3D-/Inkjet-Printed RF Packages and Modules for IoT Applications up to sub-THz frequencies

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Challenges for Packaging up to sub-THz /mmW

- Millimeter-wave (mm-wave) wireless technology ranging 30–300 GHz emerging in industry for 5G, automotive radar
- System-level packaging an integral component of any wireless system

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
Additive Manufacturing (AM) Solutions

Fabricate wireless systems in a rapid, scalable, and purely-additive fashion

1. Additively fabricate electronic structures
   - Reduce material waste and processing tools/steps
   - Remove high temp and pressure, less package stress

2. High process reconfigurability
   - Multi-application processing with single tooling technology
   - Short-run prototyping and mass-scale production

*Where can AM fit in with mm-wave packaging?*
Mm-Wave Packaging with Printing

**Inkjet Printing**
- Materials:
  - Photoactive resins, thermoplastics, ceramic pastes, conductive adhesives
- 3D interconnects
- RF substrates
- Die attach

**3D Printing**
- Materials:
  - Polymer solutions, metallic nanoparticle dispersions, carbon nanomaterial suspensions
- Dielectric lenses
- Encapsulations
- Die-embedded leadframes
## Additive vs Subtractive Fabrication

<table>
<thead>
<tr>
<th>Technology</th>
<th>Feature Size (um)</th>
<th>Multi-Layer</th>
<th>Cost</th>
<th>Speed</th>
<th>Waste</th>
<th>Area (m²²)</th>
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<td>Milling</td>
<td>200</td>
<td>No</td>
<td>Low</td>
<td>Slow</td>
<td>High (Dust)</td>
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<td>Laser Ablation</td>
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<td>High</td>
<td>Fast</td>
<td>Medium (Excess Ink)</td>
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<td>Screen Printing</td>
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<td>Low</td>
<td>Fast</td>
<td>Negligible</td>
<td>∞</td>
</tr>
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</table>
Stereolithography (SLA) 3D Printing

- DLP or laser-based exposure system
- Resolution determined by pixel or laser spot size
  - 1080p DLP projector → ~40 um resolution
- SLA advantages compared to FDM/Direct-Write
  - Room temperature process, no heated/pressure extrusion
  - High resolution with low surface roughness (hundreds of nm)
  - Sequential layer polymerization → truly solid object
  - Simple scalability (highlighting DLP)
Using SLA for Packaging

• Combine SLA and direct write methods
  – Place components into printed cavities
  – Resolution too low for interfacing dies


• Layer-by-layer masking and PVD metal deposition
  – High resolution, embedded ICs
  – Requires mask for each pattern

SLA 3D Printing and Characterization

- Tools: LittleRP tabletop 3D printer, Viewsonic PJD7820HD DLP projector
- Materials: Vorex (photosensitive resin), Porcelite (ceramic-loaded resin)

**Goal:** characterize dielectric properties of SLA materials at E-band (55–95 GHz)

1. Material samples printed to match WR-12 waveguide cavity dimensions (3.01 x 1.55 x 1 mm)
2. S-parameters of printed cavity fills measured across E-band
3. Models satisfying Kramers-Kronig relation used to extract $\varepsilon_r$ and $\tan\delta$ from measurements
Dielectric Characterization

- Variations less than ± 2% and ± 7% for Vorex and Porcelite sample measurements, respectively
- Linearity observed up to and beyond 90 GHz
- Ceramic-loaded Porcelite material exhibits higher $\varepsilon_r$
- $\varepsilon_r$ and $\tan \delta$ comparable to standard epoxy mold compound materials
3D-Printed Encapsulation

- Selective patterning of die encapsulation on metallic leadframes

**Standard 1 mm-Thick Encapsulation**

**Text and Detailing**

**Lens Integration**
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)
How can we integrate these two technologies?

Incorporate through-mold-vias (TMVs) within the package

mm-Wave SoP: 3D and Inkjet Printing

Inkjet print on-package components (IEEE APS 2015)

Inkjet print dielectric ramps for mm-wave interconnects and antennas (IEEE IMS 2016)

Incorporate through-mold-vias (TMVs) within the package
Through Mold Vias (TMVs)

- Interface encapsulated IC with peripherals on top of package
- Ultra-thin package-on-package (PoP) stack ups
- Laser drilling used to selectively remove encapsulation
- Limited to BGA with diameter ~250um and pitch ~500um

Use 3D printing to fabricate IC encapsulation with through-mold-vias (TMVs)

1. 3D print encapsulation with ramps, inkjet print TMV interconnects
2. 3D print encapsulation cavity fill to seal die and internal interconnects
3. Inkjet print multilayer antennas/passives/etc topology
4. 3D print final encapsulation
Printed TMVs with SLA and Inkjet Printing

- Ramp TMVs 3D-printed to interconnect die with top of encapsulation
- CPW interconnects inkjet-printed onto 3D-printed ramps and sintered at 150 °C

- Measurements < 67 GHz with continuity up to 65° slope
- 65° ramp: length is < 500 um for 1 mm tall encapsulation
- Insertion loss: 0.5–0.6 dB/mm at 60 GHz → 10x improvement from wirebond interconnects
Thermal Cycling

• Thermal cycling used to investigate long-term stress and harsh environments for 3D-printed SLA materials
• Printed samples (5 x 5 x 1 mm) cycled from -40 °C to 125 °C with 2 °C/min ramp for 5 cycles
Surface Roughness

- “Flat” surface of a DLP SLA print (Vorex photoresin)
- 100–300 nm roughness appearing periodically, corresponding to approximate size of a DLP pixel
- Compare to 10’s of um roughness with FDM and direct-write 3D printing
Reconfigurable “Smart Packaging” Structures

