Inkjet-Printed Paper/Polymer-Based "Green" RFID and Wireless Sensor Nodes: The Final Step to Bridge Cognitive Intelligence, Nanotechnology and RF?

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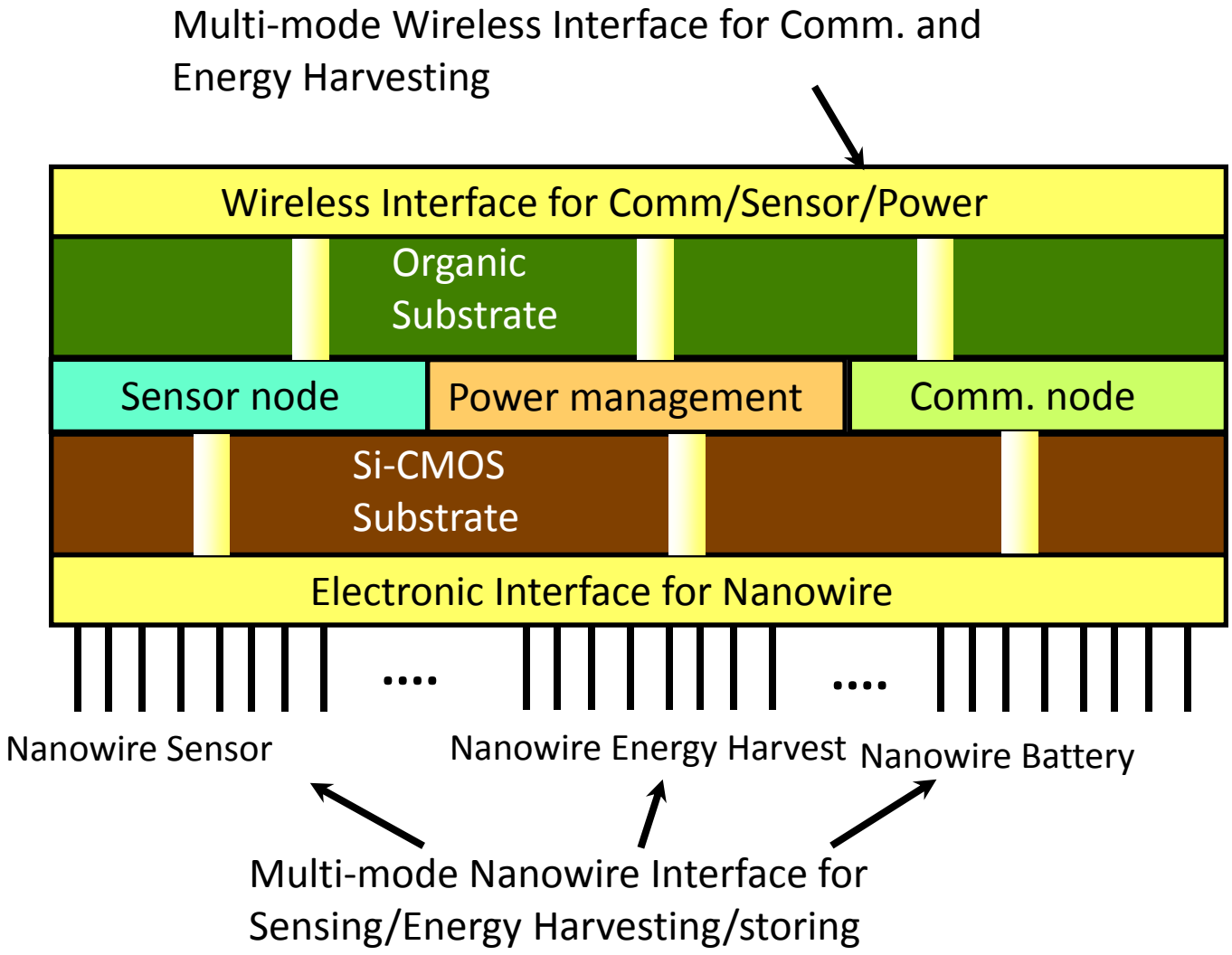
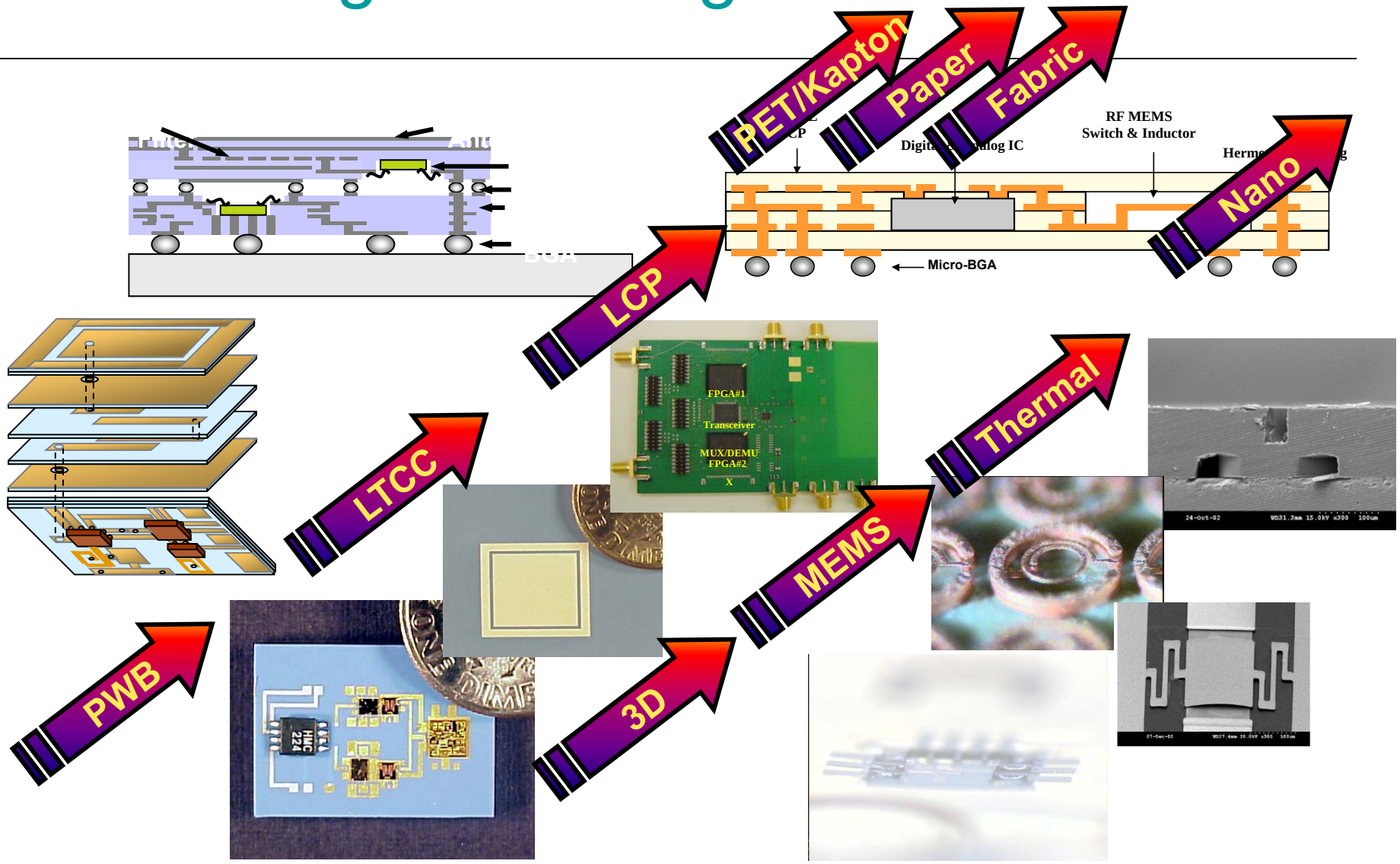
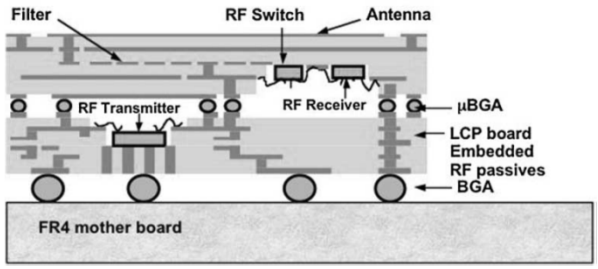
3D Integrated Platforms

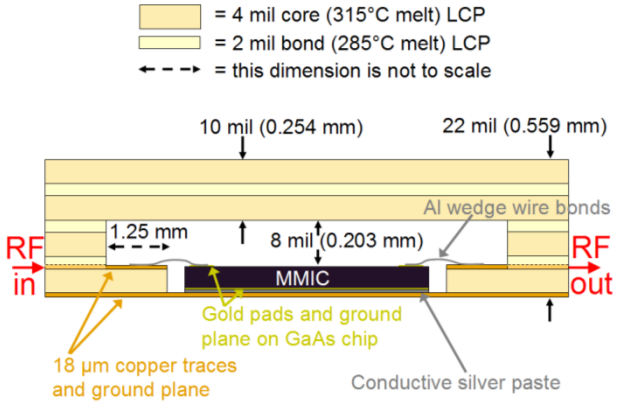


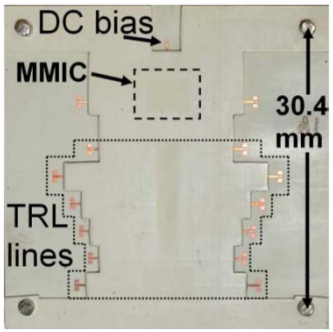
Enabling Technologies in the future



LCP 3D Integration

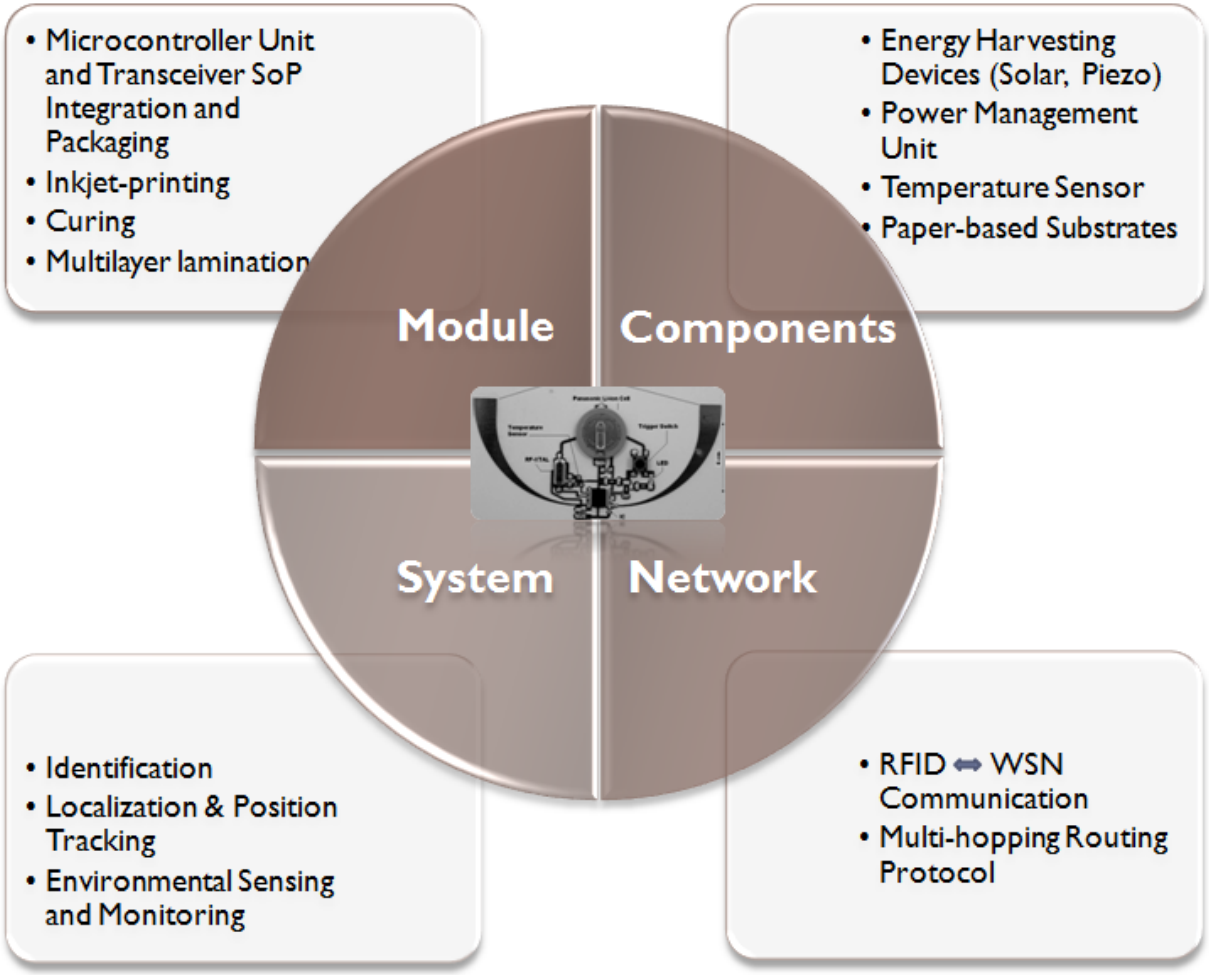






- Multiple layers of thin-film LCP can be arranged and laminated to form low-profile lightweight packaging structures for active devices
- Flip-chip and/or wire bonds may be used for the interconnections for active devices
- Low melting temperature LCP layers (285 C) are used to adhere generally thicker high melting temperature core layers (315 C) to create a homogeneous LCP package stack-up
- Laser or mechanical drilling can be used to selectively remove parts of certain layers in arbitrarily desired shapes, which, when laminated with solid layers, become cavities for embedded active or passive devices
- Cavities also provide an excellent opportunity for the easy integration of RF MEMS devices
- Passive components, off-chip matching networks, embedded filter, and antennas are implemented directly into the SOP boards by using multilayer technologies.

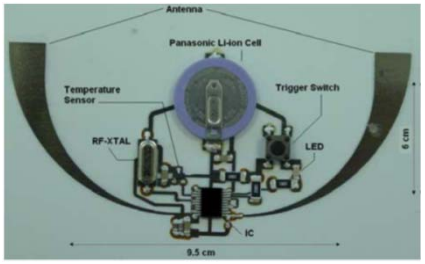
Inkjet-Printed RF Electronics and Modules on Paper



IFC/SRC 4.1.1 Broadband/Multiband Conformal and Wearable Antennas up to mmW/THz

Task Goal : Developing Inkjet-printed Wearable/Conformal "Multimode" Antenna and Antenna Arrays with Ultrabroadband Range (up to THz), High Gain (up to 30dBi), High Efficiency (90%+)

Concept

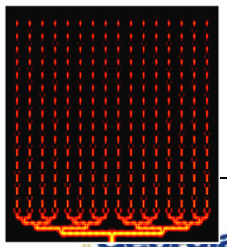


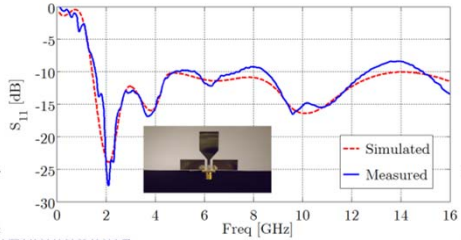
Technology Nugget

- Innovative wearable inkjet-printed antennas and antenna arrays on paper and organic-based substrates
- Flex-independent high-gain, high-efficiency radiation performance up to mmW
- Nested-loop Scalable-band antennas
- SOP-on-LCP/paper integration with printed passives
- UWB enhanced range (up to 1km+) semi-passive
- Multi-band/multi-mode performance for easy integrability w/ transceiver (wireless sensor, power harvesting.

Year 1 Progress

- Realized the first inkjet-printed MIMO Tri-B system
- Developed flex-free 3D "Magic Cube" antennas
- Developed Nested-Loop 2/3-Band Arrays
- Extended CNT/inkjet-printed process up to 15 GHz
- Developed 15dbi+ gain antenna array around 75GHz
- Initial integration on paper/flex with range of 200m





Year 2, 3 Plan

- Year 2
  - *Integrate with short-range wearable test-bed
  - *Developing 50% BW Wearable antenna
  - *Target Gain: 20dbi/Range: 1km (>20GHz)
- Year 3
  - . Integrate with ALL Wireless Interface
  - . Target Efficiency : 90%/Range: 5km
  - . Target Gain: 30dbi/Bandwidth > 100 %

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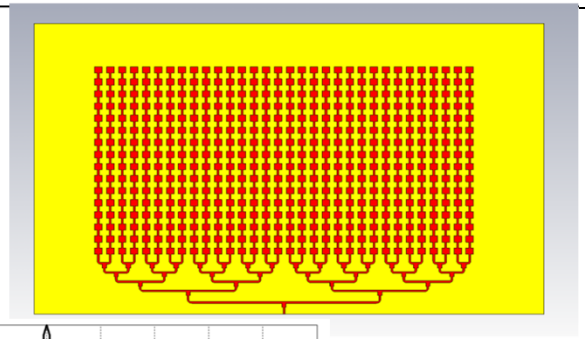
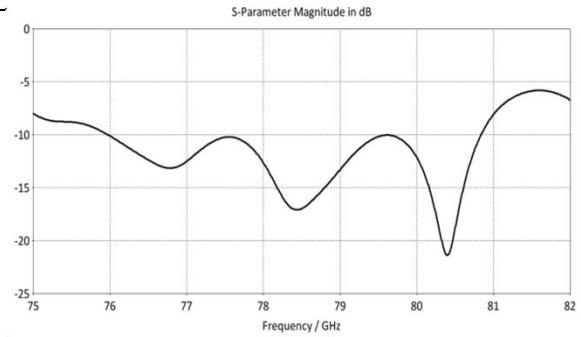
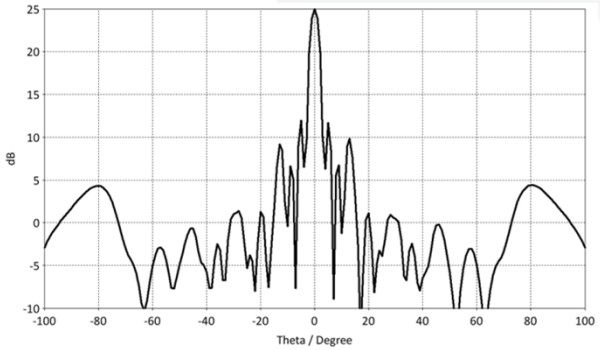
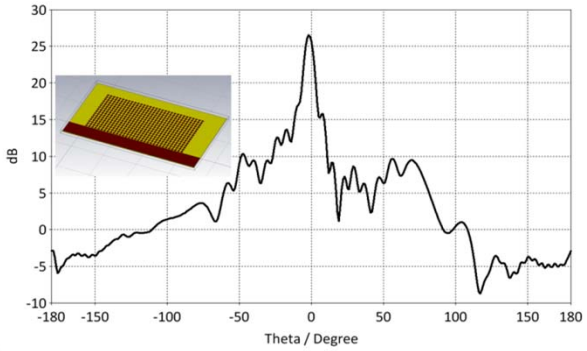
Conformal Flexible mmW Arrays for Radars/mmID's (BW=5GHz around 76-81GHz) with Gain 25dbi+





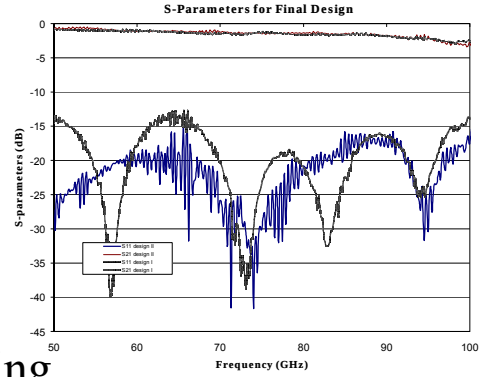


Gain (H-cut, Phi=0) at 80GHz



Gain (E-cut, Phi=90) at 80GHz

- Best reported antenna in 76-81 GHz range
- Directivity > 25dBi from 76-81 GHz
- Aperture efficiency=73% (32x16 array)
- <3 deg H-cut beamwidth
- Most broadband reported ustrip-CPW interconnect (bottom right)
- 3D organic module integration
- 4x-6x cheaper than WG (waveguide)
- 6x-8x lighter than WG ones
- Conformal shape /Fully-printed
- Can cover short/med/long range radar bands
- Effective range > 300m-400m
- Easy to extend to 120/240GHz imaging



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S-parameters for 3D Transition CPW-CPW

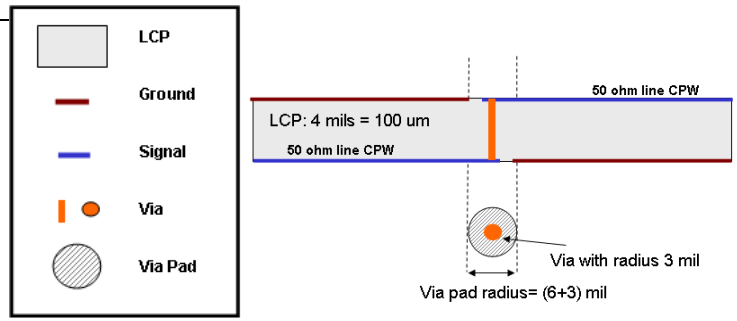
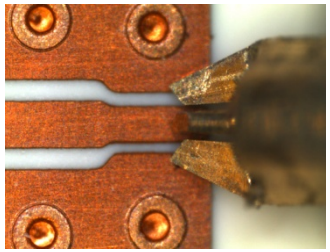
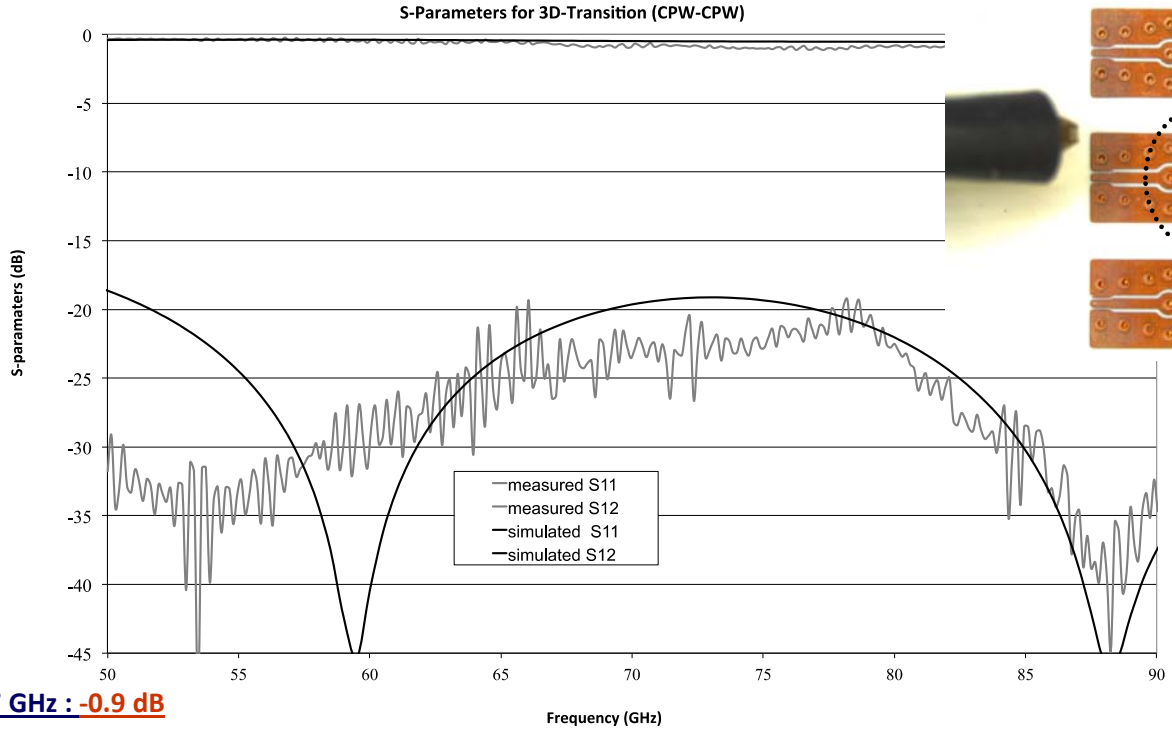
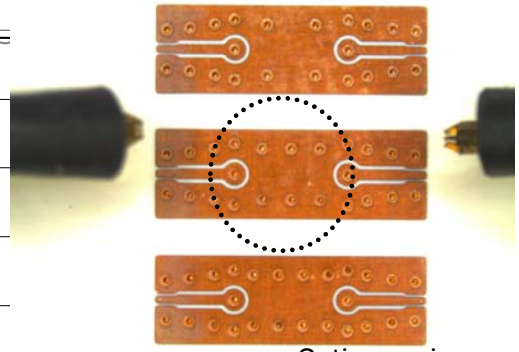


Photo of GSG Probe tips at the structure launch







Optimum via spacing (center to center): 500 µm

*** S_{21} for back-to-back transition at 77 GHz : -0.9 dB**

A. Rida, A. Margomenos, T. Wu, and M. M. Tentzeris, "Novel Wide-band 3D Transitions on Liquid Crystal Polymer for Millimeter-Wave Applications up to 100 GHz", pp. 953-956, *IEEE International Microwave* Symposium Boston, MA, USA, June 2009.

