/m^2]$$

[2]

$$|P_r| = \frac{1}{2}\frac{|E_f|^2}{\eta_0} \quad [W/m^2]$$

$$\eta_0 = 120\pi \simeq 377\,\Omega$$

Intrinsic vacuum impedance

Application	Power density (mW/cm^2)
Old UHF TV band	10^{-9}
FM radio @ 50 km from 100kW base station	10^{-7}
ISM bands: Zigbee/Bluetooth/WIFI	$10^{-8}/10^{-7}/10^{-6}$
Standard ambient level with no high power equipment	10^{-6} – 10^{-5}
GSM, UMTS (3G telecom) @ 10 m from base station	10^{-6} – 10^{-4}
Cellular phone @ 50 m from base station	10^{-4} – 10^{-2}
Solar Power Satellite (SPS) **Wireless Power Transmission (WPT)**	10^{-1} - 10
Solar radiation in the visible range	10^{2}

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Solar Power Satellite (SPS) Wireless Power Transmission (WPT)	10^{-1} - 10
Solar radiation in the visible range	10^{2}

Frequency range	E-field strength (V/m)
0-1 Hz	–
1-8 Hz	10000
8-25 Hz	10000
0.025-0.8 kHz	250 / f
0.8-3 kHz	250 / f
3-150 kHz	87
0.15-1 MHz	87
1-10 MHz	$87 / f^{0,5}$
10-400 MHz	28
400-2000 MHz	$1{,}375 \cdot f^{0,5}$
2-300 GHz	61

Recommendation, Council. "519/EC of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)."Official Journal L 197 (1999)

Frequency range (MHz)	RMS electric field strength (V/m)	RMS magnetic field strength (A/m)	RMS power density (E-field, H-field) (W/m^2)
0.1-1	1842	16,3 / f	(9000 , 100000 / f^2)
1-30	1842 / f	16,3 / f	(9000 / f^2 , 100000 / f^2)
30-100	61,4	16,3 / f	(10 , 100000 / f^2)
100-300	61,4	0,163	10
300-3000	–	–	f / 30
3000-30000	–	–	100
30000-300000	–	–	100

IEEE Std C95. 1-2005. "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 KHz to 300 GHz." New York: The Institute of Electrical and Electronic Engineers, 2005.

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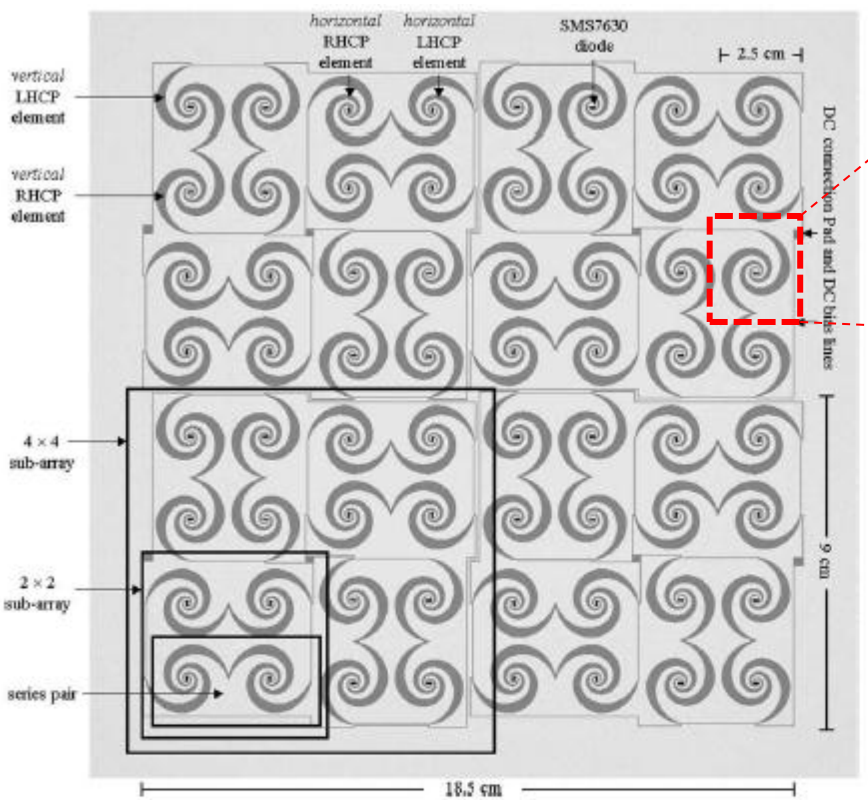
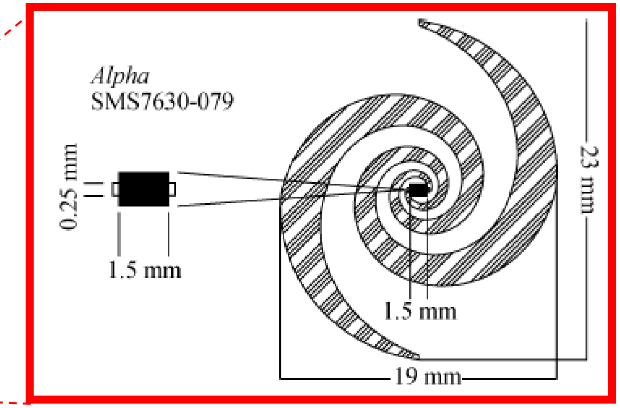




$$A = A_{\text{eff}} = 25\ \text{cm}^2 \qquad (7)$$

we estimate incident power levels of

$$P_{\text{RFmin}} = 250\ \text{nW} \quad P_{\text{RF max}} = 2.5\ \text{mW}. \qquad (8)$$

Assuming a dc–dc conversion efficiency of 90% and rectification efficiencies of

$$\eta(P_{\text{RFmin}}) = 1\% \quad \eta(P_{\text{RFmax}}) = 20\% \qquad (9)$$

an average dc power output is obtained as

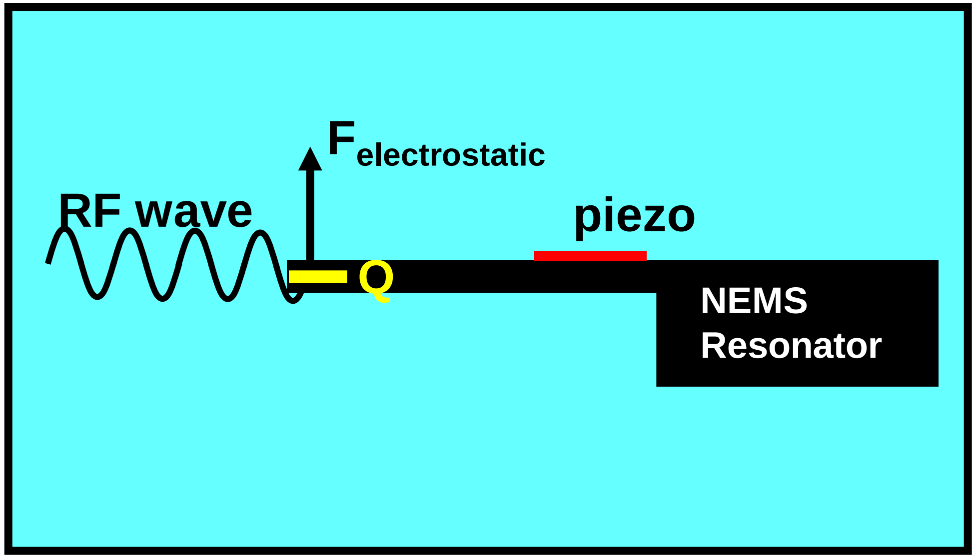
$$P_{\text{dcmin}} = 2\ \text{nW} \quad P_{\text{dc max}} = 450\ \mu\text{W}. \qquad (10)$$

Drawbacks:

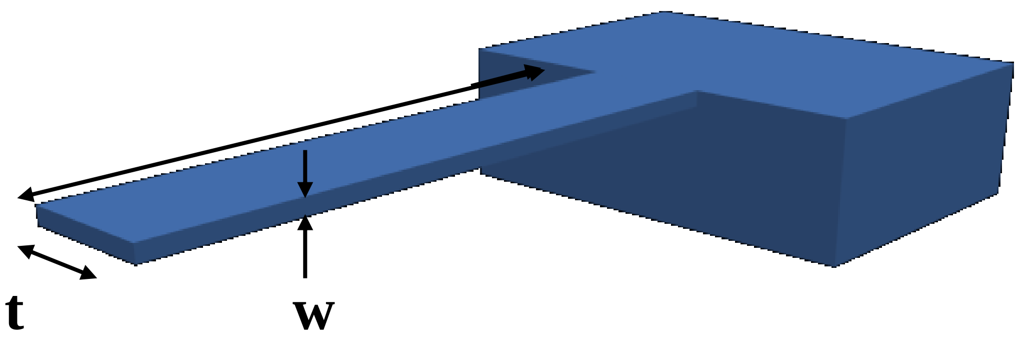
1) Dimensions of the rectenna in the cm scale: no integrable

2) “Natural” Source power densities very low: pW/cm^2 – nW/cm^2

The MEMSTENNA concept



Some basics on NEMS. Mechanical characteristics



$$k = \frac{E}{4} \cdot \frac{w^3 \cdot t}{l^3} \quad \text{(N/m)}$$

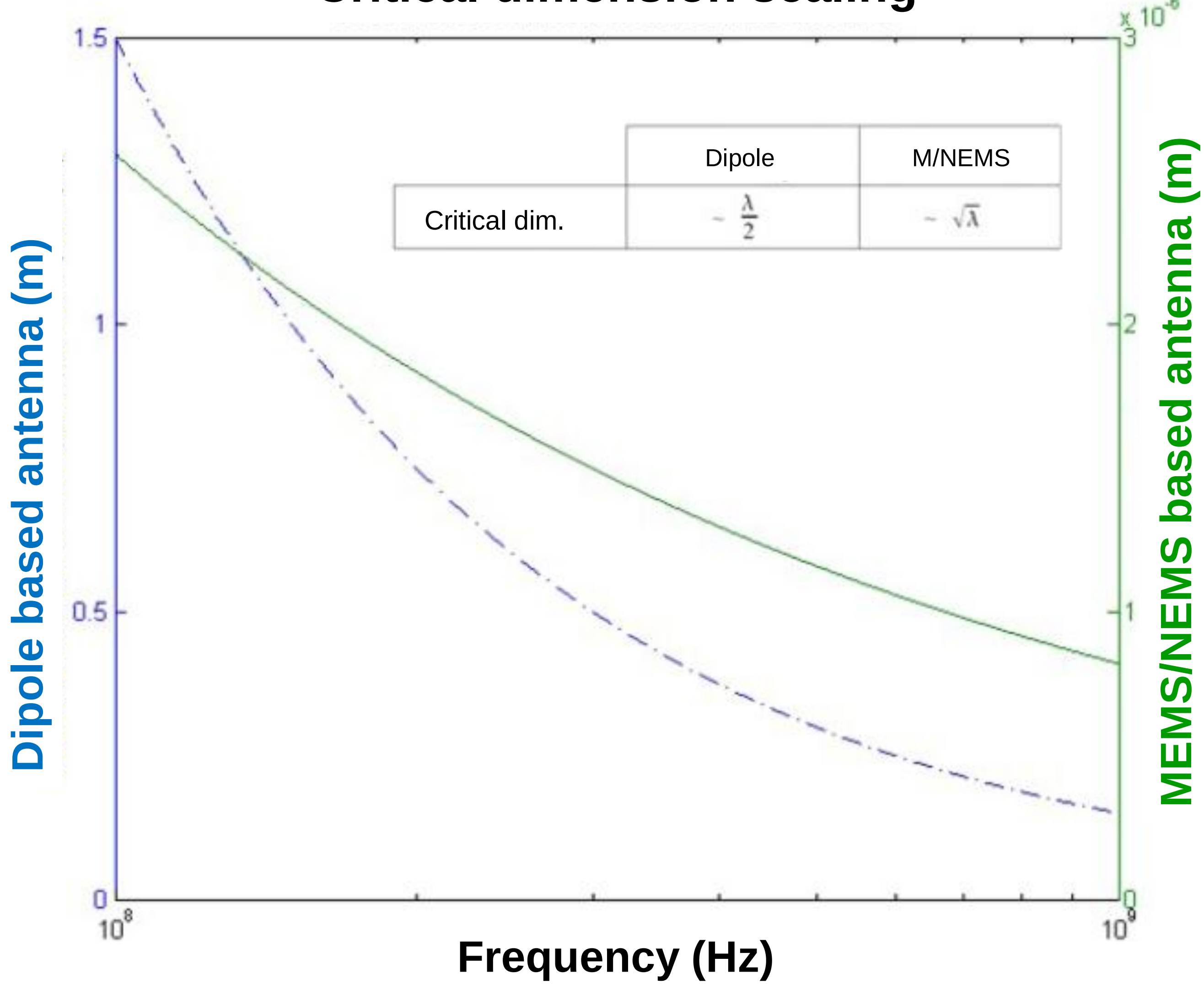
$$f_{res} = 0.162 \cdot \sqrt{\frac{E}{\rho}} \cdot \frac{w}{l^2} \quad \text{(Hz)}$$

