4D mmW/5G Metasurfaces and Wireless Sensors combining additive manufacturing, morphing and ML technologies

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Additive Manufacturing Technologies: A Manufacturing Revolution

Additive Manufacturing technologies

- Inkjet Printing
- 3D Printing

Passive Components ex: Antenna, filter, balun
3D Printed Via for Ground or Power
Encapsulation Ground Plane Power Plane
IC with Different Thickness
Thermal Vias
3D Printed Flexible Substrate
Ramp CPW for Signal Lines

Athens, USA

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The First Fully Printed Autonomous Wireless Modules (IoT/5G)

28GHz Backscatter RFID-enabled Sensing 5G/IoT module

12-18 GHz Tunable System-on-Antenna for IoT
Fully Printable Rugged Conformal Interconnects up to mmW/sub-THz

Printed 3D RF Interconnects

- **Goal:** mitigate losses from bond wires/ribbons and package transitions for MMIC devices
- **Surface mount**
  - MMIC die bonded to PCB
  - Dielectric ink printed to form 3D ramps up to surface of die
  - Metallic ink printed to pattern interconnects from PCB to die
- **Cavity-embedded**
  - MMIC die bonded to GND of cavity within PCB
  - Dielectric ink printed to fill gaps between die and PCB
  - Metallic ink printed to pattern transitions from PCB to die across printed gap fills

Efficient interconnects essential for system-on-package (SoP) solutions

- Loss at 40 GHz: 0.6–0.8 dB/mm
- Inductance half of typical wirebond (0.4 nH/mm)
Fully Additively Manufactured Self-Monitoring MultiChip Modules (MCM)

FEM MCM Includes PA LNA and Switch MMICs integrated onto printed “intelligent” (EMI Suppressing/ self monitoring) package
Camera-inspired 3D Lens-based mmlD: wide interrogation angle for “agnostic” wireless links

Provides retro-directive behavior through focalizing on the RF ‘pixels’.

Interrogation experimental setup at 80 m.

Interrogated up to 80 m away with a proof-of-concept reader.

Broad solid angular coverage up to $\pm 28^\circ$ of -10 dB beamwidth.
Cascaded 3D Lens-based mmID: even wider angular coverage

Through cascading multiple lenses, overcoming the gain/angular coverage trade-off is enabled.

Solid angular coverage increases to $\pm 40^\circ$, while being within 1 dB of peak gain of the single lens-based mmID.
Cross-shaped dipole FSS element shows enhanced bandwidth, support for orthogonal linear polarization and ease of fabrication.

25% frequency tunable range over two polarization directions.

Horizontal (x-axis) polarization with different folding angles.
3D printed Liquid-metal-alloy microfluidics-based Zigzag and Helical Antennas for Origami Reconfigurable Antenna “Trees”

- “Tree” (zigzag/helical antenna) with dual-band (3GHz/5GHz) operability and different polarizations (linear/circular).
- Varying radiation patterns with “tree” compression.

3D Printed “Kirigami”-Inspired Deployable Bi-Focal Beam-Scanning Dielectric Reflectarray Antenna for mm-Wave Applications

- Design enabled by a series of a “Kirigami”-inspired two-stage snapping-like element structure.
- Can be retracted by 66% to save space.
- Bifocal phase distribution method is utilized to optimize performance of the array.
- Realized -30° to -10° and 10° to 30° beam-scanning ability.

4D Printed Origami-inspired Tunable Multi-layer Frequency Selective Surface

- Fully additive hybrid (3D and inkjet) printing processes to realize a flexible two-layer substrate with conductive traces on both top and bottom.
- Significant strength improvement over paper-based origami structures.
- "Morphing" design that would be otherwise difficult to fabricate using traditional paper-based substrates.
- Operability in mm-wave frequencies up to at least 28 GHz.

Hybrid Printed Electromagnetic Pressure Sensor using Metamaterial Absorber

- Absorption frequency varied with substrate thickness: electromagnetic pressure sensor with mechanically transformable substrate.
- Absorption frequency 5.2 to 5.66 GHz by applying 0 and 20 N pressure; device sensitivity = 7.75 x 10^-8 Hz/mm (0.2 x 10^-8 Hz/N); and repeatability was retained up to 100 cycles.

Fig. 5. Fabrication process for the proposed hybrid (3D and inkjet) printed EM sensor.

Fig. 7. Fabricated electromagnetic pressure sensor prototype (a) top and (b) side view.
Artificial Intelligence: the key enabler

Decision Trees / k-Nearest Neighbor

- **DT**
  - Widely used method based on the form of a tree structure
  - Suitable for a non-parametric model with no assumptions

- **k-NN**
  - Simple instance-based learning for prospective statistical classification
  - For input variables, Euclidean distance is used

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Machine Learning-Enhanced mmID-“Gyro” for 3-Axis Orientation Wireless Detection

Low Cost mmWave System
- Ultra-low-power, sticker-like mmWave mmID
- Comprised of four backscattering elements that are multiplexed in amplitude, frequency, and spatial domains
- Each element designed with polarization offset of 15° from each other to allow for angle of rotation encoding
- Cross Polarization antenna configuration utilized to reduce signal interference to reader
- 24 GHz FMCW Radar utilized as reader

Results
- 2 Models trained
  - Model A: Only Amplitude Response
  - Model B: Amplitude Response and Phase Difference
- Accuracy >91% achieved at up to 6 m with Model B
- Further evaluation to be performed with a finer angular resolution for an even more precise orientation detection

Data Processing/Machine Learning
- Tag rotated over ±90°, with increments of 10°, in each axis
- K-Nearest Neighbors (KNN) Algorithm
- Global Dataset of 2.8 million data samples
- 80/20 Train-Test Split

