Inkjet-Printed Nanotechnology-Enabled Zero-Power Wireless Sensor Nodes for Internet-of-Things (IoT) and M2M Applications

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ATHENA Research Group

- 10 PhD students
- 5 MS students
- 5 GT-ORS Undergraduate Students
- 5 Visiting Faculty+Stuff (Japan, France, Italy, Spain, China)
- Strong collaboration with Georgia Tech Ireland - Athlone (visited Summer 2009)
- Featured in IEEE The Institute, Wall Street Journal, Discovery Channel, CNN, Boston Globe, CBS Smartplanet, Yahoo, EE Times, engadget.com, gizmag.com
- Co-founders of the RF-DNA anti-counterfeiting technology listed among the 25 technologies featured in the 20-year anniversary issue of the Microsoft Research Center
- **http://www.athena-gatech.org**

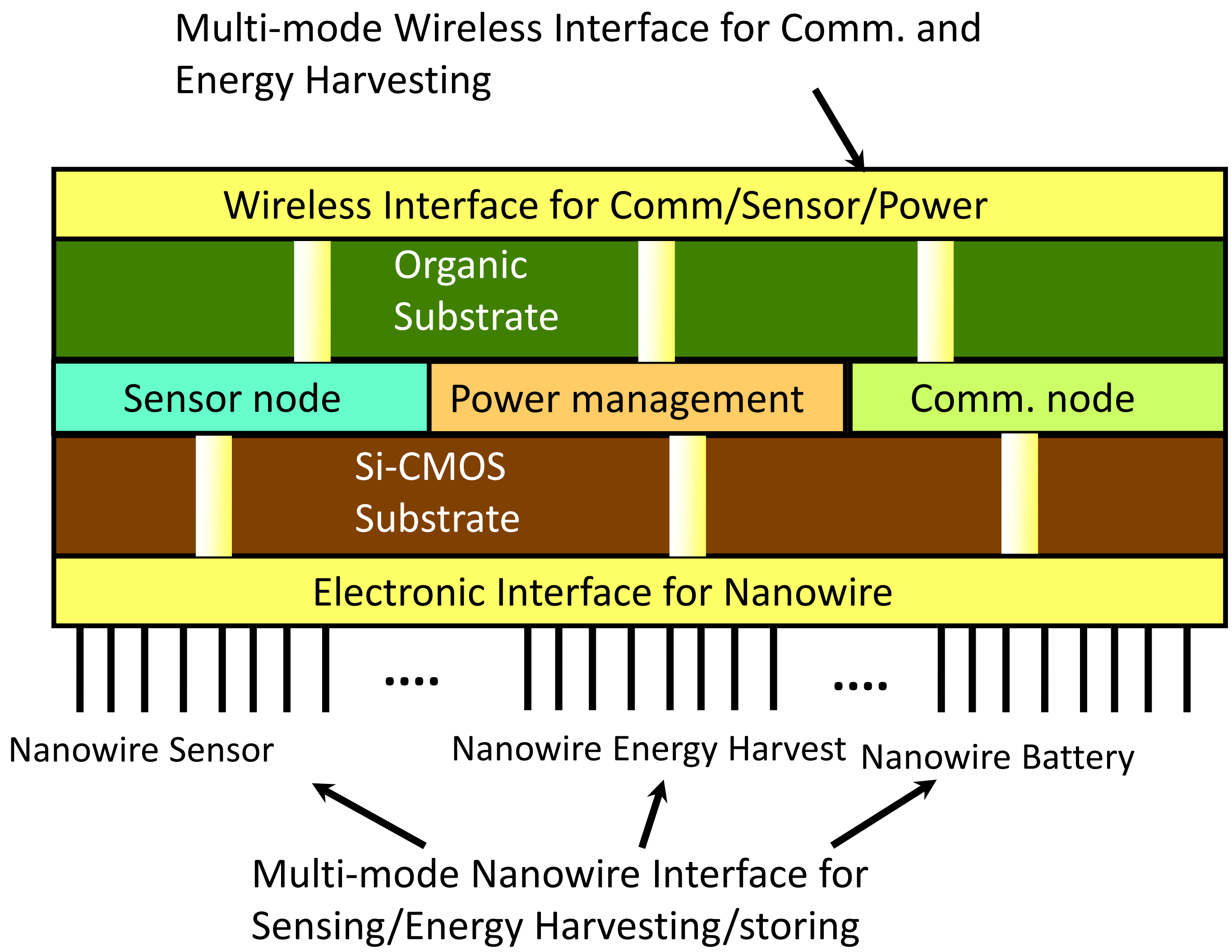
ATHENA Focus Areas

- RFID's, mmID's and RFID-enabled Sensors
- Inkjet-Printed RF electronics, antennas and sensors
- Nanotechnology-based "zero-power" wireless sensors
- Ubiquitous WSN's and Internet of Things
- "Smart Skin" and "Smart Energy" Applications
- Wearable and Implantable WBAN's
- Flexible 3D Wireless " Smart Cube" Modules up to sub-THz
- Multiform Power Scavenging and Wireless Power Transfer
- Conformal ultra broadband/multiband antennas and antenna arrays
- Paper/PET/Fabric-based Electronics

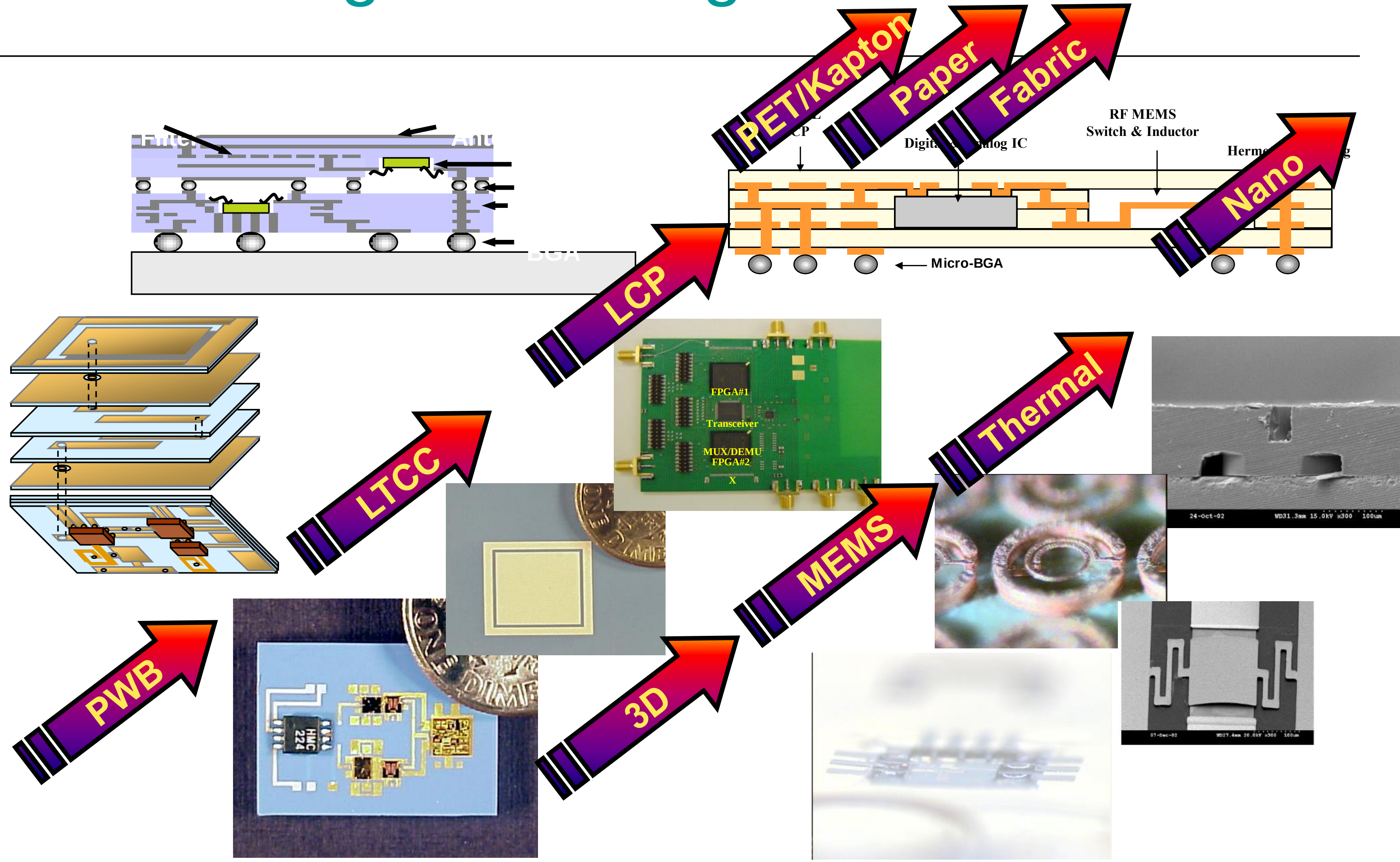
Selected Awards

- IEEE Fellow
- NSF CAREER Award
- IEEE MTT-S Distinguished Microwave Lecturer
- 2009 E.T.S. Walton Award from SFI
- 2010 IEEE APS Society P.L.E.Uslenghi Letters Prize Paper Award
- 2010 Georgia Tech Senior Faculty Outstanding Undergraduate Research Mentor Award
- 2009 IEEE Trans. Components and Packaging Technologies Best Paper Award
- 2006 IEEE MTT Outstanding Young Engineer Award
- 2006 Asian-Pacific Microwave Conference Award
- 2003 NASA Godfrey "Art" Anzic Collaborative Distinguished Publication Award

3D Integrated Platforms



Enabling Technologies in the future



Inkjet-Printed RF Electronics and Modules on Paper

Module

- Microcontroller Unit and Transceiver SoP Integration and Packaging
- Inkjet-printing
- Curing
- Multilayer lamination

Components

- Energy Harvesting Devices (Solar, Piezo)
- Power Management Unit
- Temperature Sensor
- Paper-based Substrates

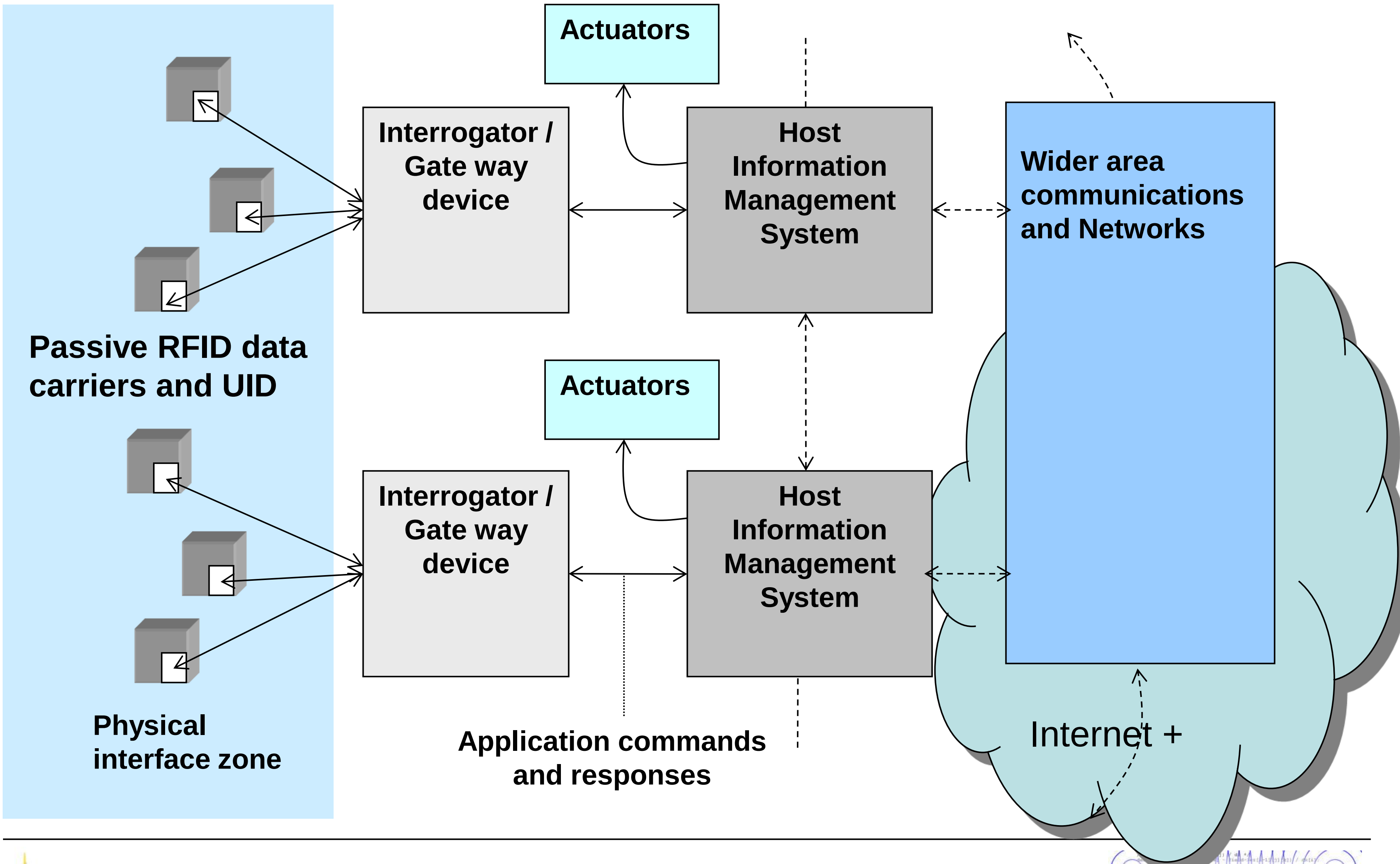
System

- Identification
- Localization & Position Tracking
- Environmental Sensing and Monitoring

Network

- RFID ⬌ WSN Communication
- Multi-hopping Routing Protocol

Internet of Things - *at its most basic level…*

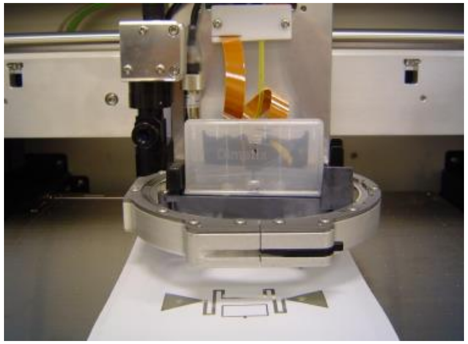


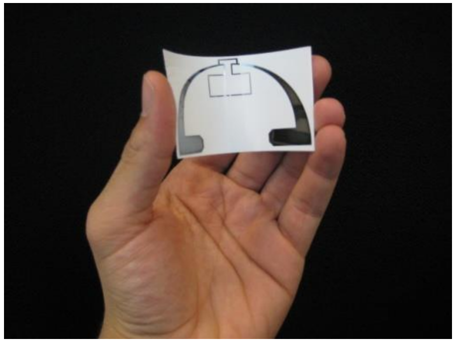
RFID Ink-jet Printed on Paper Using Conductive Ink

PAPER ELECTRONICS:

- Environmental Friendly and is the LOWEST COST MATERIAL MADE
- Large Reel to Reel Processing
- Compatible for printing circuitry by direct write methodologies
- Can be made **hydrophobic** and can host nano-scale additives (e.g. fire retardant textiles)
- Dielectric constant εr (~3) close to air's
- Potentially setting the foundation for truly

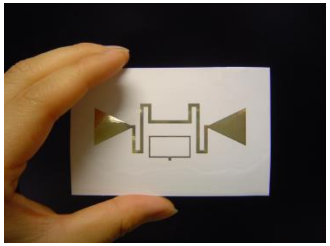
  "green" RF electronics





RFID printed on paper: conductive ink

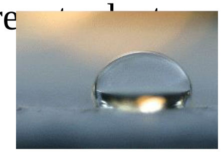
PAPER:



- Environmental Friendly and low cost

<u>(LOWEST COST MATERIAL MADE BY HUMANKIND)</u>

- Large Reel to Reel Processing
- Compatible for printing circuitry by direct write methodologies
- Can be made hydrophobic and can host nano-scale additives (e.g. fire

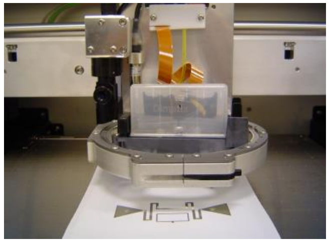


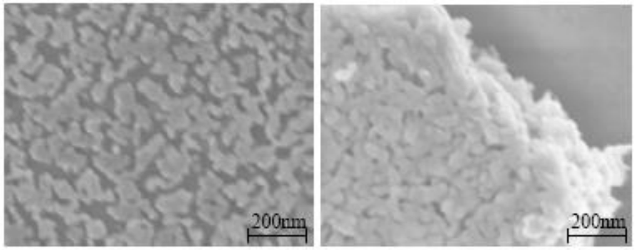
textiles)

- Dielectric constant εr (~2) close to air's

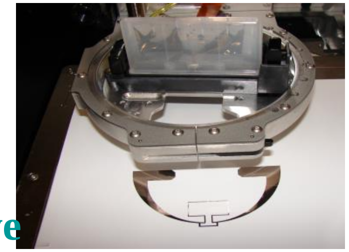
INK:

- Consisting of nano-spheres melting and sintering at low temperatures (100 ° C)
- After melting a good percolation channel is created for electrons flow.
- Provides better results than traditional polymer thick film material approach.





SEM images of printed silver nano-particle ink, after 15 minutes of curing at 100°C and 150°C

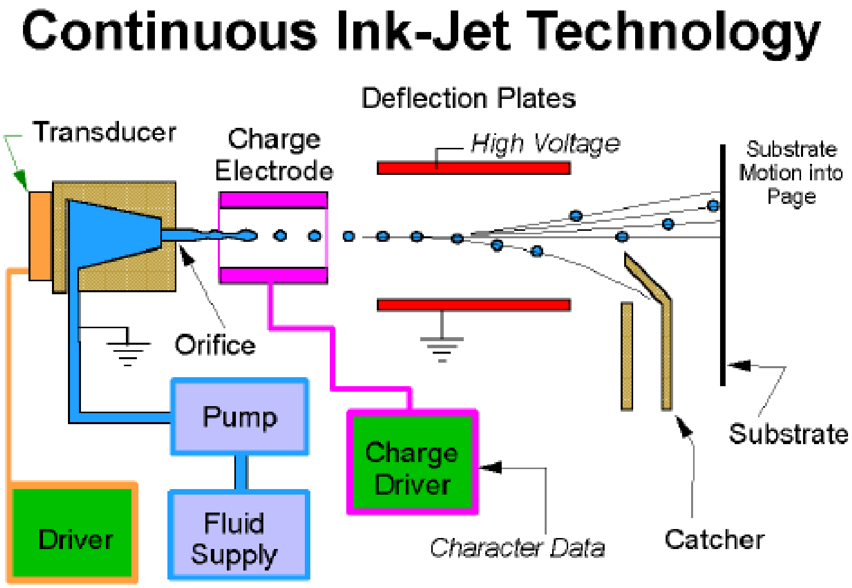


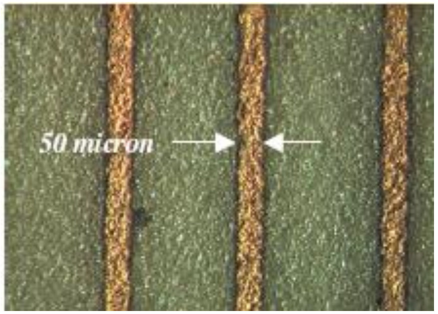
The ONLY group able to inkjet-print carbon-nanotubes for ultrasensitive gas sensors (ppb) and structural integrity (e.g.aircraft crack detection) non-invasive sensors

Inkjet-printing Technology - Printer

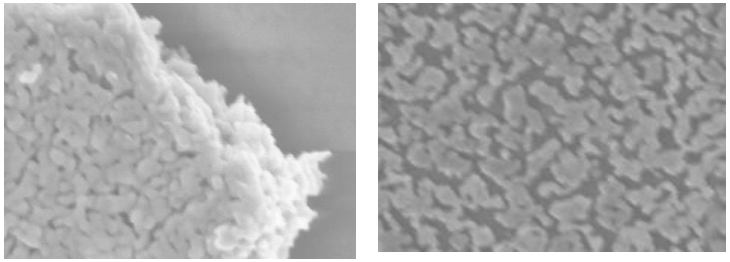
Characteristics:

- **Piezo-driven jetting device to preserve polymeric properties of ink**
- **10 pL drops give ~ 21** μm
- **Drop placement accuracy** ±**10** μm **gives a resolution of 5080 dpi**
- **Drop repeatability about 99.95%**
- **Printability on organic substrates (LCP, paper …)**

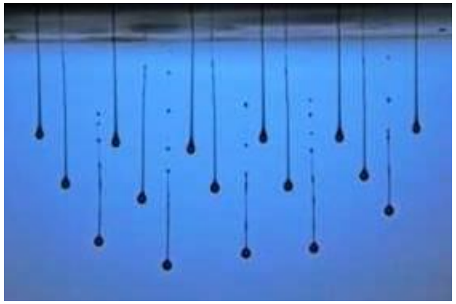




High resolution inkjet printed copper (20 μm)

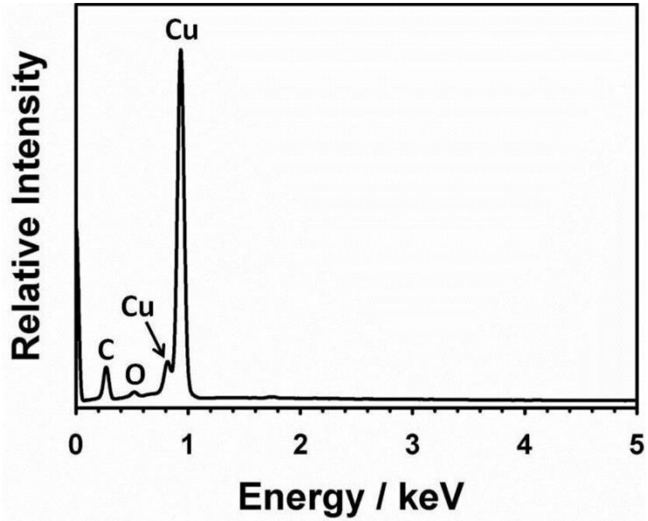


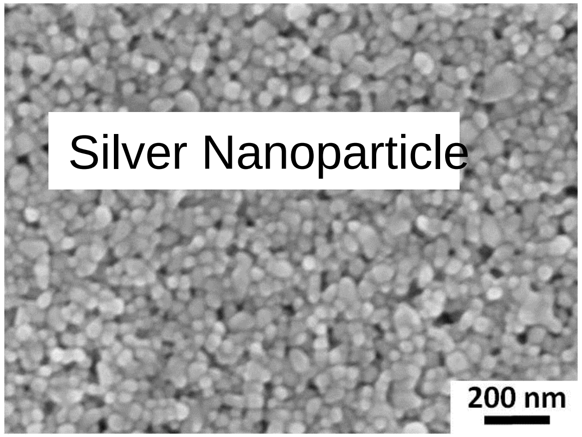
SEM Images of a Layer of Printed ink, Before and After a 15 Minute Cure at 150ºC

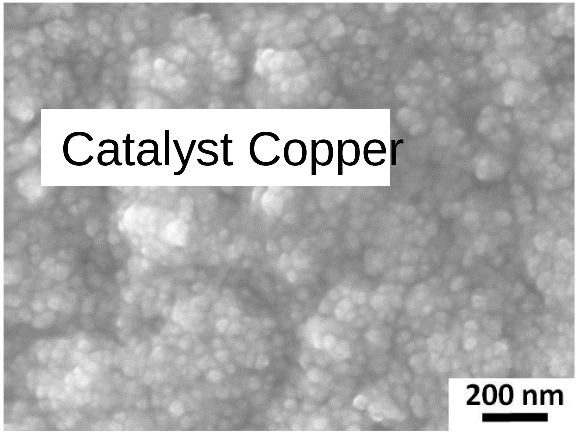


Novel Method for Inkjet Cu

- 15x cheaper than metallic nanoparticles
- Uniform, non-porous films
- Can be deposited on glass and wafers (Future integration w/ CMOS)
- Zero oxidation

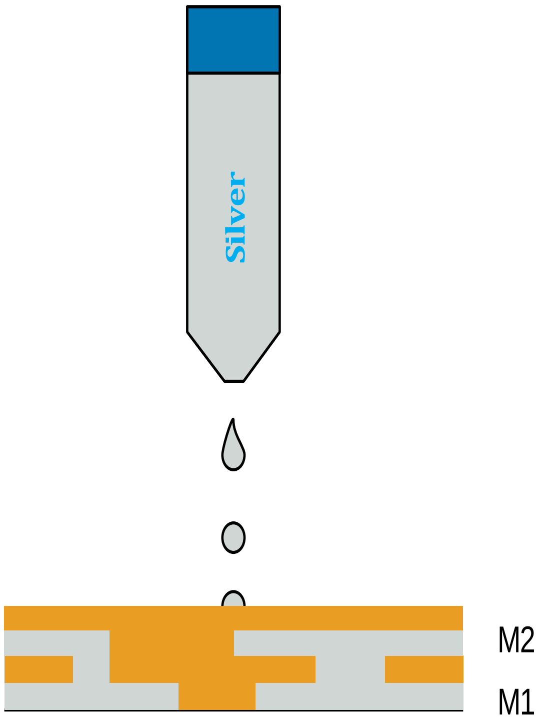






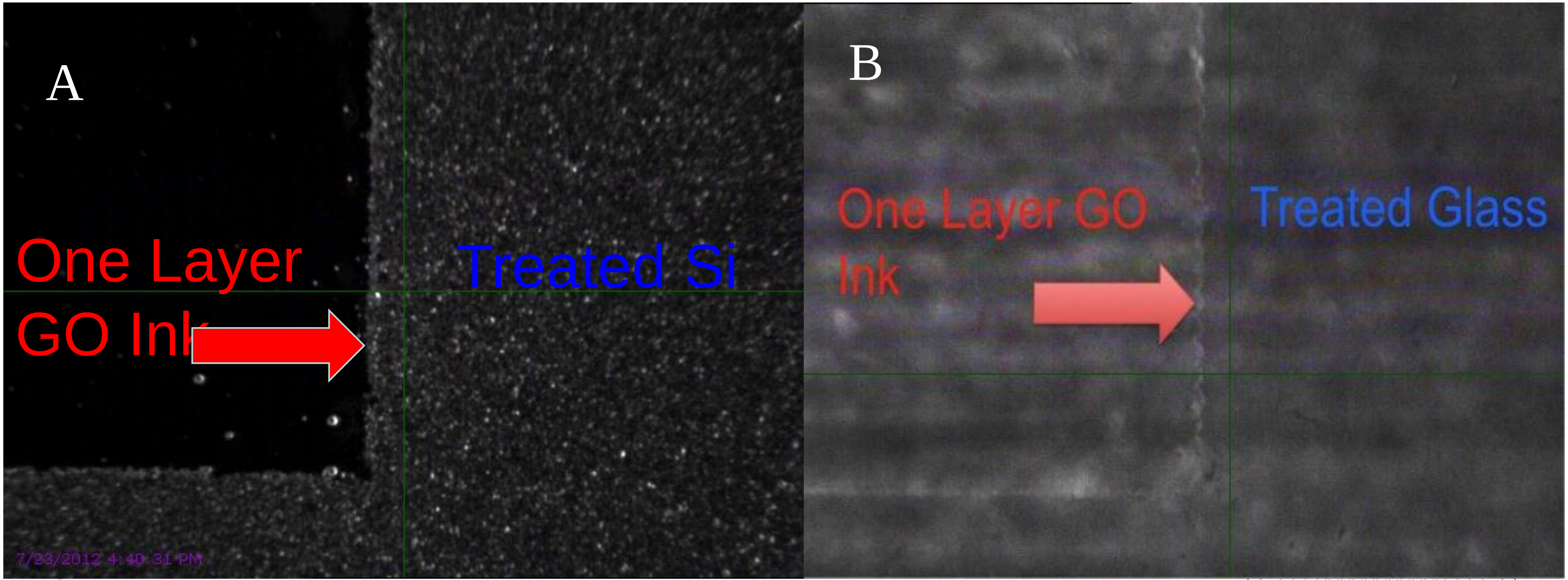
Printed Dielectrics For Multi-Layer Passives/Actives

- Inkjet Multi-Layer Process
  - Metal/Dielectric/Via layers (All Printed)
  - Post-Processing on-chip antennas/interconnects
  - MEMS
  - MIM Caps
  - Transistor Gates
  - Substrate Surface Energy Modification



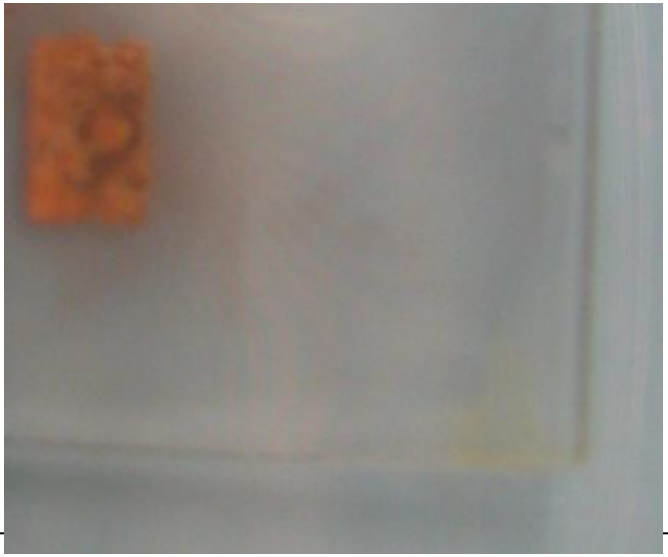
Inkjet Printing on Si/Glass

Surface modification enables inkjet printing on silicon/glass that was not possible before.