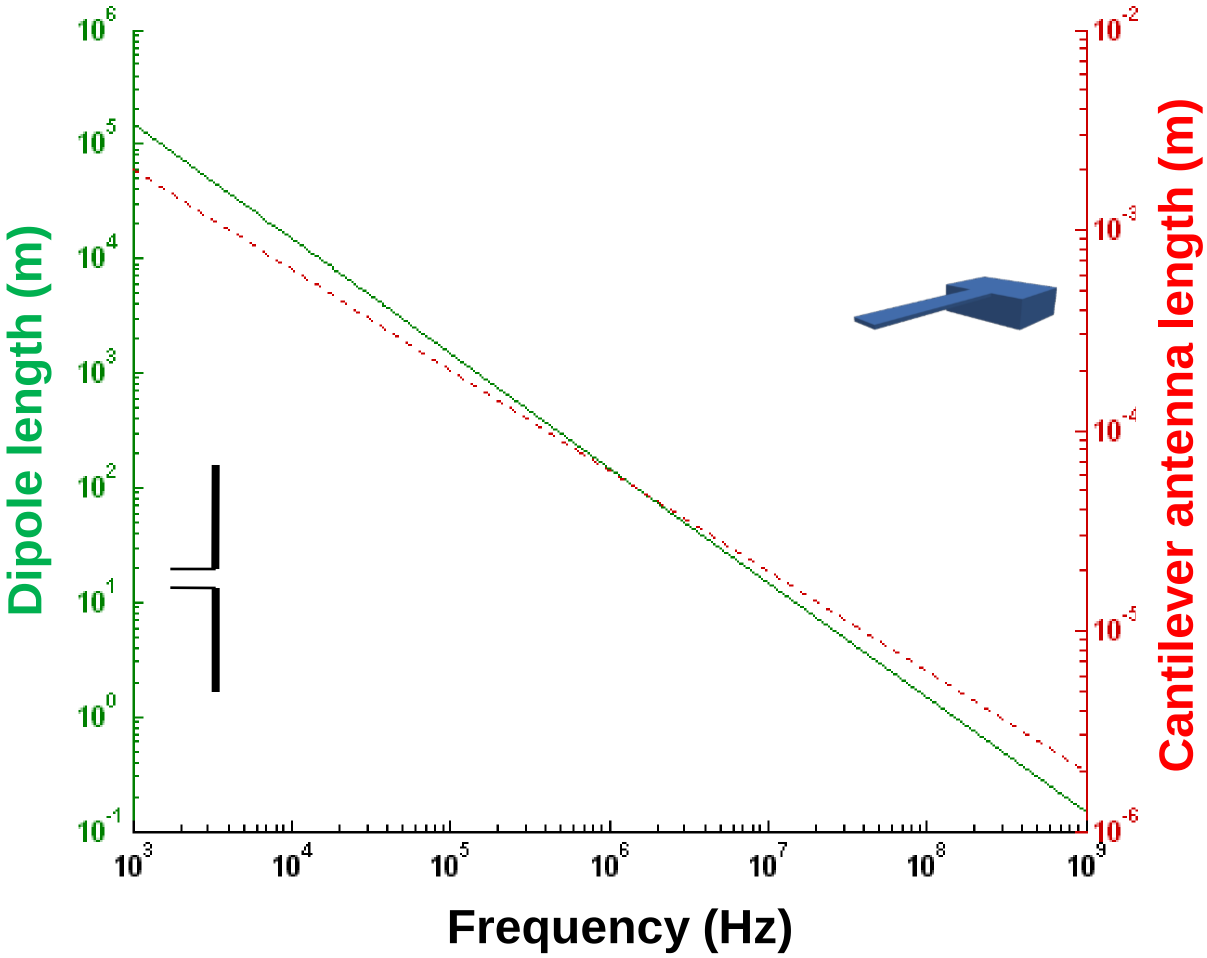
Young modulus: E_{Si}=1.79·1011 N/m^2
Density: ρ_{Si}=2.33·103 kg/m^3

$$m = \frac{k}{f_{res}^{\ 2}} \quad \text{(kg)}$$

	l(um)	t(um)	w(um)	k(N/m)	fres(kHz)	m(gr)
MEMS	450	50	2	0.2	14	10^{-6}
MEMS	125	30	4	44	364	$3 \cdot 10^{-7}$
NEMS	10	0.48	0.1	0.02	$1.4 \cdot 10^{3}$	10^{-11}

Critical dimension scaling





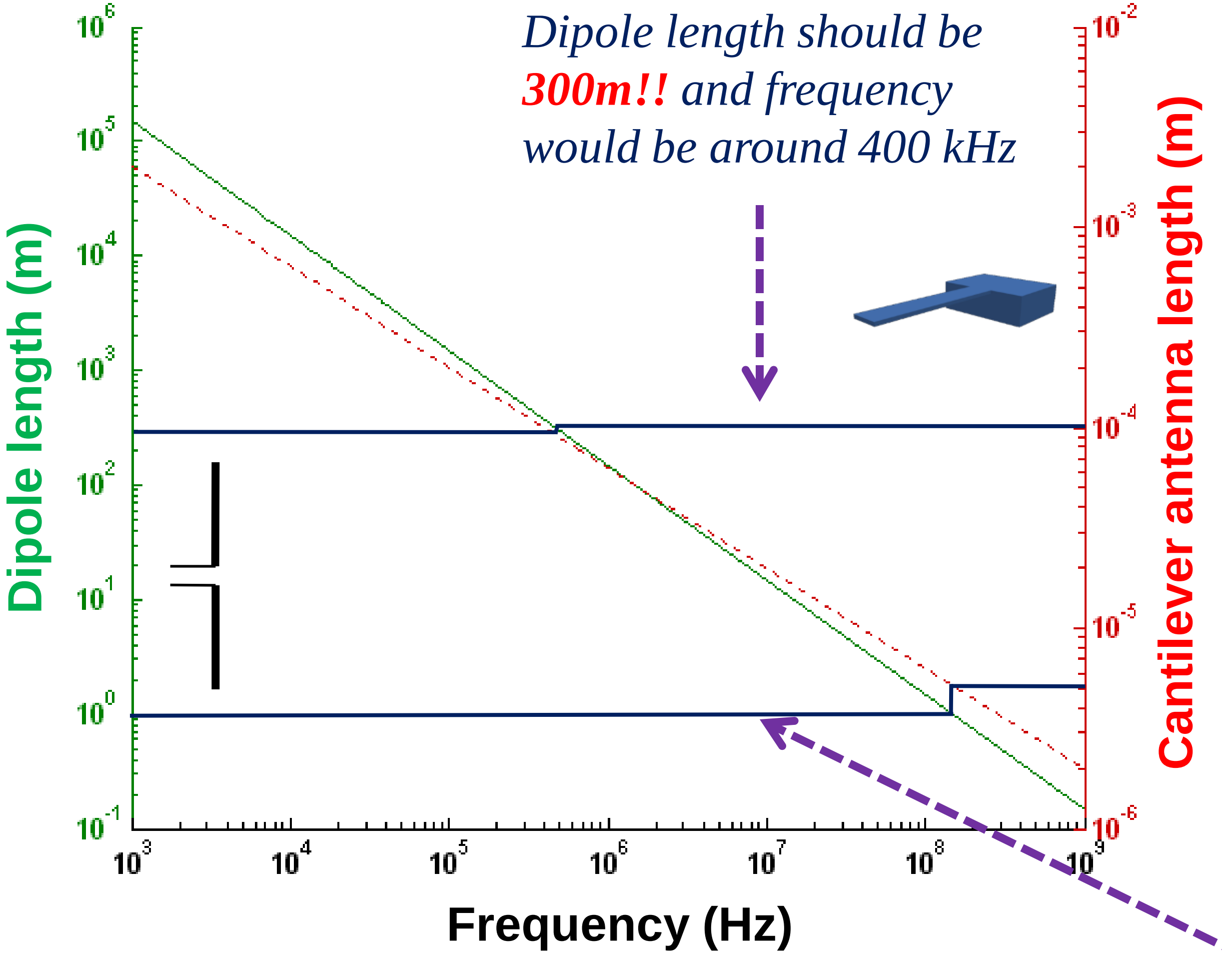
- λ/2 dipole
- Cantilever thickness and width:

$$t = 3\mu m$$

$$w = 30\mu m$$

For a cantilever 100 μm long:

Dipole length should be ***300m!!*** *and frequency would be around 400 kHz*



For a 1m dipole:

Cantilever length should be ***5μm!!*** *and frequency would be around 100 MHz*

Nanotube Radio

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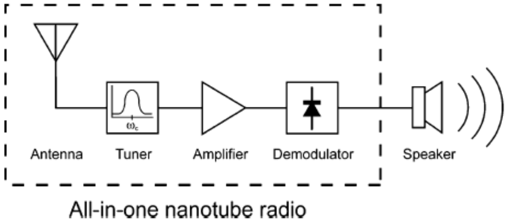
Department of Physics, Center of Integrated Nanomechanical Systems, University of California at Berkeley, Berkeley, California 94720, and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720



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3508–3511

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ABSTRACT

We have constructed a fully functional, fully integrated radio receiver from a single carbon nanotube. The nanotube serves simultaneously as all essential components of a radio: antenna, tunable band-pass filter, amplifier, and demodulator. A direct current voltage source, as supplied by a battery, powers the radio. Using carrier waves in the commercially relevant 40–400 MHz range and both frequency and amplitude modulation techniques, we demonstrate successful music and voice reception.

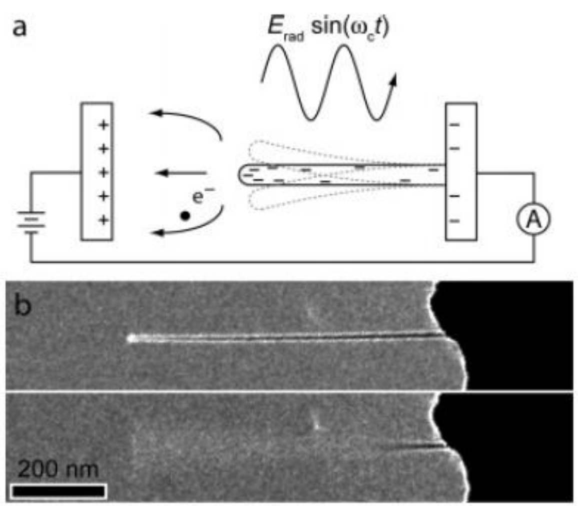
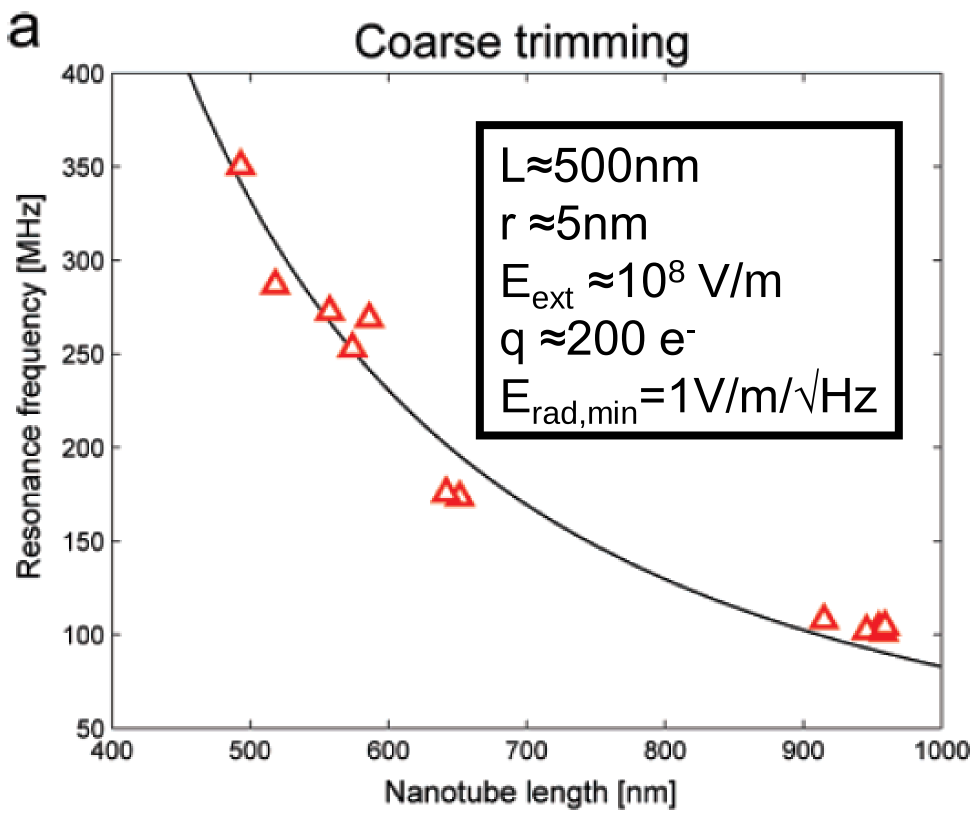
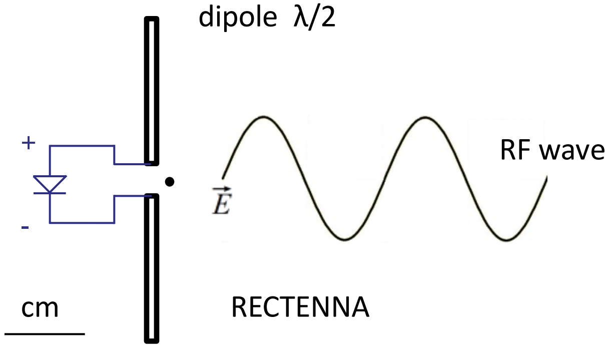


Figure 2. (a) Schematic of the nanotube radio. Radio transmissions tuned to the nanotube's resonance frequency force the charged nanotube to vibrate. Field emission of electrons from the tip of the nanotube is used to detect the vibrations and also amplify and demodulate the signal. A current measuring device, such as a sensitive speaker, monitors the output of the radio. (b) Transmission electron micrographs of a nanotube radio off and on resonance during a radio transmission.





dipole λ/2
+
-
RF wave
cm
RECTENNA

Exercise:

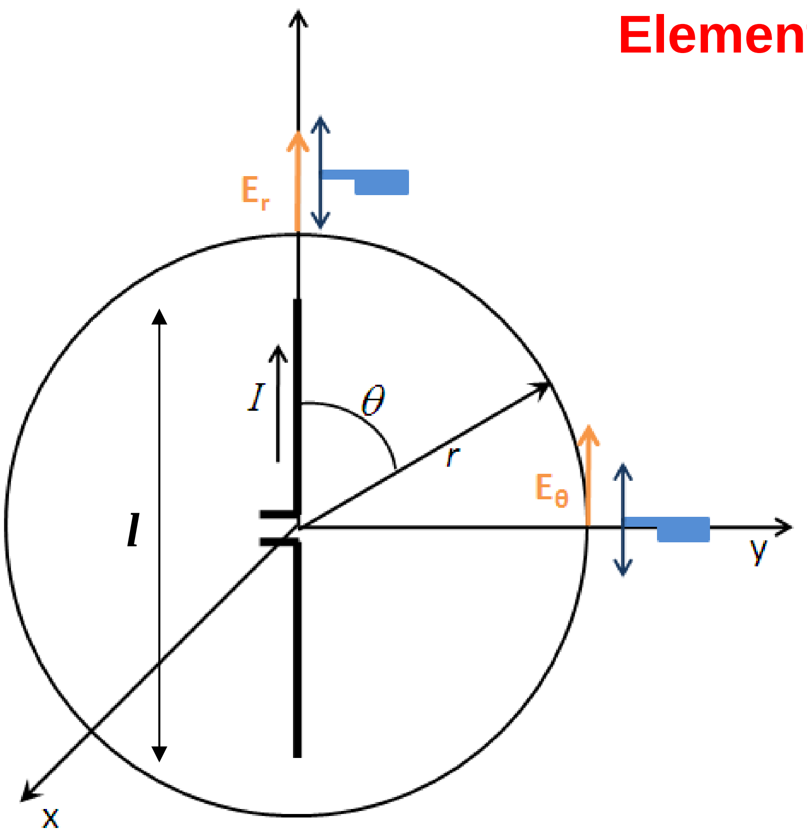
Pau Bramon

Consider a dipole antenna L=1m.
Consider a commercial cantilever (AFM) l=200um.

