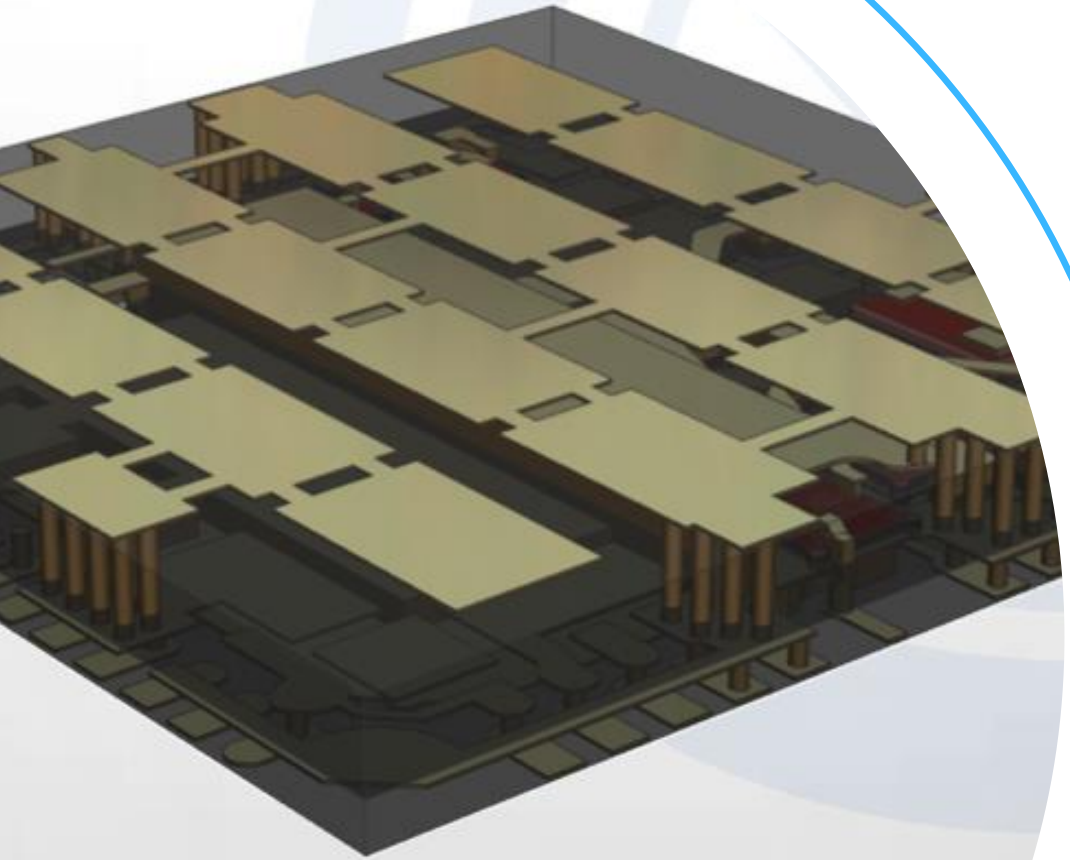


3D Printed Electronics & New Design Thinking

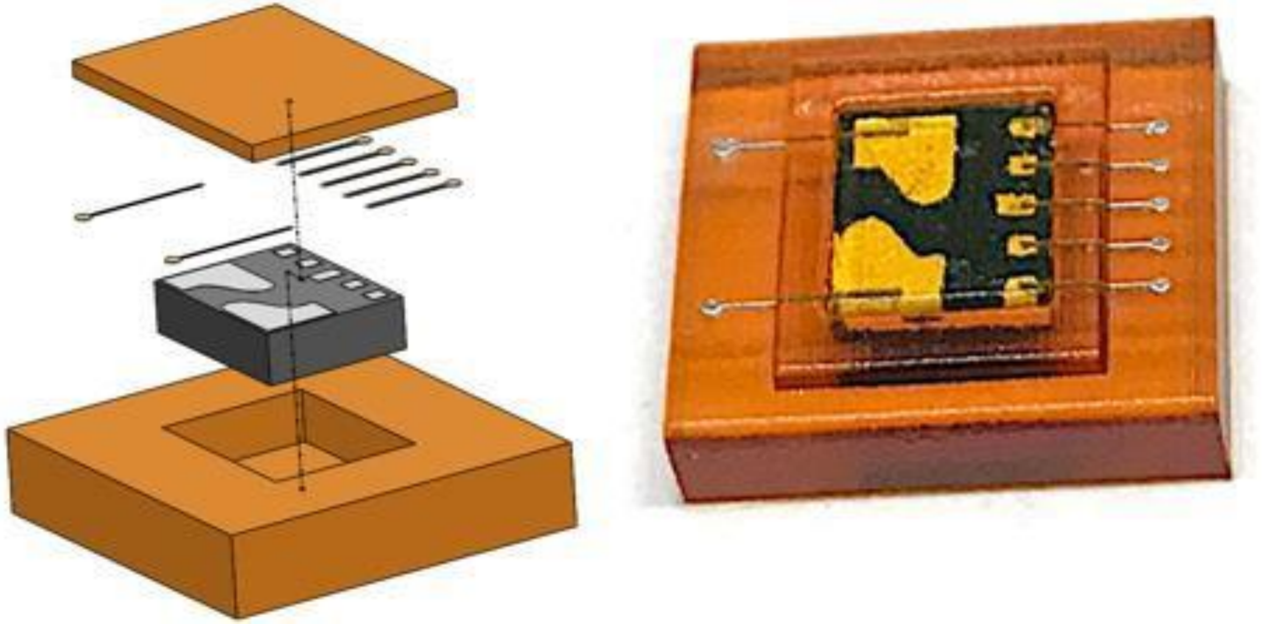
A New Age in PCB, RF Design & Packaging

MIRKO SIDOTI

14th September 2023

Agenda

- Nano Dimension introduction
- Why AME? And Why Now?
- AME RF Components
- Innovative Antennas and Arrays
- System in Package (SiP) Development Flow
- RF SiP Case Study
- Power Transistor AME Packaging Case Study
- Summary



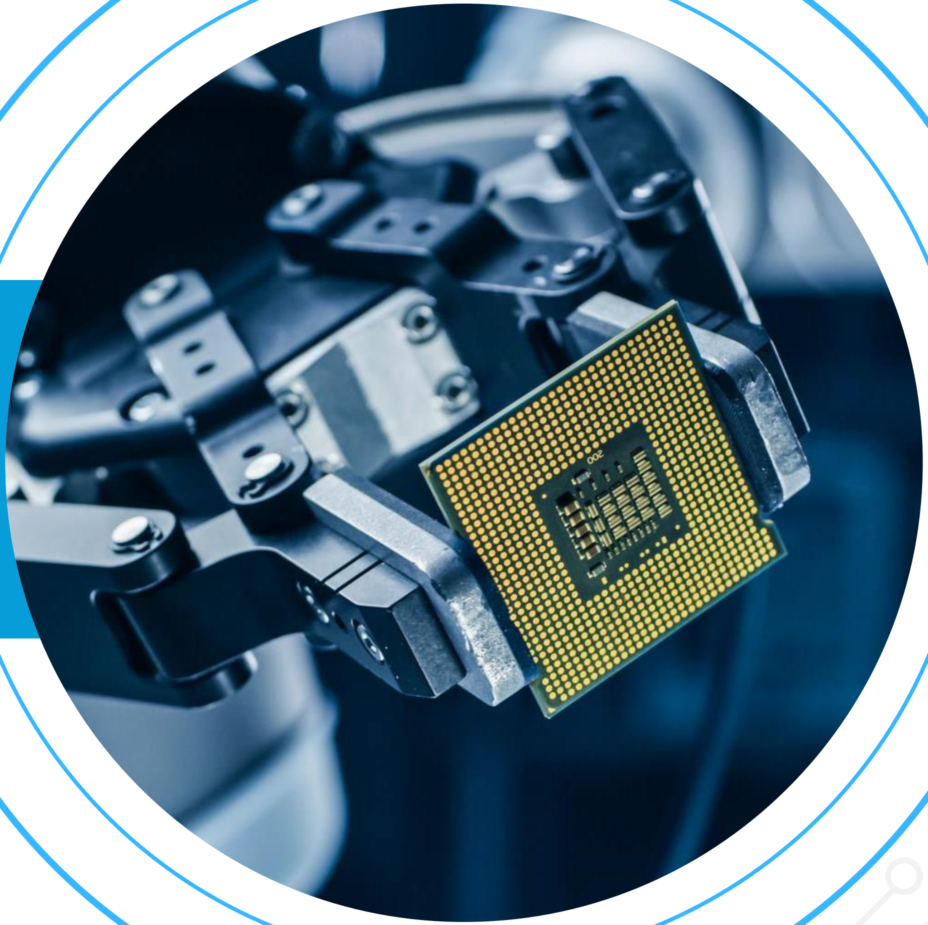
Acronyms:

AM = Additive Manufacturing

AME = Additively Manufactured Electronics

SiP = System in Package

Who is Nano Dimension?



We make…

…all of these

advanced deep learning-AI led manufacturing solutions

that are used by

industrial-level organizations

to 3D print and assemble

High Performance Electrical & Mechanical Applications

Innovative Products for True Industry 4.0 Solutions

The Critical Pieces to Manufacture High Performance Electronic and Mechanical Devices

