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

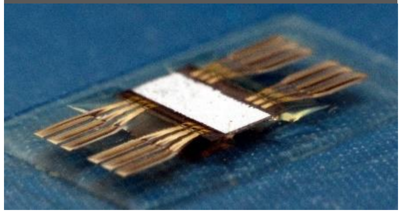
Fabricate wireless systems in a rapid, scalable, and purely-additive fashion

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

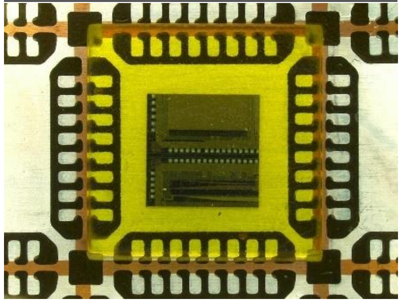


Materials:

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

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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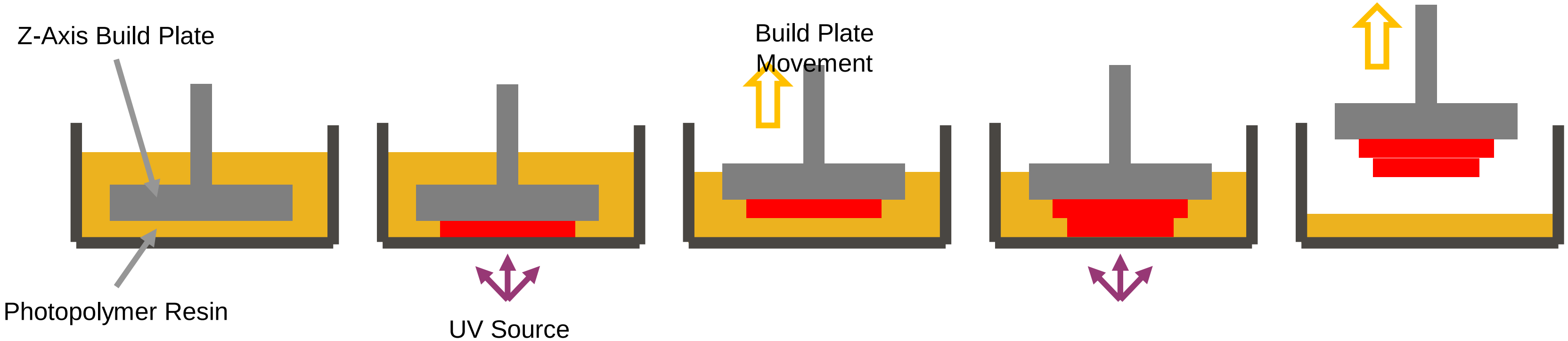
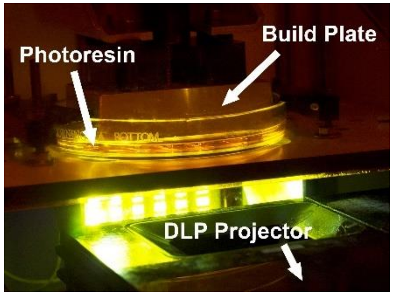
Stereolithography (SLA) 3D Printing



- 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)

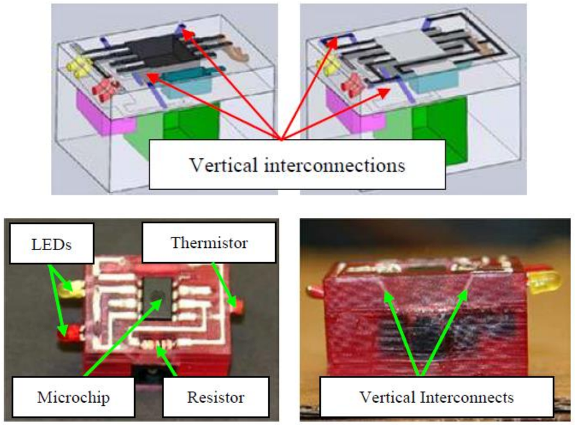


SLA Printing Setup

Using SLA for Packaging

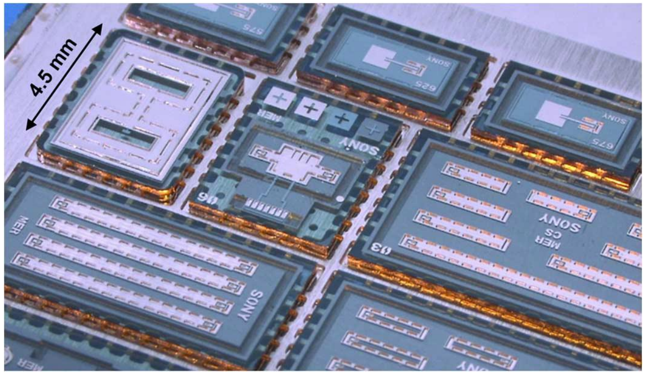
- Combine SLA and direct write methods
  - Place components into printed cavities
  - **Resolution too low for interfacing dies**

A. J. Lopes et al., “Integrating stereolithography and direct print technologies for 3d structural electronics fabrication,” Rapid Prototyping Journal, vol. 18, no. 2, pp. 129–143, 2012.



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

T. Merkle et al., “Polymer multichip module process using 3-d printing technologies for d-band applications,” IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 2, pp. 481–493, Feb 2015.



SLA 3D Printing and Characterization

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

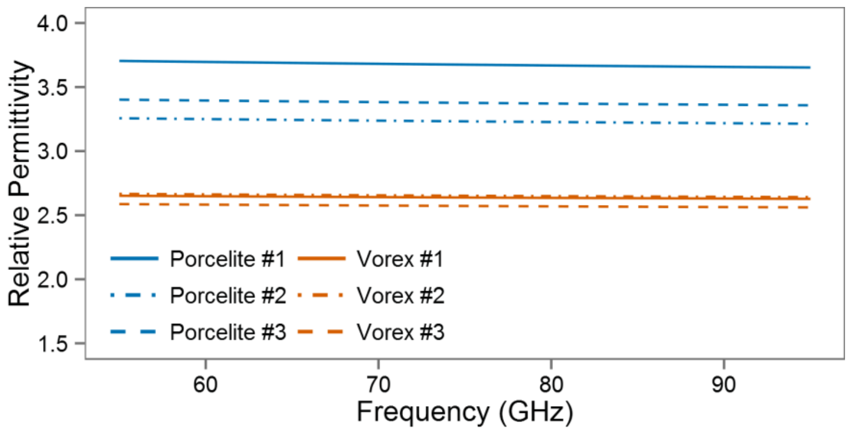
Goal: characterize dielectric properties of SLA materials at E-band (55–95 GHz)

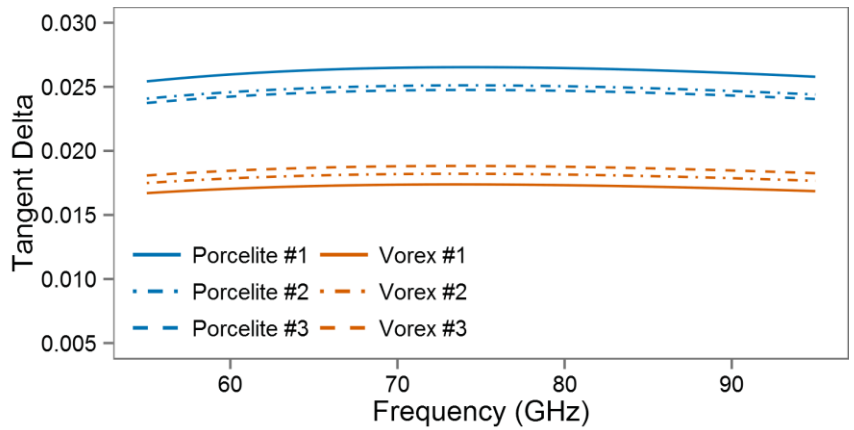
1. Material samples printed to match **WR-12 waveguide cavity** dimensions (3.01 x 1.55 x 1 mm)
2. S-parameters of printed cavity fills measured **across E-band**
3. Models satisfying Kramers-Kronig relation used to **extract ε_r and $\tan\delta$** from measurements