Inkjet Printing on Si/Glass

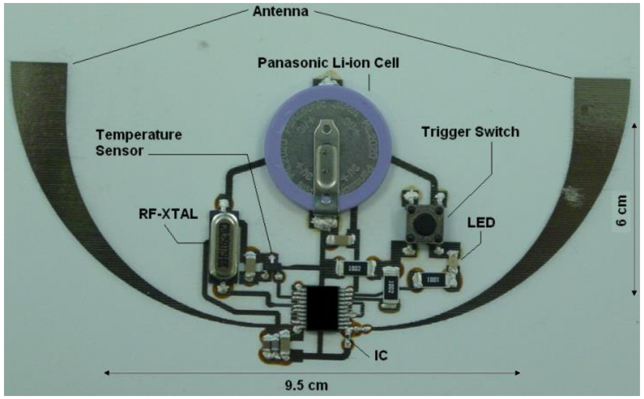
Cu as well as some other metals such as Au, Ag, Pd, Ni and Co can be printed on Si/glass in our novel approach by combining inkjet printing technology and electroless deposition.

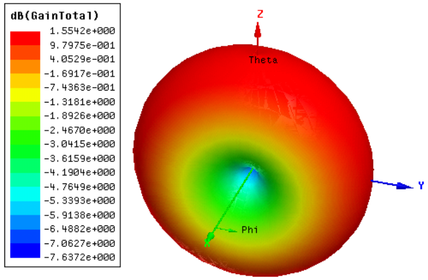


A Cu pattern printed on glass slide

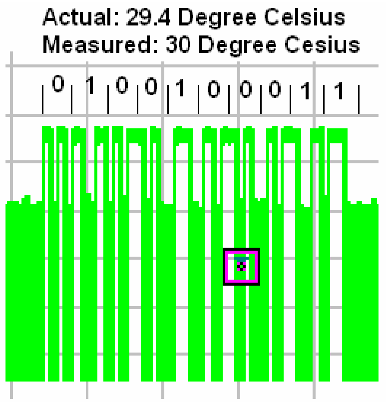
Wireless Sensor Module: 904.2 MHz

- Single Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.2 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for remote operation
- Maximum Range: 1.86 miles

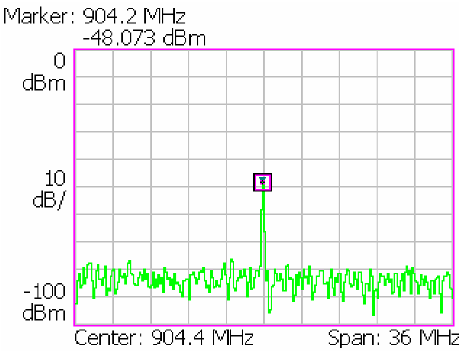




Antenna Radiation Pattern showing high gain



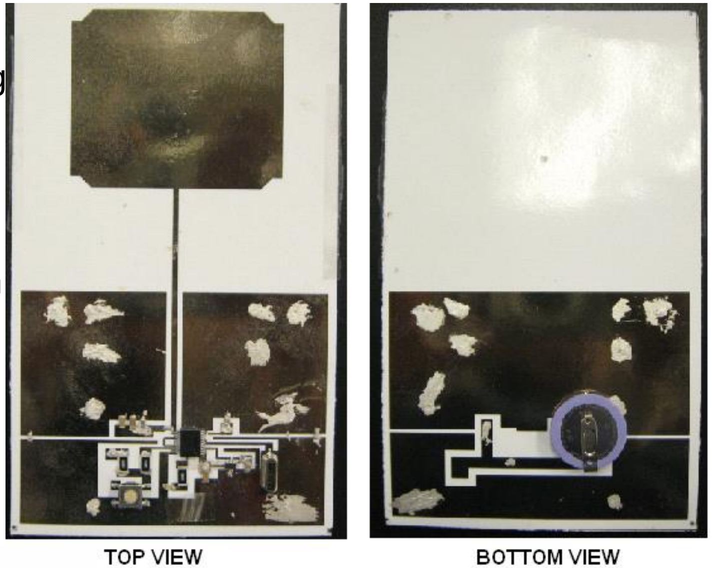
Wireless Temperature Sensor Signal sent out by module, measured by Spectrum Analyzer



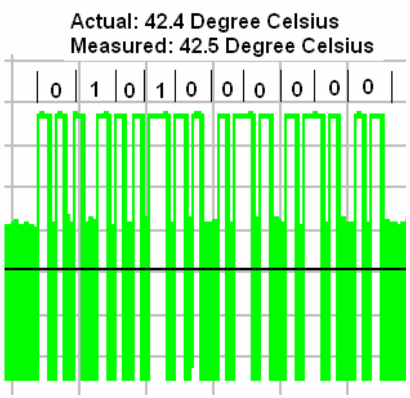
Wireless Signal Strength sent out by module, measured by Spectrum Analyzer

Wireless Sensor Module: 904.5 MHz

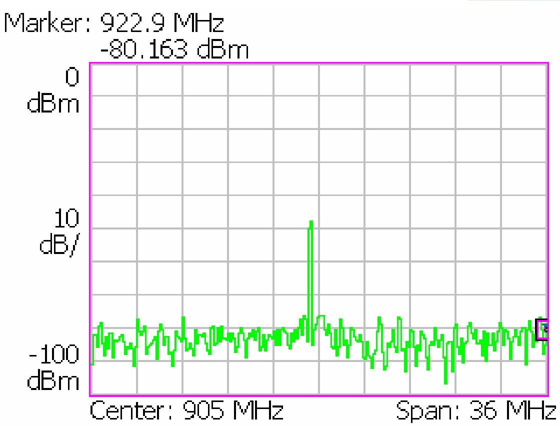
- Double Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.5 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for remote operation
- Maximum Range: < 8 miles



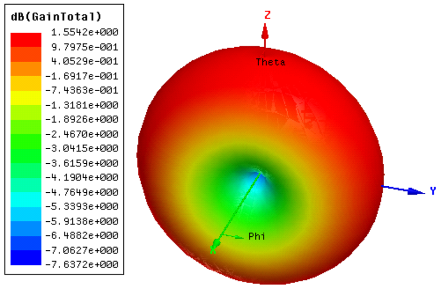
Circuit + Sensor+ Antenna on Paper



Wireless ASK modulated Temperature Sensor Signal sent out by module, measured by Spectrum Analyzer



Wireless Signal Strength sent out by module, measured by Spectrum Analyzer



Antenna Radiation Patter showing high gain

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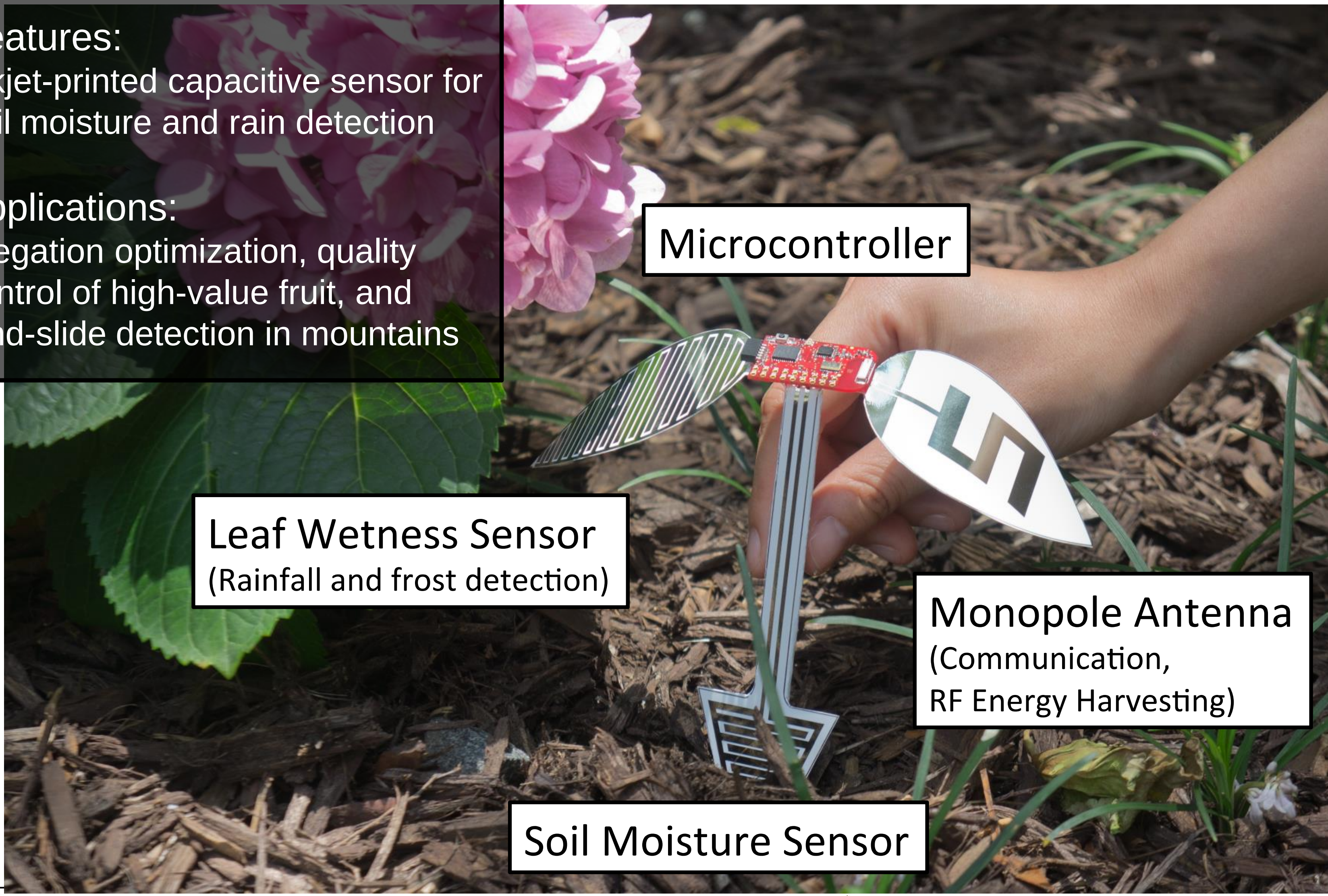
SenSprout: Inkjet-Printed Soil Moisture and Leaf Wetness Sensor

Features:
Inkjet-printed capacitive sensor for soil moisture and rain detection

Applications:
Irregation optimization, quality control of high-value fruit, and land-slide detection in mountains



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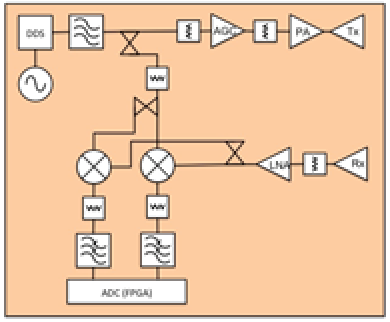
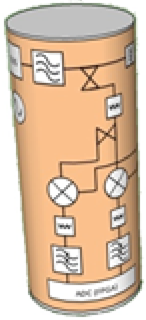
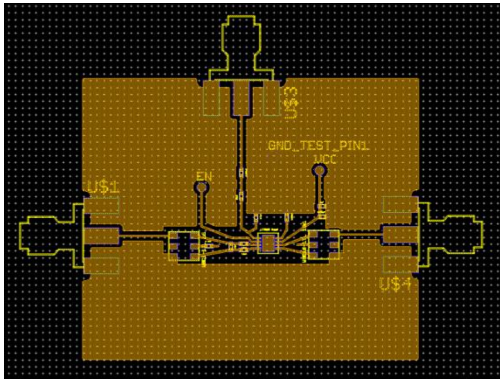
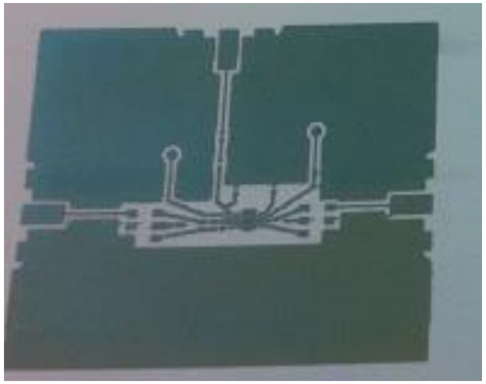
Inkjet-Printed Radar on Flexible Substrates

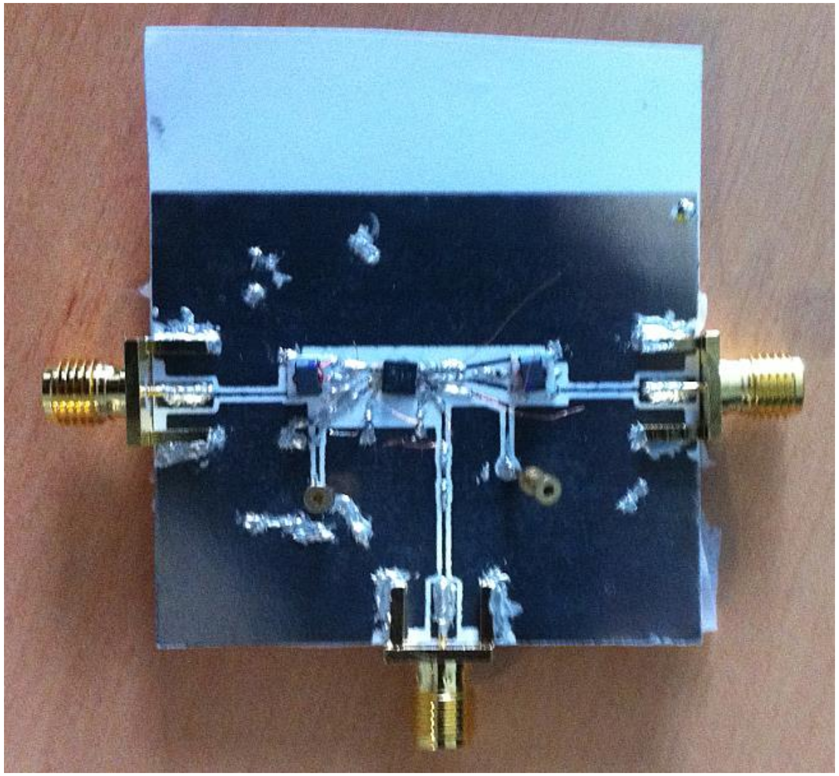
(headed by A.Traille (Doctorant-LAAS) and Prof. H.Aubert (LAAS))











A.Traille, A.Coustou, H.Aubert, S.Kim and M.M.Tentzeris,“Monolithic Paper-Based & Inkjet-Printed Technology for Conformal Stepped-FMCW GPR Applications”, accepted for Podium Presentation to the 2013 European Microwave Week, Nurnberg 2013

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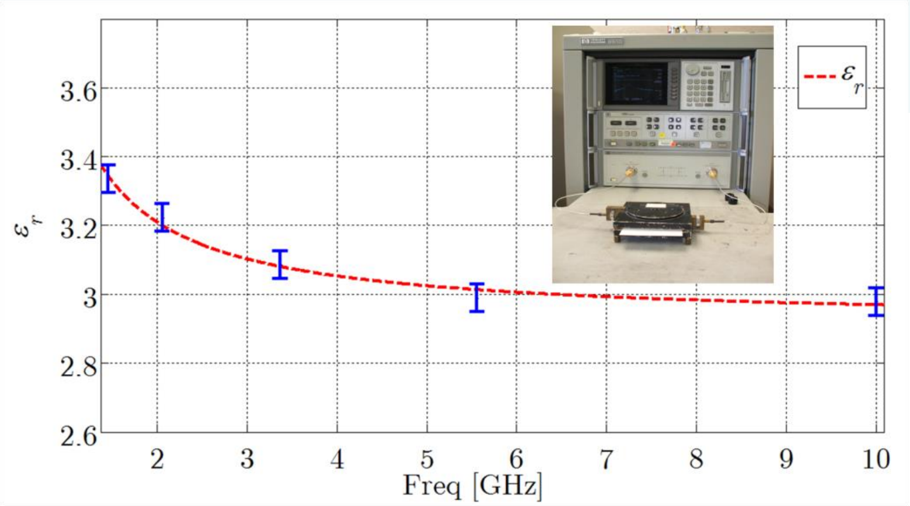
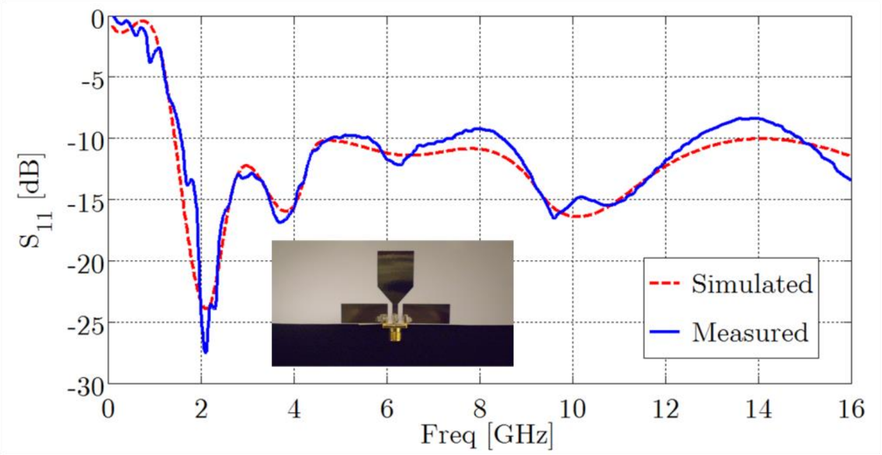
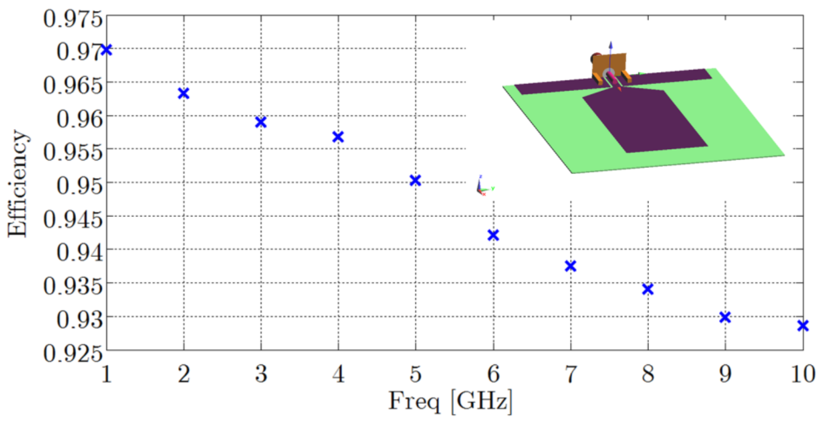
UWB Inkjet-Printed Antennas on Paper: Is it possible?







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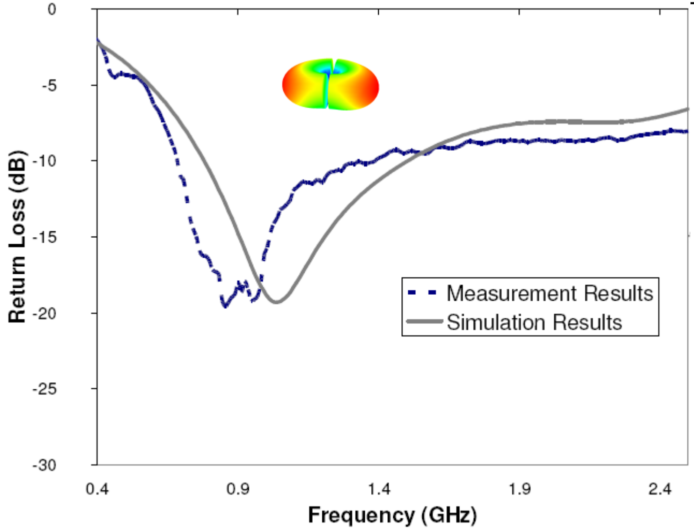
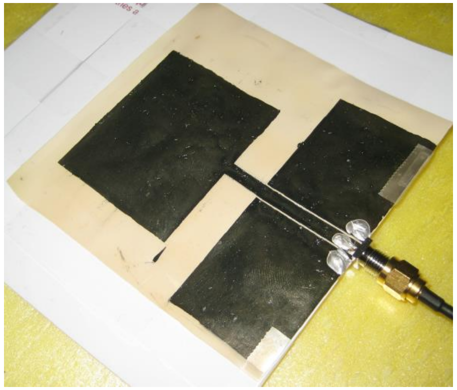
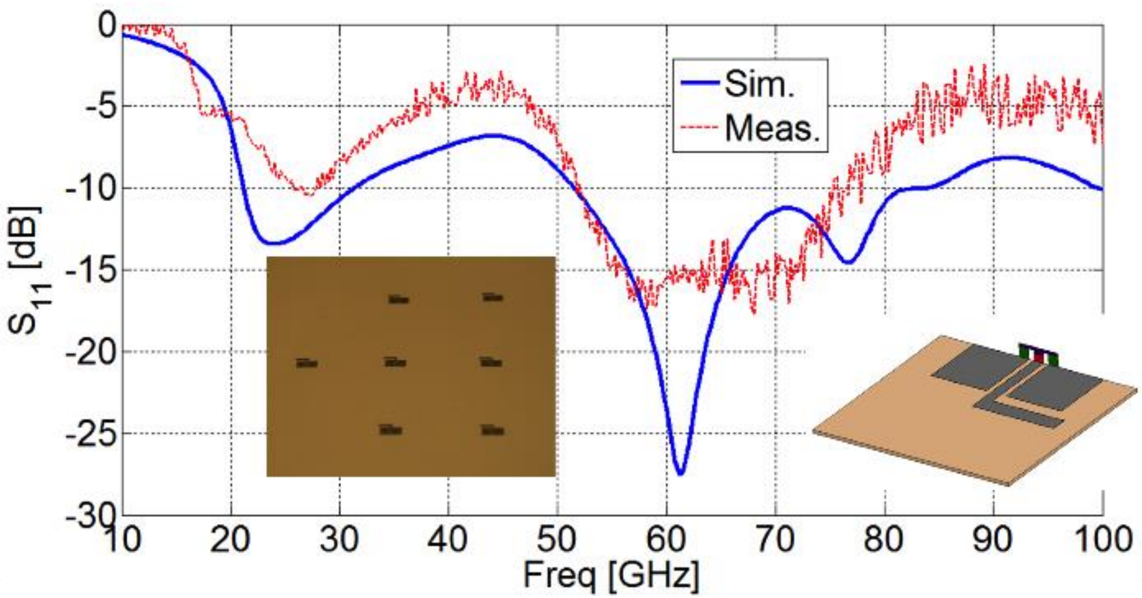
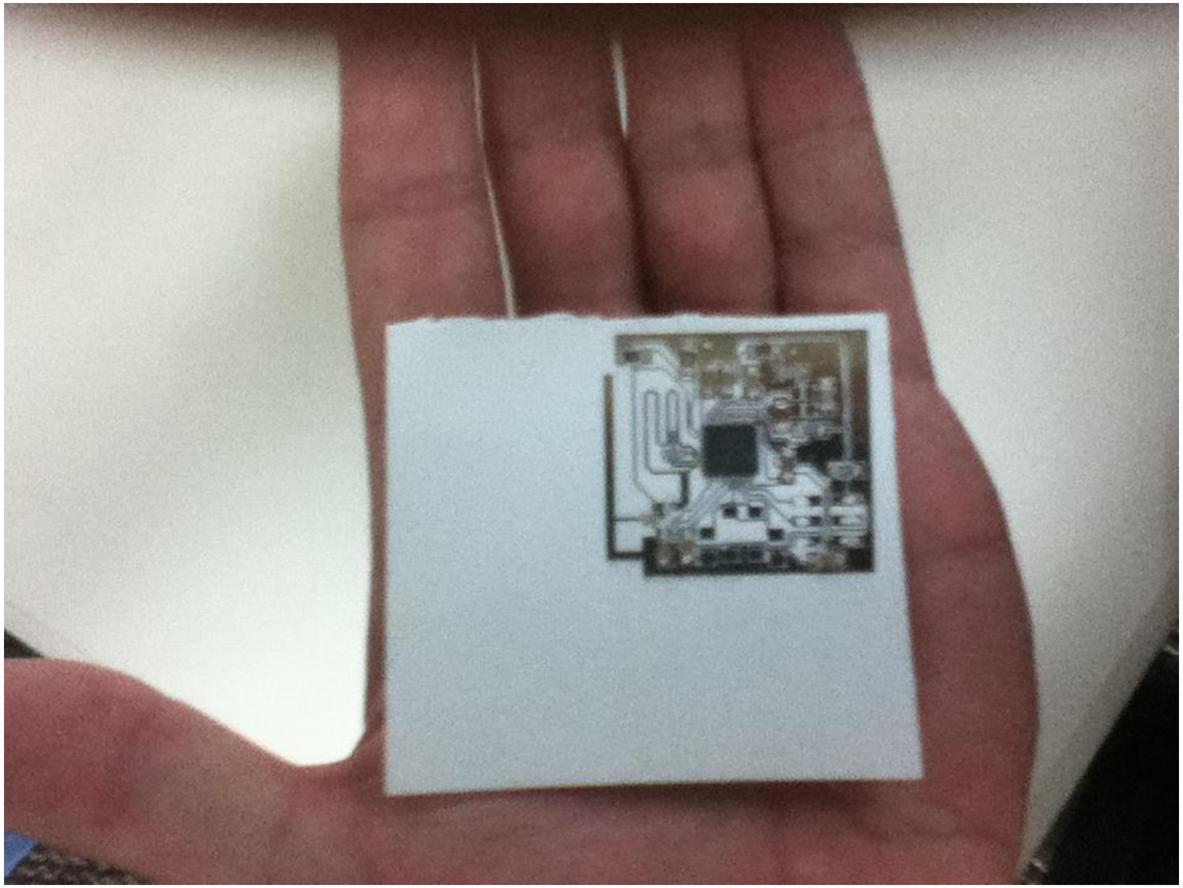
Inkjet Printing on LCP: Up to mm-Wave Frequencies





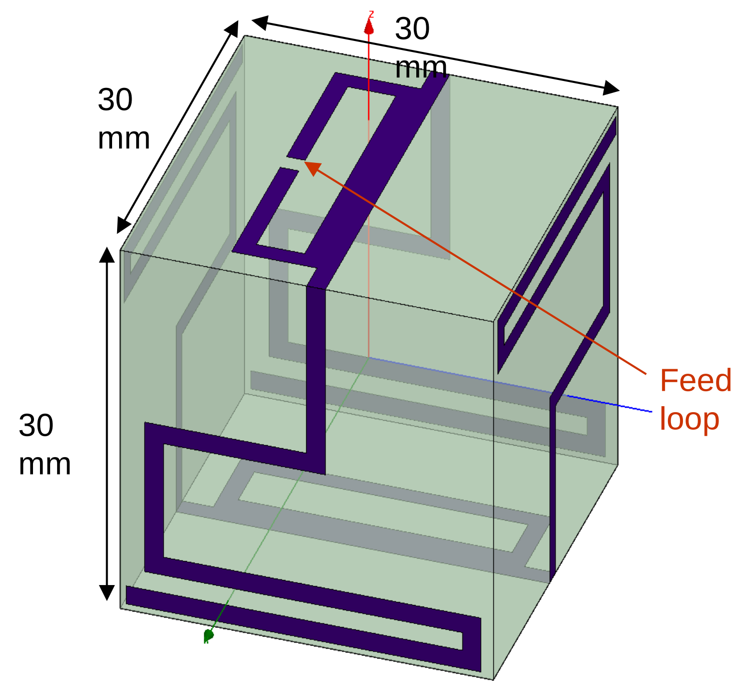


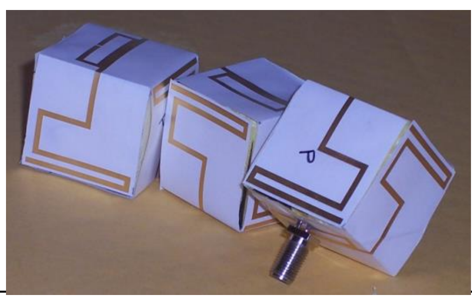
Working prototype

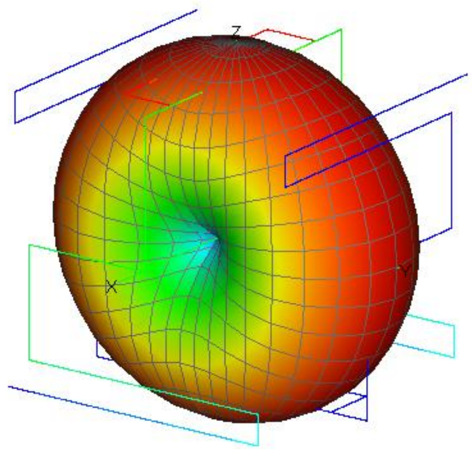


3D-"Magic Cube" Antennas

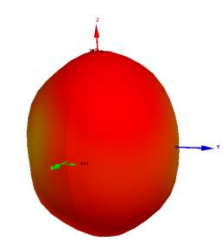
- Typical RFID/Wireless Sensor antennas tend to be limited in miniaturization by their length
- What if used a cube instead of a planar structure to decrease length dimension?
- Interior of cubic antenna used for sensing equipment as part of a wireless sensor network
- Can lead to the implementation of UWB sensors and the maximization of power scavenging efficiency, potentially enabling trully autonomous distributed sensing networks