Additive Manufacturing

DragonFly IV
Additively Manufactured Electronics

Fabrica 2.0
Micro AM

Admatec
Ceramic and Metal AM

+

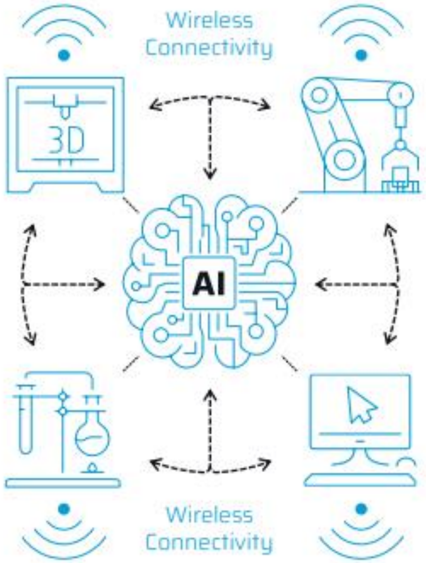
Conductive and Dielectric Inks

Ceramic

Polymer

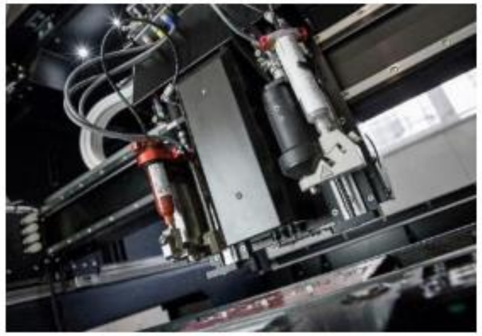
Metal

Advanced Materials & Processes



DeepCube
Deep Learning Based AI Platform

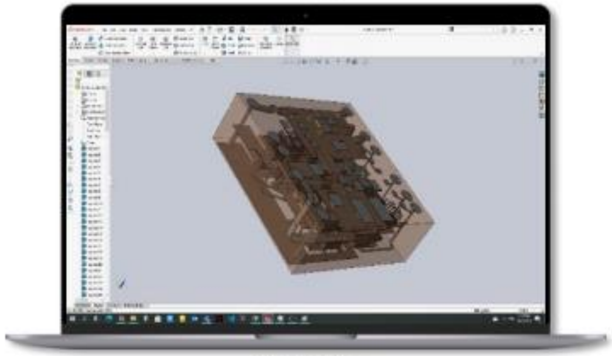
Robotics



SMT Suite of Products
Surface Mount Technology for Electronics

Digital Printing Platform
Printer control systems and software

+

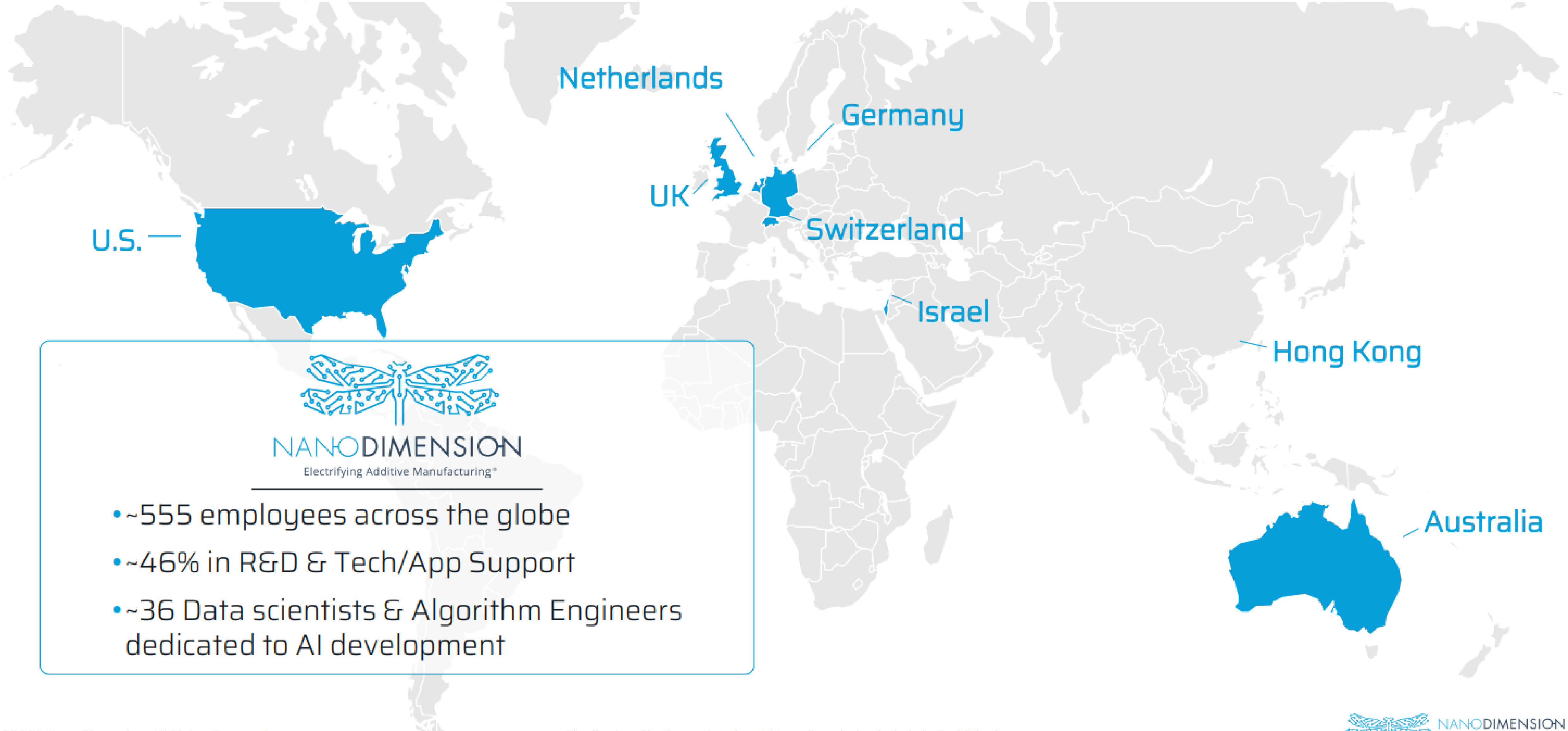


FLIGHT
Design-to-Manufacturing
Testing, simulation, and management

Software

Worldwide Presence Poised for Accelerated Growth

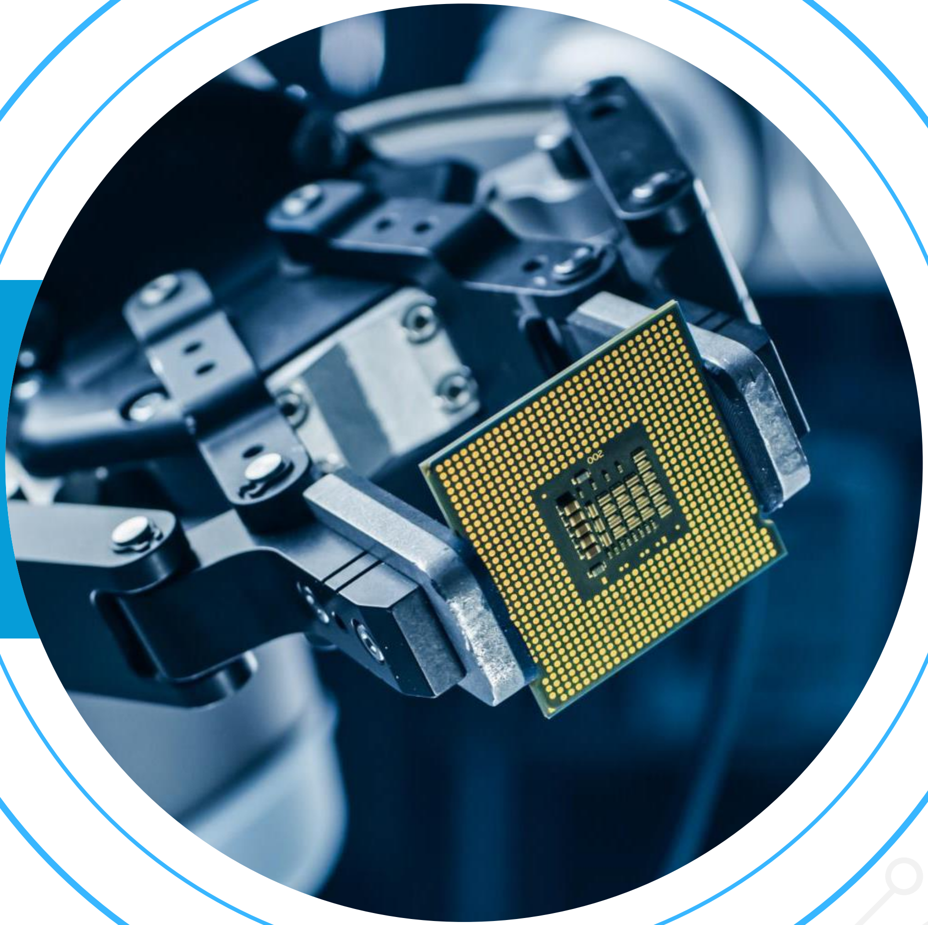
Close to Where We Need to Be For the Most Advanced Manufacturing Markets



NANO DIMENSION
Electrifying Additive Manufacturing®

- ~555 employees across the globe
- ~46% in R&D & Tech/App Support
- ~36 Data scientists & Algorithm Engineers dedicated to AI development

Why AME? And Why Now?

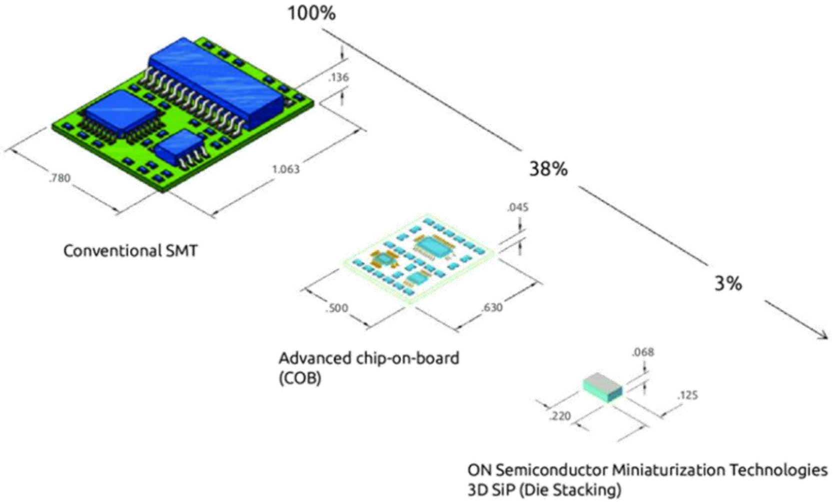


Motivation

CURRENT WORLD OF ELECTRONICS

1. Technical Limitations:

preventing improvement of performance and reduction of other factors such as weight and size



Weight and size over 90% down

2. Supply chains:

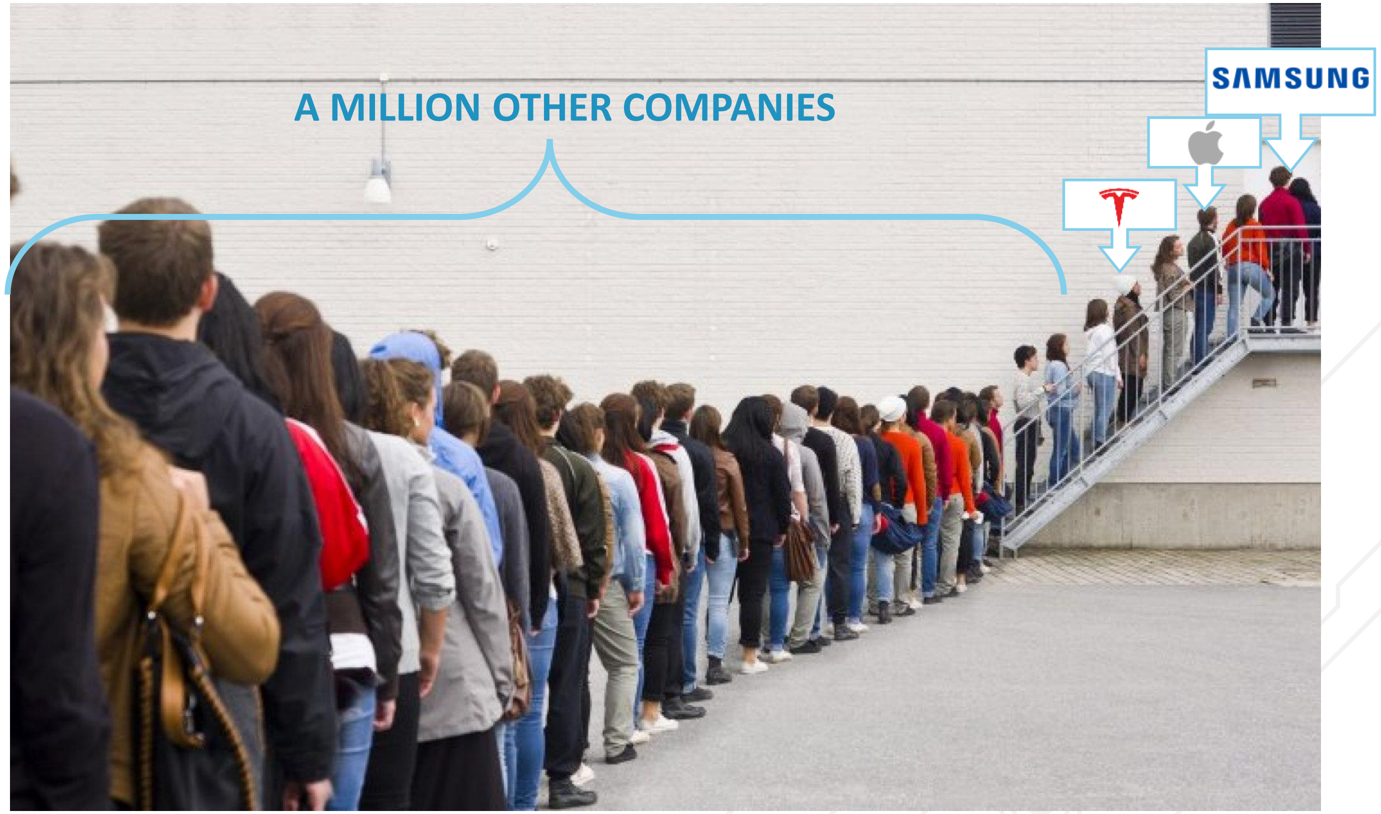
hurting most in the high variety small mix and when prototyping (long R&D cycles)

Motivation (cont.)

LONG LINES FOR PACKAGING AND PROTOTYPING

Very long lead time for small & medium-sized enterprises and very long R&D-cycles

- To produce a prototype, 4 R&D cycles are required
- each cycle has a 3-4 months lead time until supplied from the global packages & electronics manufacturer



Motivation (cont.)

TRADITIONAL MANUFACTURING VS. SUSTAINABLE AM SOLUTIONS

3. Sustainability

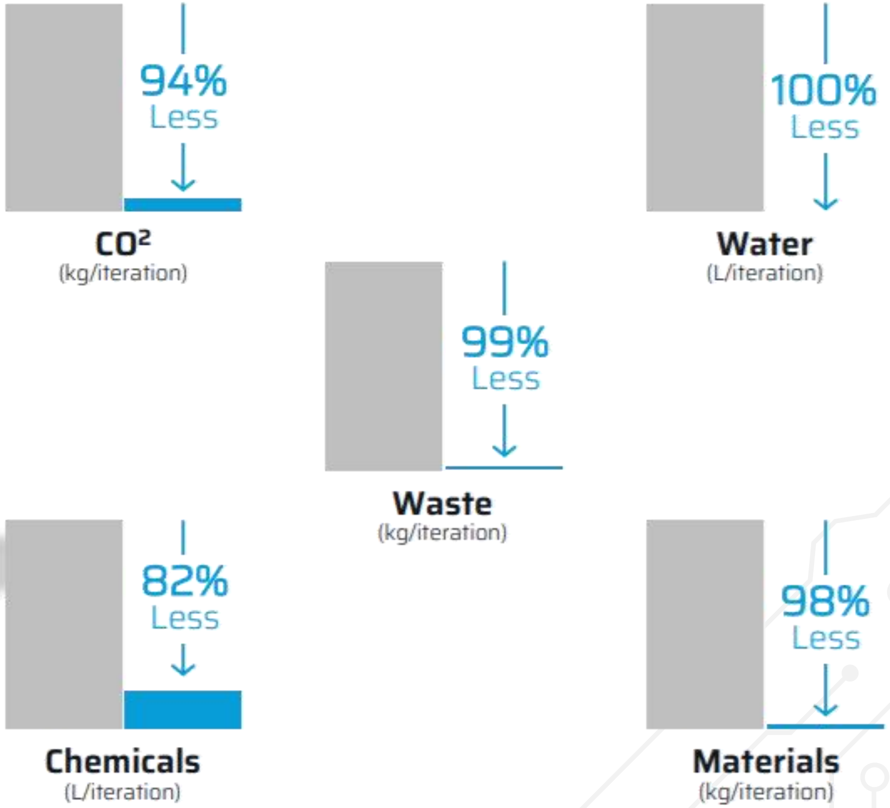
A holistic approach towards functional electronics with net zero carbon emissions

Motivation (cont.)

TRADITIONAL MANUFACTURING VS. SUSTAINABLE AM SOLUTIONS

Before

After



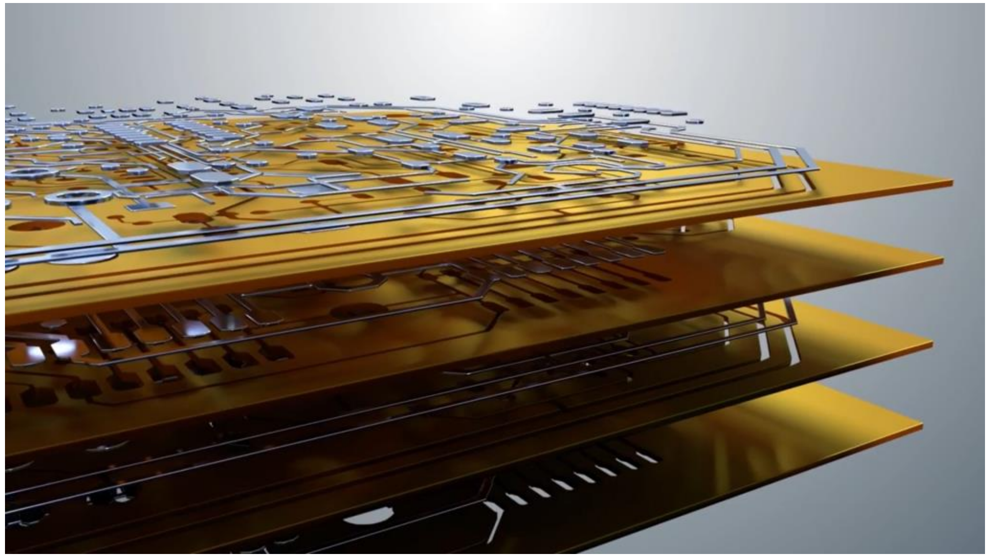
[1] Based on a 2021 study by HSSMI, a UK based sustainability consultant

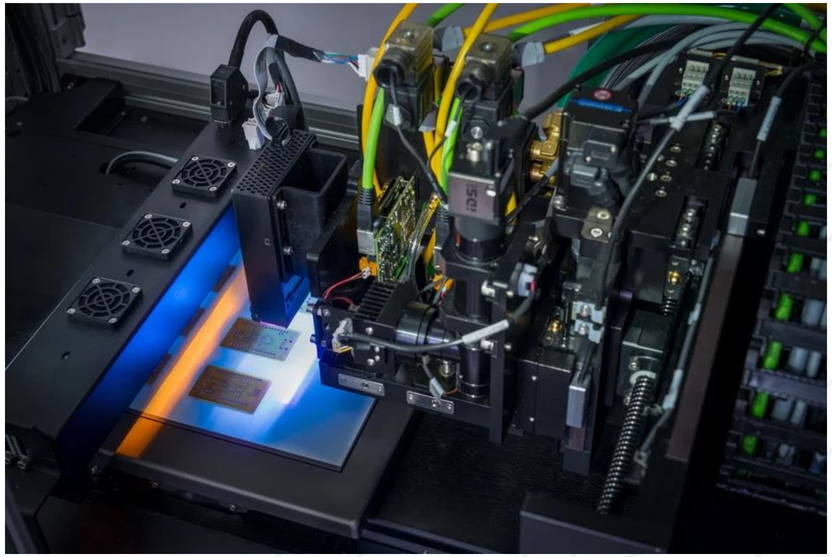
But how it works?

ADDITIVE MANUFACTURING ELECTRONICS (AME) - PROCESS DESCRIPTION

- Inkjet technology that combines UV-cured dielectric material (acrylic monomers) with silver nanoparticles (Ag NP) that undergo sintering upon IR radiation.

