5G Communications with Glass Embedding and Fanout

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Strategic Needs

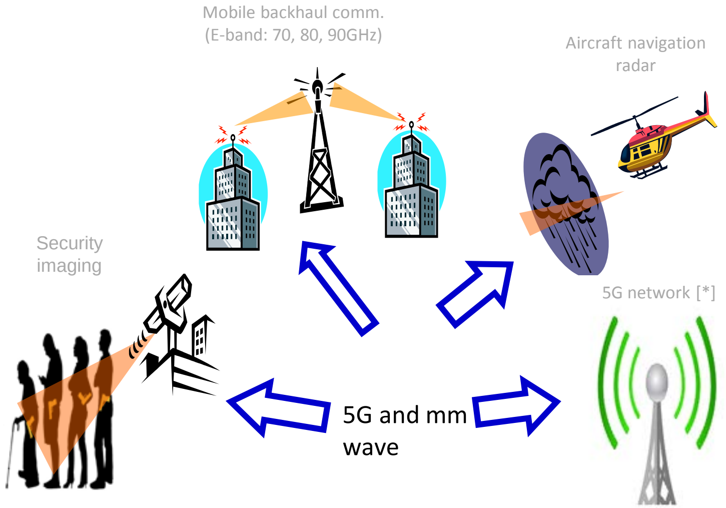
Increasing automotive, IoT, Smart City communication needs:

- Higher automation levels,
- Avalanche of wireless communication traffic volume and massive growth
- 10-100x higher data rates 4G LTE

Enable the functionality of:

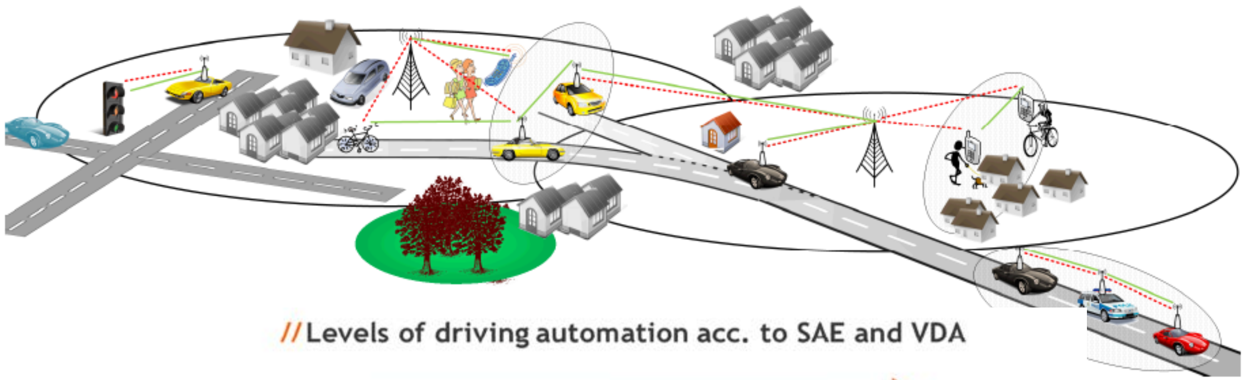
- Enhanced Cognitive Intelligence
- Automated driving with safety
- Intelligent navigation
- In-car smartphone-like infotainment (Information Society on the road)
- Predictive Maintenance
- Digitalization of transport and logistics (e.g. Intelligent Transportation Systems (ITS))

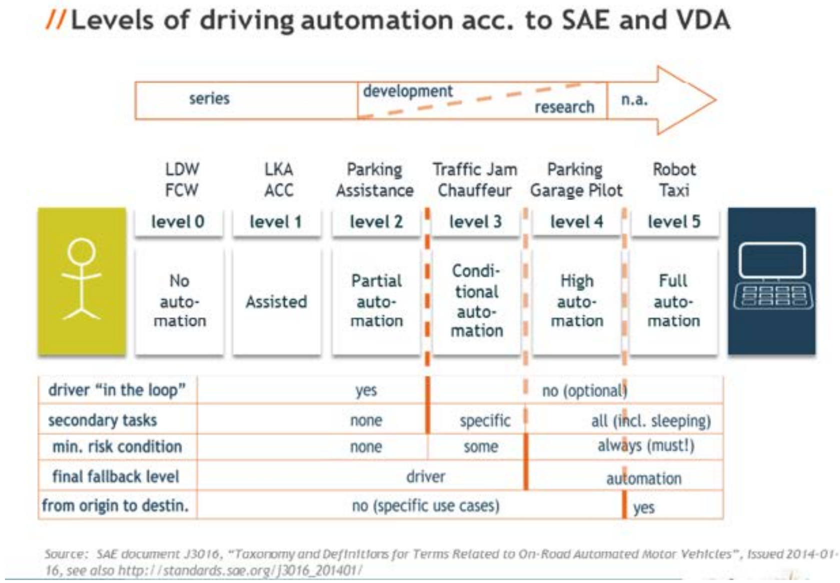
5G in Consumer Products: smartphones, IoT and Security



Vehicles connected to WiFi and providing cellular feeding WiFi hotpots connectivity for passengers

Strategic Needs II

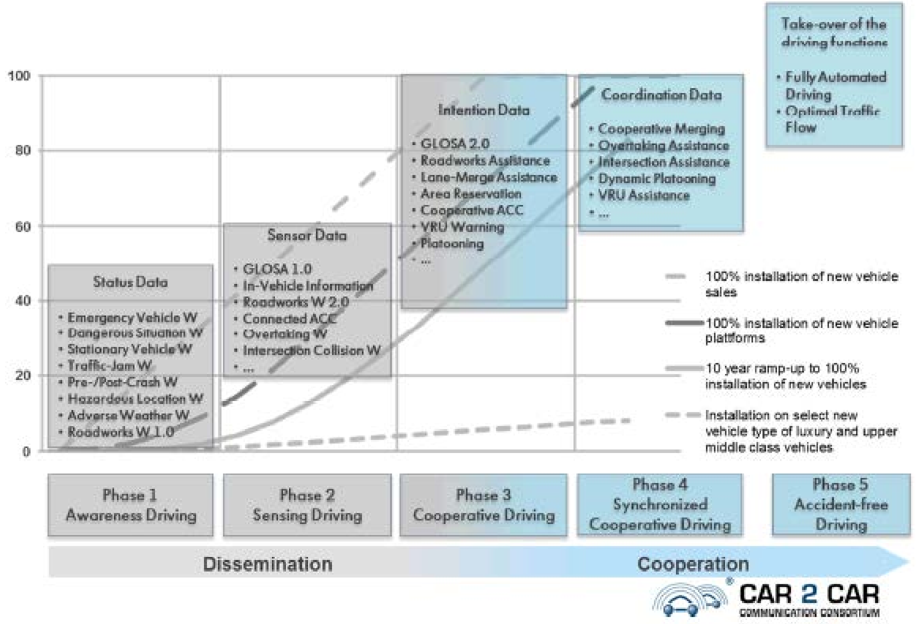




Vehicle-to-Everything (V2X): Any communication involving a vehicle as a source or destination of a message:

- Vehicle-to-Vehicle (V2V)
- Vehicle-to-Infrastructure (V2I)
- Vehicle-to-Network (V2N)
- Vehicle-to-Pedestrian (V2P)

Vehicle-to-X Roadmap

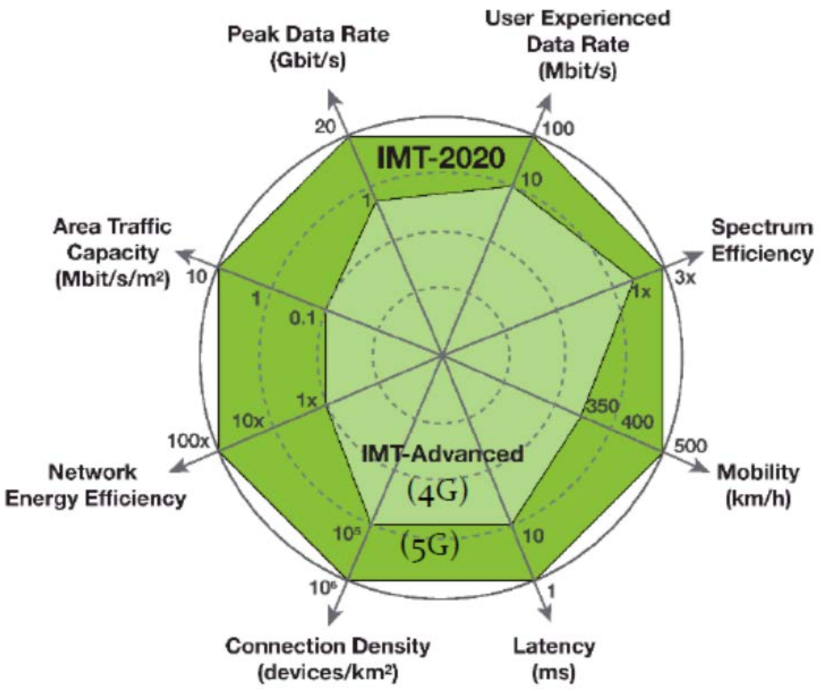


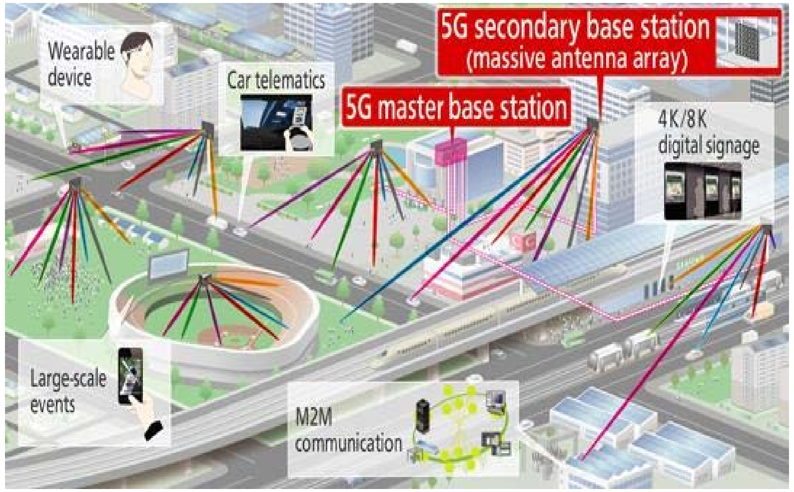
- *Intersection Collision Risk Warning*
- *Road hazard warnings (road works, car breakdown, weather conditions, etc.)*
- *Approaching emergency vehicle warning*
- *Pre-/Post-Crash*
- *Electronic Emergency Brake Warning*
- *GLOSA – Green Light Optimal Speed Advisory*
- *Energy-efficient intersection*
- *Motorcycle approaching information*
- *In-vehicle signage*
- *Red light violation warning*
- *Traffic jam ahead warning*

5G networks

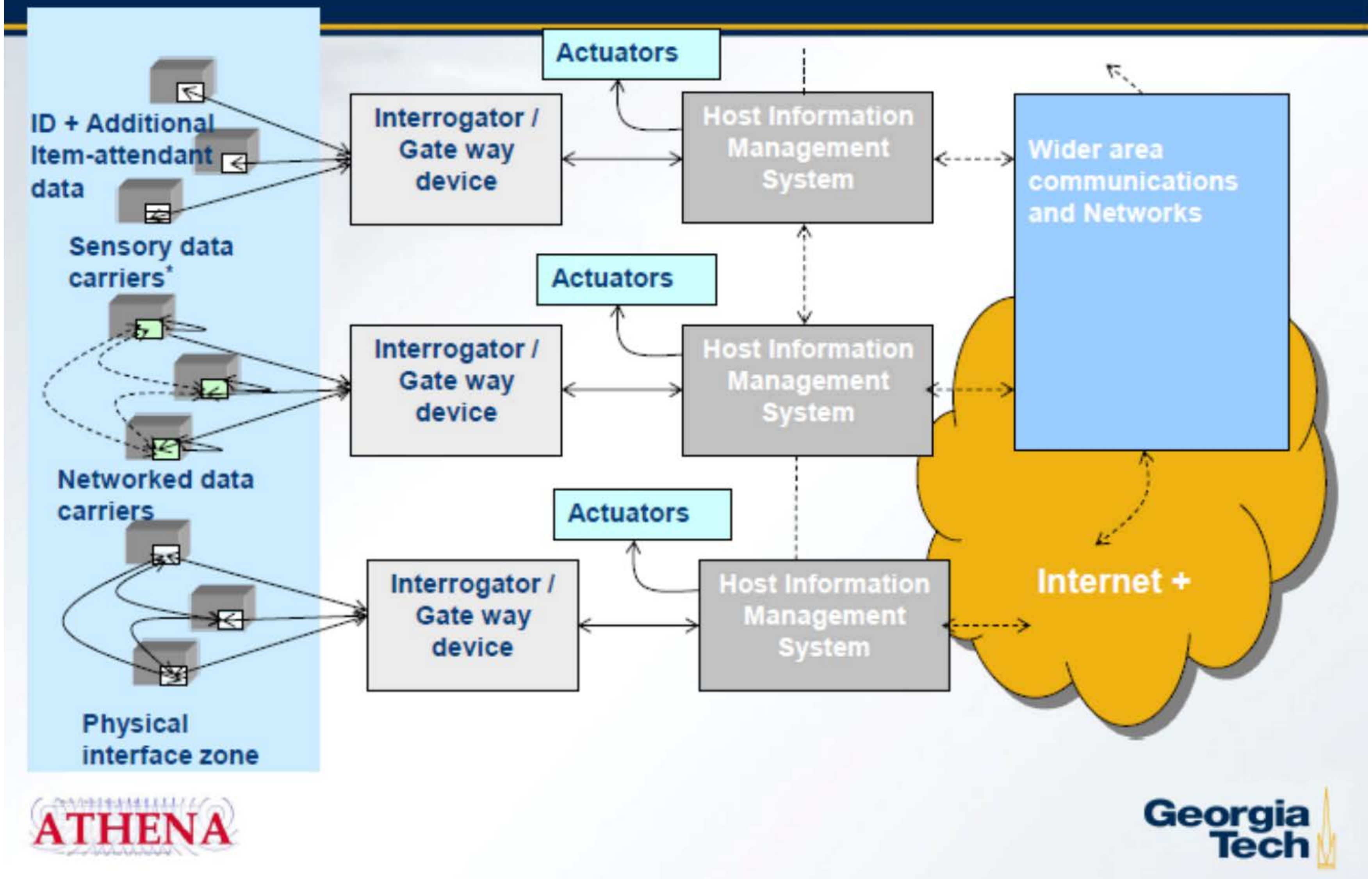
<u>Defining characteristics</u>

- Cellular network
- 75dBm EIRP FCC limitation (compared to 36 dBm for UHF RFID readers)
- Small cells (300-500m radius)
- Mm-wave
- **<u>Beamforming</u>**
- Spatial multiplexing