WR-12 Waveguide Spacers

Waveguide fill samples

Dielectric Characterization



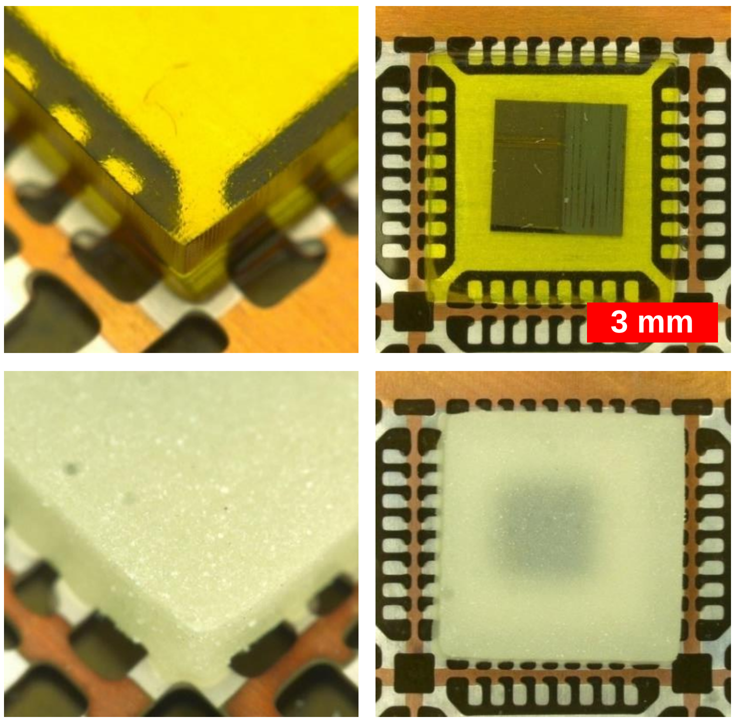


- Variations less than ± 2% and ± 7% for Vorex and Porcelite sample measurements, respectively
- Linearity observed up to and beyond 90 GHz
- Ceramic-loaded Porcelite material exhibits higher ε_r
- ε_r and tanδ **comparable to standard epoxy mold compound materials**

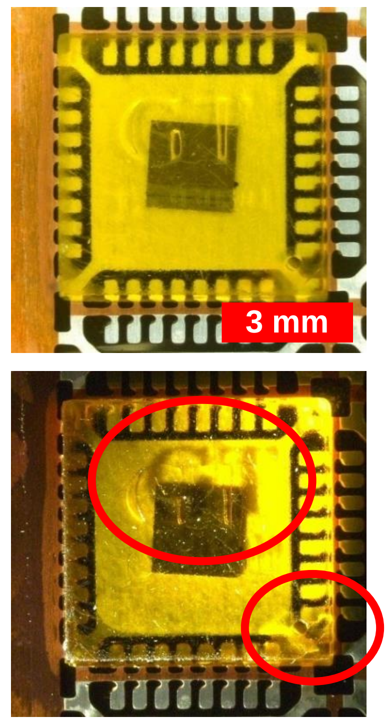
3D-Printed Encapsulation

- Selective patterning of die encapsulation on metallic leadframes

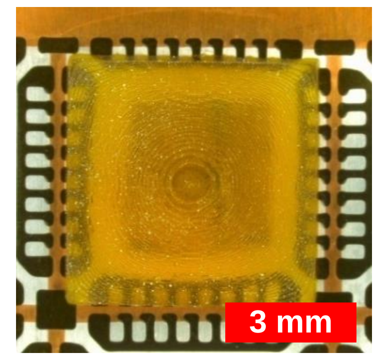
Standard 1 mm-Thick Encapsulation



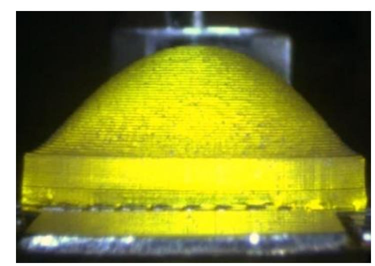
Text and Detailing



Lens Integration

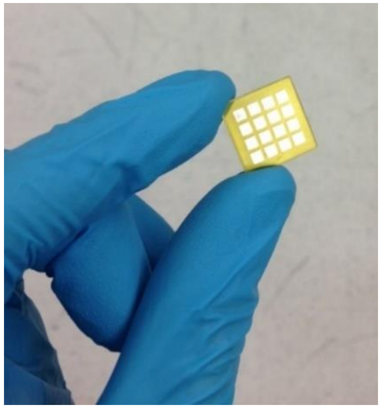


Side View

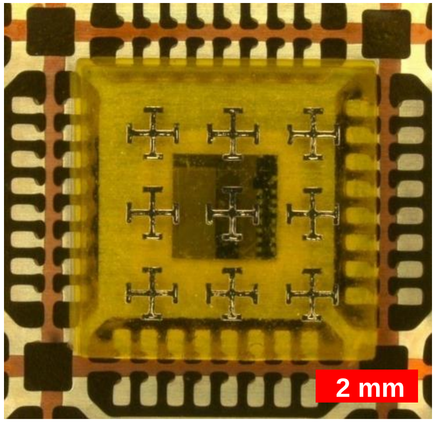


Post-Process On-Package Printing

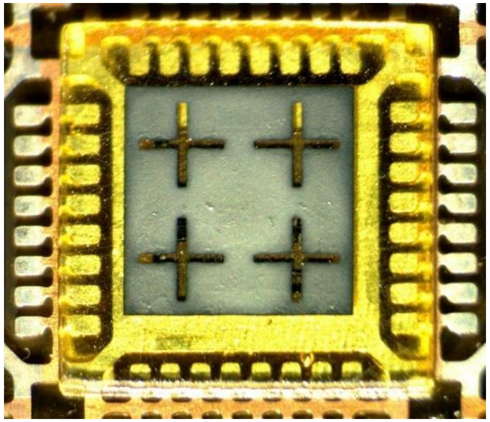
- Use inkjet printing to fabricate metallic structures on top of 3D-printed encapsulation
  - Decoupling capacitors
  - Antenna arrays
  - Frequency selective surfaces (FSS)



Periodic square FSS inkjet-printed onto 3D-printed substrate

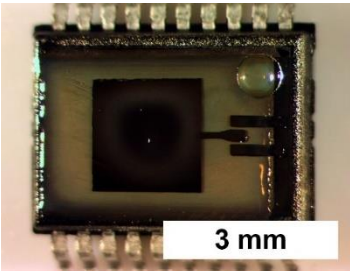


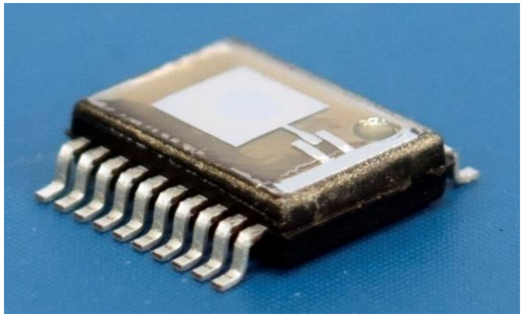
Periodic Jerusalem Cross FSS inkjet-printed onto 3D-printed encapsulation



Periodic Slotted-Cross FSS printed onto 3D-printed encapsulation

mm-Wave SoP: 3D and Inkjet Printing





Inkjet print on-package components
(IEEE APS 2015)

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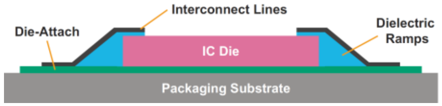
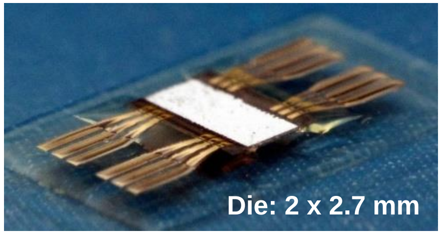
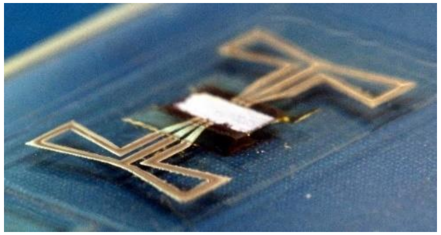






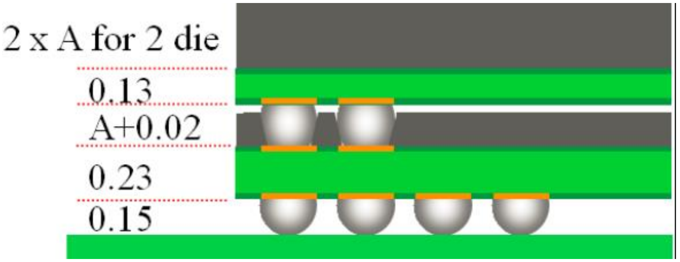
Inkjet print dielectric ramps for mm-wave interconnects and antennas
(IEEE IMS 2016)

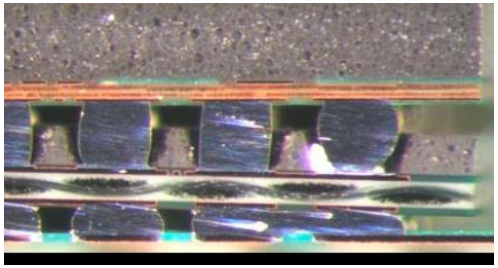
How can we integrate these two technologies?