  Result in solid objects with highly conductive patterns in shapes unachievable through traditional processes

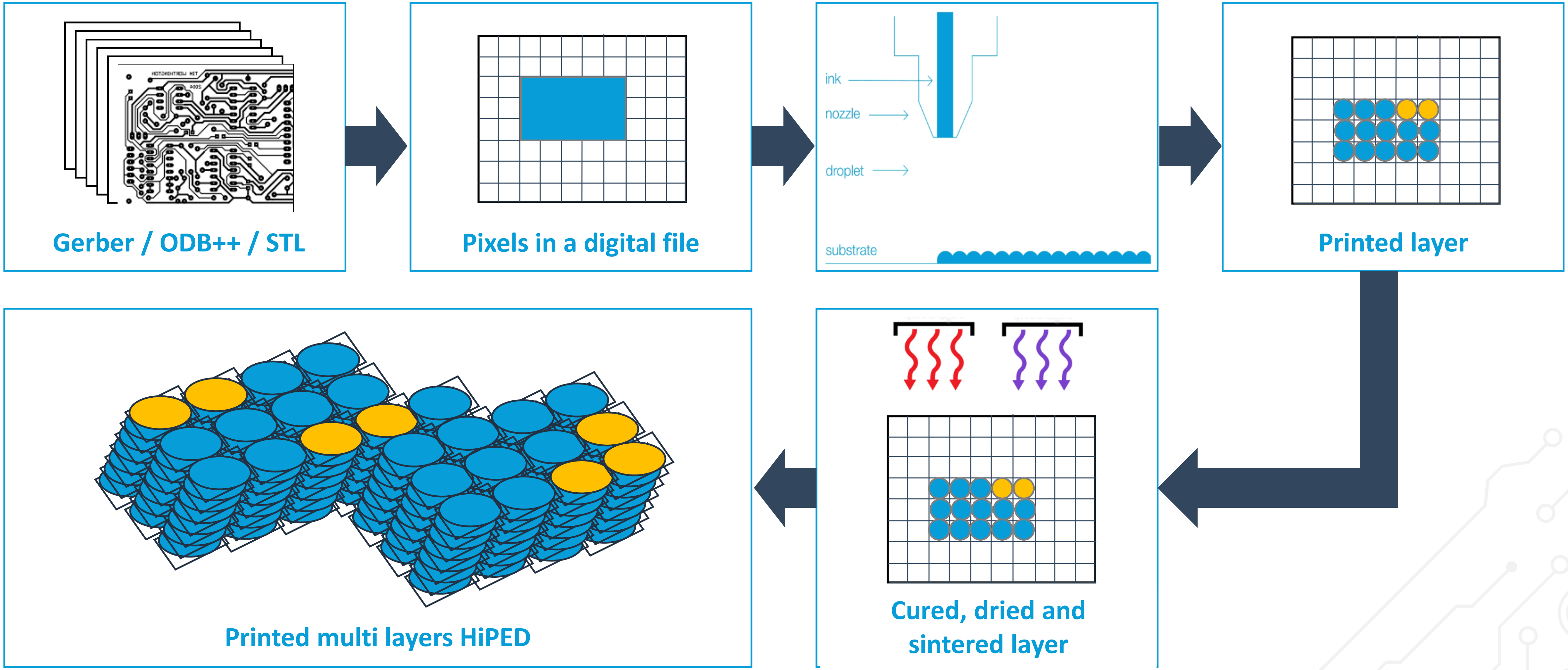




Additive Manufacturing Electronics (AME) - DragonFly

>

From a Digital design file to a Printed Hi-PED



Gerber / ODB++ / STL

Pixels in a digital file

Printed layer

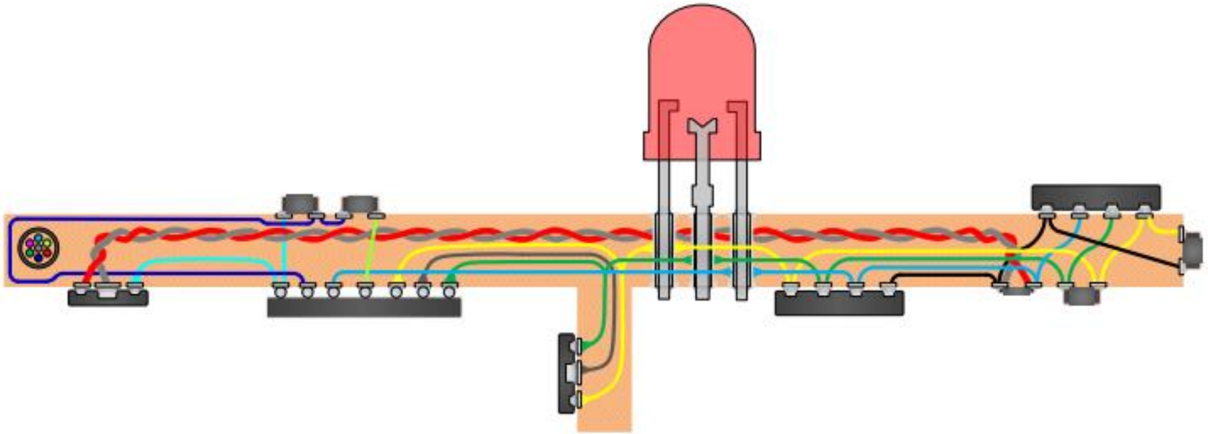
Cured, dried and sintered layer

Printed multi layers HiPED

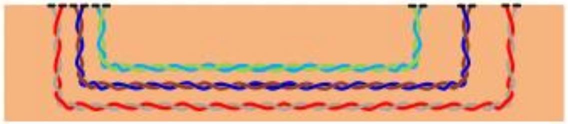
Endless Possibilities

HETEROGENOUS INTEGRATION

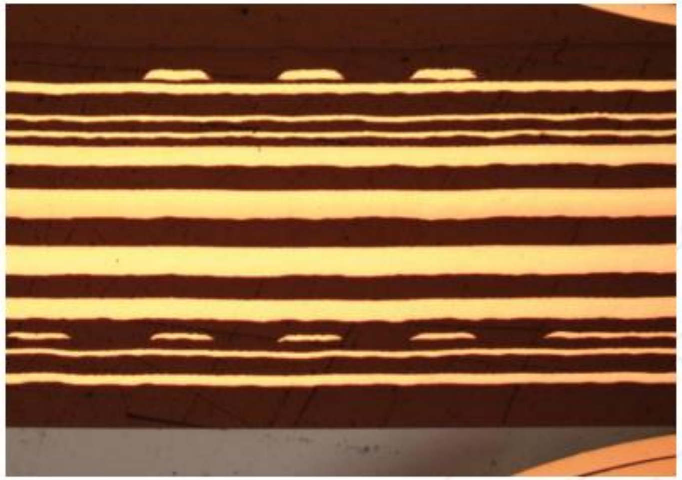
- Free form 3D electro-mechanical designs
- Devices miniaturization/condensation
- Any layer routing
- Any angle routing
- Via-less routing
- “Real” twisted pair routing
- 3D shape routing
- 3D line/spacing
- Printed 3D antennas/coils
- Eliminating loss generators



Twisted pair routing (without vias)



Bus structures (shielding option), equal to harness design

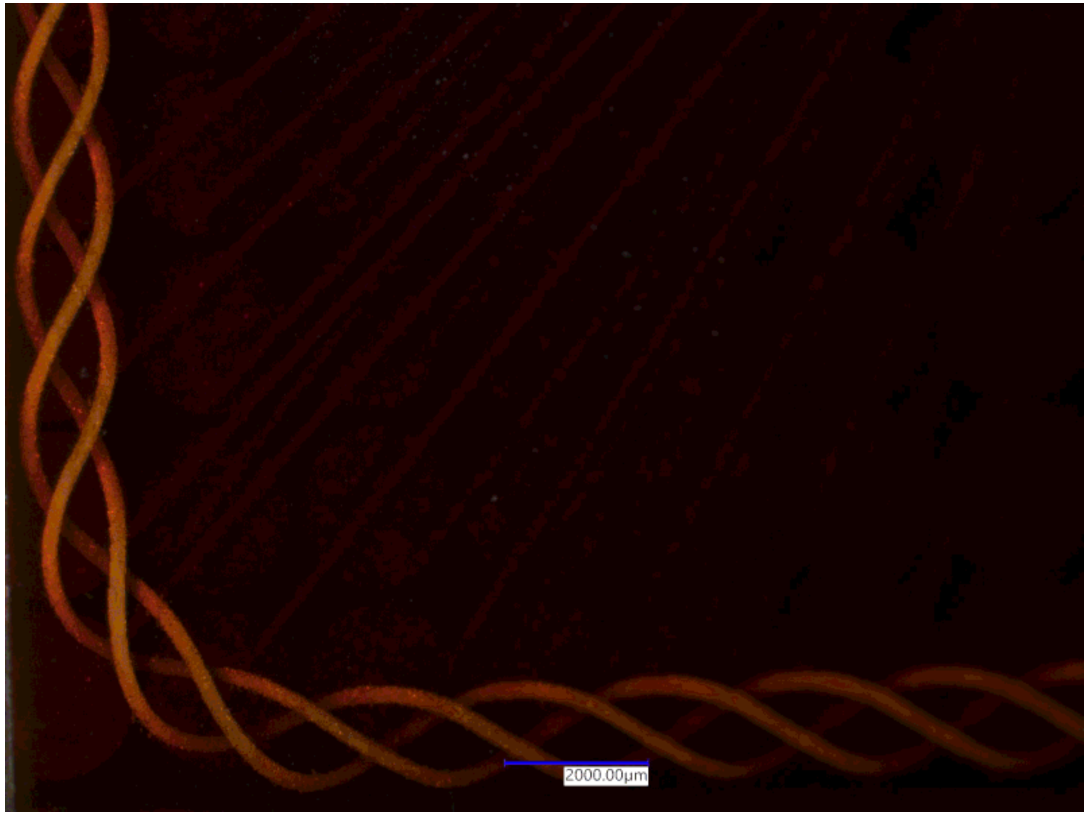


Up to 50 layers

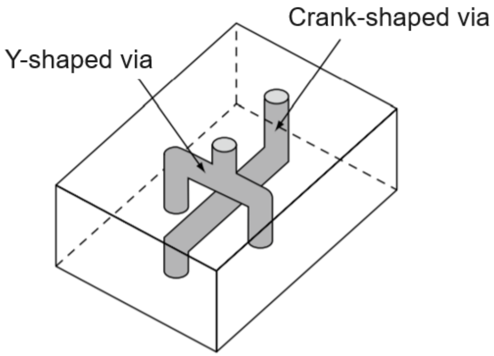
New Design Thinking

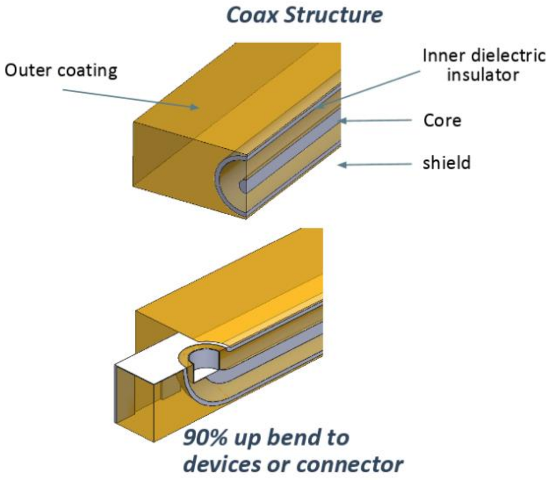
NON PLANAR TRANSMISSION LINES

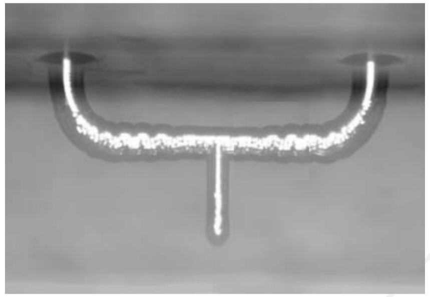
- Coaxials, twisted pairs, waveguides. Freedom of via interconnects