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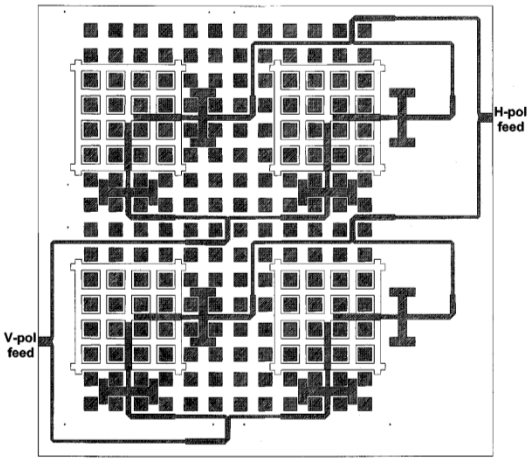
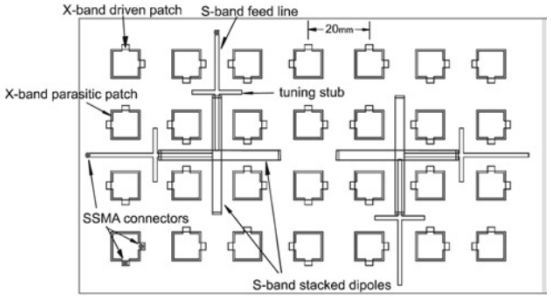
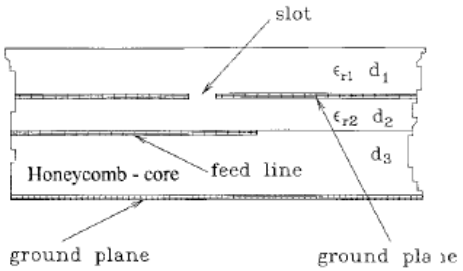
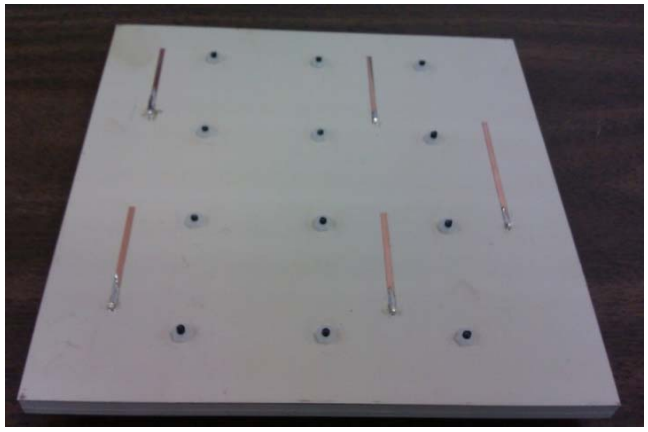
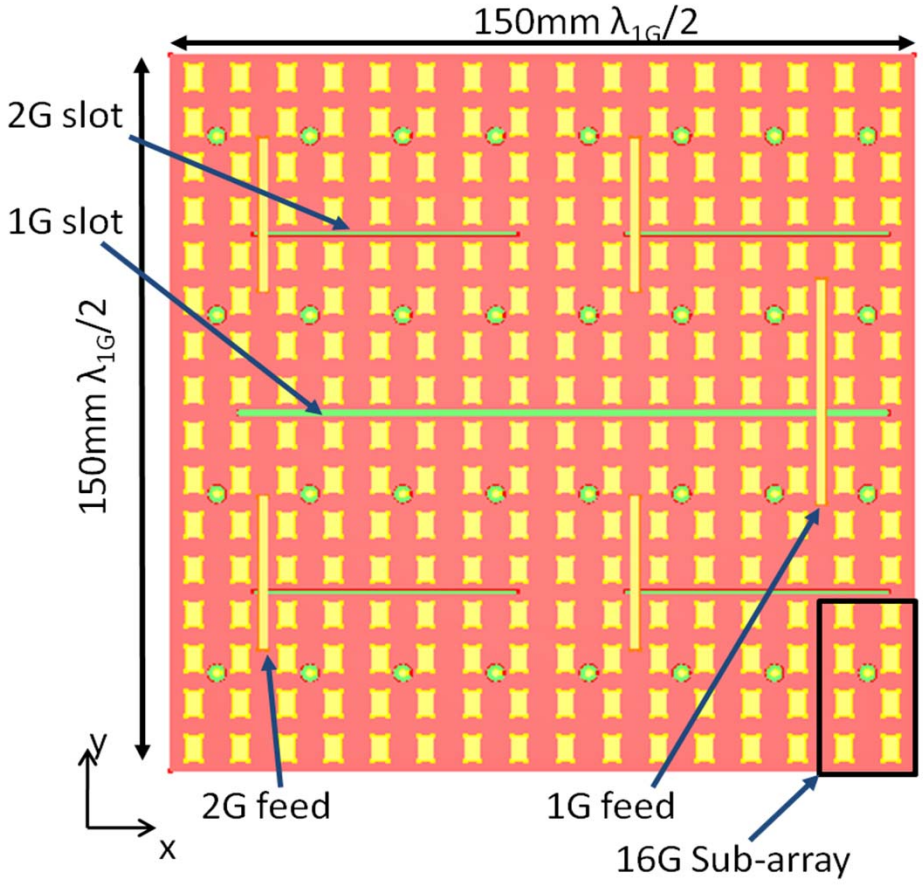
Existing Dual Band Array

	Pozar, 2001	X. Qu, W.Wang 2007	Pokuls, Pozar 1998
			
Pro	•8:1 frequency ratio •Thin: λ/29 •Dual Polarized	•3:1 Frequency Ratio •Thin: λ/11 •Dual polarized	•Wide Beam Scan •Dual polarized
Con	•Limited Beam Scan •PCB	•Limited Beam Scan •PCB	•1.8:1 Frequency ratio •Thick: λ/3.5

Ultrathin 1/2/16 GHz Triple Band Shared Aperture Array

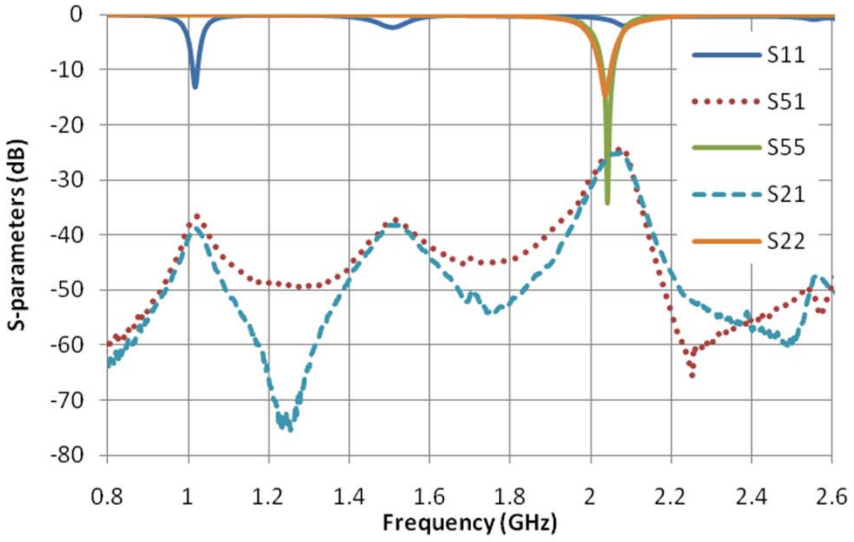
- Multilayer (no hidden Via)
- Frequency Ratio 16:2:1 (GHz)
- Thickness < 1 cm
- First ever reported 1/2/2^4 Tri-Band Shared Aperture Area Antenna Array
- Concurrent Communication and Radar/Sensing Capabilities
- Can be easily extended to subTHz imaging + comm systems

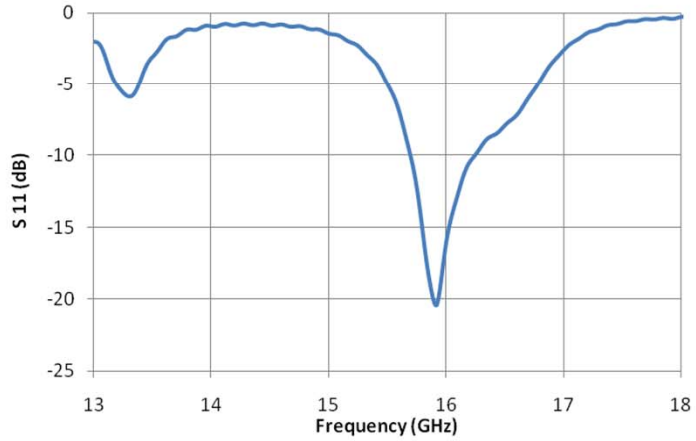


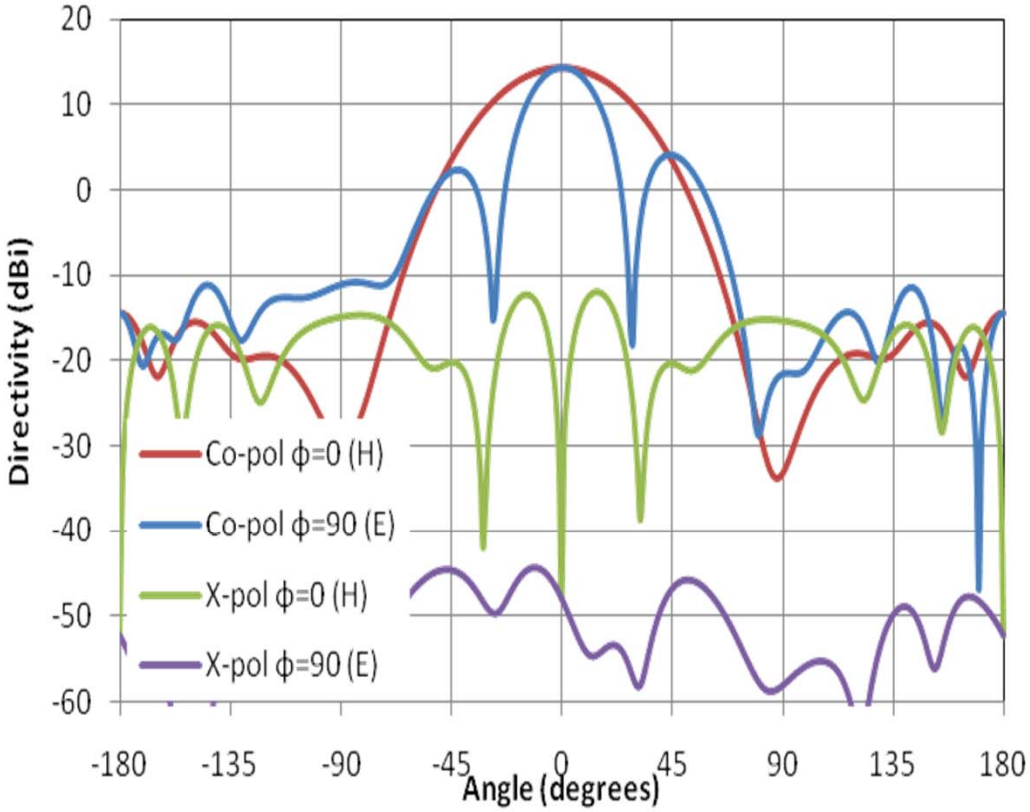


- *Testing collaboration with GTRI-SEAL*

Tri-Band Antenna Array Performance







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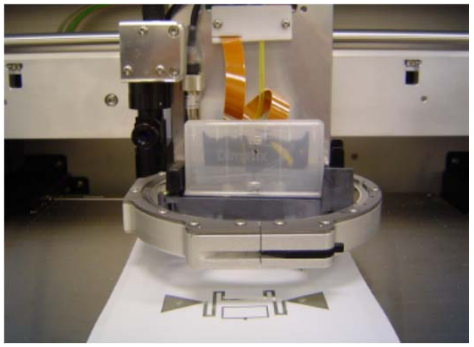
Comparison Table

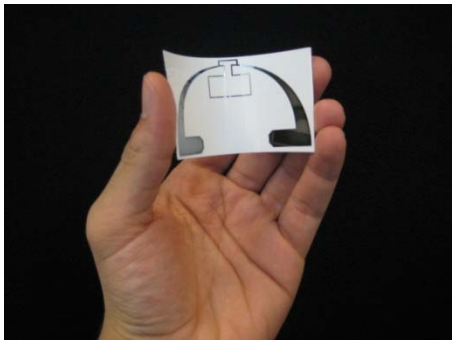
	Pozar, 2001	X. Qu, 2007	Shafai, 2000	Pokuls, 1998	**Triple**
Thickness	λ/29	λ/11	λ/27	λ/6.4	**λ/32**
Frequency Ratio	7.5:1	3:1	4:1	1.8:1	**16:2:1**
Polarization	Dual	Dual	Dual	Dual	Linear

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

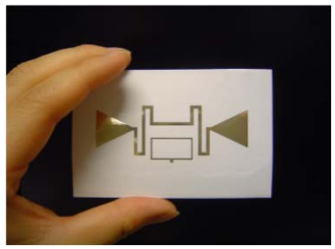
(LOWEST COST MATERIAL MADE BY HUMANKIND)

• 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 (~2) close to air's

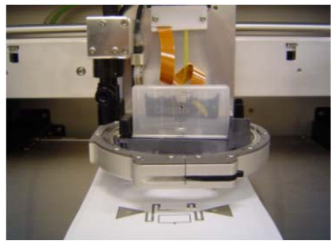


INK:

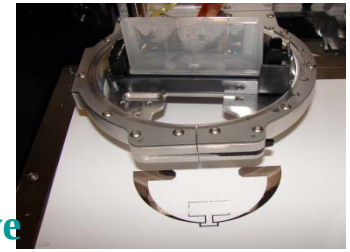
• Consisting of nano-spheres melting and sintering at low temperatures (100 °C)

• 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

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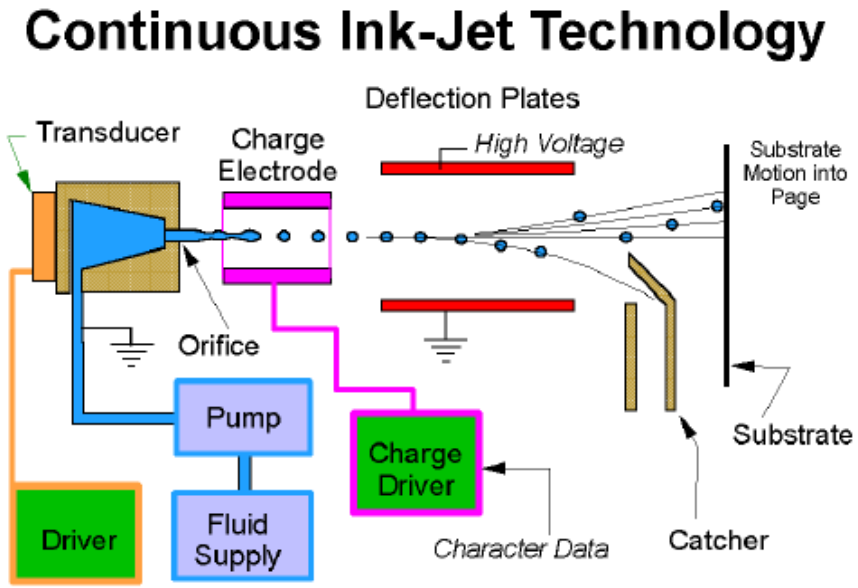
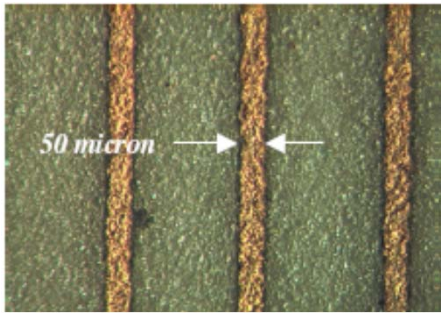
Inkjet-printing Technology - Printer

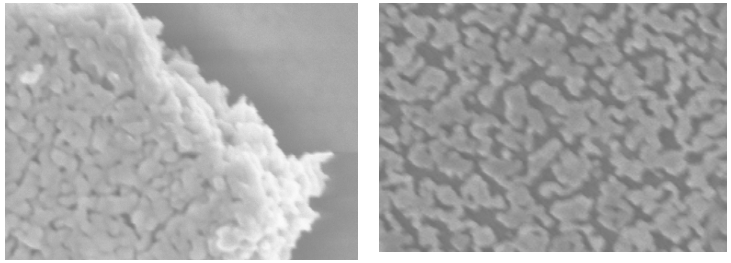
Characteristics:

- **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 …)**

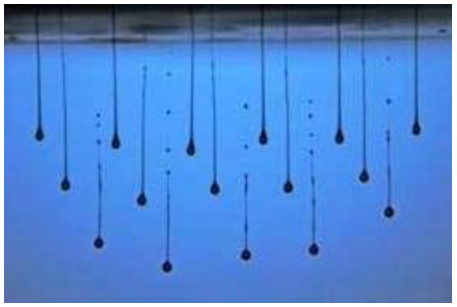




High resolution inkjet printed copper (20 μm)

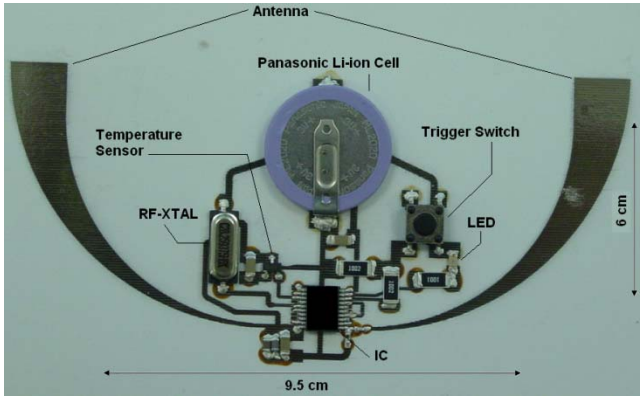


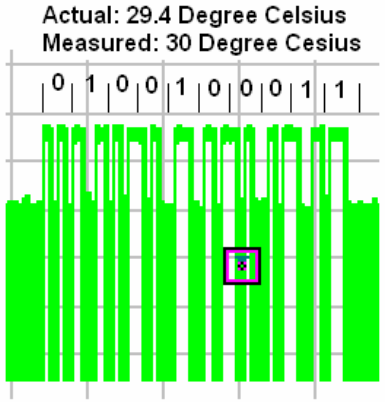
SEM Images of a Layer of Printed ink, Before and After a 15 Minute Cure at 150ºC



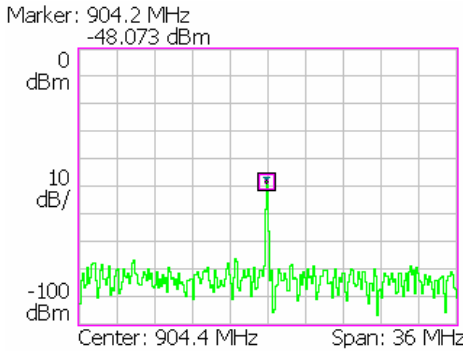
Wireless Sensor Module: 904.2 MHz

- 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

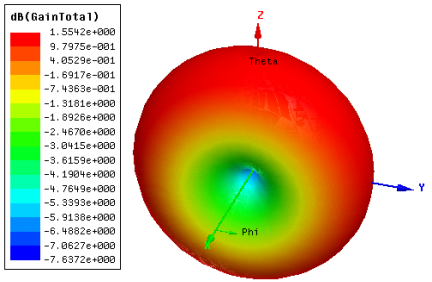




Wireless Temperature Sensor Signal sent out by module, measured by Spectrum Analyzer



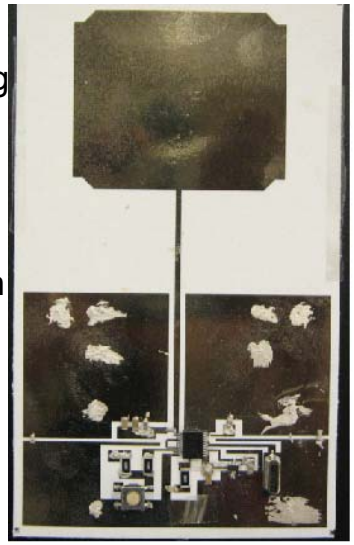
Wireless Signal Strength sent out by module, measured by Spectrum Analyzer



Antenna Radiation Pattern showing high gain

Wireless Sensor Module: 904.5 MHz

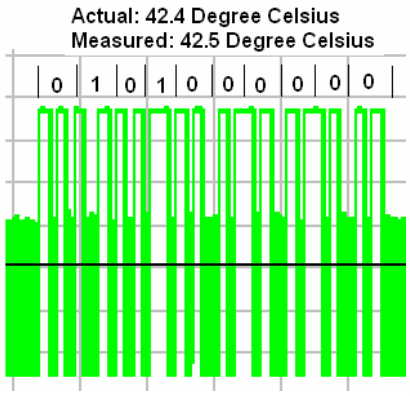
- Double Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.5 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for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