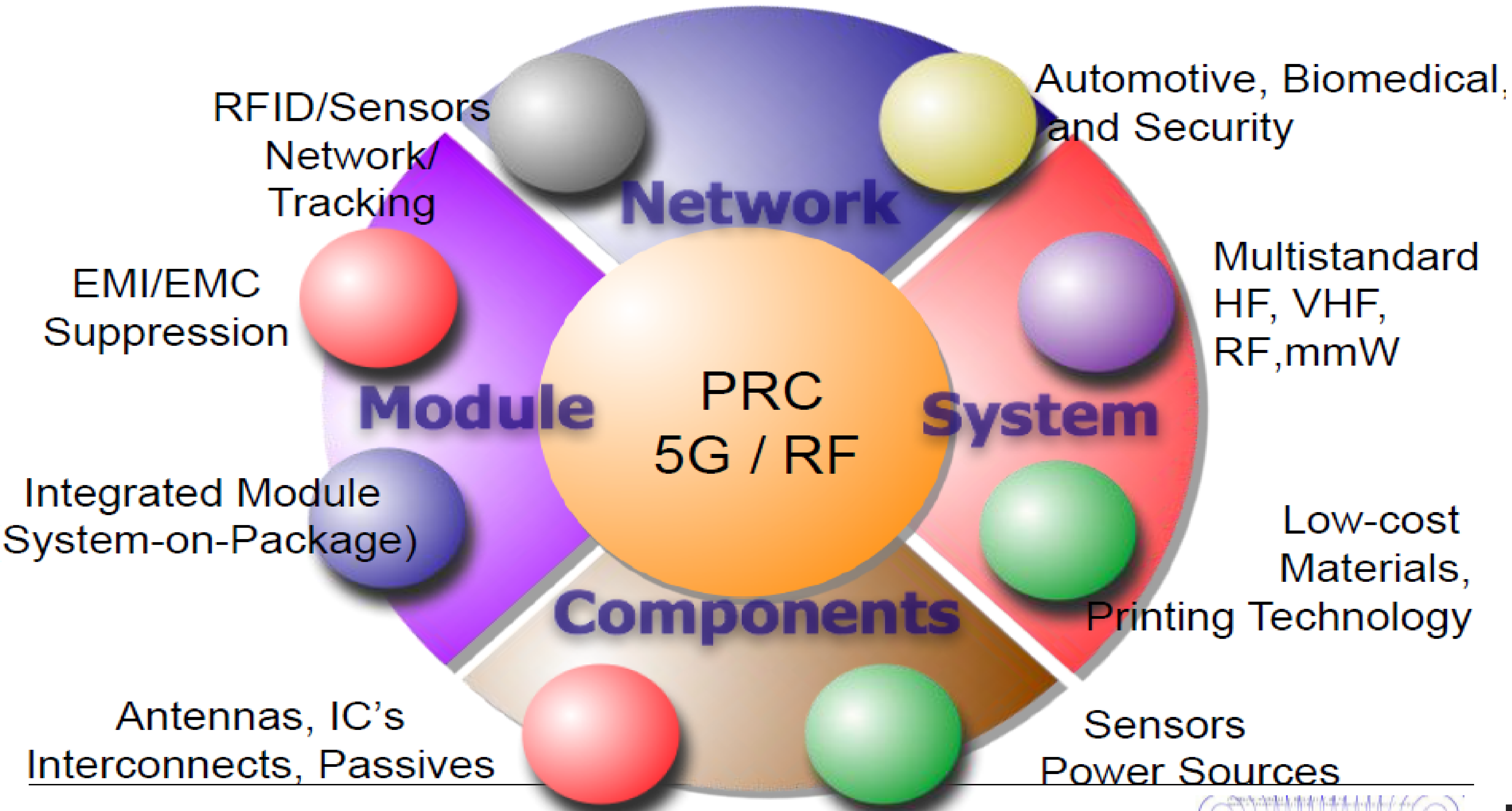


Internet of Things – *including RFID carrier variants*



P.I.R.E.A.S. Testbed

(Prototypes of Integrated RF-Enabled Agile Systems)



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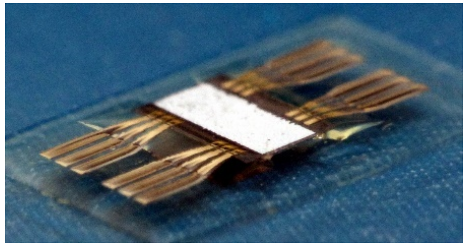
GT Research Objectives

Explore novel designs, materials, processes and 3D packaging structures and RF components to build 5G-enabled modules that accommodate V2X, IoT, SS, SC applications with superiority over LTCC and organic packages in terms of:

1) Performance,
2) Miniaturization
3) Reliability
4) Cost
5) Integrability (e.g.transparent)
6) IoT compatibility
7) Broadband/multiband (e.g. 5.9GHz/mmW) operability

Mm-Wave Systems and Packaging with Printing

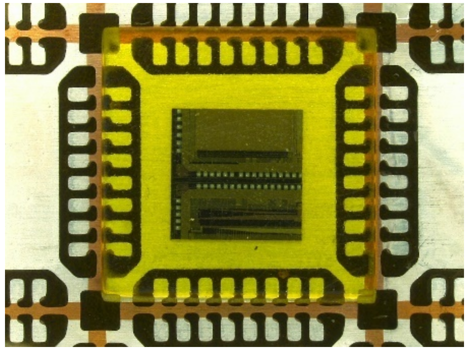
Inkjet Printing



Materials:
Polymer solutions, metallic nanoparticle dispersions, carbon nanomaterial suspensions

- 3D interconnects
- RF substrates
- Die attach

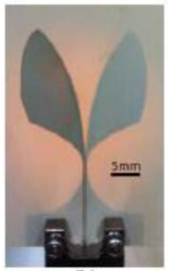
3D Printing

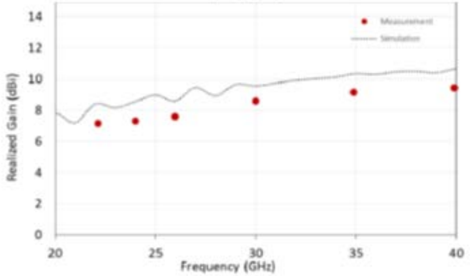


Materials:
Photoactive resins, thermoplastics, ceramic pastes, conductive adhesives

- Dielectric lenses
- Encapsulations
- Die-embedded leadframes

Printed mm-Wave Antennas

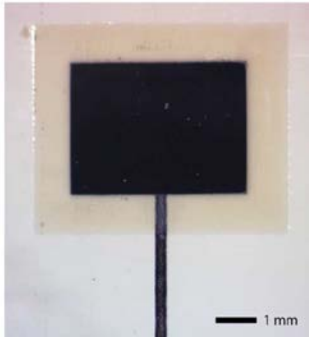


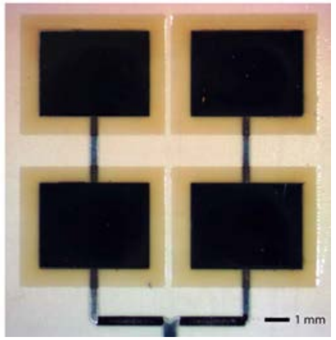


- Millimeter-wave (mm-wave) regime is emerging for automotive radar and 5G wireless
- Use printing to fabricate antennas in a low-cost and robust post-process fashion

Proximity-Coupled Patch Arrays

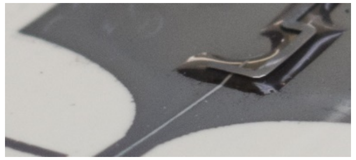
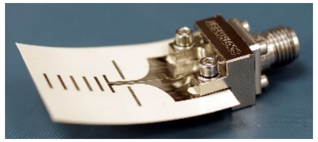
- Dielectric spacer printed to separate feed lines and patch resonators
- Exhibits high broadside gain for mm-wave applications in 24.5 GHz ISM





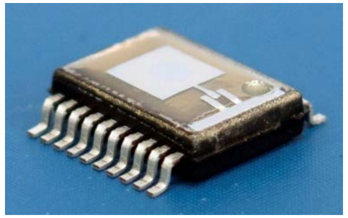
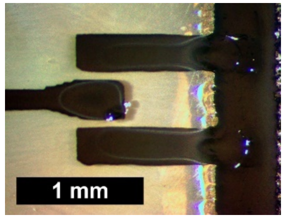
Yagi-Uda Antenna Arrays

- Dielectric substrate printed to convert microstrip feed to slot-line
- High end-fire gain achieved with multi-director configurations

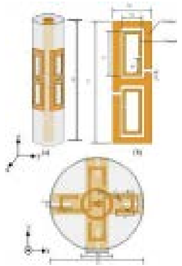



On-Package Antenna Integration

- 30 GHz patch antenna printed directly onto chip molding
- Printed ground plane provides isolation from IC package
- Can be integrated with wireless IC through aperture coupling or through-package-vias (TPV)

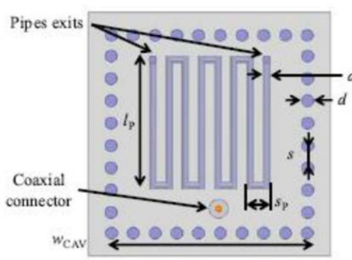
3D Printed Antennas and Systems

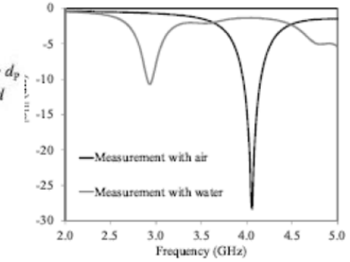


- Previous work utilizing basic FDM printers and direct write systems.
- Extremely low cost, utilizing Direct Write for metallization and FDM for dielectrics

Microfluidic Reconfigurable Microfluidic SIW

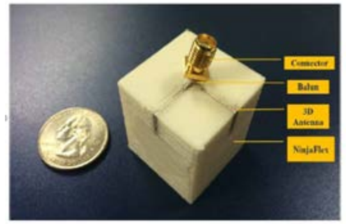
- Resonate frequency based off dielectric constant within microfluidic channels
- FDM Printed with thermoplastic polyurethane (TPU) and PLA

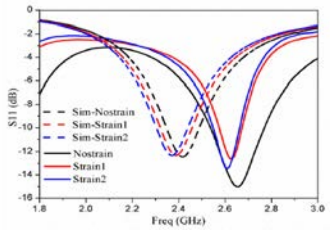




Strain Sensing Hollow Cube

- Thin lines (200 µm) of silo-ECA (electrically conductive adhesive) stretchable conductor printed on
- ~80 MHz change based on strain due to hollow interior topology of the cube.



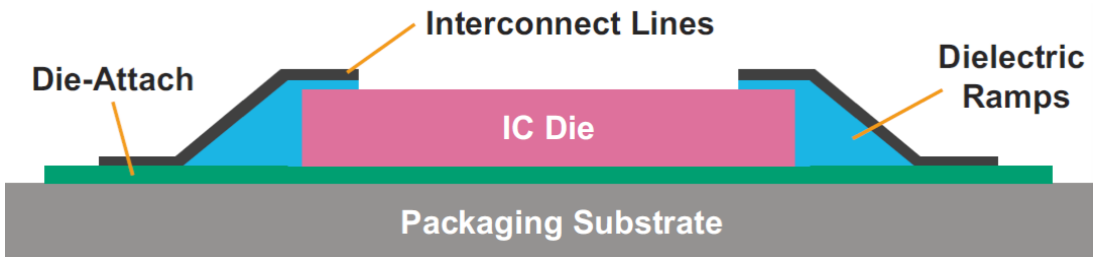


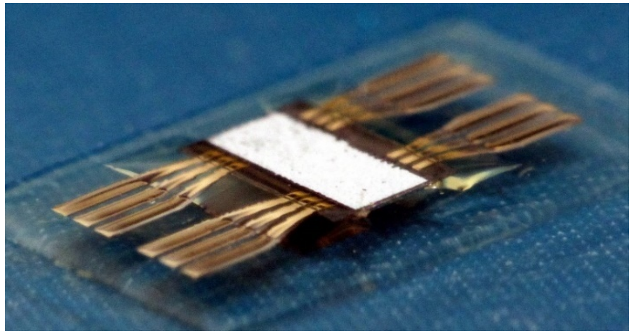
Hybrid Manufactured Vivaldi Antenna Array

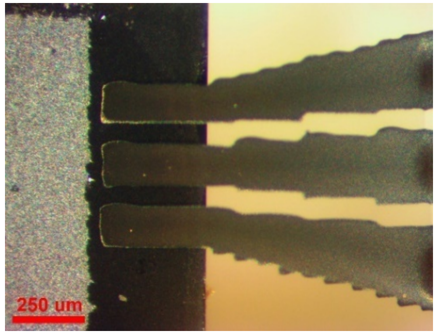
- Utilizes subtractive and additive manufacturing
- ABS/Copper Tape (subtractive)/ Dupont CB028 Silver Paste
- 2.8-8 GHz operational frequency

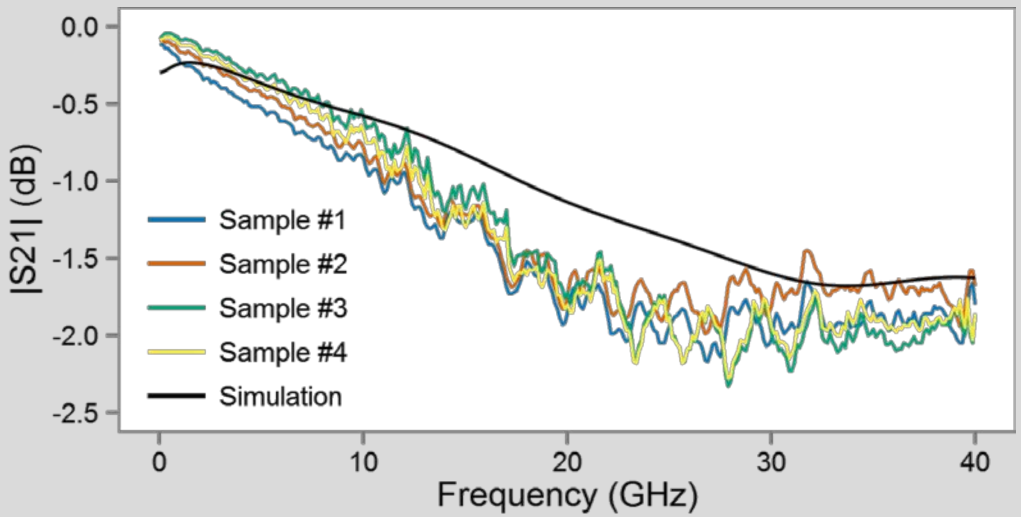
Inkjet-Printed 3D mm-Wave Interconnects

- Efficient interconnects essential for system-on-package (SoP) solutions
- Use inkjet printing to realize 3D mm-wave interconnects between IC die and packaging substrate