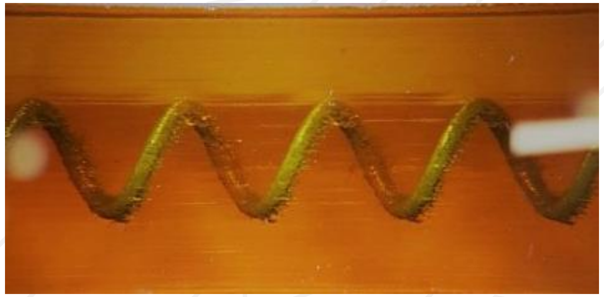


Source: J.A.M.E.S





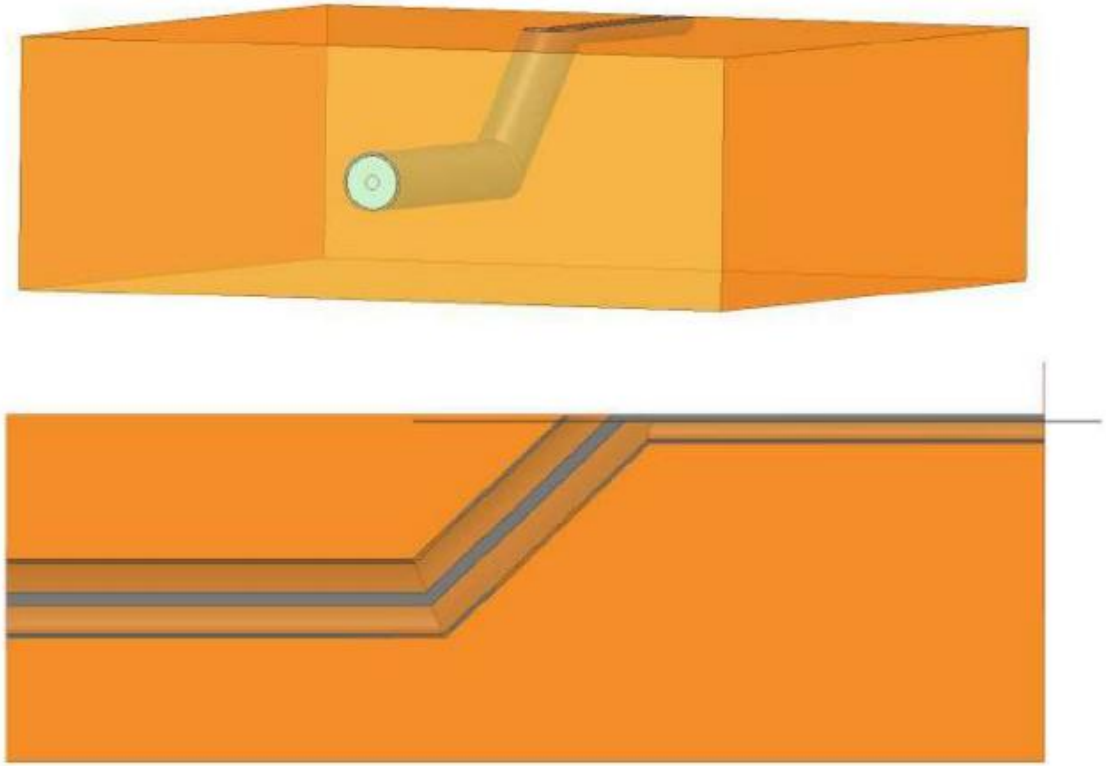


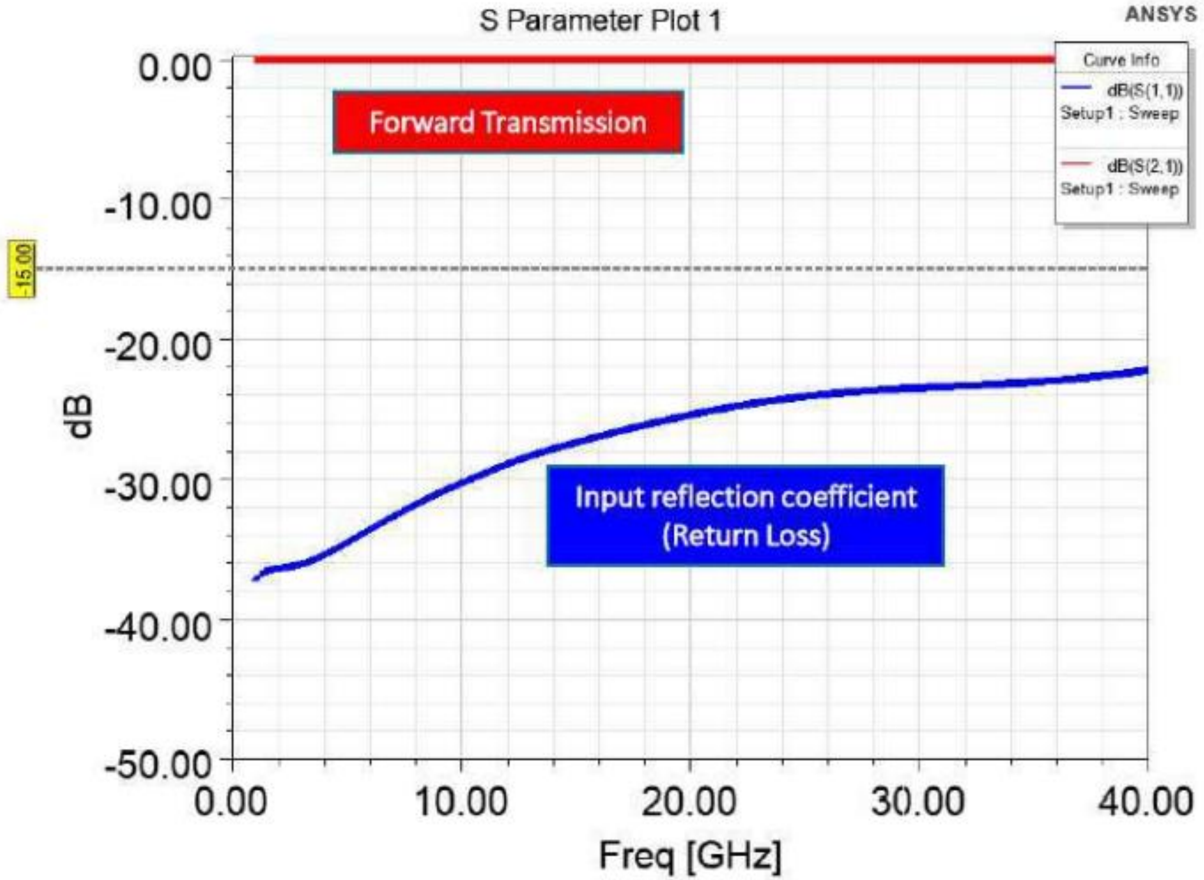


New Design Thinking

3D PRINTED COAXIAL

- Reduced microstrip effects

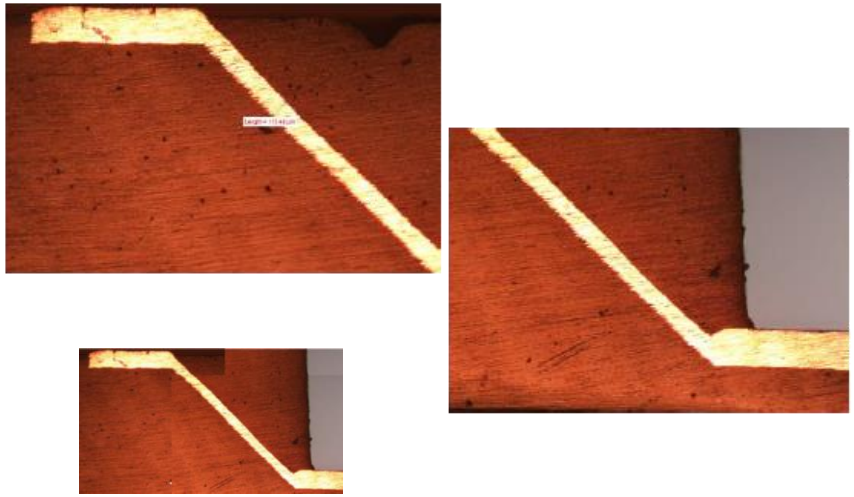




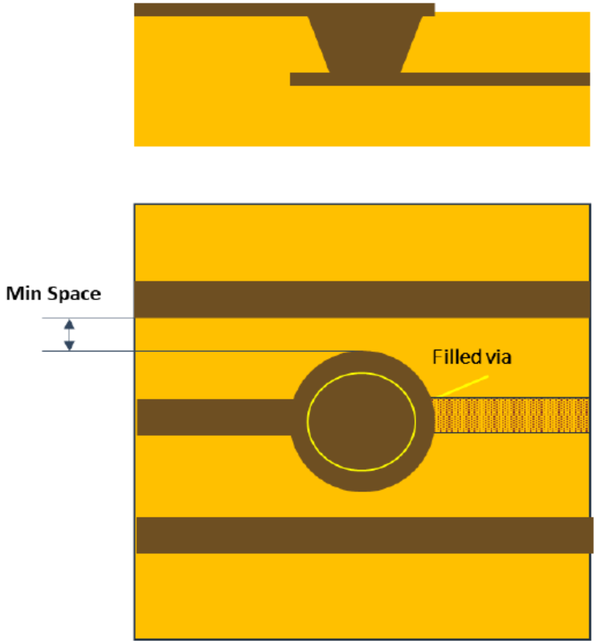
New Design Thinking

HIGHER DENSITY ROUTING

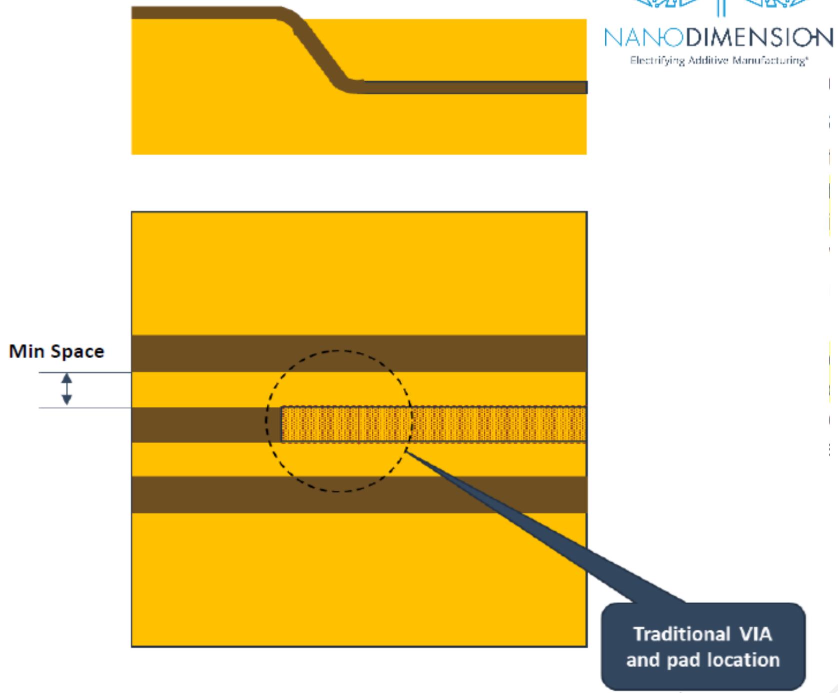
- Homogeneous Z-axis structures allow to 45 degrees vias with increased performance and space reduction

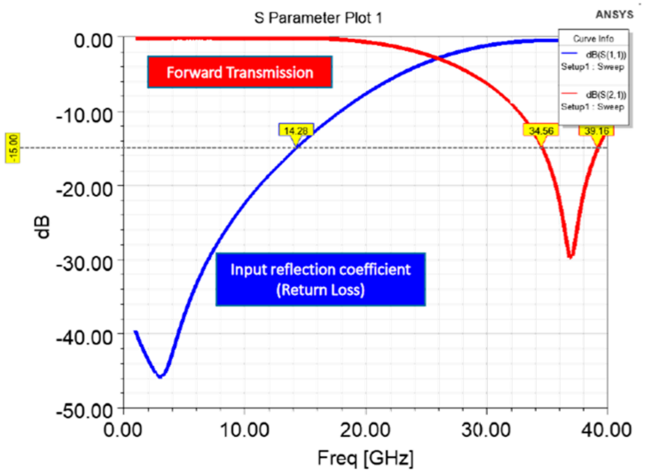


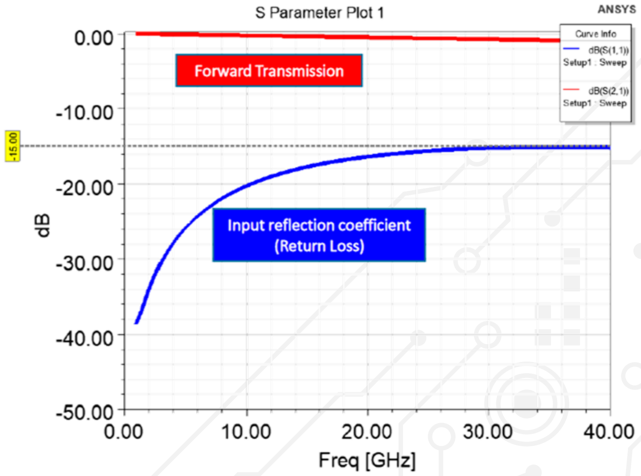
Traditional PCB Process



3D AME Process







Why Now?

DF IV

- Technology maturity: DFIV represents the 4th generation of our AME machine;
- New materials
- AME allows industry players to unleash the next level of innovation!

3D AME Fabrication – End-to-End Solution

- Multi-materials: conductive and dielectric
- Integration of 3D components in PCB
- 3D designed Hi-PEDs (High Performance Electronic Devices)
- FLIGHT SW Suite – enabler for 3D electro-mechanical devices

Support of HDI Level Elements

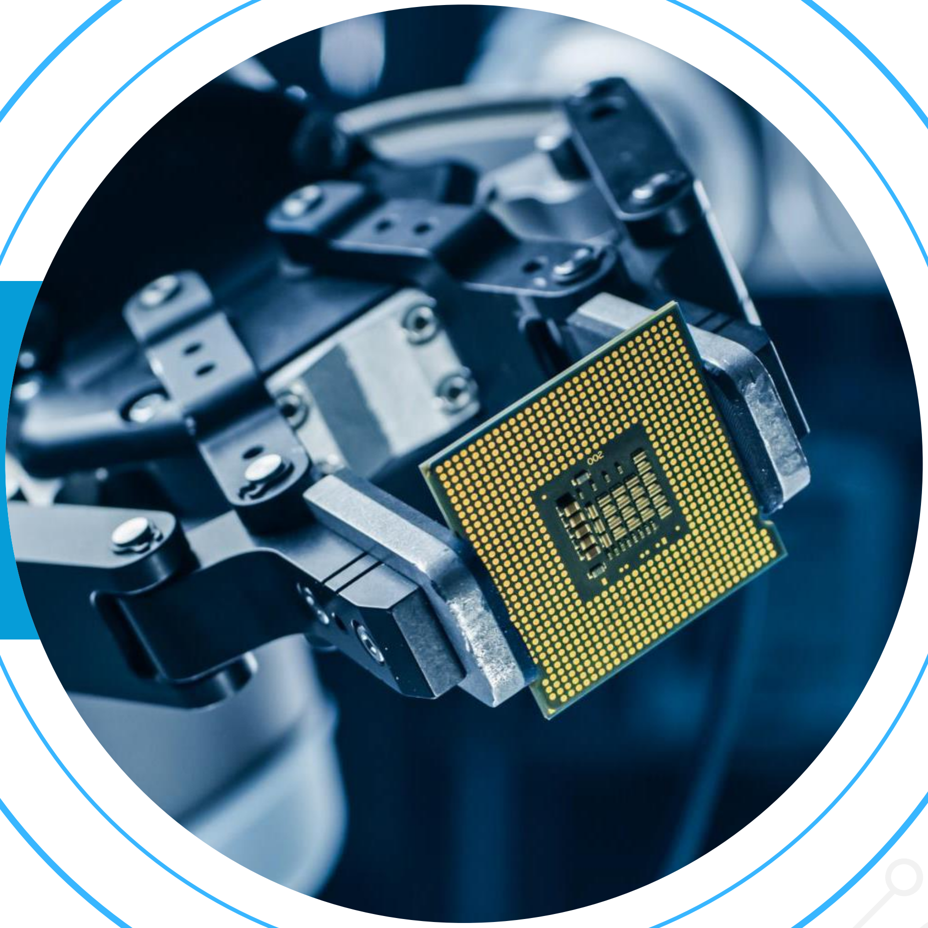
- 75µ traces; 100µm spacing
- 150µ VIA
- 350µm ball pitch

Enhanced Print Process, Optimizing Yield with Predictable Conductivity

- Excellent functional connectivity and structural integrity
- High predictable conductivity (30% ± 5% vs. bulk copper)
- Low thickness variation <5%

DragonFly® IV

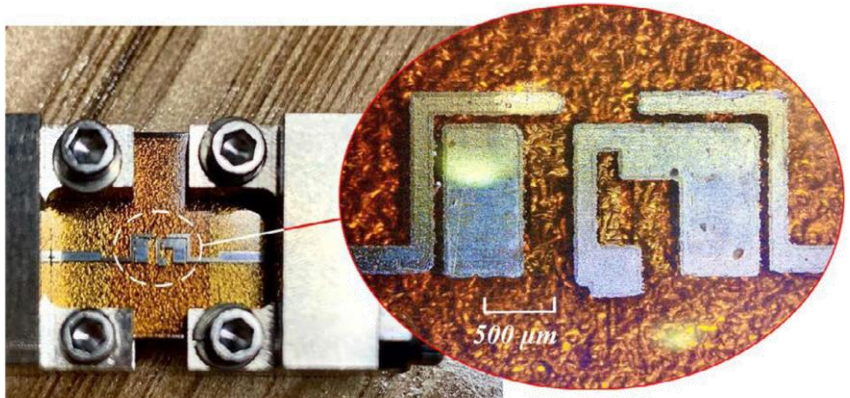
RF components



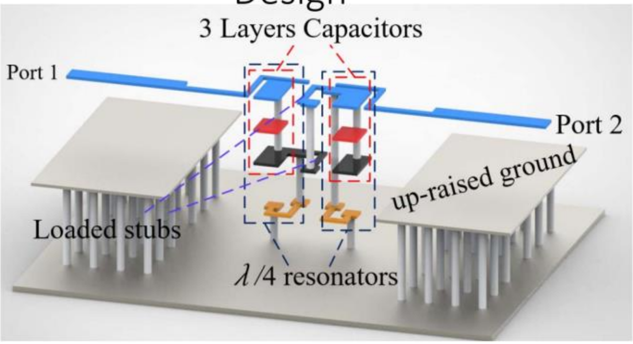
RF Examples

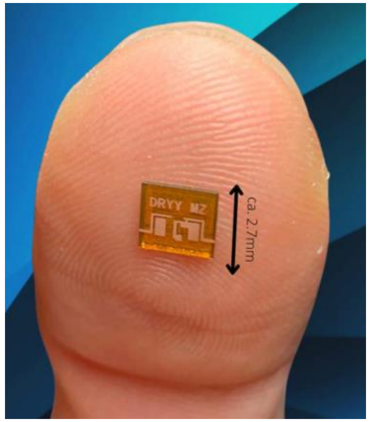
HIGH FREQUENCY FILTERS

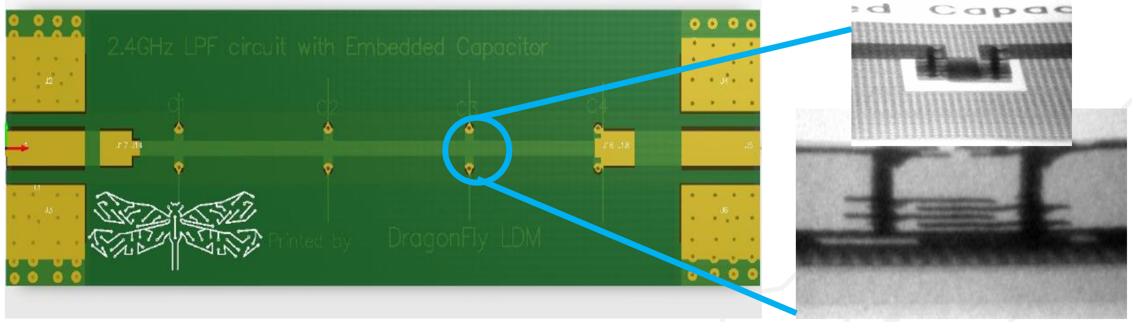
- Complex tuning iterations and extra laser trimming process is replaced by an overnight print