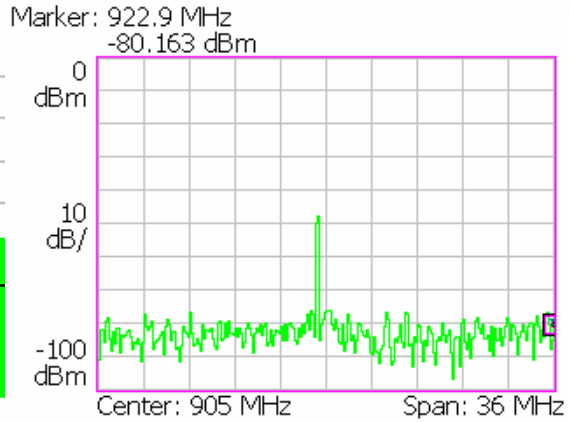
TOP VIEW

BOTTOM VIEW

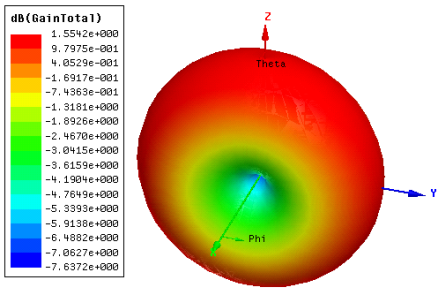
Circuit + Sensor+ Antenna on Paper



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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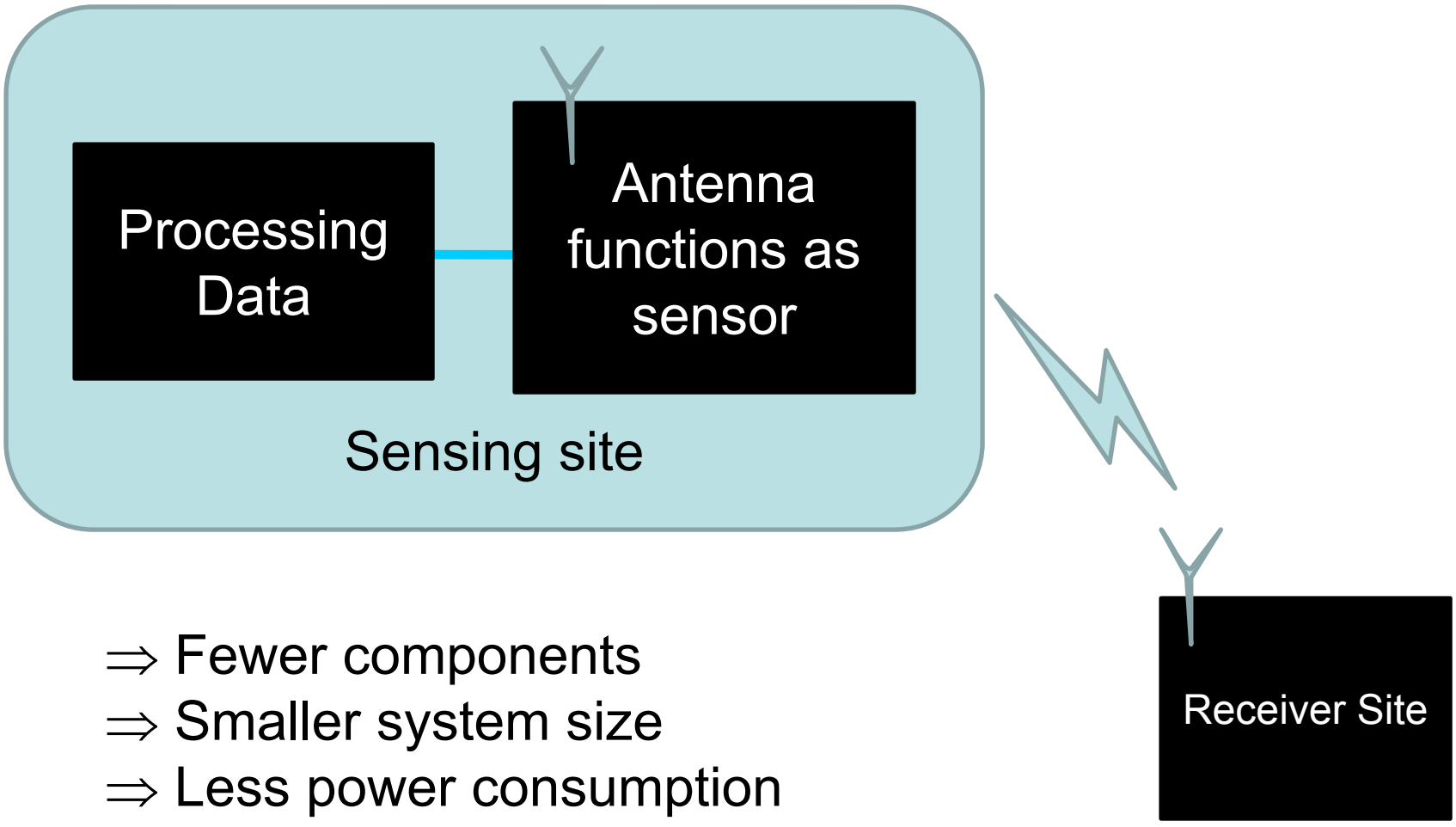
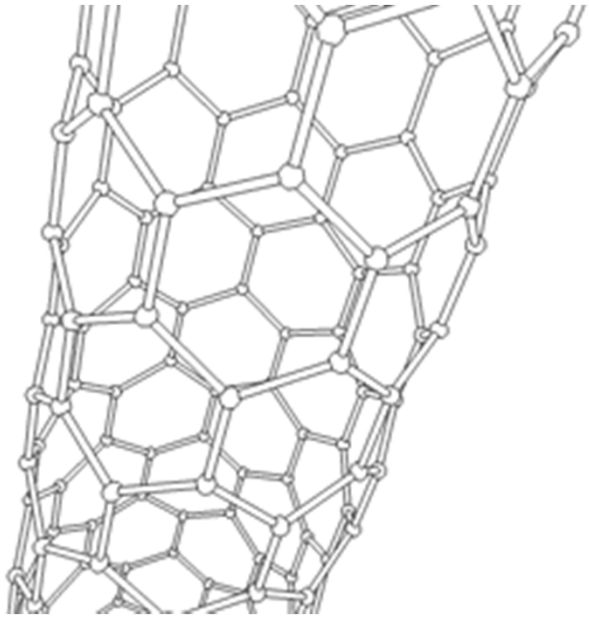
RF Wireless Pressure Transducer



⇒ 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 (NH3) and nitrogen oxide (NOx).
- The conductance change can be explained by the charge transfer of reactive gas molecules with semiconducting CNTs.

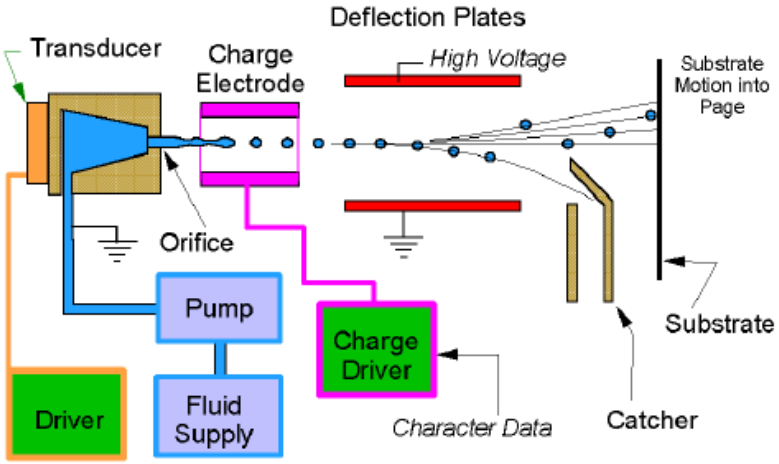


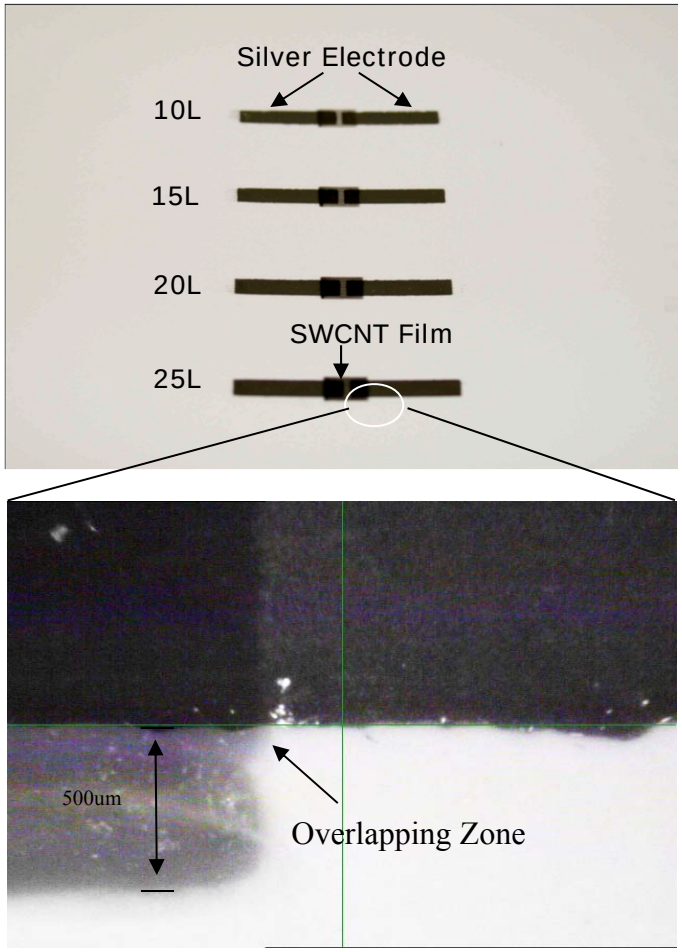
- Fabrication of CNTs film:

  -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!

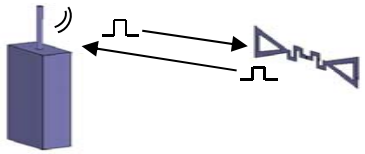
Inkjet-printed SWCNT Films



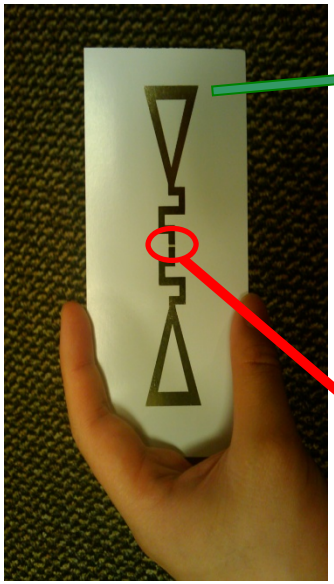


- Silver electrodes were patterned before depositing the SWCNT film, followed by a 140˚C sintering.
- The electrode finger is 2mm by 10mm with a gap of 0.8mm. SWCNT film was 2mm by 3mm.
- 1.1mm overlapping zone to ensure the good contact between the SWCNT film and the electrodes.

Gas Detection



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



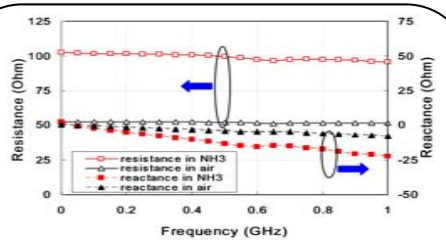
Tag Antenna @ 686MHz

Z_{ant}=42.6+j11.4 Ohm

+

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

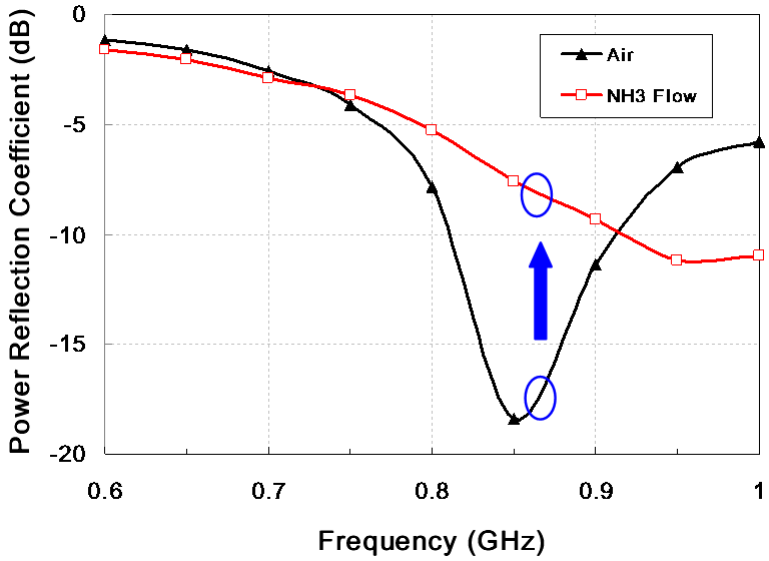
+



SWCNT Film @868MHz

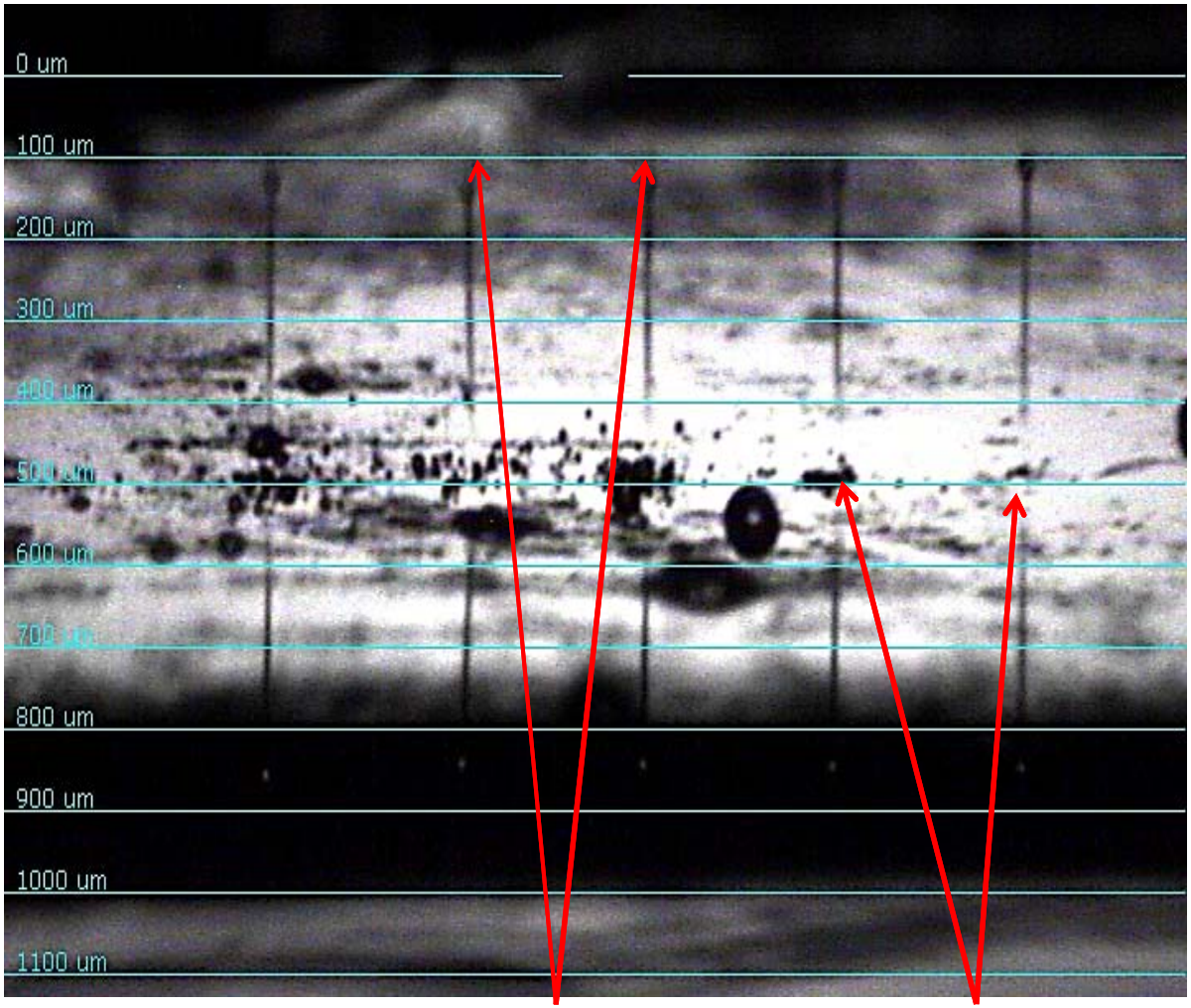
Z=51.6-j6.1 Ohm in air

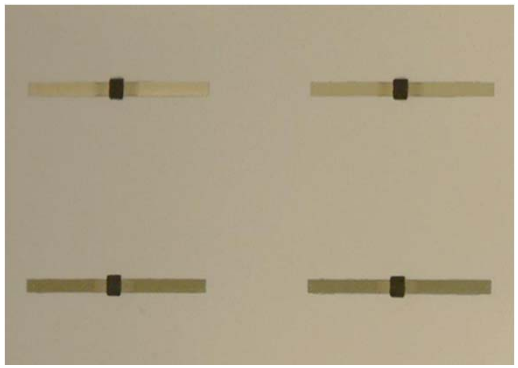
Z=97.1-j18.8 Ohm in NH3

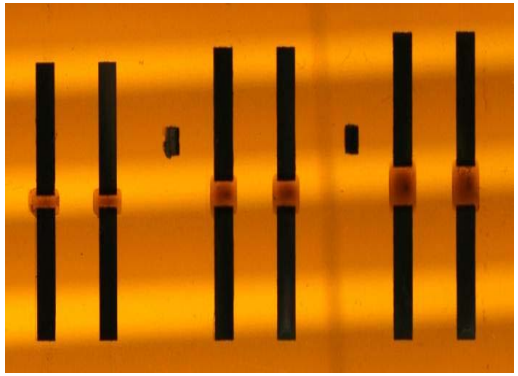


- Power reflection coefficient changes from -18.4dB to -7.6dB. At reader's side, this means 10.8dBi increase of the received power level.
- By detecting this backscattered power differnce, the sensing function is fulfilled.

