# Additively Manufactured & Origami-Based Wireless Sensing, RFID and Communication Nodes [2016 Updates]

Prof. Manos M. Tentzeris
*School of ECE, Georgia Tech, U.S.A.*
[etentze@ece.gatech.edu]

CRFID Distinguished Lecturer

# 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 | ∞ |

ATHENA

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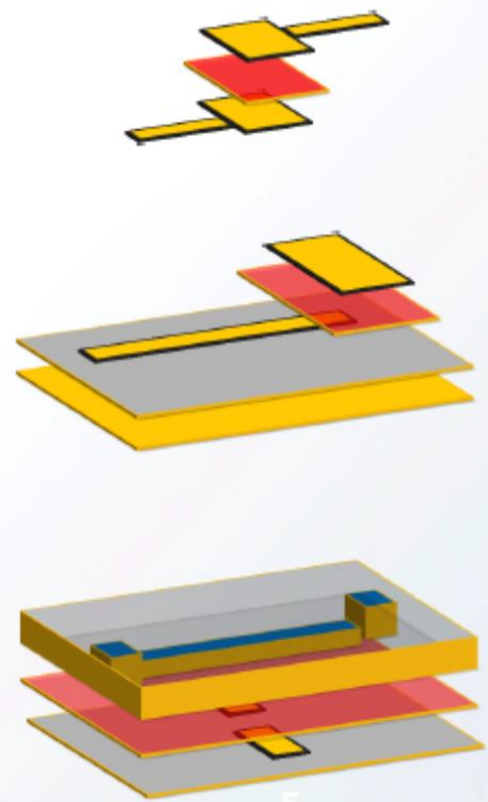
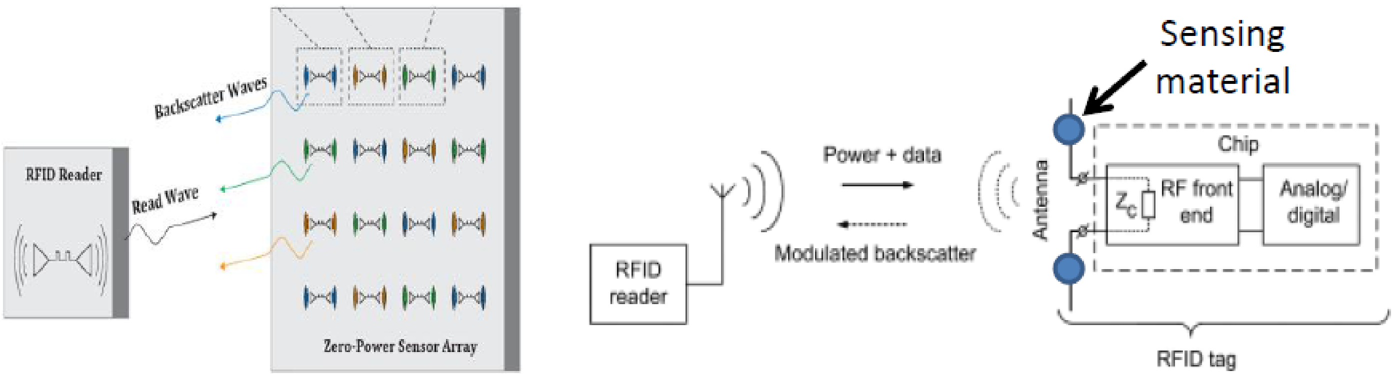
# Advantages of Fully-Printed Systems

- Low-cost fully-printed systems
  - Removal of mounted discrete components
  - Stackable interconnects and crossovers
  - Higher levels of complexity and integration



- Ability to post-process onto CMOS (Long Term)
  - High gain antennas
  - Reduce chip area (Post-processed inductors and capacitors)
  - Non-CMOS compatible components and sensors

# Smart Computational Skins

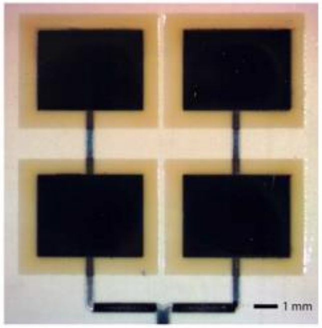



**< RFID-based wireless sensor system >**

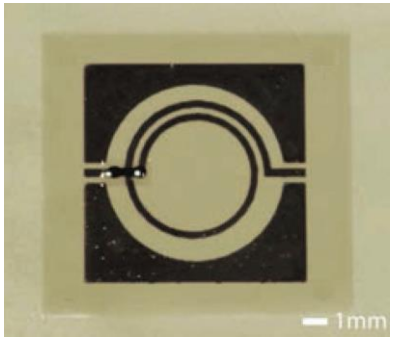
- Array of nanomaterial-based sensors
- Ubiquitous coverage with few readers
  - Low cost compared to equivalent system using standard sensors
- Many applications: gas sensor, strain sensor, etc.

# AM Flexible components

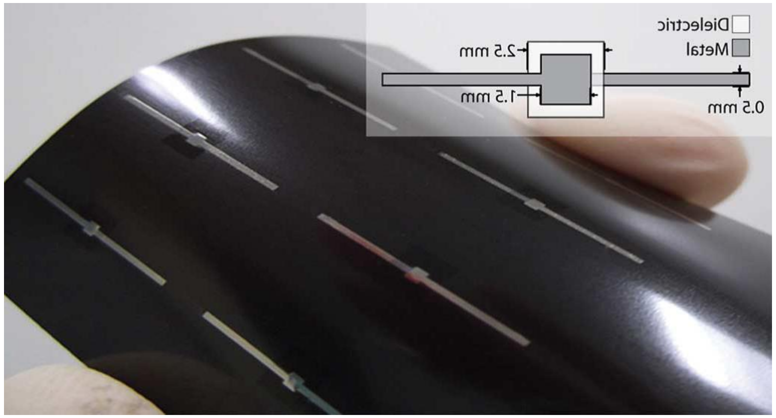
- Antennas
- Capacitors
- Inductors
- Micro-fluidics
- Sensors




Fully inkjet-printed 25 GHz patch antenna array [1]

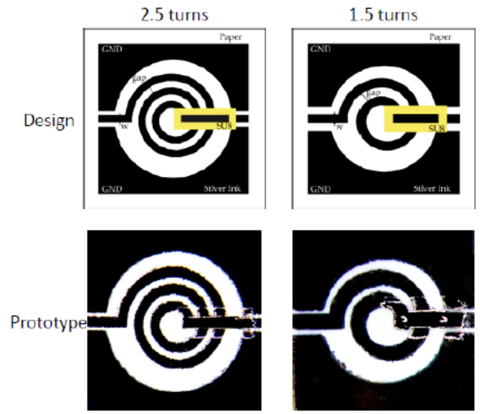



Fully inkjet-printed inductor [3]



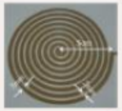
Fully inkjet-printed capacitors [2]

# AM Inductors on Paper (Actives?)




Geometry

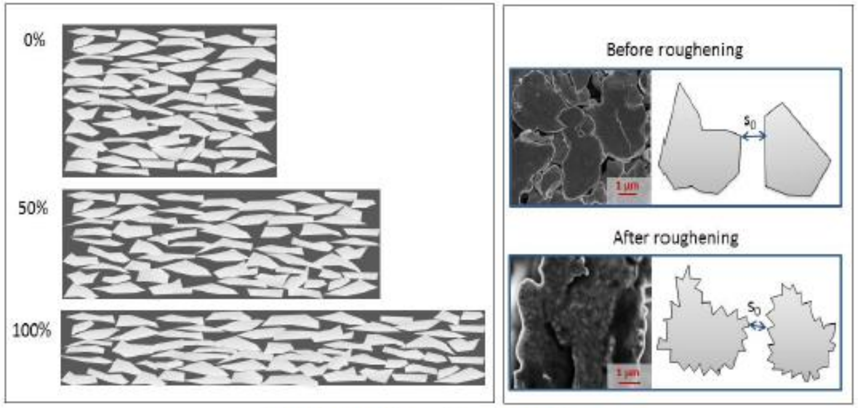
| Parameter | Value (µm) |
|---|---|
| w | 0.3 |
| gap | 0.3 |
| tm | 2.5 |
| td | 20 |

| Ref | Design | geometry | process | L (nH/mm²) |
|---|---|---|---|---|
| [11] |  | square | inkjet | 0.04 |
| [12] |  | circular | inkjet | 0.002 |
| this work |  | circular | inkjet | 43 |


[11] H. Lee, M. Tentzeris, Y. Kawahara, and A. Georgiadis, "Novel inkjet- printed ferromagnetic-based solutions for miniaturized wireless power transfer (WPT) inductors and antennas," in Antennas and Propagation (ISAP), 2012 International Symposium on, Oct 2012, pp. 14–17.
[12] S. M. Bidoki, J. Nouri, and A. A. Heidari, "Inkjet deposited circuit components," Journal of Micromechanics and Microengineering, vol. 20, no. 5, p. 055023, 2010.

# Printed Wireless Sensors

- **Printed stretchable silver**
  - Printable stretchable silver paste is developed
- **High elasticity**
  - high conductivity ($1.5x10^4$ S/m): static & stretching states
- **Operation principle**
  - Resonant frequency shifting of antenna



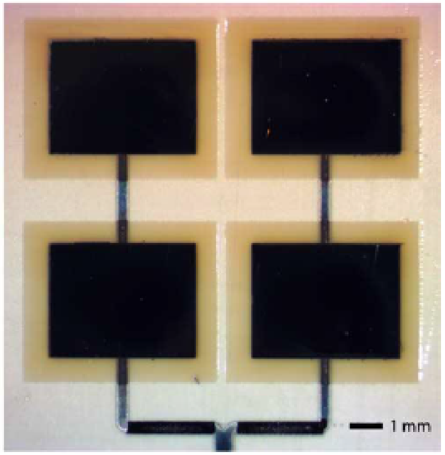

**< Stretchable silver paste >**

**< Printed antenna-based sensor >**

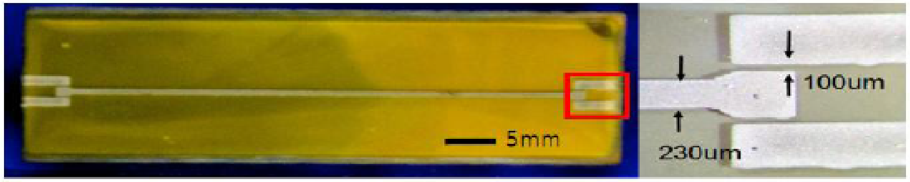
# High-Directivity Printable Antenna Arrays

## Thick Film Dielectric Applications

- Mm-Wave Antenna Structures
  - Proximity Coupled Patch Array
  - Yagi Uda Antenna Array
  - *Radar, gigabit wireless networks*