Design



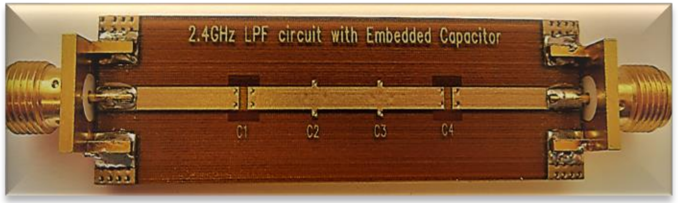




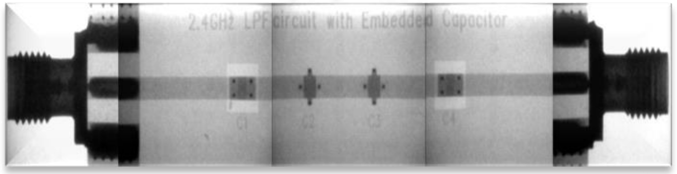
Performance of LPF

LOW PASS FILTER

Printed LPF

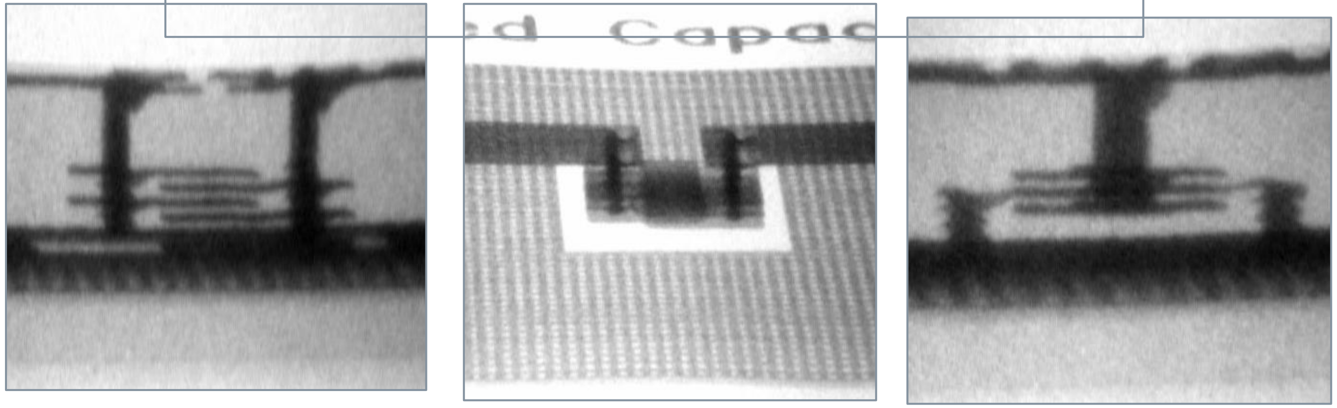


X-ray of printed LPF

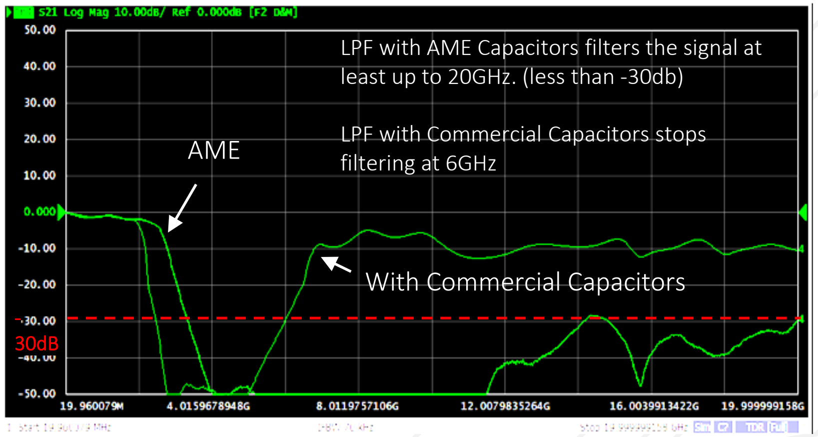


- The AME capacitor and the strip line can be placed on any layer or on different layers in the AME board whereby:
  - Increasing design board flexibility.
  - Maximizing area / volume utilization.
  - Mounting other components on the board to reduce the total size of the electronic board.
- AME capacitors exhibit a tolerance accuracy value of less than 1.5%, compared to 5% offered by off-the-shelf SMD capacitors. Therefore, AME boards with AME LPF devices offer superior stable capacitance characteristics.

X-ray of LPF capacitors and transmission strip lines



S21 - AME transmission and capacitors vs AME transmission with SMT commercial capacitors



LPF with AME Capacitors filters the signal at least up to 20GHz. (less than -30db)

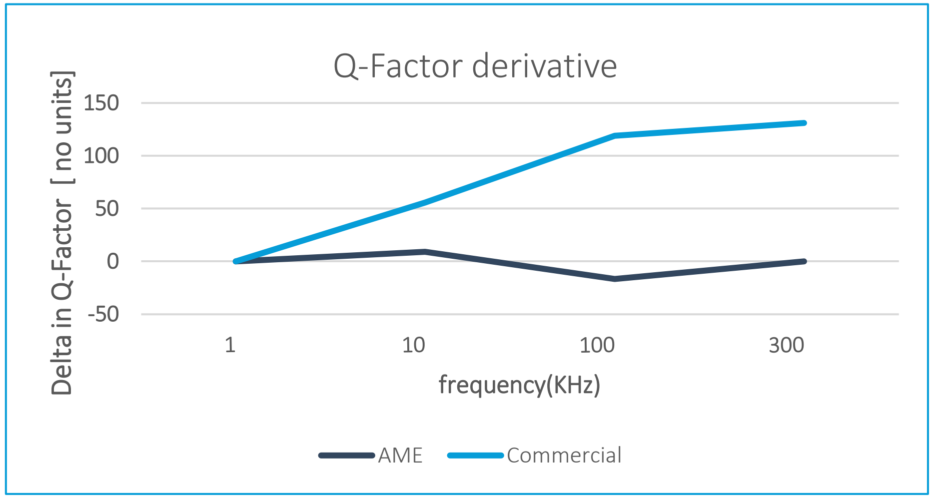
LPF with Commercial Capacitors stops filtering at 6GHz

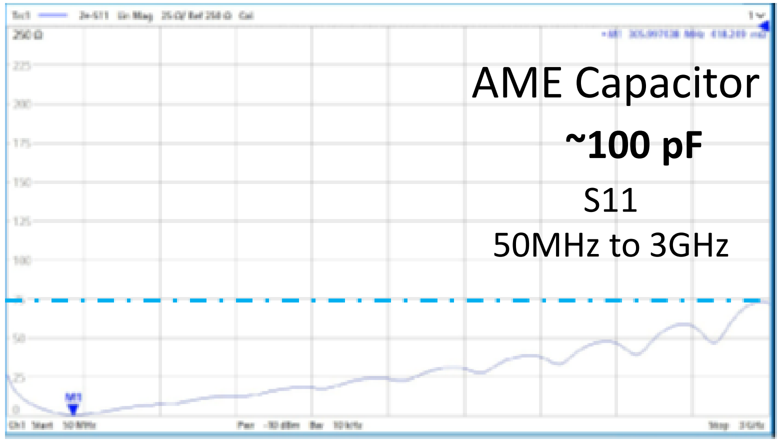
Performance of AME Capacitors

DC PERFORMANCE SUMMARY

Capacitance Range	0.1nF to 3.2 nF (at 25C)
Capacitance Variations	<1.5%
Leakage current	<1pA
Break down voltage	>1 kV
Temperature stability factor	25C-95C: 0.2 [%/C], 95C-125C: 0.4 [%/C]

Better Performance than Ceramic SMT Capacitors by Elimination of Soldering and Package

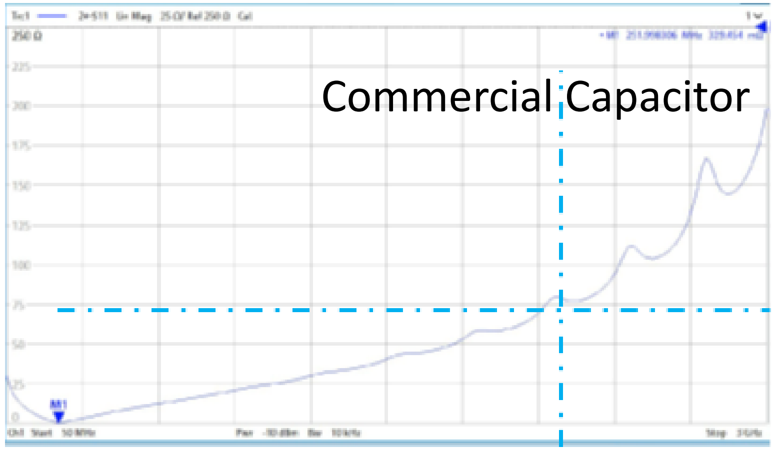


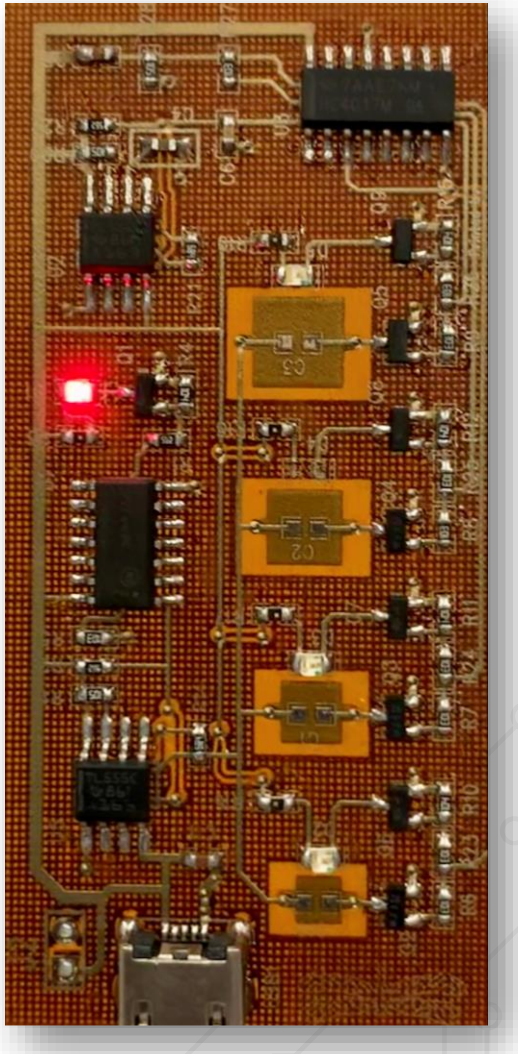

AME Capacitor

~100 pF

S11

50MHz to 3GHz


Commercial Capacitor

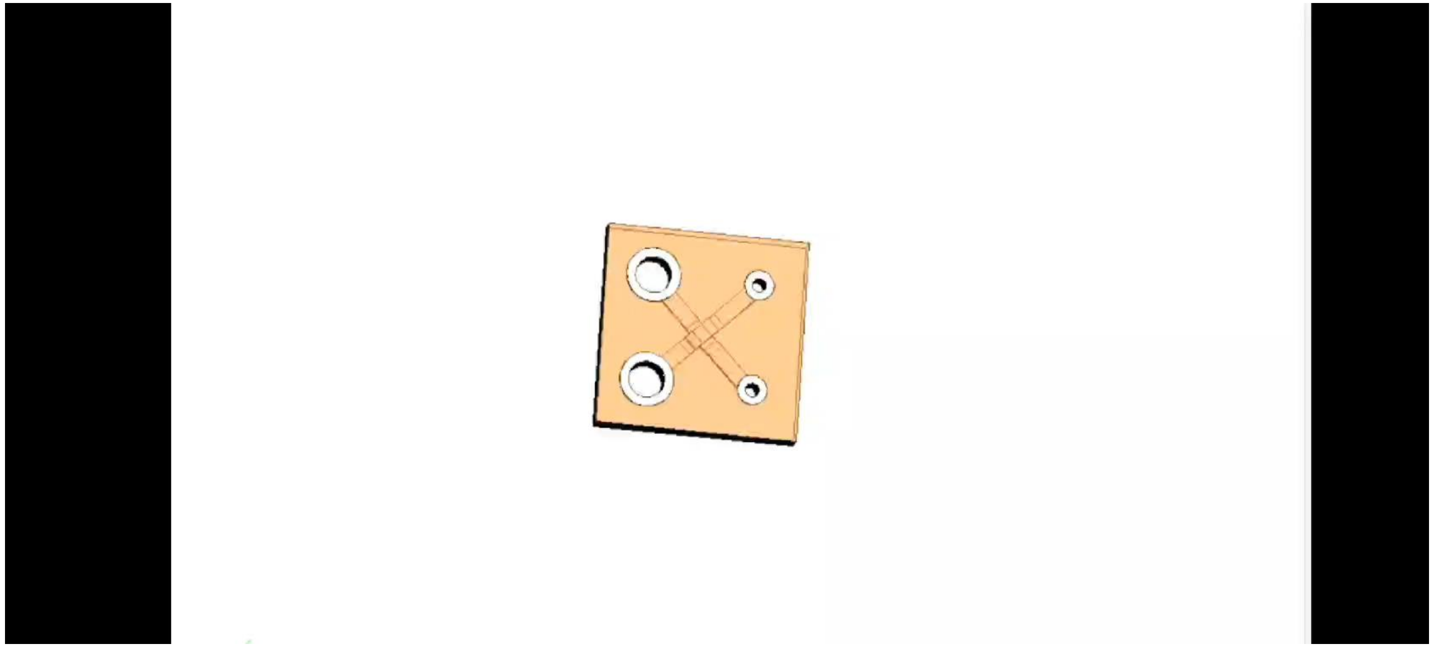


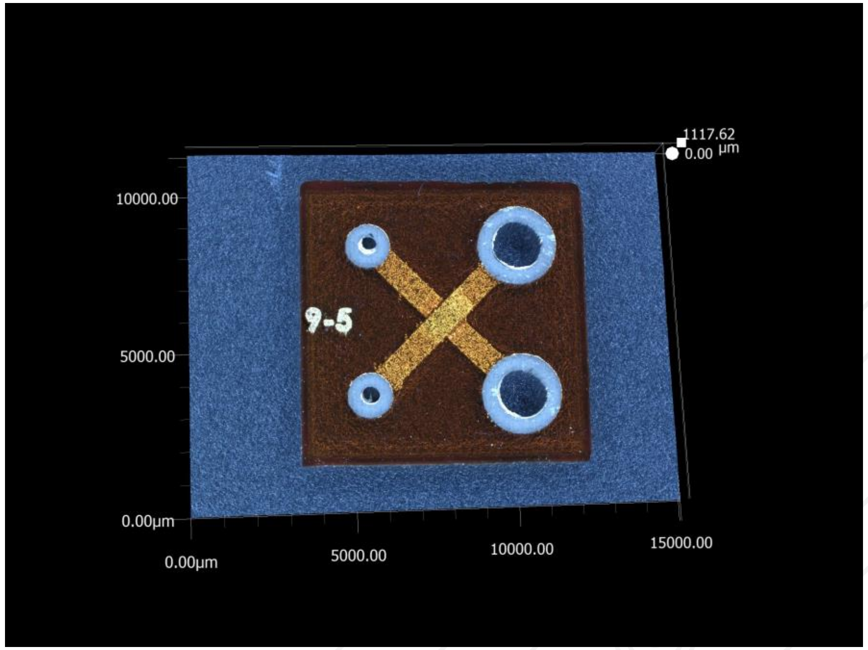
D. Sokol, M. Yamada, J. Nulman, "Design and Performance of Additively Manufactured In-Circuit Board Planar Capacitors," IEEE Transactions on Electron Devices, 2021, Digital Object Identifier: 10.1109/TED.2021.3117934