Inkjet-Printed Graphene Oxide samples

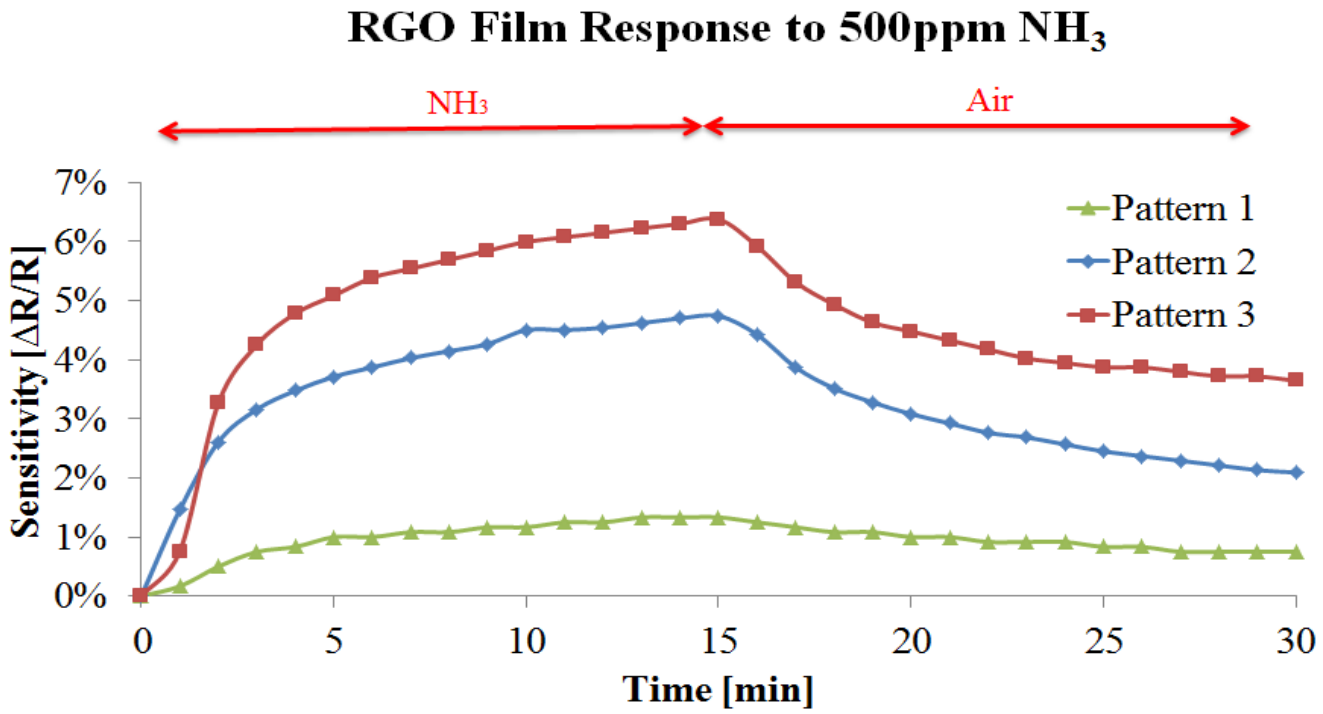




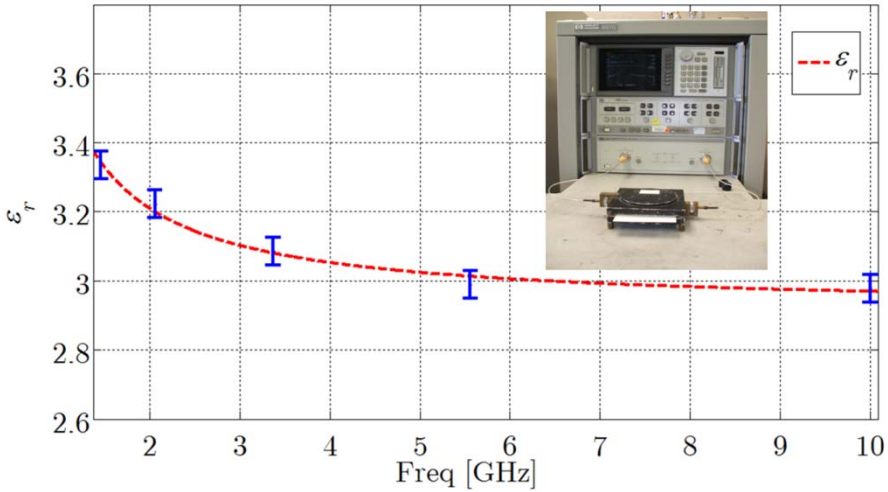


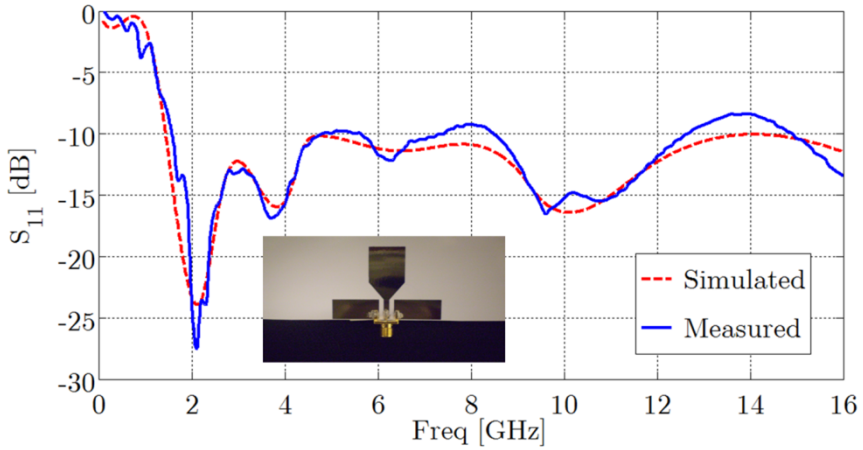
GO Ink Drop **Nozzle**

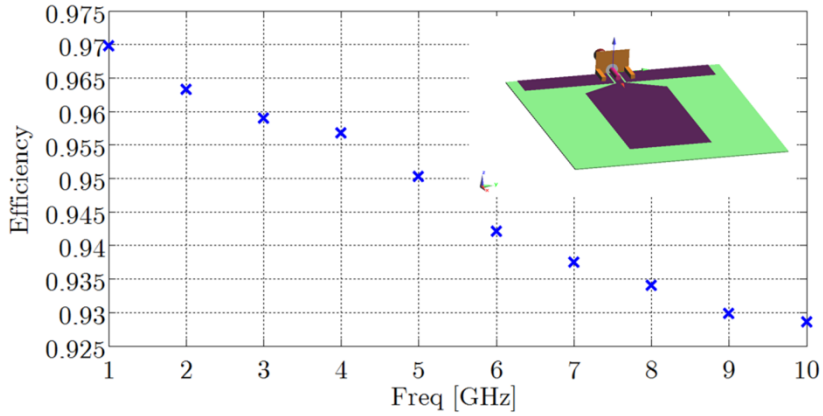
RGO sample performance under test gas



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







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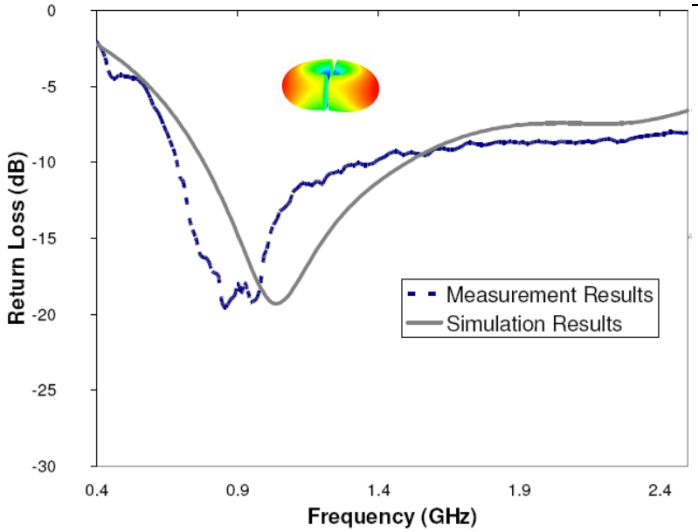
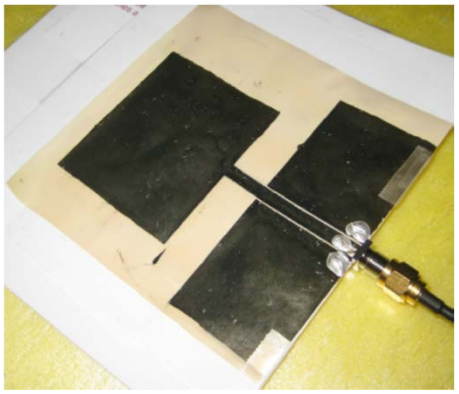
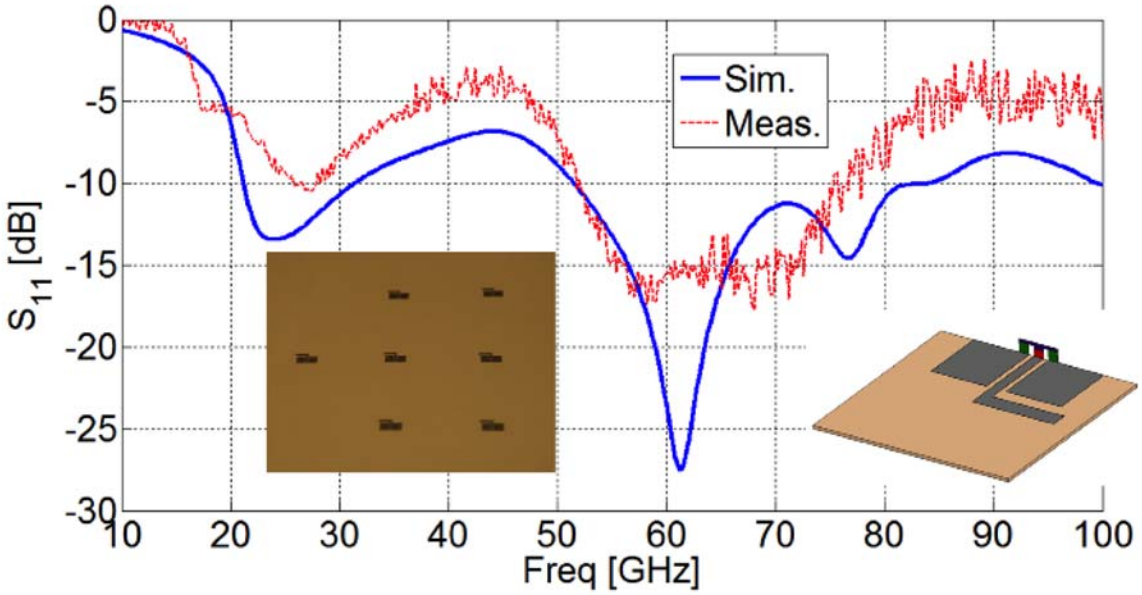
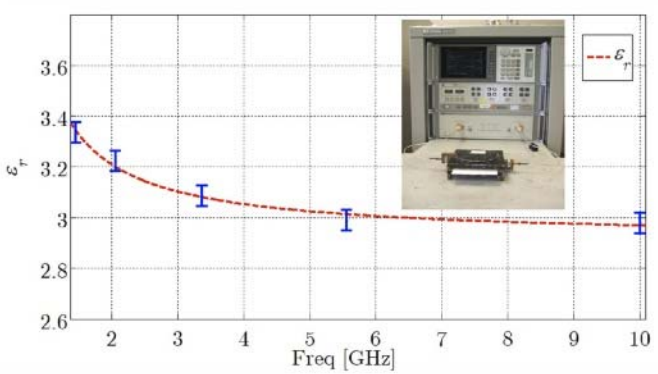
Inkjet Printing on LCP: Up to mm-Wave Frequencies

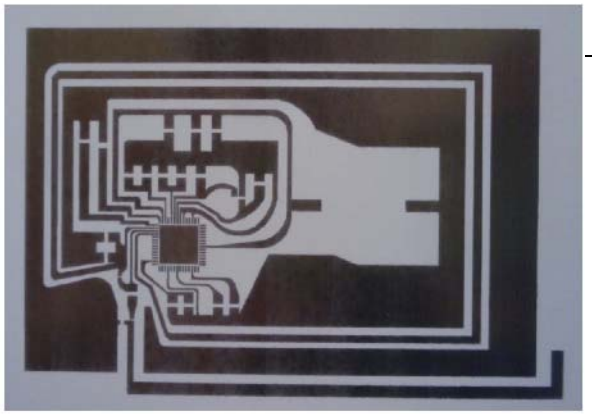


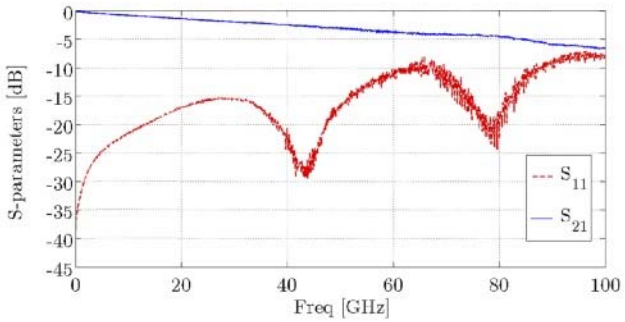


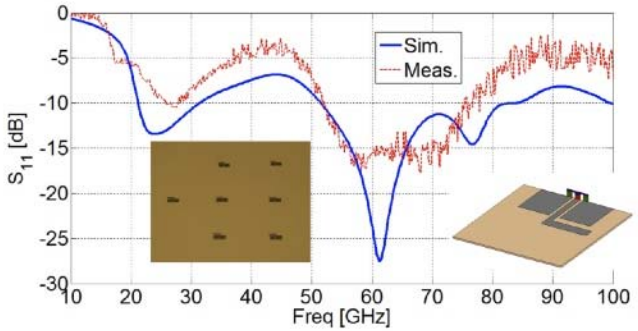


Extension of Inkjet Printing up to 60 GHz









First demonstration of inkjet printing technologies up to 80 GHz (5x better than state of the art)

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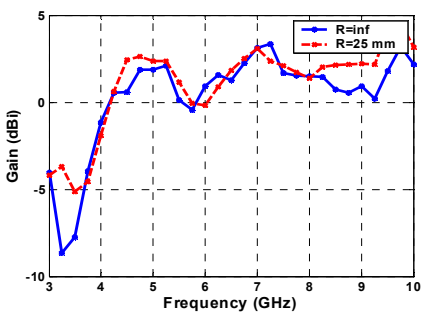
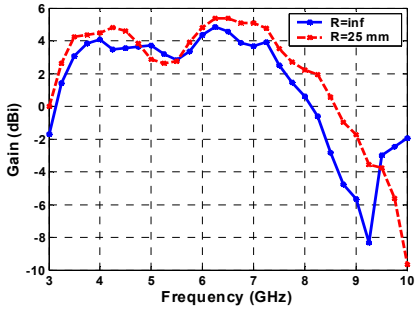
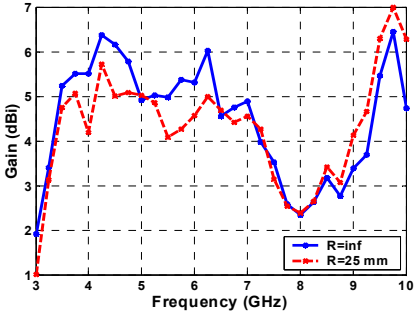
High Gain Performance and Consistent Pulse Fidelity (Ultrawideband) with Folding



(a)

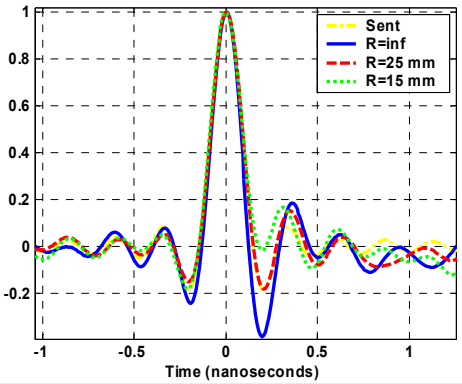


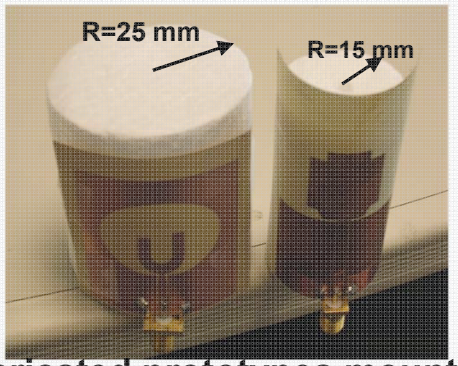
(b)



(c)

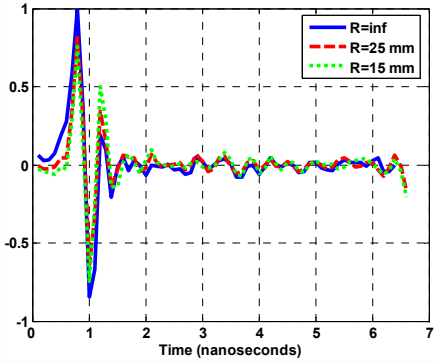
Raised Cosine Pulse





Fabricated prototypes mounted on Styrofoam cylinders

Impulse Response



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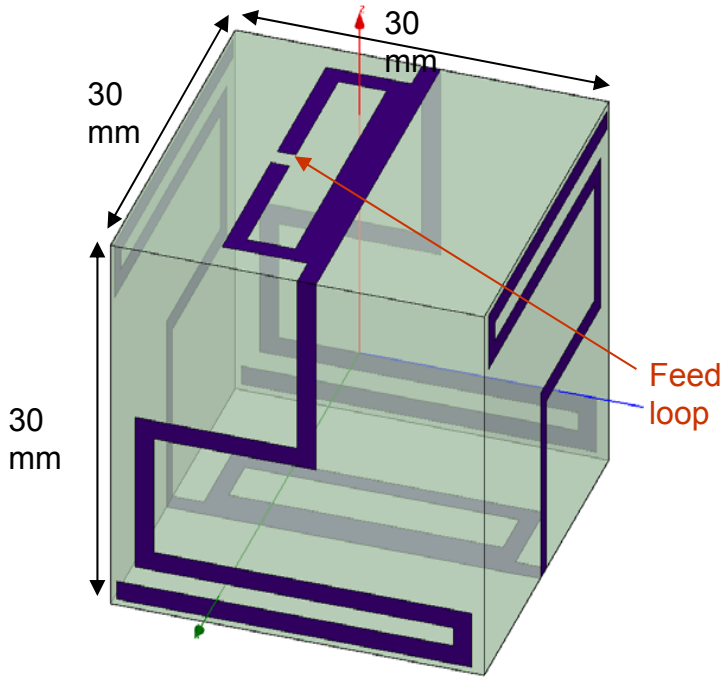
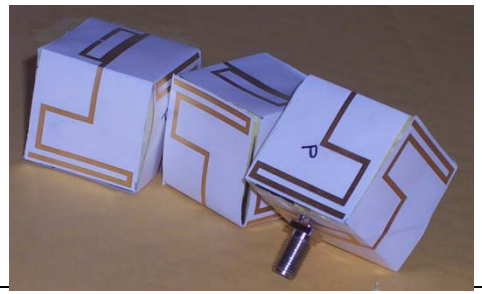
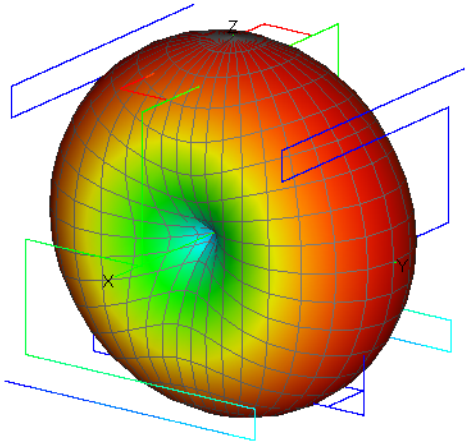
3D-"Magic Cube" Antennas

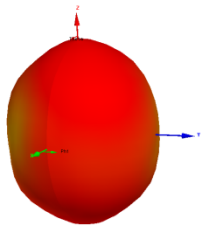
- Typical RFID/Wireless Sensor antennas tend to be limited in miniaturization by their length
- What if used a cube instead of a planar structure to decrease length dimension?
- Interior of cubic antenna used for sensing equipment as part of a wireless sensor network
- Can lead to the implementation 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



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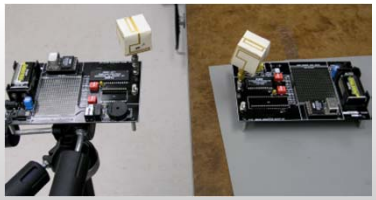
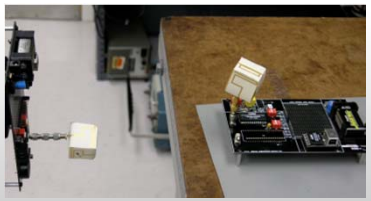
Experimental Set-Up

ORIENTATION #1



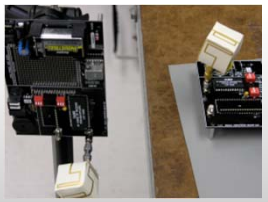
Tx and Rx co-polarized

ORIENTATION #2

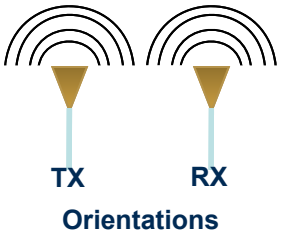


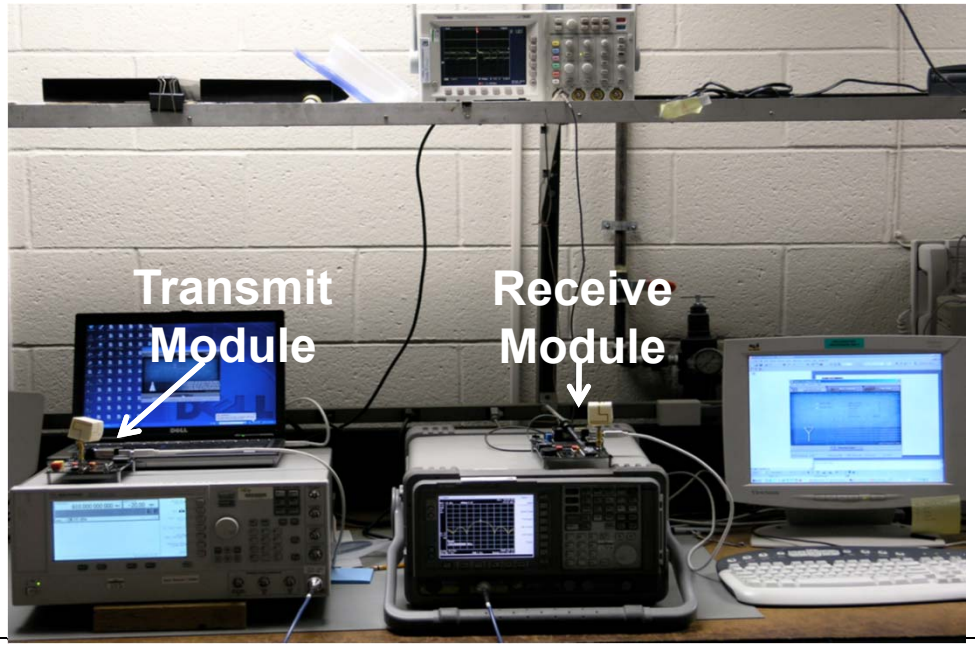
Tx and Rx orthogonal

ORIENTATION #3



Tx and Rx random



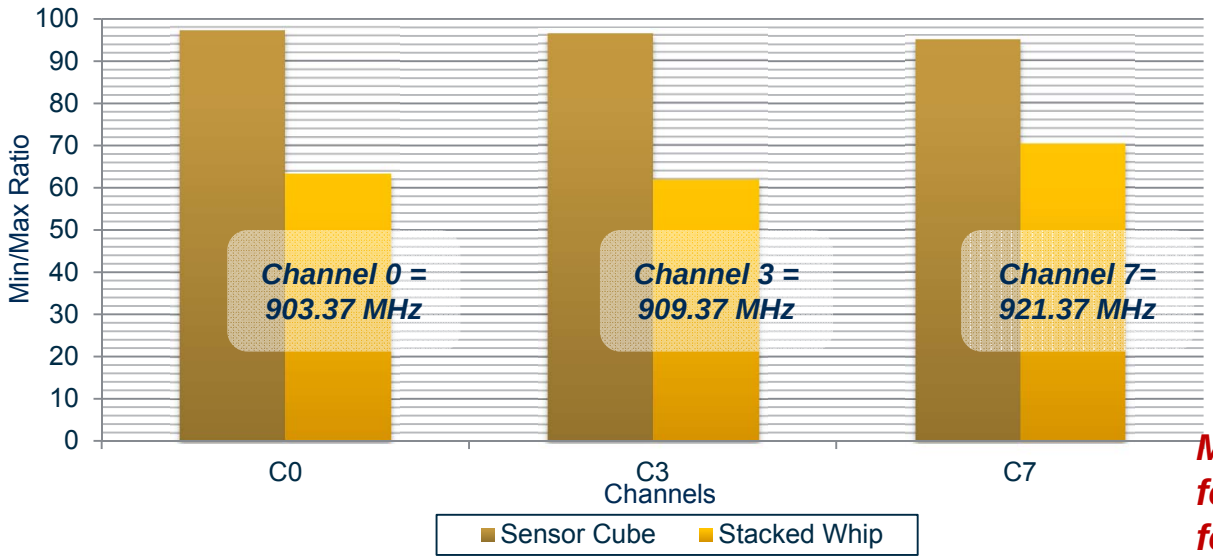


Outdoor Range Measurement

TX

RX

Min/Max Distance Ratio for All Orientations



- **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)

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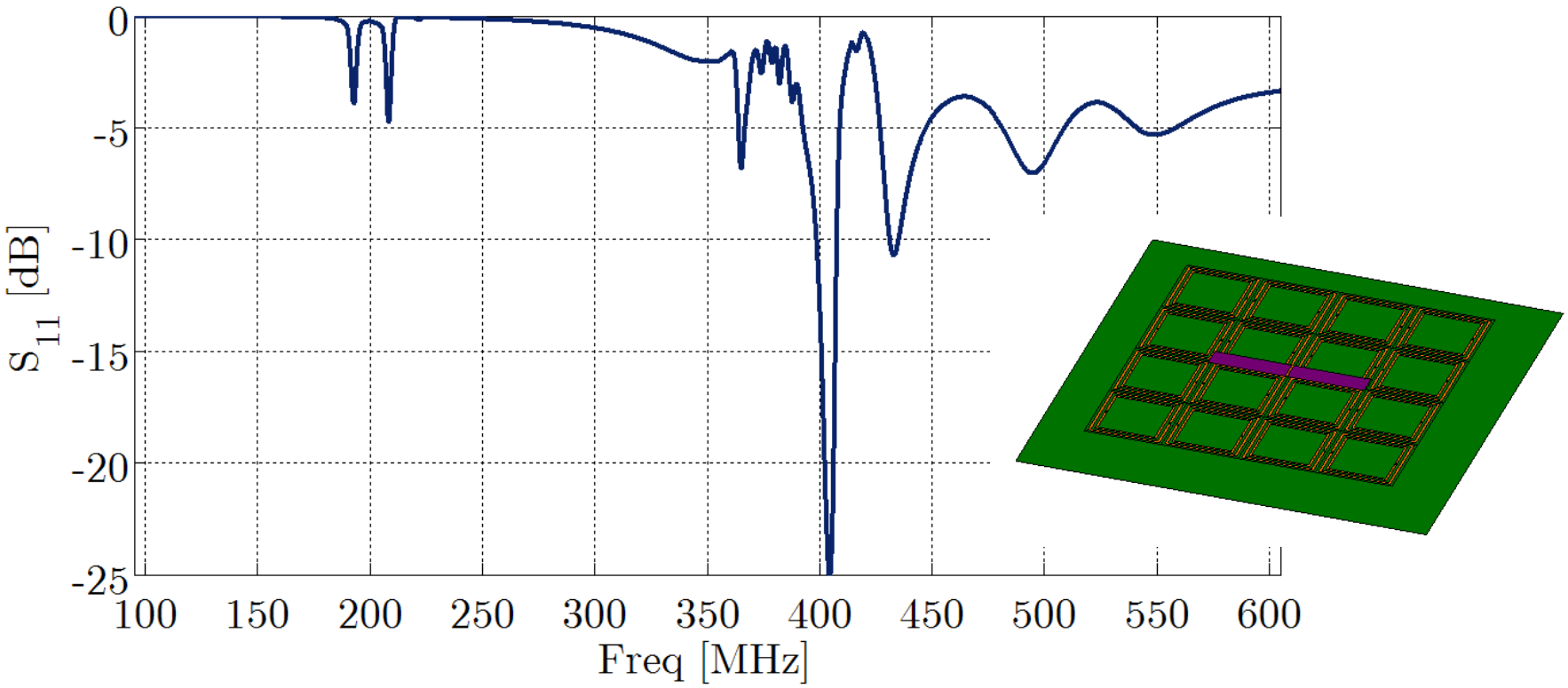
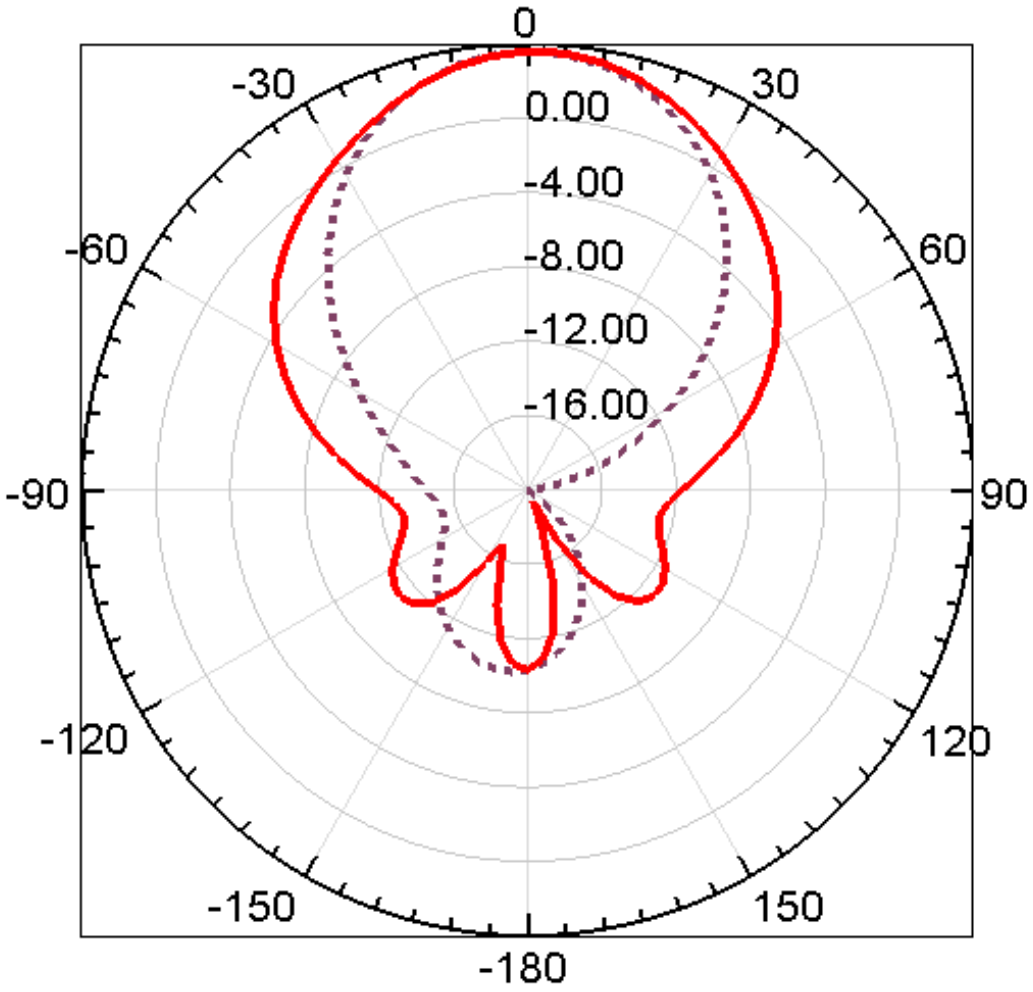
Antenna on Top of Engineered Surface



- A 4x4 split ring resonator array with a dipole placed on the surface (feeding now shown) and the resulting simulated antenna reflection coefficient.