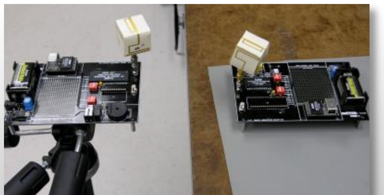


The first trully 3D maximum power-scavenging antenna on paper

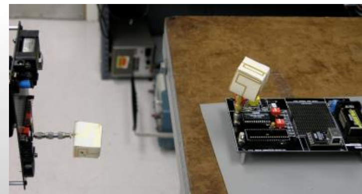


Experimental Set-Up

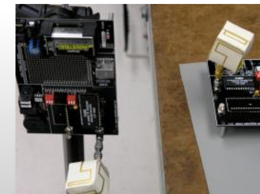
ORIENTATION #1



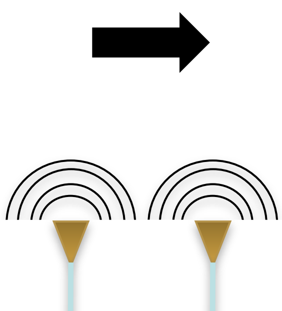
ORIENTATION #2



ORIENTATION #3

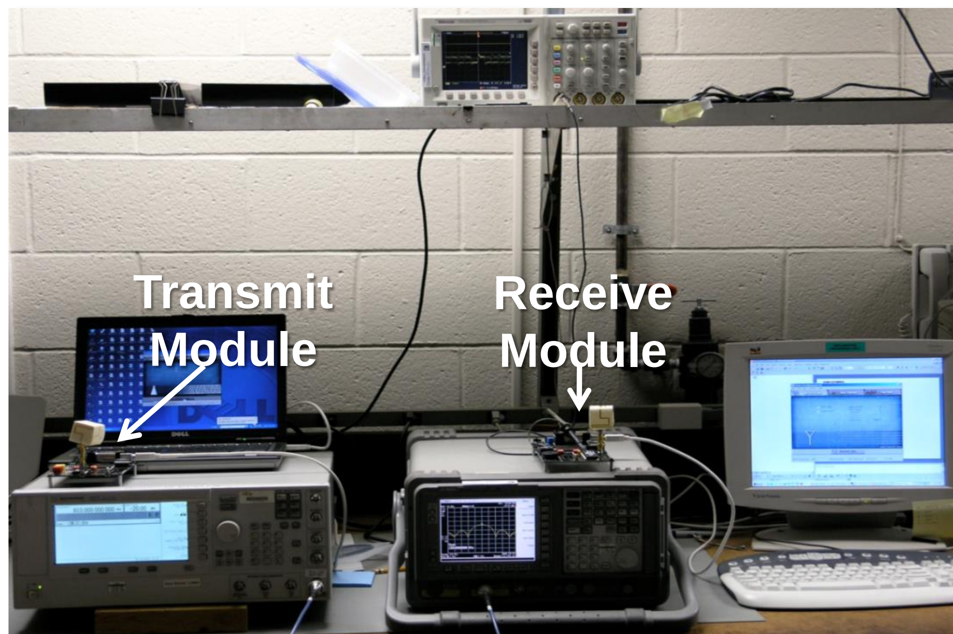


Tx and Rx co-polarized | **Tx and Rx orthogonal** | **Tx and Rx random**



TX RX

Orientations



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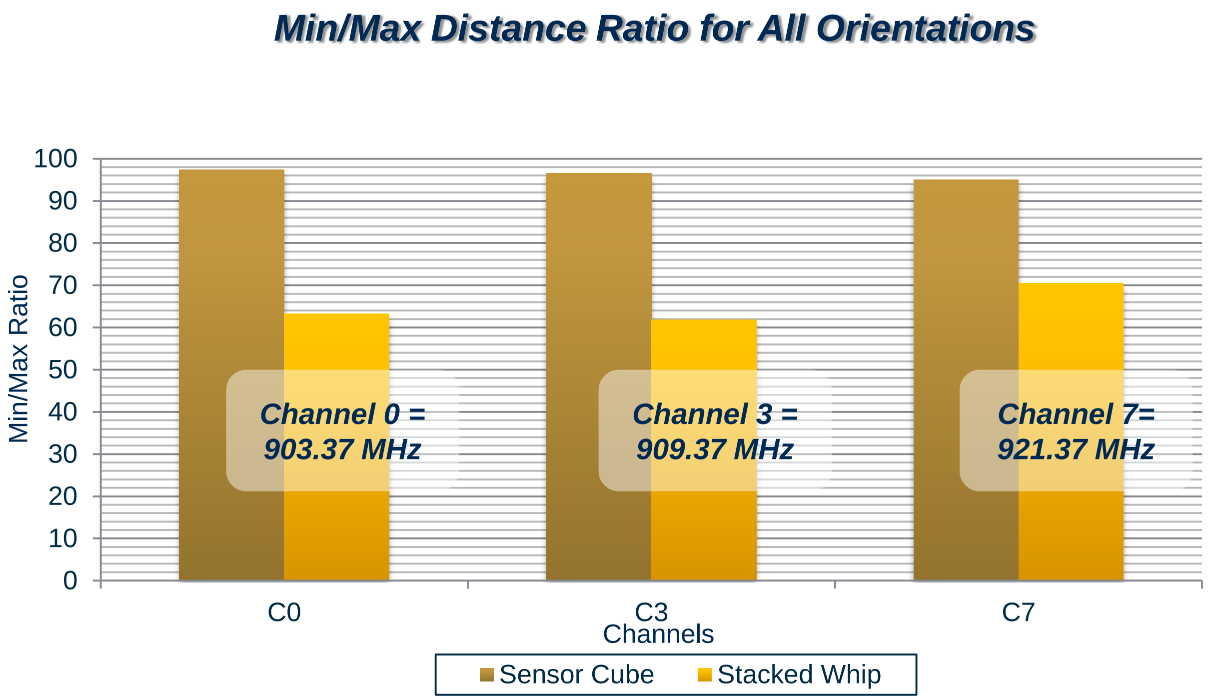
Outdoor Range Measurement

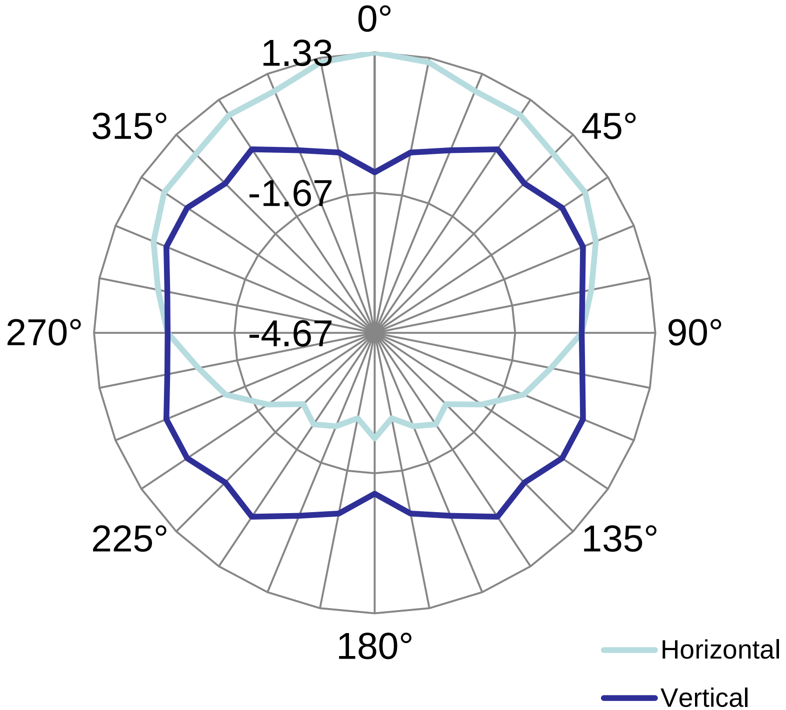


- **Maximum Whip-Whip Distance is 0.12 miles**
- **Maximum Cube-Cube Distance is 0.116 miles**

More variability with orientation for the whip antenna (65% vs. 95% for the cube antenna)

Isotropic Radiator

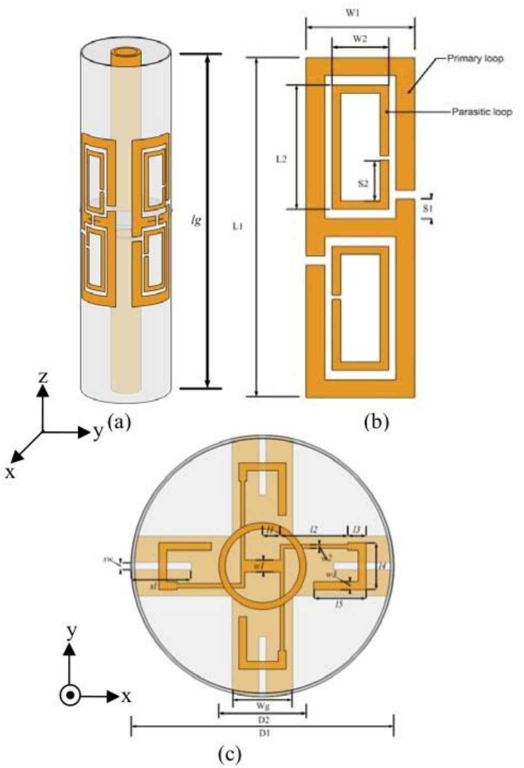
Radiation Pattern of 915MHz Printed Antenna Folded Around FSS Cube

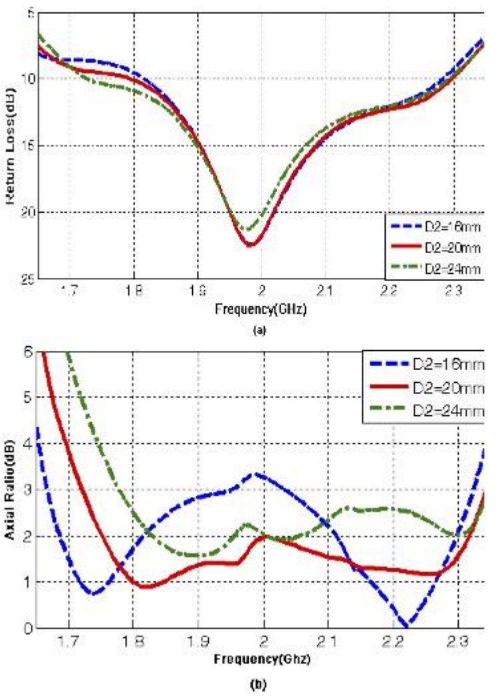


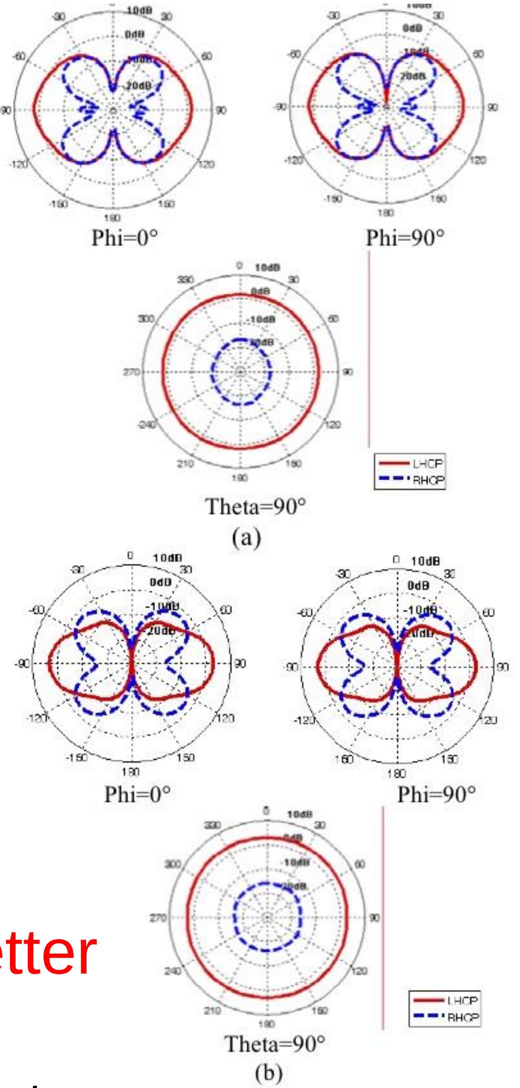
Horizontal Orientation

Vertical Orientation

Omnidirectional Broadband CP Antenna







The first CP Antenna with

30%+ AR Bandwidth (10x better than state of the art)

Also: omni, flex independent

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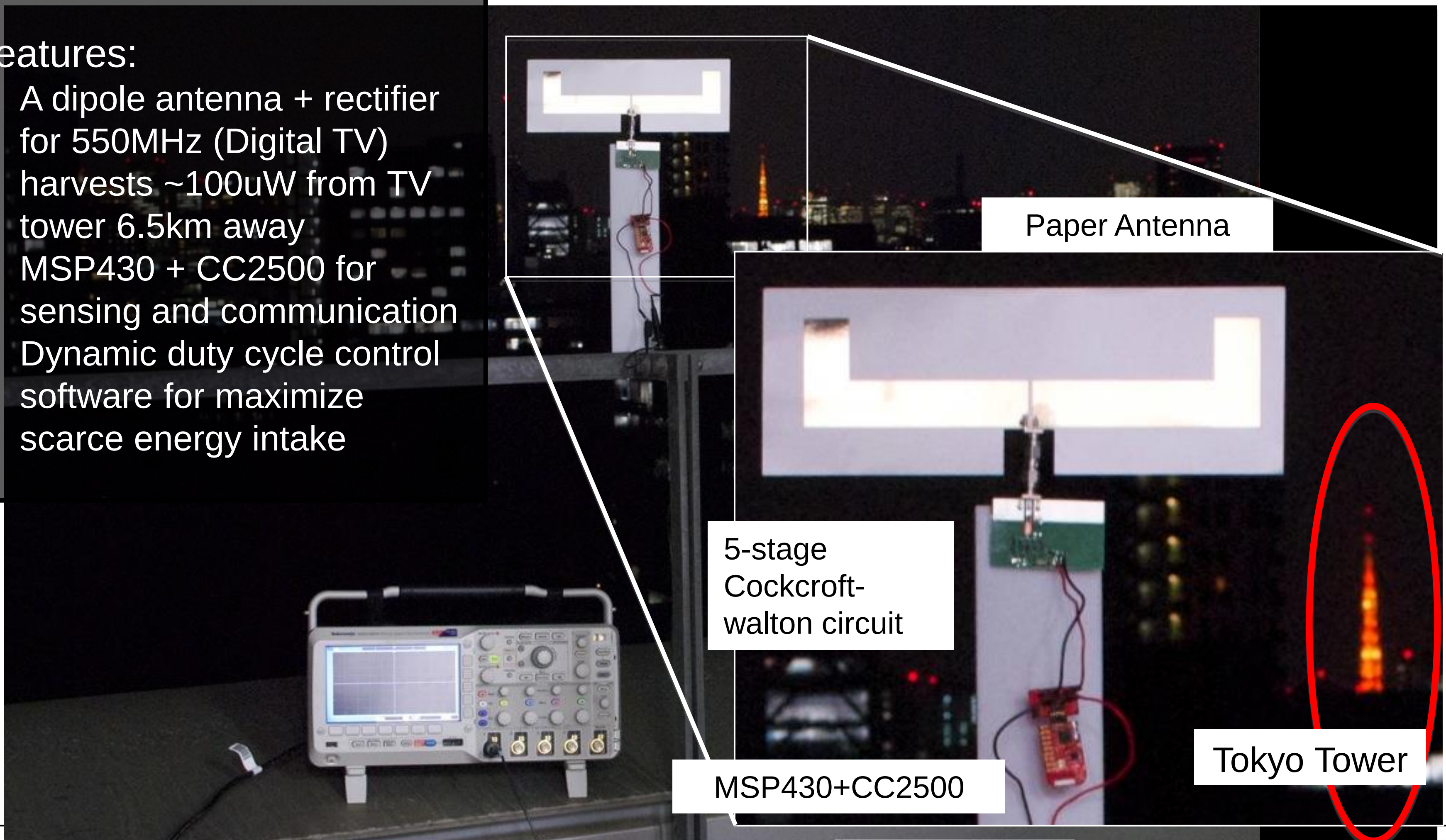
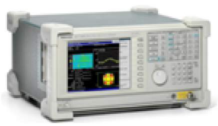
“Autonomous” Wireless Sensor Node Powered by RF Energy Harvesting

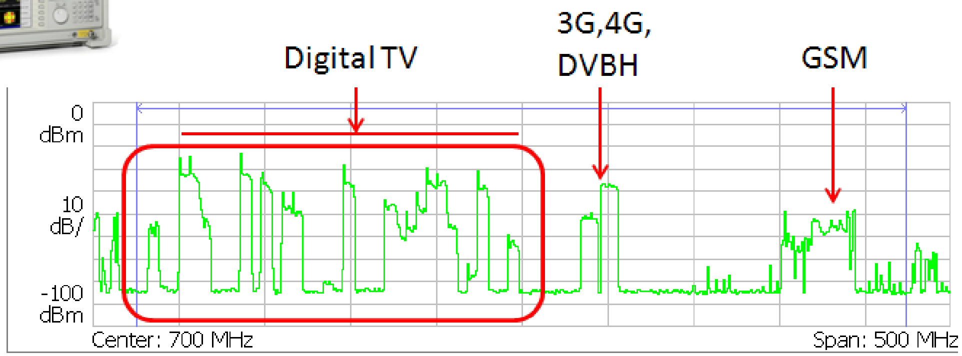
Features:

- A dipole antenna + rectifier for 550MHz (Digital TV) harvests ~100uW from TV tower 6.5km away
- MSP430 + CC2500 for sensing and communication
- Dynamic duty cycle control software for maximize scarce energy intake



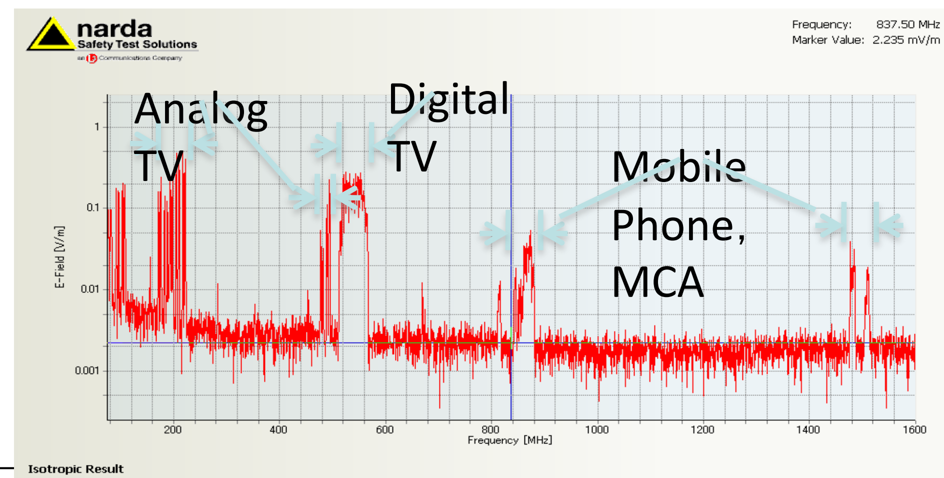
Ambient RF: How much is out there?





- Ambient RF: Atlanta

- Ambient RF: Tokyo



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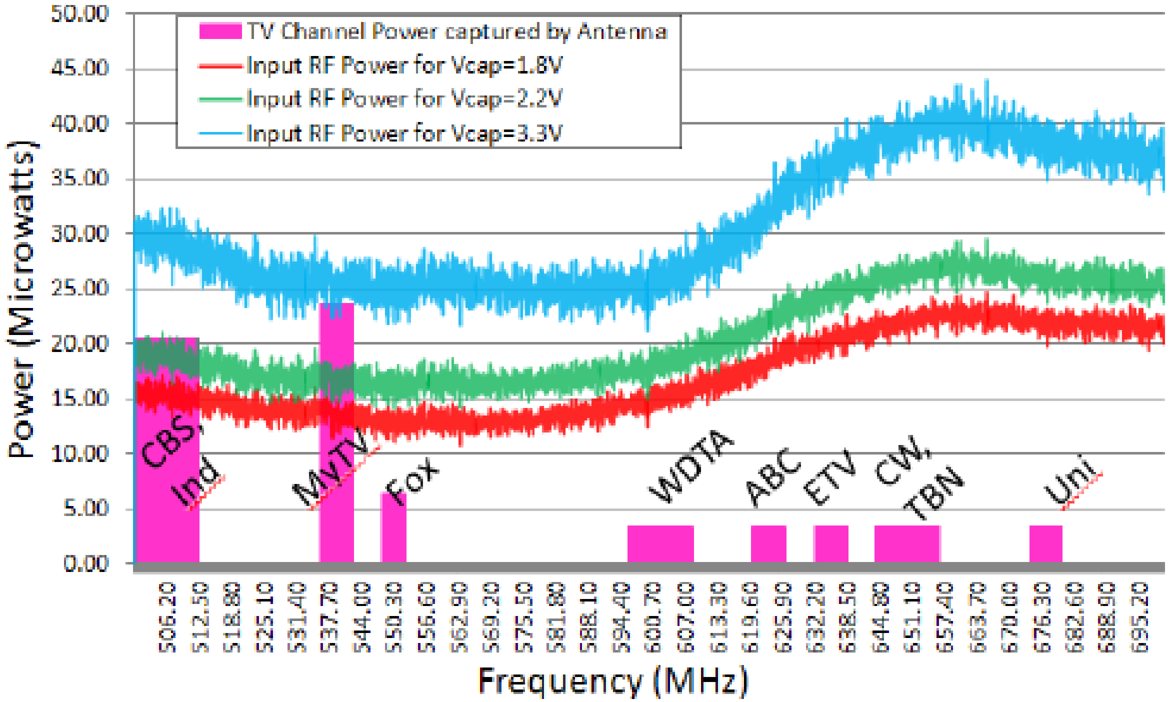
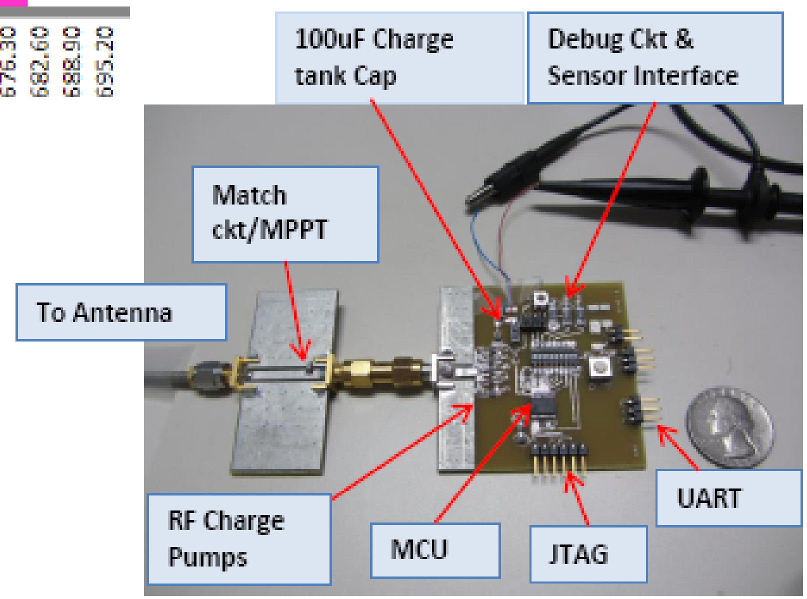
Energy Harvesting circuit to capture power from air



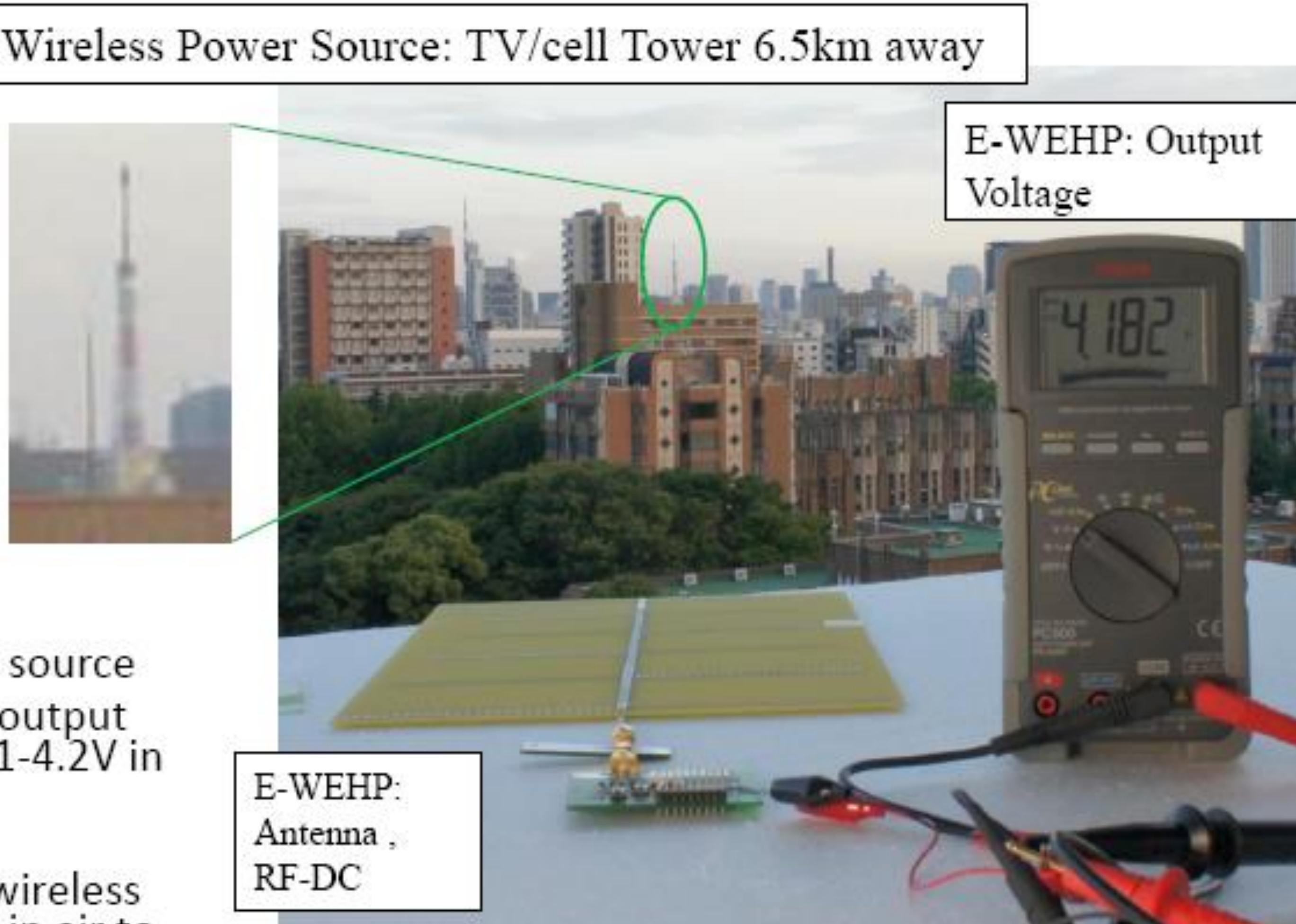
- **EH Circuit performance**
- 12 μ-watts of wireless power -> 1.8V DC out
- 17 μ-watts of wireless power ->2.2V DC Out
- 25 μ-watts of wireless power -> 3.3V DC out

- **EH Circuit design includes:**
  - Converts microwatts of wireless power to over 3V of DC output signal
  - No batteries - Uses Capacitor to wireless power
  - Powers up microcontroller for power management and sensing applications



- R.Vyas, B.Cook, Y. Kawahara, M. Tentzeris. *"EA Self-sustaining Autonomous Wireless Sensor Beacon Mote Powered from Long Range, Ambient RF Energy"*, accepted to IEEE International Microwave Symposium, 2013

Energy Harvester performance in field



- At 6.5 km from source
- RF-DC charges output Capacitor to 4.1-4.2V in 3mins
- Needs just 28 microwatts of wireless channel power in air to give 4.2V

- **R.Vyas, B.Cook, Y. Kawahara, M. Tentzeris .,** *"E-WEHP: An Embedded Wireless Energy Harvesting Platform for Powering on Embedded Sensors using existing, ambient digital TV Signals present in the Air"*, IEEE MTT, Nov 2012

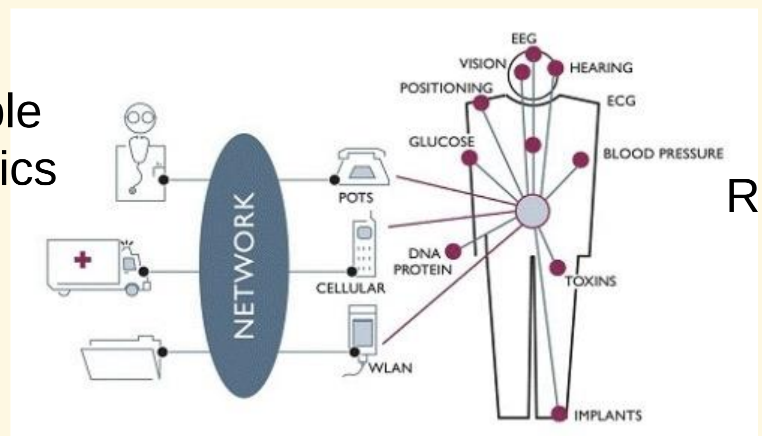
Introduction

In the new area of the **Internet of Things** the focus of this work is about..