Q1) Would it be possible to demonstrate the MEMSTENNA concept with these two elements?

Q2) Which would be the order of magnitude of the mechanical energy harvested by the MEMSTENNA?

Elemental Dipole / Near field conditions



- Wavelength>> Dipole length $\lambda \gg l$
- Uniform current distribution

MEMSTENNA placed close the dipole antenna

$r \ll \lambda$ $r \sim l$

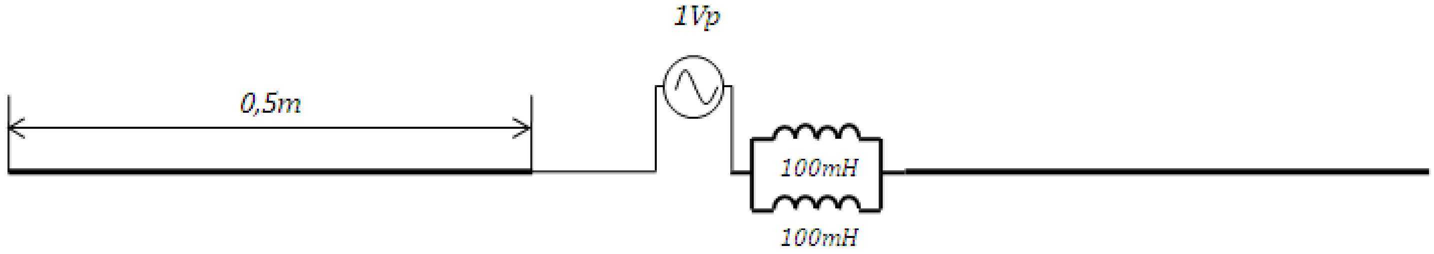
$$|E\theta| = \eta \frac{I\, l\, \lambda}{16\pi^2 r^3} sin\, \theta$$

$$|Er| = \eta \frac{I\, l\, \lambda}{8\pi^2 r^3} cos\, \theta$$

$kr \ll 1$

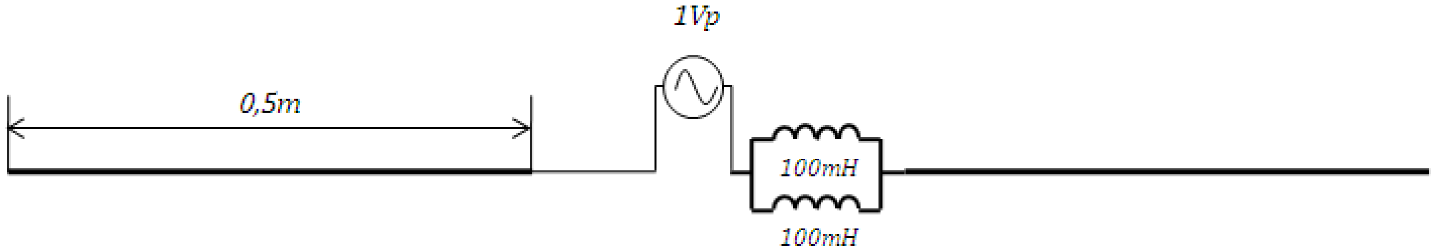
Quasiestatic electric fields

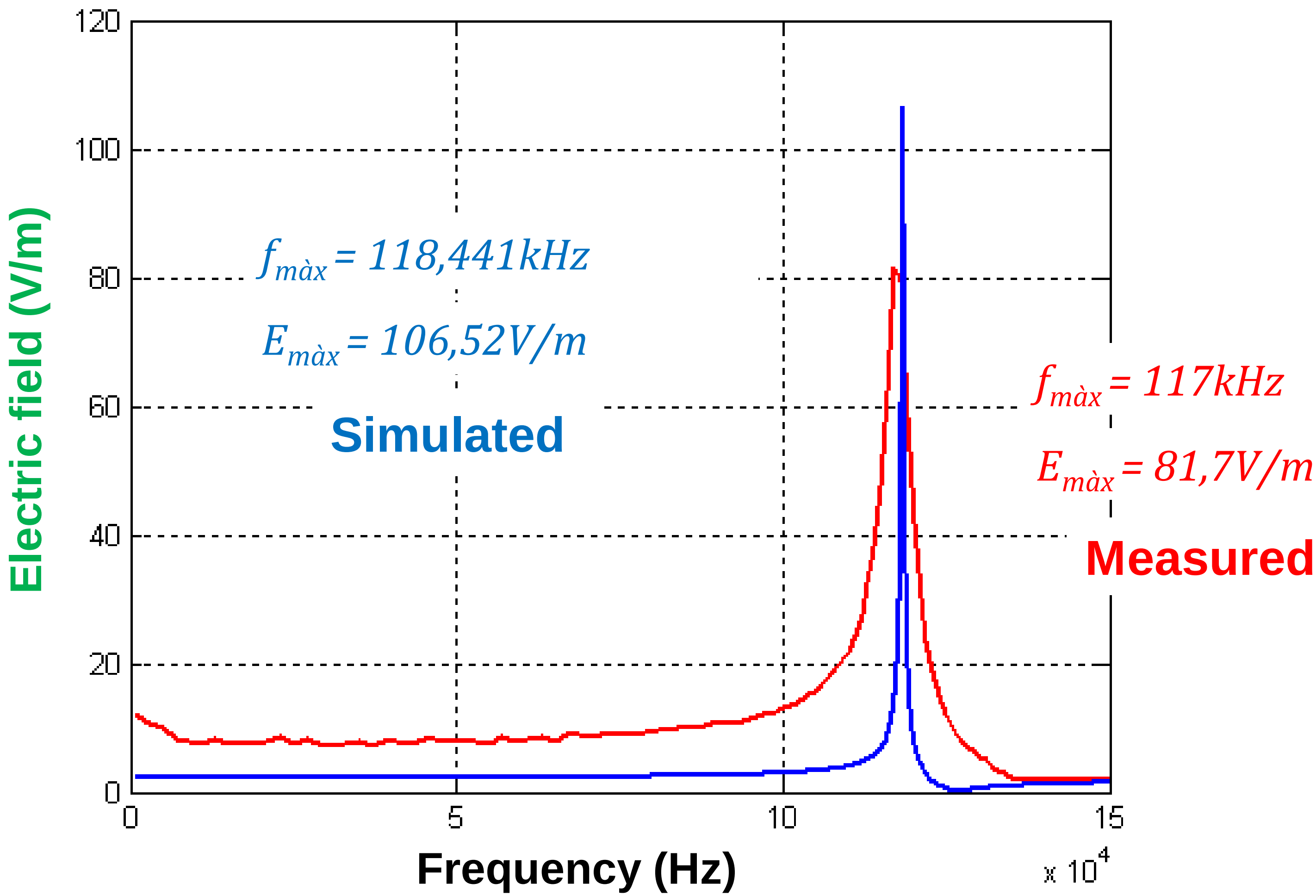
An elemental dipole antenna has to be designed to operate at f=100kHz

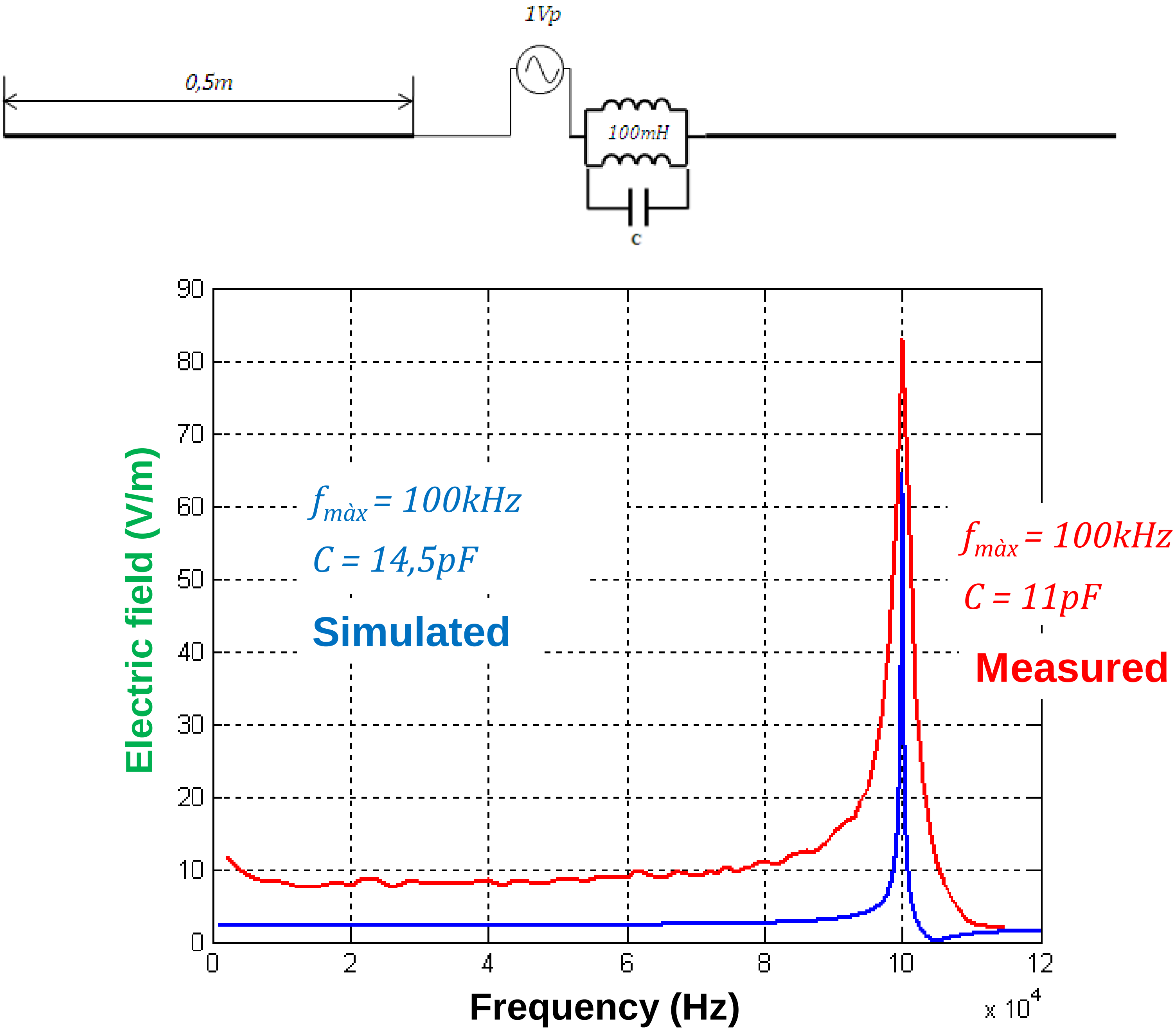


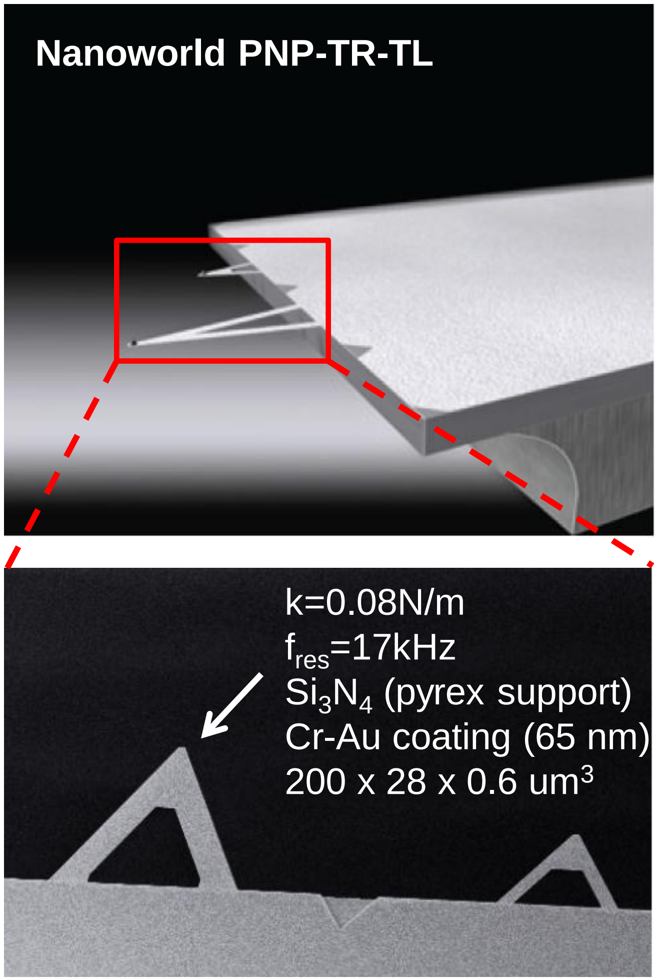
Autoinductaces are calculated to have a selfresonance around 100kHz