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

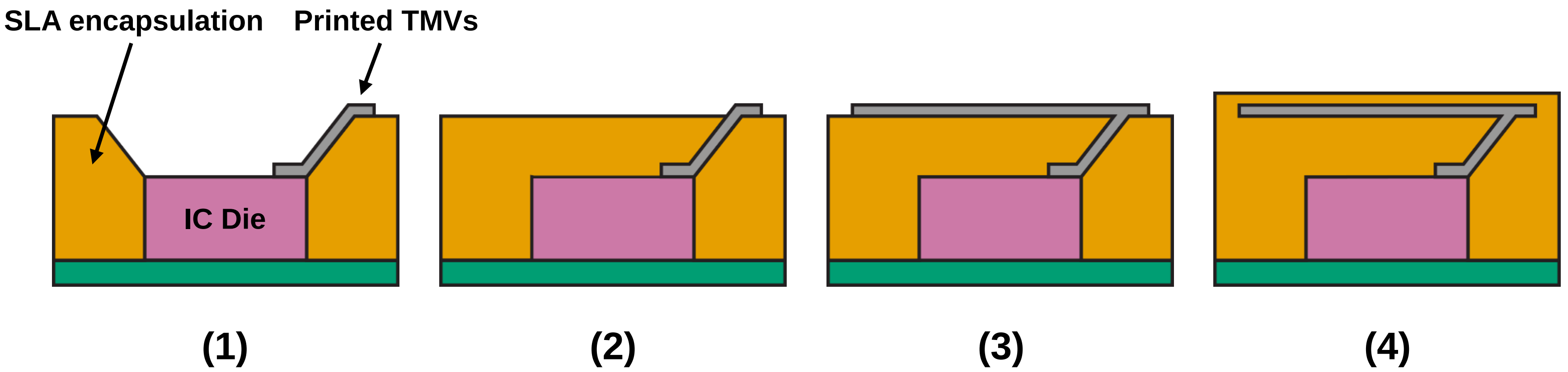




Use 3D printing to fabricate IC encapsulation with through-mold-vias (TMVs)

A. Yoshida et al., “A study on an ultra thin pop using through mold via technology,” in 2011 IEEE 61st Electronic Compon. and Technol. Conference (ECTC), May 2011, pp. 1547–1551.

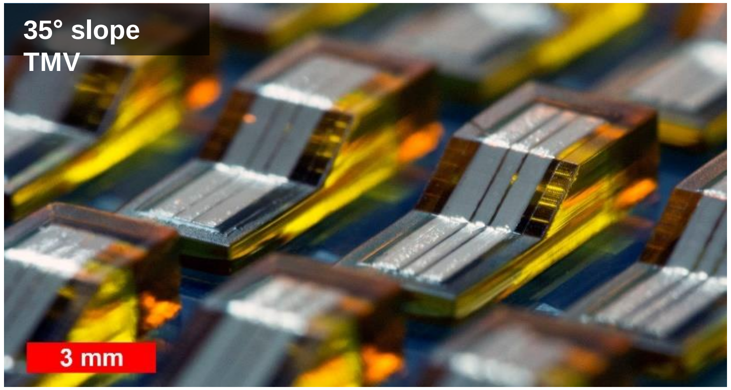
TMV Fabrication Process Flow

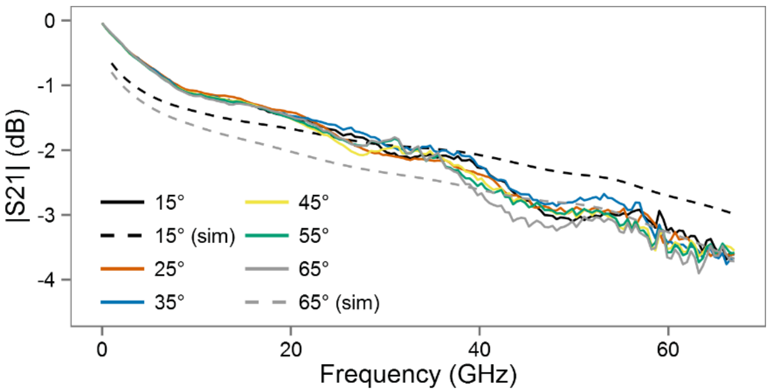


2D Side-View Model of Printed 3D SoP Encapsulation

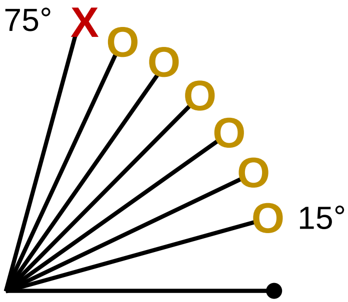
1. 3D print encapsulation with ramps, inkjet print TMV interconnects
2. 3D print encapsulation cavity fill to seal die and internal interconnects
3. Inkjet print multilayer antennas/passives/etc topology
4. 3D print final encapsulation