Health Monitoring

Physical Activity Monitoring

Wearable Electronics



Rehabilitation Methods Improvements

Safety

Instantaneous data elaboration

EBG Ground Plane

- Reflection phase characteristic method
- Illuminate plane wave to the EBG ground plane
- Monitoring phase of the reflected wave (S_{11})

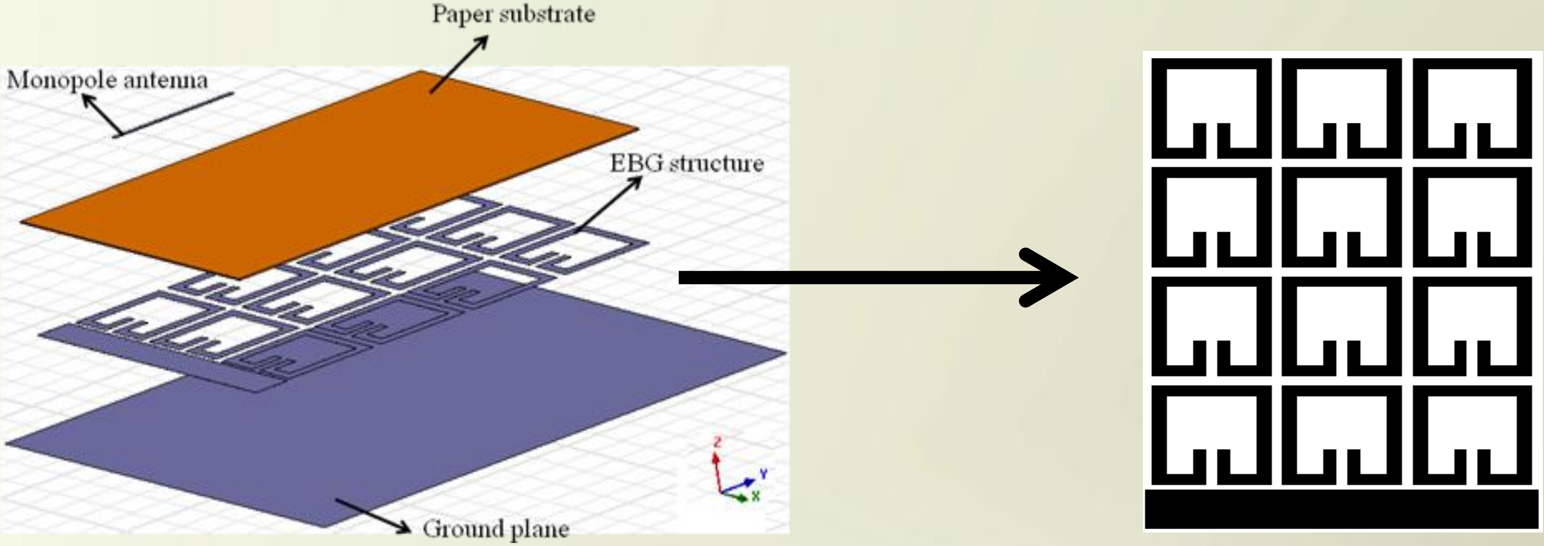


Fig6. (a) Antenna Geometry

(b) Layout of EBG surface

company logo

Communication Range Improvement

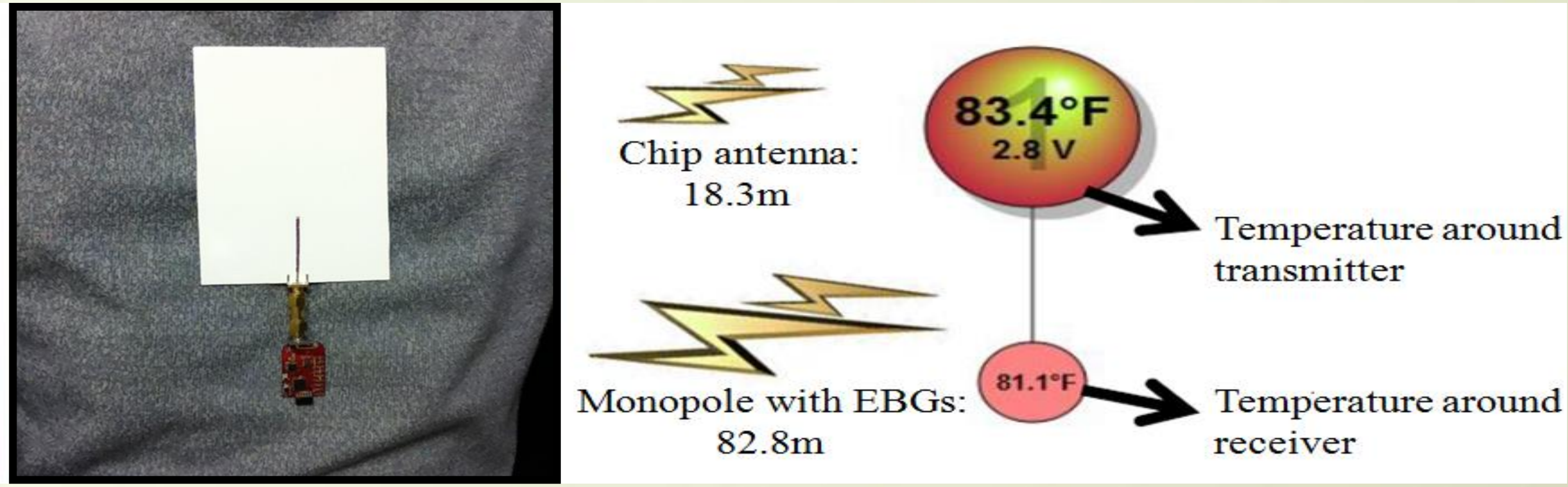
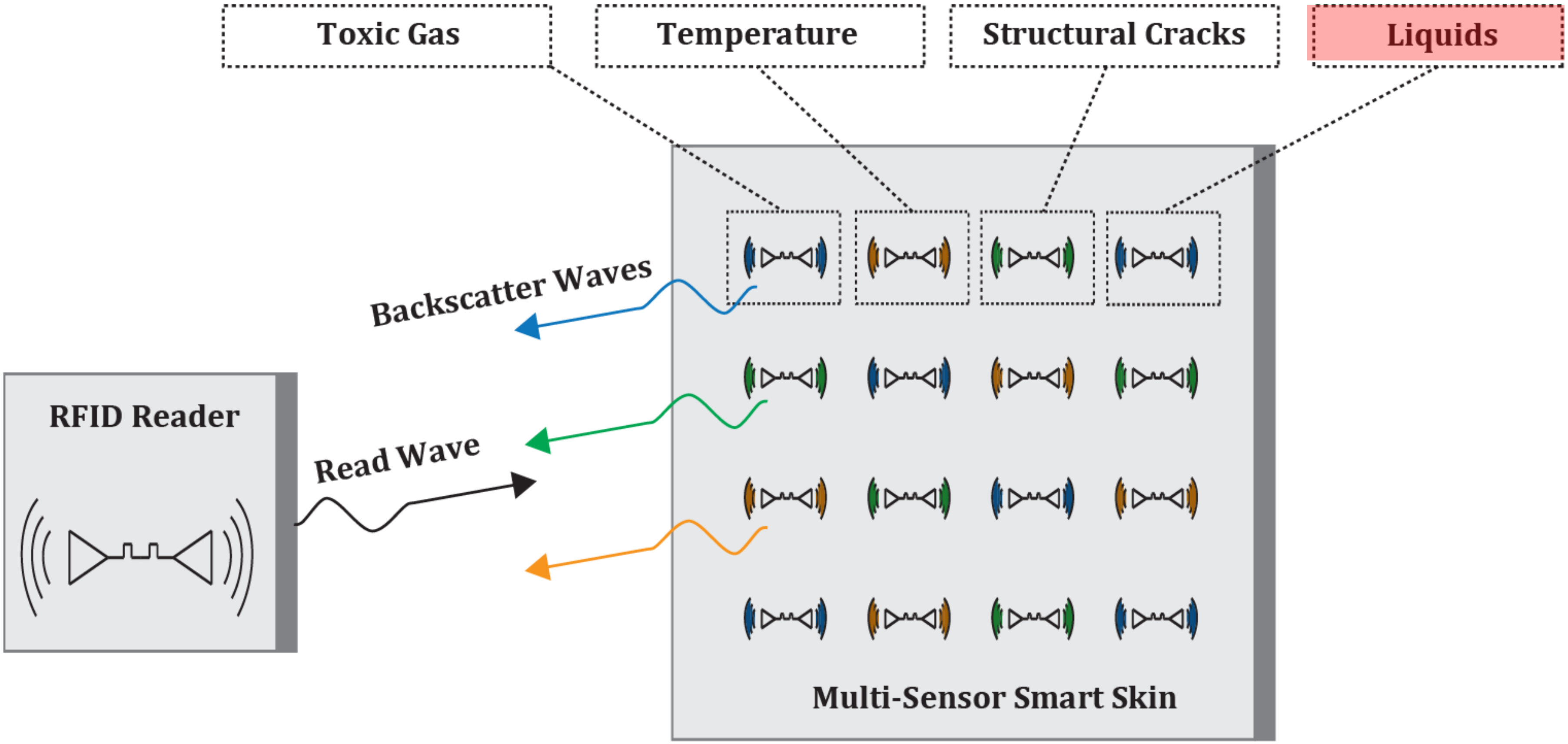


Fig13. Communication range measurement

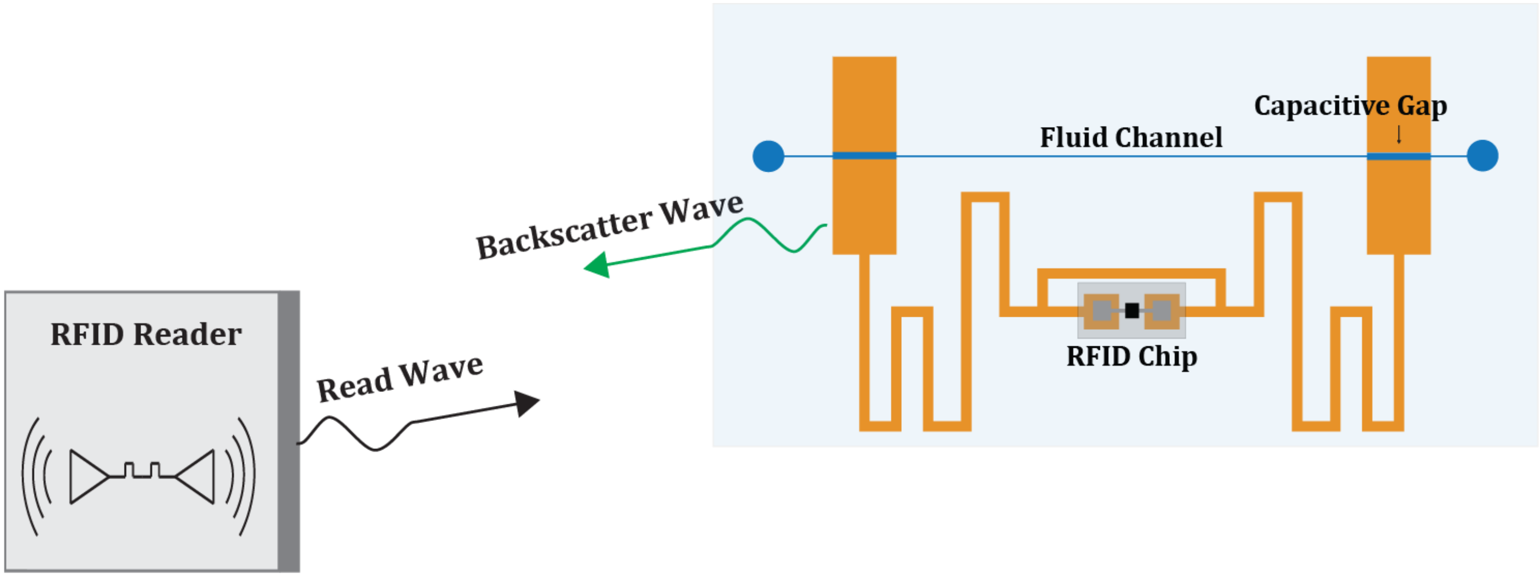
- Communication range is improved
  - Original chip antenna: 18.3 m
  - The proposed antenna: 82.8 m
- Range is increased by a factor of four

“Smart Skin” Platform

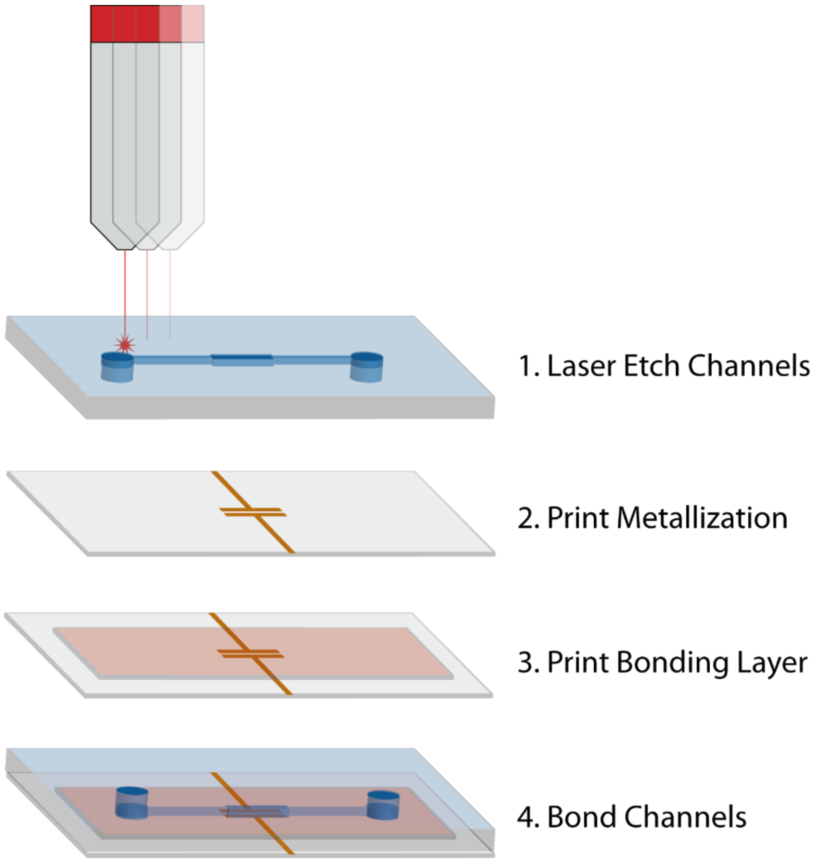


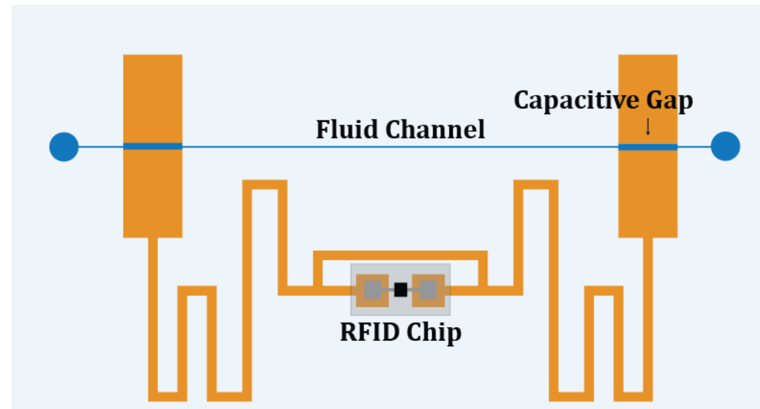
Proposed Microfluidic RFID Tag

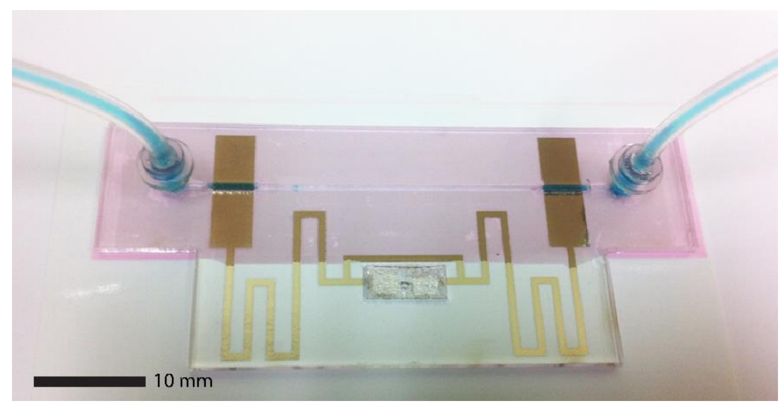
- Microfluidic-integrated RFID antenna
  - Utilizes capacitive microfluidic gap to load antenna
  - Change in fluid ε_r causes change in f_r
  - RFID chip provides digital backscatter modulation



Inkjet Microfluidic Fabrication

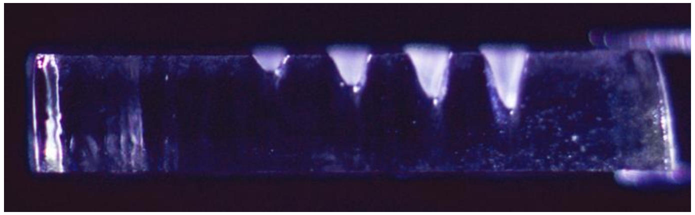




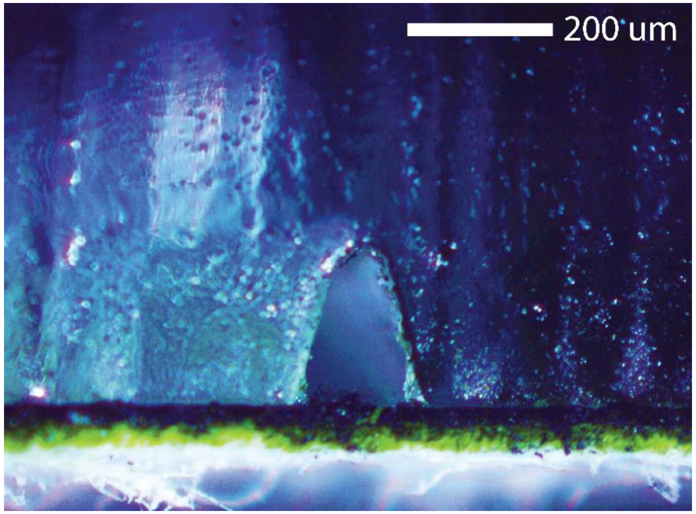


Inkjet Microfluidic Fabrication

- Laser engraved channels
  - Etch acrylic
  - Vary laser power/focus
  - Depths as low as 50 um

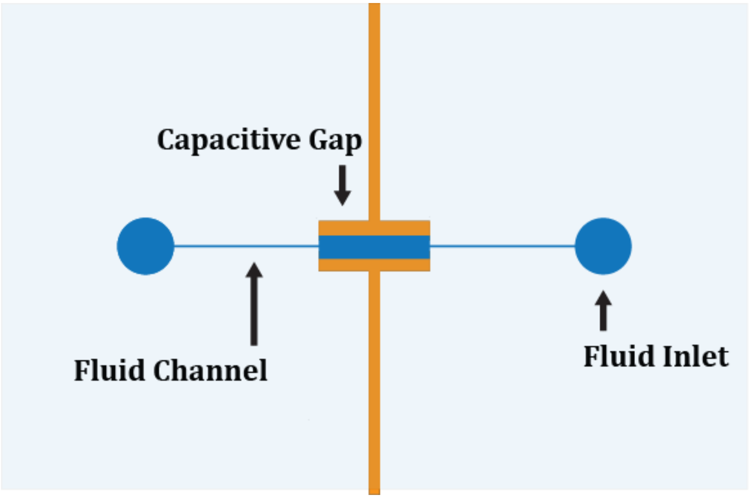


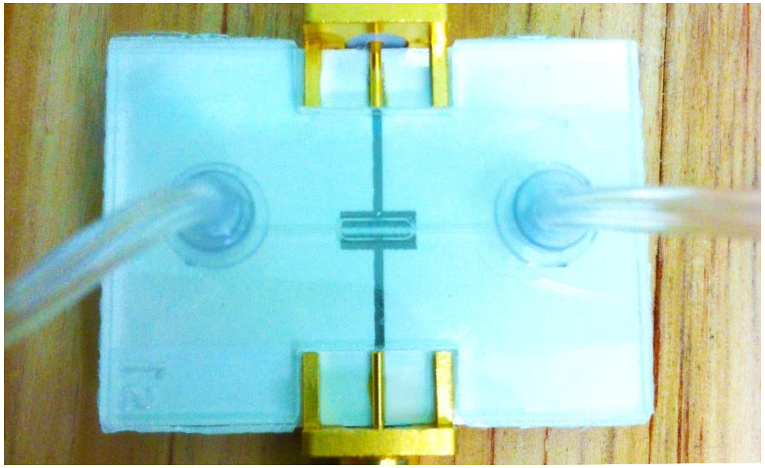
- Bonded channels
  - Ultra-thin bonding layer
  - No channel clogging



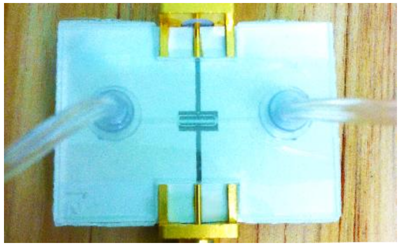
Inkjet Microfluidic Varactor

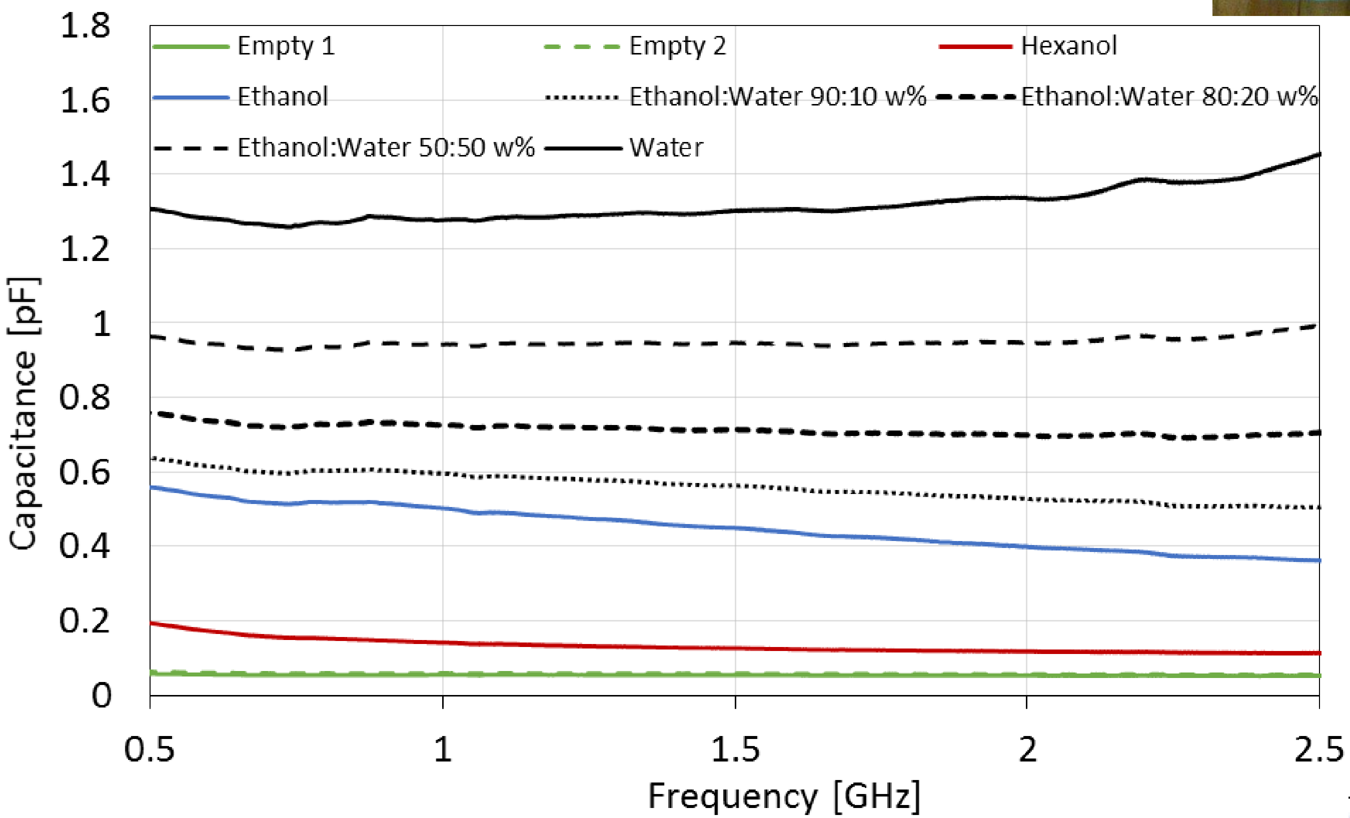
- Fabricate capacitor to extract gap impedance
- Requires 1 uL of fluid
- Load capacitor with:
  - 1-Hexanol (Er = 3)
  - Ethanol (Er = 15)
  - Water (Er = 73)