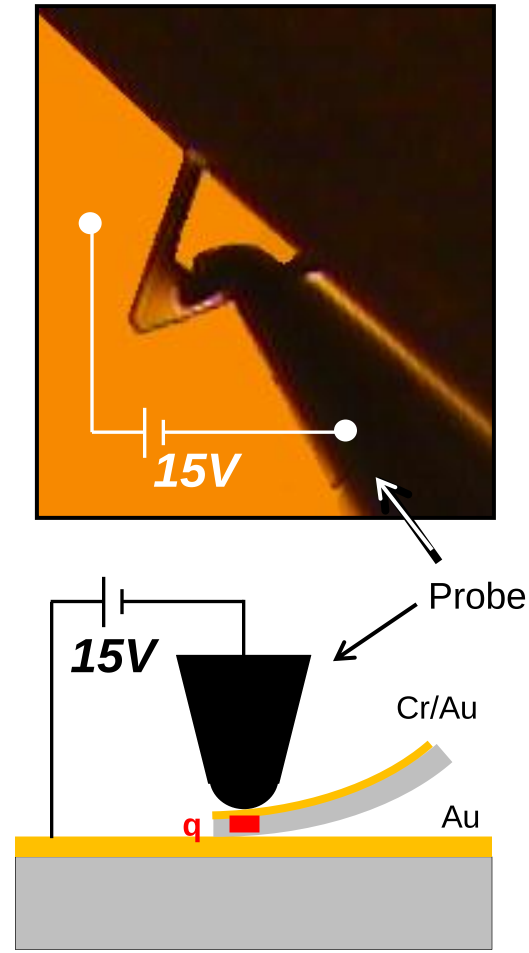
Electric field is measured 20cm away from the dipole antenna.

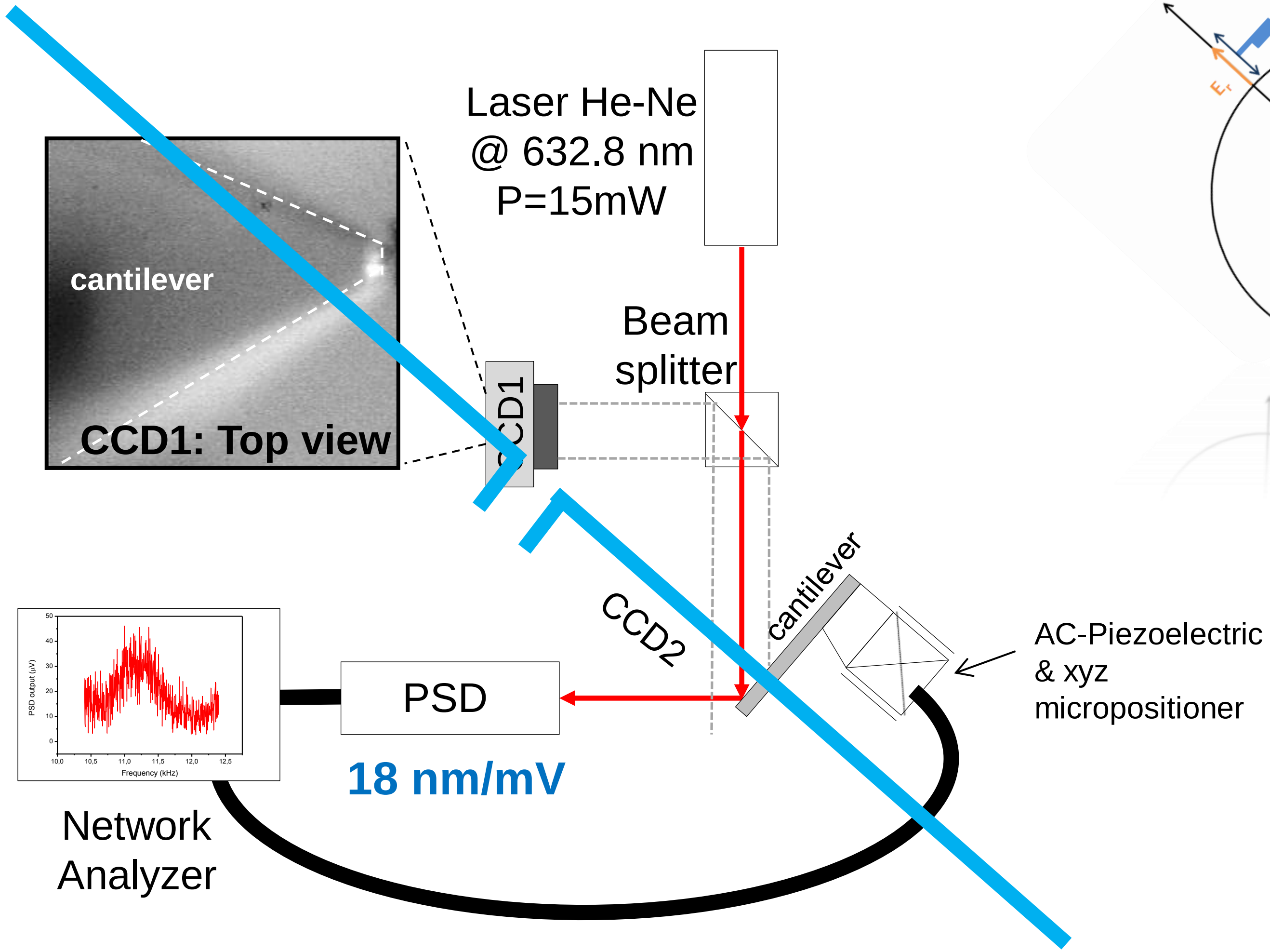

1Vp
0,5m
100mH
100mH

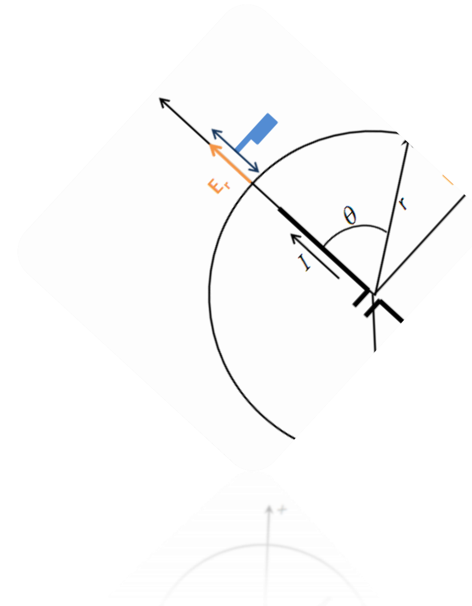

120
100
80
60
40
20
0
0
5
10
15
x 10^4
Electric field (V/m)
Frequency (Hz)
$f_{màx}$ = 118,441kHz
$E_{màx}$ = 106,52V/m
Simulated
$f_{màx}$ = 117kHz
$E_{màx}$ = 81,7V/m
Measured

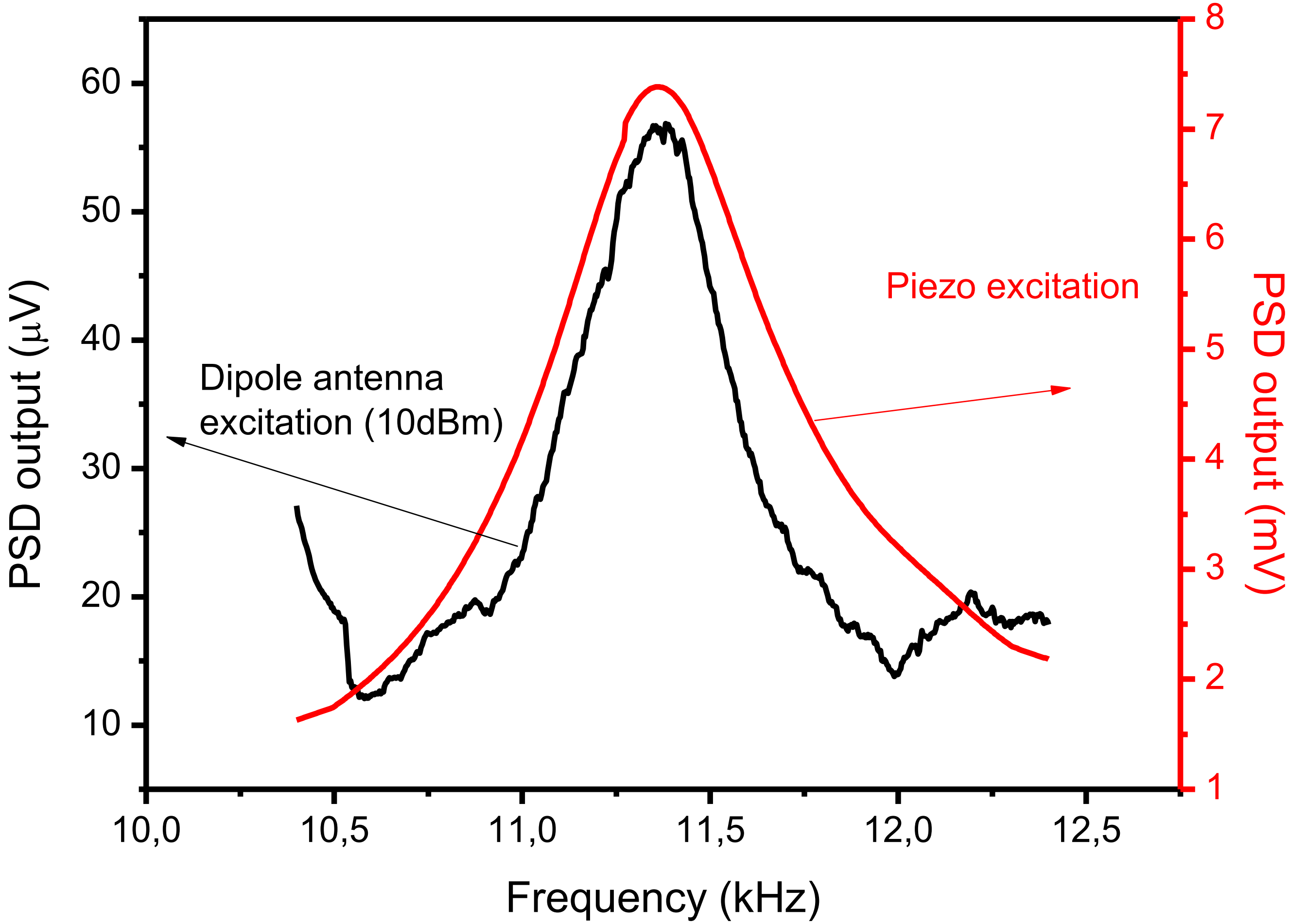

1Vp
0,5m
100mH
c
Electric field (V/m)
Frequency (Hz)
x 10^4
$f_{màx}$ = 100kHz
C = 14,5pF
Simulated
$f_{màx}$ = 100kHz
C = 11pF
Measured


Nanoworld PNP-TR-TL
k=0.08N/m
f_{res}=17kHz
Si_3N_4 (pyrex support)
Cr-Au coating (65 nm)
200 x 28 x 0.6 um^3