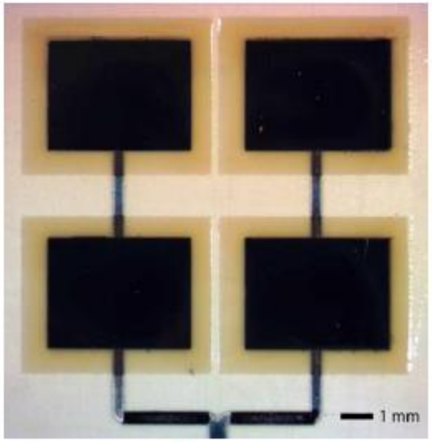



- Fully Printed RF Structures
  - Microstrip T-Resonator
  - *Mat. char., substrate isolation*

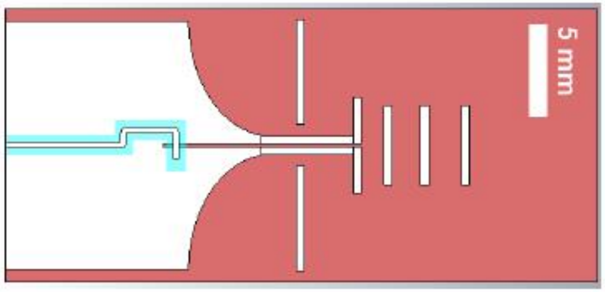


# Printed mmWave Antennas

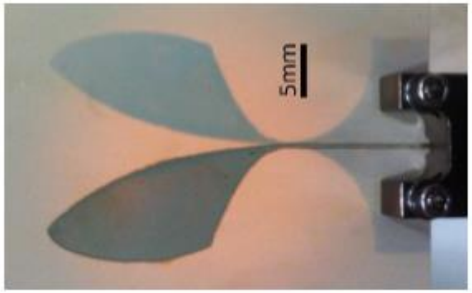
- New era of high frequency technology
  - Gigabit wireless networks
  - Automotive radar
  - Biological imaging
- High gain > 7 dBi
- 24.5 GHz ISM band
- On-chip integration
  - Post-processing antenna fab
  - Inter/intra-chip wireless communication




< Printed patch array antenna >

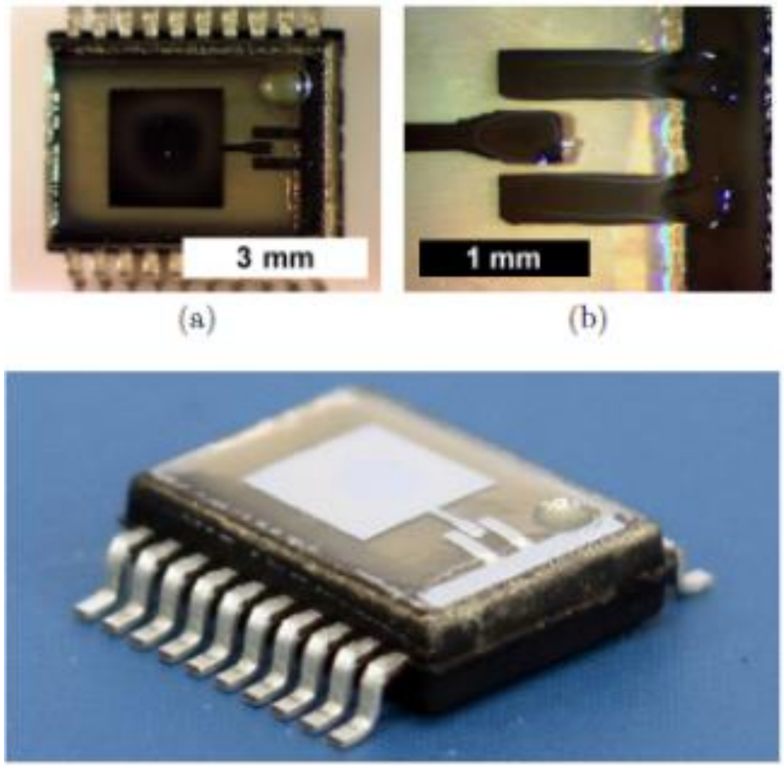



< Printed Yagi-Uda antenna >



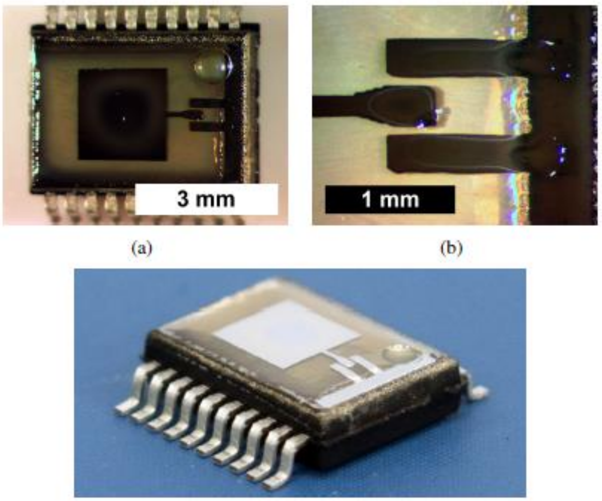

< Printed Vivaldi antenna >

# Inkjet-Printed On-Chip & On-Package sub-THz Antennas & Passives




(a) (b) (c)

# On-Package Inkjet-Printed 30 GHz Antenna



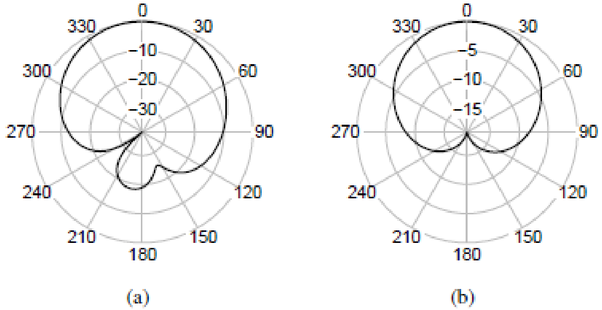
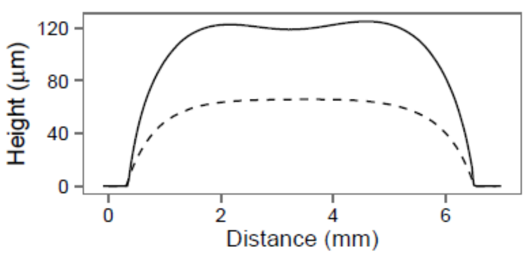
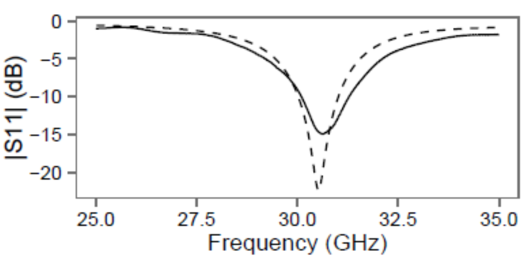
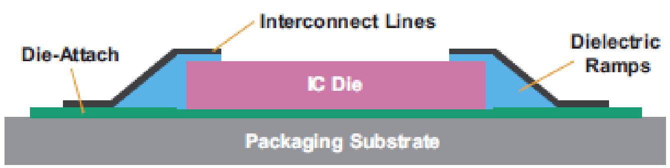



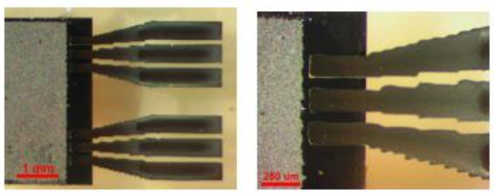

Fig. 4. Simulated (a) YZ and (b) XZ normalized radiation pattern cuts.



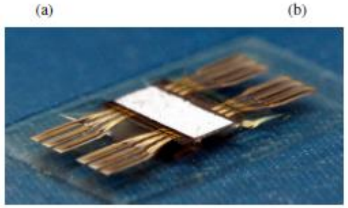



# On-Package Inkjet-Printed 3D-Interconnects for mmW

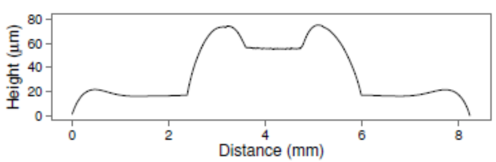


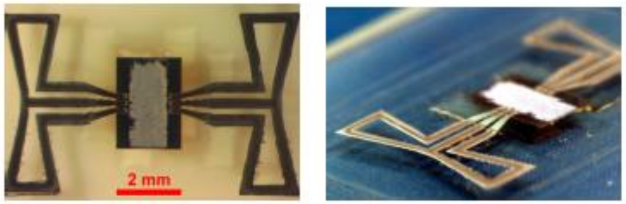




(a) (b)

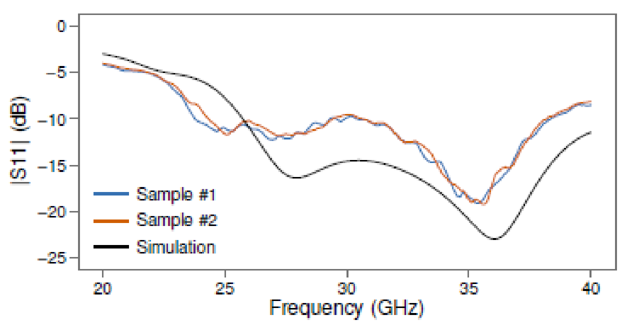


(c)

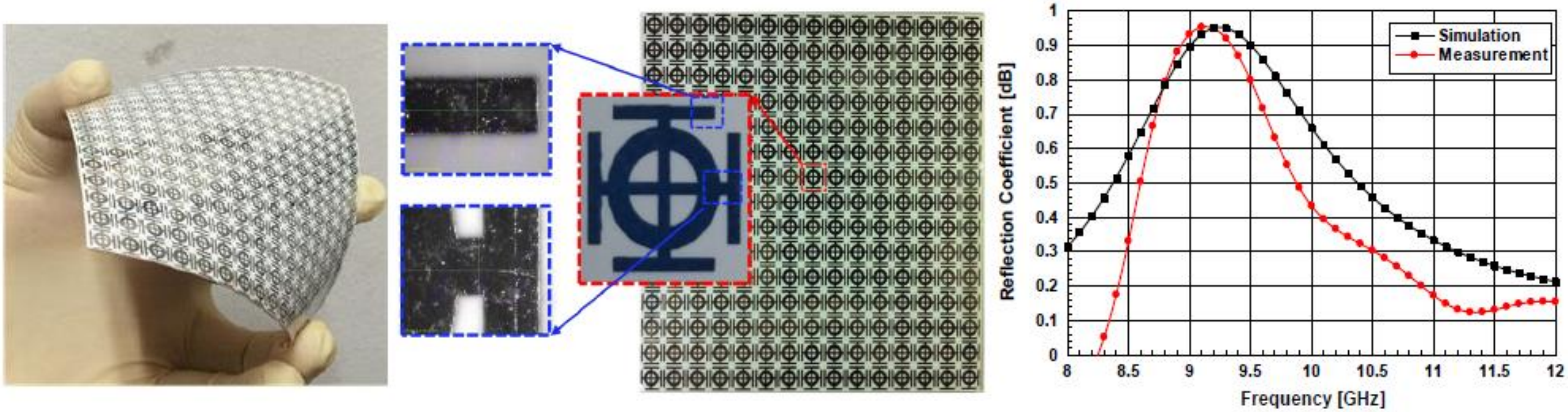



(a) (b)