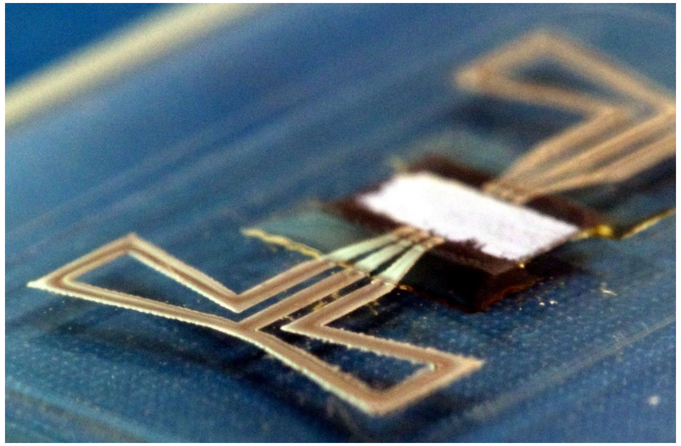


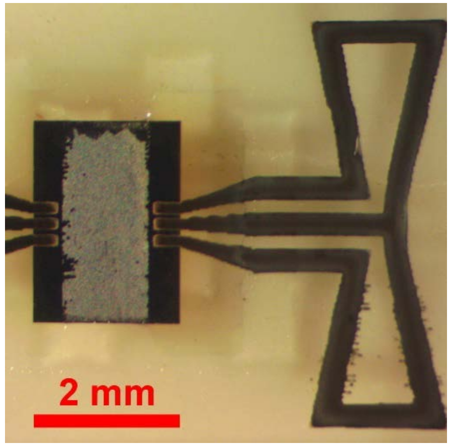


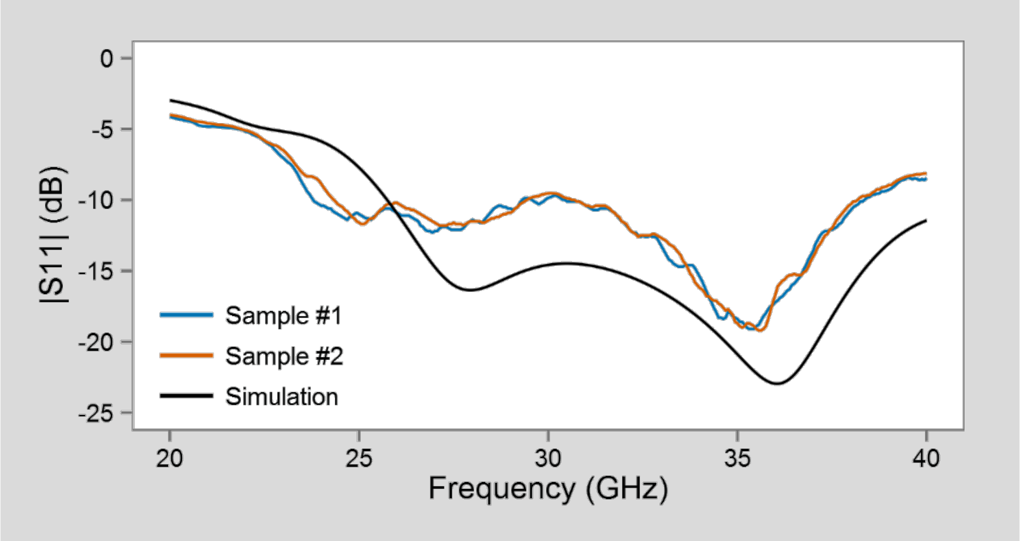
- Loss at 40 GHz: **0.6–0.8 dB/mm**
- Inductance **half** of typical wirebond (0.4 nH/mm)

Mm-Wave SoP Antenna Integration

- Use inkjet-printed interconnects to **directly interface** IC die with SoP antenna
- Minimize system complexity, interconnect length, and transmission losses







- Wideband CPW-fed bowtie antenna covering 23–40 GHz using glass as RF substrate
- Multilayer printing allows for **isolation from packaging substrate** in future efforts

Additive vs Subtractive Fabrication

Technology	Feature Size (um)	Multi-Layer	Cost	Speed	Waste	Area (m^2)
Milling	200	No	Low	Slow	High (Dust)	0.1
Laser Ablation	20	No	High	Slow	Medium (Vapors and Dust)	0.05
Photolithography	0.01	Yes	High	Slow	High (Chemical)	0.66
Microcontact Printing	0.1	Yes	Medium	Medium	Negligible	0.01
Gravure Printing	5-10	Yes	High	Fast	Medium (Excess Ink)	∞
Screen Printing	10-20	Yes	Medium	Fast	Low(Excess Ink)	0.8
Inkjet-Printing	1-20	Yes	Low	Fast	Negligible	∞

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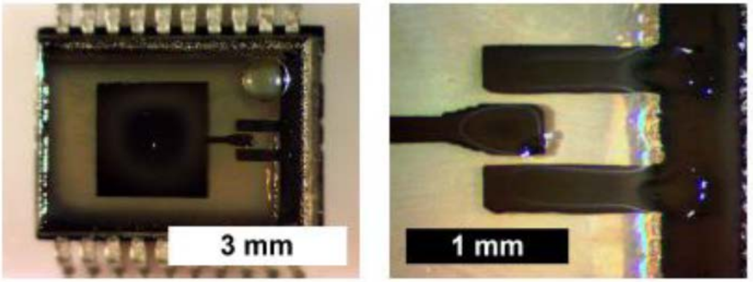
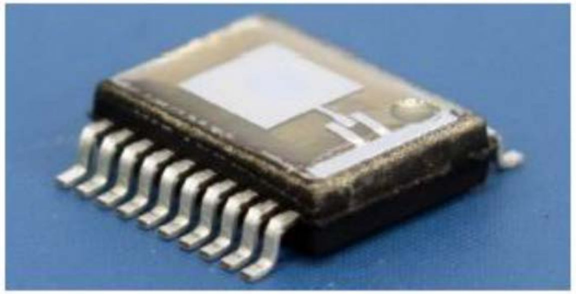
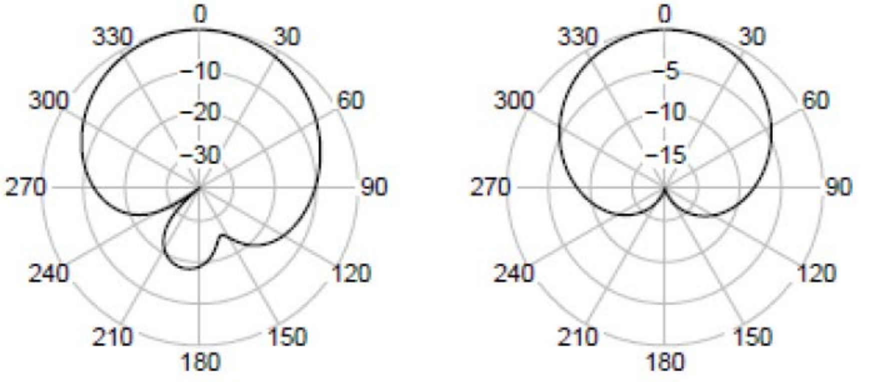
Inkjet-Printed On-Package 30 GHz Antenna



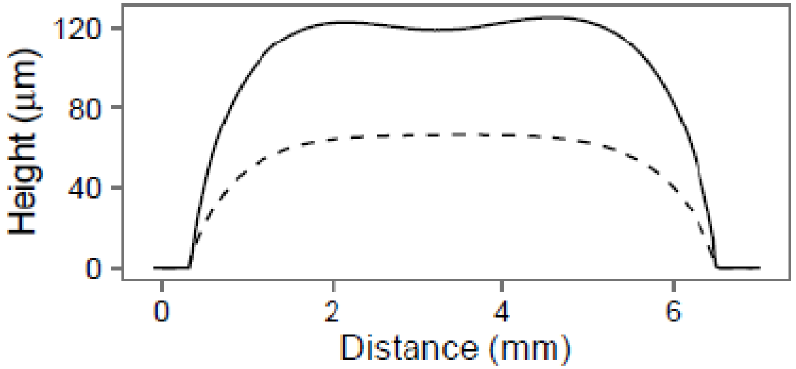
(a) (b)

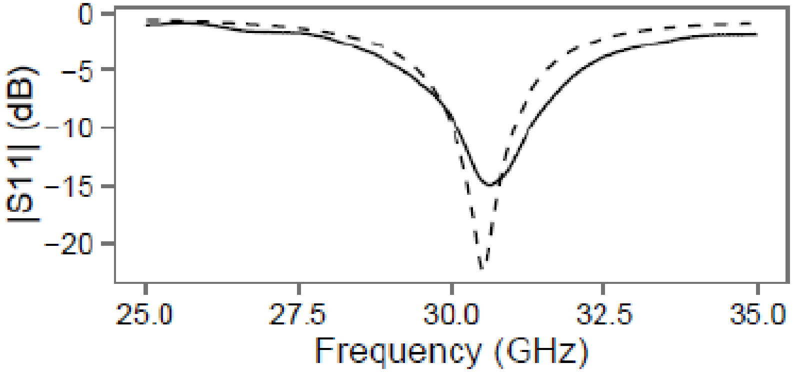




(a) (b)

Fig. 4. Simulated (a) YZ and (b) XZ normalized radiation pattern cuts.





Source from Prof. Manos M. Tentzeris

Van-Atta reflect-arrays: Ultra-low-power "A+S" Wireless Nodes with 1km+ Ranges

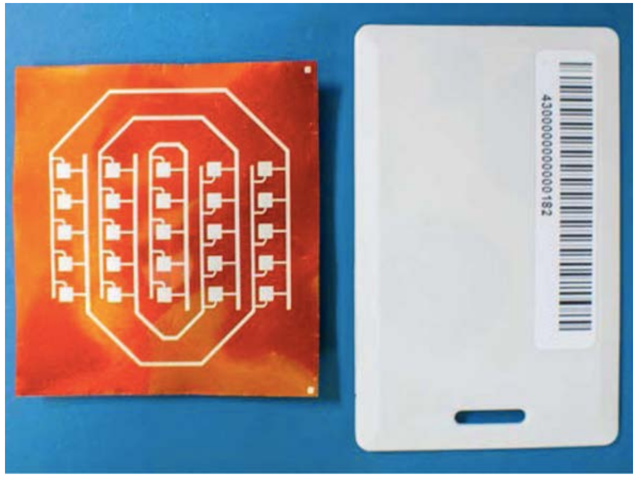
- Unique combination of properties
  - Arbitrarily high RCS (fully scalable)
  - Largely angle independent monostatic response
  - Cross-polarized response

- Reader system consequences
  - High frequency operable (unused bands)
  - High gain, compact, reader antennas (long range)
  - Narrow beamwidth reader antennas (clutter isolation)

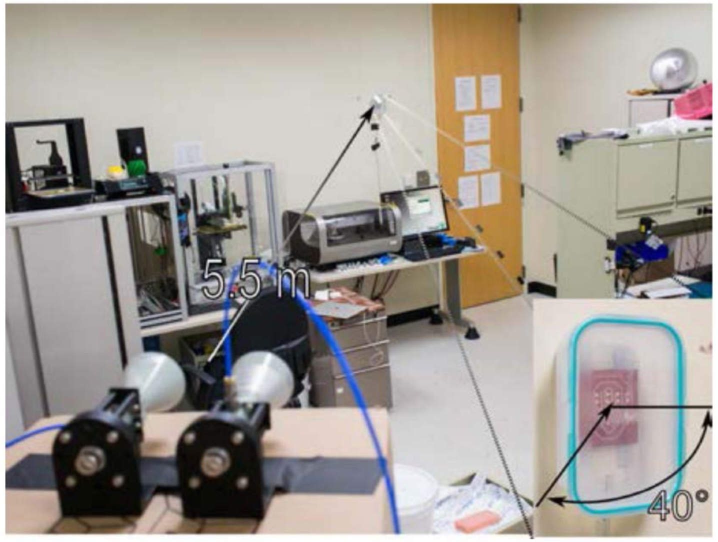
- Operational advantages
  - **Unprecedented (angle independent) reading range (1km+)**
  - Extremely high clutter-induced-interference isolation
  - Compactness
  - Unique Authentication + Multiagent Sensing ("A+S")

Printed mm-Wave Chip-less RFID/Humidity Sensor

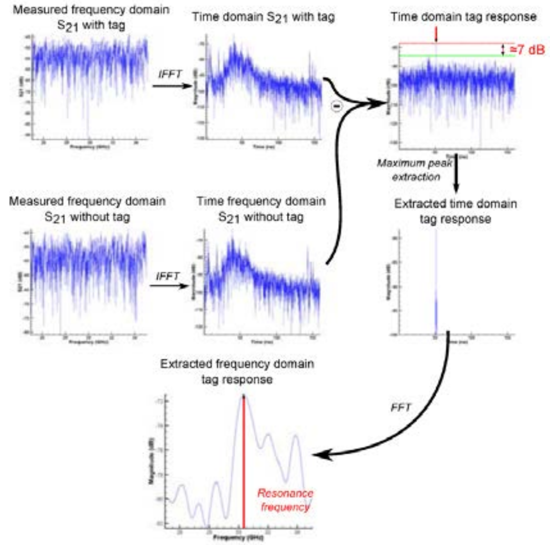
- Fully printed mm-wave passive system inkjet-printed Van-Atta reflect-array, consisting of 25 patch antennas on a surface Range finder, RFID, and humidity sensor
- Over a range of 140° variation of the angle of incidence of the interrogation signal, the RCS varied only by 10 dB, even for flexed configurations



25-Patch Van-Atta reflect array printed on Kapton. The area similar to a credit card or traditional RFID card