RF Examples

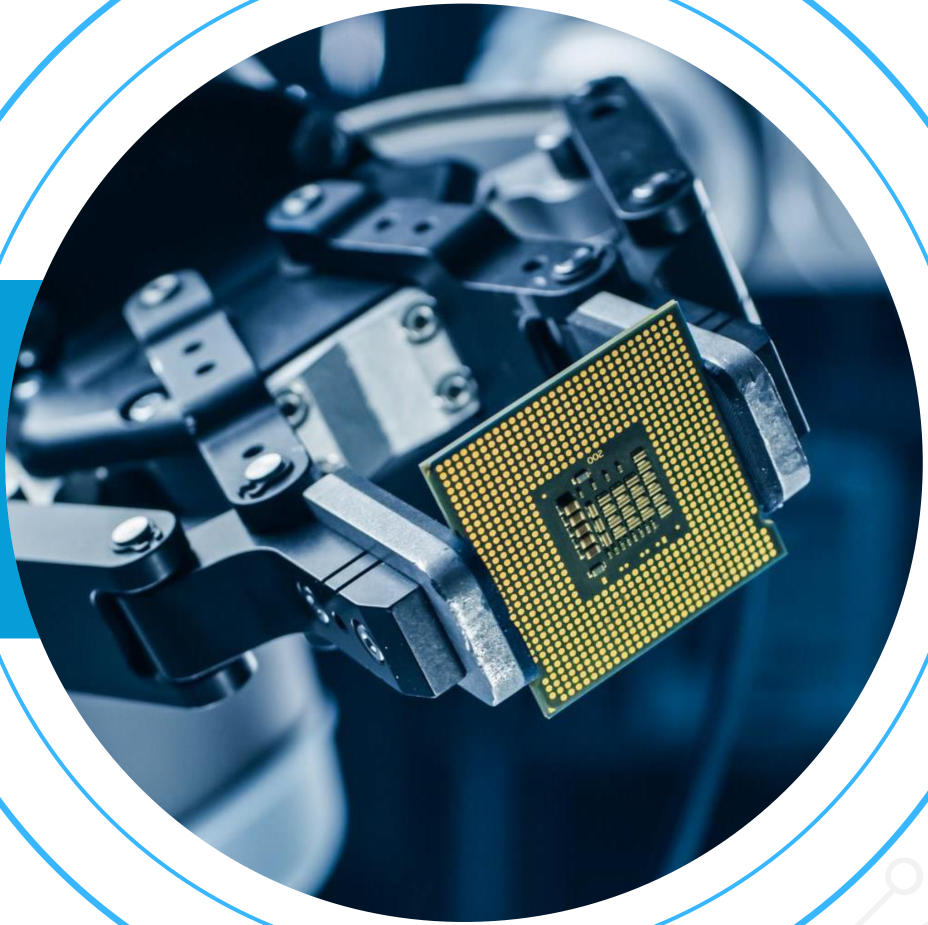
RF CROSSOVER

- The 3D AME hybrid structure is crucial for RF signal distribution in antenna applications. It utilizes a 3-dimensional crossover RF design and RF simulation for optimal performance.





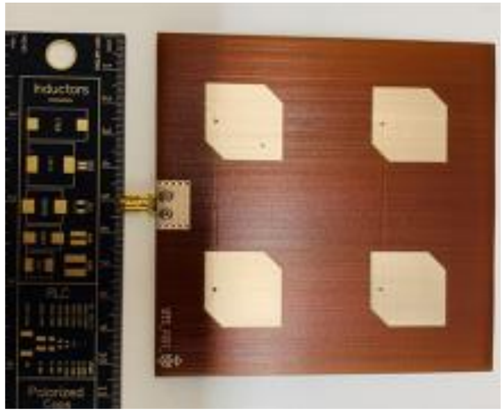
Innovative Antennas and Arrays



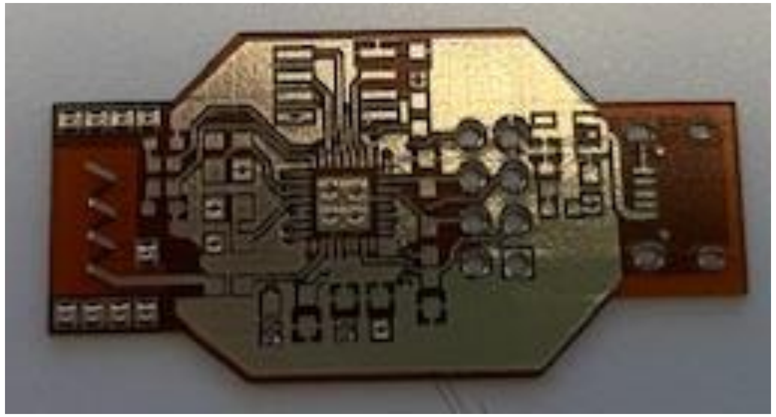
New Design Thinking

3D-PRINTED ANTENNAS AND RESONATORS

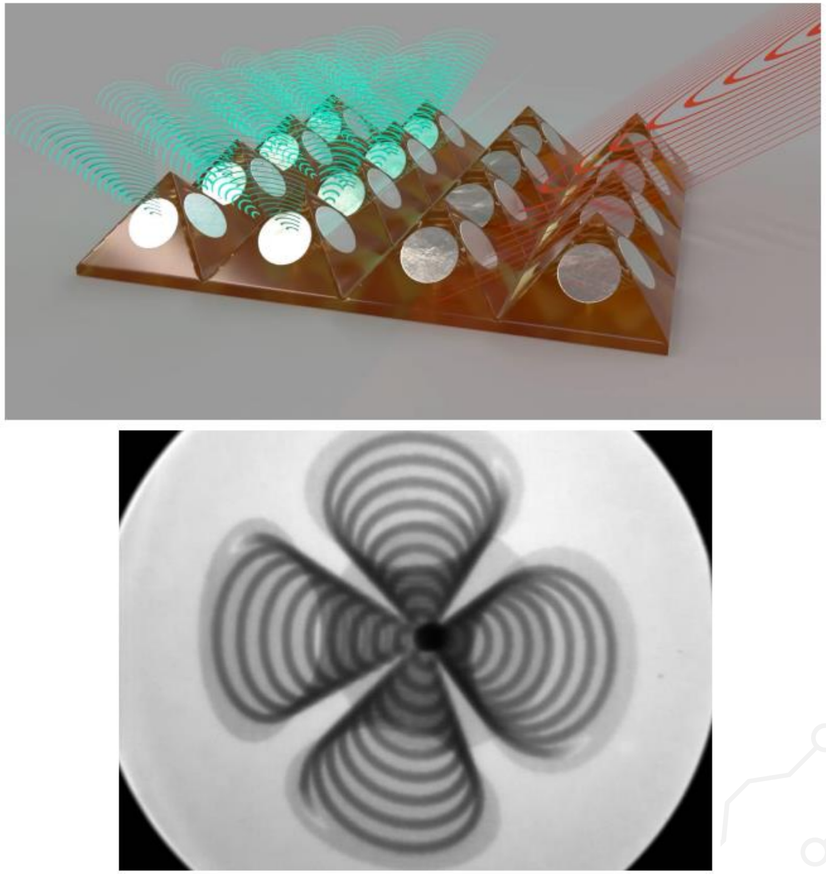
- AME technology is an enabler for new designs of antennas
- Design freedom in the 3D space enables unique antennas such as: Omni directional antennas, coils antennas, special shaped phased-array antennas, etc.



Multilayer Array of Stacked Patches



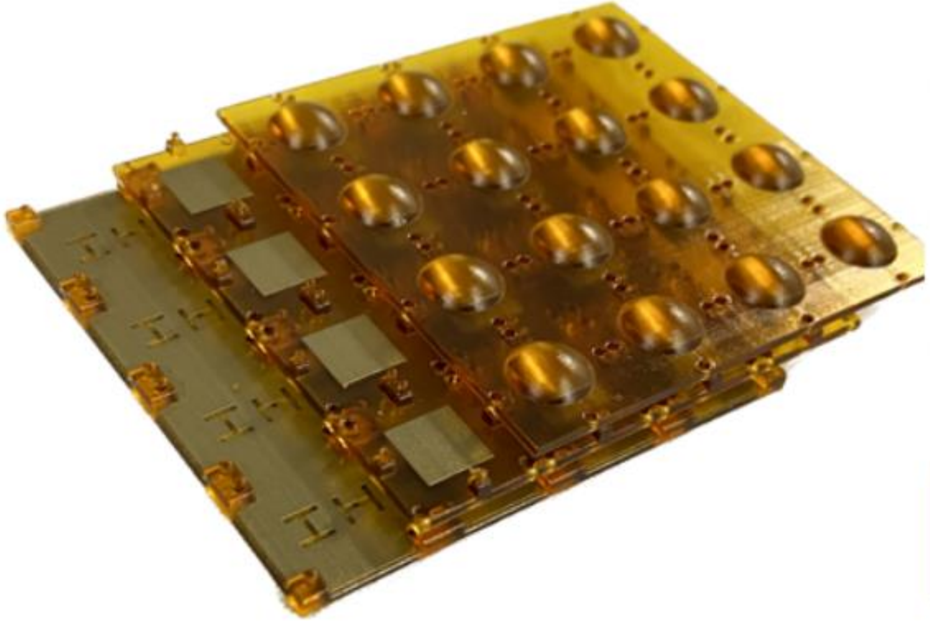
Metamaterial Antenna



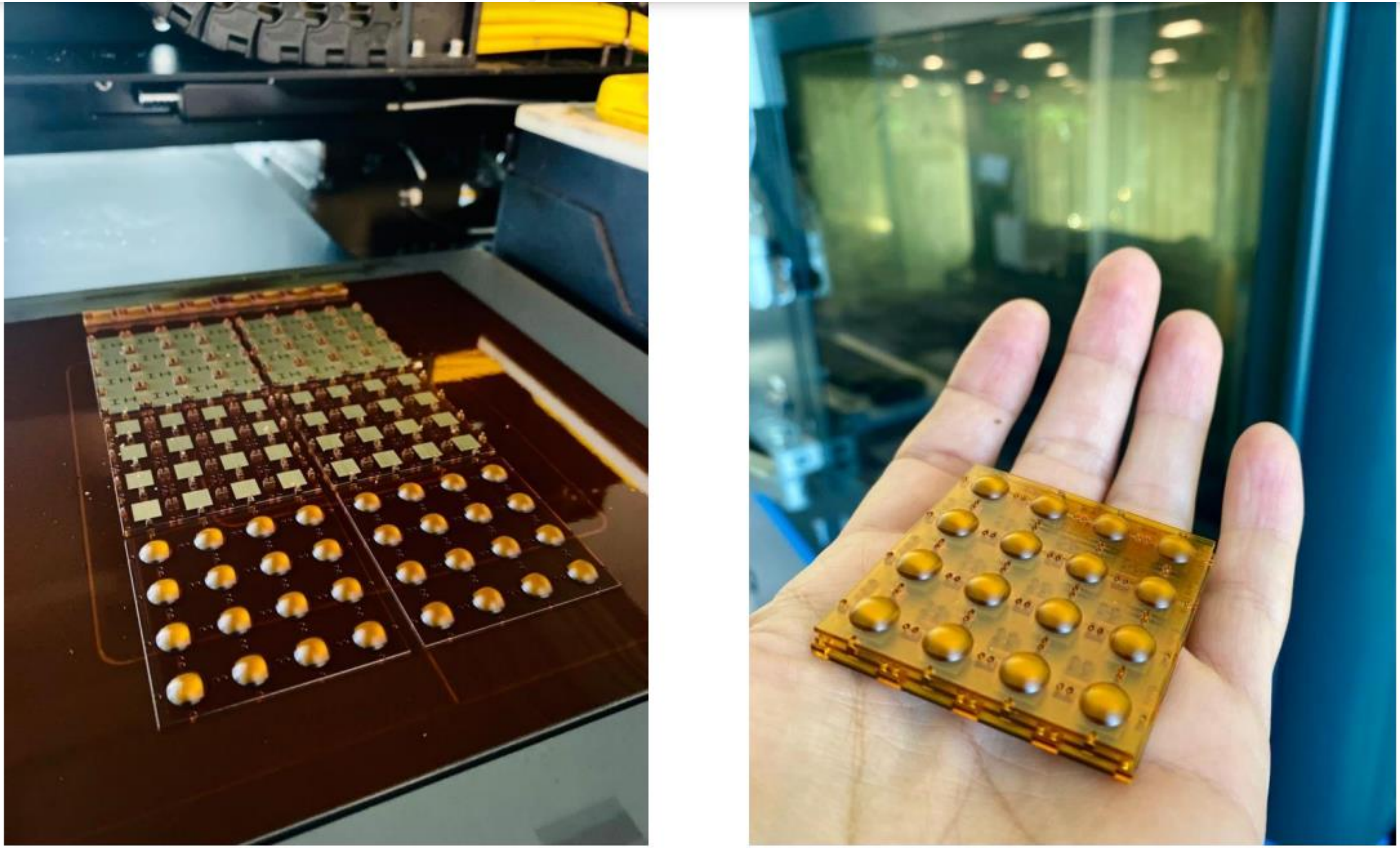
Phased array Antenna

AME X-Band Dual-Polarized Stacked Patch Phased Array Antenna with Dielectric Lens

Phased array antennas are very sophisticated radiating structures which are costly and time consuming to prototype. An AME X-Band (10GHz) stacked patch antenna has been designed in 3 boards that put together via lego-like structures printed in between boards. Air dielectric provides minimum loss. Splitting geometry in 3 parts significantly reduces the print time.



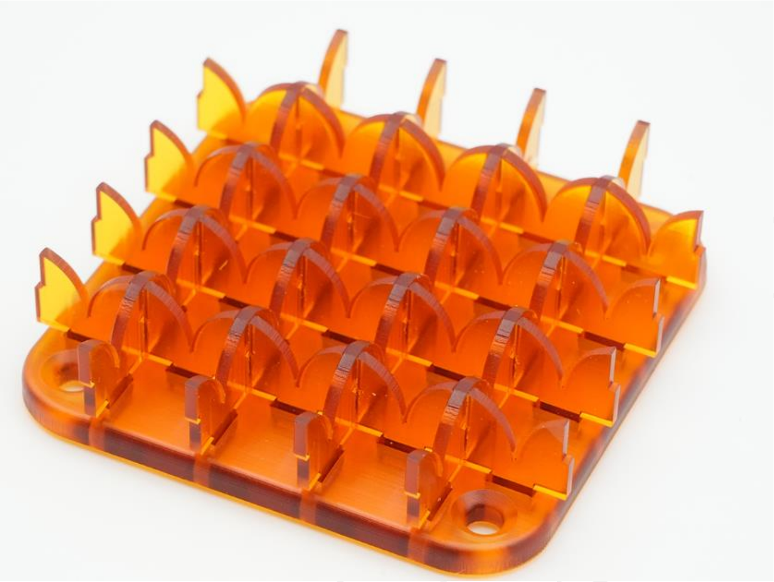
Application	Radar, 5G/mmWave Networks
Design Consideration	Air spaced stacked patch antenna boards, LEGO-like assembly, hemispherical dielectric lens for wide angle scanning optimization
Sample Features	50mm square, 6mm overall thickness
Printing Time	9 hours
Ink Consumption	0.4ml CI, 7.7ml DI



RF Examples

AME ANTENNA ARRAY CONCEPT

- The assembly of RF-PCBs often requires special care, with time-consuming manual mountings and a large number of screws that must be positioned precisely. One goal of this AME design concept is to simplify assembly by using a 3-dimensional but flat formfactor for radiation elements and an RF-distribution motherboard.
- Direct-printed coaxial wires can distribute RF-transporting signals while preserving signal integrity and power, thus avoiding connectorized interfaces.