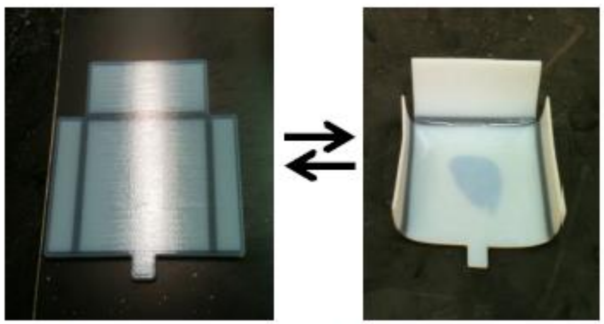
# Printable EMI/EMC Isolation Structures



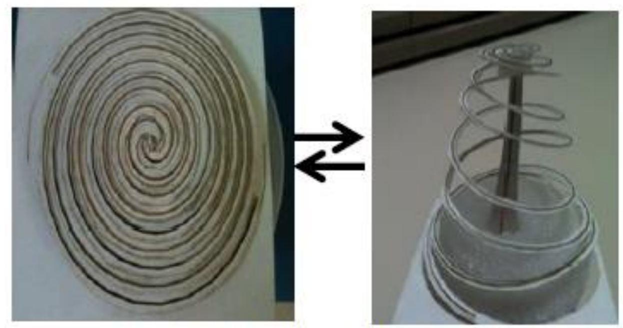

- We proposed a novel, flexible inkjet-printed metamaterial absorber on paper.
- The proposed absorber was fabricated on a paper substrate using silver nanoparticle ink.
- The proposed absorber exhibits 95.4% absorptivity at 9.13 GHz.
- The proposed absorber exhibits over 95% of absorptivity at 9.13 GHz for an angle of incidence of less than 40° and polarization insensitivity.

# Reconfigurable Origami Electronics

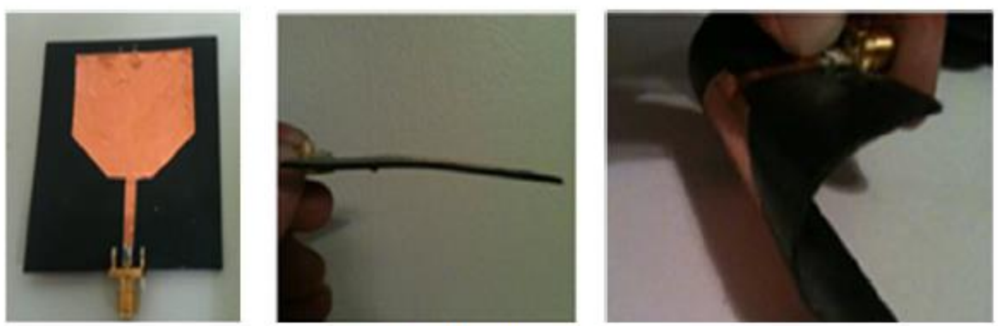
- Use case: Reconfigurable/flexible antenna
- Incorporate 3D printing & heat



< Temperature sensitive antenna >



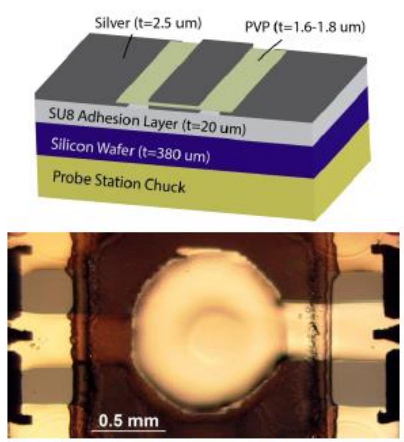
< 3D printed spiral antenna >



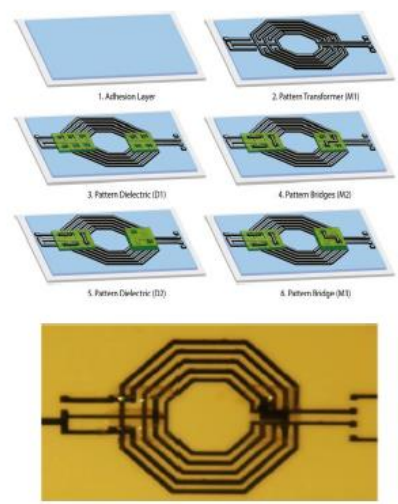
< 3D printed flexible substrate >

# RF Components on Cellulose? (Q,SRF)

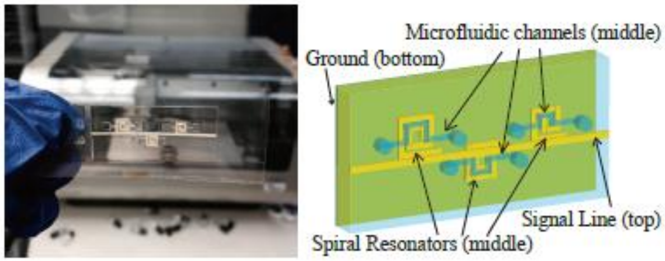
- Printed capacitor & inductor for on-chip applications
  - Capacitor & inductor are printed on silicon (Si) substrate
  - Fully printed structure (metal & dielectric)
  - Broad range of capacitance (10 ~ 50 pF) & inductance (10 ~ 30 nH)
  - High Q-factor value up to 25

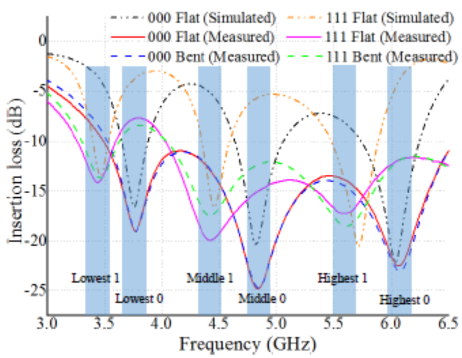


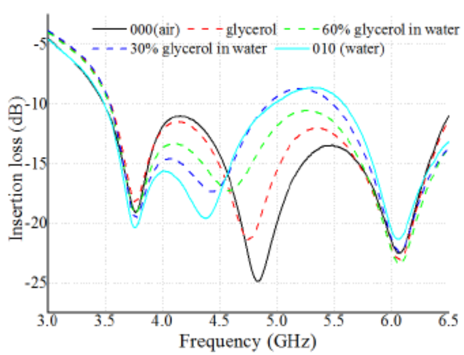

< Fully inkjet-printed multilayer capacitor >



# All Inkjet-Printed Microfluidics Chipless RFID



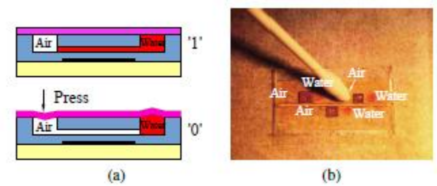
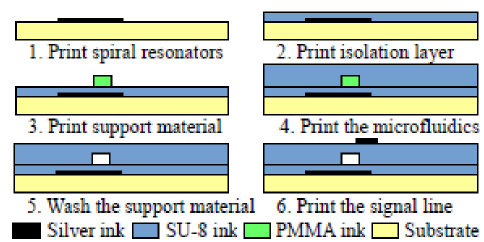
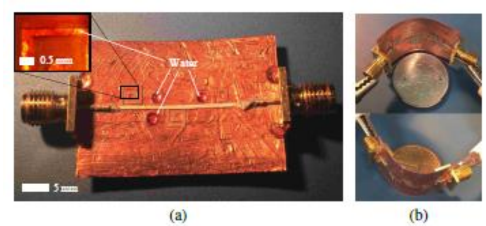
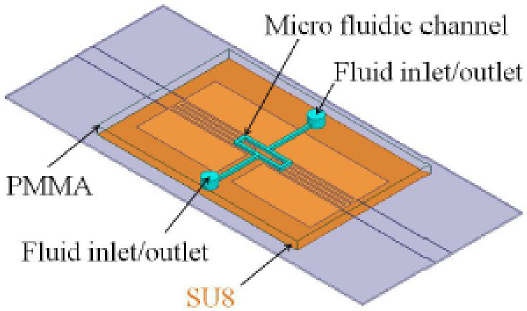



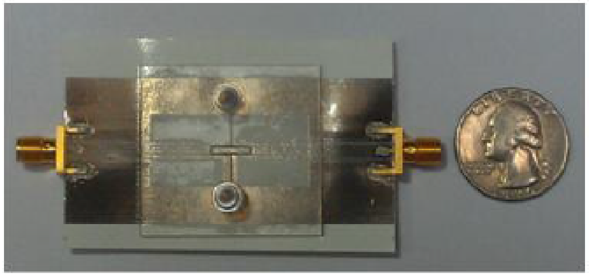

Fig. 2: One possible way to encode the chipless RFID module. (a) A side view of how to encode the RFID by pressing the "button". (b) A photo of a realization of the above mentioned method by covering the prototype with a Polydimethylsiloxane (PDMS) sheet and pressing the "button" with a cotton swab.