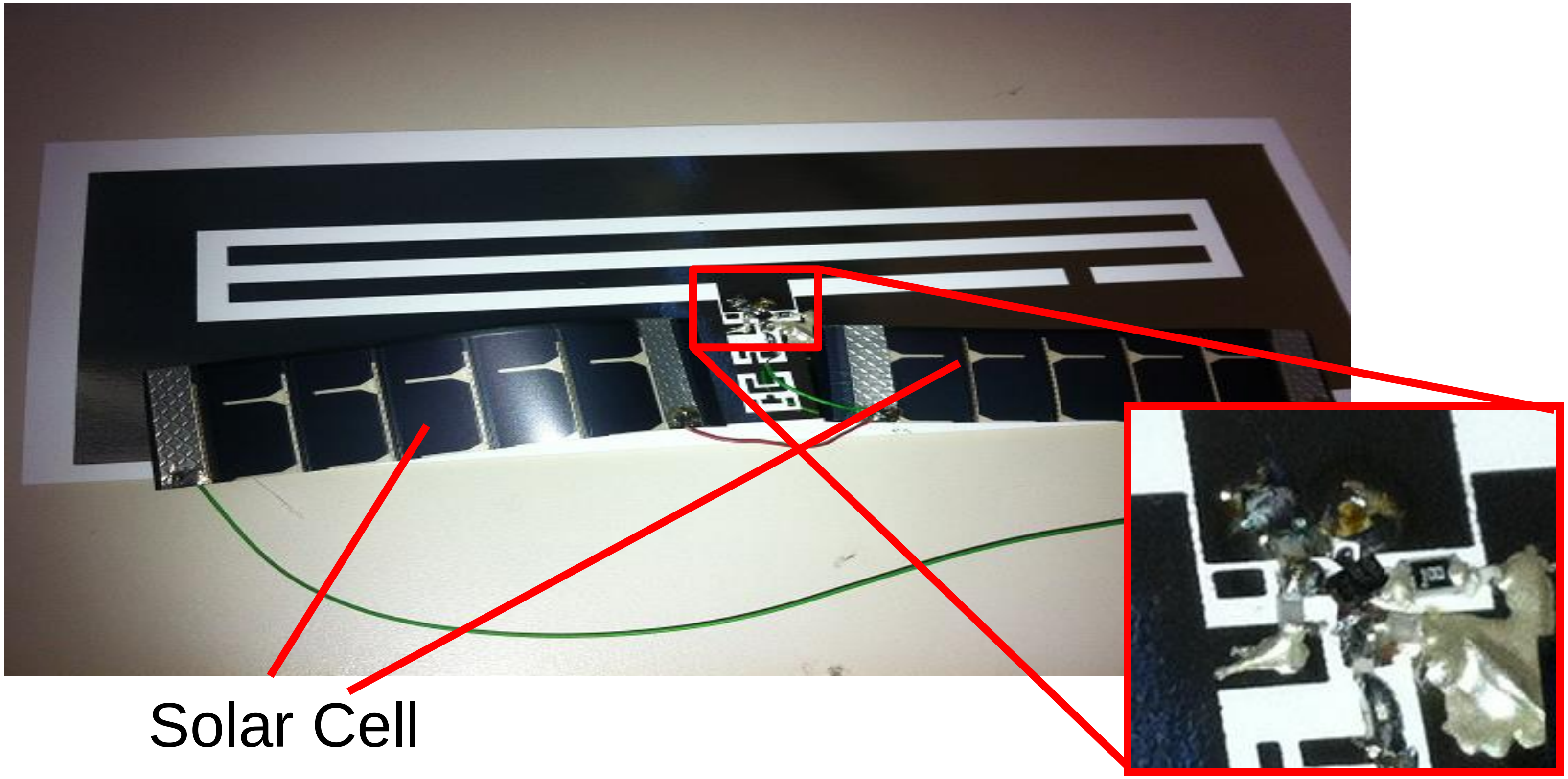


Inkjet Microfluidic Varactor





Beacon Oscillator

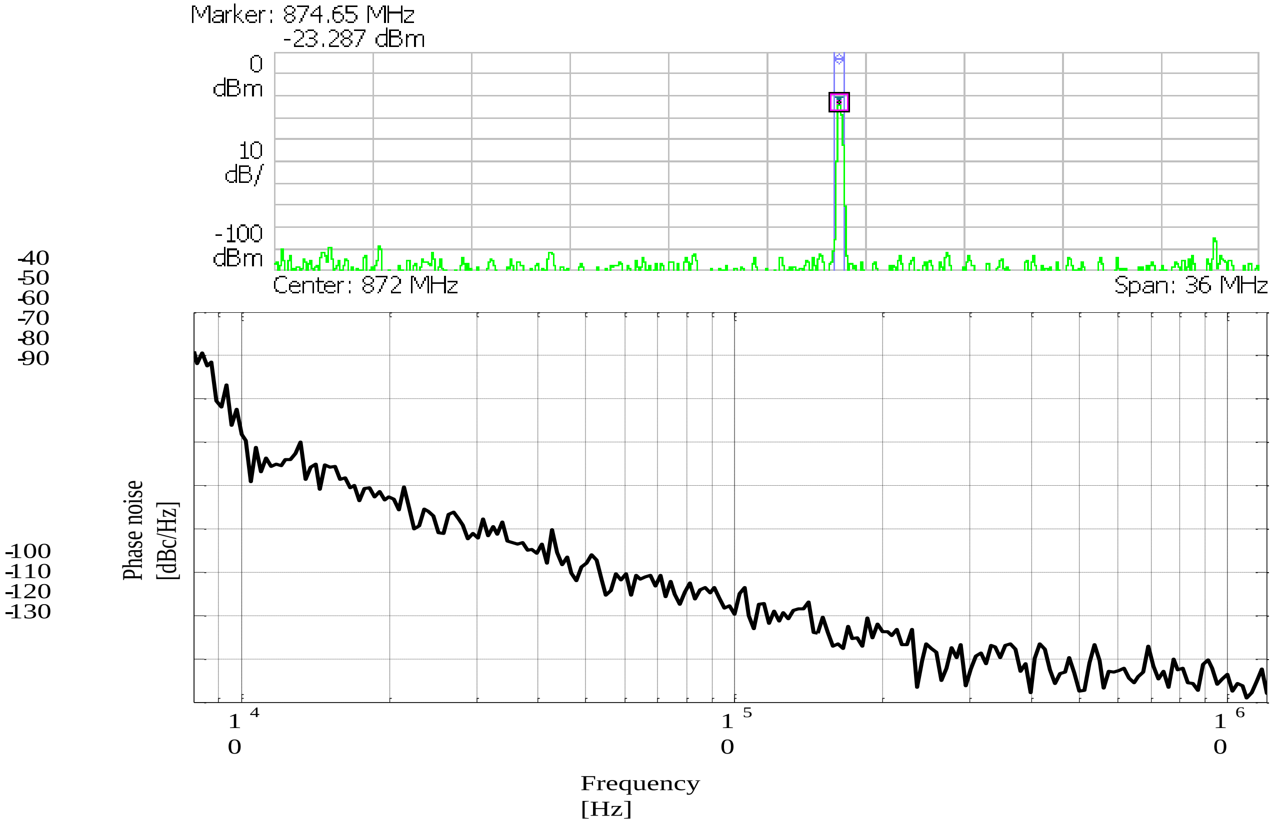


Solar Cell

Oscillator circuit

- Solar powered inkjet printed stand alone beacon oscillator
- Green environmentally friendly technology
- Localization application

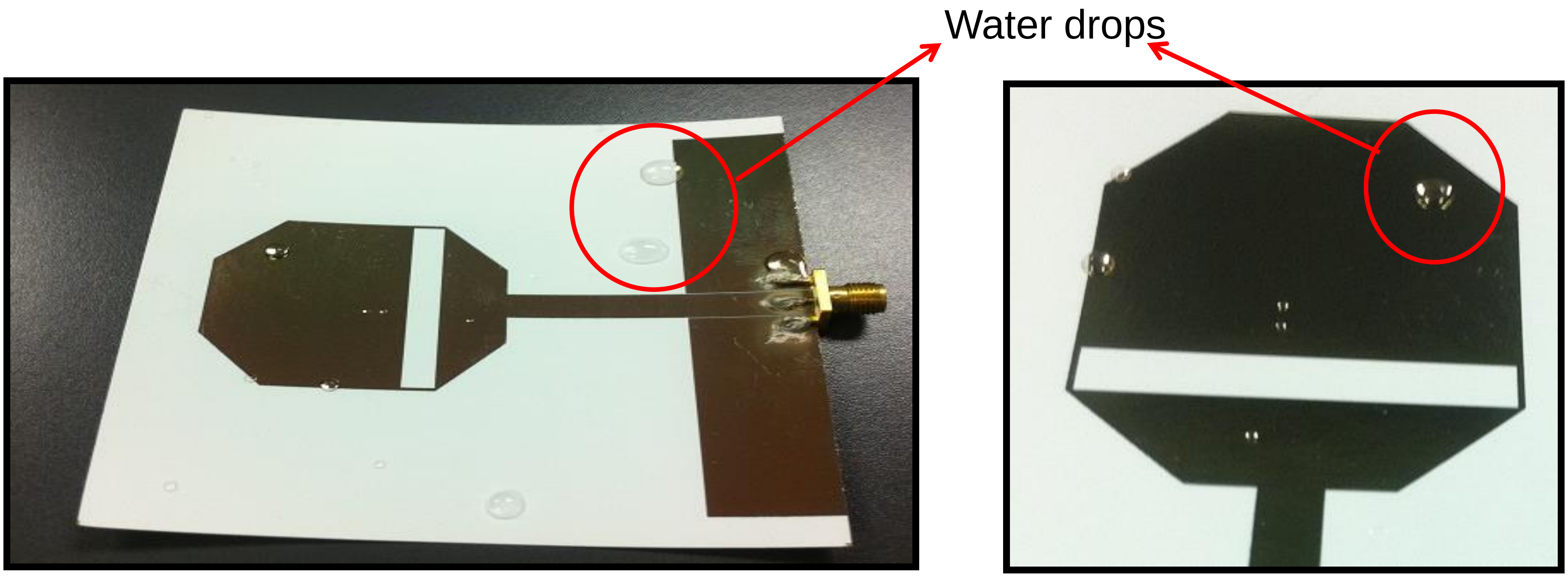
Beacon Oscillator



- The carrier frequency: 874.65 MHz
- Low phase noise: -68.27 dBc/Hz @ 10kHz from the carrier frequenc

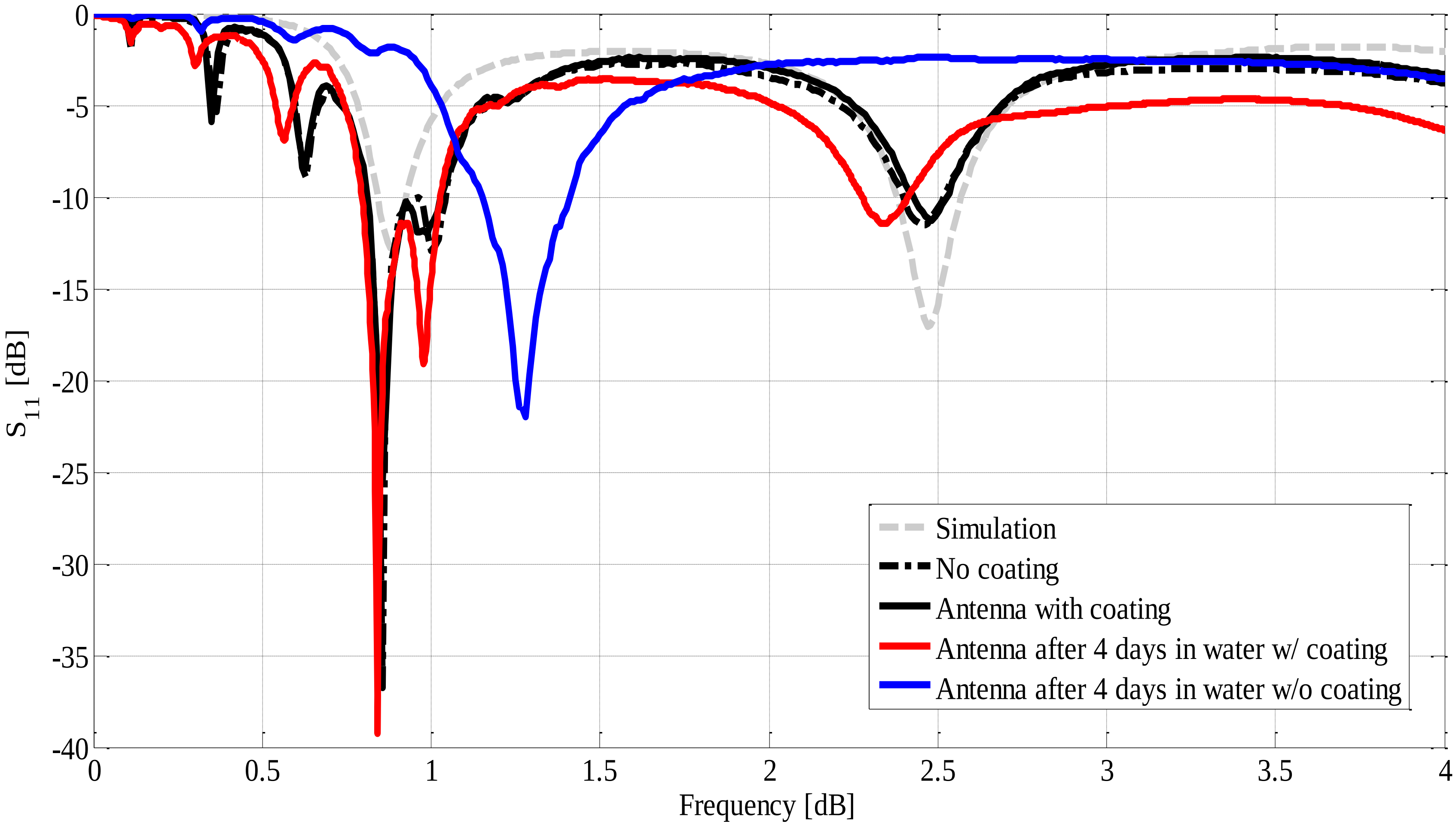
  -123.6 dBc/Hz @ 1MHz from the carrier frequer

Parylene Coating for Protection



- The antenna covers 900 MHz & 2.4 GHz
- Linearly polarized
- Parylene C type is deposited (about 1um)
- Hydrophobic & waterproof surface is created

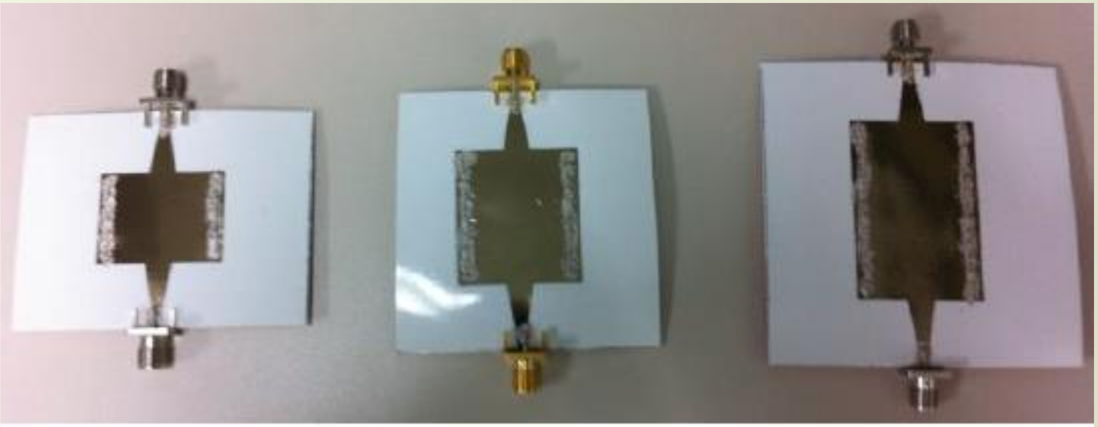
Parylene Coating for Protection



- No performance degradation after water contact

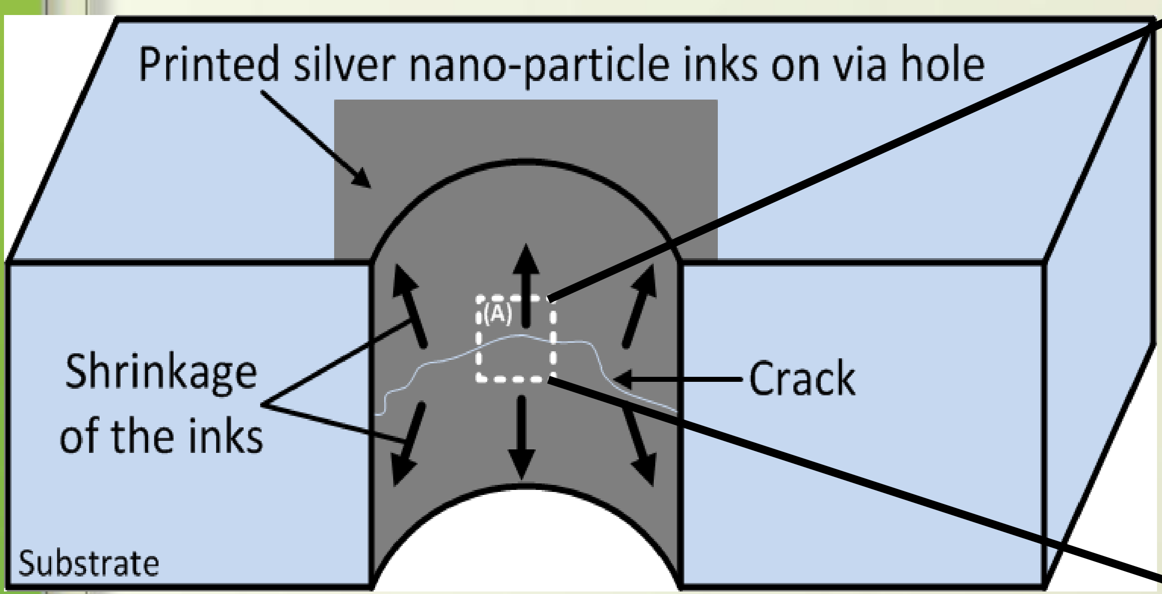
Inkjet-Printed Passives - Waveguide

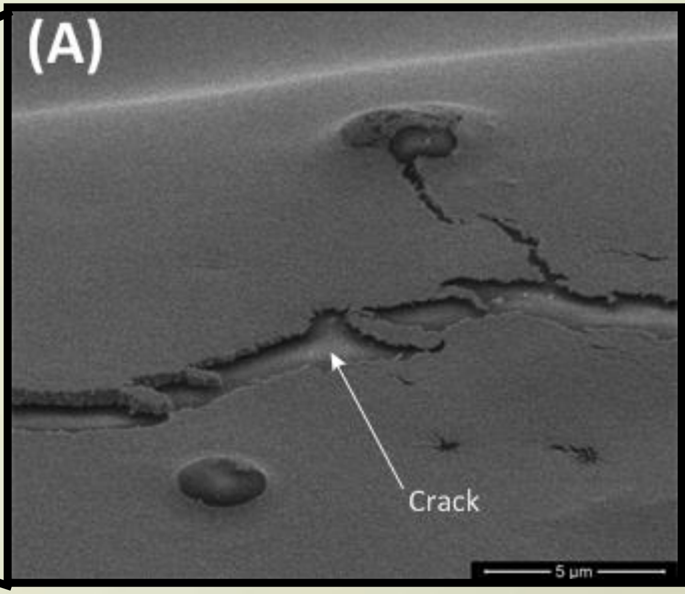
- Substrate Integrated Waveguide (SIW)
  - High system integrity
  - Innumerable applications on organic paper substrate in mmWave area
  (ex: Radar, traveling wave antenna, etc)



< SIWs in different length >

Inkjet-printed Via on Vertical Via Hole





(a) Inkjet-printed via on the vertical via hole

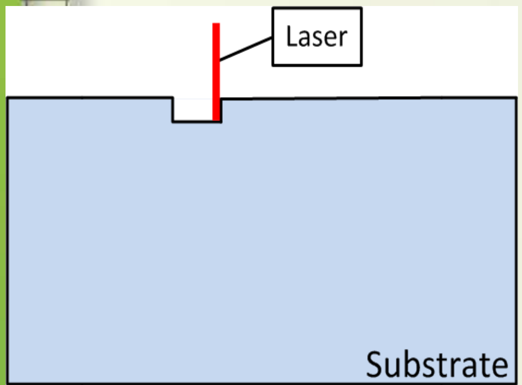
(b) SEM image of the crack

< Crack formation of inkjet-printed via on the vertical via hole >

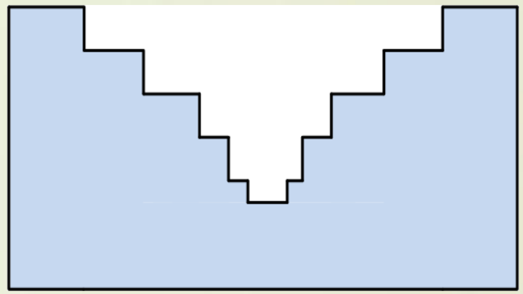
- A vertical via hole on thick substrate (> 500 μm):
  - Crack formation due to the sintering process and the gravity

company logo

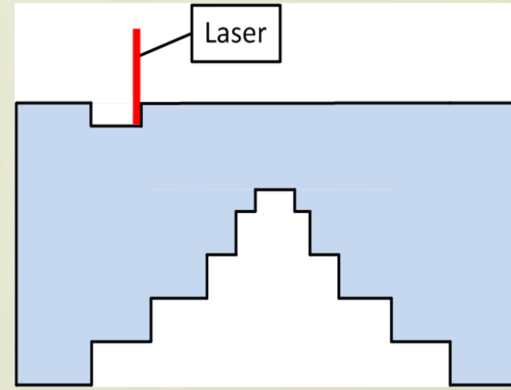
Stepped-via Fabrication



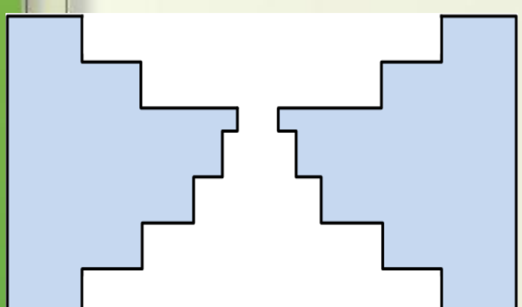
(i) Laser drilling: Top



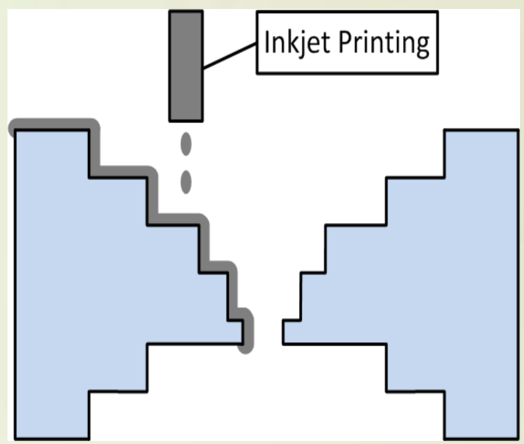
(ii) Drilled via hole: Top



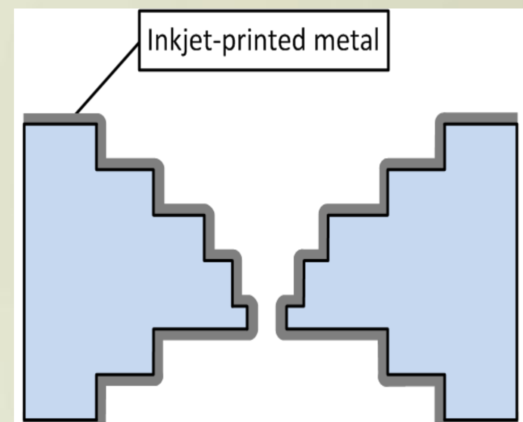
(iii) Laser drilling: Bottom



(iv) Drilled via hole: Bottom



(v) Inkjet printing & Sintering

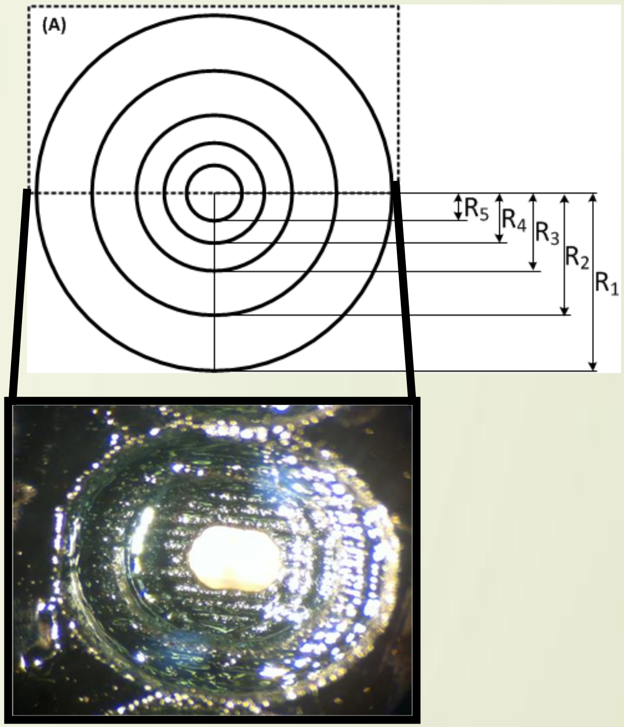


(vi) Fabricated stepped via hole

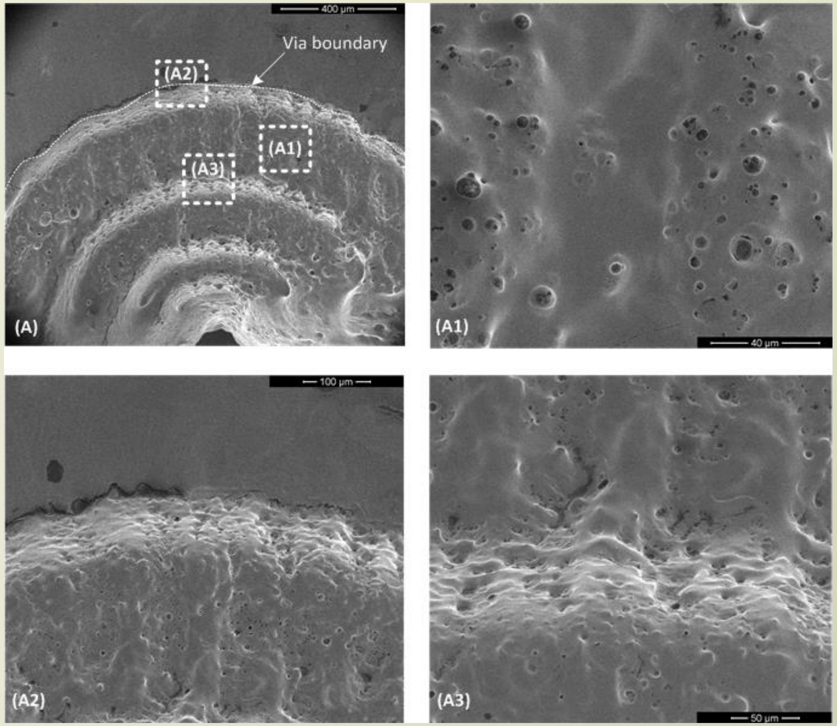
Stepped Via Hole: Top view

Radius	Value (mm)
R_1	1.00
R_2	0.63
R_3	0.40
R_4	0.25
R_5	0.16

(a) Radii table



(b) Via geometry



(c) SEM images

< Geometry of stepped via hole and SEM images: Top view >

- Substrate: PMMA (polymethyl methacrylate)
- Thickness: 1 mm

company logo

Georgia Institute of Technology

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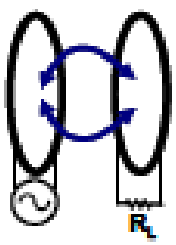
Smart WPT Systems

- Smart WPT systems address all the above problems of traditional SCMR in order to develop a WPT that is:
  - Highly efficient (mid-range)
  - Compact in size
  - Misalignment insensitive
  - Real-Time Matching
  - Broadband

WPT Techniques

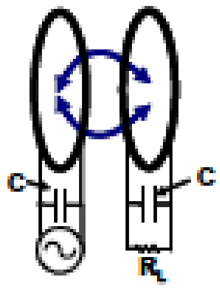
Inductive Coupling



Operates at f_o

- Very poor efficiency

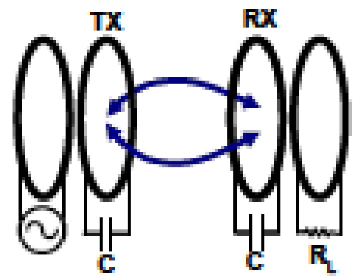
Resonant Inductive Coupling



Operates at $f_o = f_r = 1/\sqrt{LC}$

- Poor Efficiency
- Larger efficiency than inductive coupling due to RLC circuit resonance