- Verowhite: Stiff polymer
- TangoBlack: Flexible, Stretchable polymer (rubber-like)
- Grey60: Hinges, exhibit shape memory effect (SME)

Printed with Objet 260 PolyJet 3D printer, silver nanoparticle ink for patch antennas

3D Printed Flexible/Compressible/Stretchable Packages

- Wearable sensing platform
- Ultra flexible
- 3D printed
  - Low cost
  - Customized
  - Flexible
- Sensing capability
  - Microfluidics liquid sensing

Wenjing Su, Zihan Wu, Yunnan Fang, Ryan Bahr, Markondeya Raj Pulugurtha, Rao Tummala, and Manos M. Tentzeris, "3D Printed Wearable Flexible SIW and Microfluidics Sensors for Internet of Things and Smart Health Applications", *IEEE International Microwave Symposium (IMS)*, 2017, accepted
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
3D Printed Electronics

- Microfluidic models can be fabricated
- Multijet printing deposits layer by layer via inkjet nozzles
- Silver epoxy filling to realize resistive, inductive, capacitive passive devices components
- RLC resonator can be created with passives for wireless dielectric sensing, enabling a milk cap food sensor
3D Printing of Complex Antennas

- Laser-based stereolithography used to print structures with different materials
- Flexible/stretching structures for origami-based microfluidic antennas.
- Complex patterns for impossible to realize antennas without 3D printing

(Top) Chinese fan antenna
(Bottom) Photonic Crystal

(Left) 3D printed fractal antenna
(Right) Voronoi based antenna
Helical/zigzag antenna “Tree” with (a) original and (b) compressed

Advantages:
- Better link detectability (for given aperture sizes)
- More power available to mm-wave readers
- Large tags can be very directive
- No interference with other readers

Drawbacks that we eliminate
- RF powering is very difficult at mm-wave: Solar
- Mm-wave components and materials are expensive: Minimalist design, printed
- Large tags cannot be read from all directions: Van-Atta
Printed, flexible, backscatter-modulation Van-Atta sensor km-Range “patch” 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
    - Great resolution (below 0.5m)
Summary

Combination of inkjet and 3D printing technologies allows for the realization of low-cost, scalable, application-specific mm-wave / sub-THz wireless systems

- Extracted $\varepsilon_r$ and $\tan\delta$ of SLA materials, yielding suitable characteristics for SoP solutions
- Demonstrated various IC encapsulation schemes with SLA 3D-printing (lens and FSS integration)
- Fabricated and measured printed sloped TMV interconnects for interfacing IC dies with SoP components in 3D encapsulations
3D Printing Techniques – Direct Write

• Micro dispensing
  – Physical deposition of wide variety of materials
  – Often can be incorporated with multiple materials much easier than optical methods

• Examples:
  – Direct write, Aerosol jet, Fused deposition modeling (FDM, multijet printing)

3D printing of electronics with IC’s by depositing silver with a Voxel8 3D printer
Fused Deposition Modeling - FDM

- Deposit heated plastic
- Materials: Thermoplastics
- Resolutions:
  - XY: 200-400 um
  - Z: 20-100 microns
- Advantages:
  - Multiple materials
    - Wide range of polymers
  - Easy to add different tools
- Disadvantages:
  - Porosity
  - Resolution (comparatively)
Extremes of Direct Write

- Resolution Extremes
  - nScrypt micro-dispensing system
  - Layer heights of 1 um
  - Deposition width of ~15 um
  - Deposits wide assortment of materials from 1 cPs (viscosity of water) to 1,000,000 cPs (4x of thickness of peanut butter)

nScrypt nTip and smartpump enabling high resolution dispensing
PolyJet Printing

- Prints polymers with inkjet tech.
- Resolutions:
  - XY: 1600 dpi
  - Z: 16 microns
- Advantages:
  - Multiple polymers
- Disadvantages:
  - Proprietary Polymers Only

Multimaterial polyjet printing of polymers for a cell phone mockup.
3D Printing Techniques - Optical

- Optical-based methods
  - Laser-based techniques
    - Need to trace the entire pattern
  - Digital mask systems
    - Scalability, exposes entire layer at once
    - No increase in print time to print many devices at once
    - i.e. digital micromirror devices (DMD)

- Examples:
  - Selective Laser Melting/Sintering, Stereolithography (laser or DLP)

(Left) Traditional SLA. (Right) Two photon absorption
Selective Laser Sintering SLS

- Fuse polymers/metals
- Resolutions:
  - Z: 5-25 microns
  - XY: <30 microns

- Advantages:
  - Has natural support material
  - Metallization

- Disadvantages:
  - Single Material
  - Roughness/Porosity

Micro Laser Sintering (MLS)
• Resolution Extremes
  – 2 photo polymerization (i.e. Nanoscribe)
  – XYZ resolution limited to near diffraction limit, 100 nm.

Microneedles for bio applications

(Top) Demonstration structures.
(Bottom) Photonic Crystal
Complex 3D Printed Metamaterials

• Reverse hall effect structure that has opposite polarity
  – 2PP printed polymer structure
  – Coated with smooth thin zinc oxide via atomic layer deposition

K vector plot demonstrates resonance at 6700 cm$^{-1}$
Complex 3D printed structures

- Combine SLA and direct write methods
  - Place components into printed cavities
  - Resolution too low for interfacing dies

Complex 3D printed structures

- Layer-by-layer masking and PVD metal deposition
  - High resolution, embedded ICs
  - Requires mask for each pattern

3D Printed Packaging for MMIC and mm-Wave

- Utilize low cost digital light projection (DLP) Stereolithography
- Selective patterning of die encapsulation on metallic leadframes

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<th>Text and Detailing</th>
<th>Lens Integration</th>
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3 mm

Side View