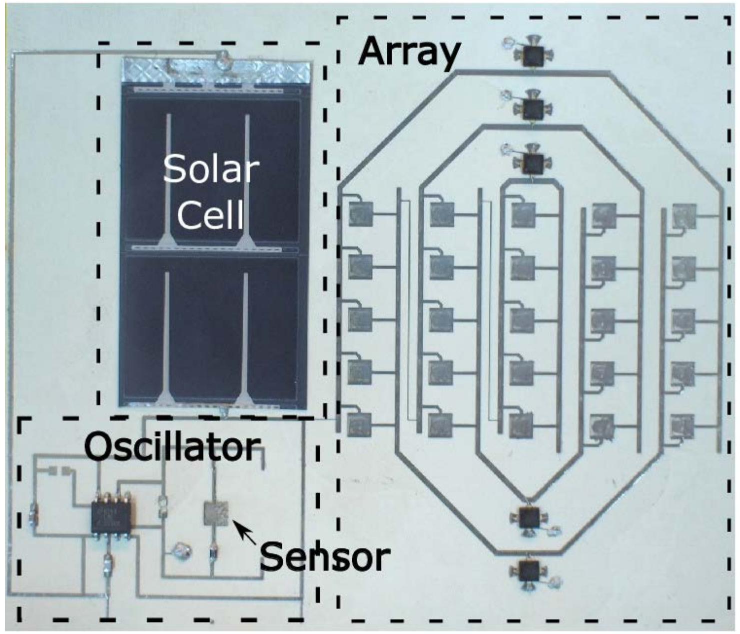
Testing environment. Max range was limited by hallways (~30 m) and still functional



Resonance frequency shifts from 27–31.5 GHz with 100–0% relative humidity, respectively

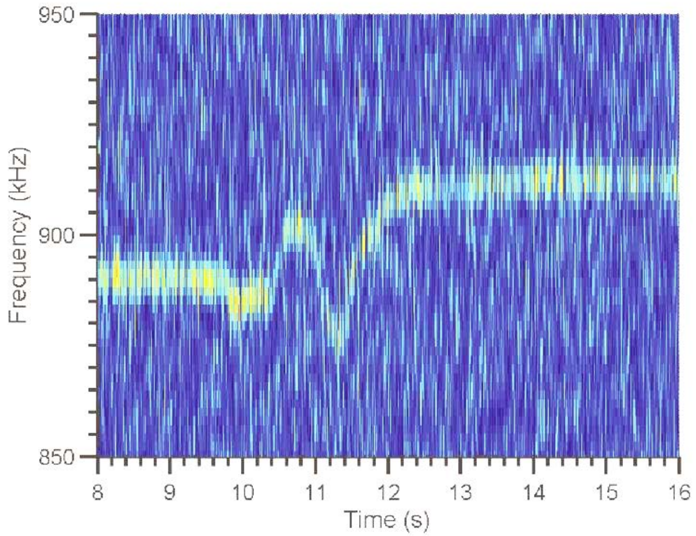
Printed, flexible, backscatter-modulation Van-Atta sensor structure

- Active backscatter-modulation Van-Atta
- All the advantages of the passive Van-Atta + non-linear response
- Enables this new structure with
  - Ultra-long-range reading capabilities (up to several kilometers)
  - Outdoor or indoor energy autonomy with solar cell:
    - Ultra-low power consumption (200uW)
  - Almost immediate integration of any of our printed gas sensors
    - Several on the same platform, in the future



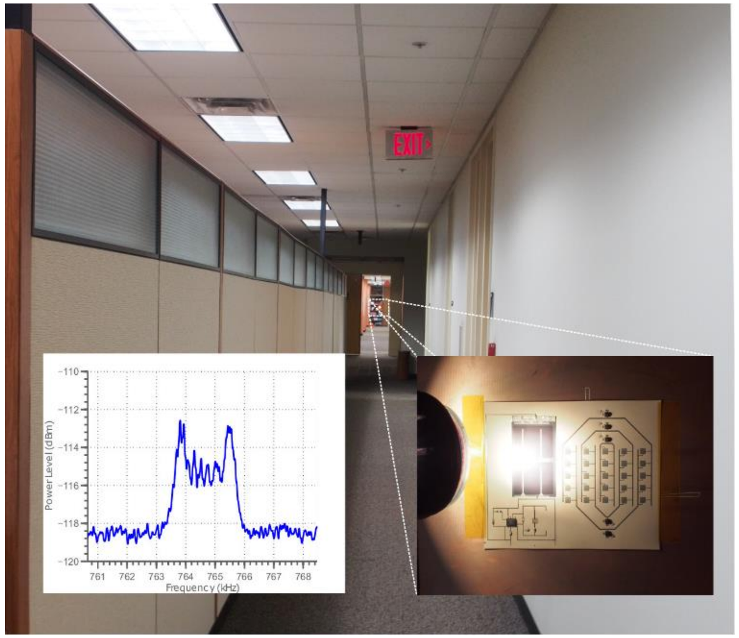
Backscatter-modulation Van-Atta structure: sensing

- Printed CNT-PABS ammonia sensor was integrated
- Short ammonia sensing event was measured (as shown on the IF spectrogram)
  - Very quick response

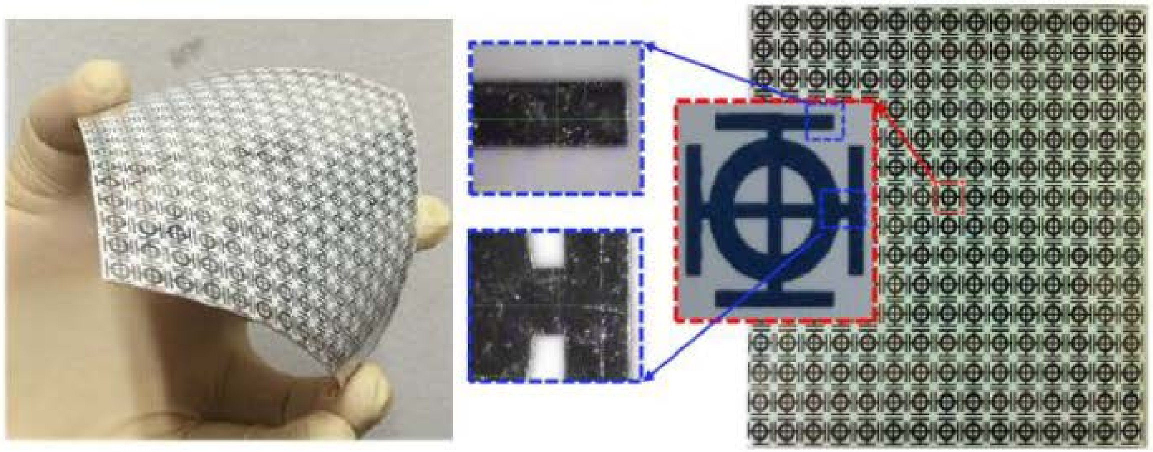


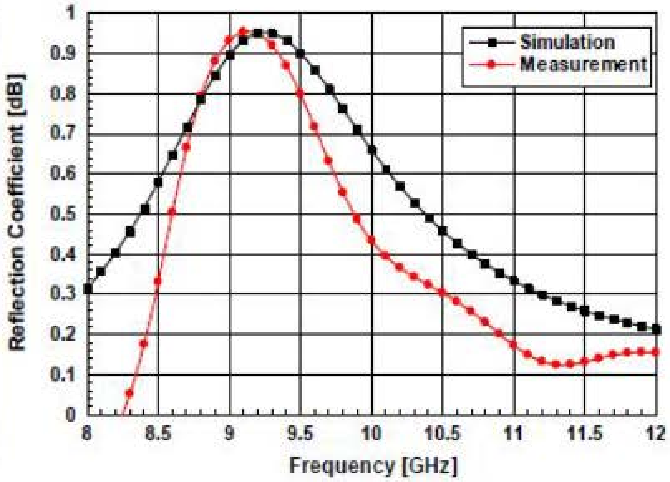
Backscatter-modulation Van-Atta structure: Ultra-long-range (100m+)

- Sensor interrogation was demonstrated at a record range of 580m (80m+ here)
- Range is now only limited by the poor noise performance of our mm-wave signal generator
  - Range would be extended to kilometers with higher performance LO



Inkjet-Printed 2D/3D EMI/EMC Isolation Structures



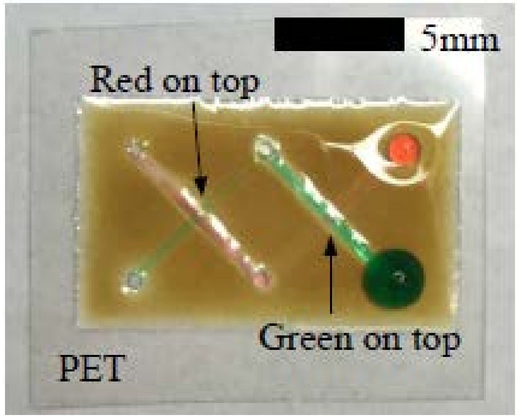


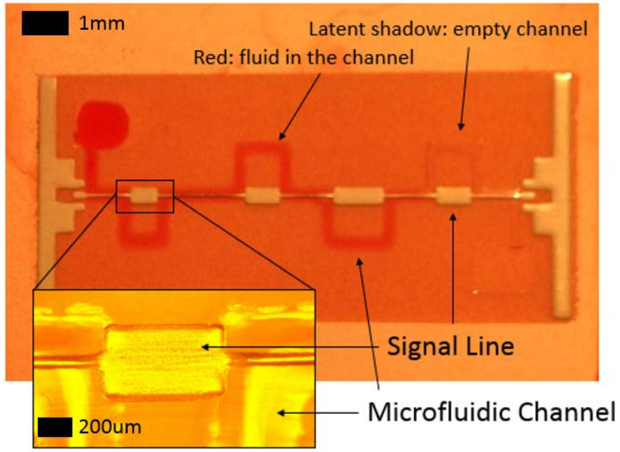
- Flexible inkjet-printed metamaterial absorber on paper
- Silver nanoparticle ink
- 95% absorptivity at 9.13GHz for an angle of incidence of less than 40° and polarization insensitivity

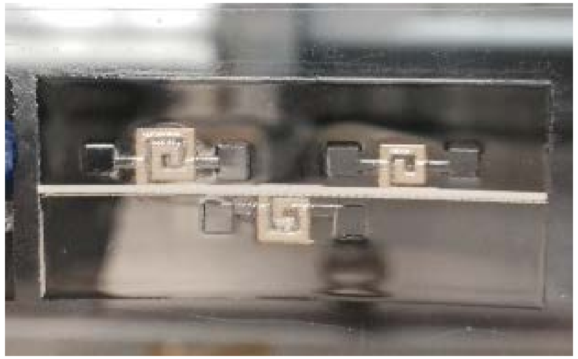
Source from Prof. Manos M. Tentzeris

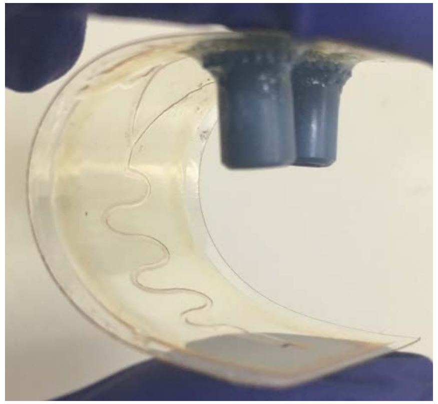
Flexible Inkjet-Printed Microfluidics

- Small channel down to 60 um*0.8 um
- Flexible
- On virtually any substrate (e.g.glass)
- Tunable microwave structures
- Ideal for water quality monitoring and biosensing



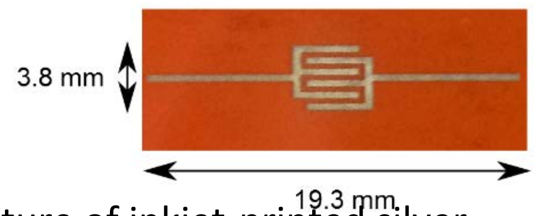




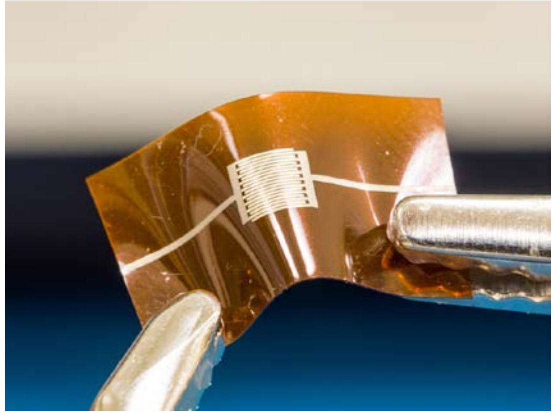


Wireless CNT-Based Gas Sensors

- Printing of 5 to 30 layers of CNT ink
- Drying at 100°C for 10 hours, under vacuum
- Chemical functionalization of film
- Printing of electrodes with silver nanoparticle ink (SNP)
- Drying and sintering at 110°C for 3 hours