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

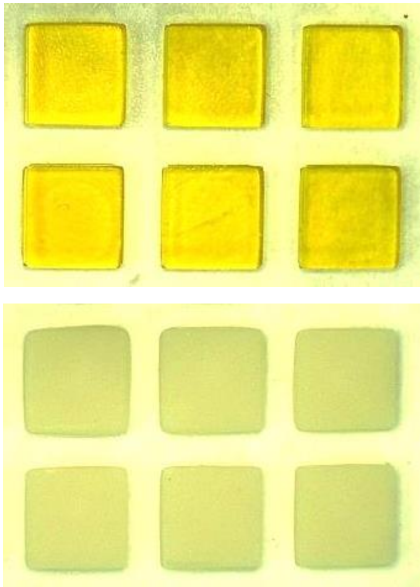


SLA 3D-Printed Ramp Slopes

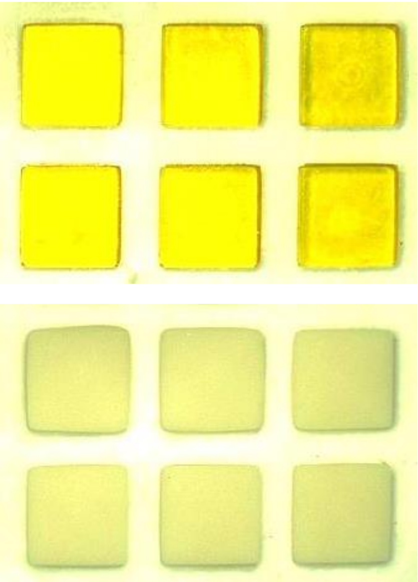
Thermal Cycling

- 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

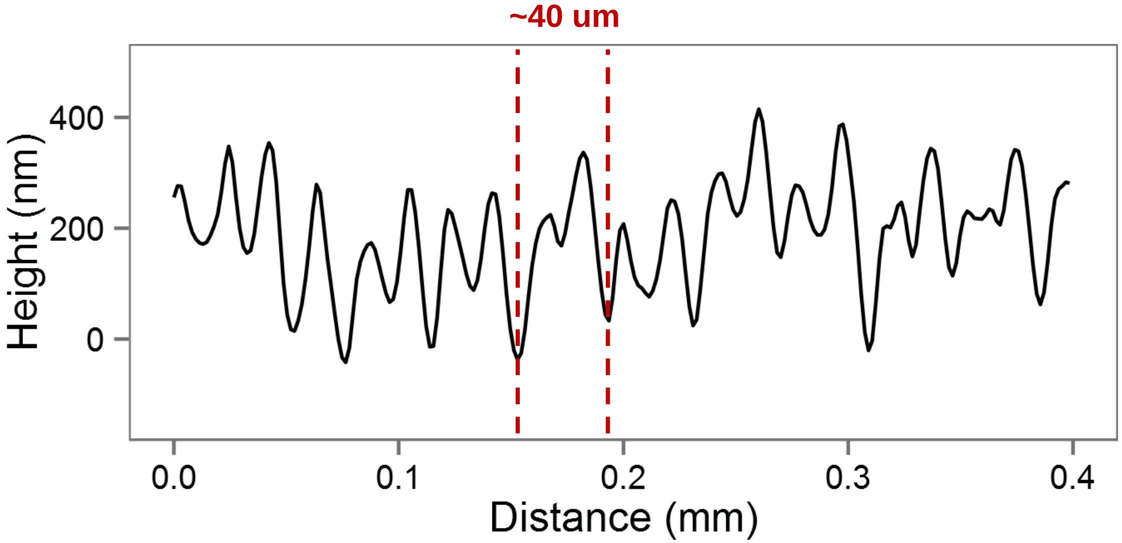
Before Cycling



After Cycling



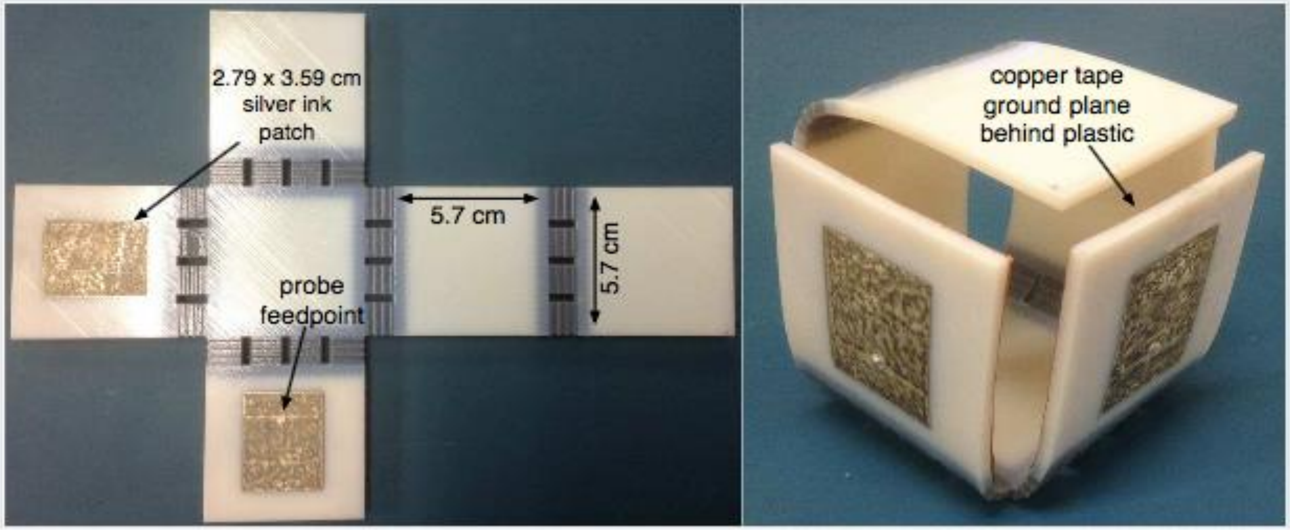
Surface Roughness



- “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, Strechable polymer (rubber-like)
- Grey60: Hinges, exhibit shape memory effect (SME)

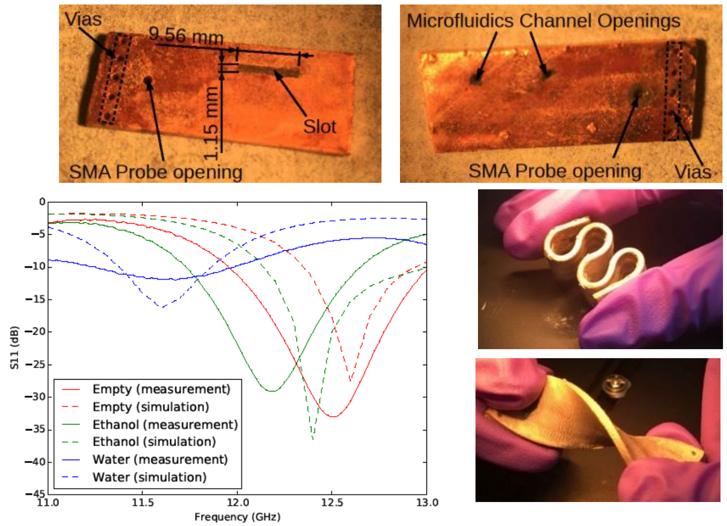


Printed with Objet 260 PolyJet 3D printer, silver nanoparticle ink for patch antennas

J. Kimionis. "3D-printed Origami Packaging with Inkjet-printed Antennas for RF Harvesting Sensors," IEEE Transactions on Microwave Theory and Techniques, vol.63, no.12, Dec. 2015

3D Printed Flexible/Compressible/Stretchable Packages

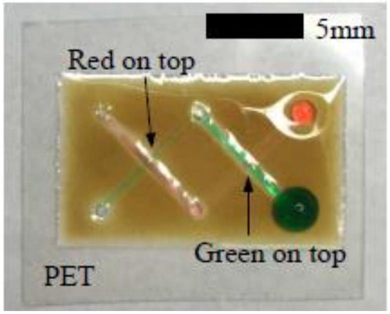
- Wearable sensing platform
- Ultra flexible
- 3D printed
  - Low cost
  - Customized
  - Flexible
- Sensing capability
  - Microfluidics liquid sensing

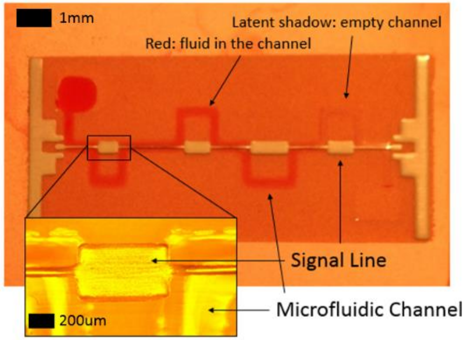


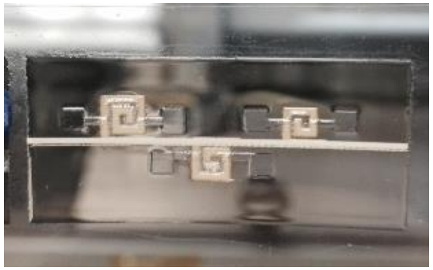
Wenjing Su, Zihan Wu, Yunnan Fang, Ryan Bahr, Markondeya Raj Pulugurtha, Rao Tummala, and Manos M. Tentzeris, "3D Printed Wearable Flexible SIW and Microfluidics Sensors for Internet of Things and Smart Health Applications", *IEEE International Microwave Symposium (IMS)*, 2017, accepted

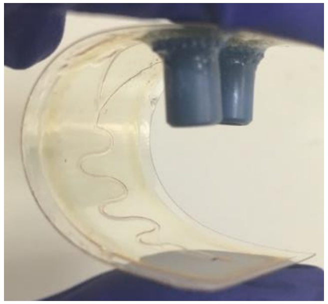
Flexible Inkjet-Printed Microfluidics

- 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



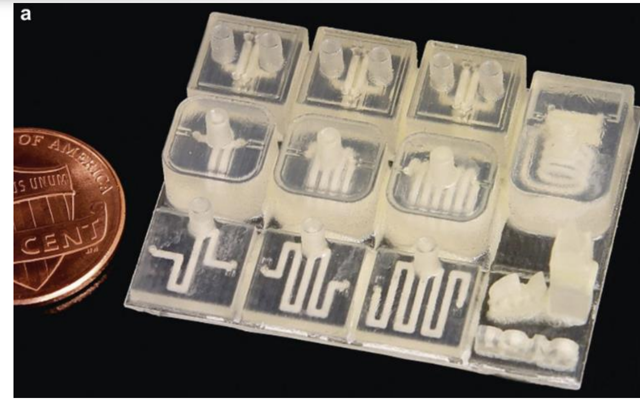




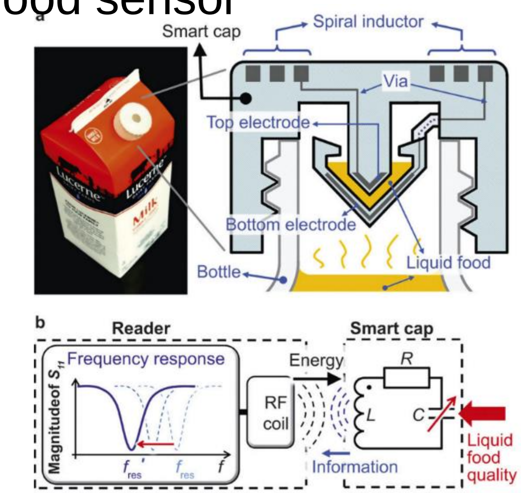


3D Printed Electronics

- **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

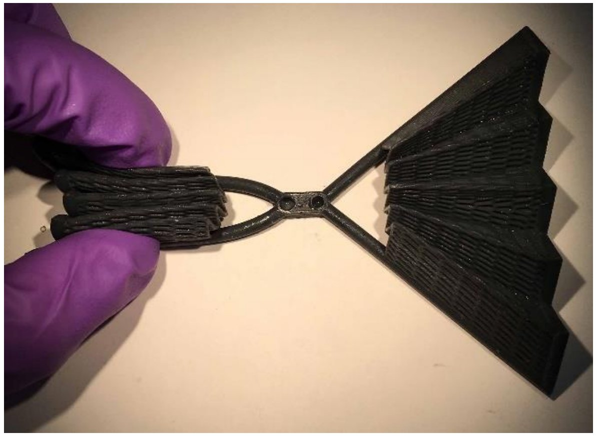


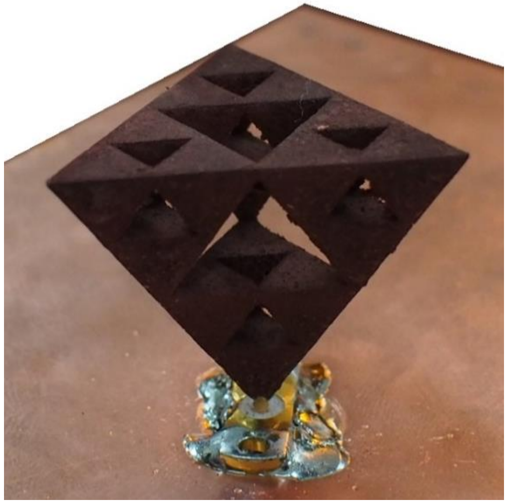
(Top) 3D printed RLC components (Bottom) IoT food sensor