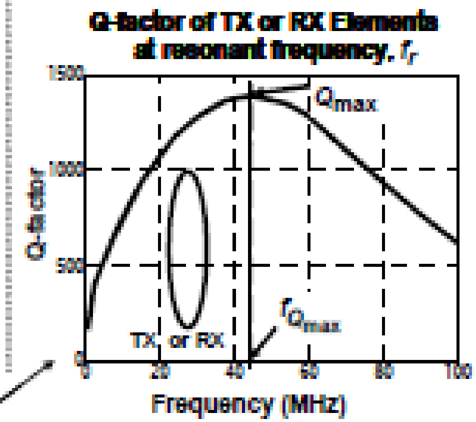
SCMR System



Operates at $f_o = f_{Q_{max}} = f_r = 1/\sqrt{LC}$

- Large Efficiency due to $f_r = f_{Q_{max}}$

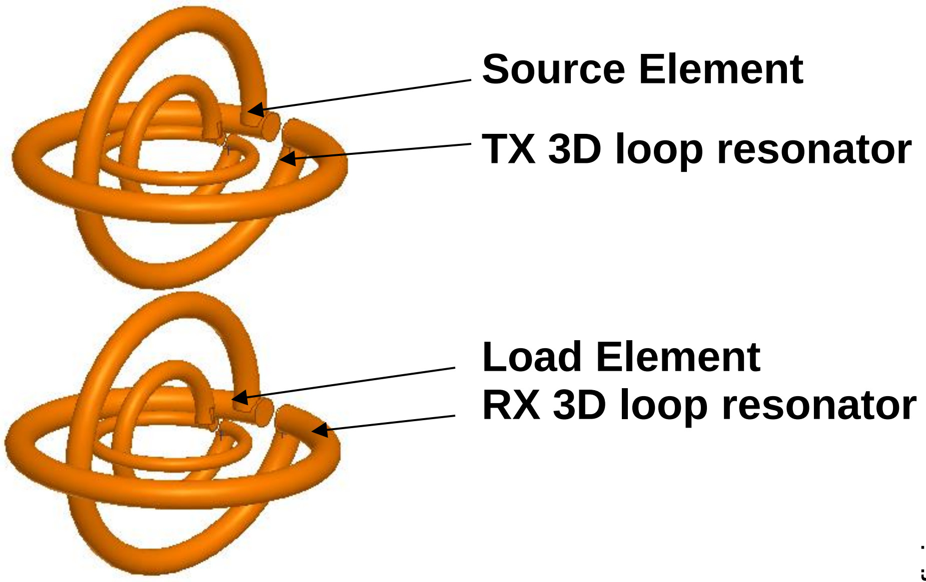
SCMR Resonant Element

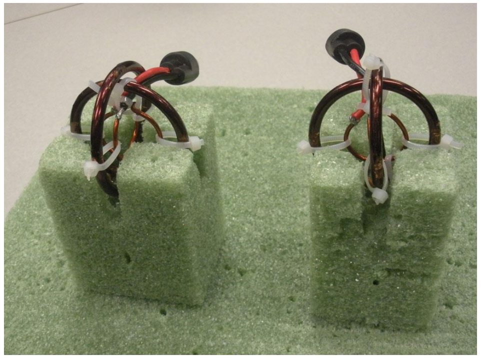


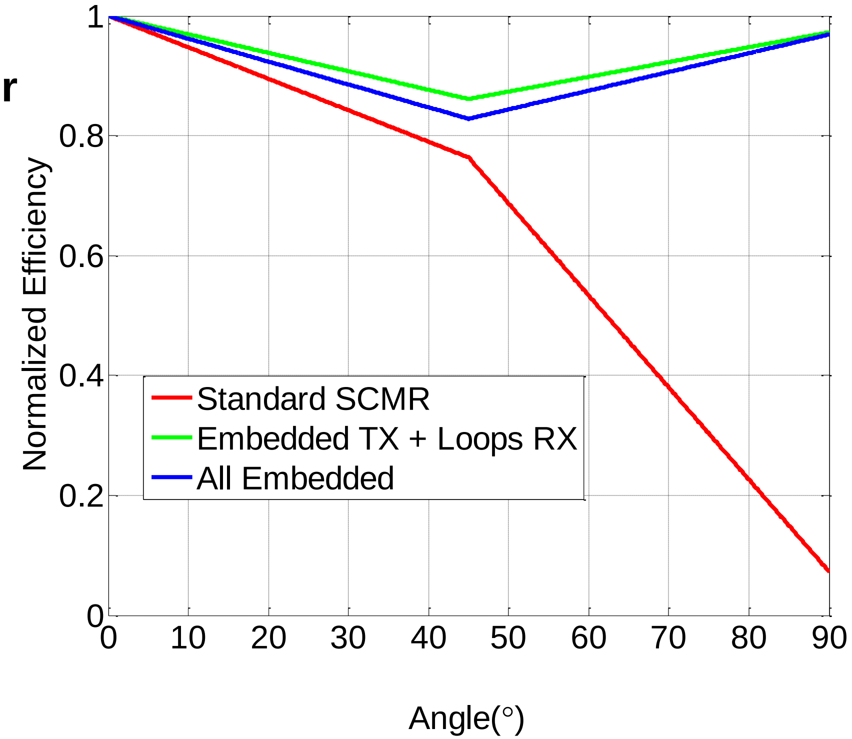
- TX and RX elements naturally exhibit maximum Q-factor at a specific frequency $f_{Q_{max}}$

- L is the inductance of each element; the schematic assumes that each element has only a distributed inductance (this is true for loop elements)
- C is the external capacitance added to resonate the elements
- Other SCMR elements (e.g., helices, spirals, split ring resonators) can have both distributed inductance and capacitance

Misalignment Insensitive Highly Efficient WPT

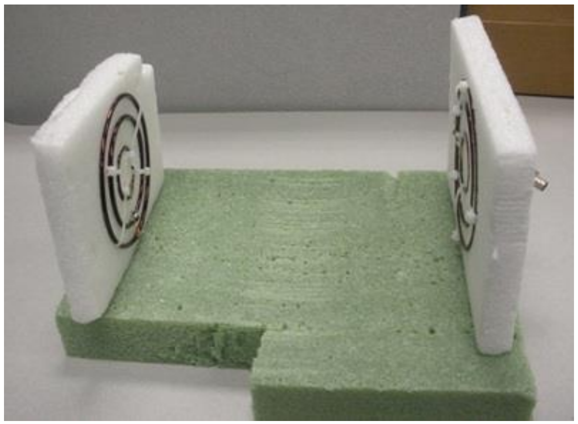


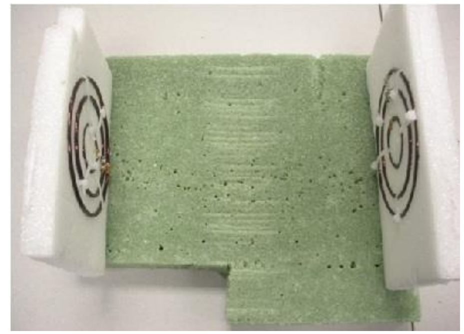




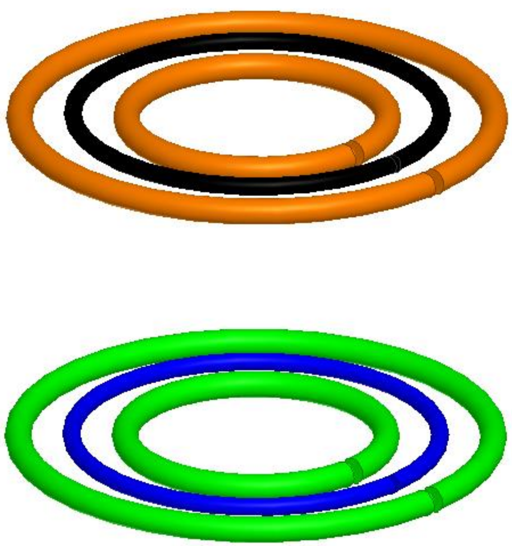
Provisional patent # 61/658,636

Broadband & Highly Efficient WPT





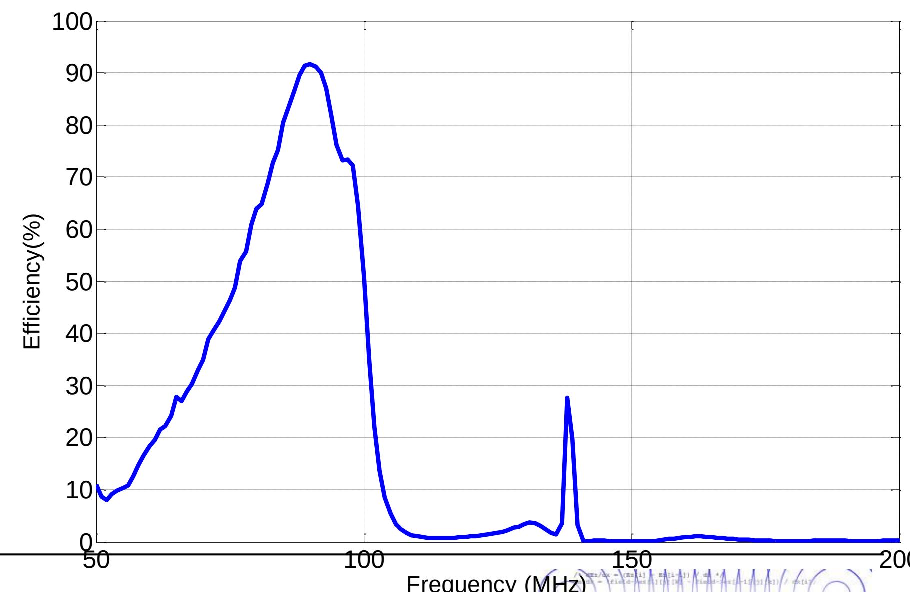
Distance = 7 cm



Legends

- RX resonator
- RX load
- TX resonator
- TX Source

Measurements



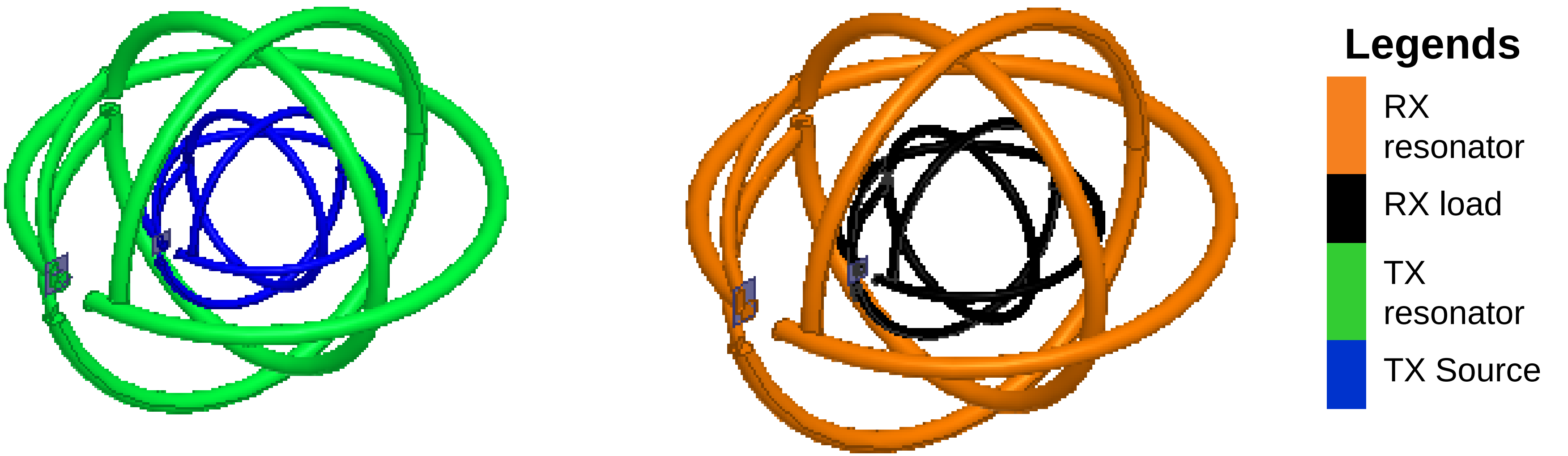
Georgia Institute of Technology

ATHENA

Provisional patent # 61/662,674

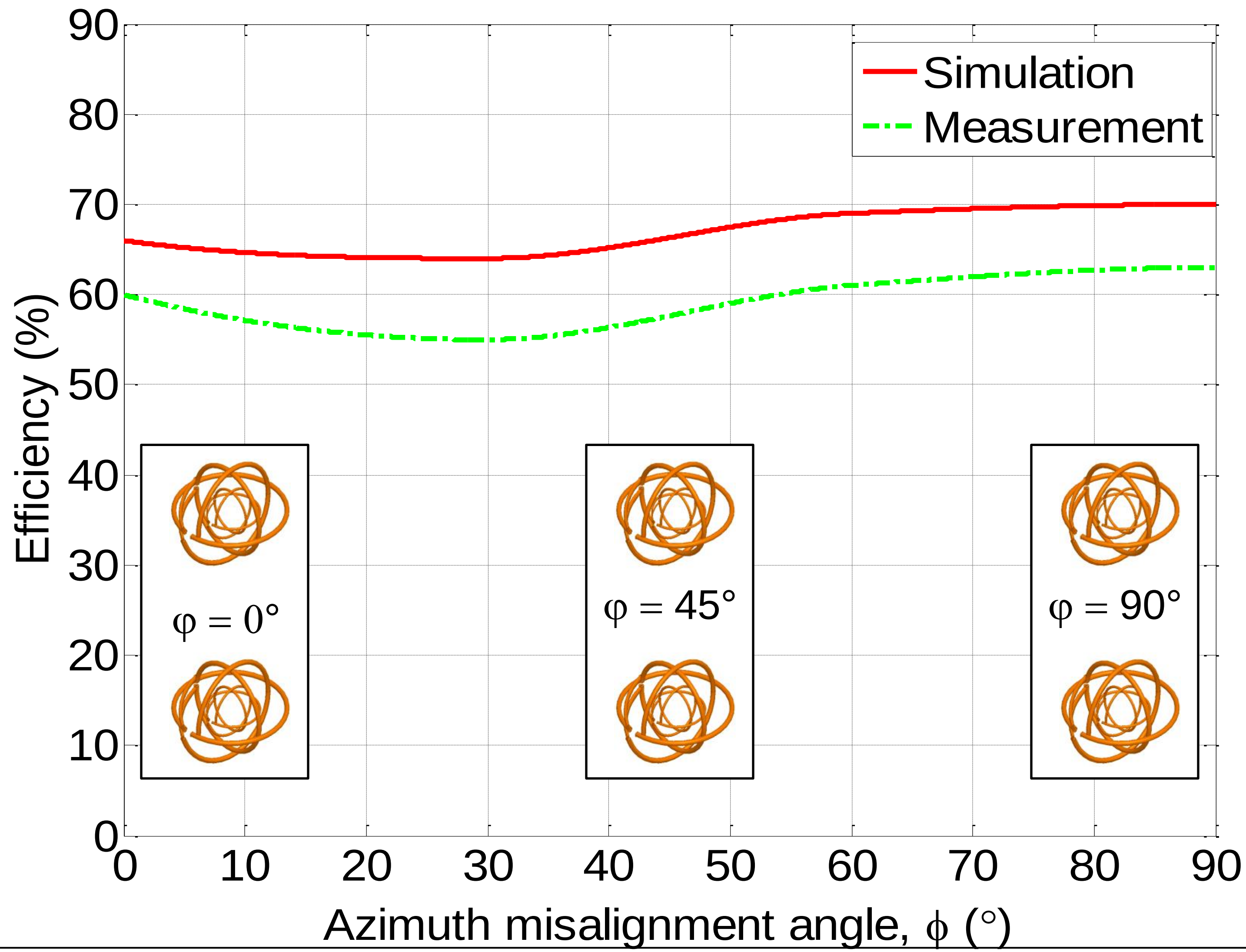
Design 2: Embedded 3-D loops

Each 3-D loop comprises of three connected orthogonal loops

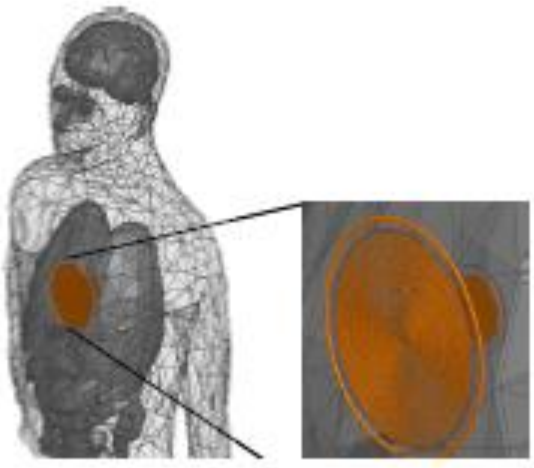


- The RX and TX resonator elements as well as the source and load elements are 3-D continuous loops
- Each 3-D loop comprises of three connected orthogonal loops.
- The source and load loops are embedded inside the TX and RX resonators, respectively
- This type of system has a spherical symmetry and therefore, it is expected to have misalignment insensitive performance.

Design 2- Embedded 3-D loops Angular Azimuth Misalignment

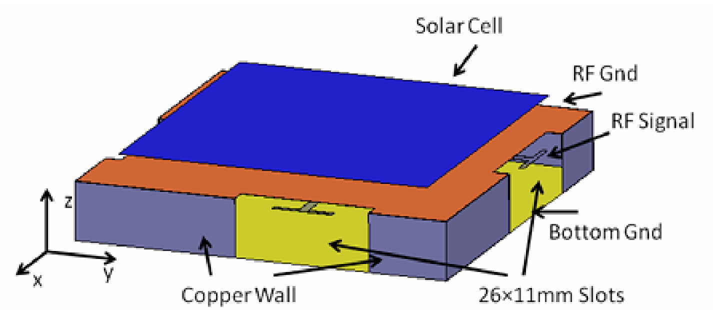


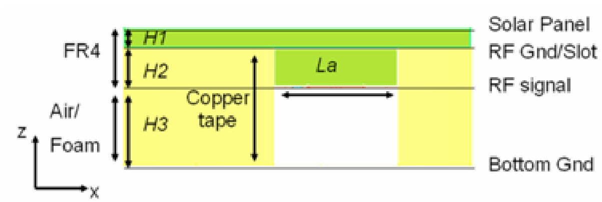
Preliminary Implantable Results

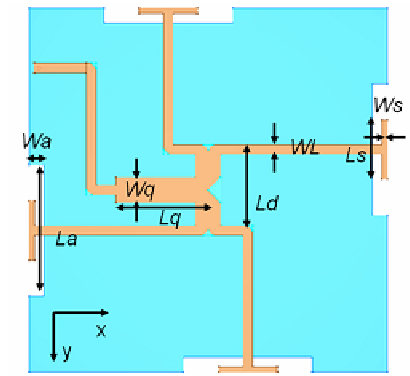


- **60x-80x better than inductive coupling**
- **SRR-based shapes enabled miniaturization below λ/200**

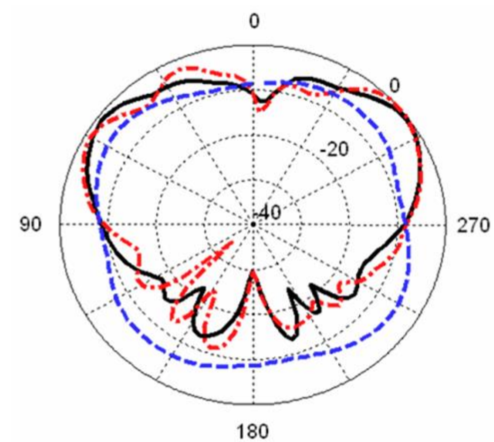
Solar Antennas



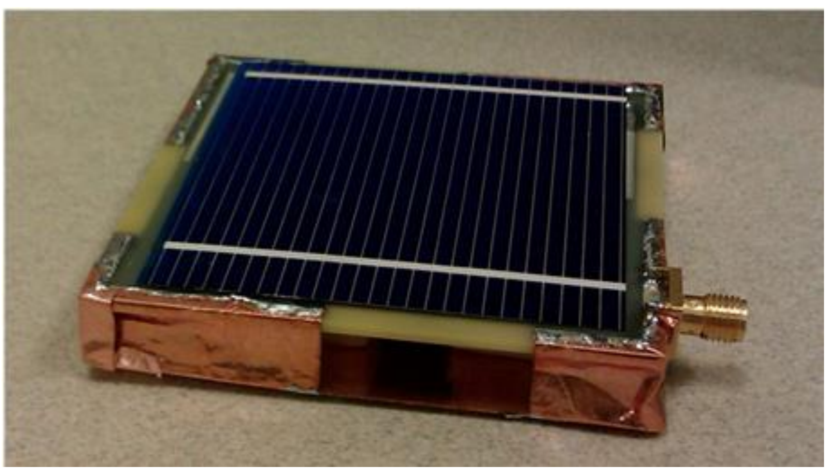


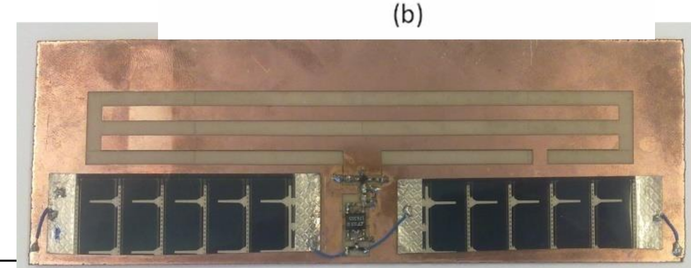


- Silicon in PV cell used as an antenna substrate
- Novel Slot type Antenna
- Gain 2-4dBi
- Directive Pattern



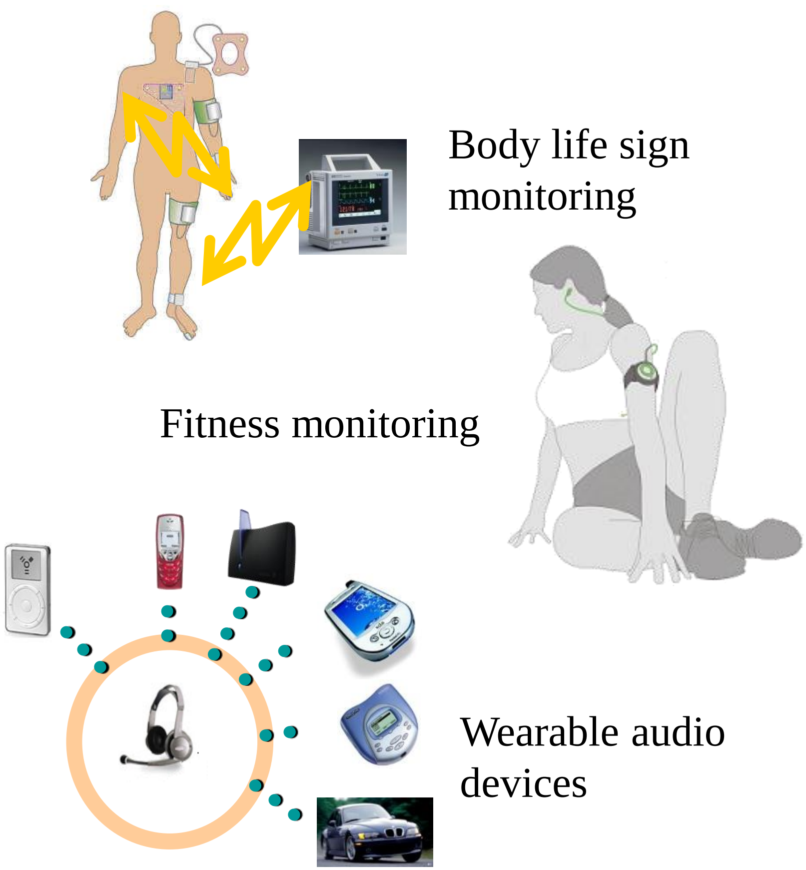
(b)





Motivation

Body Area Network-Usage Scenarios



CHALLENGE

Battery limits usability and autonomy

⇩

An alternative source of energy is required to power up the device

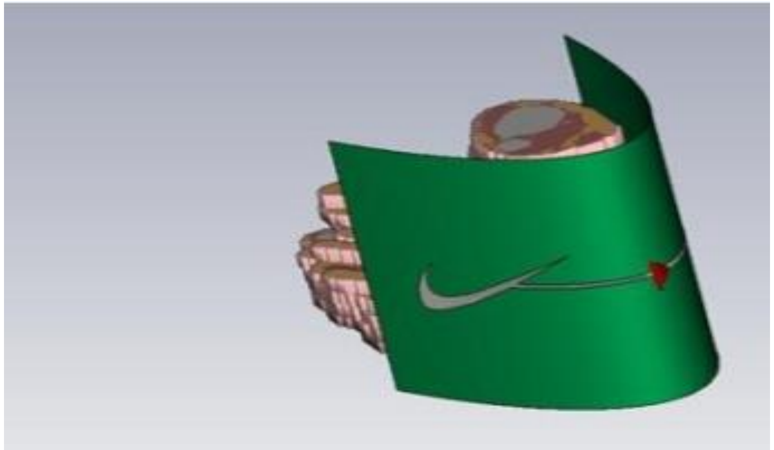
GOAL

Power up an RFID node to allow communication from the body to the reader without the use of battery

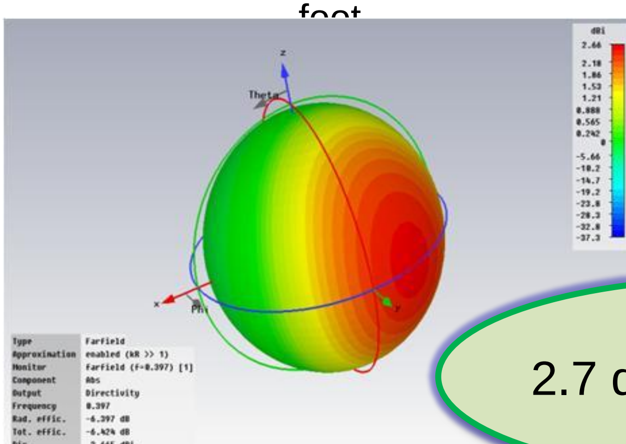
⇩

AVOIDING BATTERY REPLACING IN RFID BODY AREA NETWORK

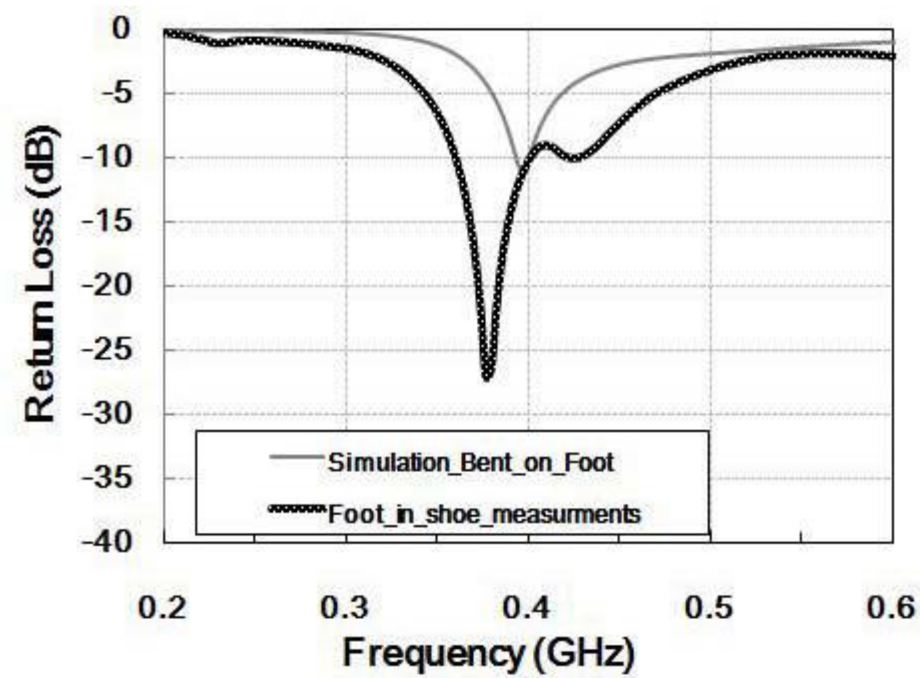
Wearable Tag Antenna Design



Bent antenna electromagnetic model of the foot



Far Field Radiation Pattern



Measured and Simulated Return Loss

2.7 dBi @ 397 MHz

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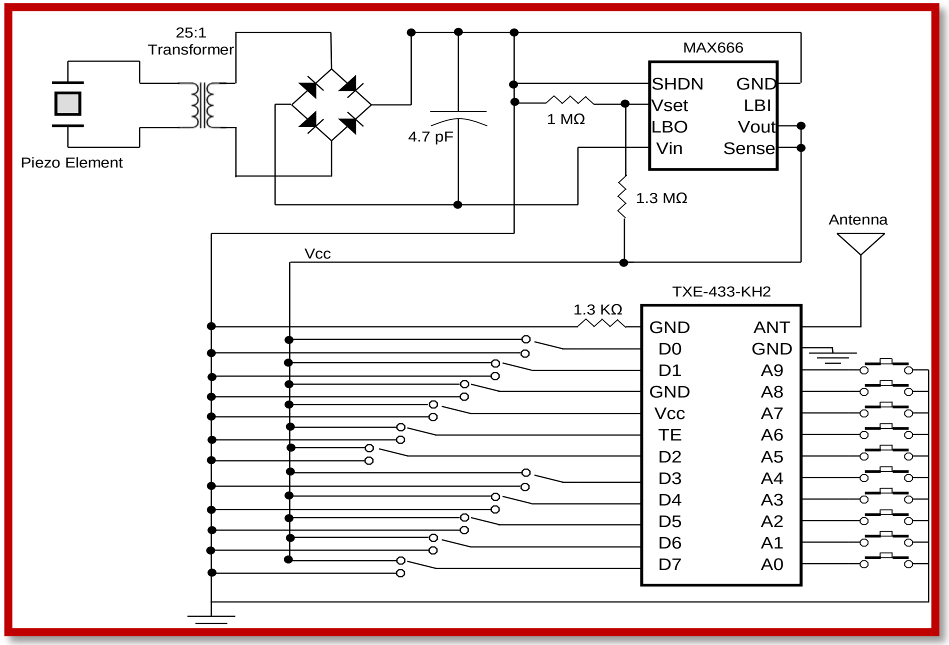
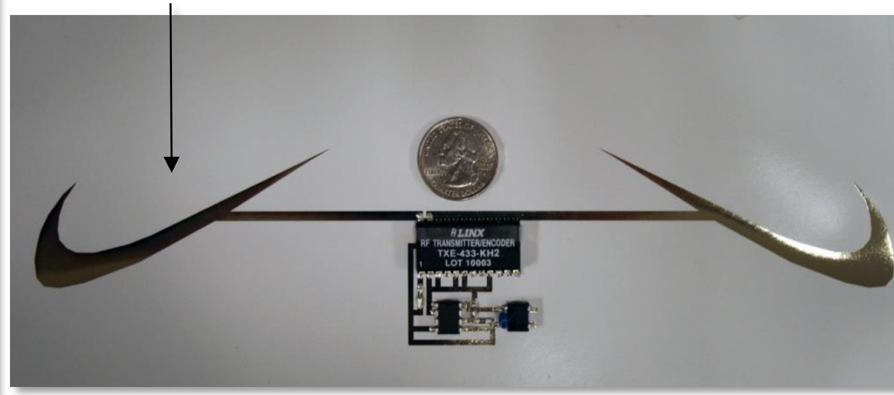
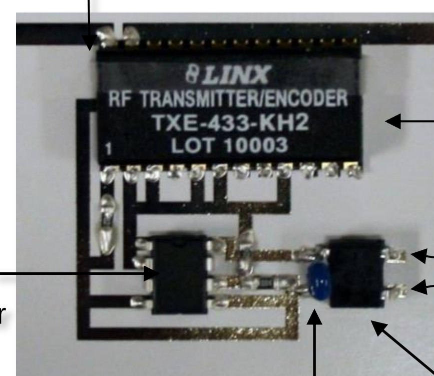
Circuit Implementation