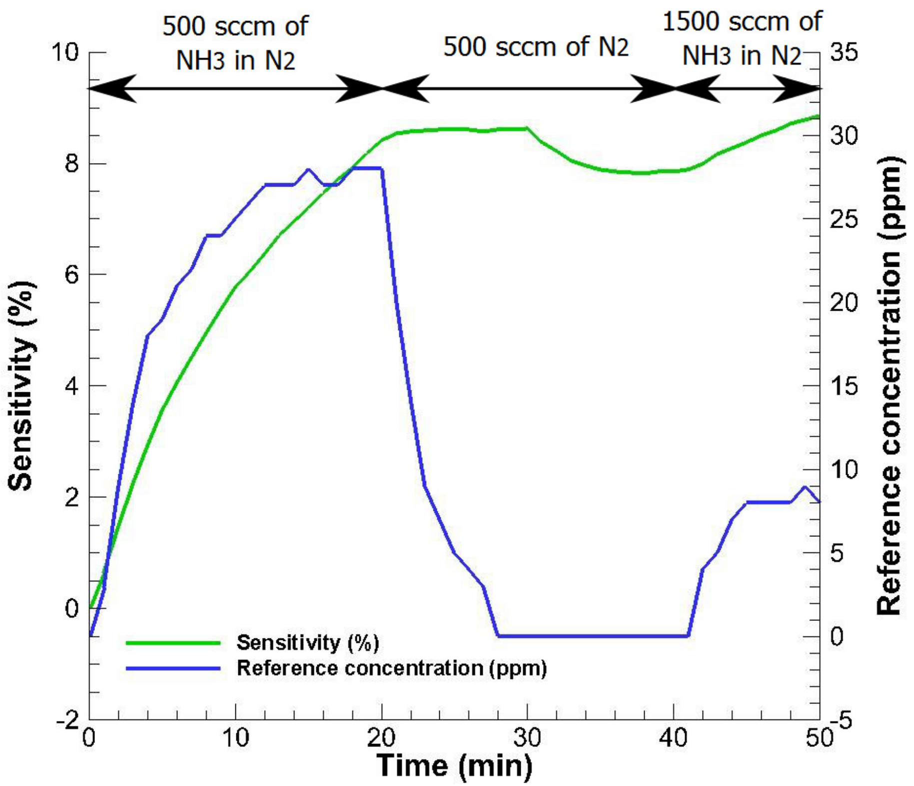


Picture of inkjet-printed silver electrodes



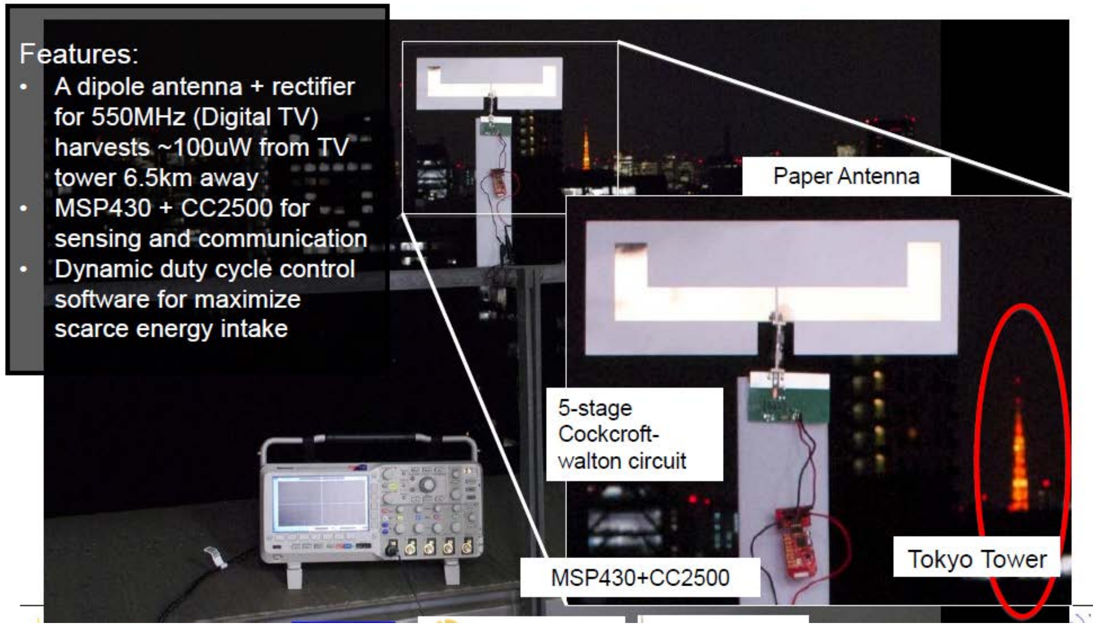
Results for rGO sensor

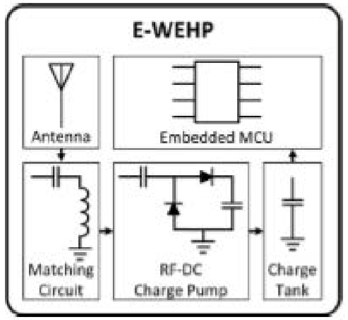
- Response time comparable to that of commercial sensor
- Sensitivity of 8.5% to exposure to 28 ppm of NH_3
- To our knowledge, highest sensitivity fully inkjet printed rGO ammonia sensor

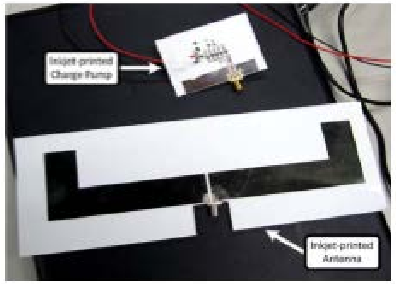


Measured sensitivity of rGO sensors (green) and reference NH_3 concentration (blue)

Additively Manufactured Ambient Long-Range RF Energy Harvester



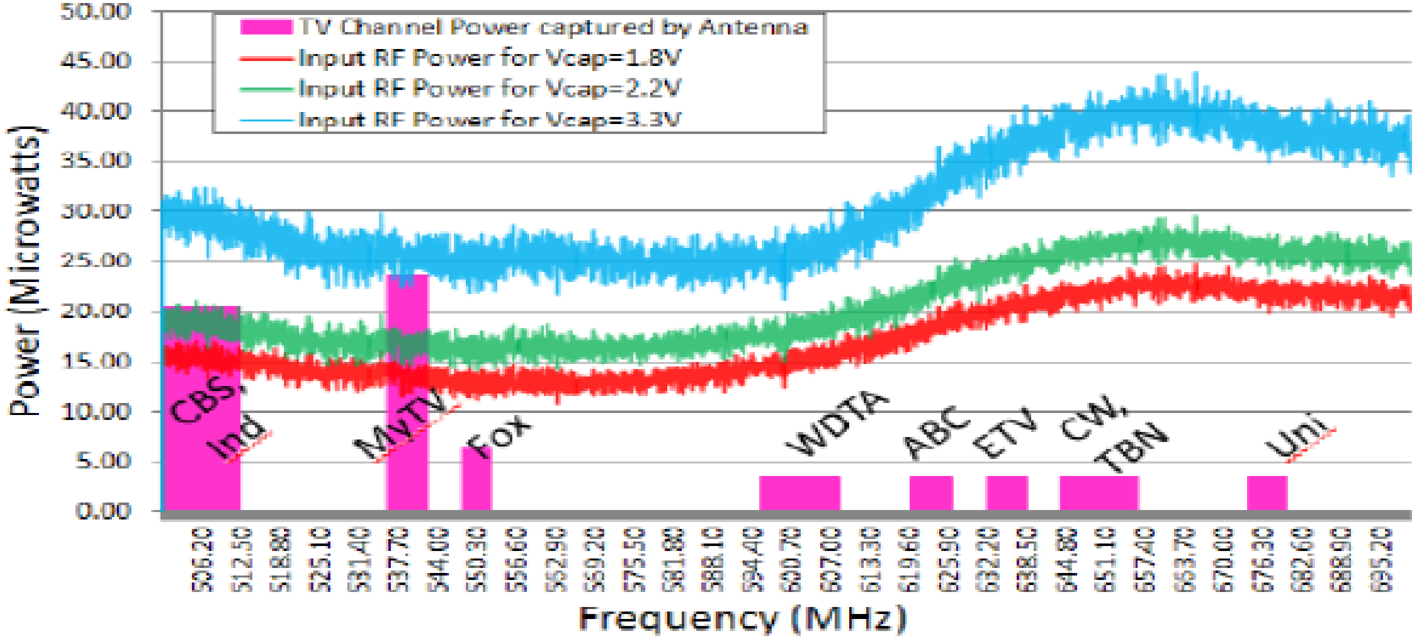




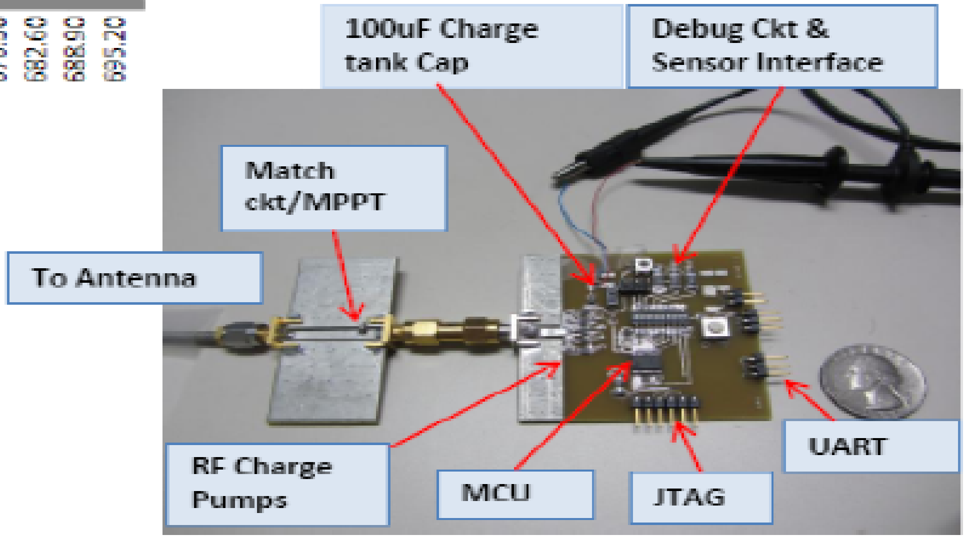
R.J.Vyas, B.Cook, Y.Kawahara and M.M.Tentzeris, ``E-WEHP: A Batteryless Embedded Sensor Platform Wirelessly Powered from Ambient Digital-TV Signals", IEEE Transactions on Microwave Theory and Techniques, Vol.61, No.6, pp.2491-2505, June 2013.

S.Kim, R.Vyas, J.Bito, K.Niotaki, A.Collado, A.Georgiadis and M.M.Tentzeris, ``Ambient RF Energy-Harvesting Technologies for Self-Sustainable Standalone Wireless Platforms", Proceedings of IEEE, Vol.102, No.11, pp.1649-1666, November 2014.

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

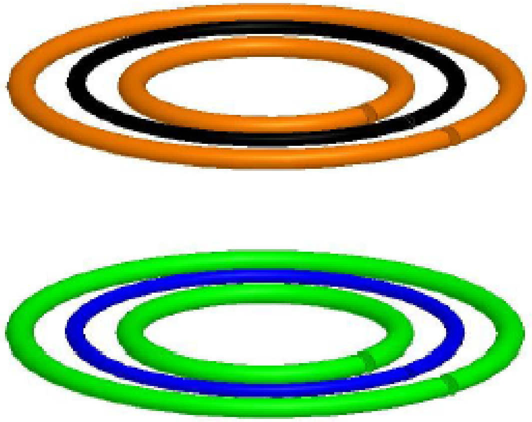


- **EH Circuit design includes:**
  - Converts microwatts of wireless power to over 3V of DC output signal
  - No batteries - Uses Capacitor to wireless power
  - Powers up microcontroller for power management and sensing applications

  - 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

Broadband & Highly Efficient WPT

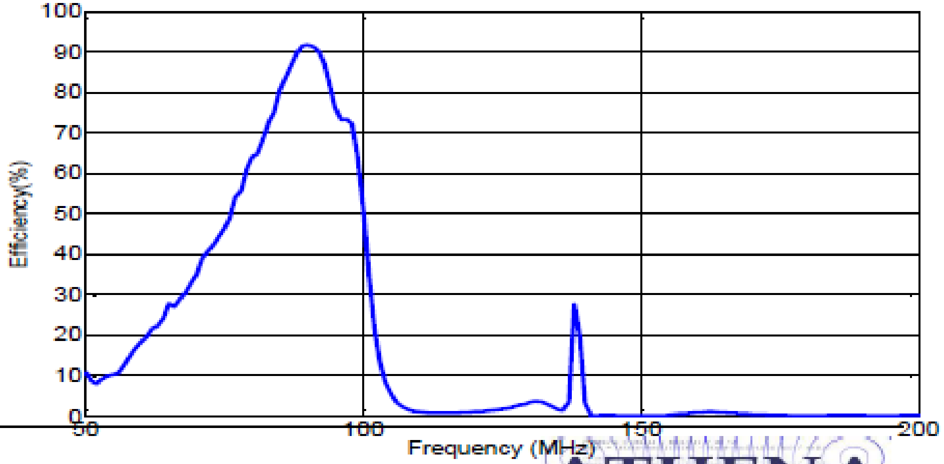
Distance = 7 cm



Legends

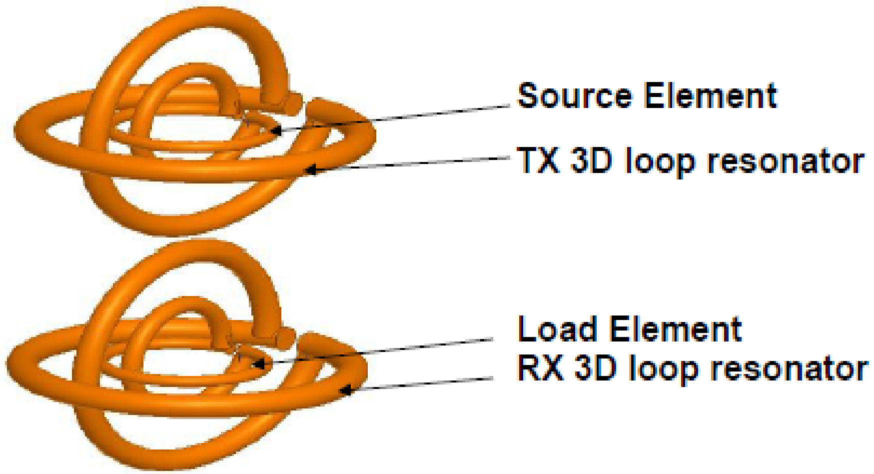
- RX resonator
- RX load
- TX resonator
- TX Source