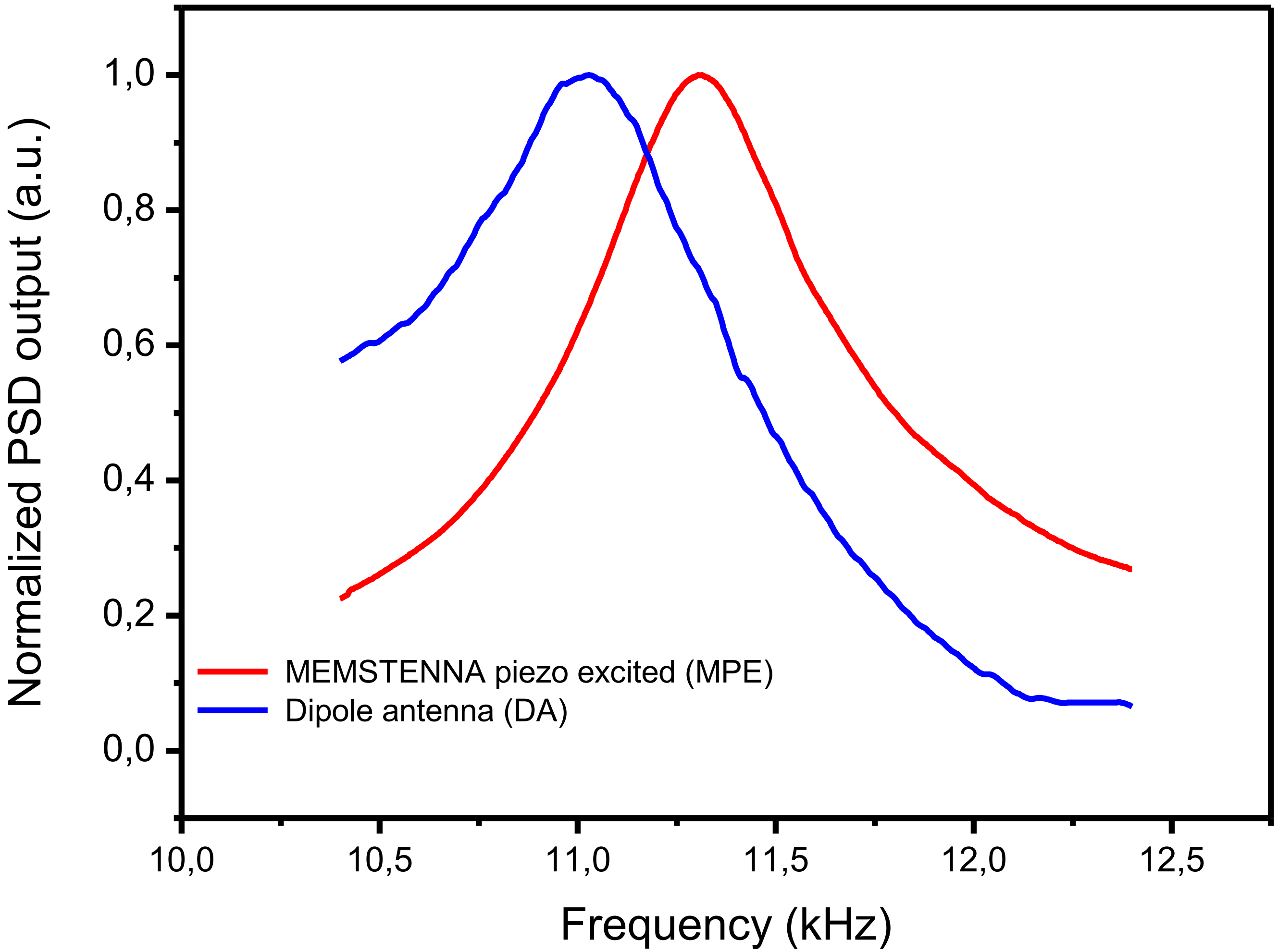

15V
Probe
15V
Cr/Au
q
Au

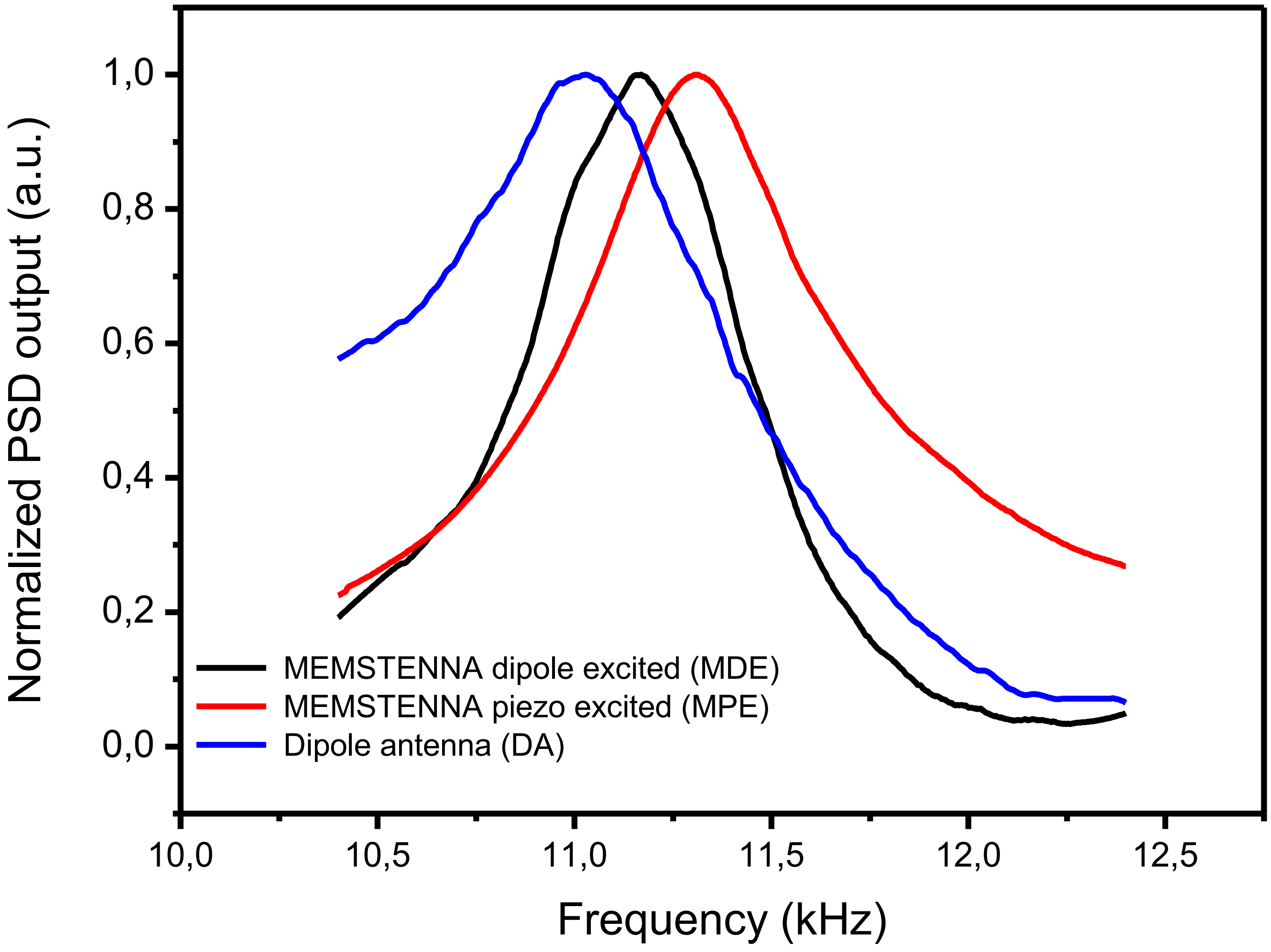

Laser He-Ne
@ 632.8 nm
P=15mW
cantilever
CCD1: Top view
CCD1
Beam
splitter
CCD2
cantilever
AC-Piezoelectric
& xyz
micropositioner
PSD
18 nm/mV
Network
Analyzer
PSD output (µV)
Frequency (kHz)



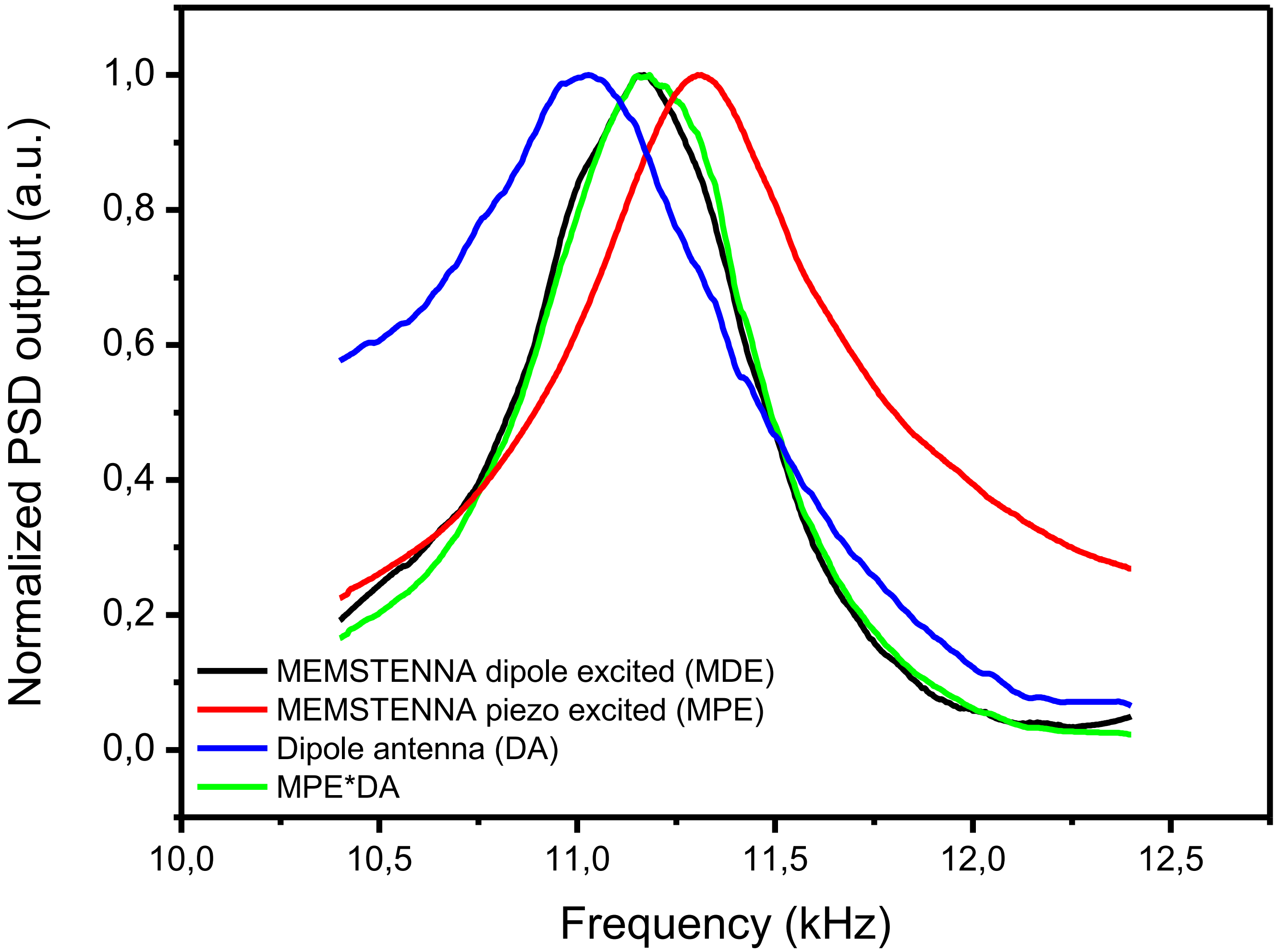


Dipole antenna
excitation (10dBm)
Piezo excitation
PSD output (μV)
PSD output (mV)
Frequency (kHz)
10,0
10,5
11,0
11,5
12,0
12,5
10
20
30
40
50
60
1
2
3
4
5
6
7
8

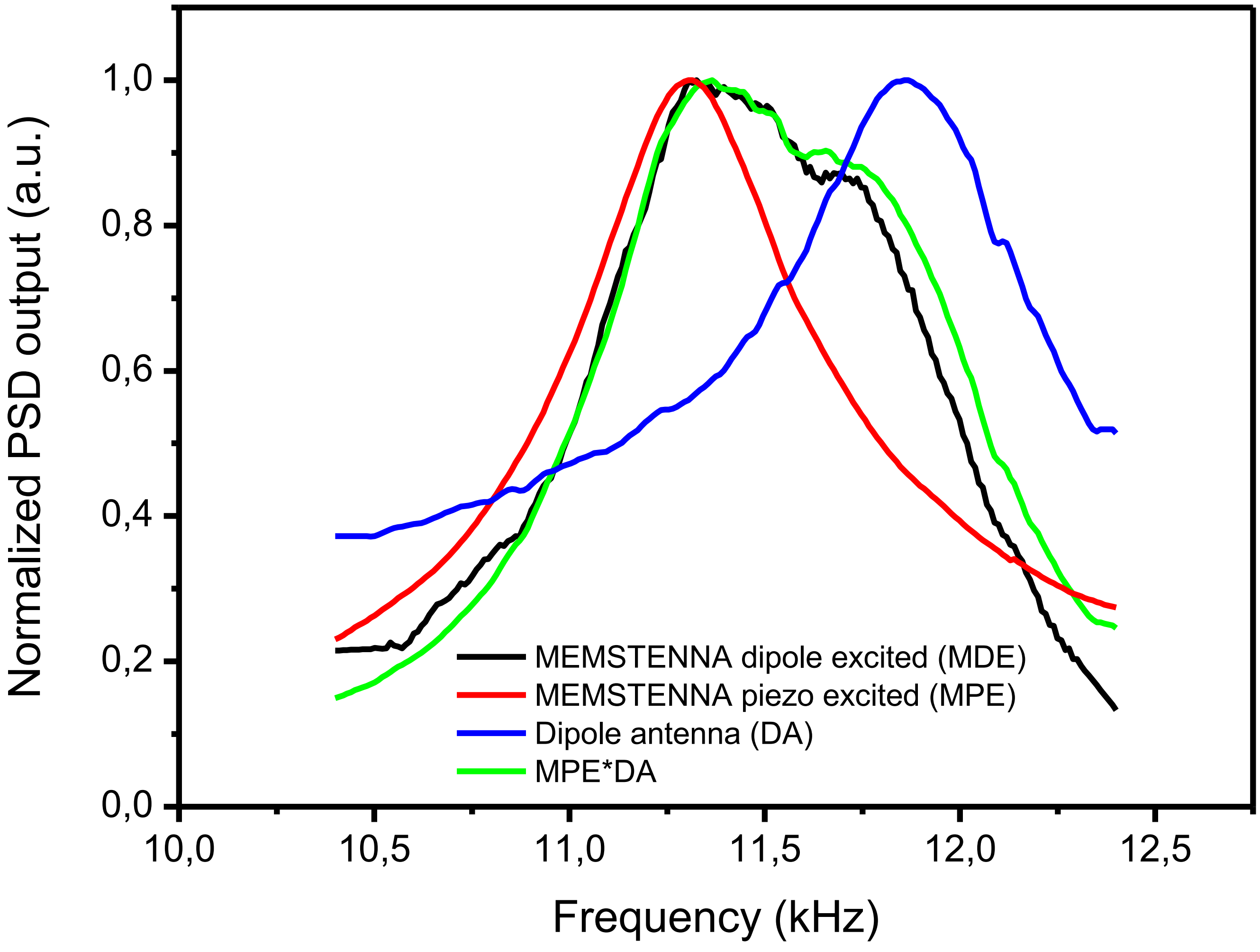

Normalized PSD output (a.u.)
1,0
0,8
0,6
0,4
0,2
0,0
MEMSTENNA piezo excited (MPE)
Dipole antenna (DA)
10,0
10,5
11,0
11,5
12,0
12,5
Frequency (kHz)