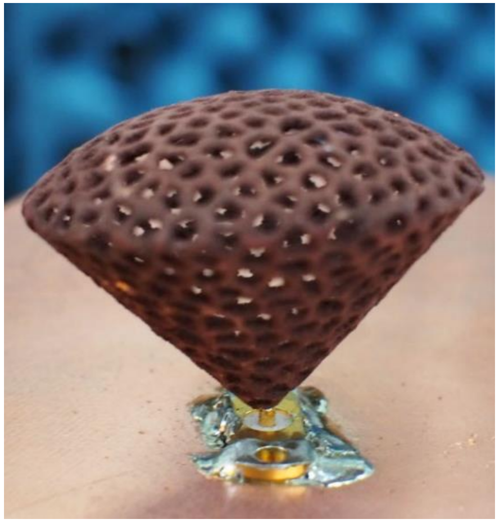


3D Printing of Complex Antennas

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

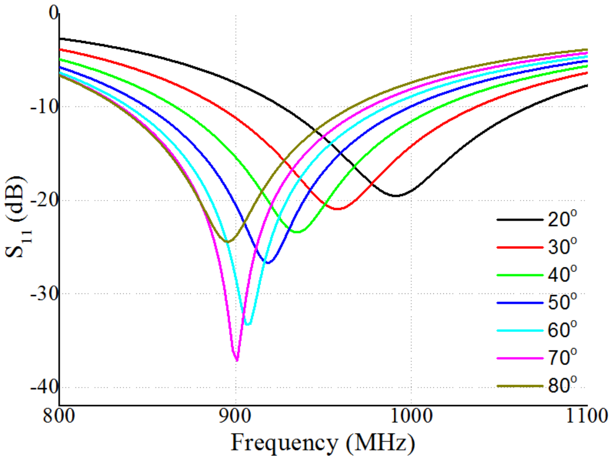






(Left) 3D printed fractal antenna
(Right) Voronoi based antenna

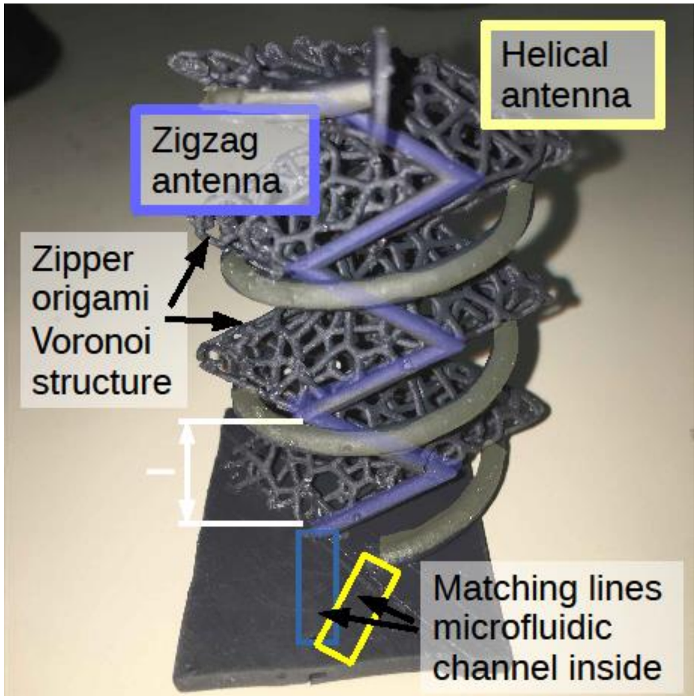
(Top) Chinese fan antenna
(Bottom) Photonic Crystal



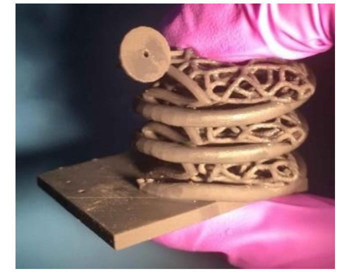
ECTC 2017
The 67th Electronic Components and Technology Conference

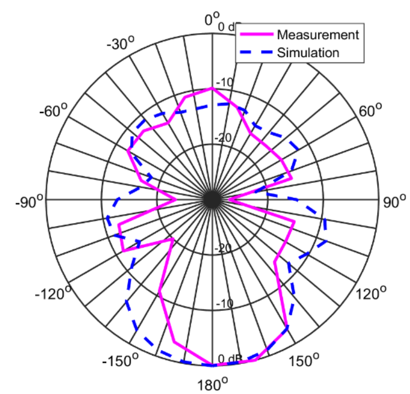
Georgia Institute of Technology

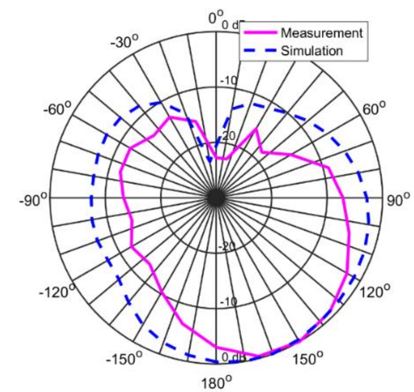
Reconfigurable Antenna Structures



Compress







Helical/zigzag antenna “Tree” with (a) original and (b) compressed

T. Merkle et al., “Polymer multichip module process using 3-d printing technologies for d-band applications,” IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 2, pp. 481–493, Feb 2015.

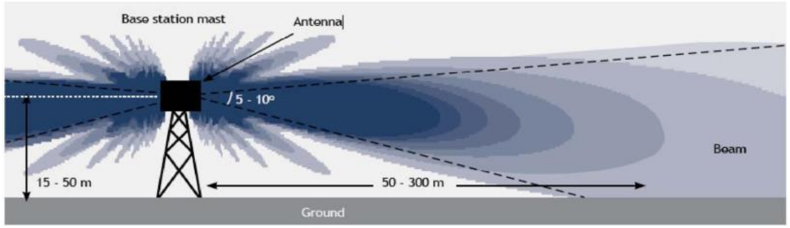
5G for IoT, Wearables and Smart Skins

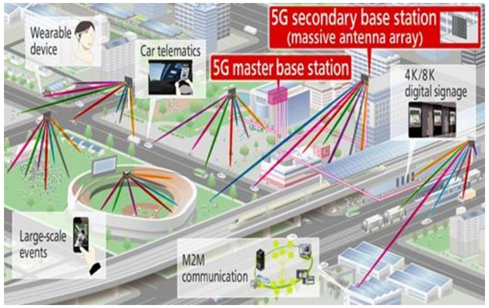
Advantages:

- 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

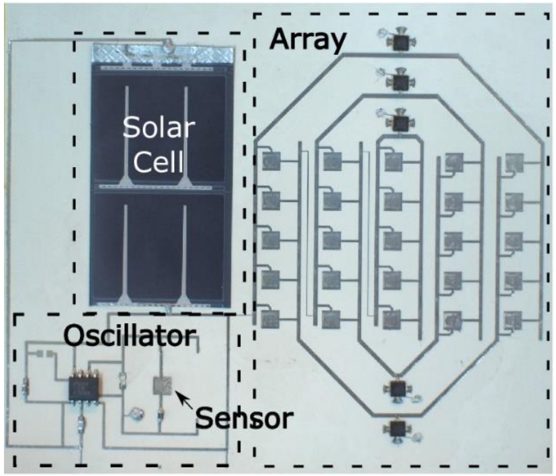
- RF powering is very difficult at mm-wave: Solar
- Mm-wave components and materials are expensive: Minimalist design, printed
- Large tags cannot be read from all directions: Van-Atta

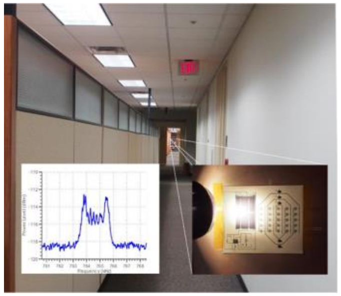


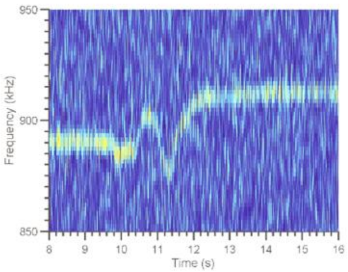


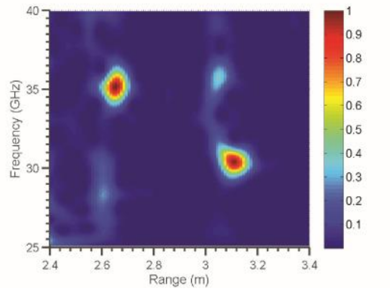
Printed, flexible, backscatter-modulation Van-Atta sensor km-Range “patch” structure