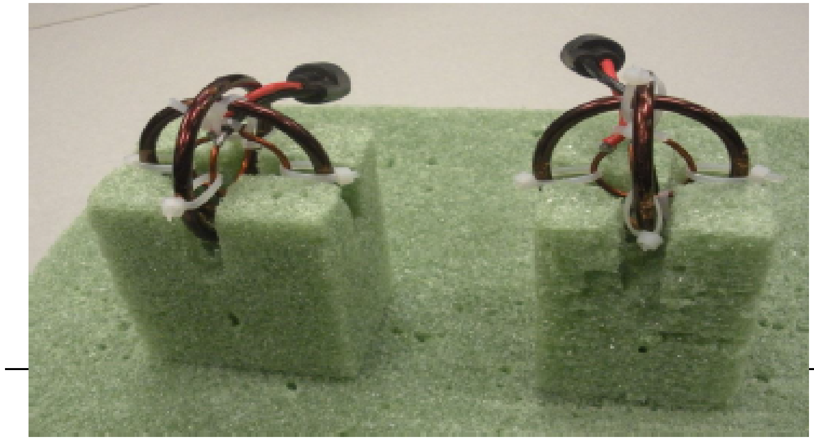
Measurements

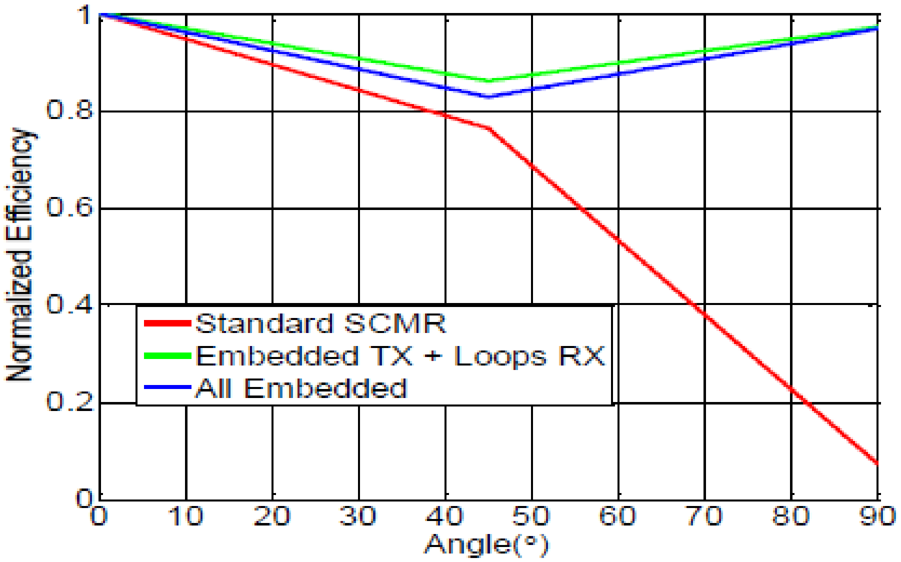


Provisional patent # 61/662,674

Misalignment-Insensitive Highly-Efficient WPT

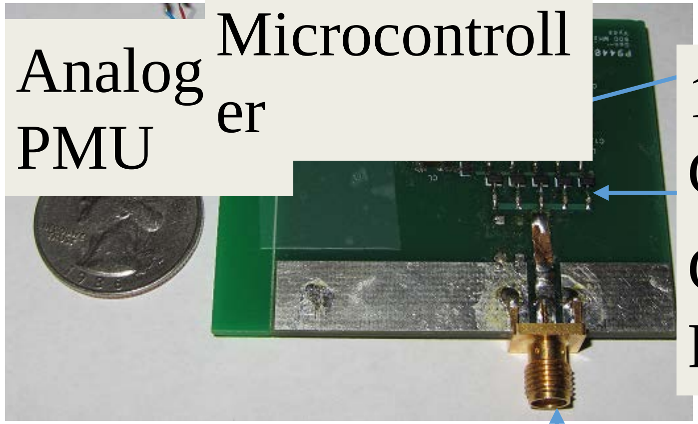






Provisional patent # 61/658,636

Wireless Energy Harvesting Circuit



Analog PMU

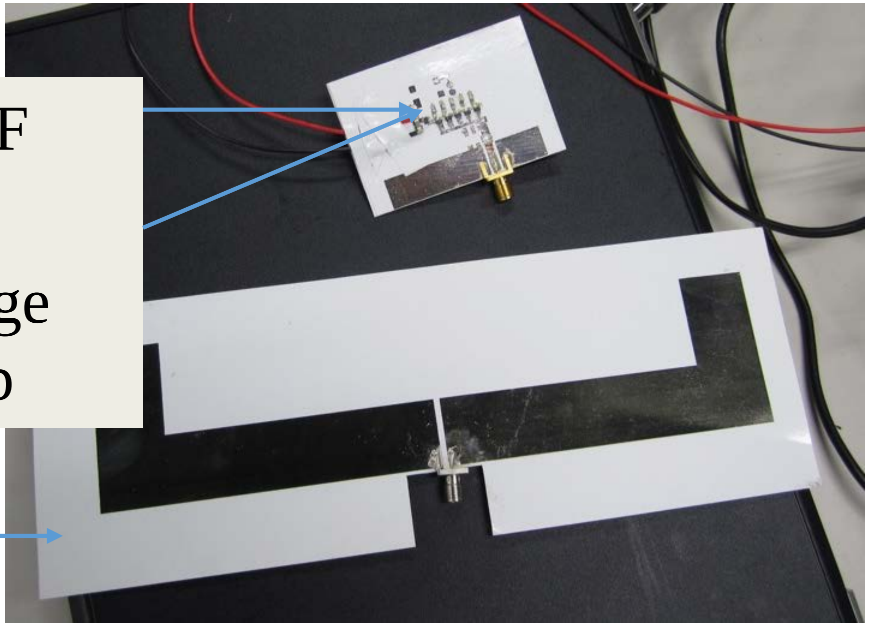
To Microcontroller

100uF Cap

Charge Pump

FR-4 version

To Antenna



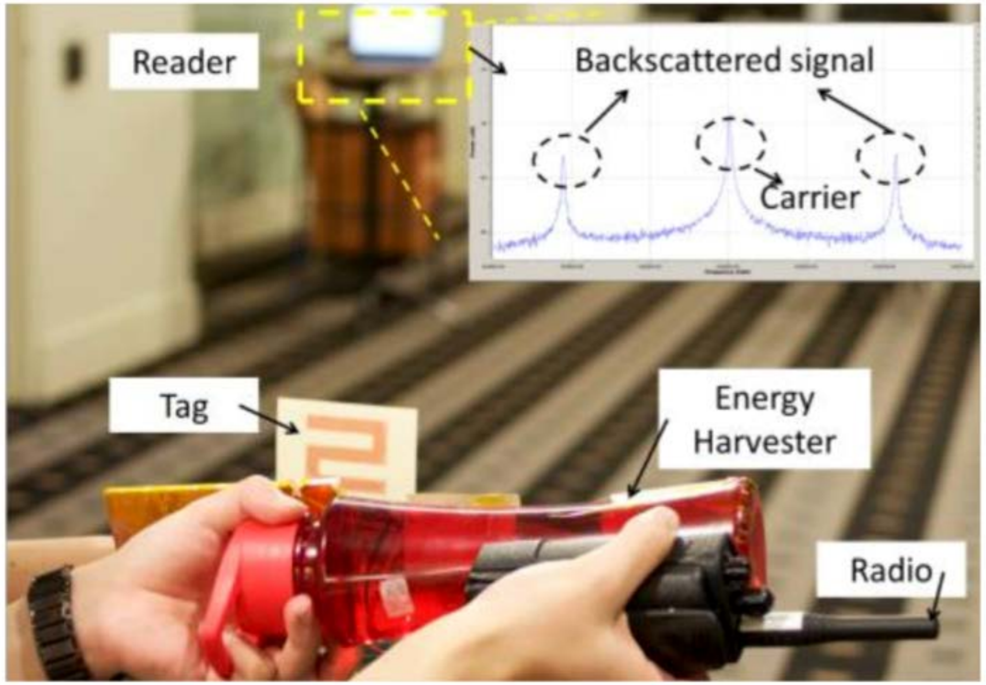
Inkjet Printed version on paper

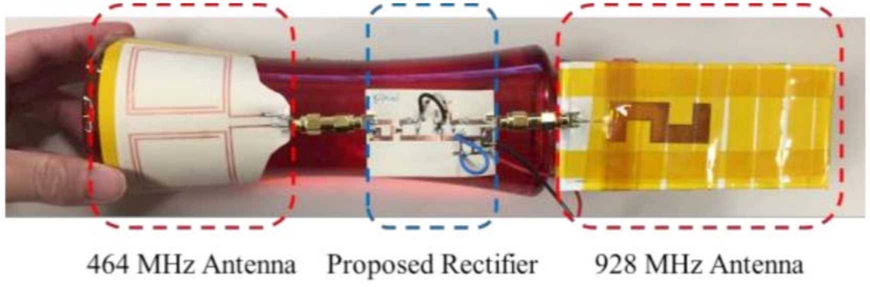
- Converts Wireless Power in air due to cell and TV signals into usable DC
- Antenna: Converts E-field in air to RF sine wave
- RF Charge Pump: Converts RF Sine Wave and steps it up to higher DC Voltage
- Charge Tank 100uF Capacitor: Stores harvested RF Power
- Power Management Unit: Works with Microcontroller firmware to
- BATTERY-LESS

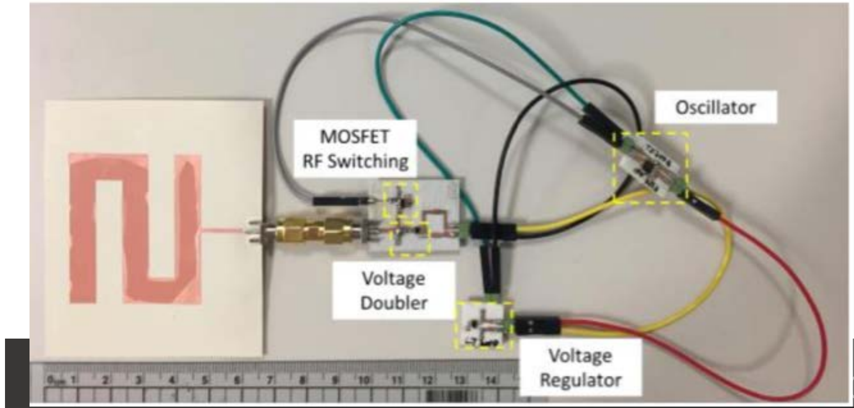
R.Vyas et al.**, "***A Battery-Less, Energy Harvesting Device for Long Range Scavenging of Wireless Power from Terrestrial TV Broadcasts*", IEEE International Microwave Symposium, June 2012

RF energy harvesting for on-body communication/sensing

- Wearable flexible backscattering capable on-body communication/sensing platform powered by energy harvester for two-way talk radio

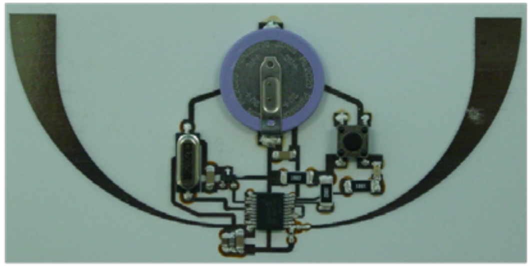




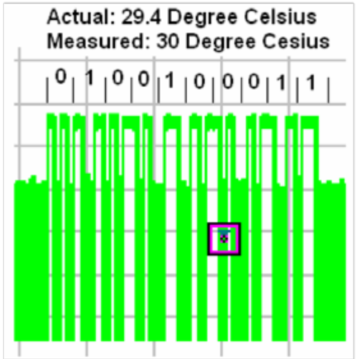


Wireless Sensor Module: 904.2 MHz

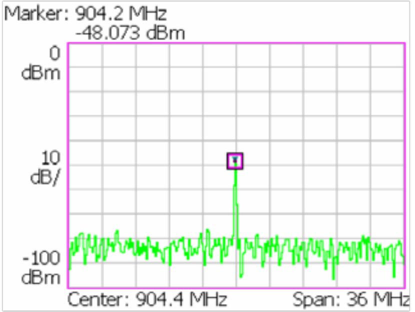
- Single Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.2 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for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



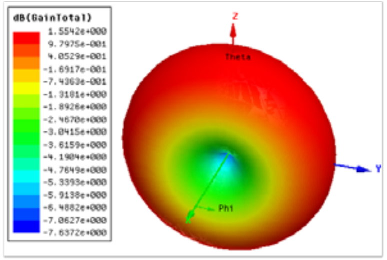
Circuit +Sensor+ Antenna on Paper



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



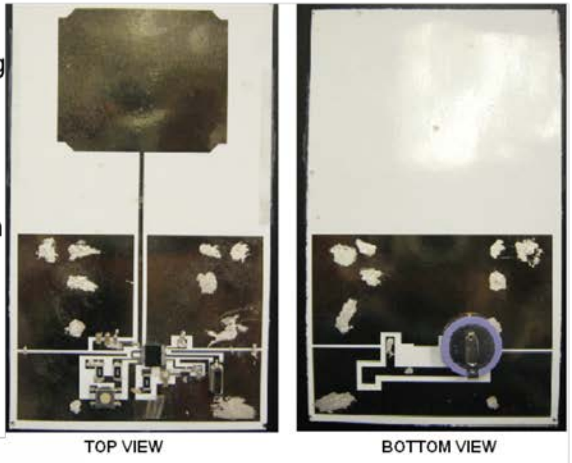
Wireless Signal Strength sent out by module, measured by Spectrum Analyzer



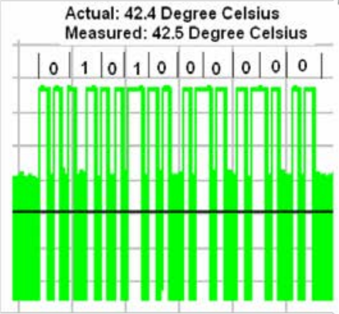
Antenna Radiation Pattern showing high gain

Wireless Sensor Module: 904.5 MHz

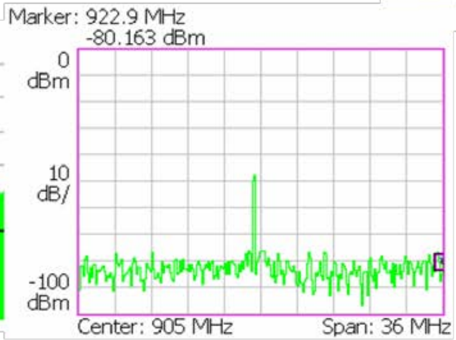
- Double Layer Module Circuit printed on Paper using inkjet technology
- Integrated microcontroller and wireless transmitter operating @ 904.5 MHz
- Module can be custom programmed to operate with any kind of commercial sensor, environment & Communication requirement
- Rechargeable Li-ion battery for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