Logo Antenna



Port to Antenna



RF Transmitter

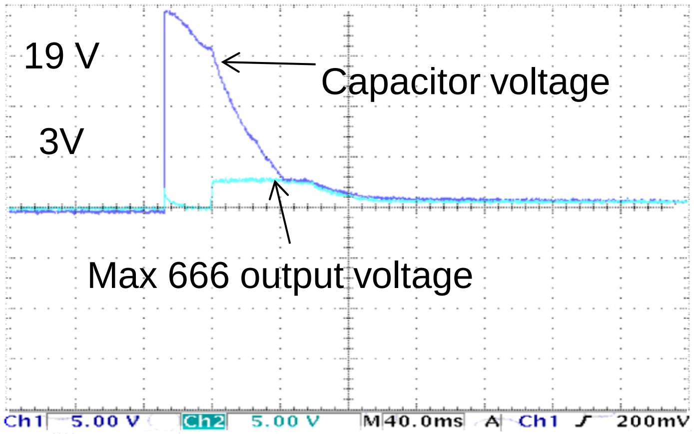
MAX666
Voltage Regulator

Connection to Transformer

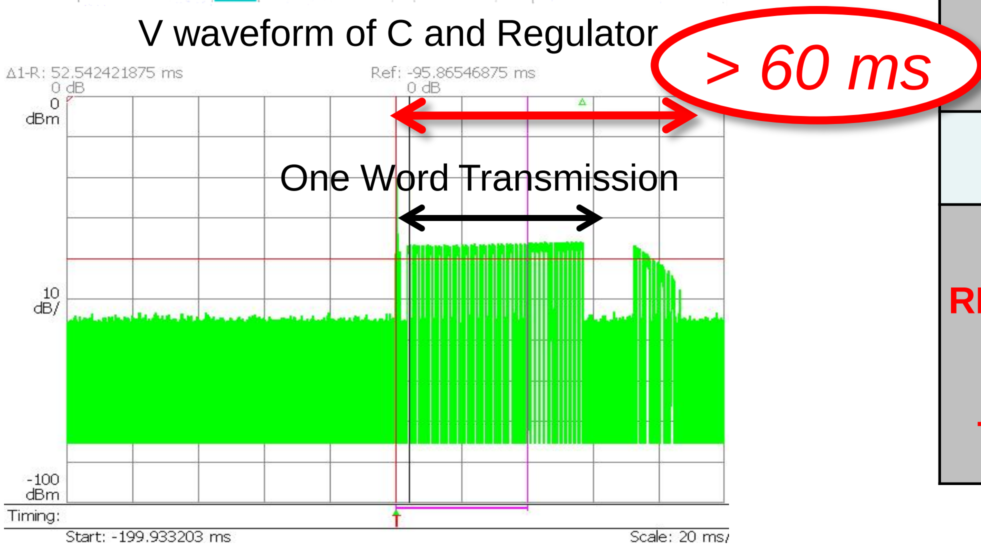
Diode Bridge

Storage
Capacitor

Circuit Implementation



V waveform of C and Regulator



Transmitted signal captured by the RTSA

ENERGY PROVIDED BY THE PUSHBUTTON	stored in the capacitor	848.4 µJ
UNUTILIZED ENERGY	below 2.7 V capacitor voltage, the active RFID tag stops transmitting	17.1 µJ
AVAILABLE ENERGY	848.4µJ - 17.1 µJ	**831.3µJ**
ENERGY REQUIRED BY THE CIRCUIT FOR A ONE-WORD TRANSMISSION	POWER needed for 50 ms operation: 9mW	**450 µJ**

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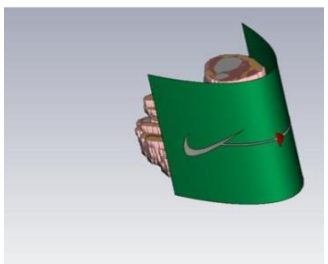
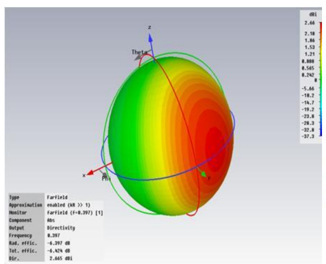
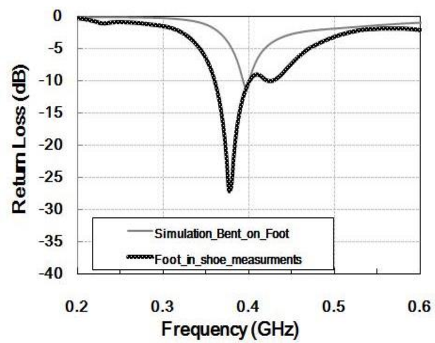
Human motion powered wireless tag

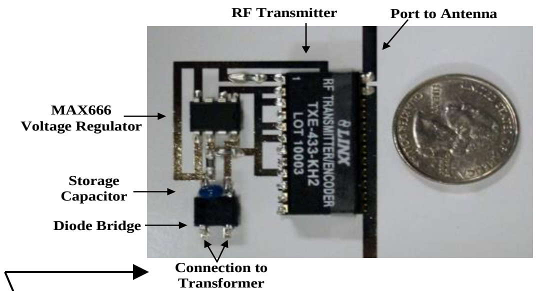
Nike logo printed antenna performance



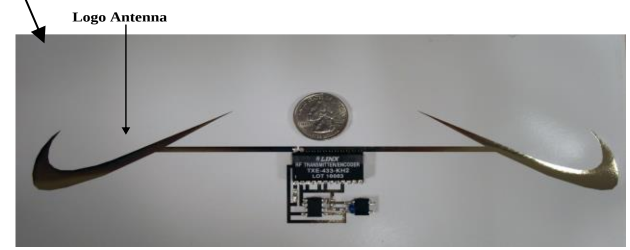




Tag circuit



(a)



(b)

Step powered RFID communication

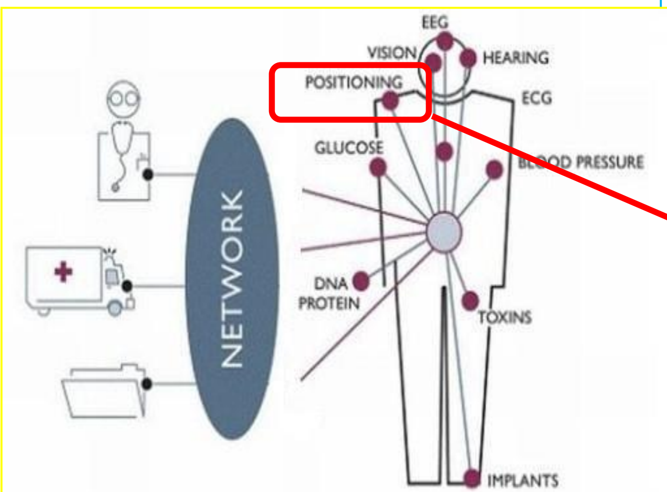
Introduction

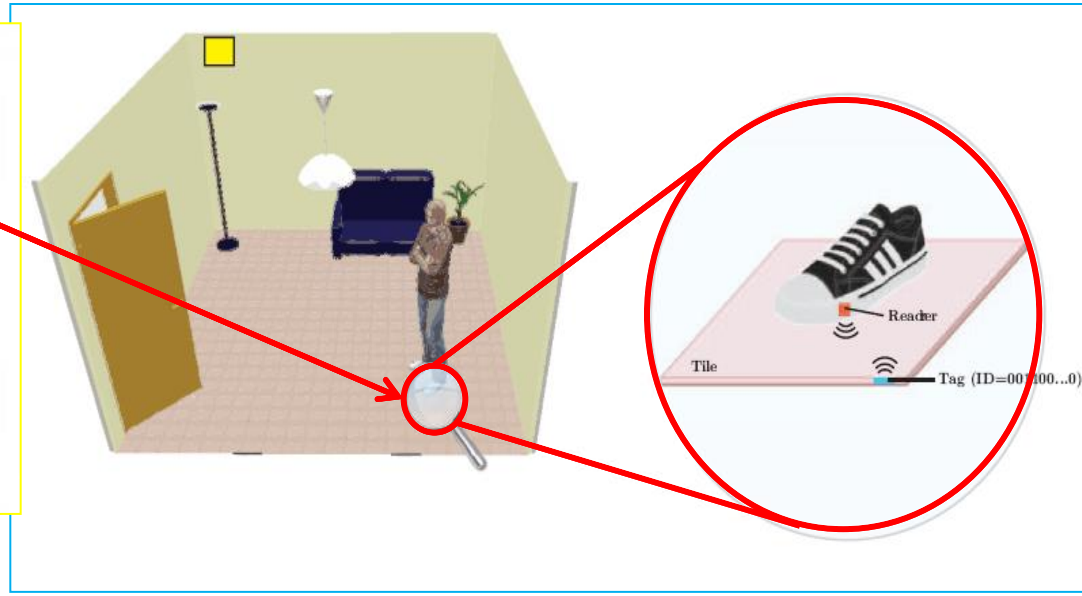
Enabling Technology has to be

- Power Autonomous
- Unobtrusive

Objective of this project → design a wearable, partially self-powered health monitoring and indoor localization shoe-mounted sensor module

Localization: Overview





Personal Area Network

«Smart Tile»
mapped matrix of NFC tags embedded in the floor for localization purposes

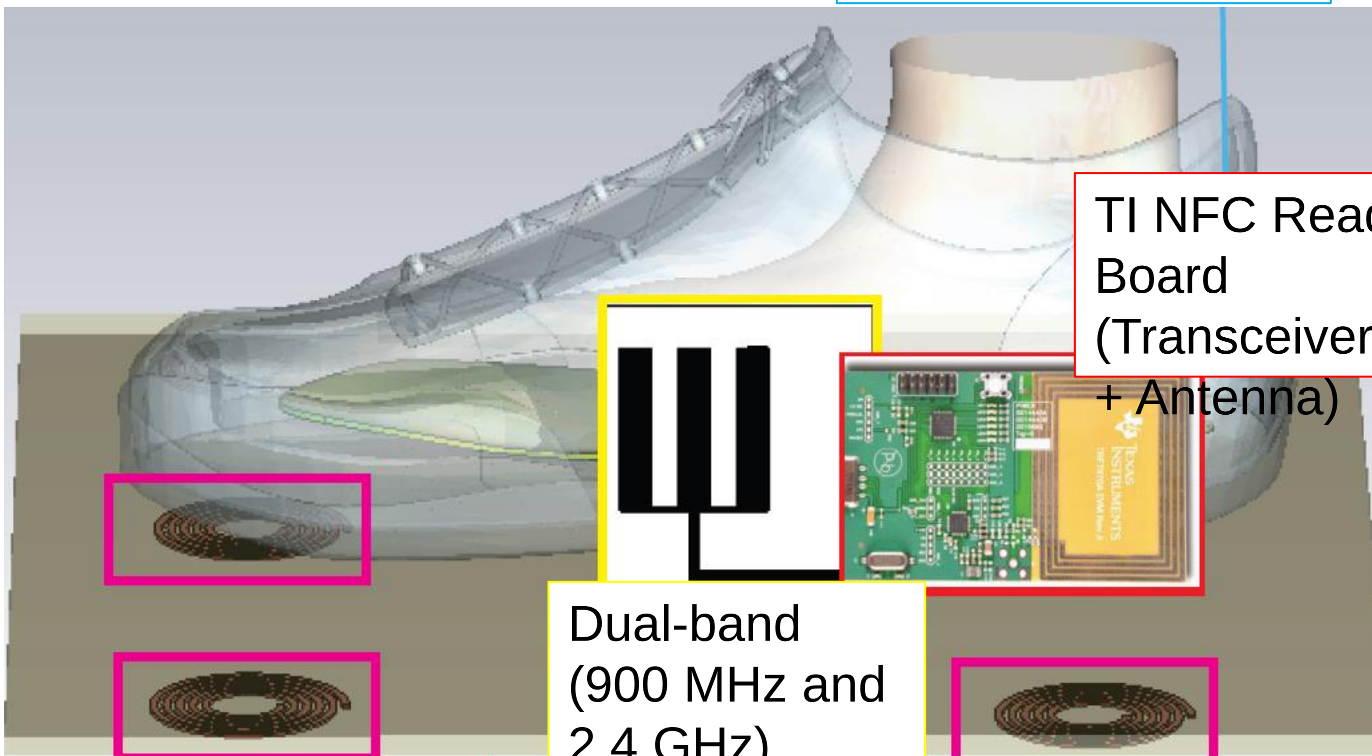
Partially self-powered shoe-mounted NFC reader

Dual-Band Wearable

Adidas-Shaped Atnenna

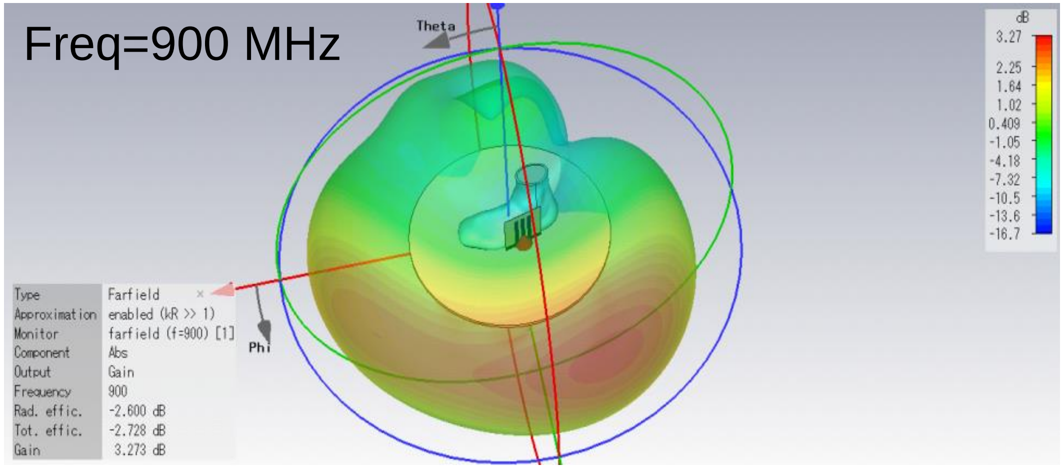
- Unobtrusive wearable antenna design
- Dual Band: 900 MHz and 2.4 GHz
- Deopsited nano particle silver ink on organic substrate (photo paper) technology

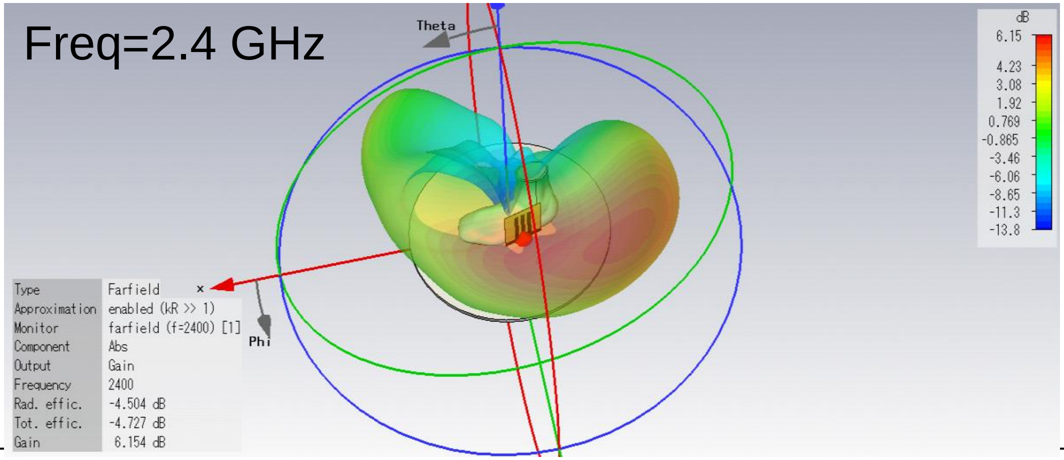
System Architecture Description



Simulated/Measured Return Loss

Simulated Antenna Radiation Patterns





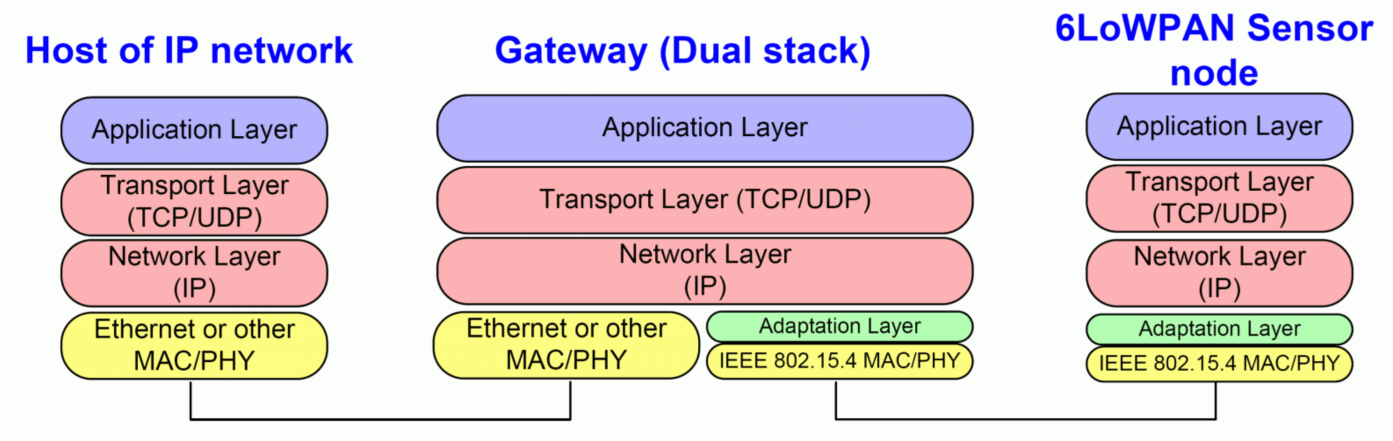
- Excellent performance in term of radiation pattern for both 900 MHz and 2.4 GHz standards, considering the presence of the foot
- Gain > 3dB

Localization: NFC system test

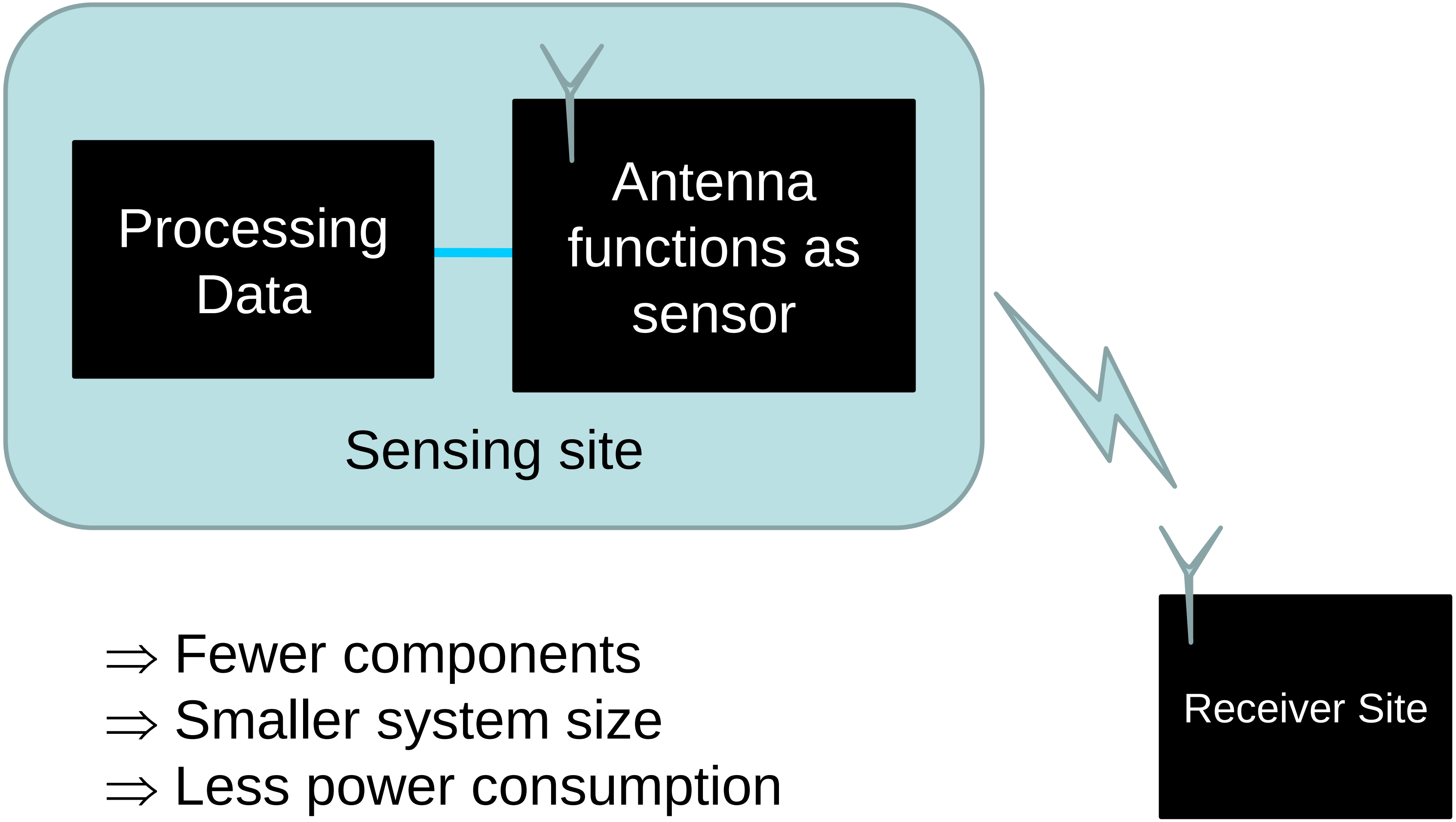
- Test → moving the tag from position 1 to 8 (shown in the figure) the maximum reading distance has been measured.
  The reader is placed at the center of the tile either vertically and horizontally.

Why 6LoWPAN?

- IPv**6** over **Lo**w-power Wireless **P**ersonal **A**rea **N**etworks -> native support of the IPv6 protocol stack on the end device
- A low-power communication protocol based on the IEEE 802.15.4 PHY and MAC layer
- Backed up by an active IETF Working group with real prototypes
- The **network**, **transport** and **application** layers of the 6lowPAN protocol stack (right) are the same as those of the IPv6 stack (left) and the necessary changes exist in the **adaptation layer** on top of the IEEE 802.15.4 medium access control and physical layer.



RF Wireless Pressure Transducer



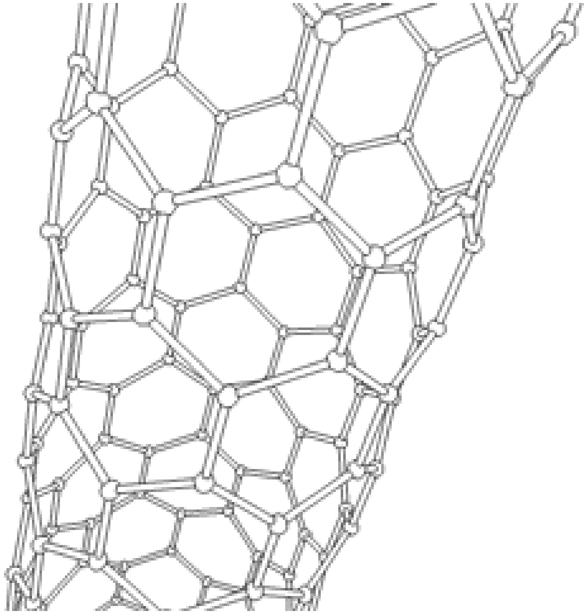
⇒ Fewer components
⇒ Smaller system size
⇒ Less power consumption

Carbon Nanotubes as Gas Sensor

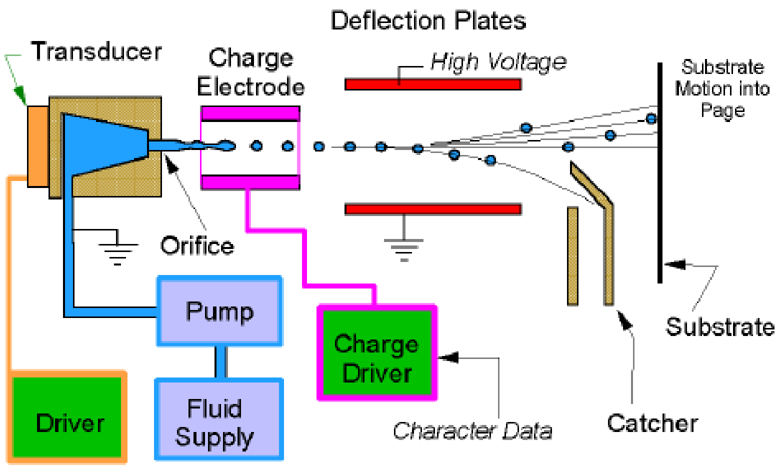
- CNTs structure can be conceptualized by wrapping a one-atom-thick layer of graphite into a seamless cylinder.
- Single-walled CNTs and Multi-walled CNTs
- A diameter of close to 1 nanometer, with a tube length that can be many thousands of times longer.
- CNTs composites have electrical conductance highly sensitive to extremely small quantities of gases, such as ammonia (NH_3) and nitrogen oxide (NO_x).
- The conductance change can be explained by the charge transfer of reactive gas molecules with semiconducting CNTs.
- Fabrication of CNTs film:

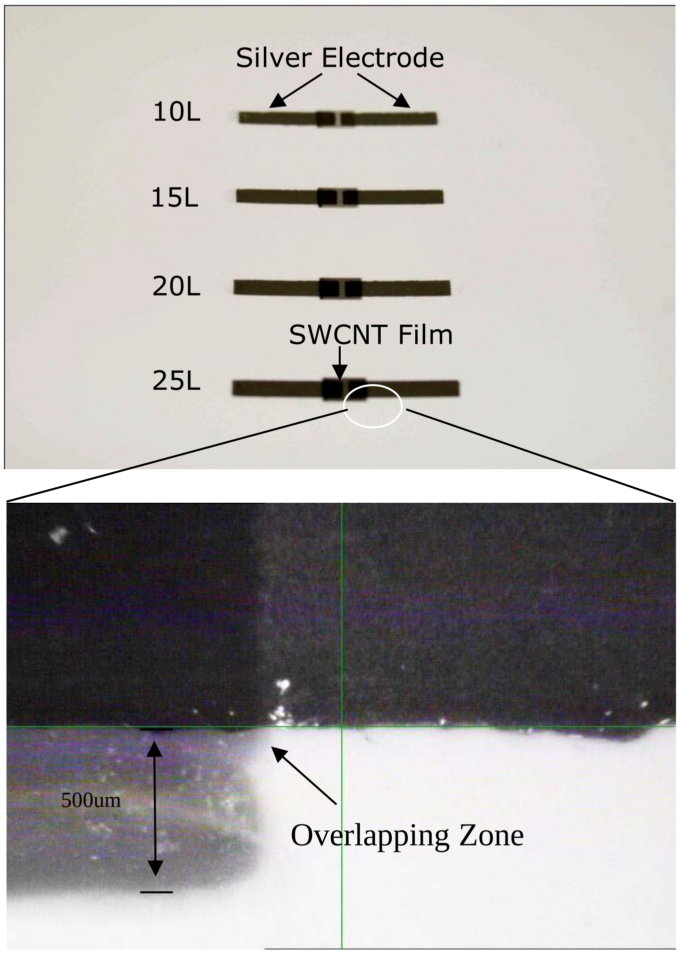
  -Vacuum Filtering, dip coating, spray coating, and contact printing, requiring at least two steps to achieve the patterns.

  -Can it be inkjet-printed? Yes, if you can develop the recipe!



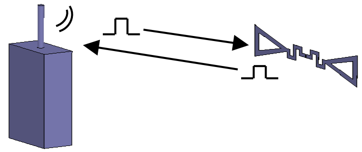
Inkjet-printed SWCNT Films



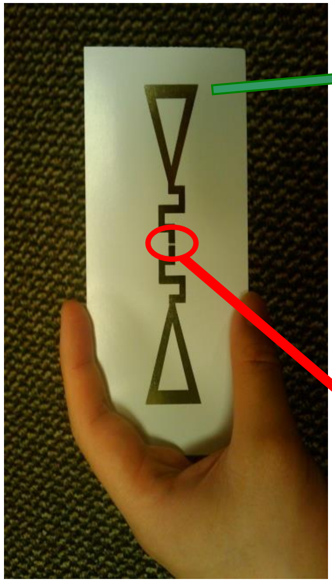


- Silver electrodes were patterned before depositing the SWCNT film, followed by a 140°C sintering.
- The electrode finger is 2mm by 10mm with a gap of 0.8mm. SWCNT film was 2mm by 3mm.
- 1.1mm overlapping zone to ensure the good contact between the SWCNT film and the electrodes.