RF Examples

CONFORMAL ARRAY

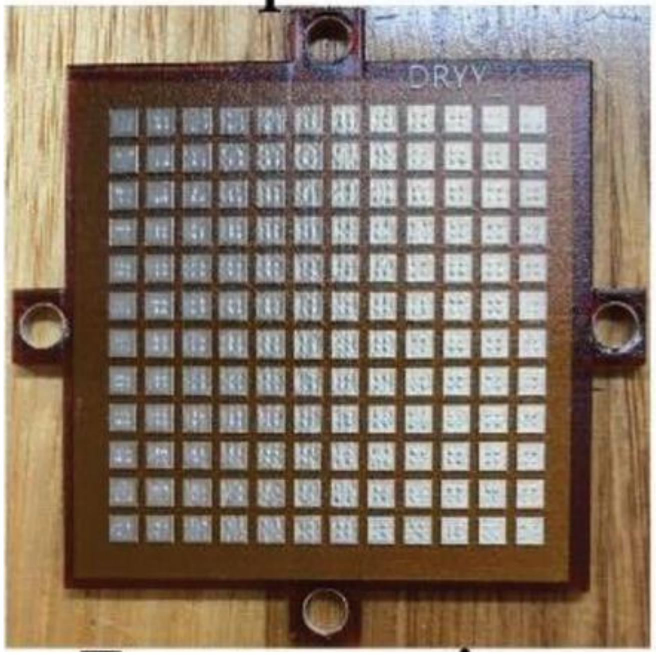
- Conformal antenna arrays have many benefits, including improved radiation patterns and wide angle scanning. This flexible conformal aperture coupled antenna array was 3D printed in under 6 hours.

RF Examples

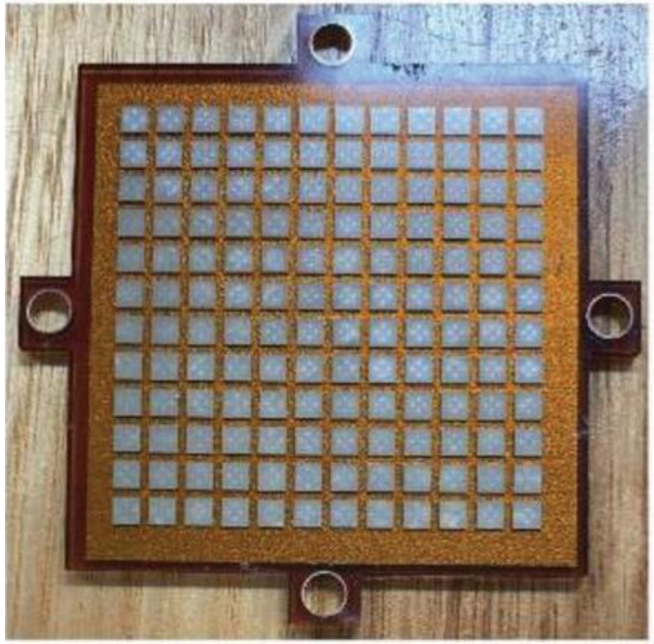
METAMATERIALS AND METASURFACES

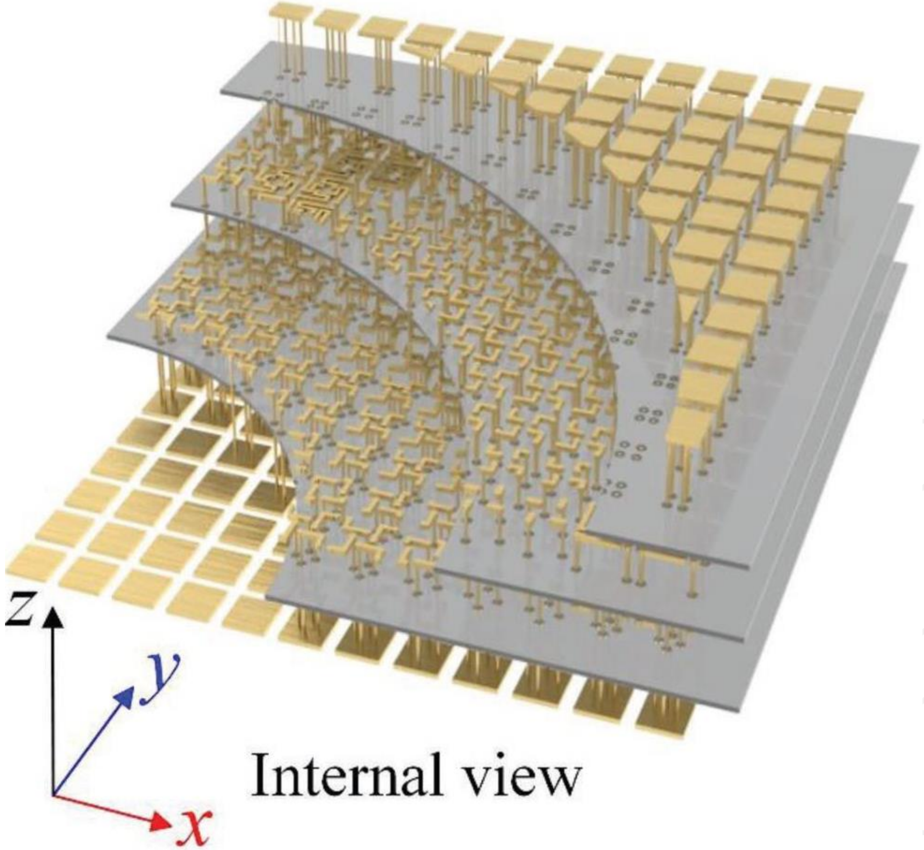
- Additively Manufactured Polarization Insensitive Broadband Transmissive Metasurfaces for Arbitrary Polarization Conversion and Wavefront Shaping

Top view



Bottom view



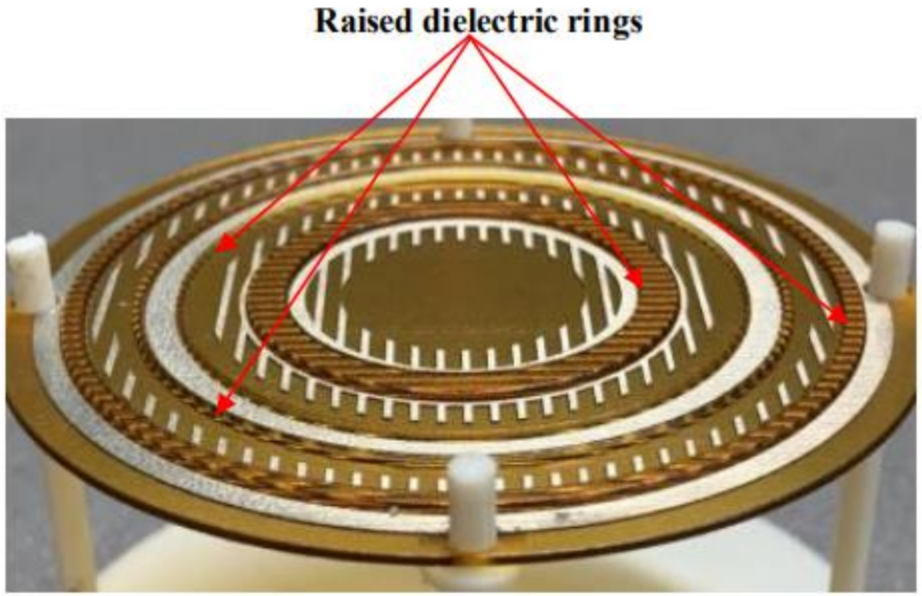


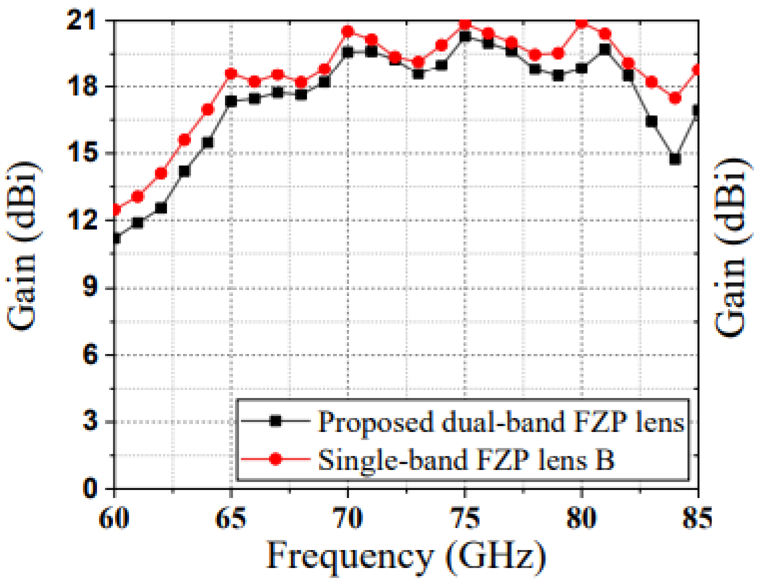
Internal view

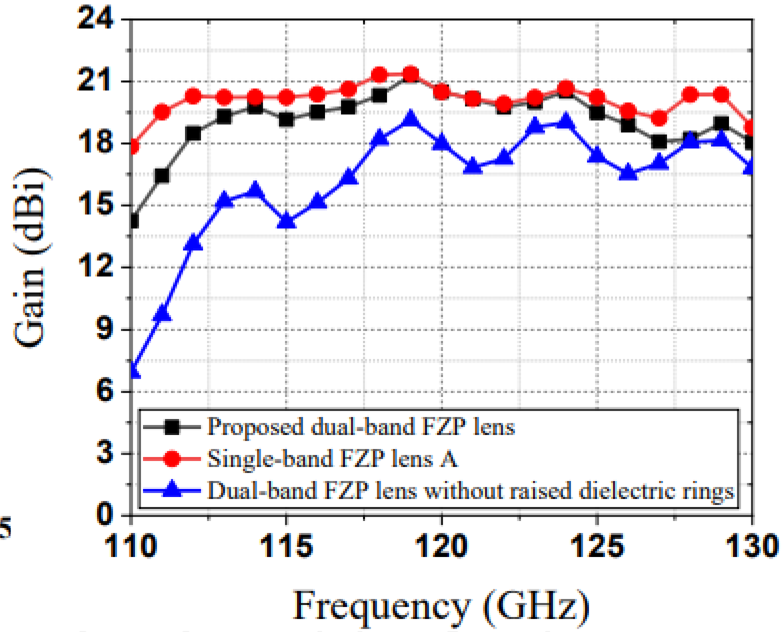
RF Examples

DUAL BAND METALENS ANTENNA

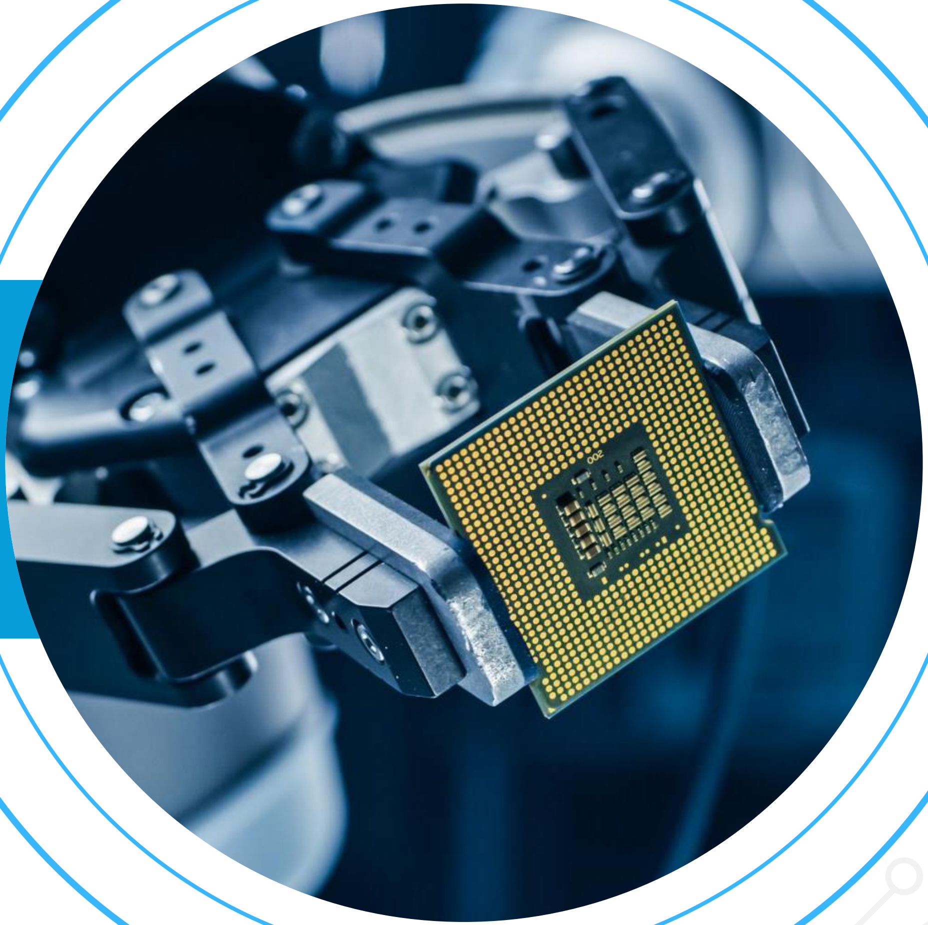
- Additively Manufactured Millimeter-Wave Dual-Band Single-Polarization Shared Aperture Fresnel Zone Plate Metalens Antenna
- Measured peak gains of 20.3 dBi and 21.9 dBi @ 75 GHz and 120 GHz