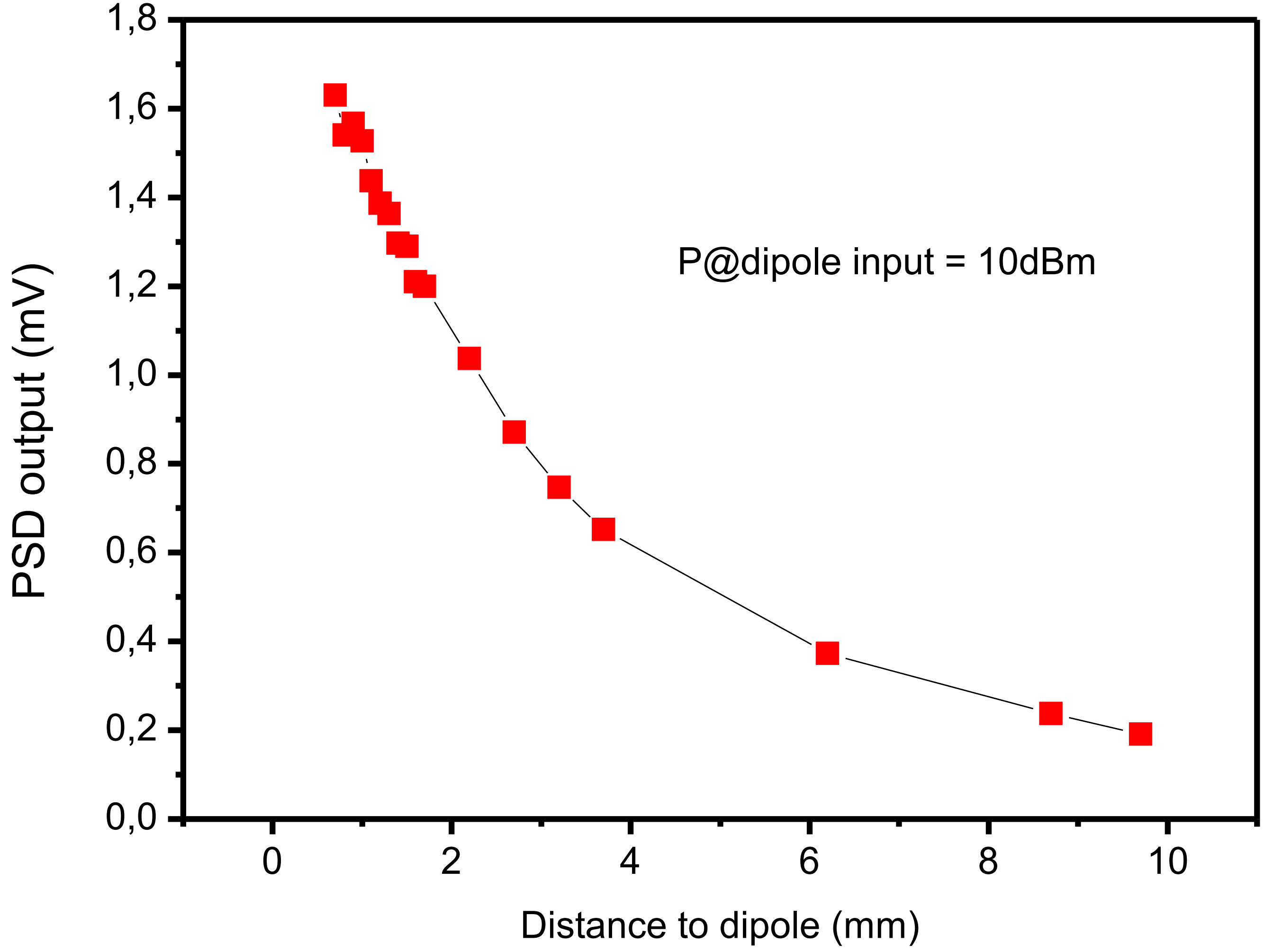
Normalized PSD output (a.u.)
1,0
0,8
0,6
0,4
0,2
0,0
10,0
10,5
11,0
11,5
12,0
12,5
Frequency (kHz)
MEMSTENNA dipole excited (MDE)
MEMSTENNA piezo excited (MPE)
Dipole antenna (DA)



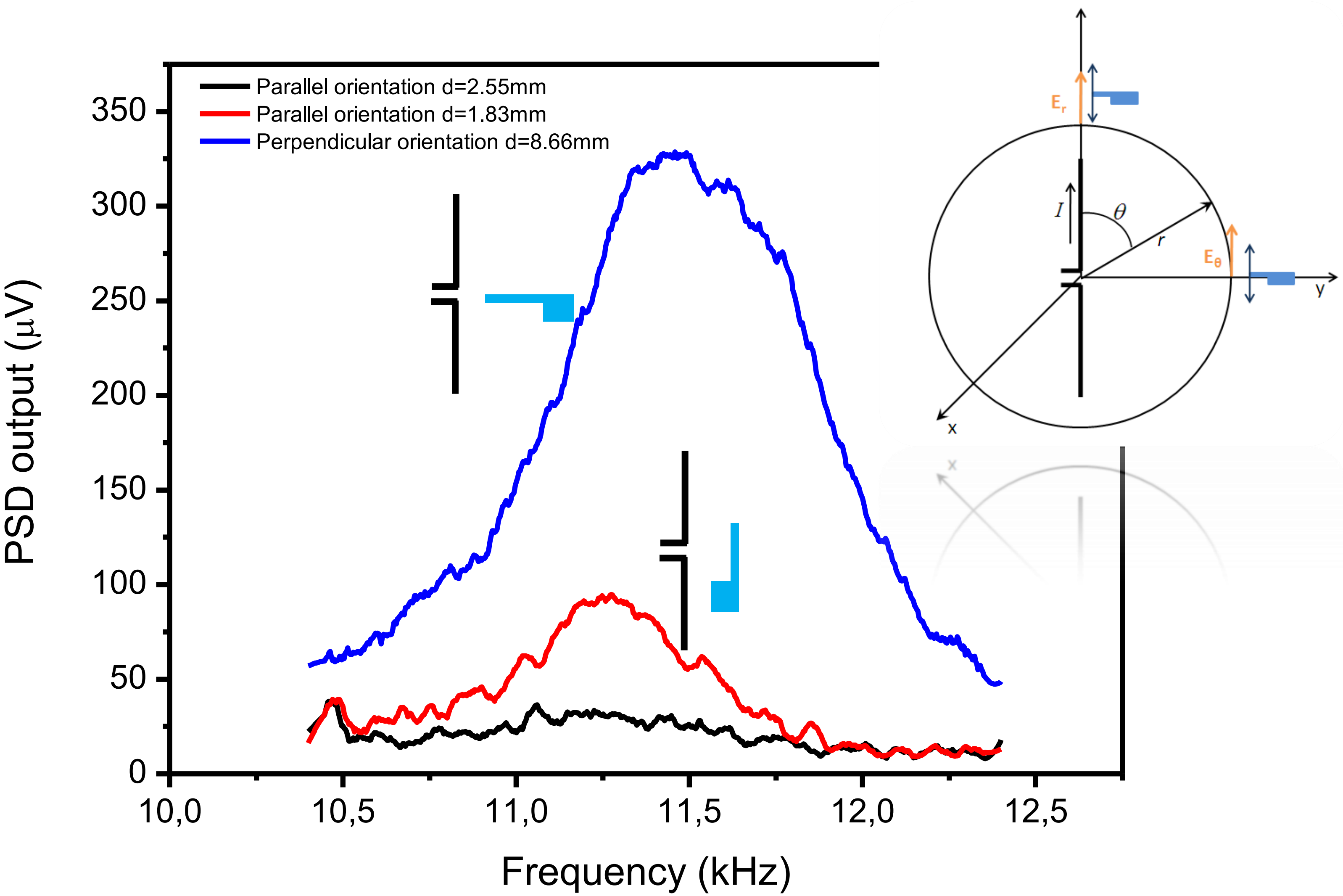
Normalized PSD output (a.u.)
1,0
0,8
0,6
0,4
0,2
0,0
10,0
10,5
11,0
11,5
12,0
12,5
Frequency (kHz)
MEMSTENNA dipole excited (MDE)
MEMSTENNA piezo excited (MPE)
Dipole antenna (DA)
MPE*DA

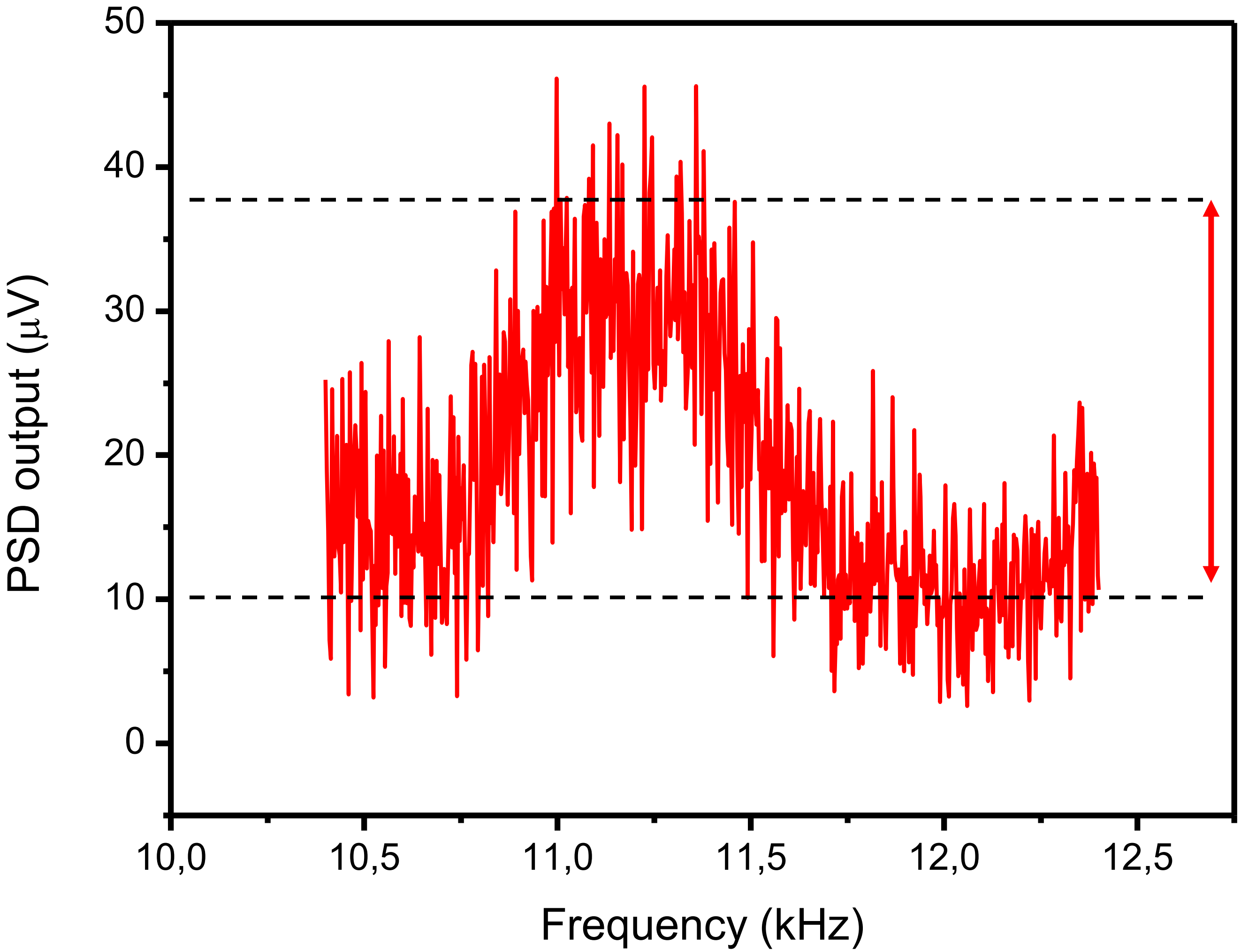


1,0
0,8
0,6
0,4
0,2
0,0
10,0
10,5
11,0
11,5
12,0
12,5
Normalized PSD output (a.u.)
Frequency (kHz)
MEMSTENNA dipole excited (MDE)
MEMSTENNA piezo excited (MPE)
Dipole antenna (DA)
MPE*DA



1,8
1,6
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
PSD output (mV)
0
2
4
6
8
10
Distance to dipole (mm)
P@dipole input = 10dBm


Parallel orientation d=2.55mm
Parallel orientation d=1.83mm
Perpendicular orientation d=8.66mm
PSD output (μV)
Frequency (kHz)
0
50
100
150
200
250
300
350
10,0
10,5
11,0
11,5
12,0
12,5
I
θ
r
y
x



d=53 mm
E(@53 mm)=1250 V/m
q=10 fC, Q=12, k=0.08N/m

1.87 nm

30 μV ⇨ **0.54 nm**

If Q=1000 (vacuum)

⇩

z = 0.1-0.2 μm

APPLIED PHYSICS LETTERS **102**, 153901 (2013)

Inducing bistability with local electret technology in a microcantilever based non-linear vibration energy harvester