Digital Signal Processing
- Amplitude Response of each antenna element
- Phase Difference of neighboring elements using Arctangent Demodulation Algorithm

<table>
<thead>
<tr>
<th>Range</th>
<th>Model A</th>
<th>Model B</th>
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<tr>
<td>0.5 m</td>
<td>99.60%</td>
<td>99.87%</td>
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<td>1 m</td>
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<td>10 m</td>
<td>45.01%</td>
<td>77.88%</td>
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</table>
Self-Calibrated “Flex-compensating” Flexible Arrays

- Conformal applications of arrays allows for superior integration in wearables, aerospace and communication platforms.
- However, phase error causes gain degradation -> Needs Correcting

Requires a way to adaptively know the current bending condition in order to accurately correct for bending

90% accuracy and only 0.071dB in gain error
Fully Printable Tile-by-Tile Reconfigurable Intelligent Surfaces

- Independent **beam-steerable** flexible planar TX and RX antenna array systems
- Frontend ICs with built-in phase shifters to steer the array of each tile, with **individually controlled radiating element**
- Corporate feed network connects **removable tiles** to build a larger array
- **Flexible tiles and feeding network** can be conformally wrapped around curved surface
Computer Vision Aided Calibration of Tile-Based Phased Arrays
The Internet of Smart Skins

• Thin, Flexible device: the Skin
• Ultra-low-power: <20 μW
• Battery-less: Energy Harvesting
• Long-range: 250m+
• Localizable in real time (cm accuracy): single-reader localization (Angle+range)
• Metal-mounting compatible
• Enhanced by 5G+/6G.

[5S Challenge: Smart-Scalable-Sustainable-Speedy-Secure]
Wireless Charging of UAV constellations/Wireless Sensor Modules Using 5G / 5G as a Wireless Grid

How does it work

**Dual Combination: RF + DC**

1. **Scavenge mm-Wave Signals**
   Antenna arrays connected to the antenna ports of the Rotman lens scavenge the mm-wave energy from all directions.

2. **RF Combine and Focus**
   The Rotman lens combines internally all the mm-wave signals collected by the antennas and focuses them to one beam port on the opposite side, where a rectifier is connected.

3. **Rectify and DC Combine**
   The rectifiers connected at the beam ports of the Rotman lens convert the mm-wave energy to DC power. The DC combiner enables an efficient voltage extraction irrespective of the direction of the incoming signal.
Wireless Charging of UAV constellations/Wireless Sensor Modules Using 5G / 5G as a Wireless Grid

**Breaking the High Gain and Large Beamwidth Trade-off at mm-Wave Frequencies**

- Electrically large antennas
- High gain and lack of isotropic behavior
- Use of BFNs

![Rotman Lens for mm-wave harvesting](image)

![Multi-Beam Coverage](image)
Optimal compromise (Na=8, Nb=6):
- High array factor of 5.95 dB
- 120° total angular coverage

- Beamwidth and array factor maintained over a large bandwidth exceeding 20 GHz

**Scalable and Broadband Structure**

P1, P6: Edge Beams
P2, P5: Secondary Beams
P3, P4: Center Beams
Breaking the trade-off

- Eight serially-fed patch antenna arrays added
- Simultaneous 17dBi gain and 110° angular coverage at 28GHz
- Minor gain deterioration under severe bending
Reconfigurability by 8uW switches, low power oscillator is used to provide ASK modulation to the signal.

Addressed NLOS challenge in RIS

2.5dBm turn-on power, harvest 28GHz 11m away and communicate 125m with 75dBm EIRP
“Zero-Power” mmWave Smart Skins for Structural Health Monitoring

- Capability to detect cracks and <20 u-strain
- Range extended to 10 meters through the use of Solar Power

Frequency multiplexing allows dense implementation and discrimination in range

Sensor able to capture strain profile while embedded in composite material

(a) Sensor instrumentation on the aluminum specimen
Sensor Highlights in ATHENA Lab

(a) Chemical warfare nerve agent simulant diethyl ethylphosphonate (DEEP)
(b) Chemical warfare nerve agent simulant dimethyl methylphosphonate (DMMP).
(c) Chemical warfare blister agent simulant methyl salicylate.
(d) Resonator sensor for CO2.
(e) Sensors for the aggregation pheromone of flour beetles.
(f) - (g) Sensors for NH3.

(h) Interdigitated electrode design to increase surface area

- Sensitive element is deposited between fingers
- Composition on target analyte
- CNT functionalized with different molecules
Wearable Inkjet-Printed CO2 Sensor

• Preliminary results on FR4 substrate
• Use of UV light to reduce recovery time
• Slope change due to different concentrations

Spacing: 142-176 um
Finger: 204 – 214 um

Kapton

Other substrates: Rogers, Teslin paper, FR4
Printed Covid antibody sensors

Inkjet-printed electrode
On Teslin® paper

Inkjet-printed electrode
On Kapton® PI film

3D-printed Electrode and coated with rGO

Commercial electrode

Enzyme
Secondary antibody
Covid-19 antibody (detection target)
Covid-19 antigen
High surface area graphene (40 layers)
Working electrode

Working electrode
Reference electrode
Counter electrode

Covid-19 antibody sensor
Printed Covid antibody sensors

Detection of both natural and synthetic Covid antibodies

- Clear differentiation between Covid-19 negative and positive blood samples
Zero-Power Environmentally-Friendly Self-Healing “Morphing” (4D) 5G+/mmW Fully-Additively Manufactured Platforms and Reconfigurable Intelligent Surfaces with “Smart Skin” Tile-by-Tile Sensing and Ultrawideband Frequency/Pol Reconfigurability

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