Simulated Antenna Gain in two vertical cuts (Φ=0, 90°)



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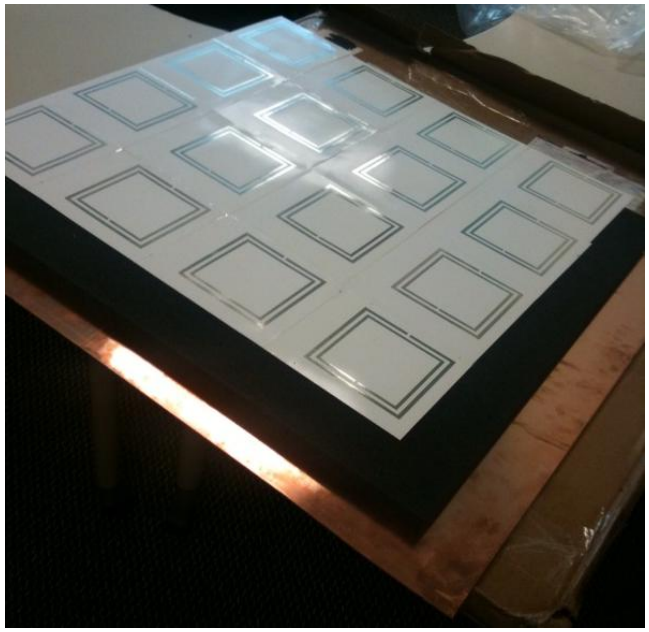
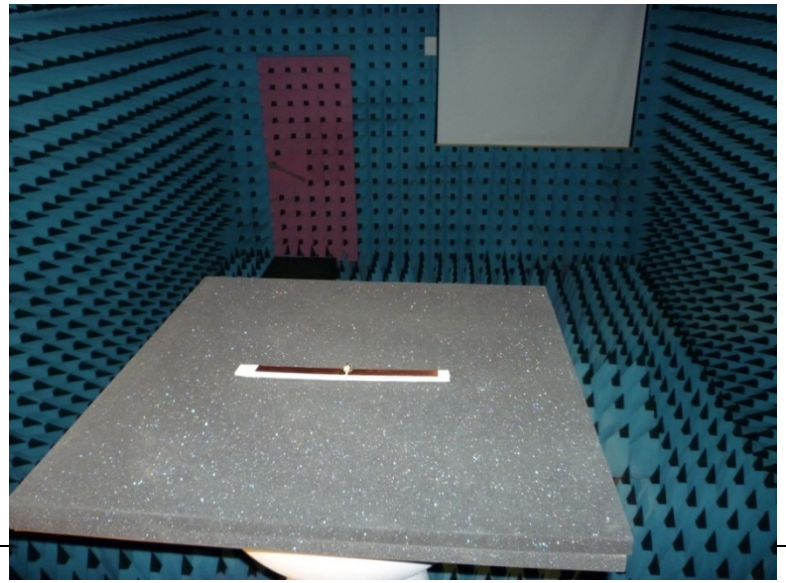
Fabrication

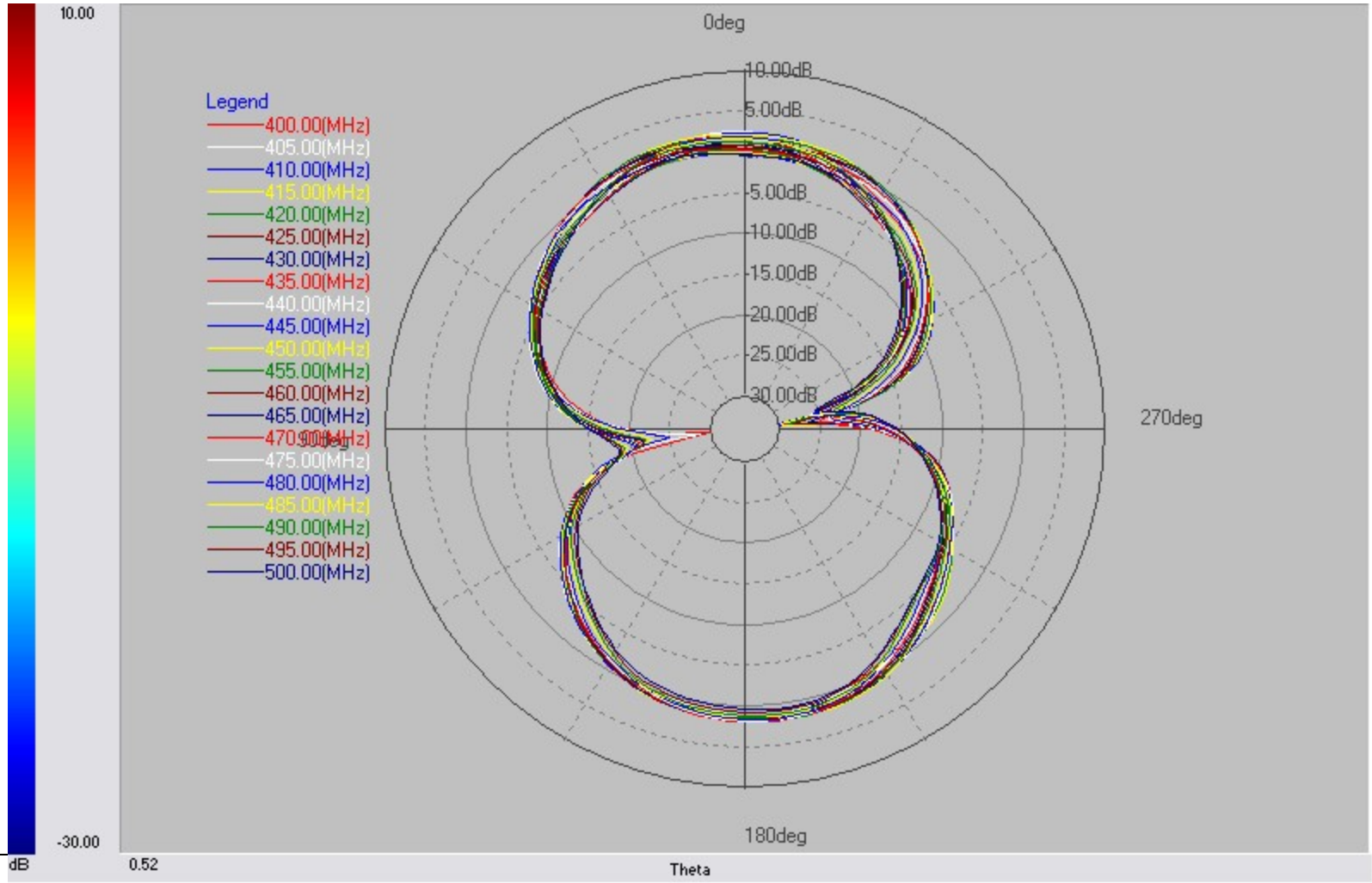
- 16 split ring resonators printed on paper substrate, and assembled using small amount of tape
- 2 pieces of foam, 81cm x 81cm, glued to copper sheet and EBG





- Measurements conducted at Satimo

Dipole without EBG:
E Total. dB Phi=0 deg



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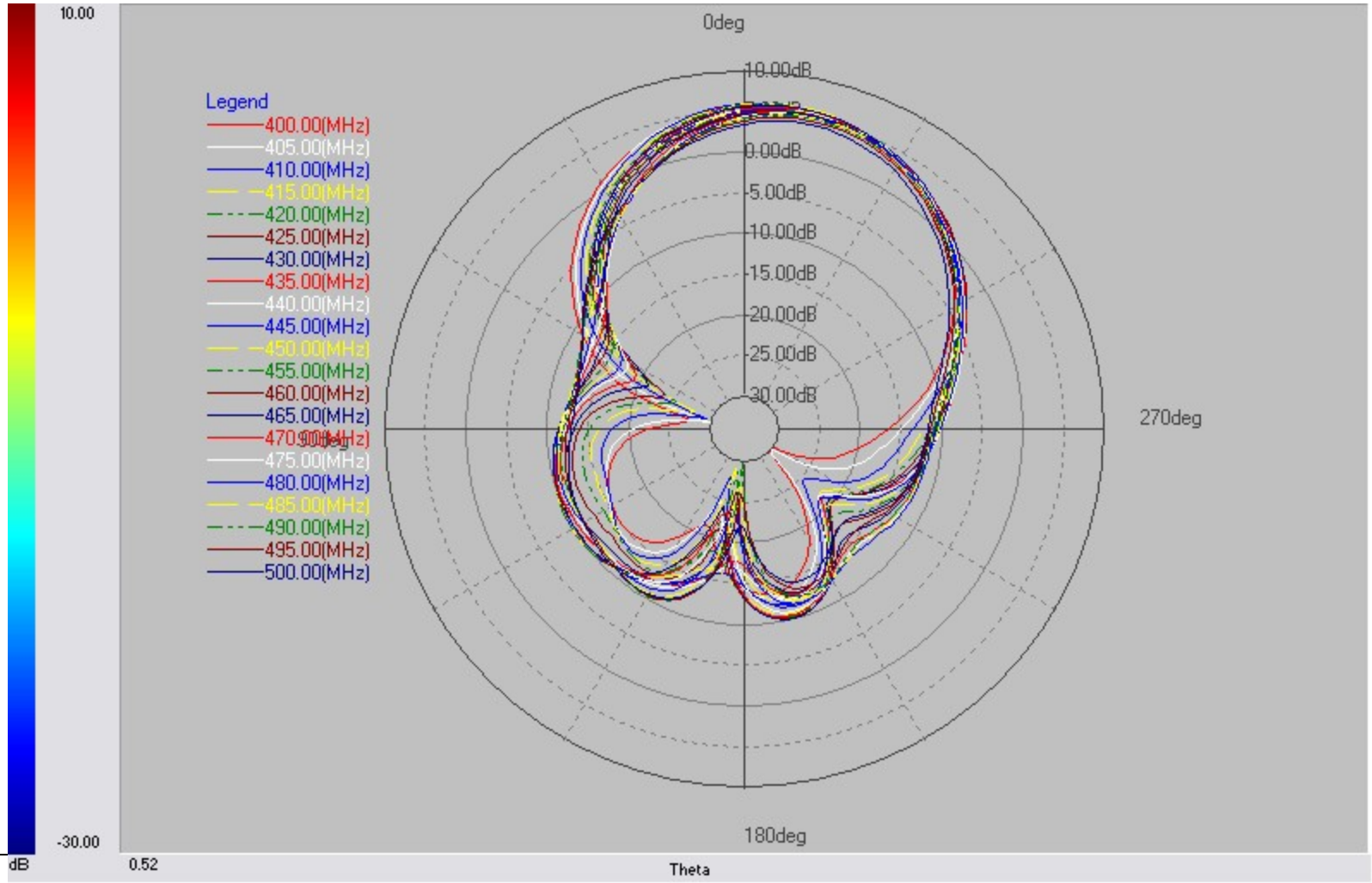
Dipole with EBG:
E Total. dB Phi=0 deg



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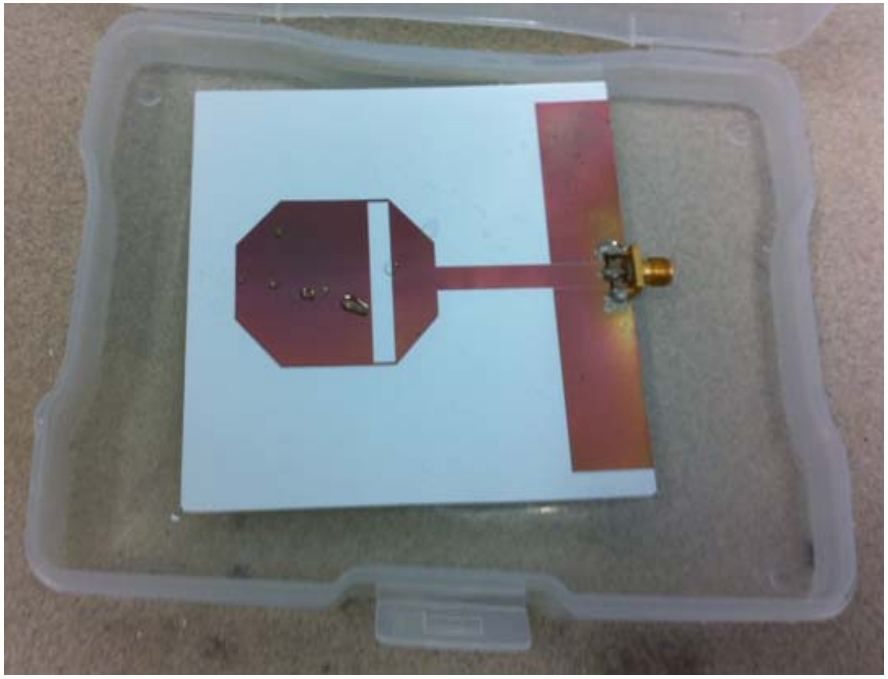
Printed Antenna in the Water



< Antenna W/ coating>

< Antenna W/O coating>

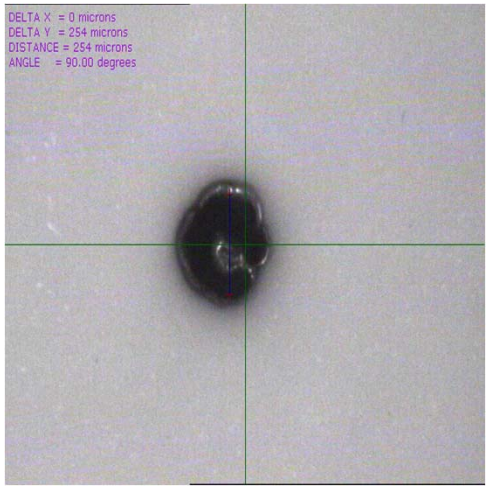
< Antennas in the water after 1 Hr>

The coated antenna can survive in the water

Laser Resolution Test

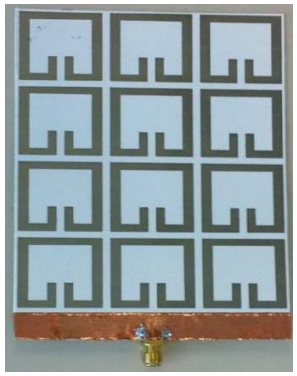
< Diameter: 56 um >

< Diameter: 150 um >

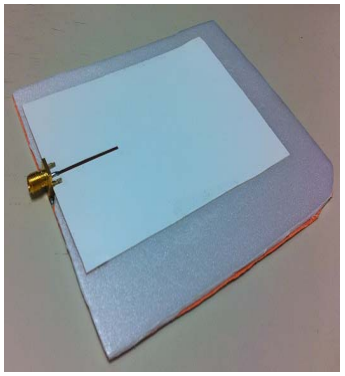


< Diameter: 254 um >

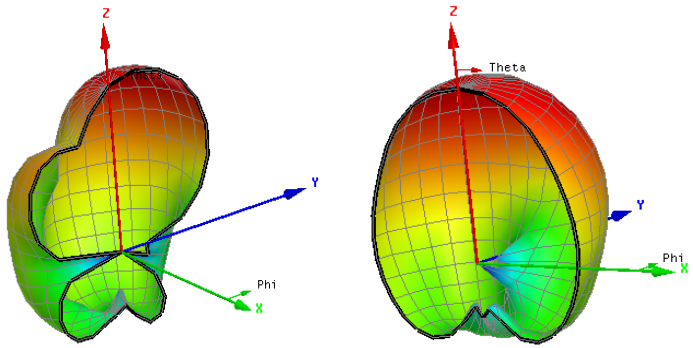
- A via hole which's diameter is 50um is successfully punctured
- The next step is metallization of the via holes



(a) Printed EBG

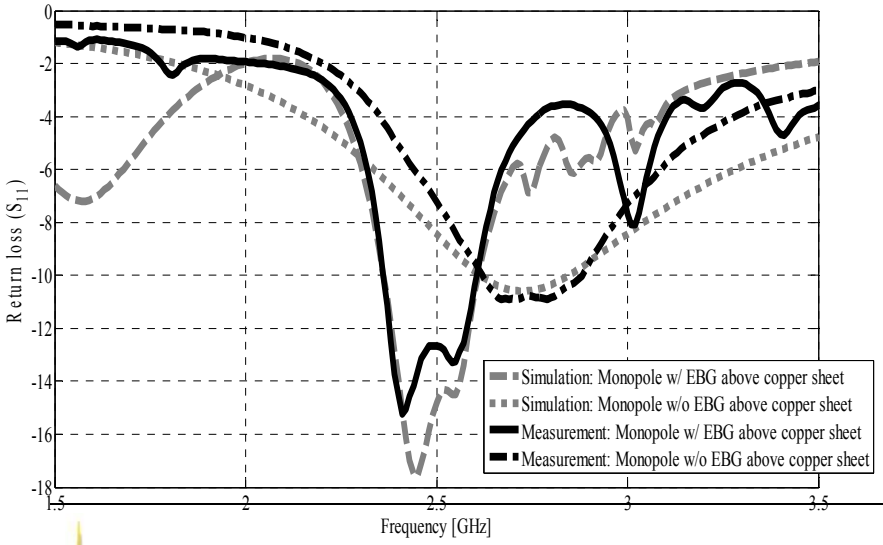


(b) antenna prototype

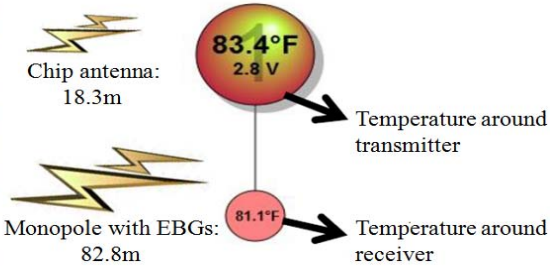


(a)E-plane (b) H-plane

< Radiation Patten>



< Measured Return Loss (S_{11}) >



< Communication Range Comparison>

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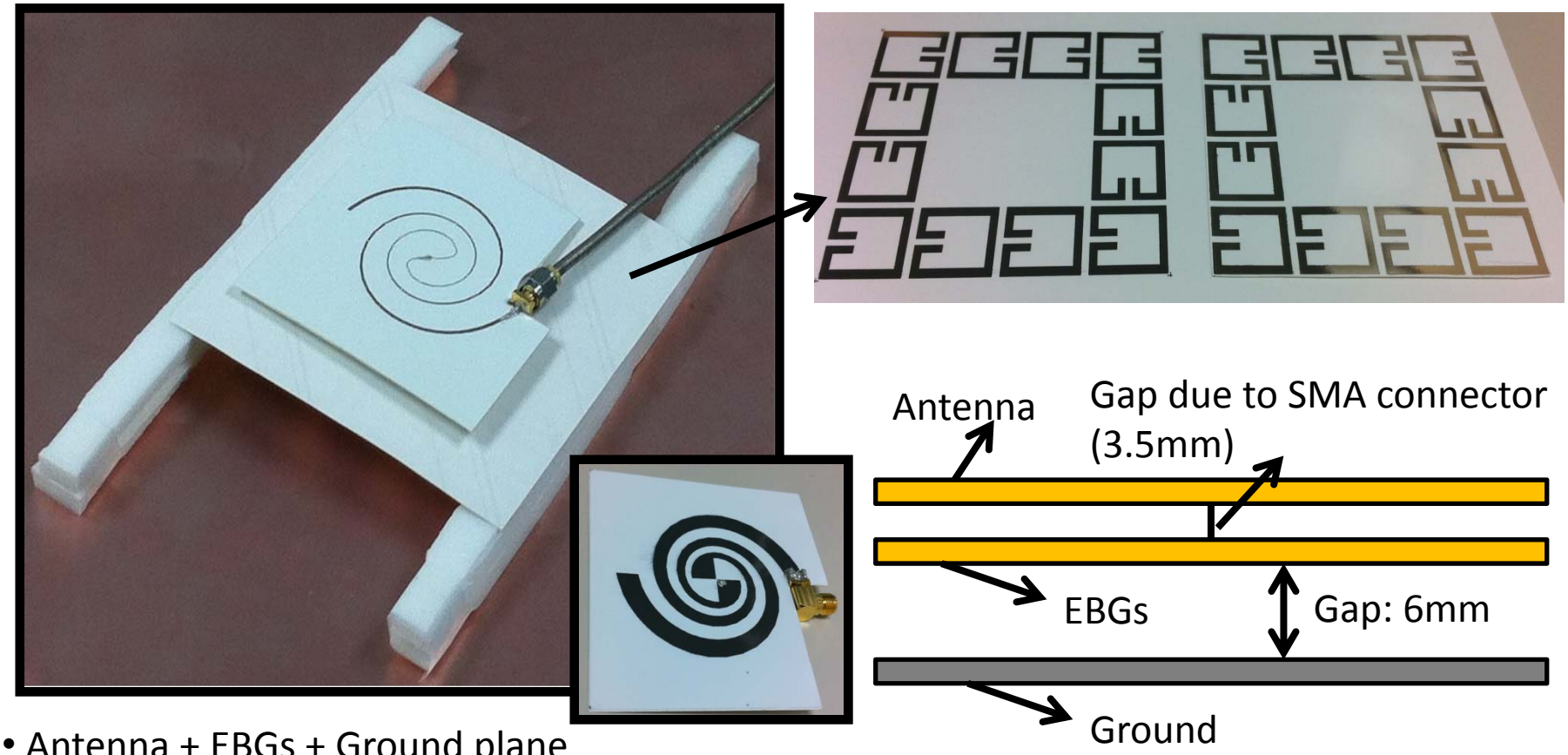
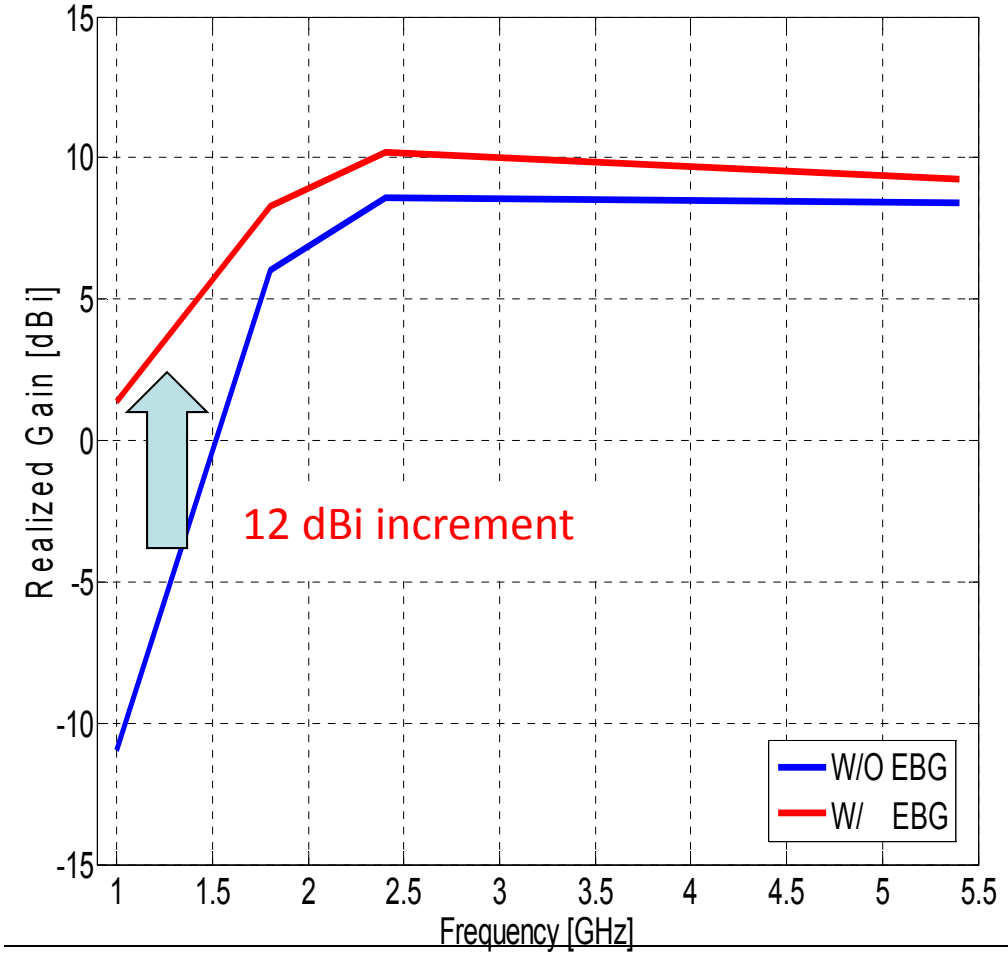