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[1]*Departament d'Enginyeria Electrònica, Universitat Autònoma de Barcelona, Bellaterra 08193, Spain*
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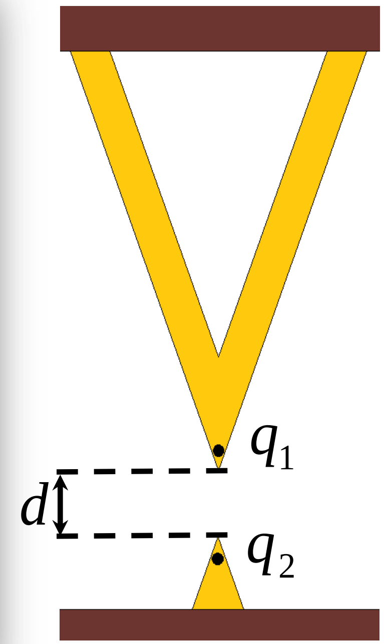
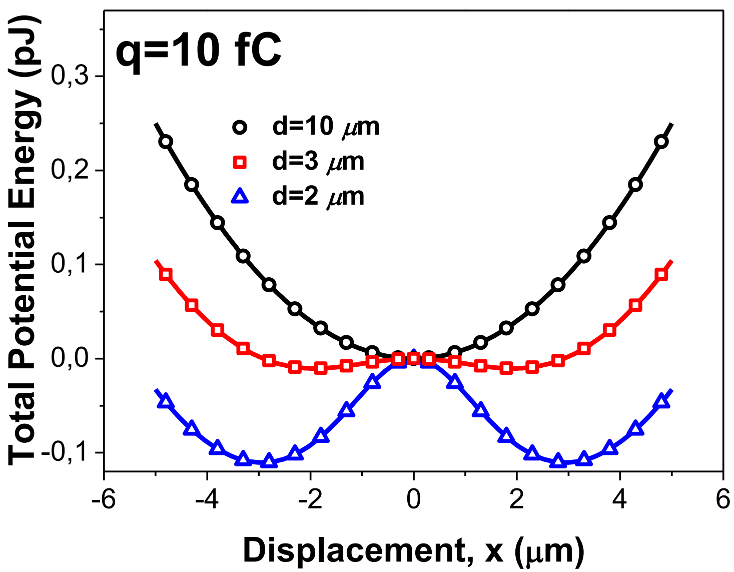
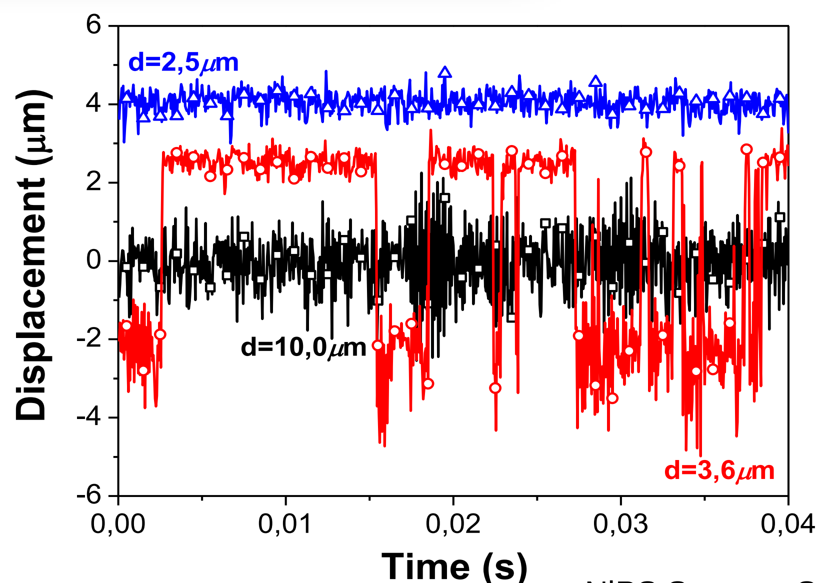
(Received 22 January 2013; accepted 21 March 2013; published online 16 April 2013)

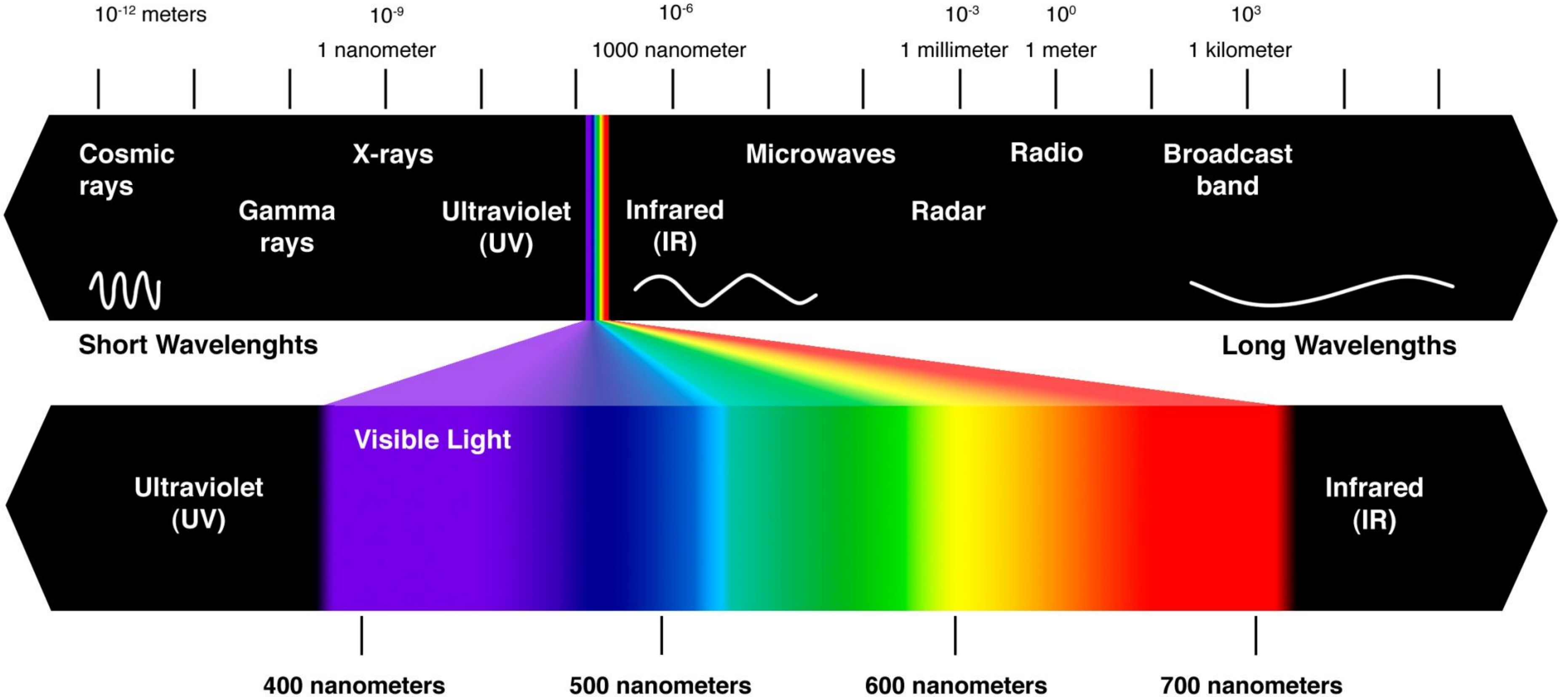
A micro-electro-mechanical system based vibration energy harvester is studied exploring the benefits of bistable non linear dynamics in terms of energy conversion. An electrostatic based approach to achieve bistability, which consists in the repulsive interaction between two electrets locally charged in both tip free ends of an atomic force microscope cantilever and a counter electrode, is experimentally demonstrated. A simple model allows the prediction of the measured dynamics of the system, which shows an optimal distance between the cantilever and the counter electrode in terms of the root mean square vibration response to a colored Gaussian excitation noise. © *2013 American Institute of Physics.* [http://dx.doi.org/10.1063/1.4800926]



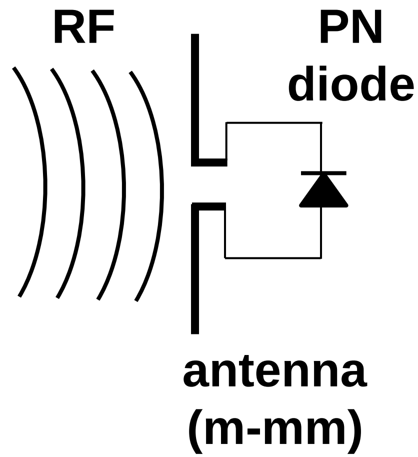




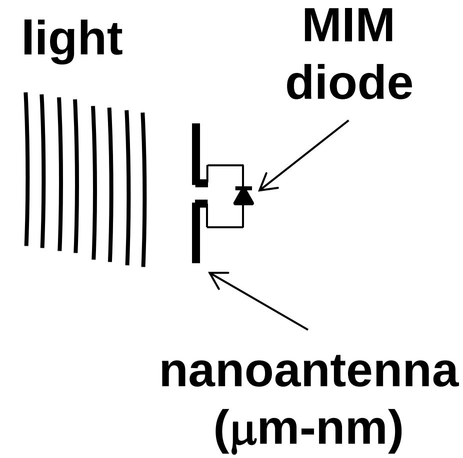
The electromagnetic spectrum



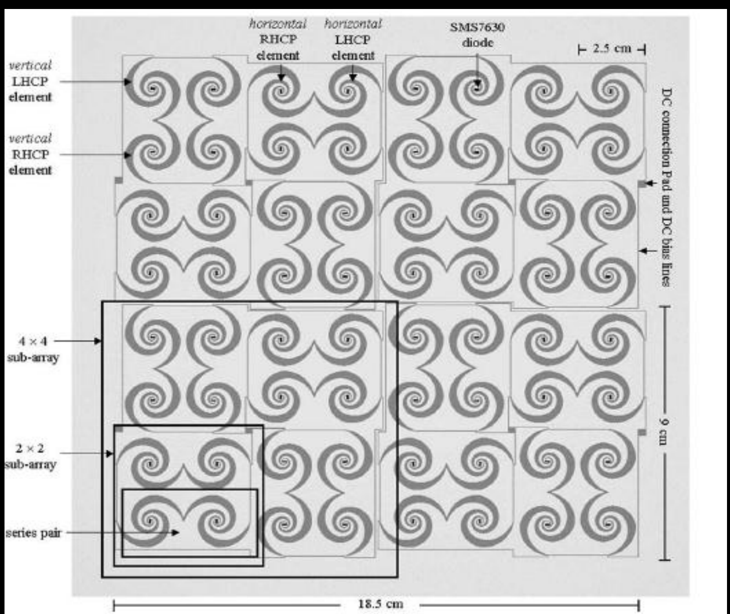
RF Rectenna
(RFR)



Optical Rectenna
(OR)

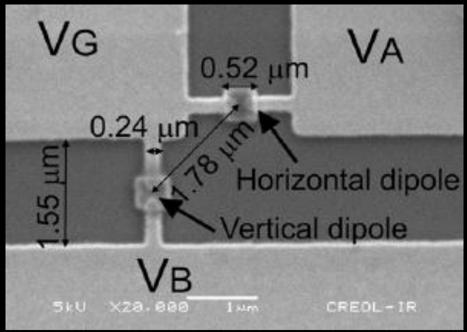


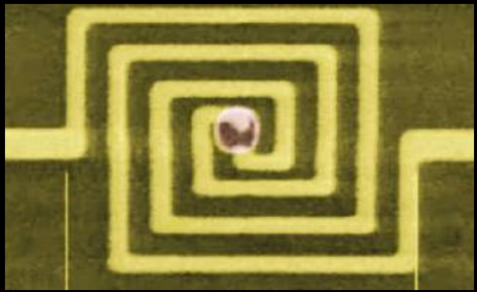
GHz rectenna



Hagerty et al., “IEEE Trans on MTT”, (2004)

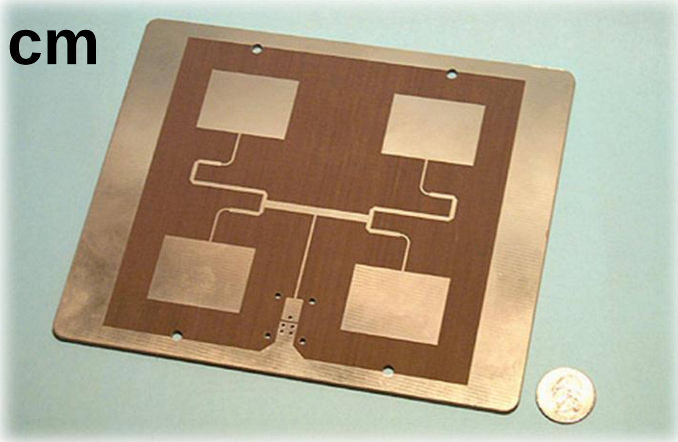
THz optical rectenna



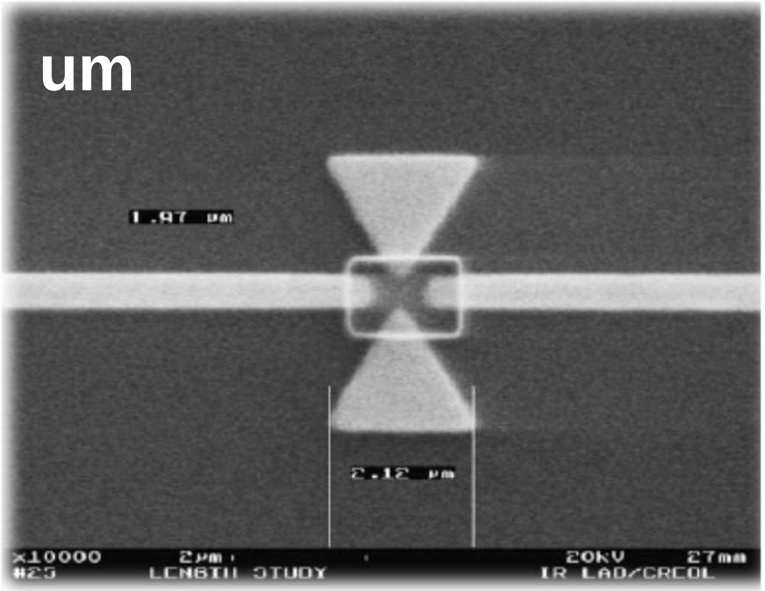


Alda et al. Opt. Lett. (2009)