- 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)









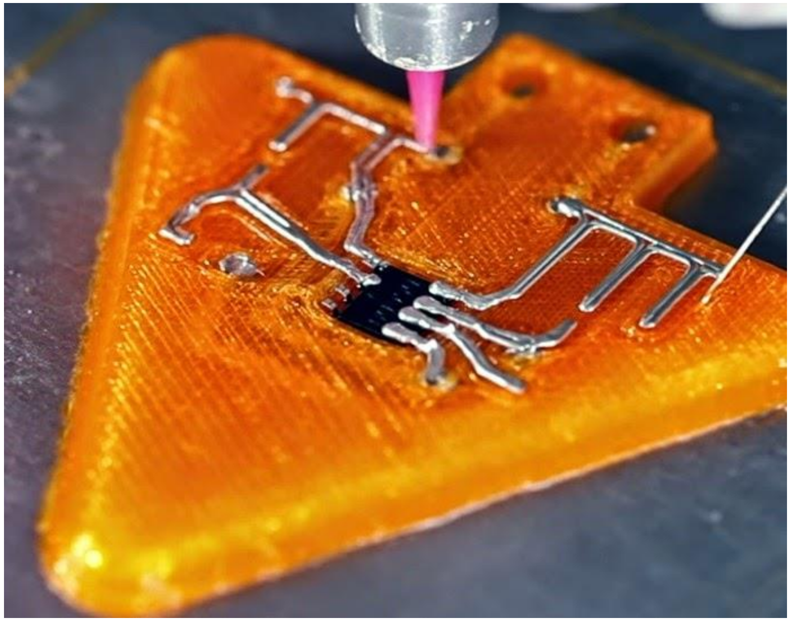
Summary

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

- Extracted ε_r and tanδ 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

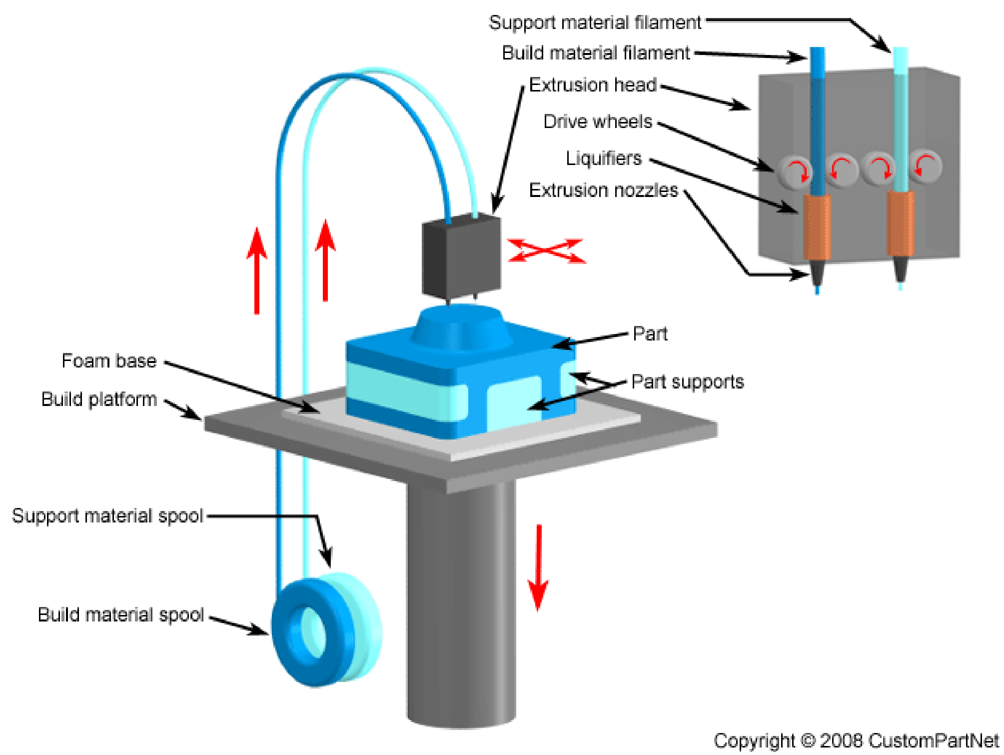
- Micro dispensing
  - Physical deposition of wide variety of materials
  - Often can be incorporated with multiple materials much easier than optical methods
- Examples:
  - Direct write, Aerosol jet, Fused deposition modeling (FDM, multijet printing



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)



Traditional FDM machine

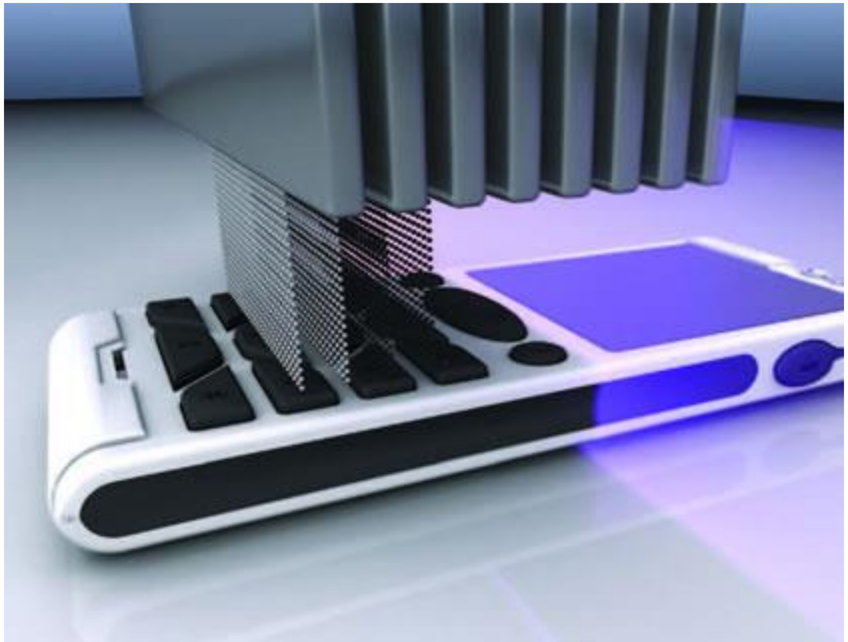
Extremes of Direct Write

- 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

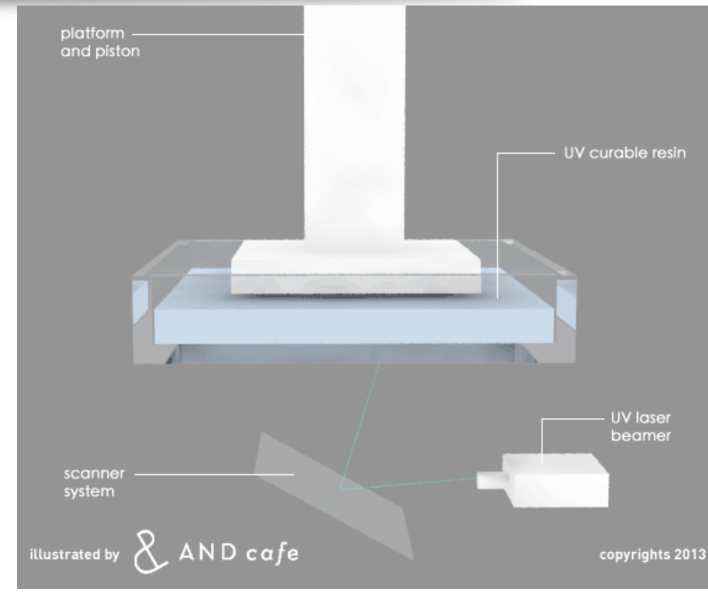
- **Prints polymers with inkjet tech.**
- **Resolutions:**
  - **XY: 1600 dpi**
  - **Z: 16 microns**
- **Advantages:**
  - **Multiple polymers**
- **Disadvantages:**
  - **Proprietary Polymers Only**

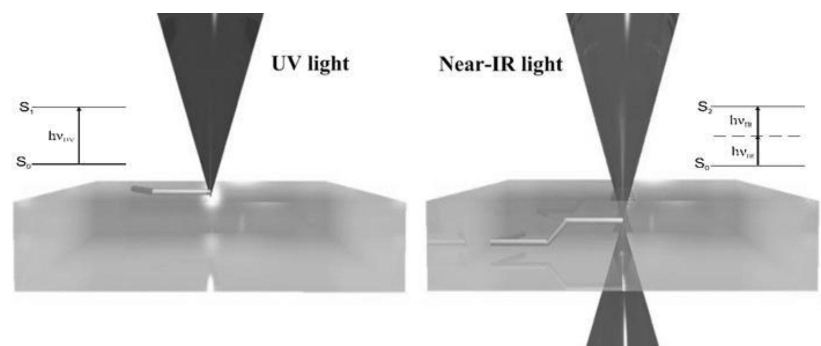


Multimaterial polyjet printing of polymers for a cell phone mockup.