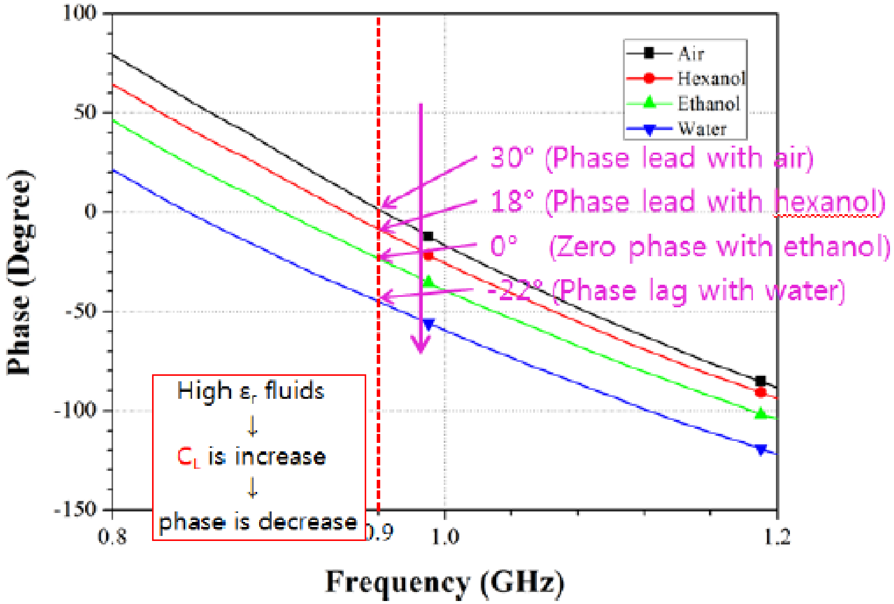


# Fluid-Dependent Phase Advanced and Delayed Line



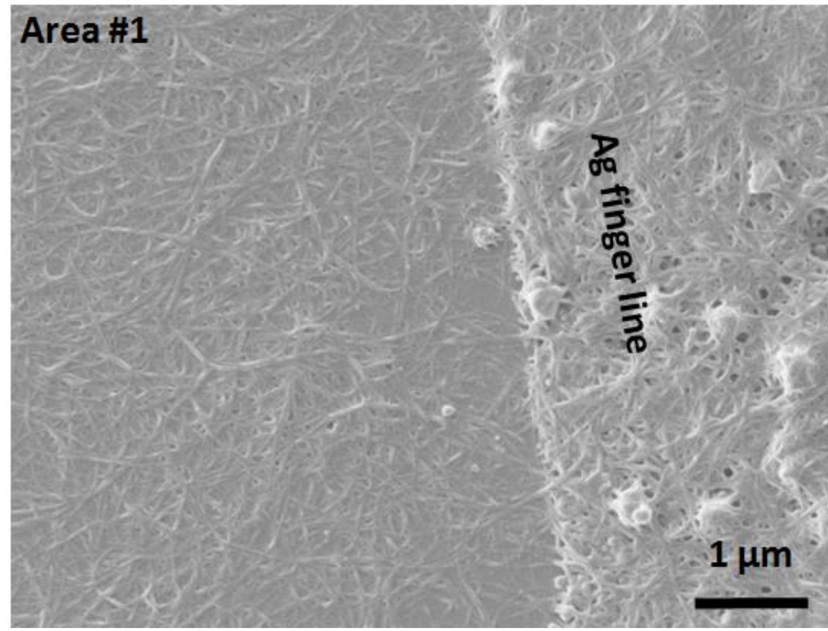






- Novel microfluidic CRLH TL using inkjet printing technology is proposed.
- Depending on the fluids used, phase lag, zero phase, and phase lead are achieved.
- From experimental results, -22° of phase delay, 0° of phase, 18° of phase advance, and 30° of phase advance are achieved at 900 MHz with distilled water, ethanol, hexanol, and air, respectively.

# Carbon nanomaterials for gas sensing

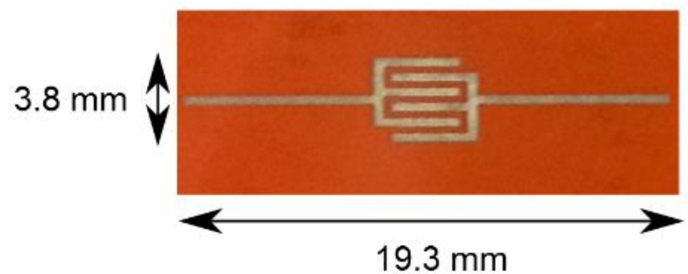
- High surface area
  - Interaction with gases
- Semiconducting/conductive properties
  - Properties to track
- Graphene and carbon nanotubes (CNTs)



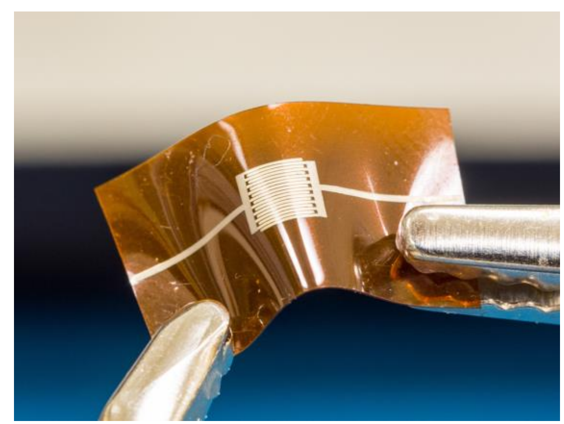
SEM image of an inkjet printed CNT film

# CNT sensor fabrication process

- 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

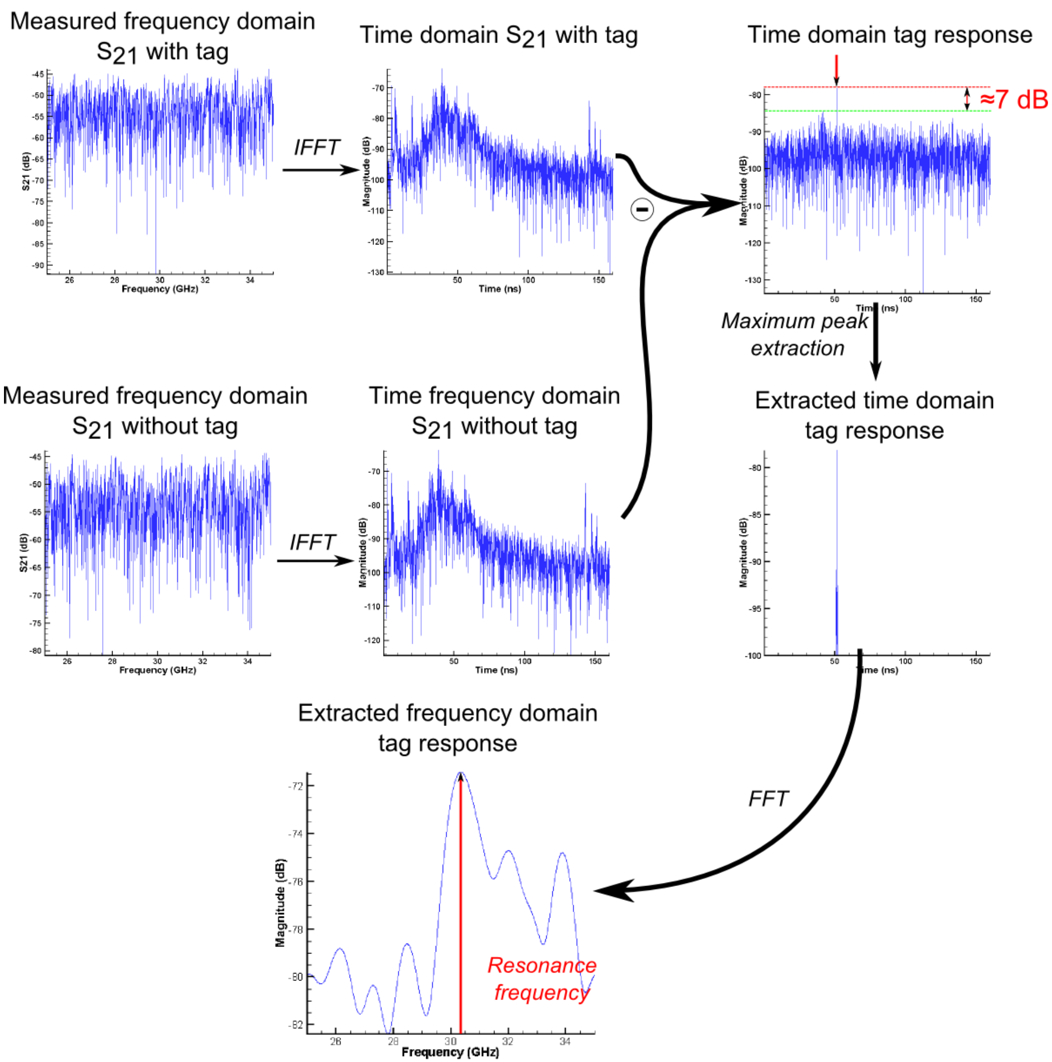


# Inkjet-Printed Van-Atta Reflectarray

- High-frequency operable
- Smaller than a credit card
- Chipless
- Fully inkjet-printed
- Flexible
- Low cost
- Completely isolated from support
- Cross-polarized response
  - Clutter isolation

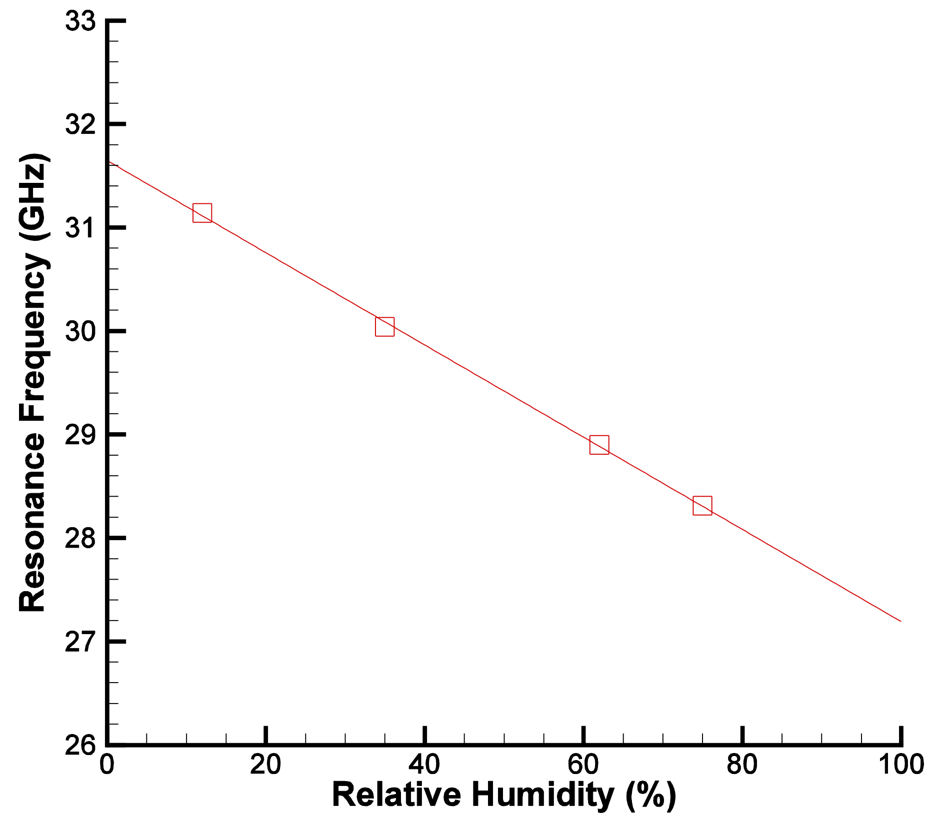
# Van-Atta reflect-array: Data processing

- Resonance frequency extraction scheme
  - Combination of two measurements (with and without tag)
  - Low complexity, fast algorithm (FFT, IFFT)



# Printed Van-Atta data sensitivity results

- Very good linearity
- Extremely high sensitivity (6.3x higher than state-of-the-art passive RFID)