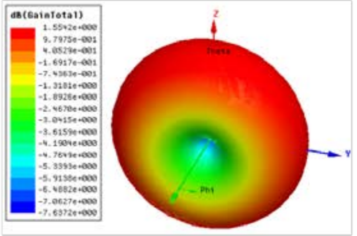
Circuit + Sensor+ Antenna on Paper



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

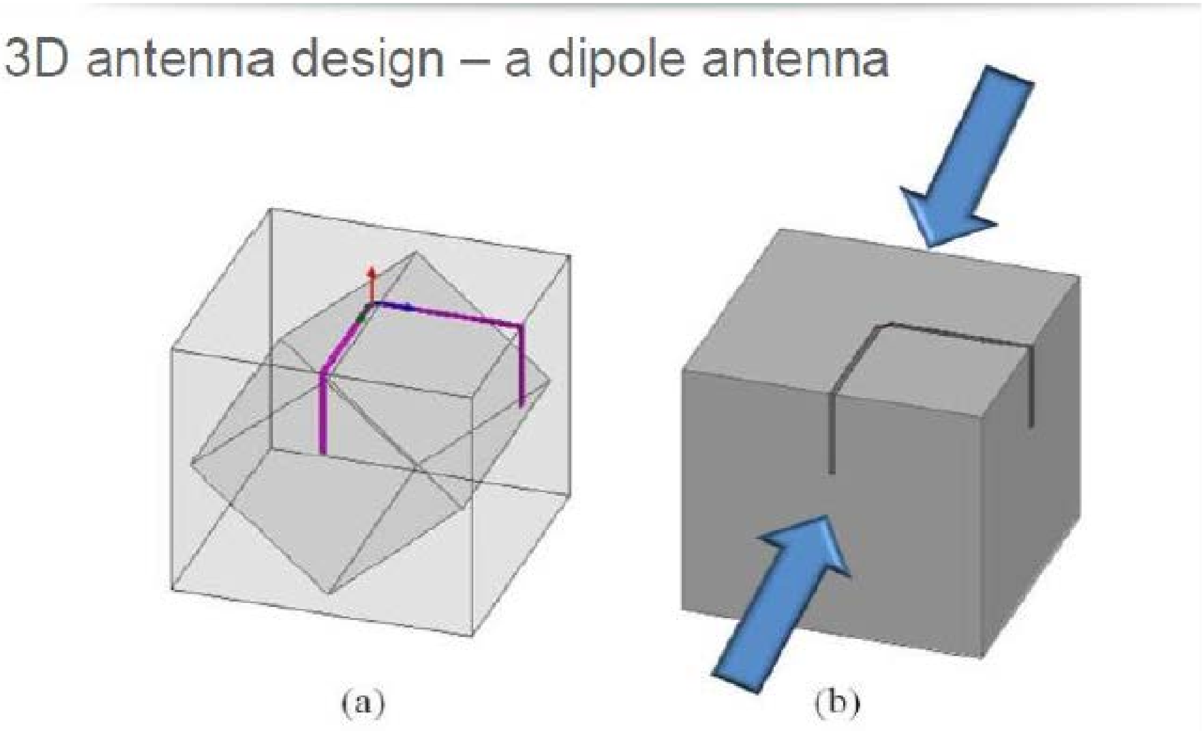


Wireless Signal Strength sent out by module, measured by Spectrum Analyzer

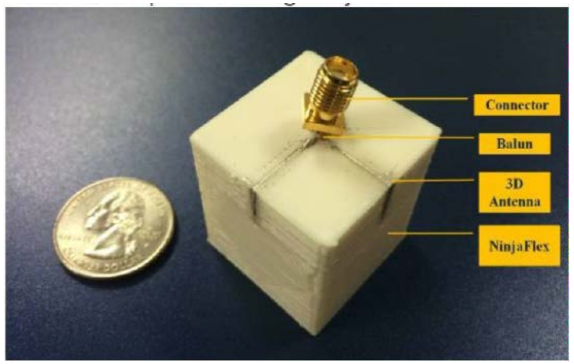


Antenna Radiation Patter showing high gain

3D-Printed Antenna with Arbitrary Embedded Cavity for Directional Strain Sensing

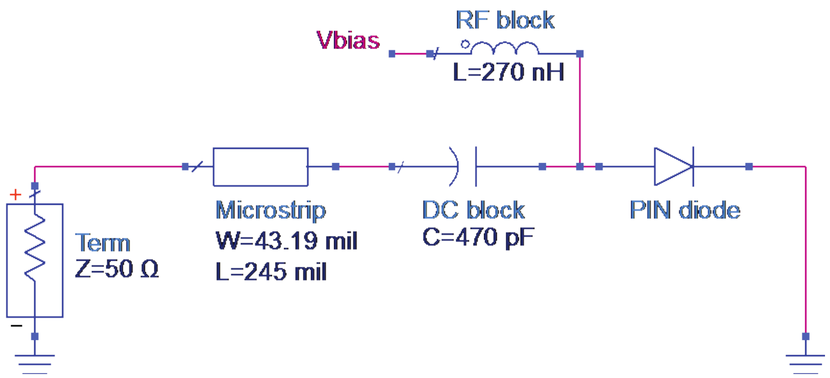


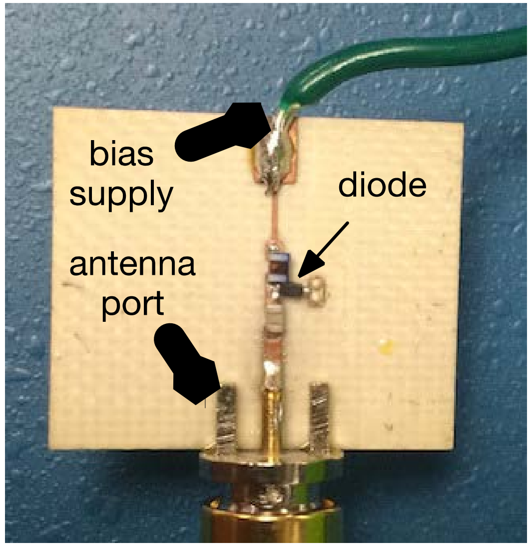
(a) 3D antenna on a hollow cube; (b) To add strain on the front and the back surfaces of the cube.



ENERGY AND BANDWIDTH EFFICIENT SENSORS

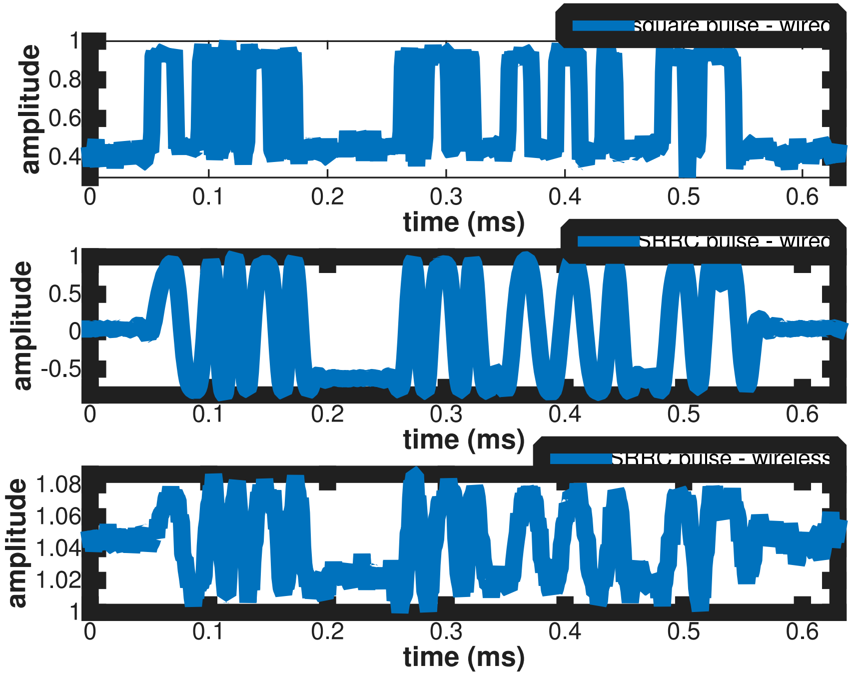
- Sensor front-ends for increased spectral efficiency
- Nanowatt-microwatt operation
- Low bias voltage 0-2V
- Can be directly interfaced to low-power microcontrollers for sensing and communication

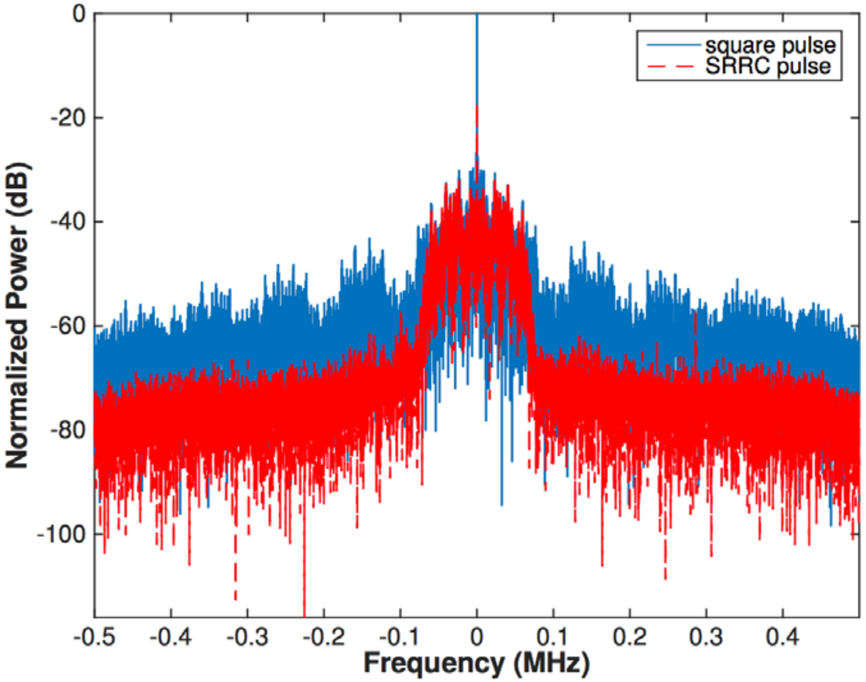




ENERGY AND BANDWIDTH EFFICIENT SENSORS

- Wired and wireless measurements with software-defined radio receiver
- Significantly **reduced bandwidth** compared to rectangular pulses
- More than 35 dB out-of-band **suppression** compared to rectangular pulses
- Can fit more sensors in the band, or transmit higher data rates <u>**(Gb/sec)**</u> from single sensor/matrix of sensors



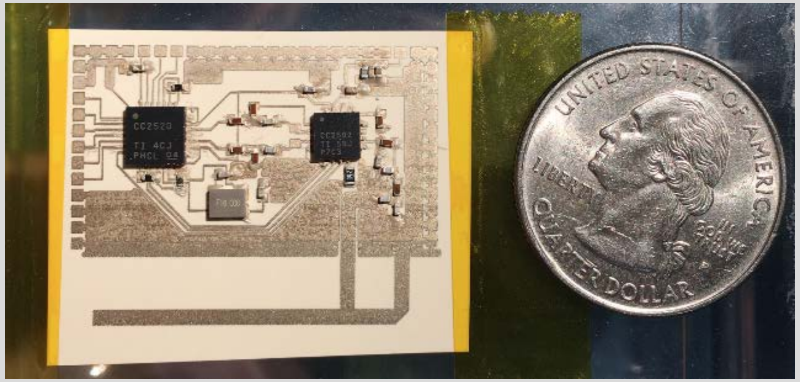


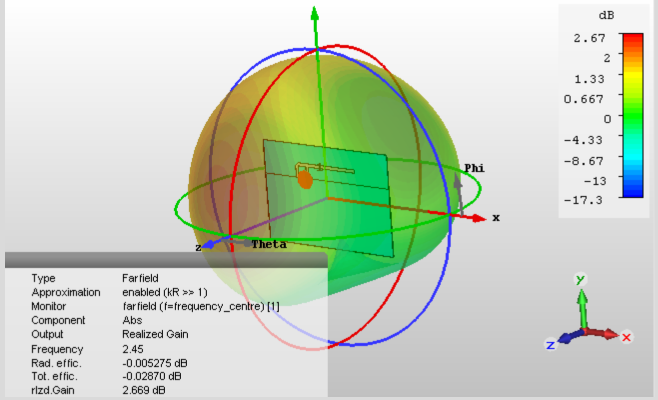
InkJet Printed MCM Prototype

- Compact module utilizing inkjet printing for next gen inkjet printed MCM packaging

- CC2520 IEEE 802.15.4/ZIGBEE RF Transceiver
- CC2592 Range Extender
- Integrated 2.4 GHz PIFA Antenna
- Liquid Crystal Polymer (LCP) Substrate
- 0402 SMD components (1x.5 mm)

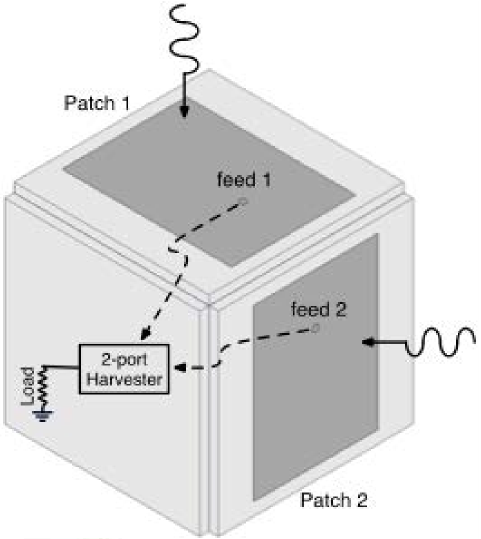
Demonstrated Prototype





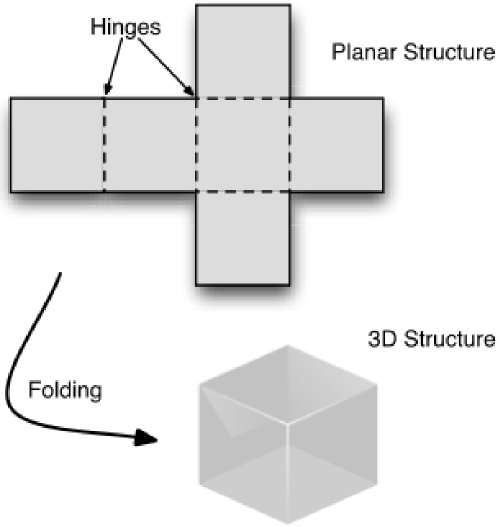
Morphing (4D-Printed) Origami-Enabled Sensor Node

- Origami systems – able to **fold and reconfigure** to deploy in field and alter performance
- Shape memory polymers (SMPs) allow for reconfigurability with the influence of external stimuli (heat, current, etc)



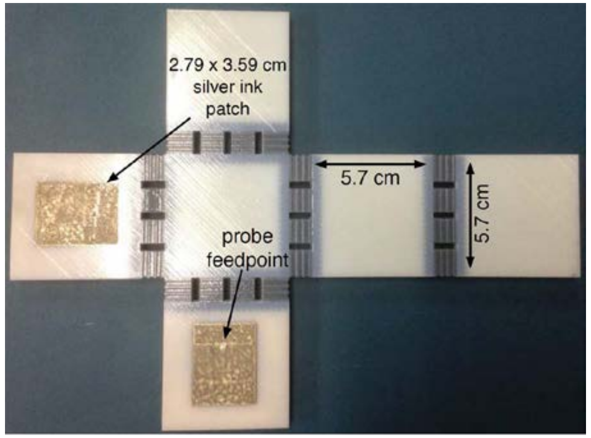
3D Wireless Sensor Node

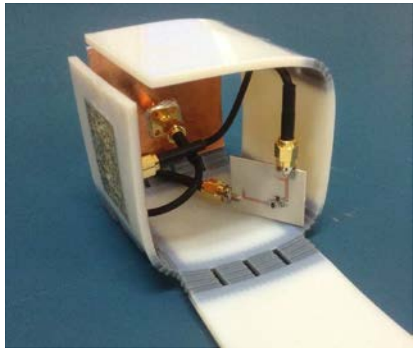
- Wireless energy harvesting for self-powered sensing
- Multiple antennas in cube shape allow for orientation-independent operation
- Fabricate planar foldable structure to reduce fabrication time