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)



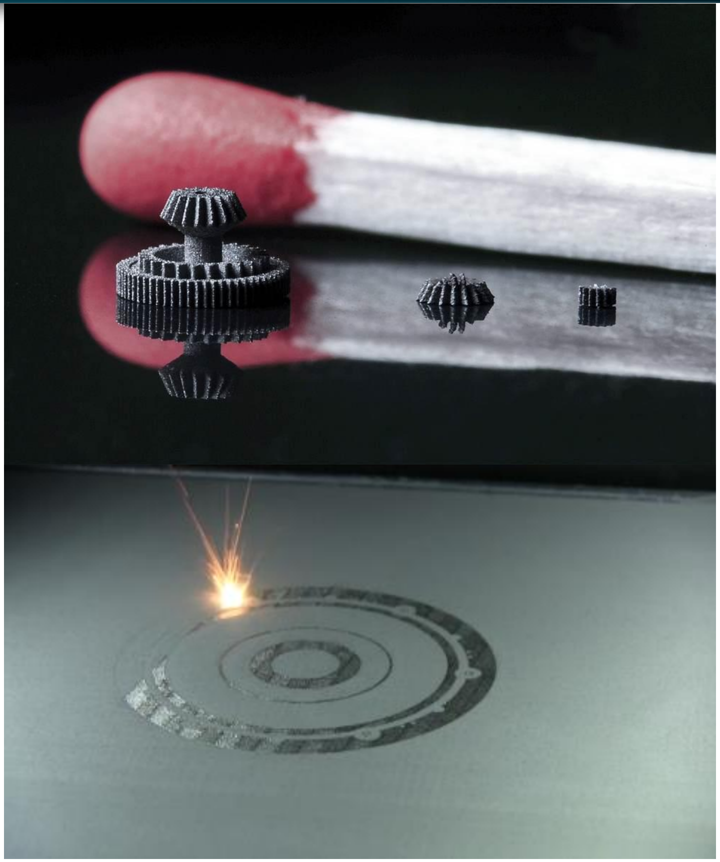


(Left) Traditional SLA. (Right) Two photon absorption

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)

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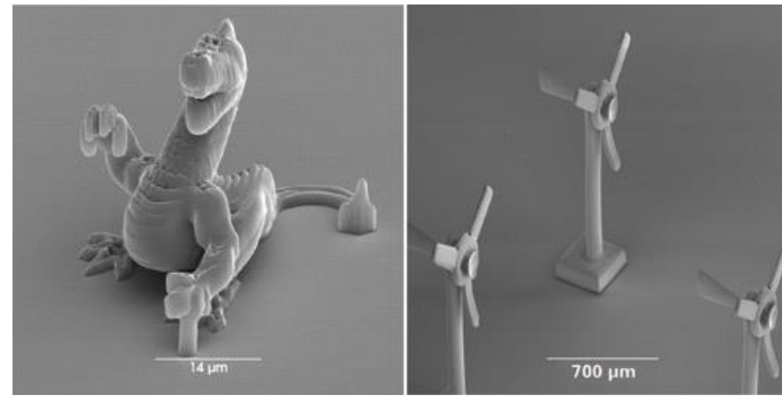
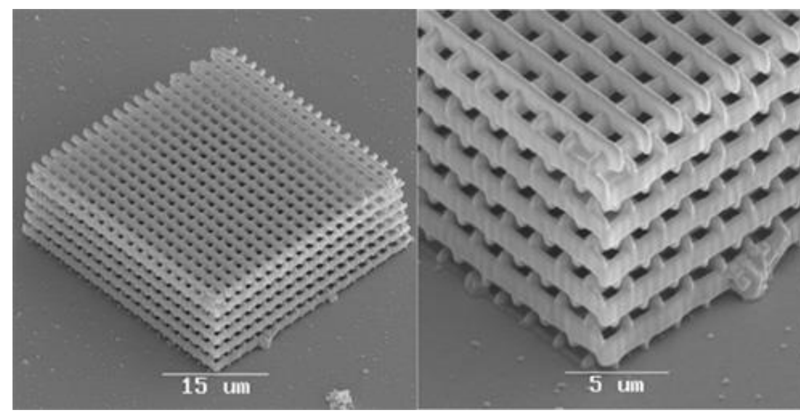
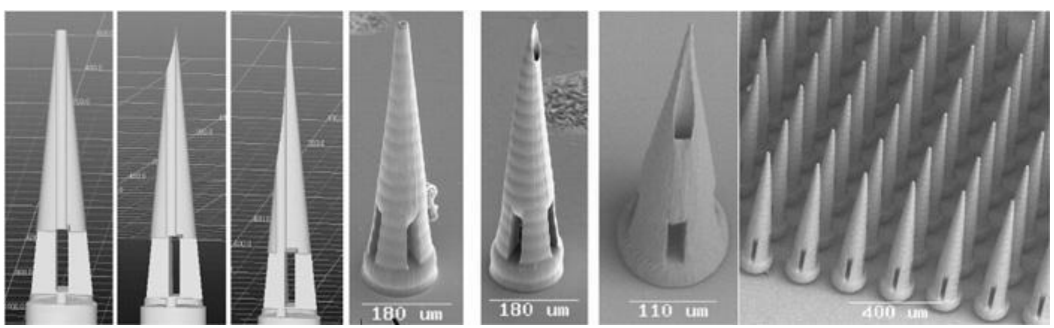
3D Printing Techniques – Optical Resolutions

- **Resolution Extremes**
  - **2 photo polymerization (i.e. Nanoscribe)**
  - **XYZ resolution limited to near diffraction limit, 100 nm.**





(Top) Demonstration structures.
(Bottom) Photonic Crystal



Microneedles for bio applications

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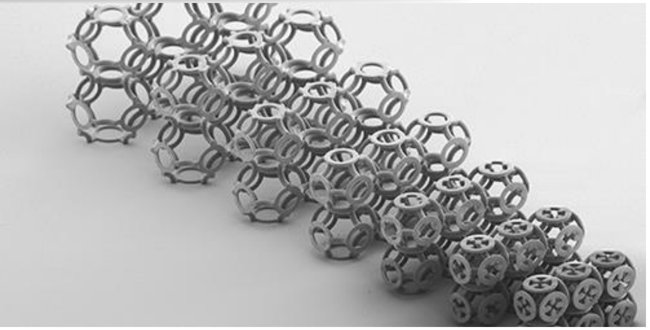
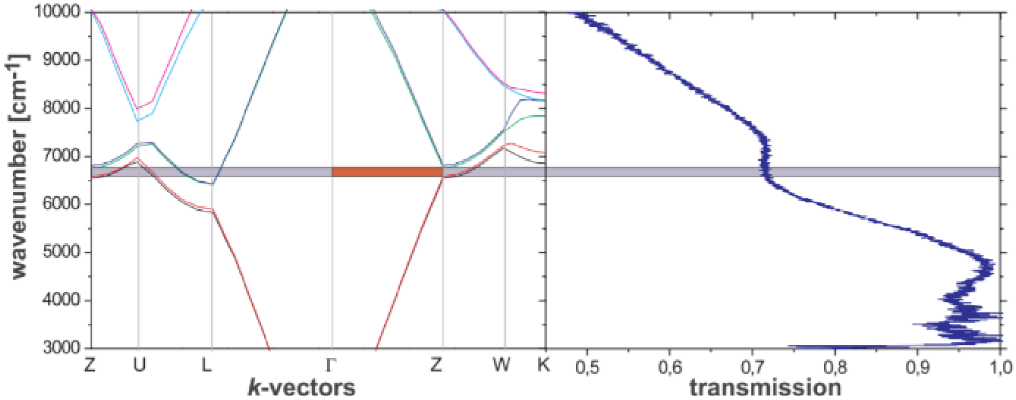
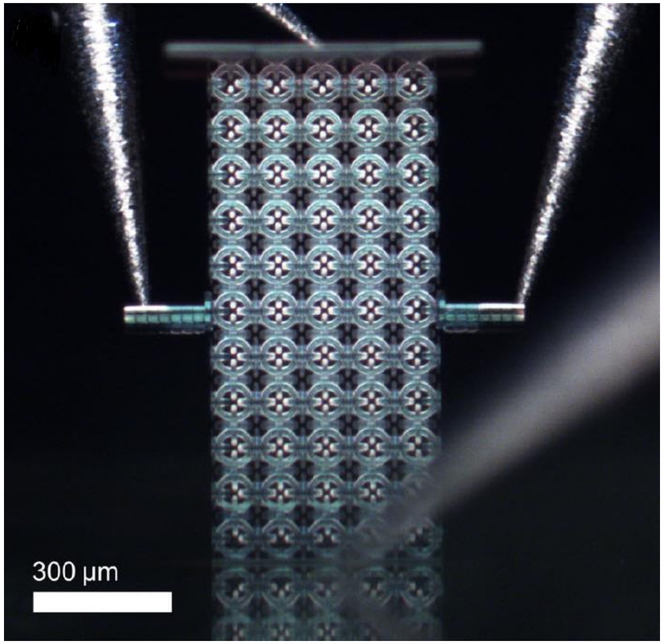
Complex 3D Printed Metamaterials