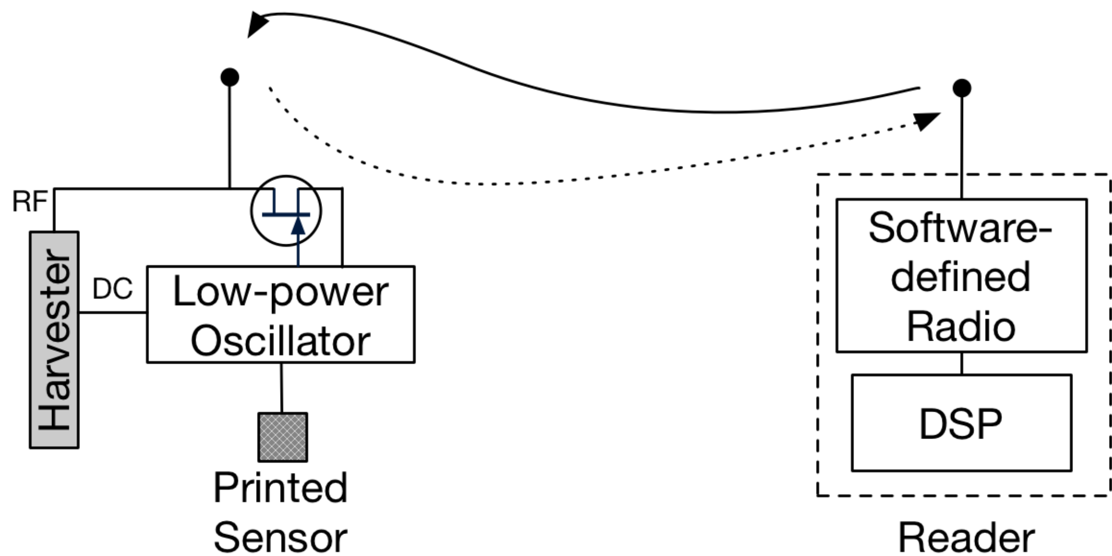


# Van-Atta reflect-array: Advantages

- 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 (10m+)
  - Extremely high clutter-induced-interference isolation
  - Compactness

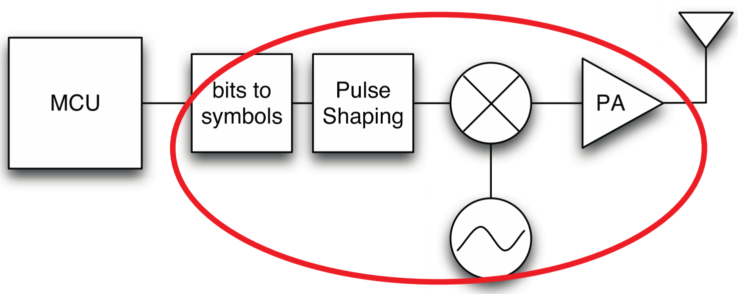
# "Zero-Power" Wireless Sensing/RFID Platform



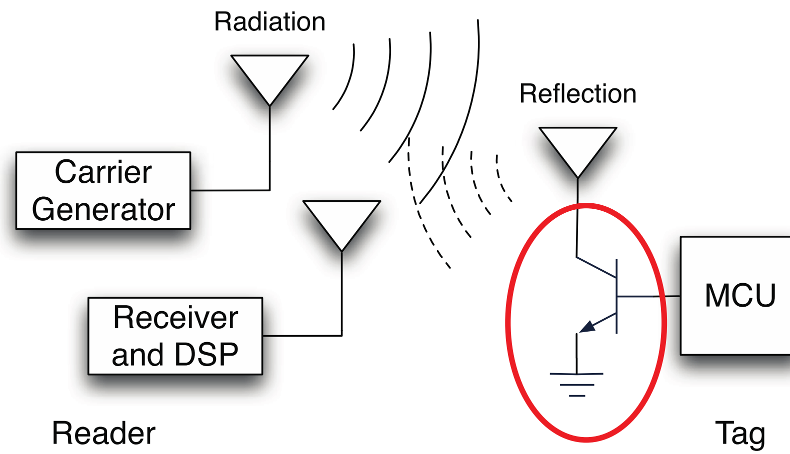

- **Sensor**
  - Low-power oscillator $F_{osc} = f(R_{sense})$
  - Autonomous harvester operation (no battery)
  - No high-directivity antennas needed for harvesting or communication
- **Reader**
  - Commodity software-defined radio

# Tag/Sensor Backscatter Communication

Active Radio

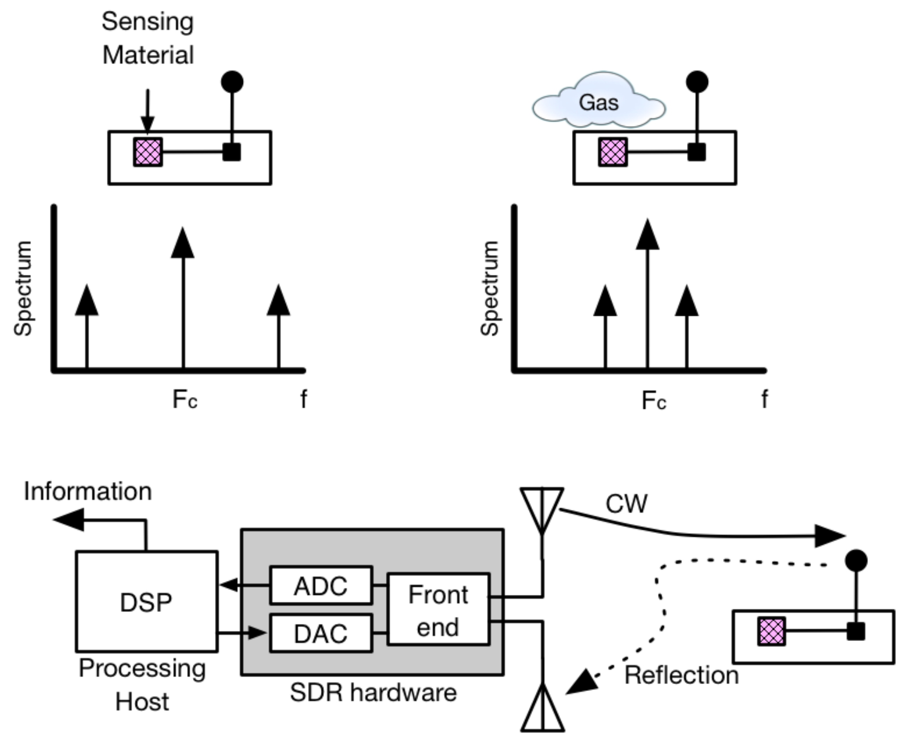



Backscatter Radio



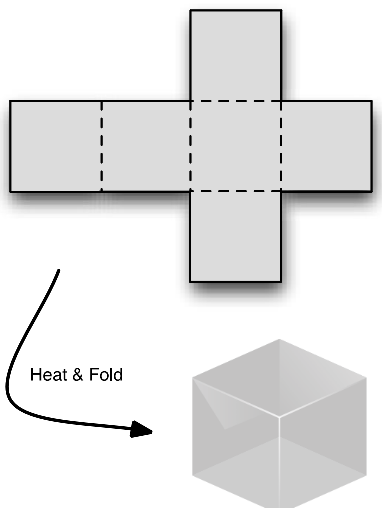

- **Challenge**
  - Communicate with low-power
- **Solution**
  - Reflect. Not radiate.
  - Load antenna with single transistor switch

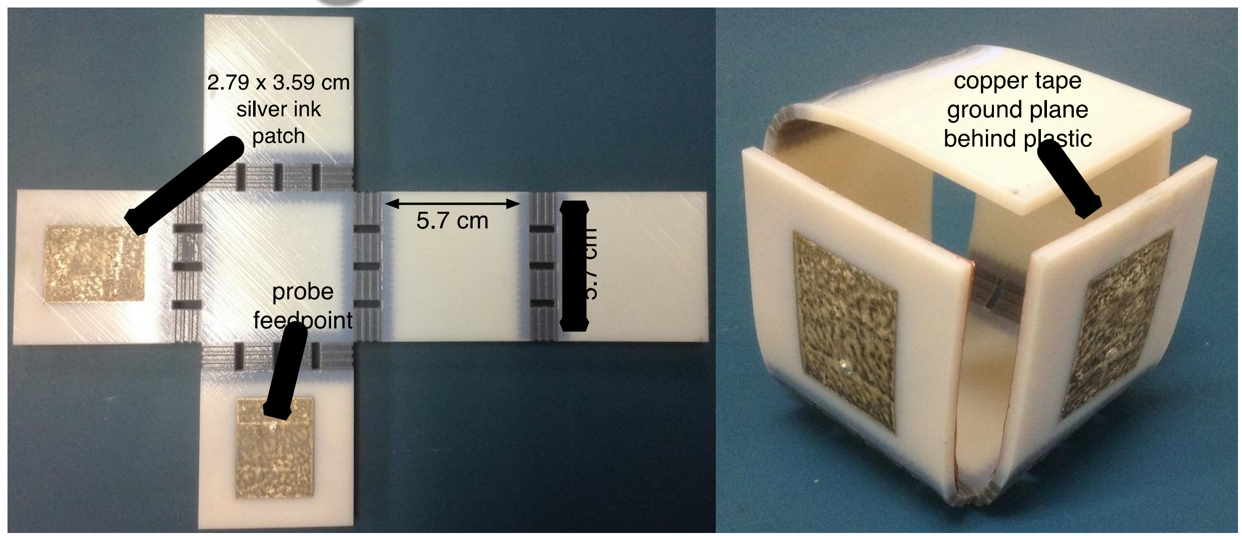
# Reader System



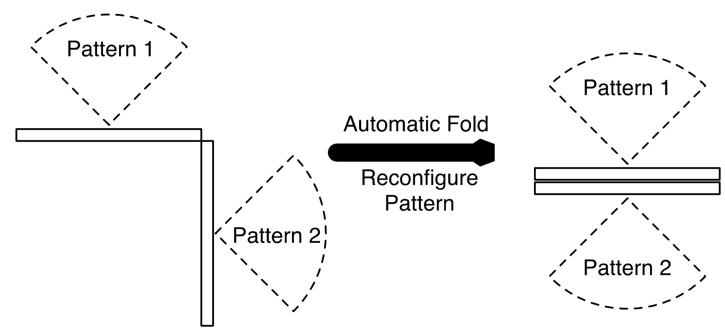

- Software-defined reader (Ettus USRP)
- Hardware RF front-end (800-1000MHz)
- DSP in software - Sensor frequency detection

# Origami reconfigurable antennas

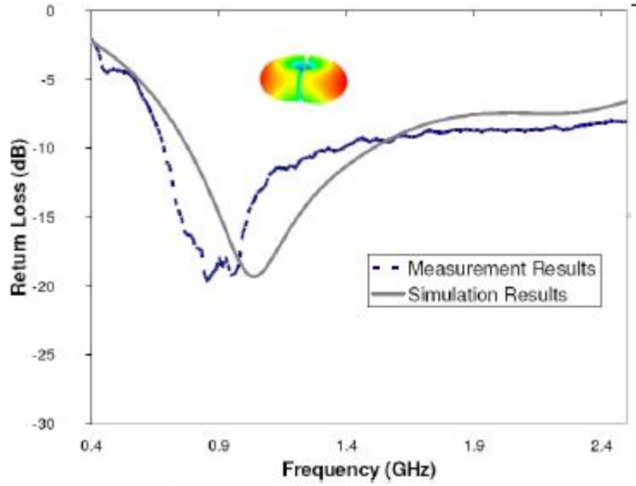


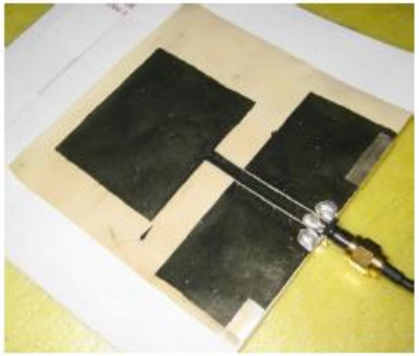

- Reconfigurable origami antennas
- Fold to different 2D/3D configurations
  - RF Harvesting from multiple sources
  - Communication diversity
- 3D-printed substrate
  - Shape-memory hinges
- Inkjet-printed patch antennas
- First all-additively-manufactured origami RF structures