- Antenna + EBGs + Ground plane
- EBGs suppress surface wave and increase axial ratio[1]
- EBGs increased gain of antenna at low frequency

Antenna Backed by Inkjet Printed EBG

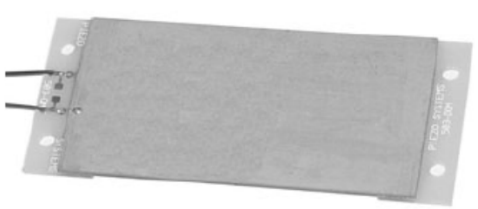


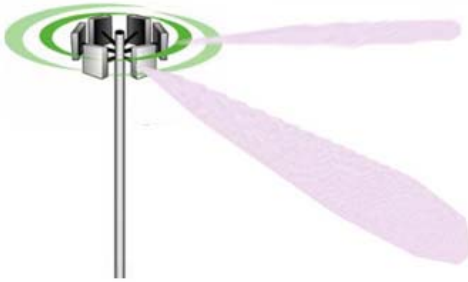
Freq.	W/O EBG Ground	W/ EBG Ground
1.0 GHz	-10.98 dBi	1.366 dBi
1.8 GHz	6.035 dBi	8.317 dBi
2.4 GHz	8.563 dBi	10.19 dBi
5.4 GHz	8.438 dBi	9.242 dBi

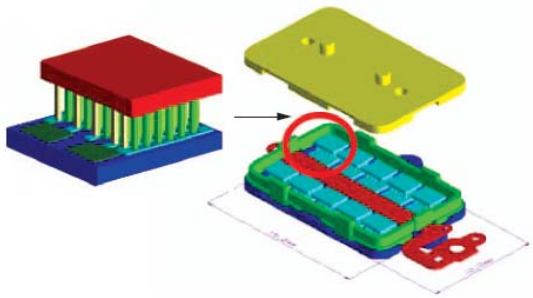
< Gain Improvement >

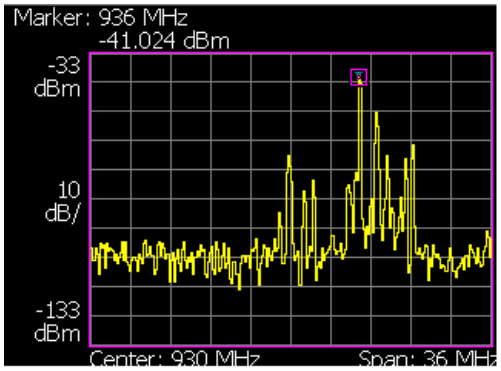
Power Scavenging

- 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

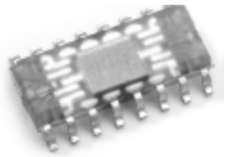




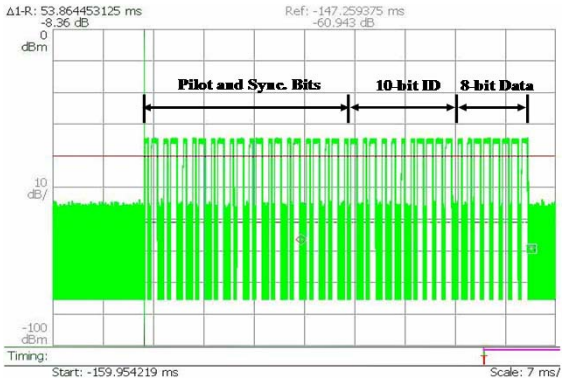


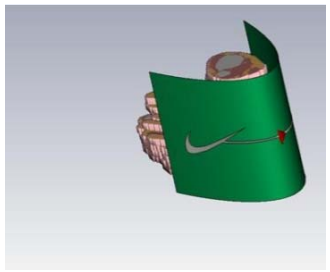


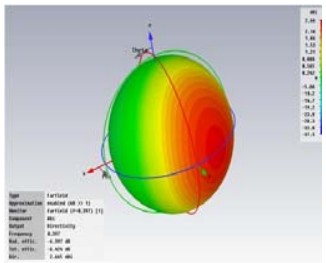
936 MHz: -41dBm (0.08μw)

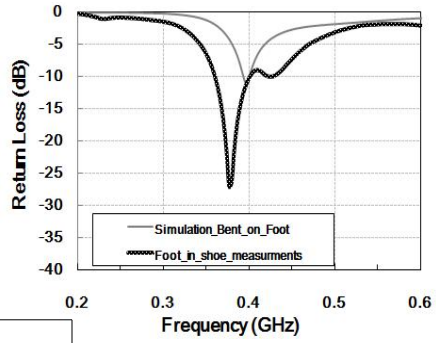


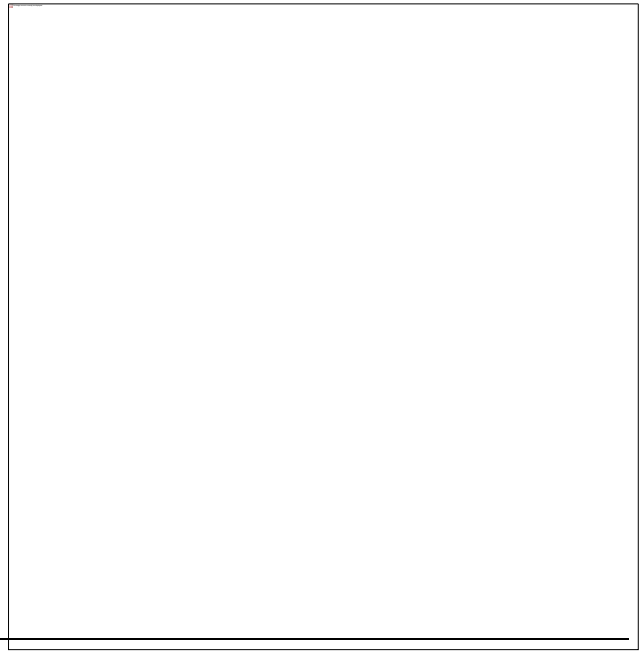
Wearable Energy Scavenger



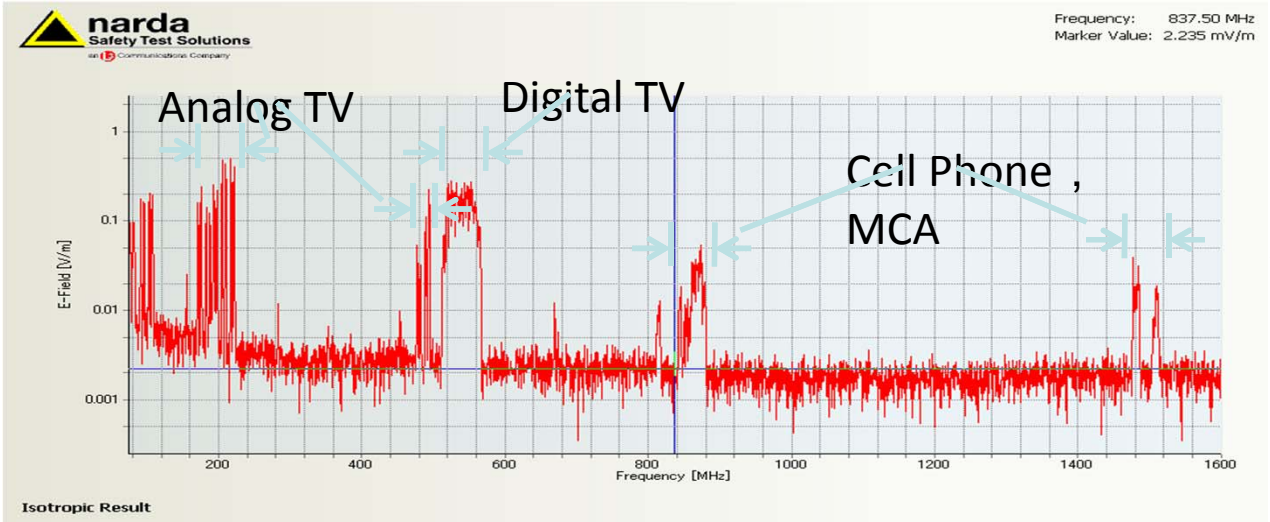








Ambient Wireless Power: Terrestrial TV Bands



Japan:

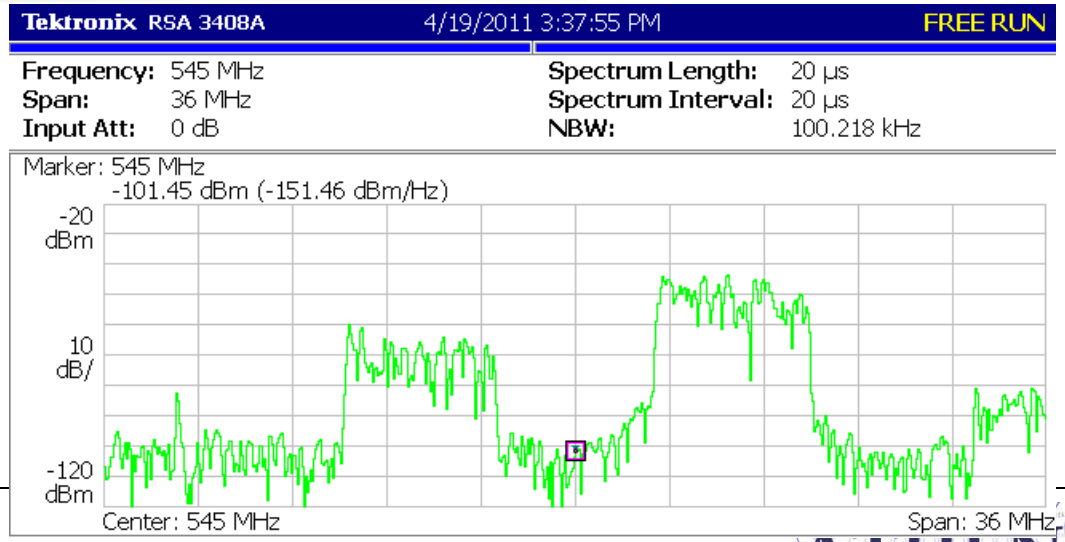
Analog TV: 460-500 MHz

Digital TV: 500-600 MHz

US:

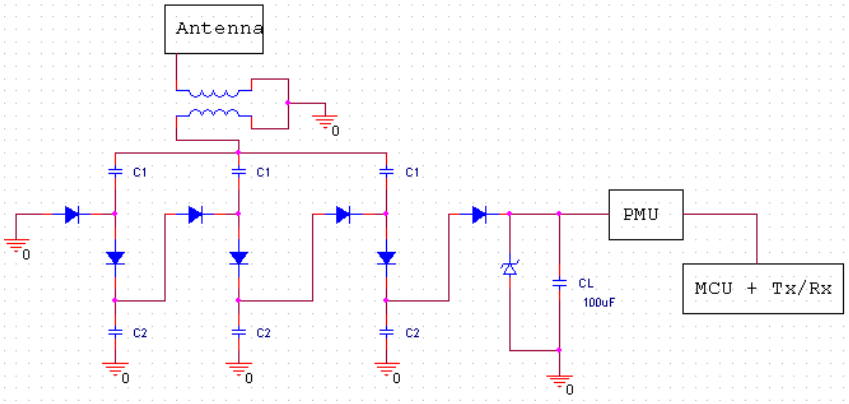
Digital TV: 500-700 MHz

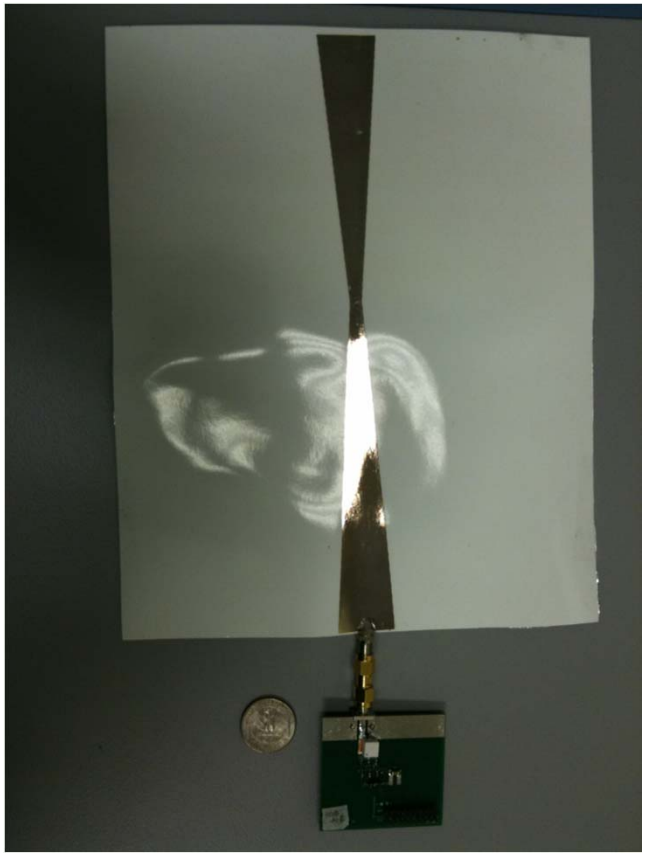
Equally spaced channels



Wireless Scavenger for TV & Cellular Signals

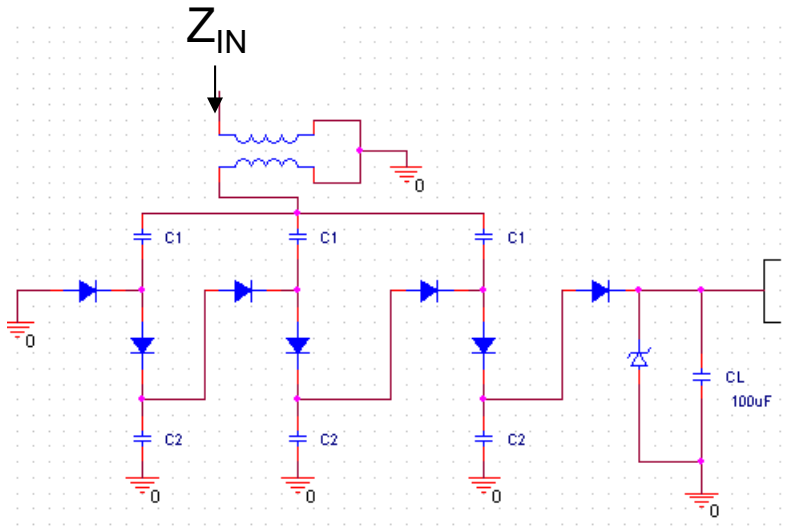
- **Turn on Power:**
  - **30uW → Charges Super cap to 1.8V in 2 mins**
  - **80uW → Charges Super cap to 3V in 3 min**
- **Used to turn on Microcontroller+ Low Power radio**



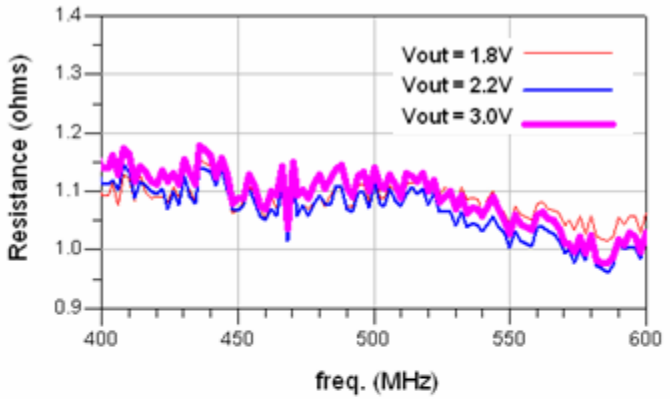


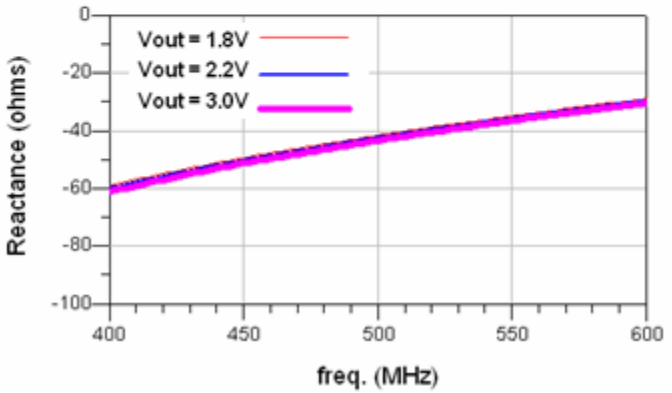
Wireless Scavenger for TV & Cellular Signals

- Captured power maximized through optimum design and matching of antenna and RF-DC charger
- Ensures high efficiency and optimum load match for different ambient power levels



V_{OUT}
=1.8V
=2.2V
=3.0V





Z_{in}: Very low series losses. Capacitive for most part

Ultrathin Integrable Batteries

NEC

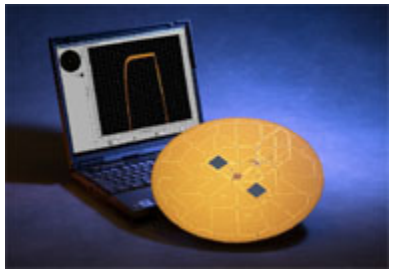
300 micron thin
No heavy metals
Environment friendly
Polymer electrolyte

Carrier film -
Plastics

Philips
Lithylene™ battery

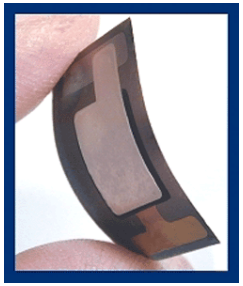
Free form factor
Porous lithium
Polymer electrolyte

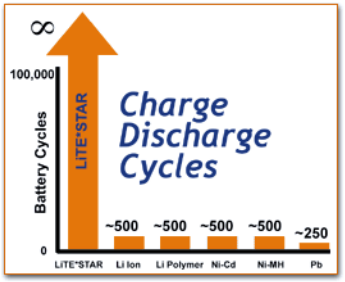
Licensed to
Stone Battery, Taiwan



ORNL

Thin film Li battery
Flexible
Smaller
Lighter
Rechargeable
Manufacturable





Infinite Power Solutions
LITE*STAR

50 Micron battery
LiPON electrolyte,
Lithium anode,
LiCoO cathode
Voltage of up to 4.0 V

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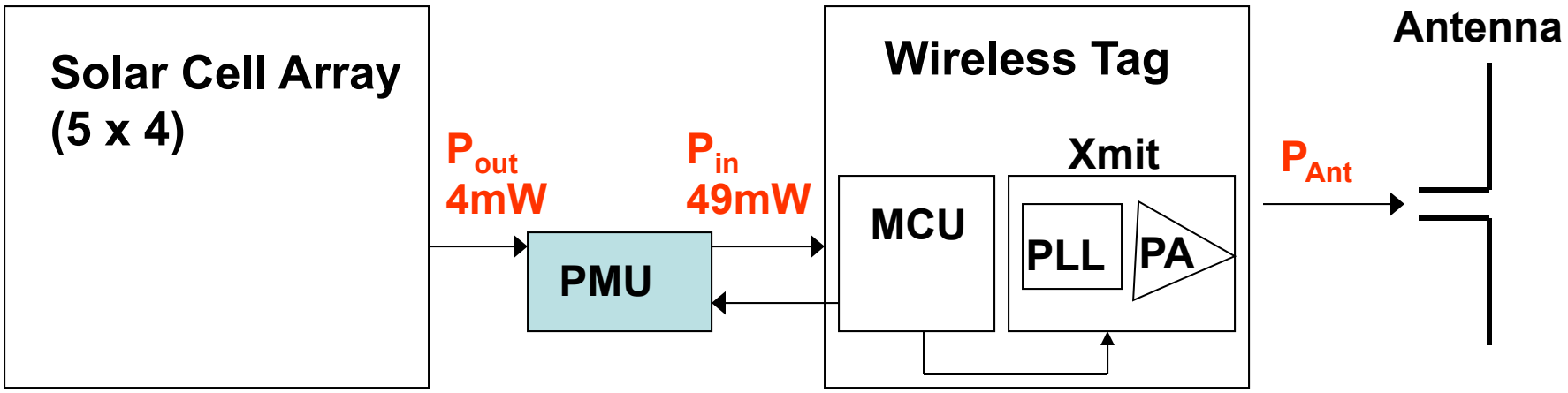
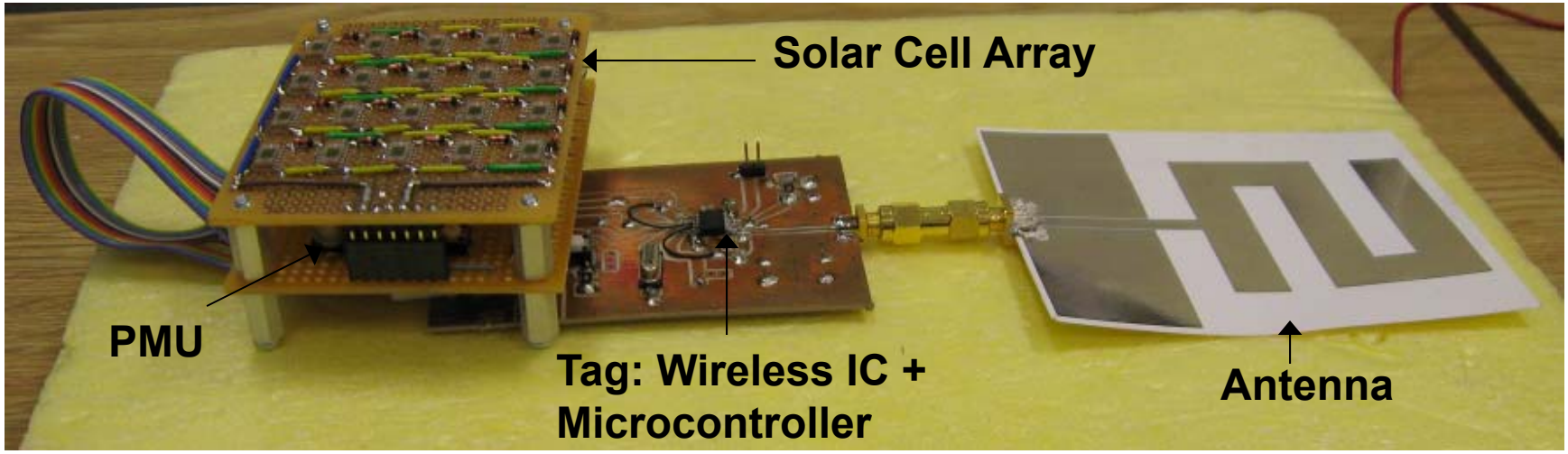
Solar Powered Battery-Less Tag