- 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}



3D printed structure and testing

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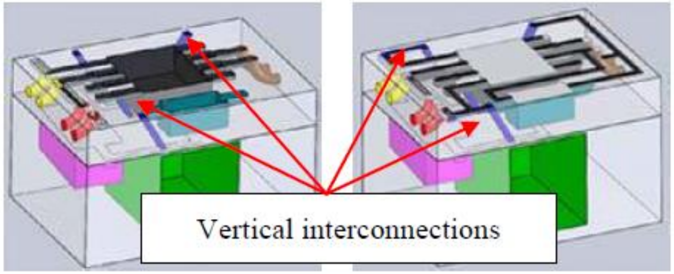
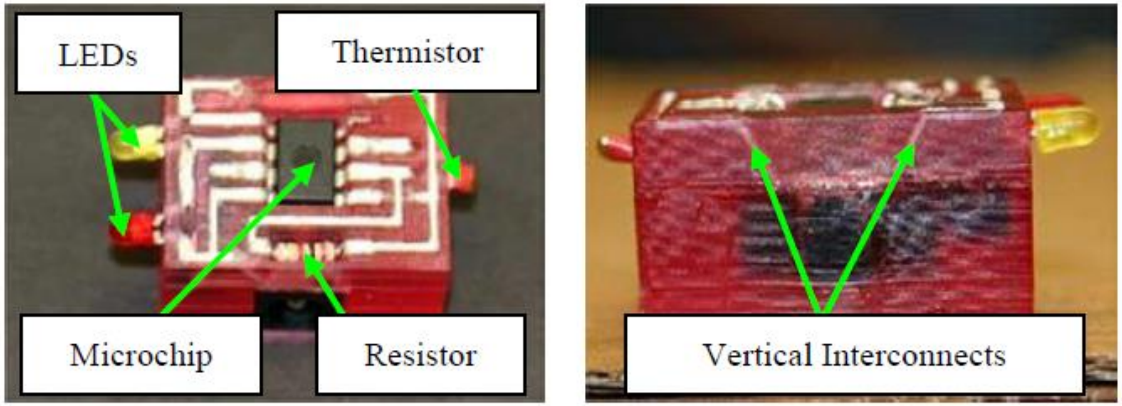
Complex 3D printed structures

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



3D modeled structure

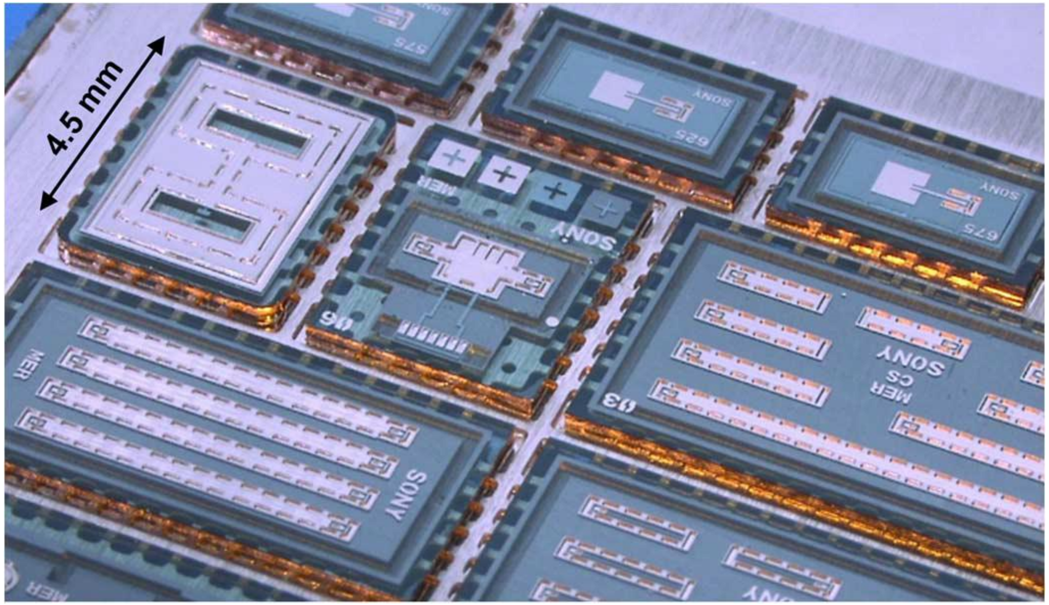


Physically realized 3D structure.

A. J. Lopes et al., "Integrating stereolithography and direct print technologies for 3d structural electronics fabrication," Rapid Prototyping Journal, vol. 18, no. 2, pp. 129–143, 2012.

Complex 3D printed structures

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

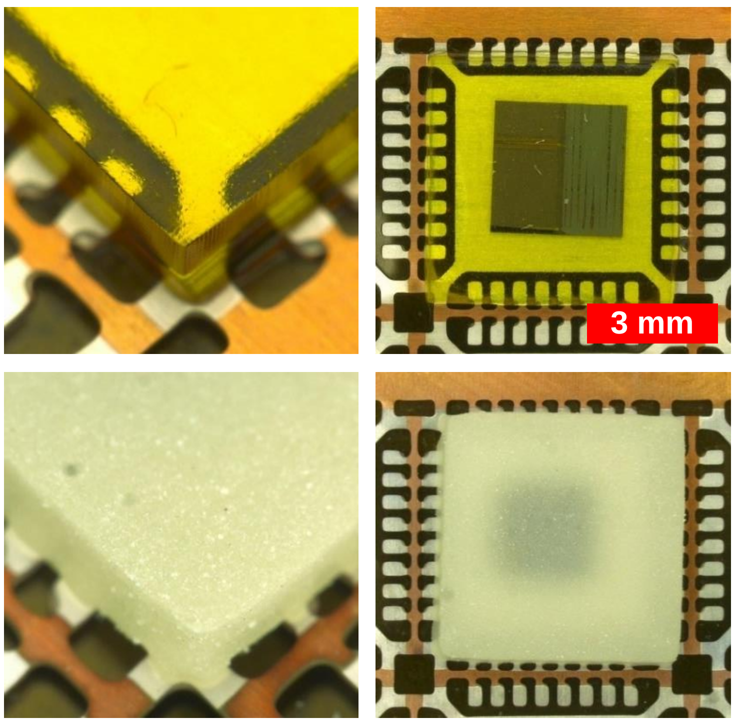


T. Merkle et al., “Polymer multichip module process using 3-d printing technologies for d-band applications,” IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 2, pp. 481–493, Feb 2015.

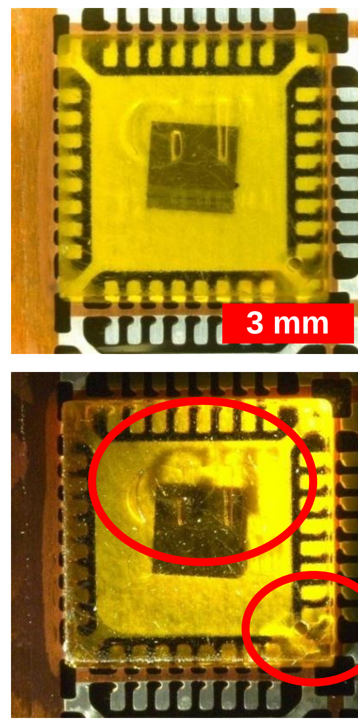
3D Printed Packaging for MMIC and mm-Wave

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

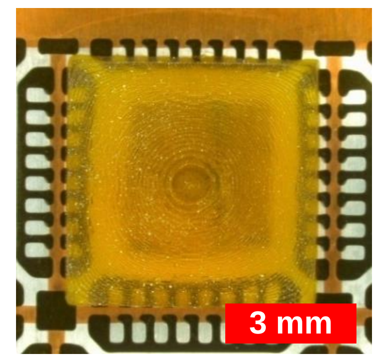
Standard 1 mm-Thick Encapsulation



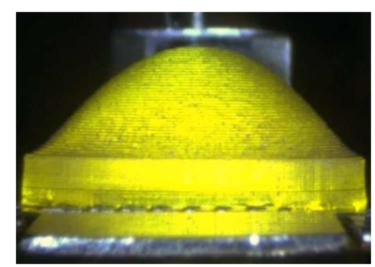
Text and Detailing



Lens Integration



Side View



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