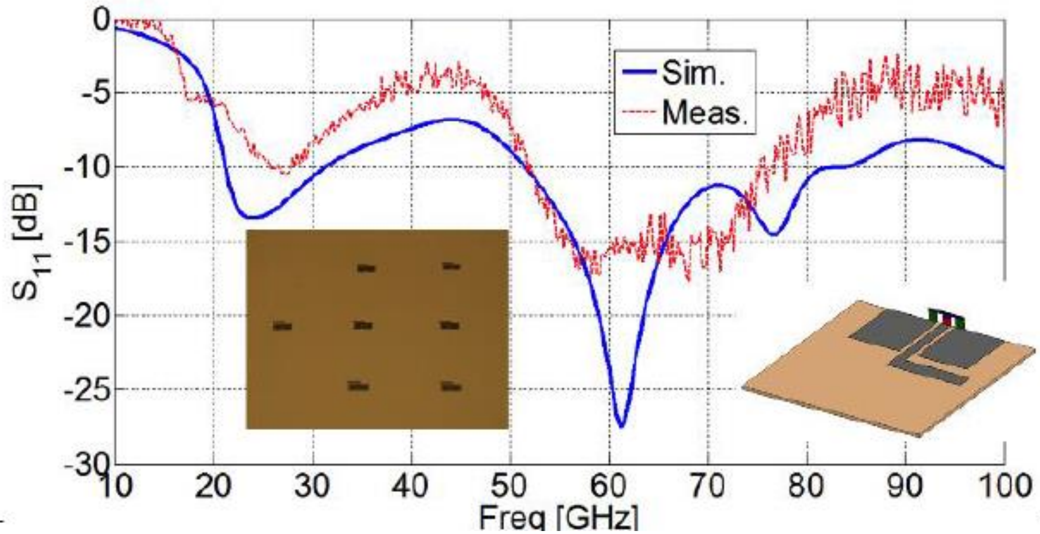


# AM (sub-THz)



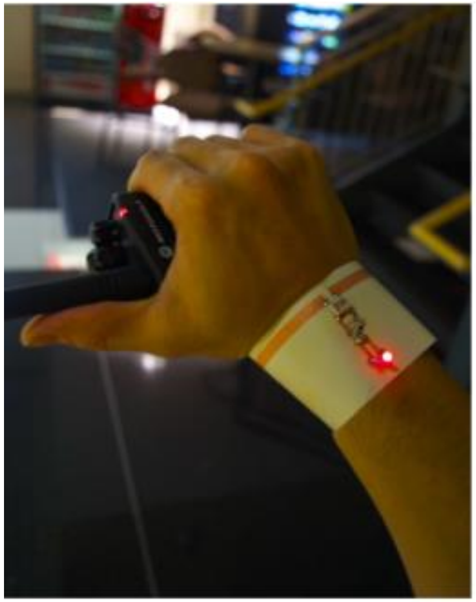
Return Loss (dB)
0
-5
-10
-15
-20
-25
-30
0.4
0.9
1.4
1.9
2.4
Frequency (GHz)
Measurement Results
Simulation Results

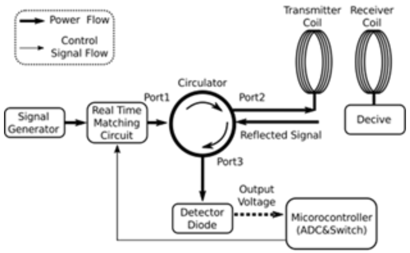



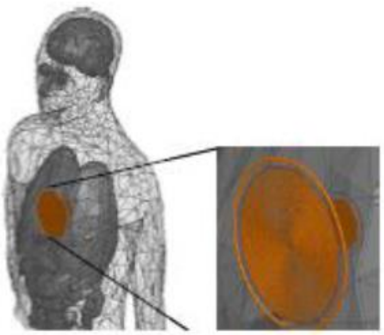


$S_{11}$ [dB]
0
-5
-10
-15
-20
-25
-30
10
20
30
40
50
60
70
80
90
100
Freq [GHz]
Sim.
Meas.

# Optimized Non-Periodic Sensor Topology? WPT?

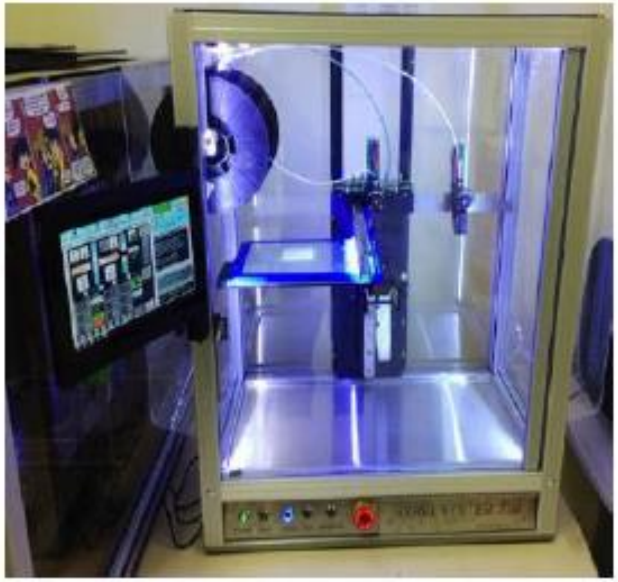




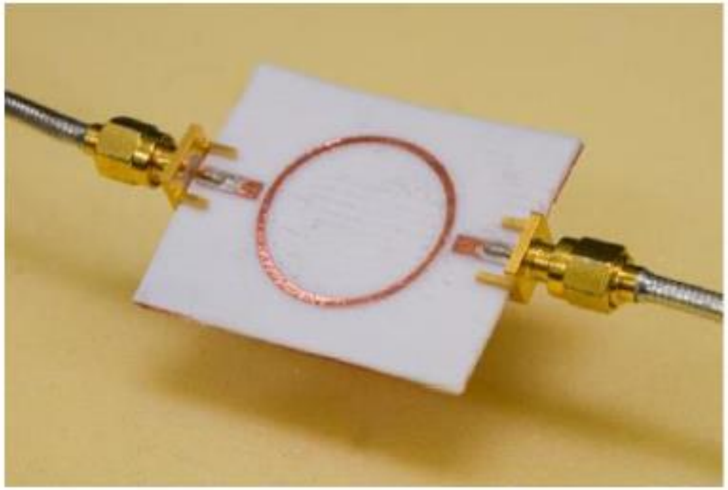
## 3D Printing NinjaFlex

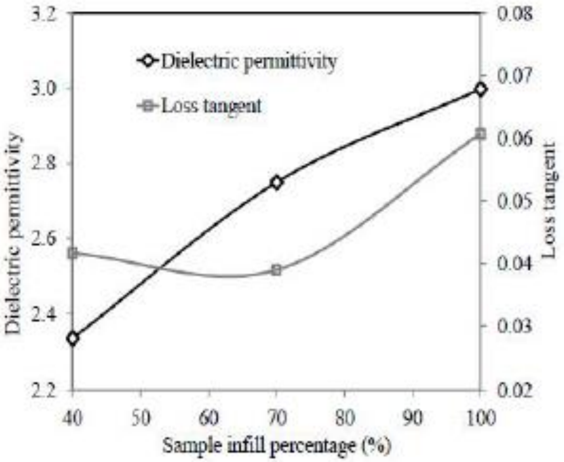
- The **Hyrel** System 30 3D printer
- A standard layer height is 100 microns.
- A rectilinear patterns for 100% infill printing
- The software is **Repetrel** which is modified from Repetier
- Common Slicing CAD software **slic3r**



# NinjaFlex RF characterization

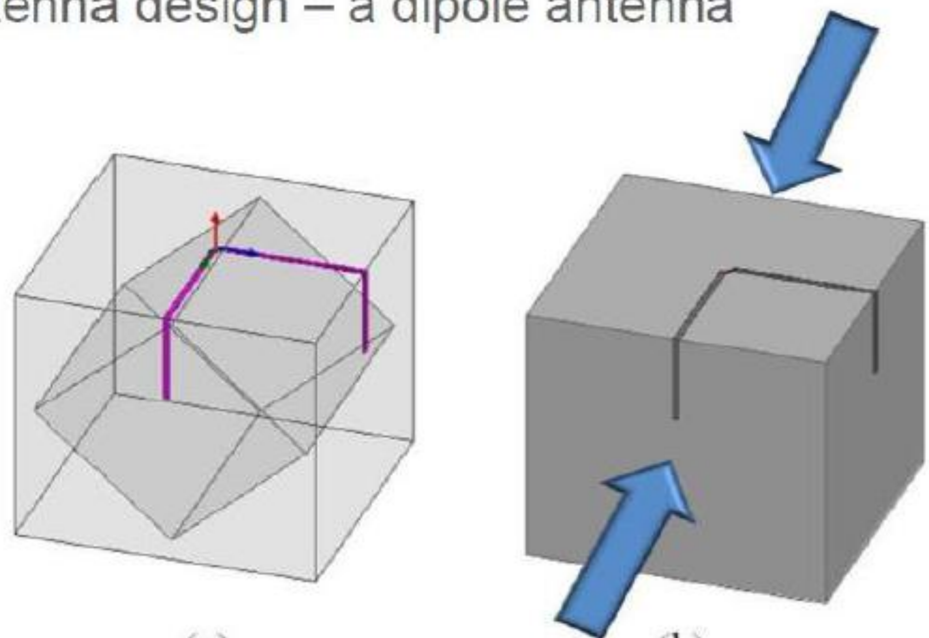
- The resonator ring design to characterize the dielectric permittivity and the loss tangent of NinjaFlex (snow) at around 2.4 GHz





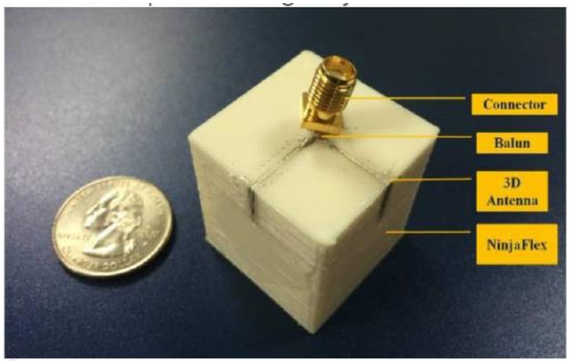
# 3D-Printed Antenna with Arbitrary Embedded Cavity