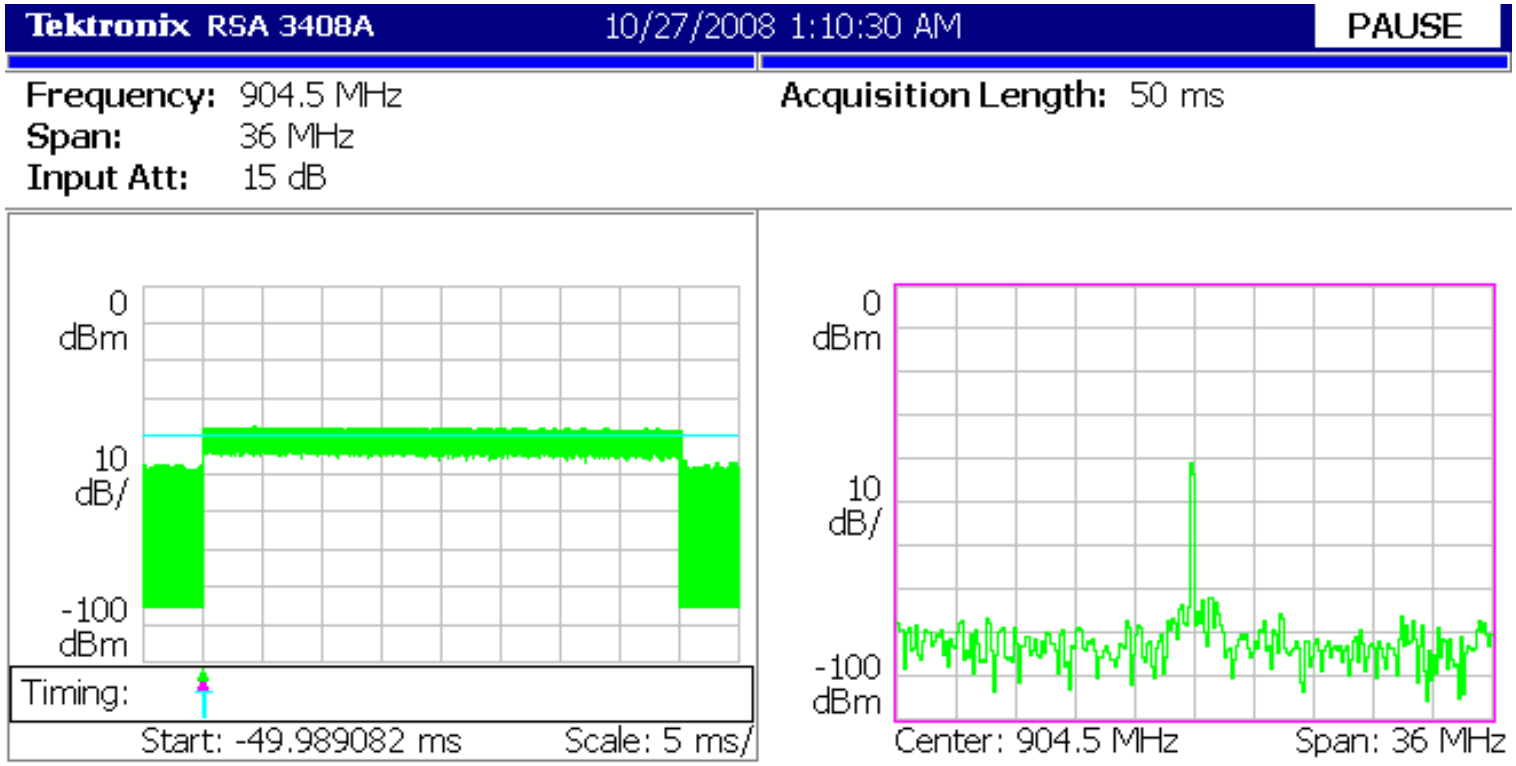


- **MCU:**
  - 8 bit RISC based Microcontroller Unit – Assembly Programming
- **PMU:**
  - Super capacitors + low power analog eelectronics.
- **Communication:**
  - Asynchronous Communication
  - Communication Frequency: 904.4 MHz (Unlicensed ISM Band)
  - Modulation Type: FSK

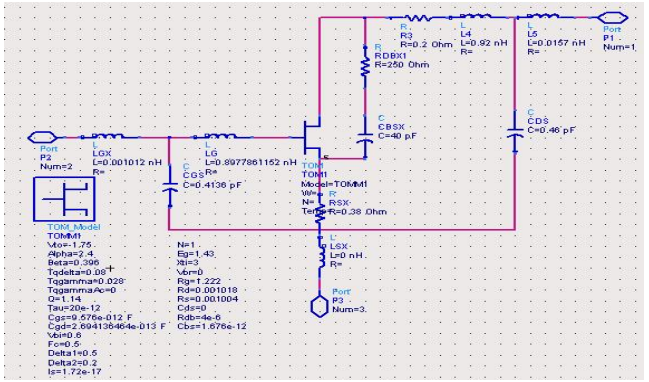
Solar Powered Tag

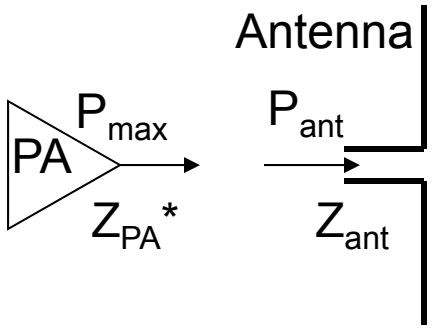


Solar Powered Communication



Power Amp. (PA) Modeling + Antenna Design





Z_{PA}* =36.95-j71.77Ω

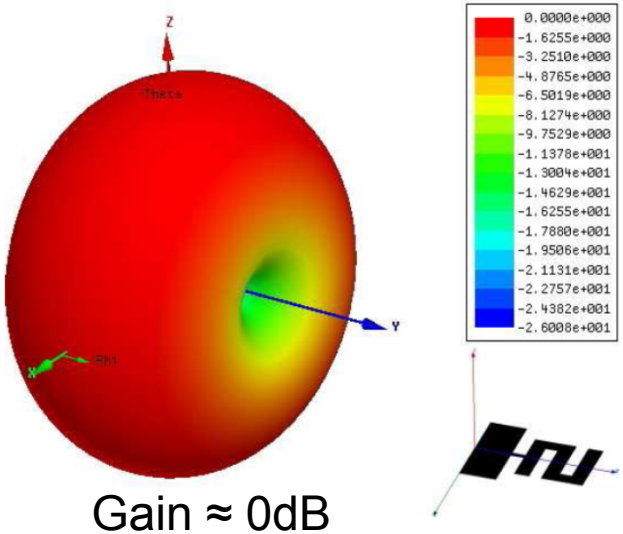
Z_{ant} = 37.3-j65.96Ω

$P_{ant}/P_{max} = (1-|S_{11}|^2)$

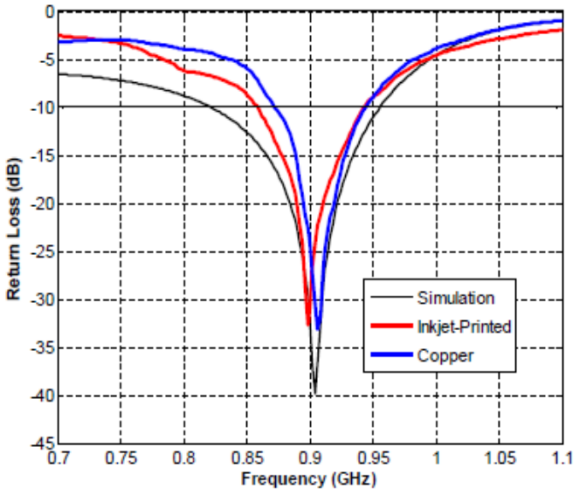
P_{ant}/P_{max} = 99.9%

Antenna $|S_{11}|$ = -30dB

@ 904.4 MHz



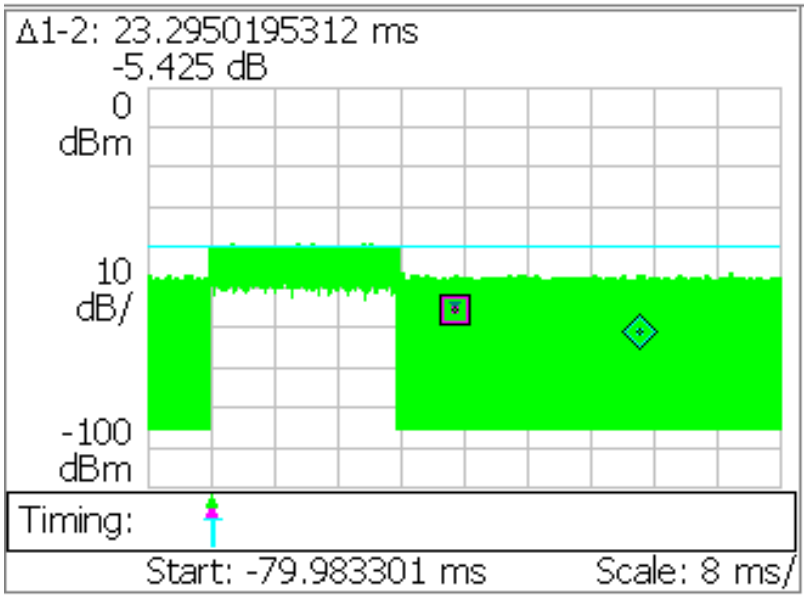
Gain ≈ 0dB

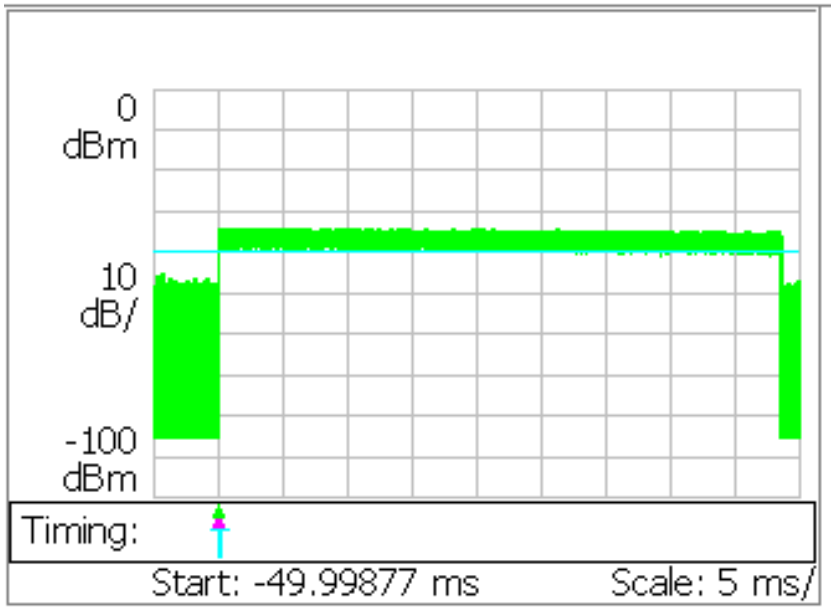


Power Management Unit

- **PMU Design 1**
  - **Solar Energy harnessed: 4.3mJ**
  - **Transmit Time achieved: 23.29ms**
- **PMU Design 2**
  - **Solar Energy harnessed: 4.3mJ**
  - **Transmit Time achieved: 43.75ms**

Increase in Efficiency by 88%





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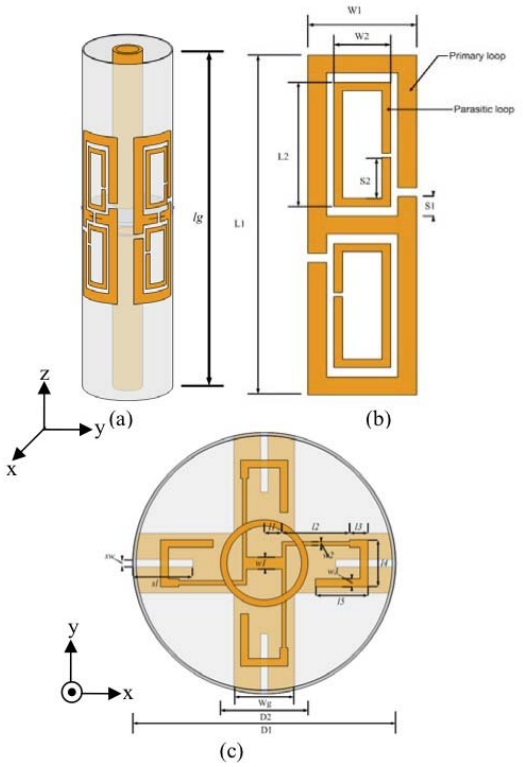
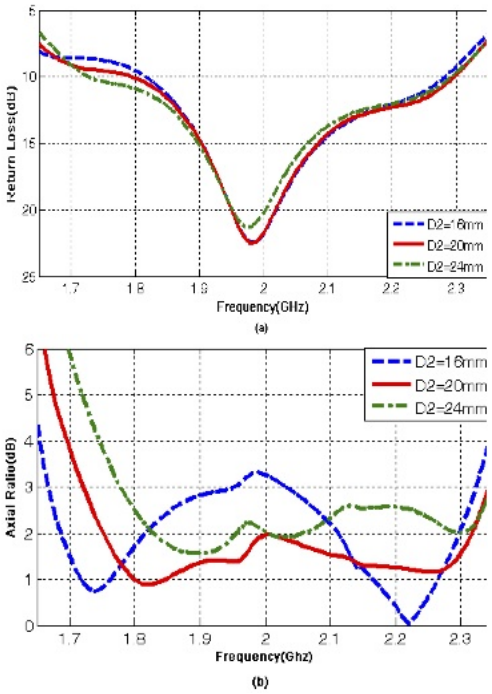
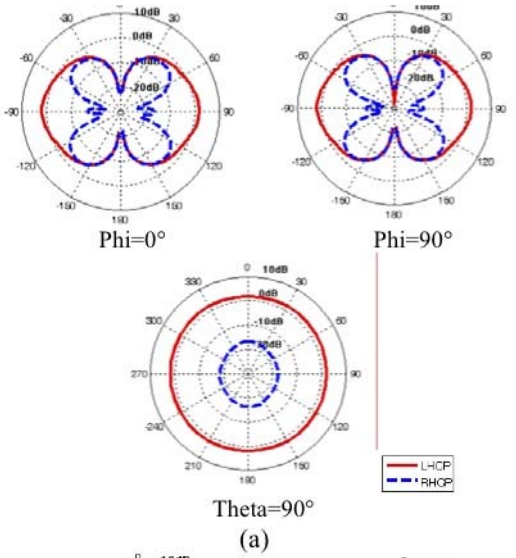
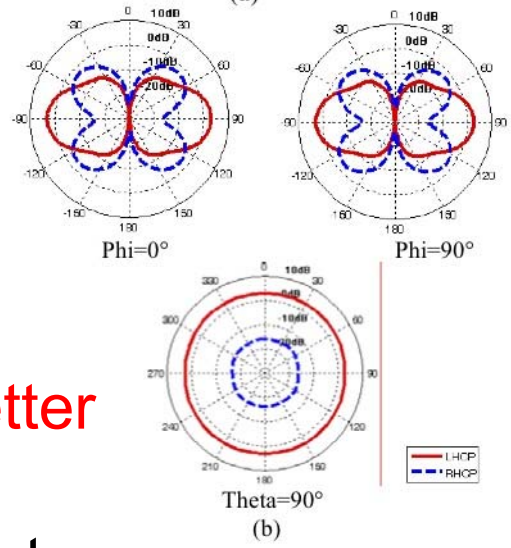
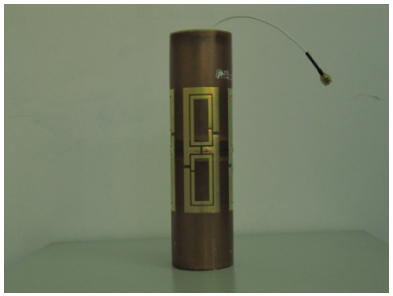
Omnidirectional Broadband CP Antenna











The first CP Antenna with
30%+ AR Bandwidth (10x better than state of the art)
Also: omni, flex independent

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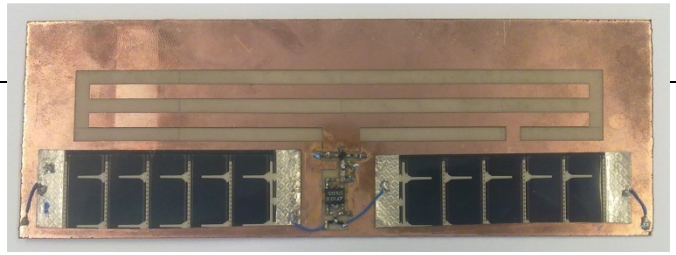
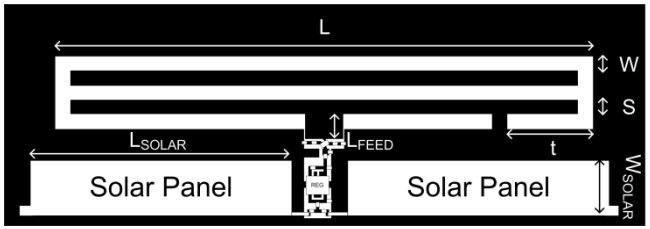
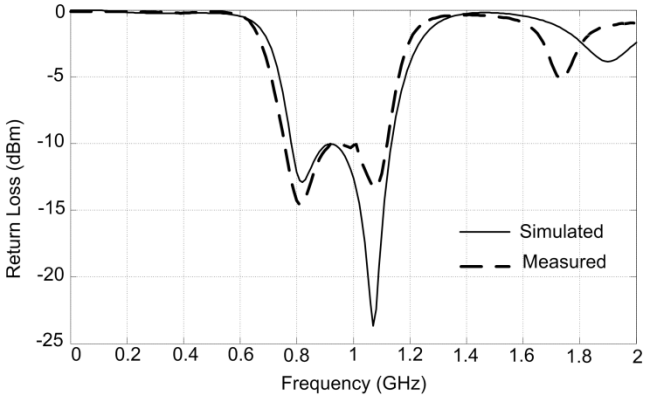
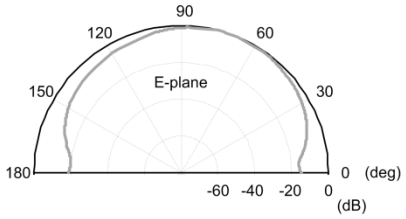
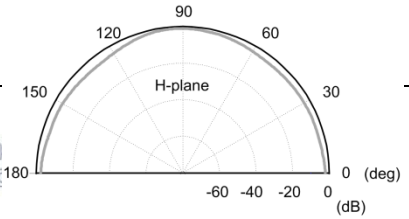
Integration of antennas with solar cells (SOLANT)

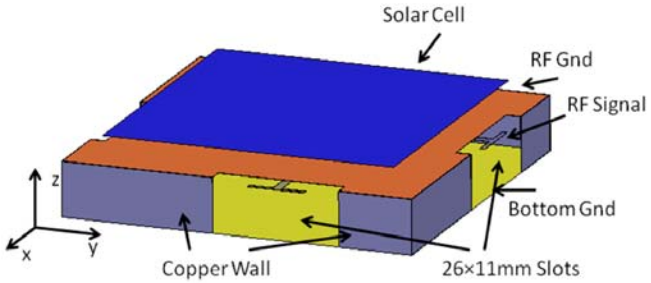


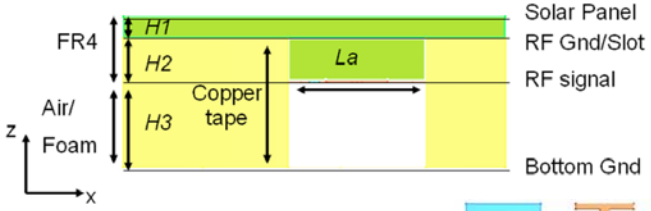


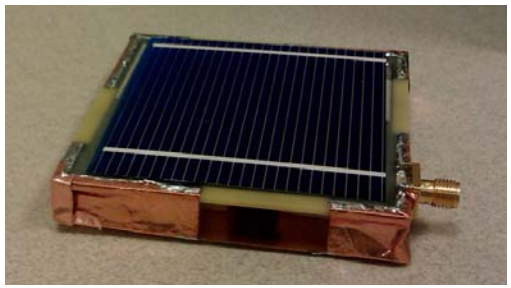


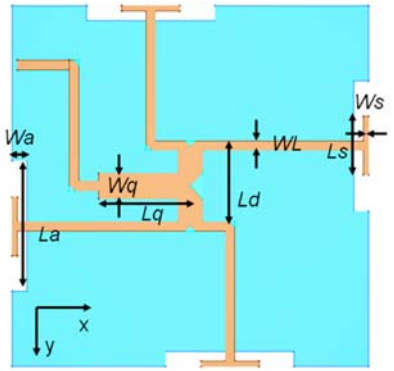


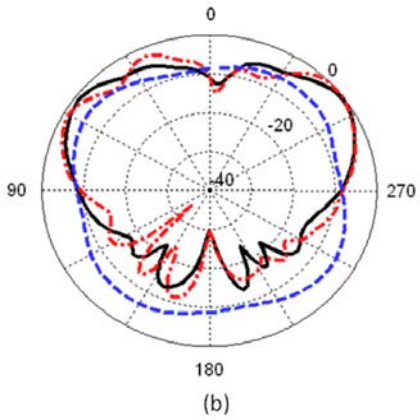




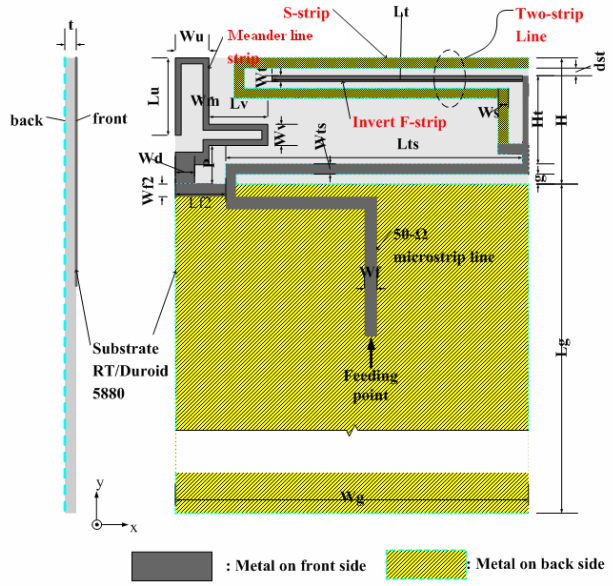


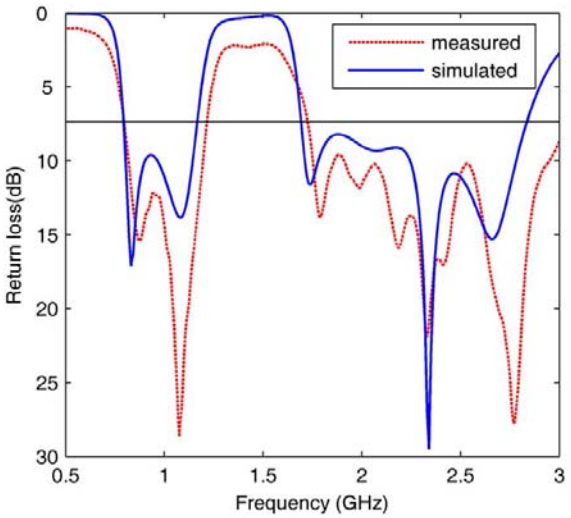


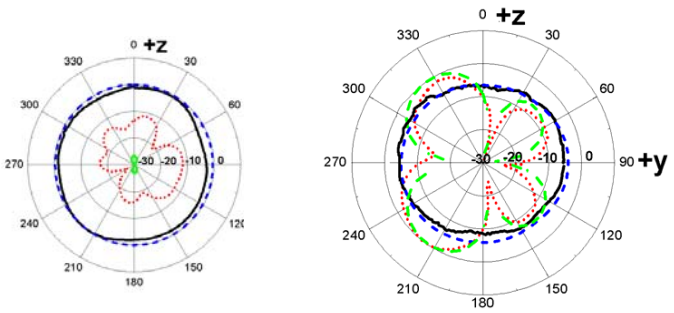




Low-Profile Vehicle-Mounted Dual-Band Ultra-Broadband (Banwidth > 40% per band)