Gas Detection



$$P_r = P_t + 2G_t + 2G_r - 40\log_{10}\left(\frac{4\pi}{\lambda}\right) - 40\log_{10}(d) + \eta$$



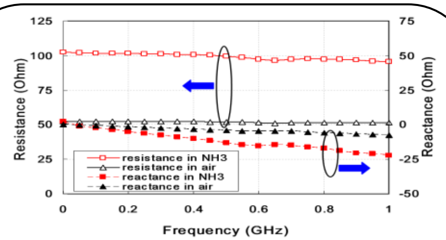
Tag Antenna @ 686MHz

Z_{ant}=42.6+j11.4 Ohm

+

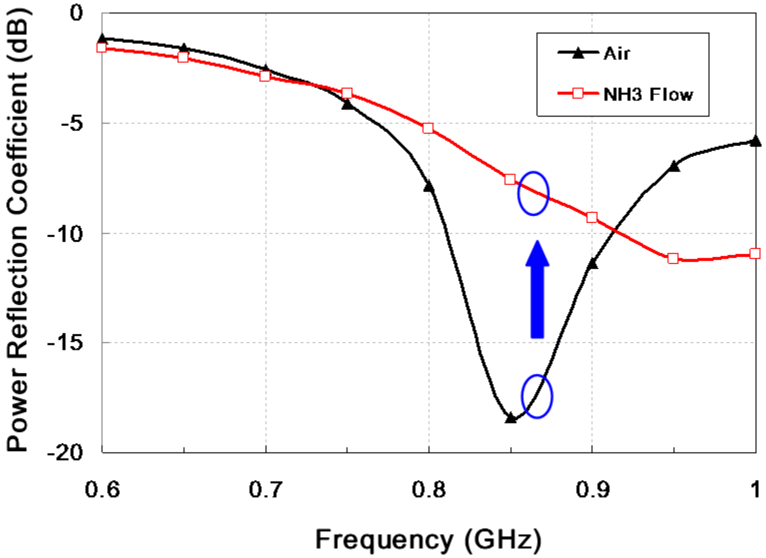
$$\eta = \left|\frac{Z_{load} - Z_{ANT}^{\ *}}{Z_{load} + Z_{ANT}}\right|^2$$

+



SWCNT Film @868MHz
Z=51.6-j6.1 Ohm in air

Z=97.1-j18.8 Ohm in NH3

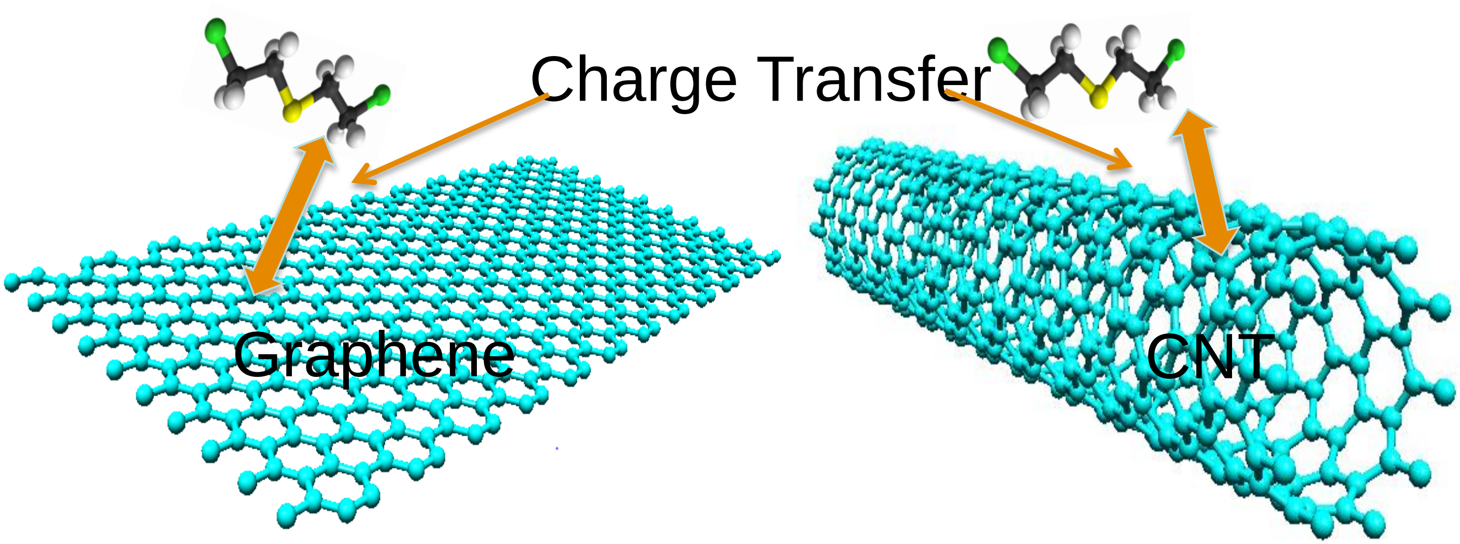


- Power reflection coefficient changes from -18.4dB to -7.6dB. At reader's side, this means 10.8dBi increase of the received power level.
- By detecting this backscattered power differnce, the sensing function is fulfilled.

Inkjet-Printed Graphene/CNT-Based Wireless Gas Sensor Modules

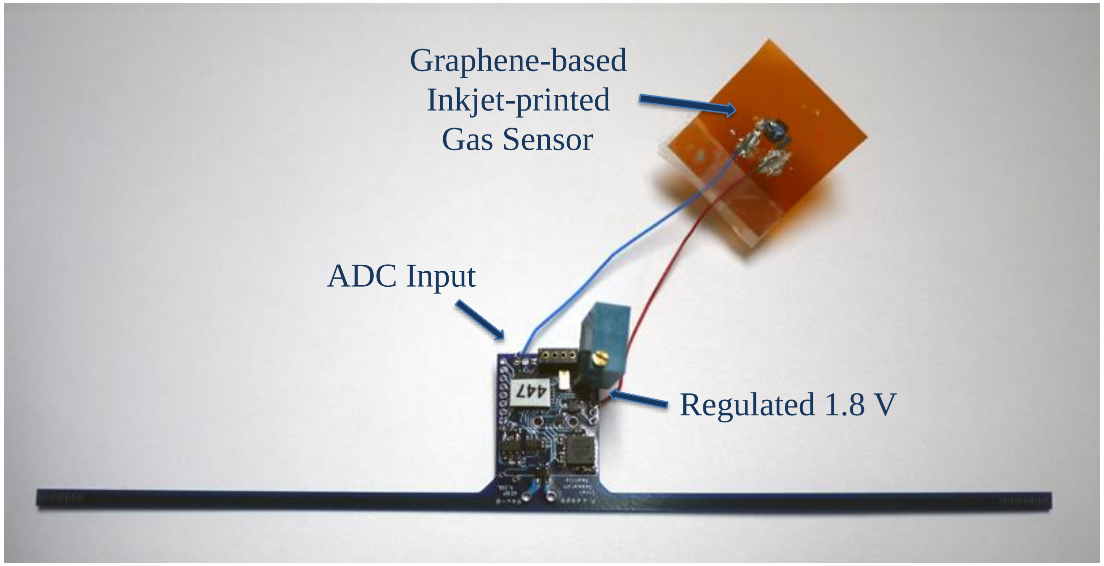
Chemical Absorption → Changing Material Properties → Measureable Electrical Quantities

Gas Sensor Technology

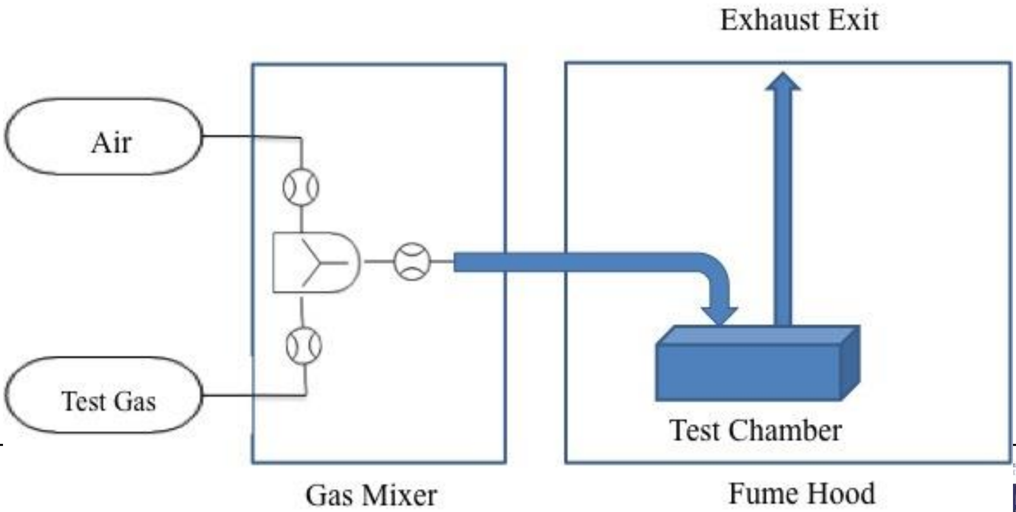


Inkjet-Printed Graphene/CNT-Based Wireless Gas Sensor Experiment

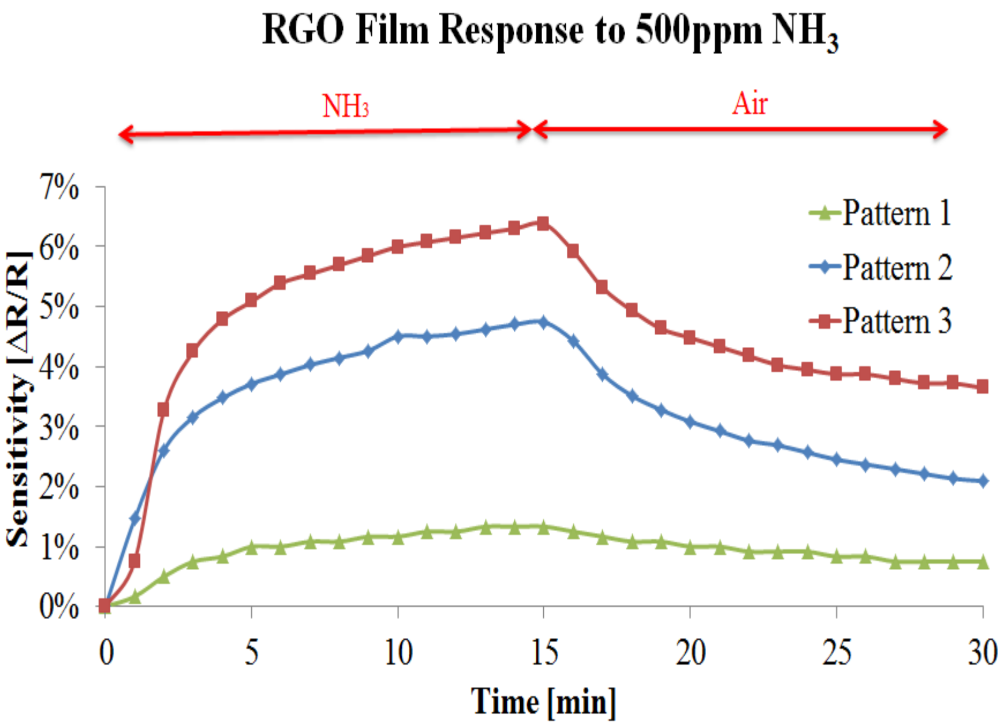
- Prototype

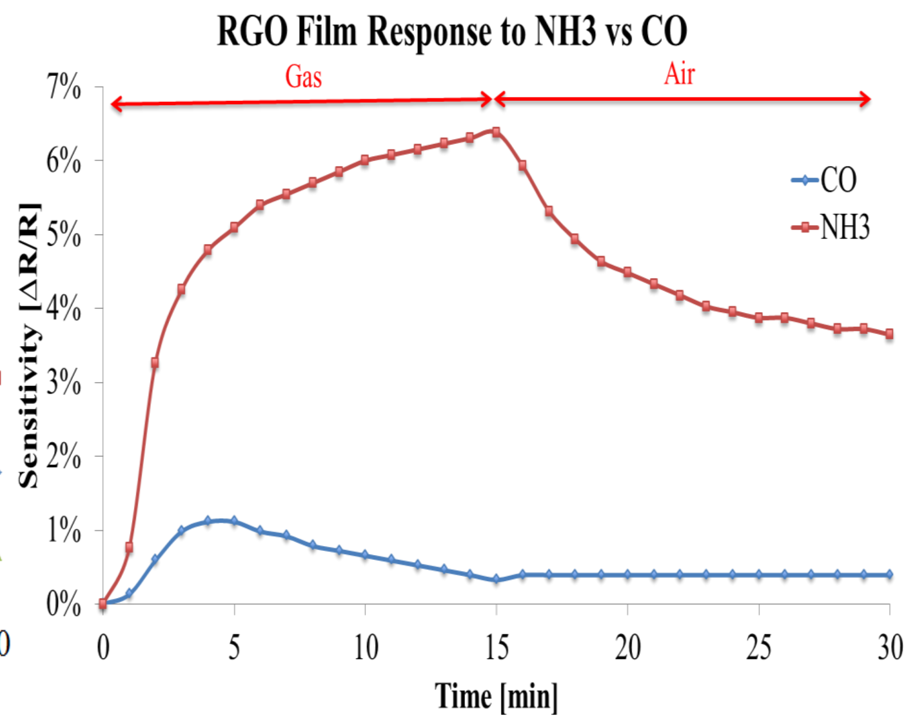


- Set-up



Inkjet-Printed Graphene-Based Wireless Gas Sensor Experiment





- **6% normalized resistance change** within 15 minutes of exposure to a concentration of 500 ppm of NH_3.

-excellent recovery time with **over 30% of material recovery** observed within 5 minutes without exposure to high temperature or any UV treatments.

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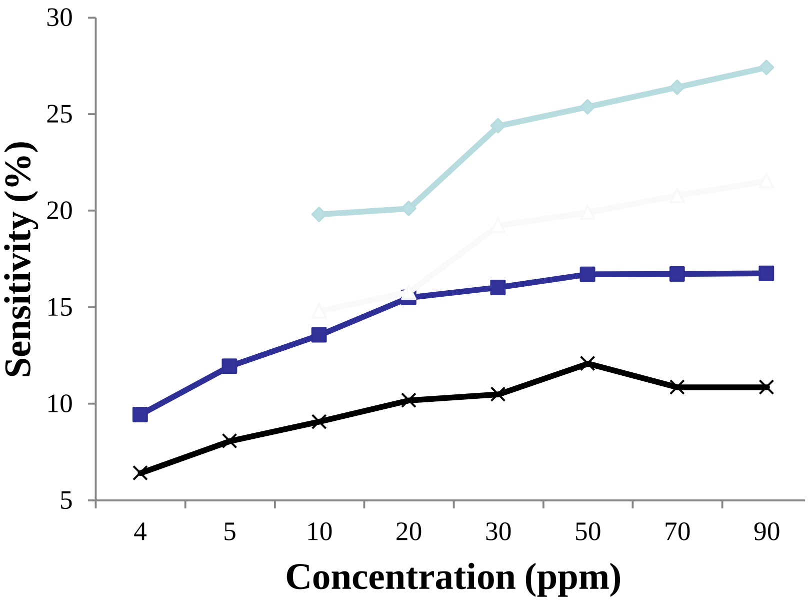
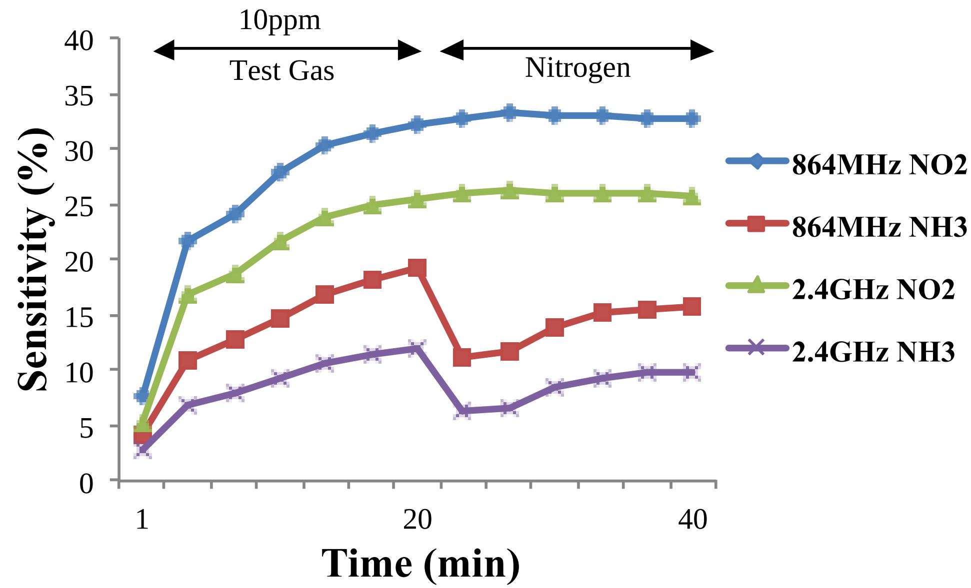
Inkjet-Printed CNT-Based Wireless Gas Sensor Experiment

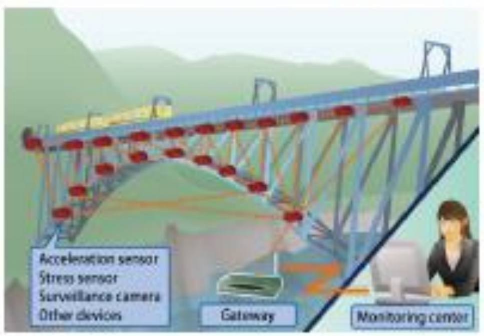




-Sensitivity of 21.7% and 9.4% was achieved for 10 ppm NO2 and 4 ppm NH3, respectively at 864 MHz

-MWNT-based gas sensor demonstrates fast response to both gases (few seconds); the sensitivity achieved at 864 MHz is 24.2% for NO2 and 12.7% for NH3 in just 2 minutes' time. Note that after testing, the sensor exposed to NH3 shows more rapid recovery

Structural Health Monitoring



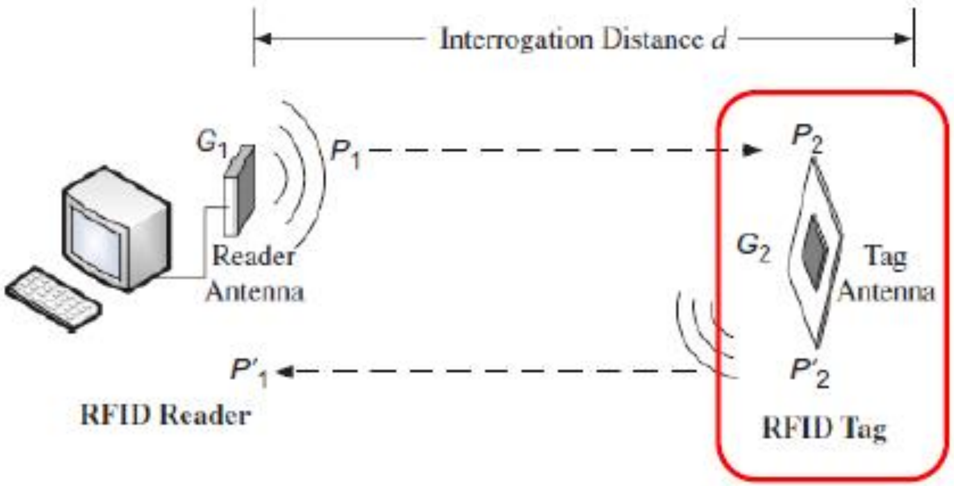
Infrastructure Health Monitoring needs

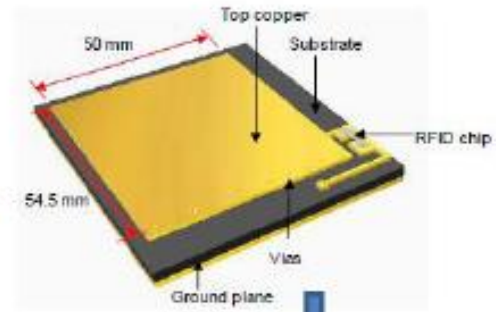
- Early warning system - microstrain
- Real Time
- Remote/autonomous sensing
- Low cost -> large scale deployment

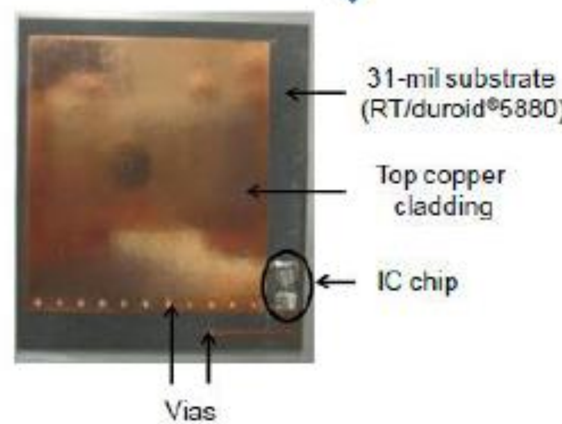
Additional Areas

- Energy – Wind, Hydro, Oil/Gas extraction
- Airline

Smart Skin Strain Sensor



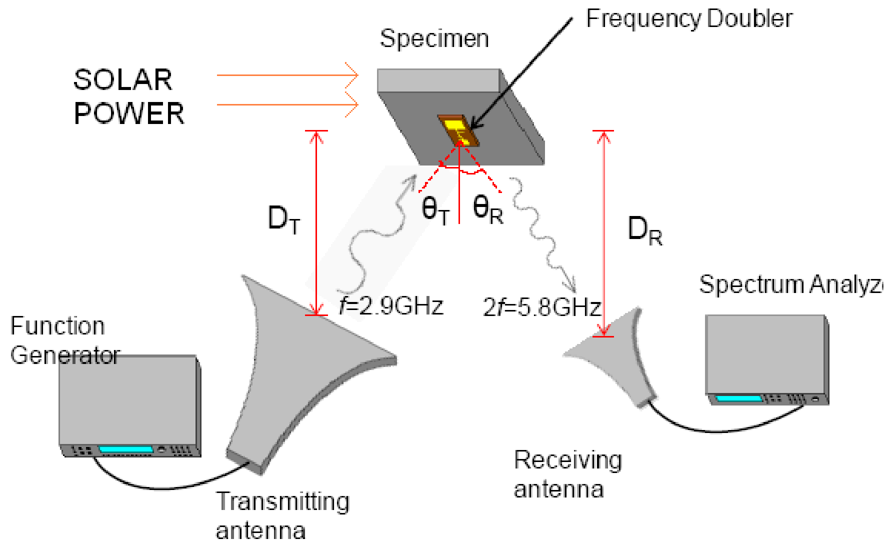




- Novel antenna based smart skin detects strain and cracks on structures it is mounted on
- Immune to iPhone effects
- Antenna sends back strain response using EPC Gen-2 Standard backscattered wireless signal
- Strain sensor used no batteries
- Range <30 feet

- Yi. X., Vyas, R., Cho, C., Fang, C.-H., Cooper, J., Wang, Y., Leon, R.T., and Tentzeris, M.M. "Thermal effects on a passive wireless antenna sensor for strain and crack sensing," Proceedings of SPIE, Sensor and Smart Structures Technologies for Civil, Mechanical and Aerospace Systems, San Diego, CA, March 11-15, 2012.

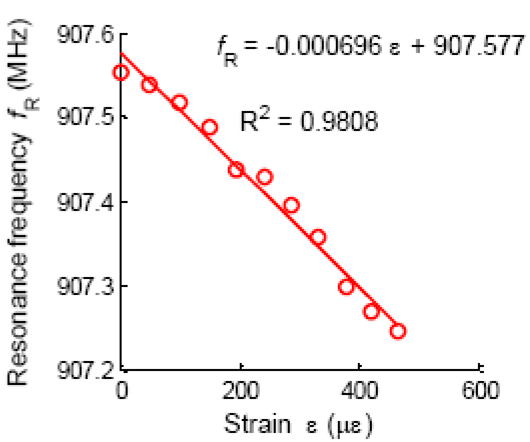
Solar Powered Smart Skins for Structural Health Monitoring

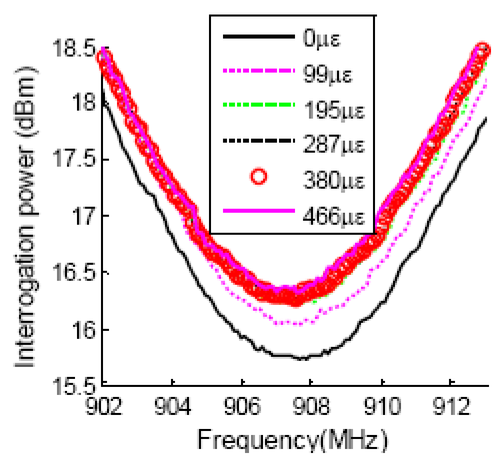


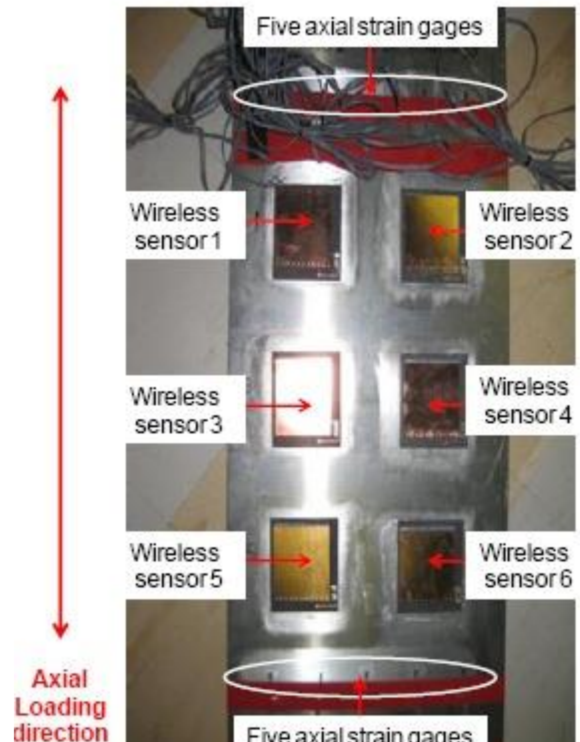
- Novel Antenna based smart skins detect strains and cracks in civil structures
- Remotely interrogated using novel RF reader
- Reader uses 2.9 GHz to remotely interrogate tag. Tag returns strain information using 5.8GHz for better strain sensitivity
- Uses Solar Powered Frequency doubling mechanism for long range

Solar Powered Smart Skins for Structural Health Monitoring

- Latest prototypes show capability to detect 20 u-strain
- Range extended to 10 meters through the use of Solar Power







(a) Sensor instrumentation on the aluminum specimen

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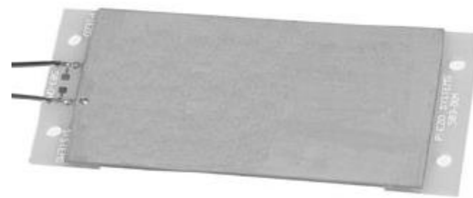
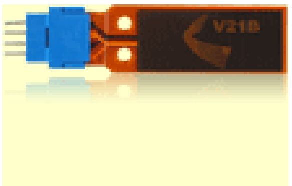
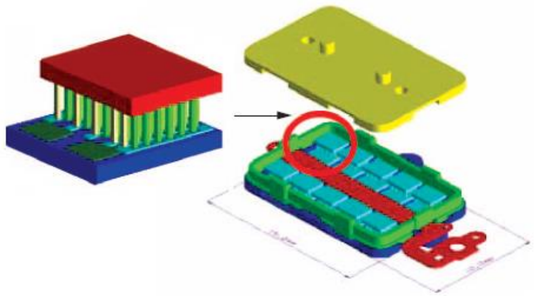
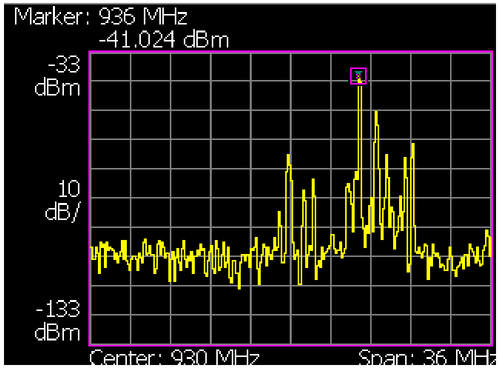
Power Scavenging

- Power Scavevenging Technologies:
  - Mechanical Motion
    - Power Density: 4μw/cm^2
    - Resonance: Hz
  - Thermal
    - Seebeck or peltier effect
    - Power Density: 60 μw/cm^2
  - Wireless
    - Power Density ≤ 1μw/cm^2
  - Solar
    - Power Density: 100 mw/cm^2
    - Does Not require differential









936 MHz: -41dBm (0.08μw)