3D antenna design – a dipole antenna



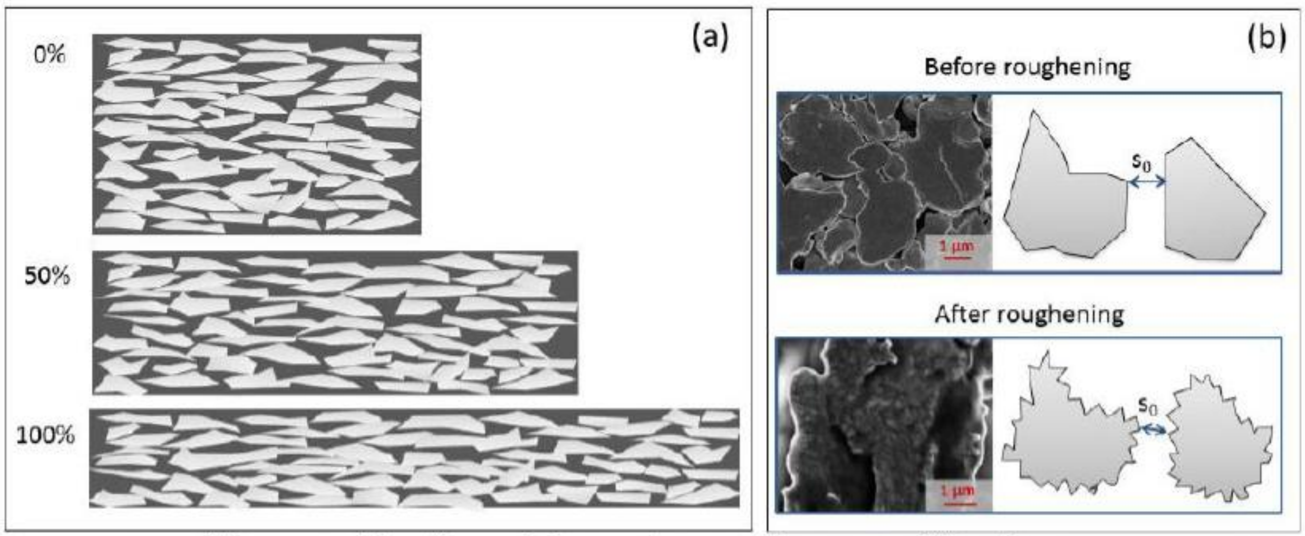
(a) (b)

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



# 3D-Printed Conductors: Stretchable Electrically Conductive Adhesives (ECA's)

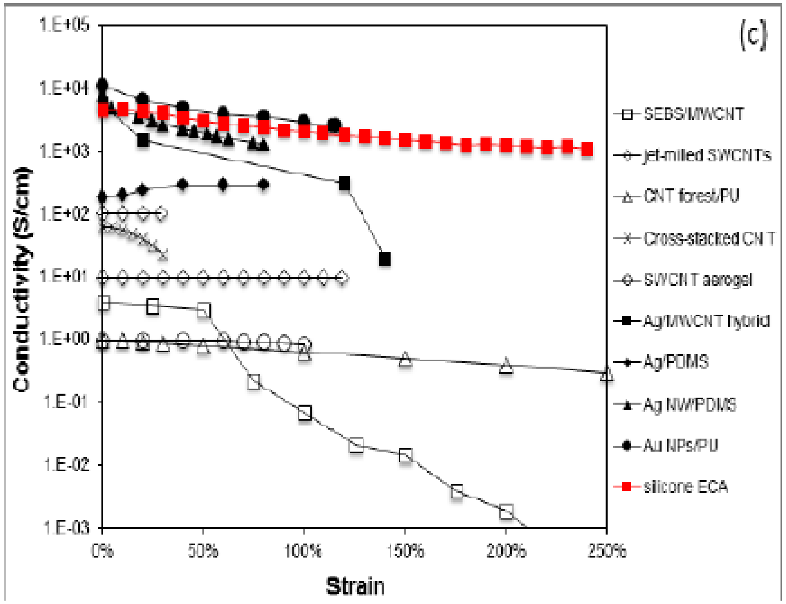
- ECA curing agent: Hydride-terminated polydimenthyl siloxane (H-PDMS)
- The iodination of the silver flakes

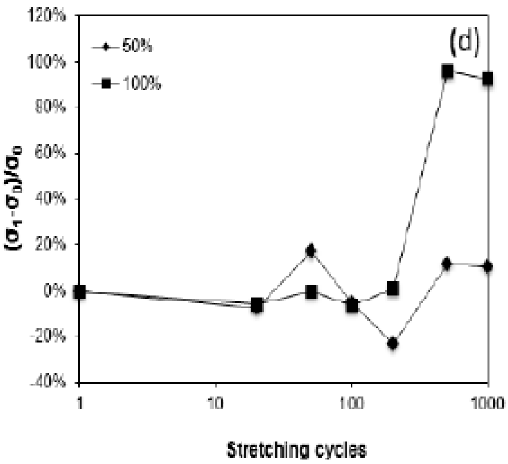



The combination of these two surface modification methods can reach an initial conductivity of $1.51 \times 10^6\ Sm^{-1}$ (80 wt% silver flakes).

# ECA's under Strain

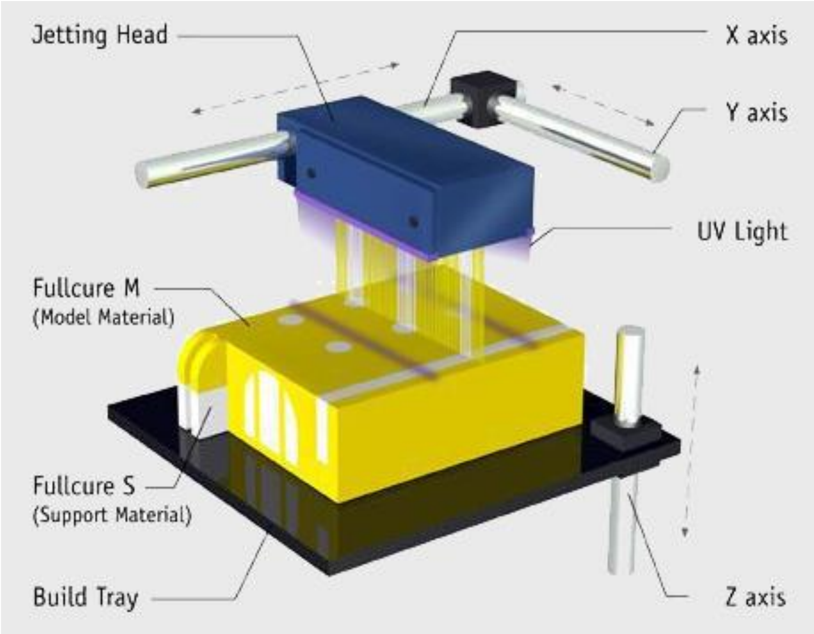
- A strip of silo-ECA is printed on silicone substrate. The applied strain is simultaneously recorded by the tensile tester.



# Printing Technique

## PolyJet 3-D Printing

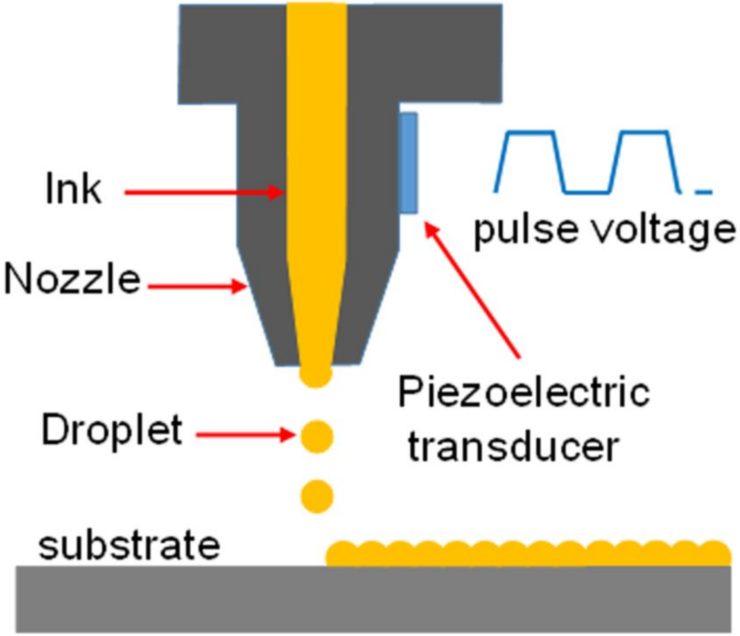



Ref: http://proto3000.com/polyjet-matrix-3d-printing-services-process.php

**Objet260 Connex 3-D Printer**

- Create smooth detailed prototypes
- Min. layer thickness of 16 μm
- Up to 200 μm accuracy

## Material Inkjet Printing

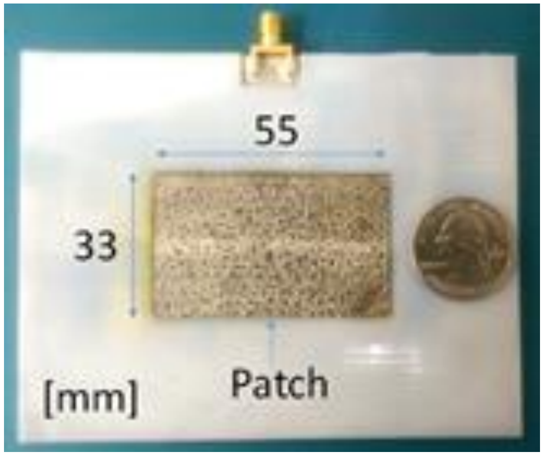


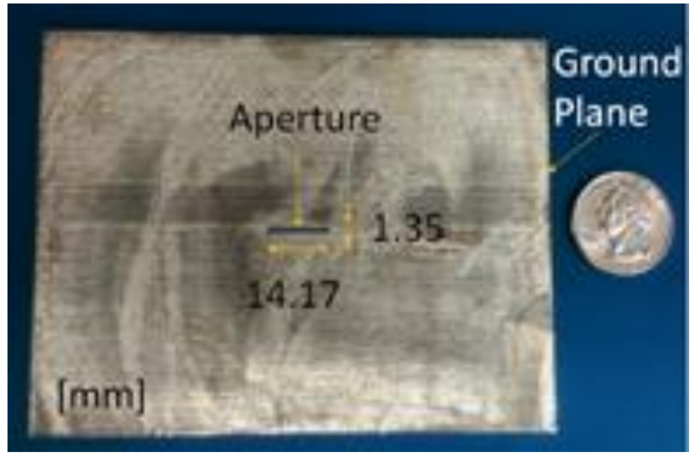

Ref: http://phys.org/news/2015-05-inkjet-kesterite-solar-cells.html

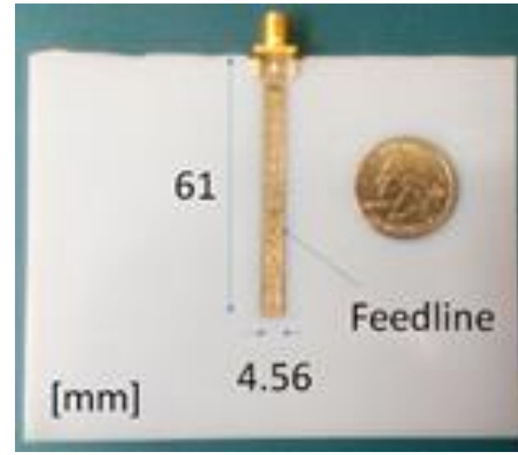
**Dimatix Material Inkjet Printer**

- Micro-precision Jetting
- 10 pl Size of droplet used
- 500 nm thin conductive layer
- Smallest feature size of 20 μm

# Fabrication of a 3-layer aperture-coupled antenna on-package



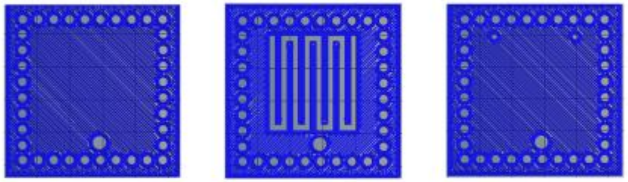

- Metallization of Verowhite by DSA
- Objet Inkjet 3D Printer
- Ground Plane
- Feedline
- Patch

# 3D-Printed on-Package Microfluidic Channel w/ NinjaFlex

Georgia Tech

### 4. Design and manufacturing of the microfluidic sensor

The designed model is then sliced to fit the requirements of the 3D printer software.