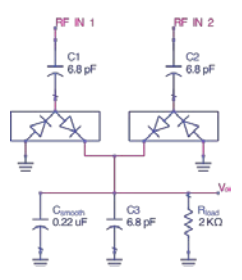
Printed Origami-Enabled Sensor

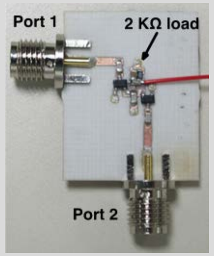
- 3D printing fabricates foldable cube package, inkjet printing fabricates metallic patch antennas
- SMP (TangoBlack/VeroWhite blend) hinges exposed to thermal treatment (50~60 °C) allowing for folding and shaping, holds shape when returning to ambient

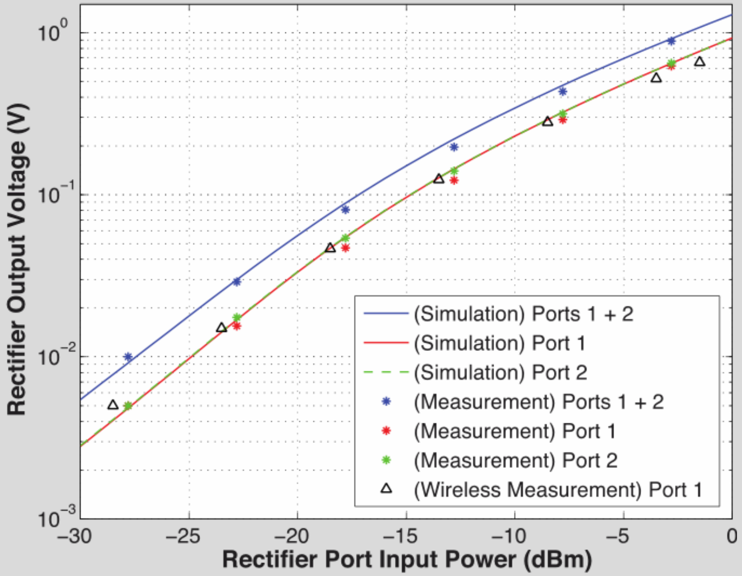




Multi-Port Wireless Harvesting







3D-Printed mm-Wave Packaging

Challenges for mm-wave system packaging:

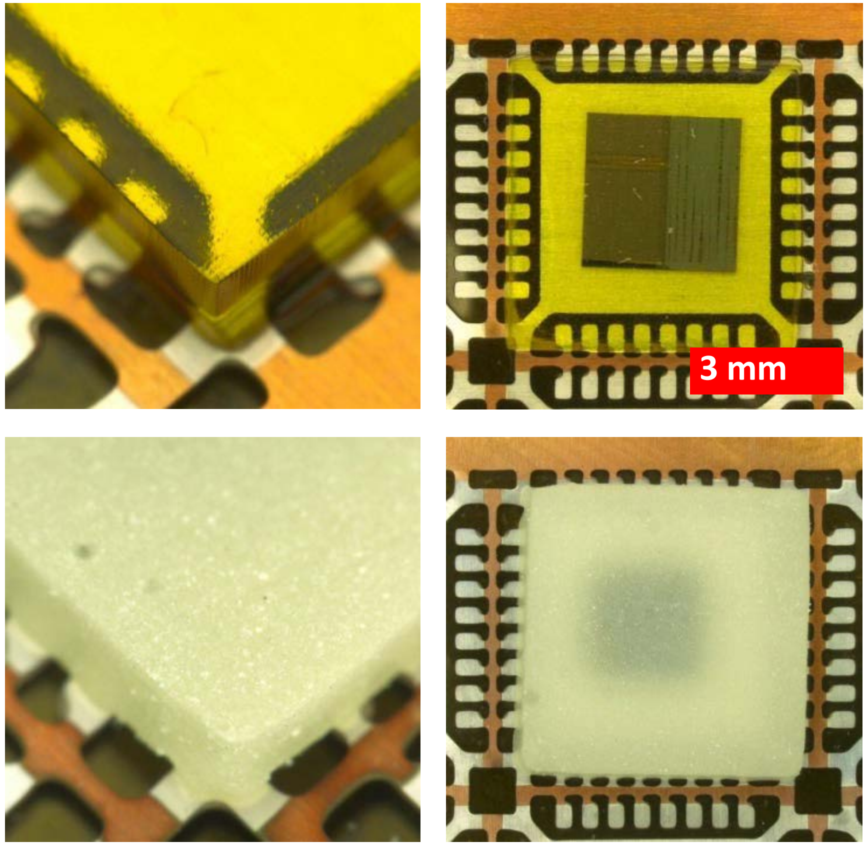
- Low-loss materials
  - Increase wireless system efficiency
  - High-frequency dielectric characterization necessary
- Miniaturization
  - Reduce package size and interconnect length
  - System-on-package (SoP) integration desired

Printing Solutions:

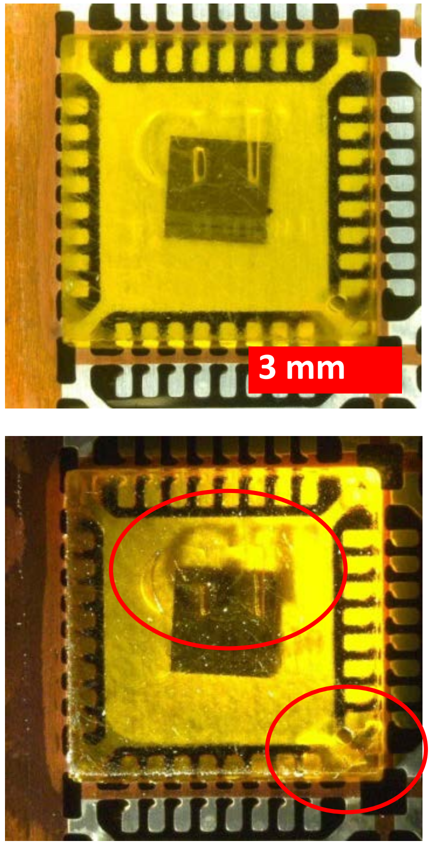
- Additively fabricate electronic structures
  - Reduce processing tools/steps
  - Remove high temp and pressure, **less package stress on die**
- High process reconfigurability
  - Short-run prototyping and mass-scale production
  - **Multi-application processing** with single tooling technology

3D-Printed Encapsulation

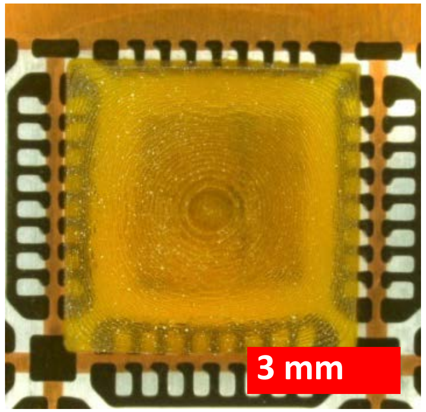
Standard 1 mm-Thick Encapsulation



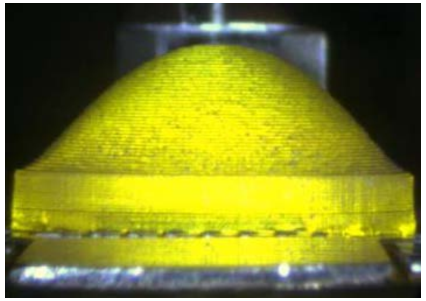
Text and Detailing



Lens Integration

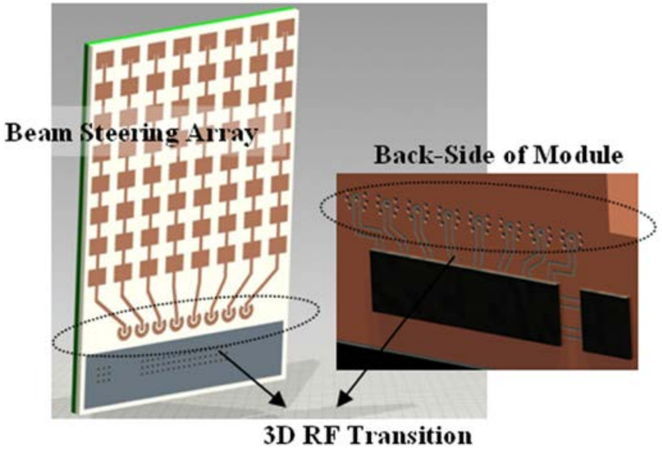


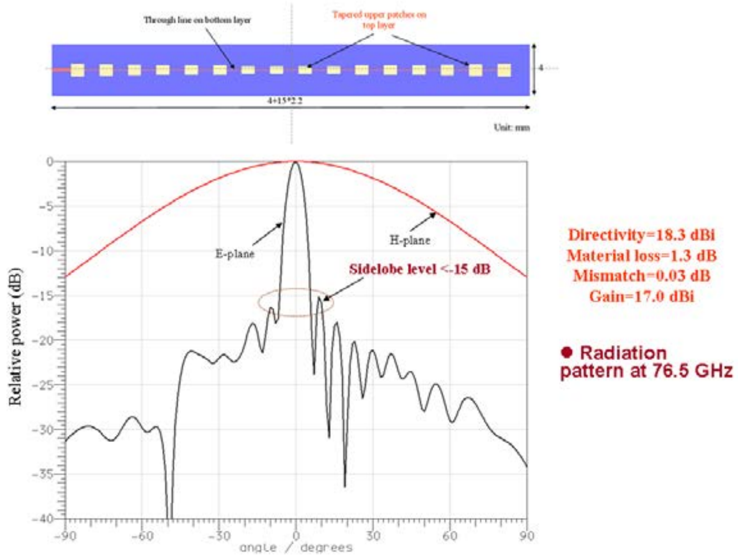
Side View

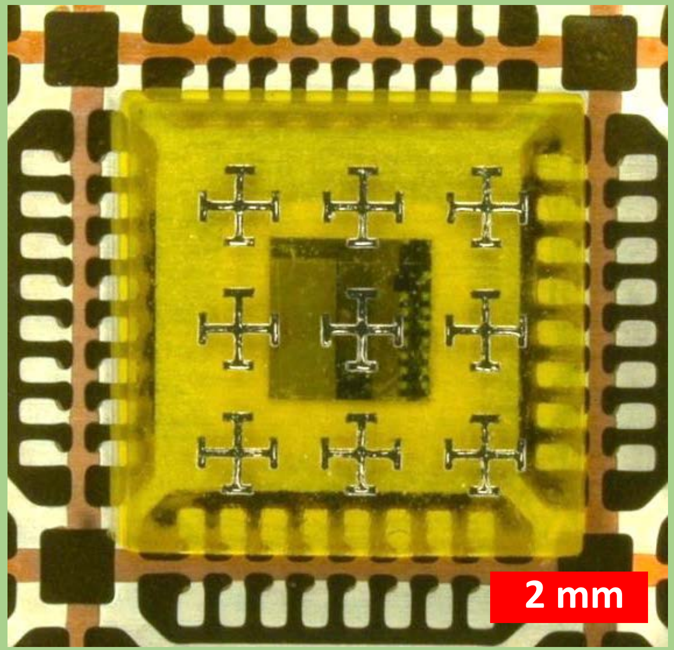


Post-Process On-Package Printing

- Use inkjet printing to fabricate metallic structures on top of 3D-printed encapsulation
  - Decoupling capacitors
  - Antenna arrays
  - Frequency selective surfaces (FSS)



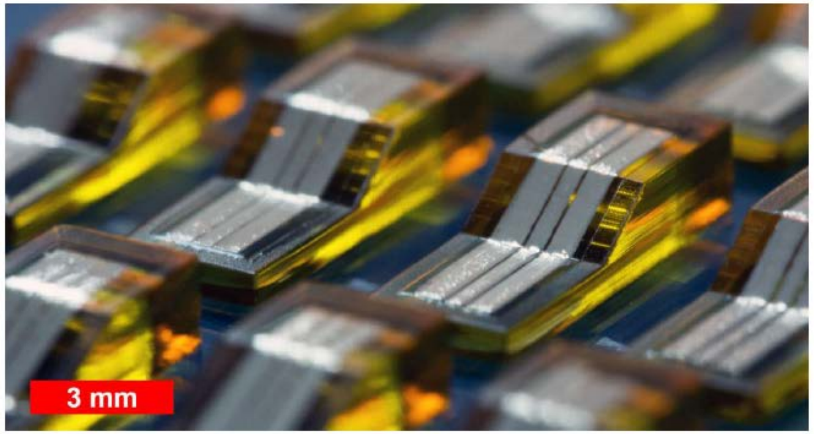


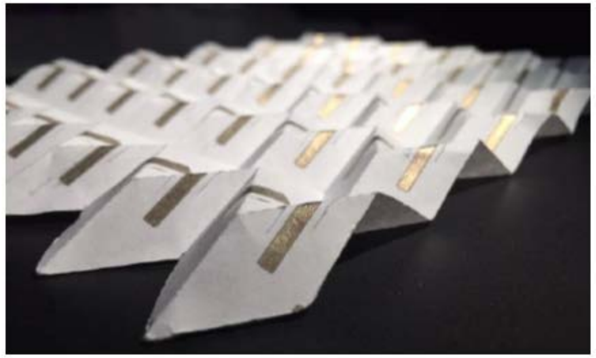


Periodic Jerusalem Cross FSS inkjet-printed onto 3D-printed encapsulation

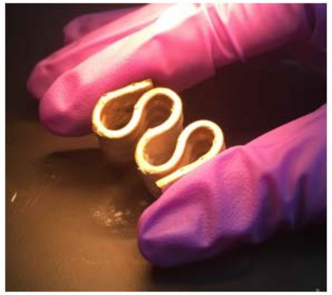
Flexible Waveguides & Interconnects/ 3D Antenna “Tree” / 4D “Origami” Broadband Flexible FSS / Zero-Power Wearables

[to be announced in IEEE IMS 2017, June 2017]





(a)



(b)

(c)