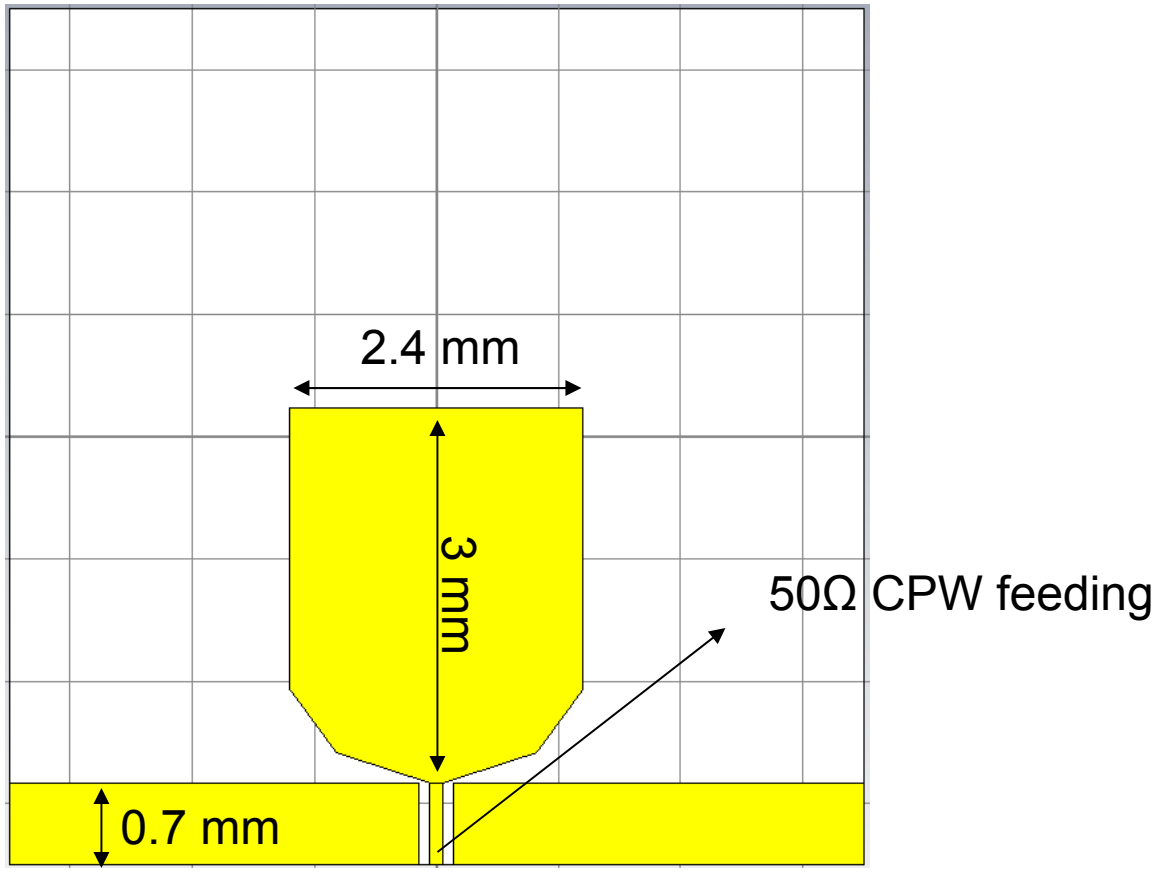


Omnidirectional radiation (900/1900 MHz)

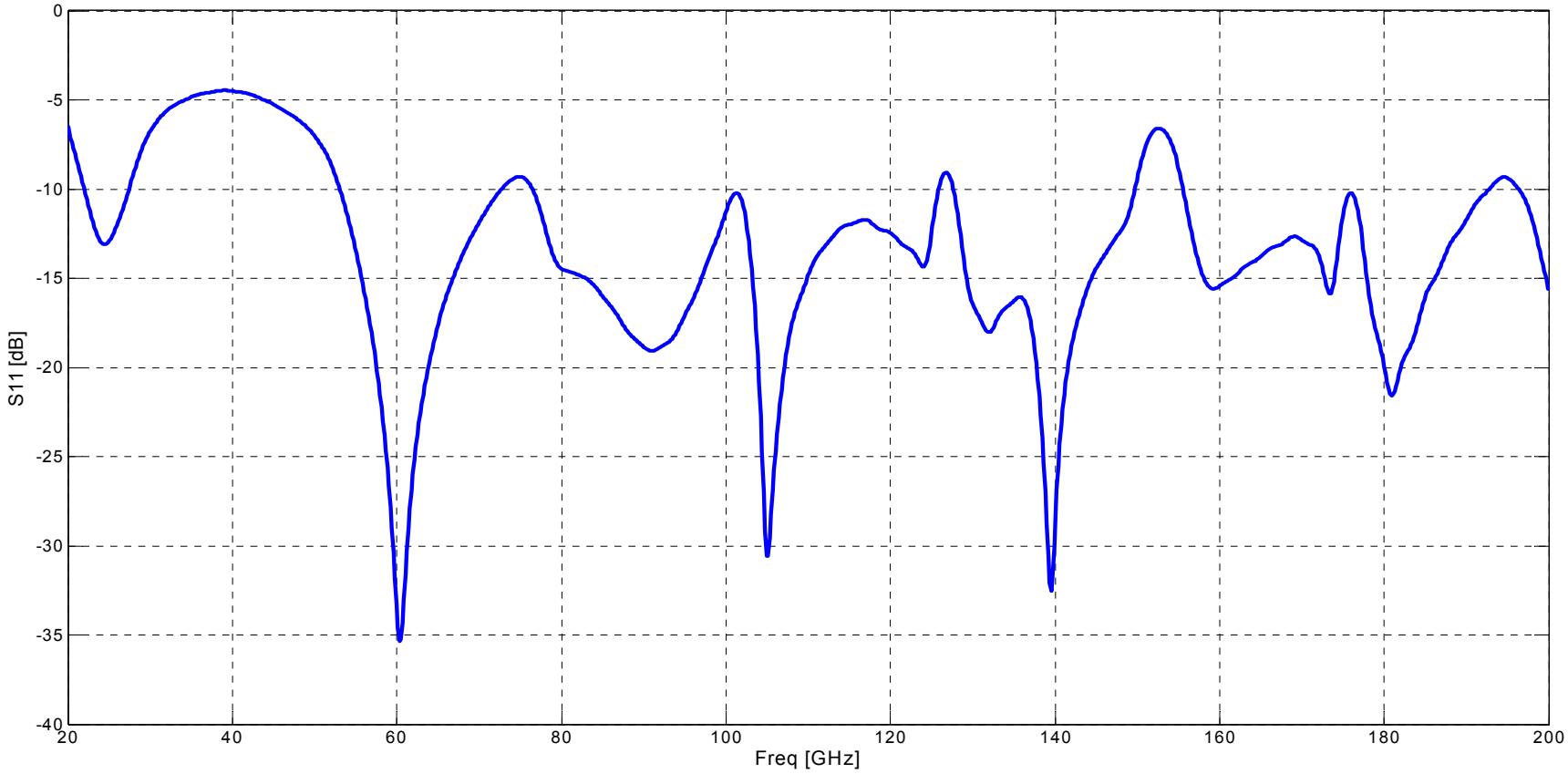
- First reported vehicle-mounted antenna covering (790-1215MHz/1710-3000MHz)
- **One** antenna covers mobileTV, 2,5G, 3G 4G cell phone band, WiFi, WiMax, RFID
- Easy-to-integrate with vehicular body
- First antenna with bandwidths >40% in two bands
- Easy-to-expand to GPS and non-GPS positioning and locating applications
- Enabling vehicle-to-vehicle and vehicle-to-stationary (Infostation) comunication
- Extremely low profile / printed / non-intrusive / concealable configuration

Georgia Institute of Technology

sub-THz Antenna Design on LCP

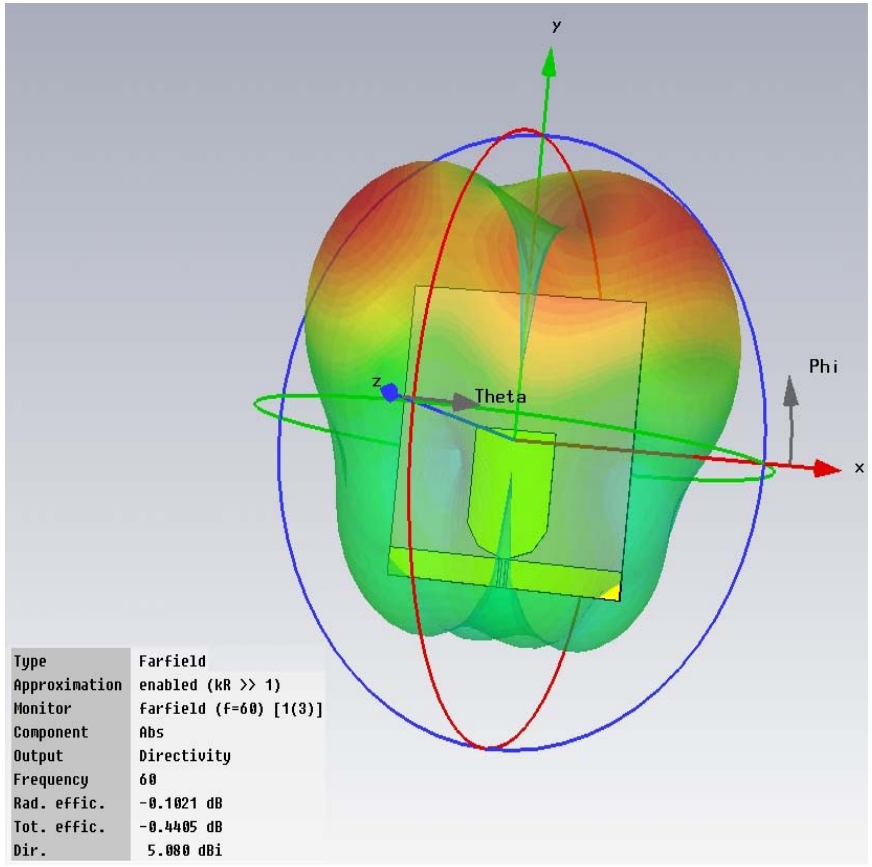


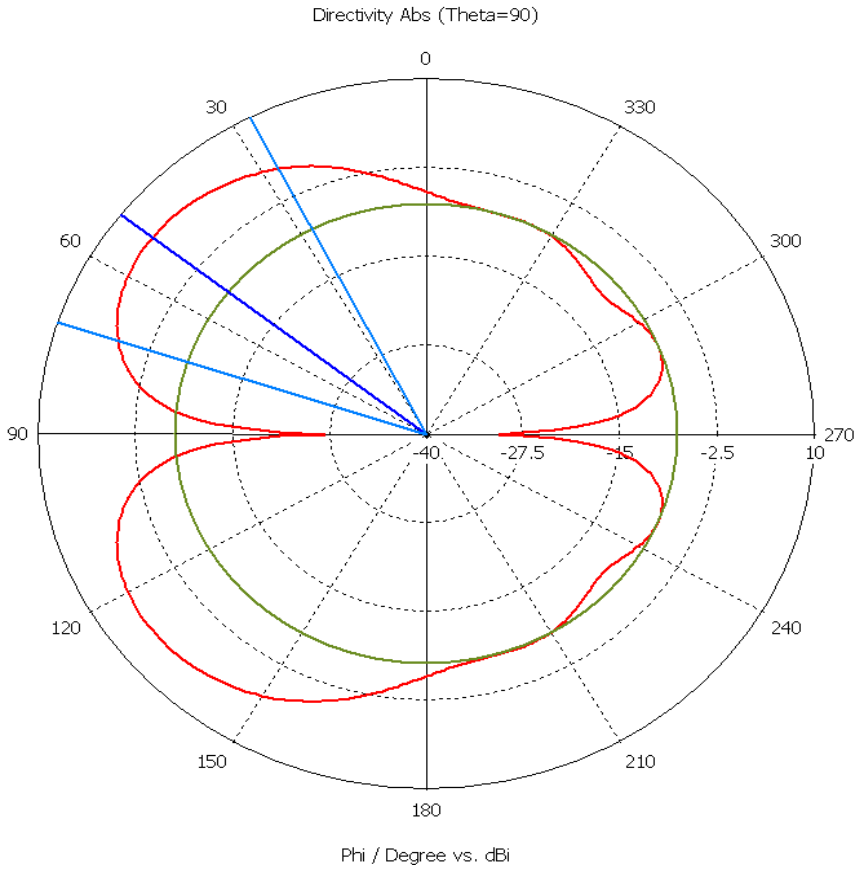
Simulation Result – S11



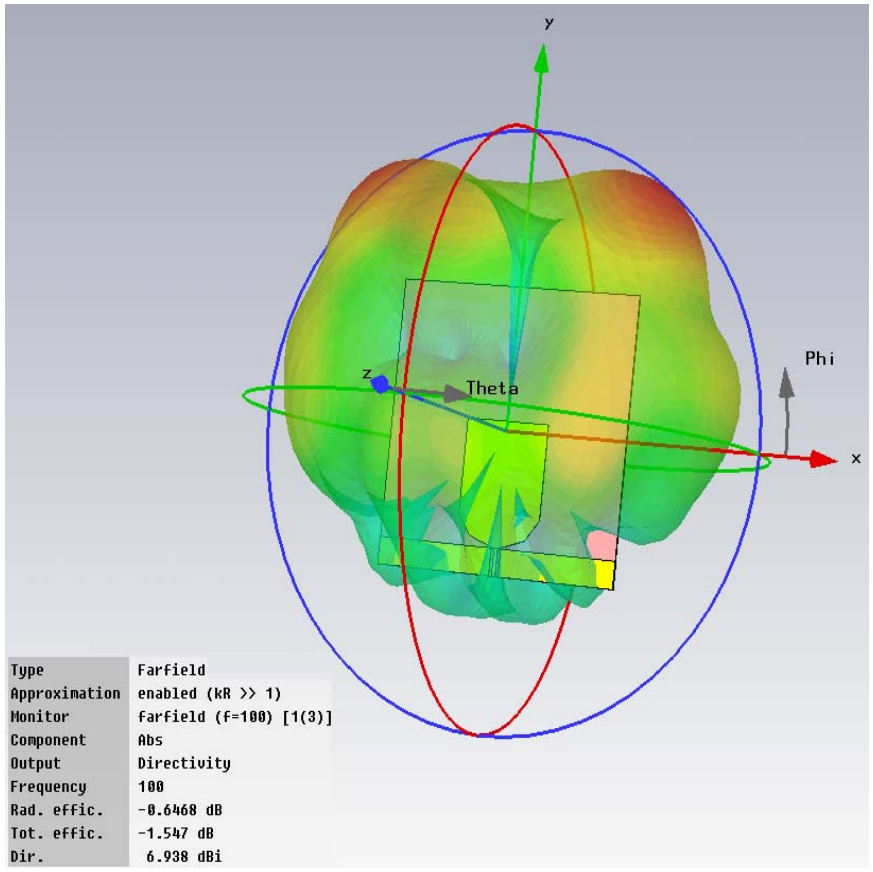
- Frequency is very similar to original design

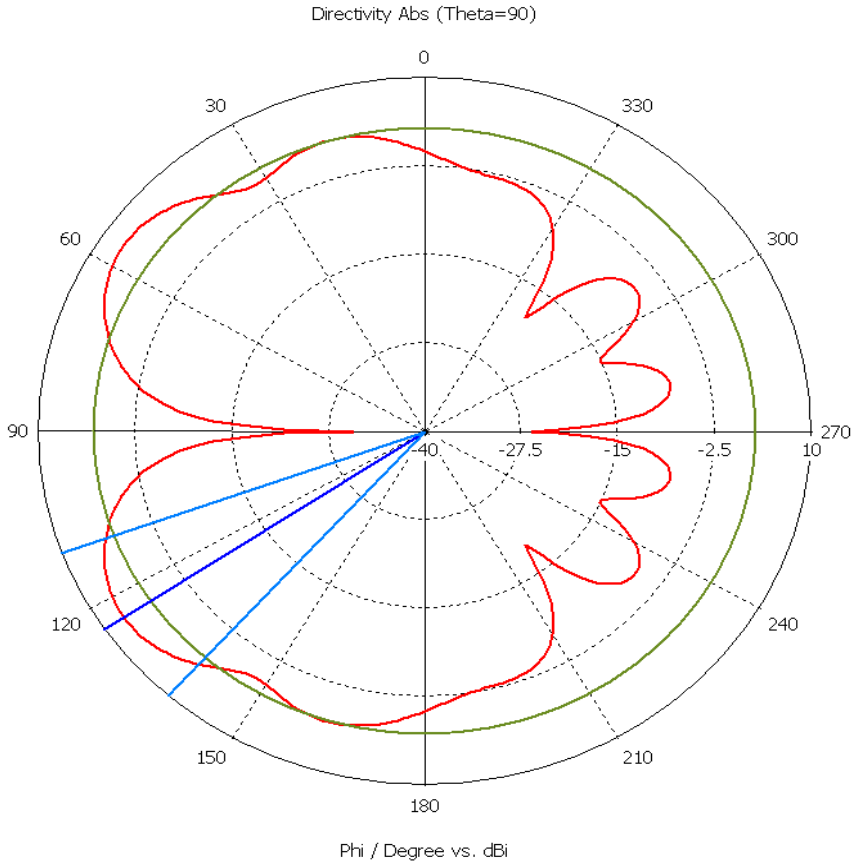
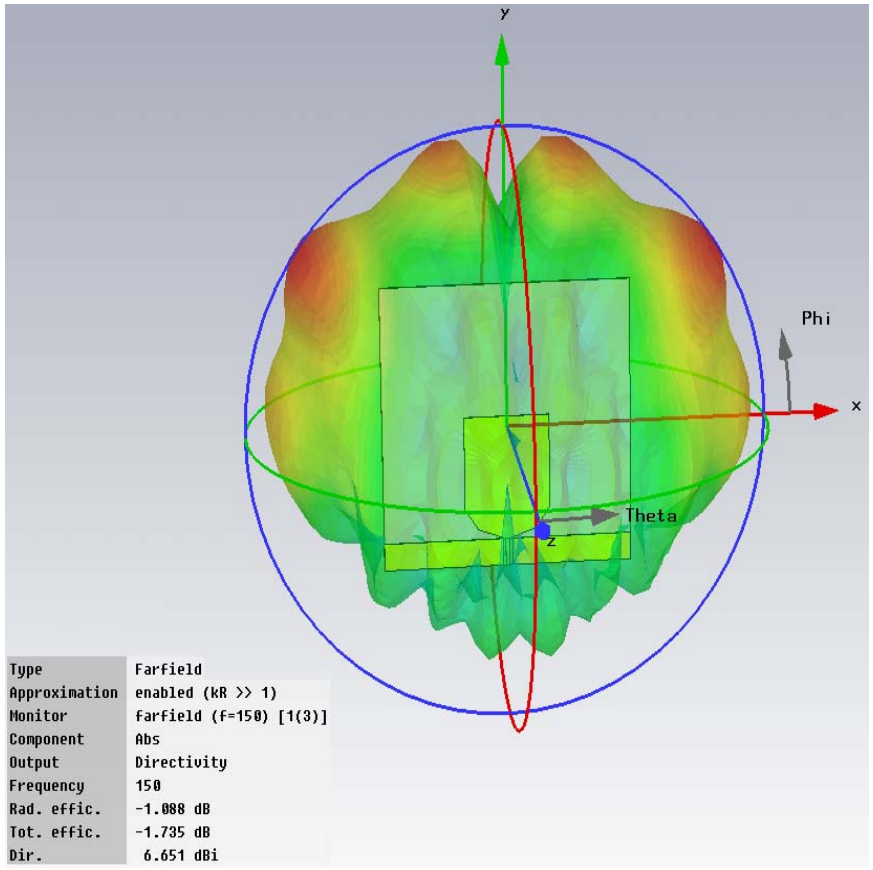
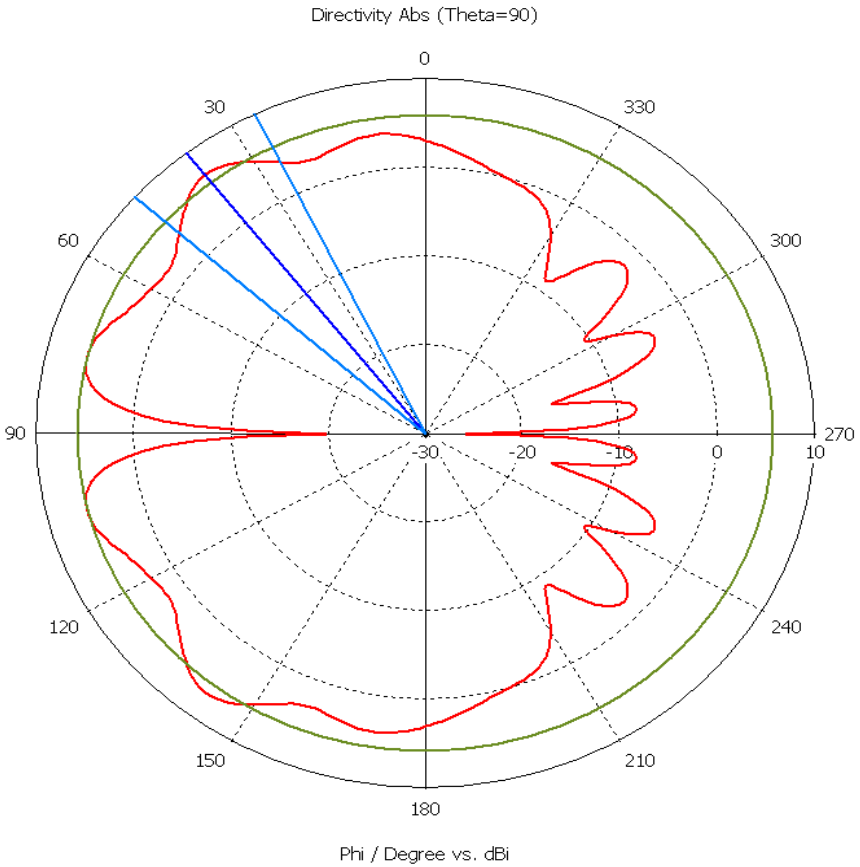
Patterns @ 60GHz





Patterns @ 100GHz





Patterns @ 150GHz