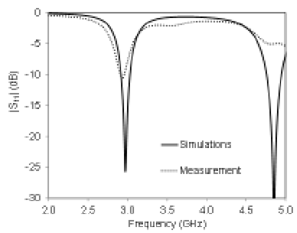
bottom layer | middle layer | top layer

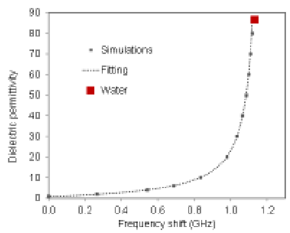
3788 mm of t-glase filament have been extruded at 240°C for 112 minutes.

Georgia Tech

### 5. Results of the preliminary tests

Water is tested and the retrieved $\varepsilon_r$ is 86. This measurement is also needed to verify the sensor's sensitivity.



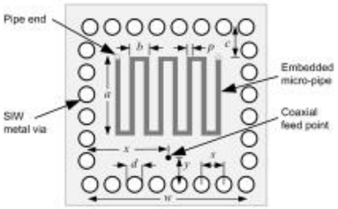



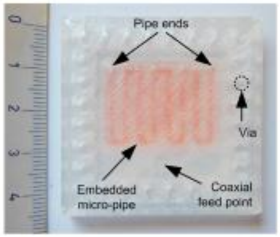



Georgia Tech

### 4. Design and manufacturing of the microfluidic sensor

A red-colored water is pumped just to show the microfluidic architecture.




Dimensions are in mm: a=19, b=5.3, c=7.5, p=2, x=18.5, y=7.5, d=3.2, s=5.1, w=37, substrate thickness t=4).



Georgia Tech

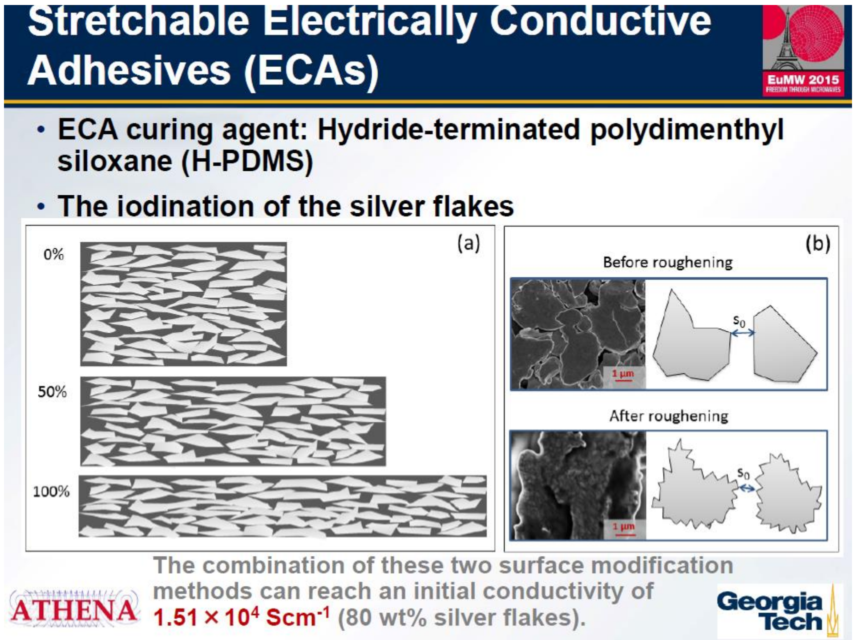
### 5. Results of the preliminary tests

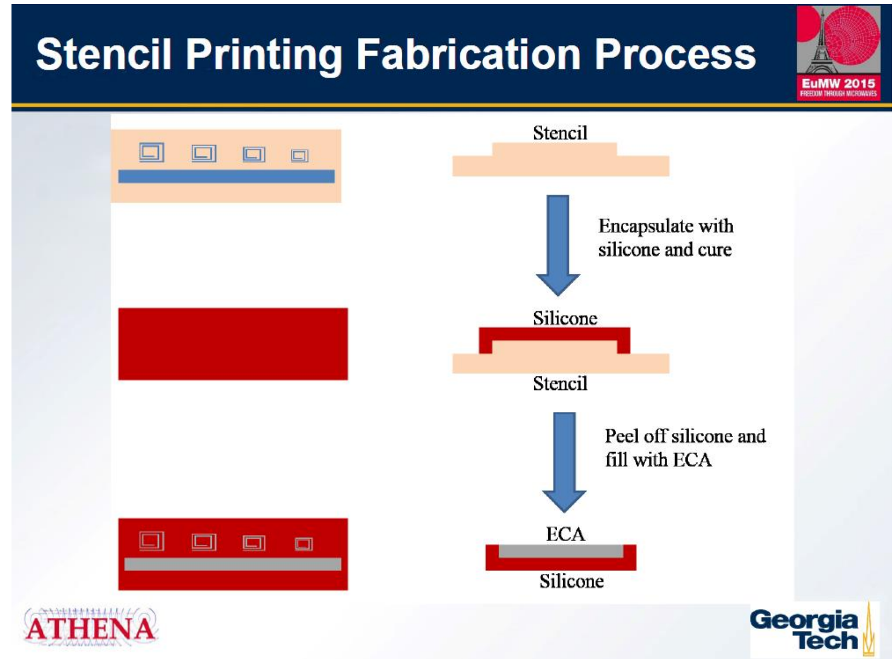
The comparison of sensitivity between the microfluidic sensors reported in the literature is carried out.

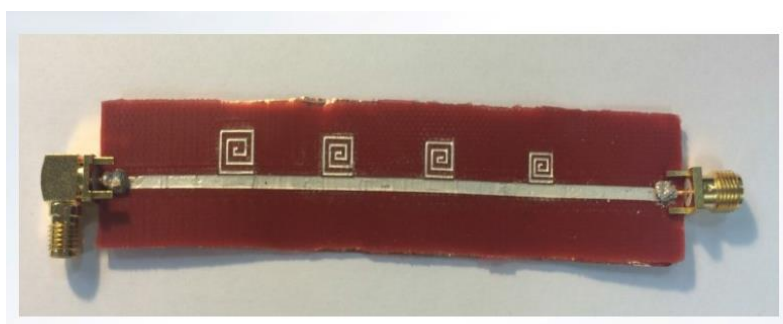
| | $f_c$ (GHz) | σ (%/$\varepsilon_r$) |
|---|---|---|
| Capacitor array * | 3.68 | 0.05 |
| Microstrip comb fingers ** | 19.95 | 0.25 |
| Split ring resonator *** | 3.07 | 0.03 |
| Paper based sensor **** | 2.10 | 0.35 |
| This work | 3.49 | 0.40 |

*J. Gordon, "Fluid interactions with metafilm/metasurfaces for tuning, sensing, and microwave assisted chemical processes," Phys. Rev. B., 2011.
**T. Chretiennot, "A Microwave and Microfluidic Planar Resonator for Efficient and Accurate Complex Permittivity Characterization of Aqueous Solutions," IEEE Trans. Microwave Theory Techn., Feb. 2013.
***A. Abduljabar, "Novel Microwave Microfluidic Sensor Using a Microstrip Split-Ring Resonator," IEEE Trans. Microwave Theory Techn., March 2014.
****B. Cook, "An Inkjet-Printed Micro-fluidic RFID-Enabled Platform for Wireless Lab-on-Chip Applications," IEEE Trans. Microwave Theory Techn., Dec. 2013.

# 3D-Printed Stretchable Conductive Adhesives (ECA’s)

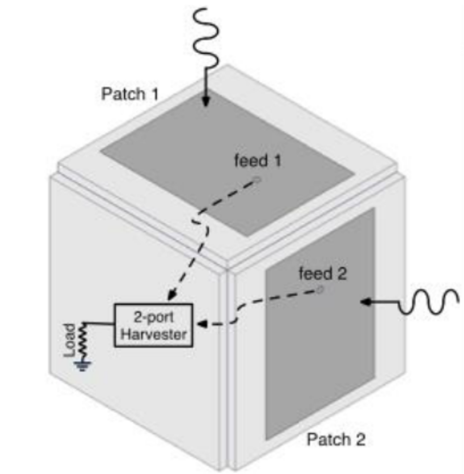


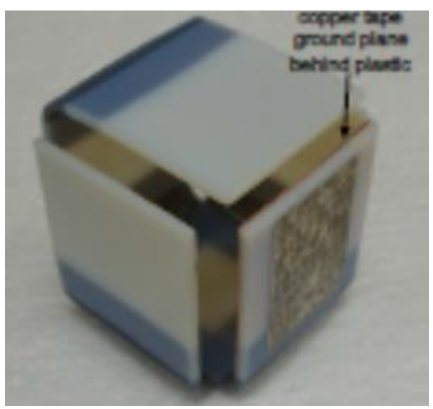



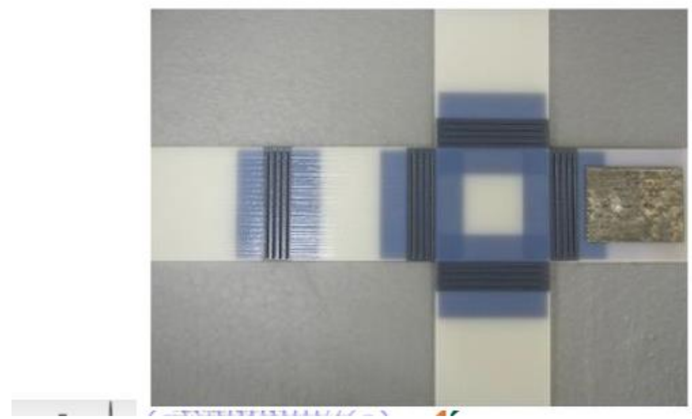
# 3D-Printed "Origami"/Shape-Changing RF Modules

- Multiple antennas on sides
- Electronics protected inside
- Sensing applications
  - Communication antennas
  - Harvesting antennas




- Cube prototype
  - Cube 3D-printed as "cross"-shape
  - Can be folded after heating to 60 C
    - Retains shape at room temperature
  - Inkjet-printed patch antenna
    - Silver ink printed *directly* on polymer



# 3D-Printed Shape-Changing Passives/Absorbers