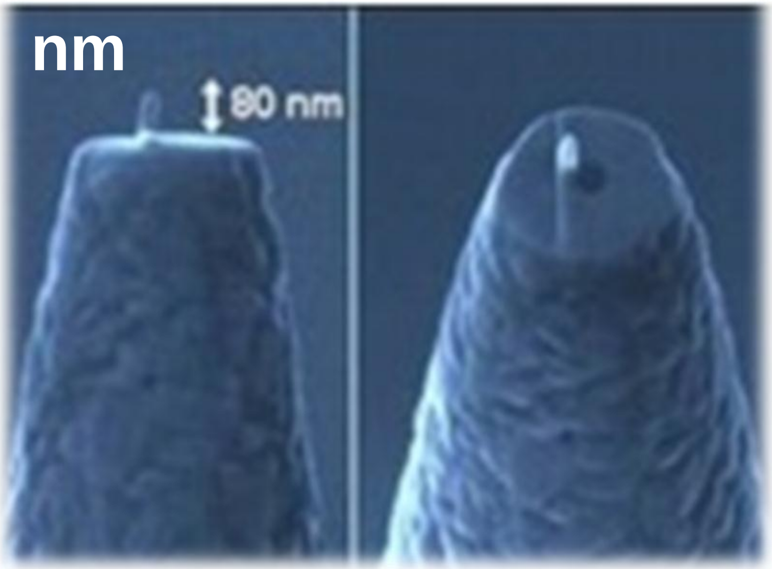
Optical nano-antenna technology



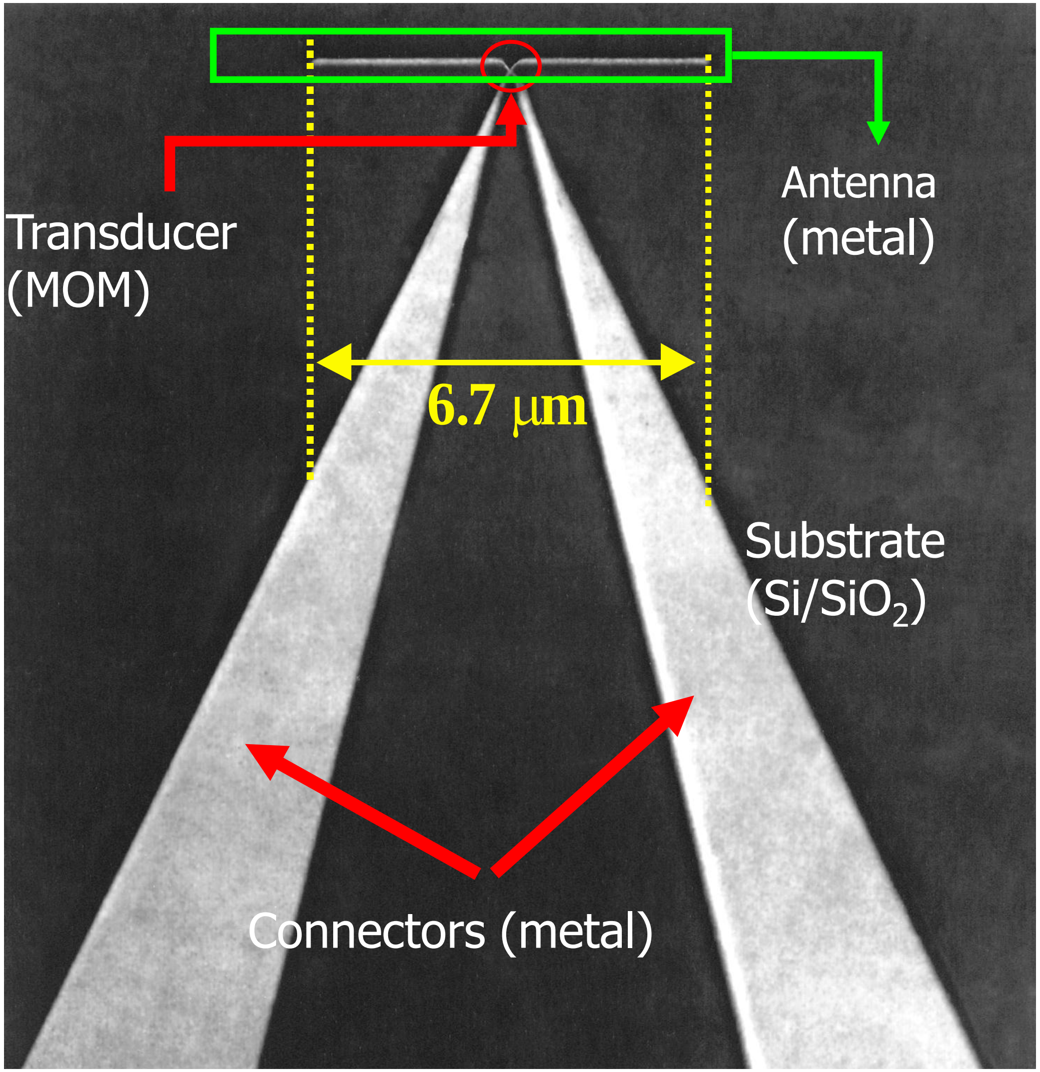
Microwave patch-antenna



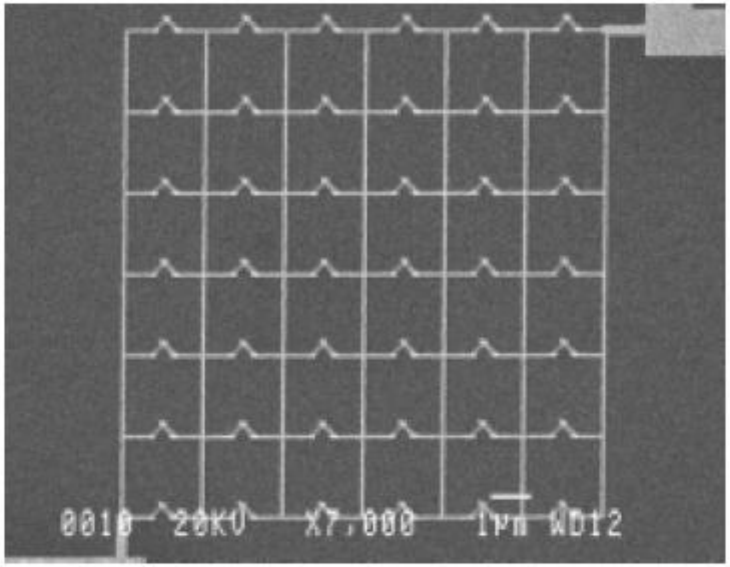
Infrared bow-tie antenna



Visible dipole antenna


Antenna
(metal)
Transducer
(MOM)
6.7 μm
Substrate
(Si/SiO2)
Connectors (metal)

Optical rectenna

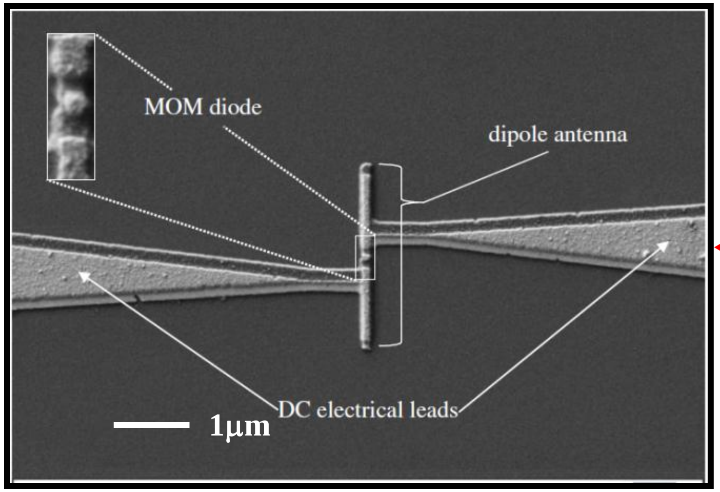


Theoretical efficiencies ≈ 96%

Shottky diodes: f < 5 THz

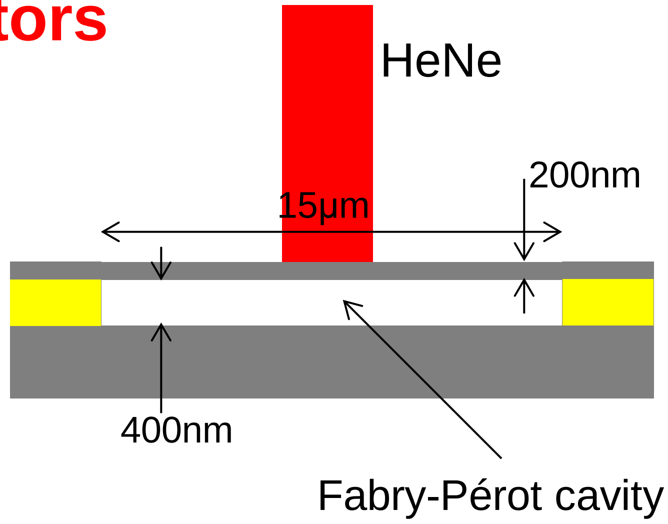
MIM diodes:
Cr/CrO_x/Au, Nb/NbO_x/Nb or Al/AlOx/Pt
f ≈ 150 THz (2um)

Two limitations:
- Integration
- Zero bias response: pour non-linearity of the i-v characteristic at V=0.



1um long dipole nanoantenna
Al/AlO_x/Pt MOM diode rectifier
Efficiency below 10^{-6}

NOEMS oscillators

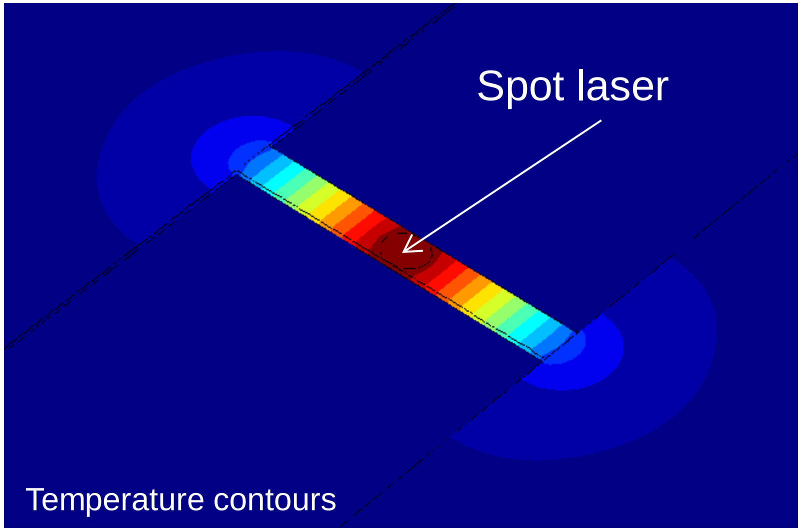


Structure example:

- Type: bridge
- Fabrication causes residual compressive stress
  - ✓ It makes the bridge to be arched 40 nm at the periphery
- Materials (from a SOI wafer)
  - ✓ Bridge: Si
  - ✓ Pillar: SiO_2
  - ✓ Substrate: Si

"Excitation" source:

- Continuous Wave (CW) HeNe laser
  - ✓ λ = 632,8 nm
- Spot radius of about 2-5 µm
- Position at the center of the beam



ZEROPOWER

Project title:

ZEROPOWER—Co-ordinating Research Efforts Towards Zero-Power ICT

Proposal no. 270005

Financed by: FP7-ICT-2009-6. Coordination and support action. ICT-6-8.9 - Coordinating Communities, Plans and Actions **in FETProactive** Initiatives

Participants: UNIPG (UNIVERSITA DEGLI STUDI DIPERUGIA), Tyndall-UCC (UNIVERSITY COLLEGE CORK, NATIONAL UNIVERSITY OF IRELAND, CORK), UAB (UNIVERSITAT AUTONOMA DE BARCELONA), UGLA (UNIVERSITY OF GLASGOW)

Duration from: 1st January 2011 to: 31st December 2013

Subvention: 104.891€ (UAB) of 550.000€ (TOTAL)

Project responsible: Luca Gammaitoni (UNIPG project coordinator). Gabriel Abadal (responsible UAB)

NiPS Laboratory – Noise in Physical Systems

Prof. Luca Gammaitoni

University of Glasgow

Prof. Douglas Paul

Tyndall National Institute

Dr. Georgios Fagas

NANERG LAB – UAB Universitat Autònoma de Barcelona

Dr. Gabriel Abadal

Aim of the project: The goal of this project is to create a coordination activity among consortia involved in "Toward Zero-Power ICT" research projects (FET proactive call FP7-ICT-2009-5, Objective 8.6) and communities of scientists interested in energy harvesting and low power, energy efficient ICT.

Project title:
OPACMEMS: Optical antennae coupled to micro and nanoelectromechanical systems
Financed by: MICINN. ENE2009-14340-C02-02
Participants: UCM (subproject 01), UAB (subproject 02)
Duration from: Oct 2009 to:Oct 2012
Subvention: 180.000€ (subproy. 02)
Project responsible: Gabriel Abadal Berini

Universitat Autònoma de Barcelona

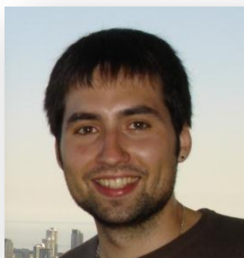
Dr. Gabriel Abadal
Department of Electronics Engineering
School of Engineering
University Autonoma of Barcelona (SP)

Universidad Complutense Madrid

Prof. Javier Alda
Applied Optics Complutense Group
University Complutense of Madrid (SP)

Aim of the project: To investigate the IR energy conversion to the electrical domain through MEMS-NEMS devices coupled to optical resonant structures for energy harvesting applications at the **nanoscale**.


Gabriel Abadal


Jordi Agustí


Miquel López-Suárez


Gonzalo Murillo (now at IMB-CNM)


Marcel Placidi (now at IREC)


Francesc Torres

NANERG LAB

NOEMS for ENERGY LABORATORY

NANO-OPTOELECTROMECHANICAL SYSTEMS FOR ENERGY LABORATORY

http://grupsderecerca.uab.cat/nanerglab/