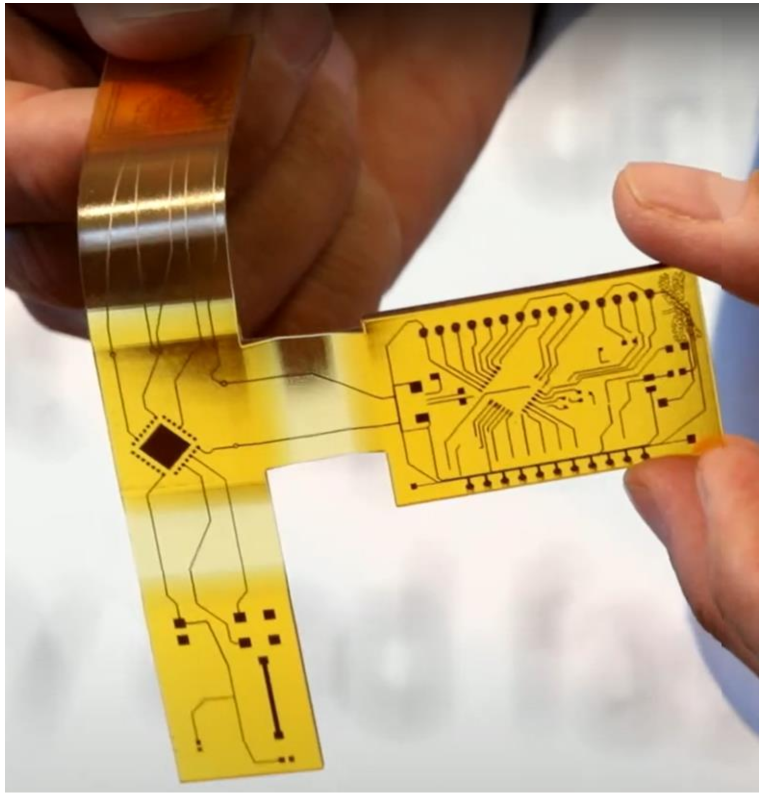
Flex and Flex-Rigid boards

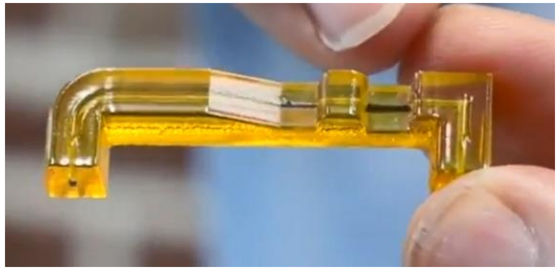


New Design Thinking

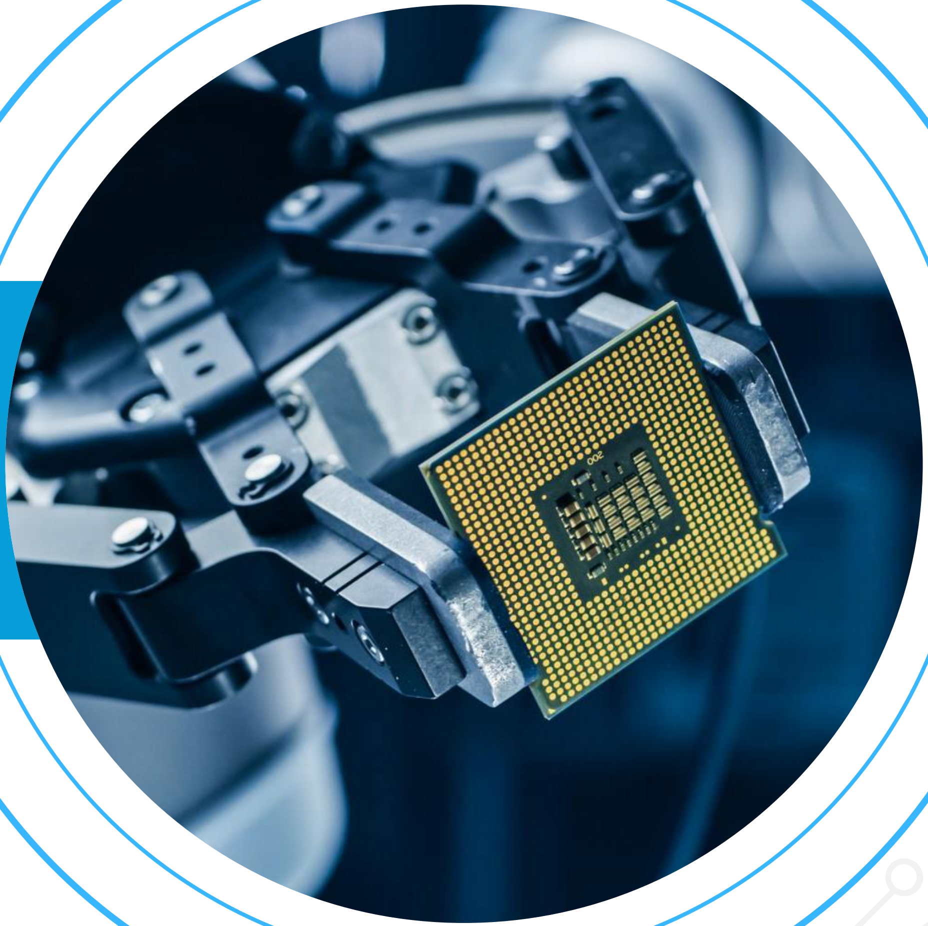
FLEXIBLE AND FLEX-RIGID STRUCTURES

- Flexible structures
- Flex-rigid assemblies
- MID (Molded Interconnect Devices)





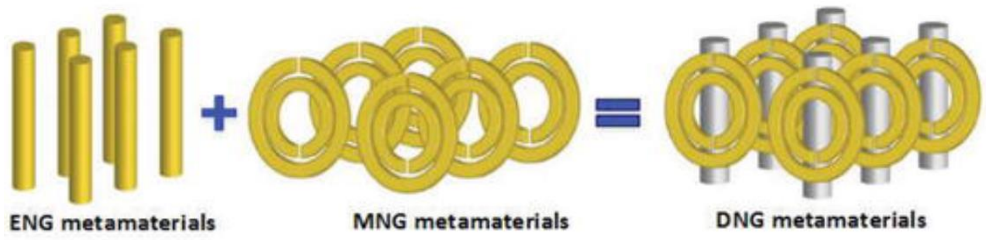
Outlook on future developments (new design thinking)

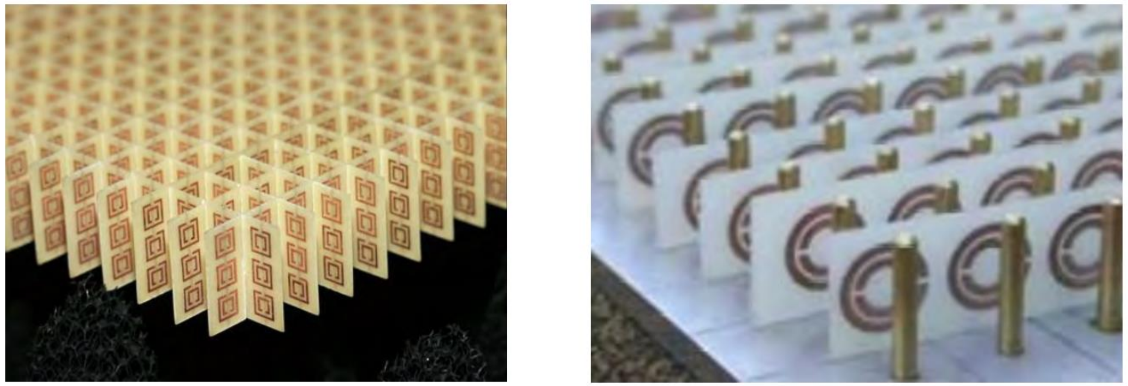


New Design Thinking

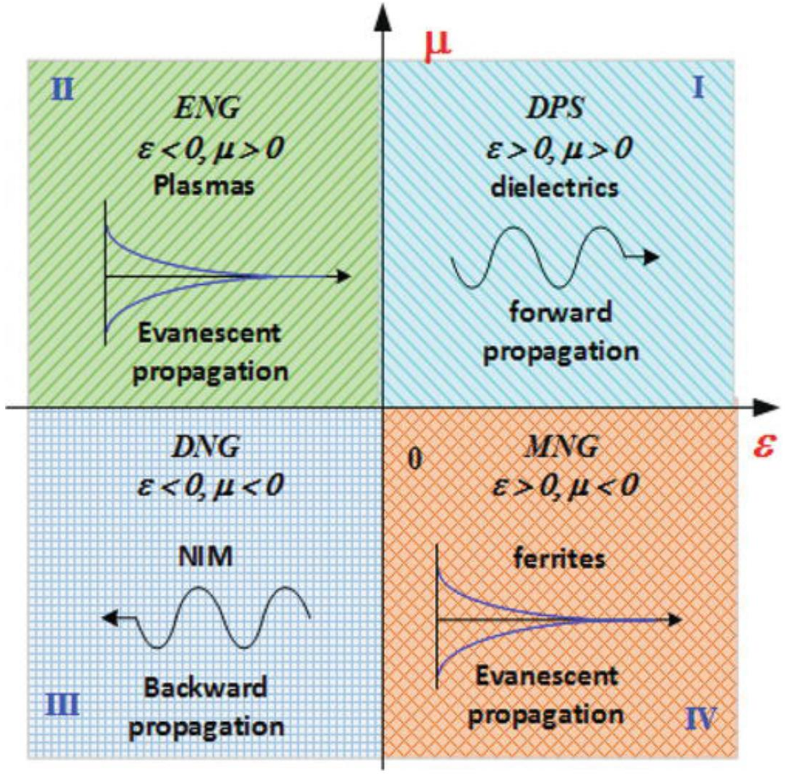
3D-PRINTED METAMATERIALS

- Conventional technologies rely on time consuming precise assembly
- AME is an enabling technology for agile design of 3D metamaterials with isotropic or quasi-isotropic behavior





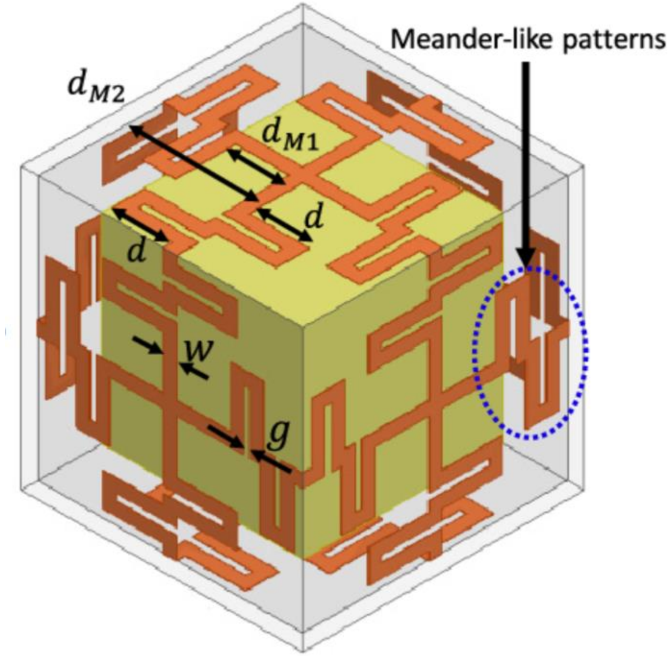
Conventional technologies

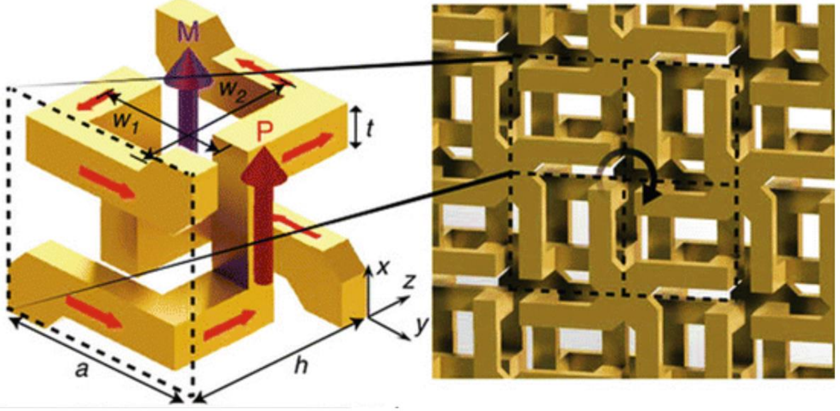


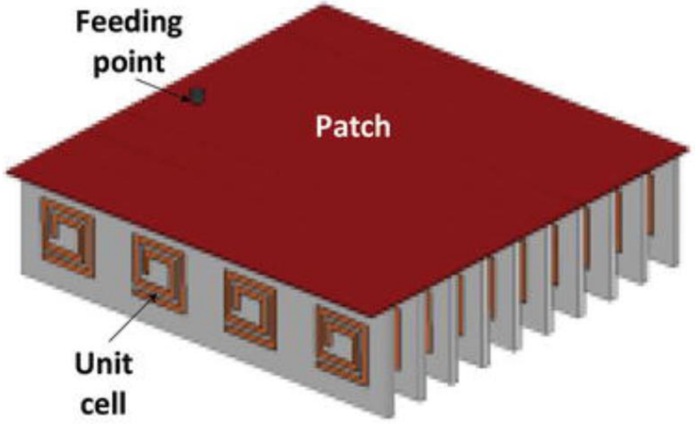
New Design Thinking

3D-PRINTED METAMATERIALS

- 3D Metamaterial cells and structures possible with AME:



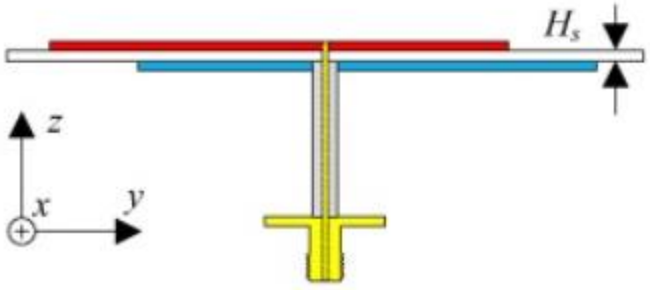


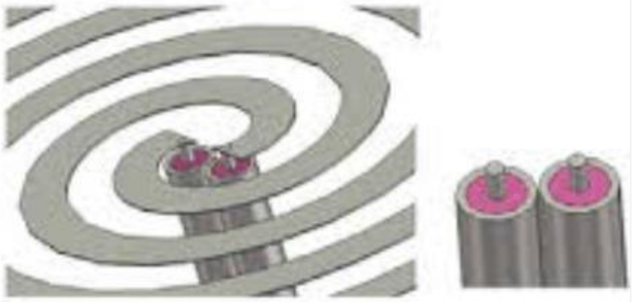


RF Examples

ARCHIMEDEAN SPIRAL ANTENNAS

- Feeding point is in the center of the spiral
- Normally a coaxial is used to feed the antenna
- Low profile design (z) are not possible





Self-complementary Archimedean Spiral

Self-complementary 4-arm Archimedean spiral antenna

Planar logarithmic spiral antenna

4-arm Sinuous antenna

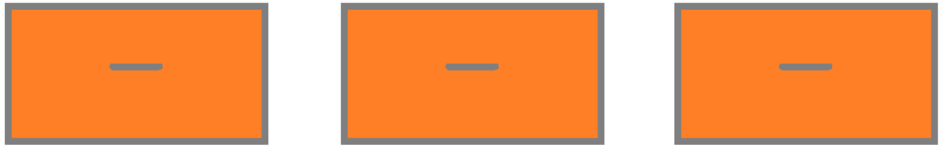
RF Examples

AME SOLUTION

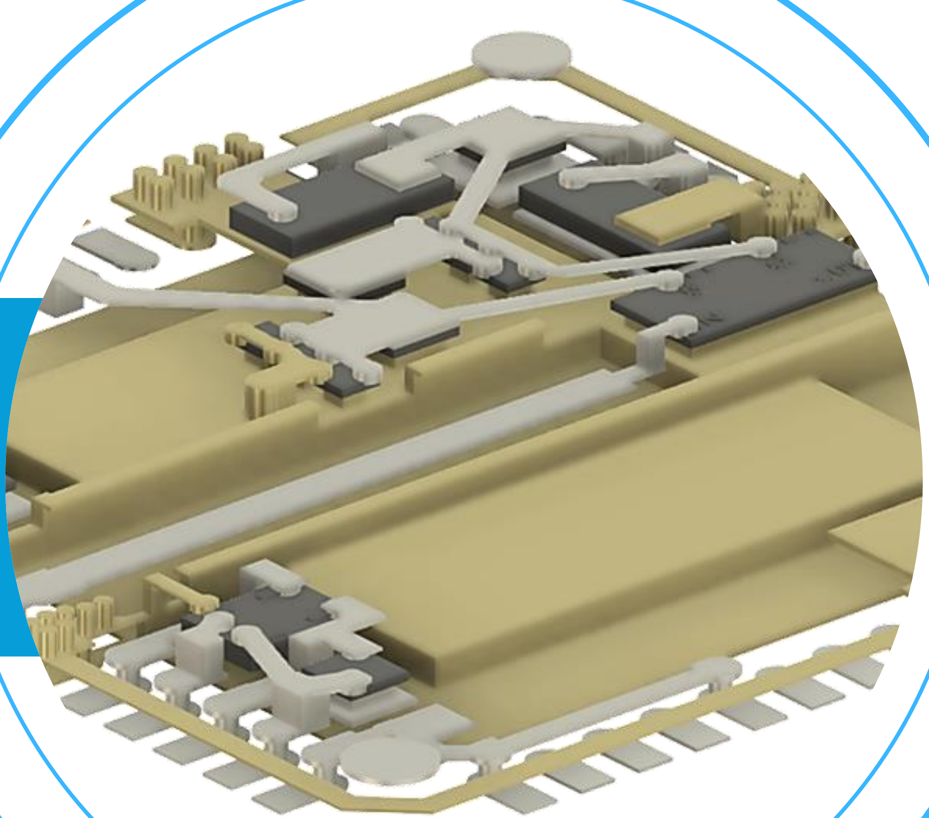
- Embedded stripline within the spiral metallization!

Spiral section

AME solution



RF Power Amplifier Board



RF Power Amplifier Board

L3HARRIS TECHNOLOGIES

- 3D printed functional RF amplifiers.
- Size:101mm x 38mm (4” x 1.5”) x 3mm thick circuit
- Print time: 10 hours.
- Materials: Silver nanoparticle conductive and dielectric inks were used for the functional electronic parts in a single print
- Components were manually soldered to the PCB.

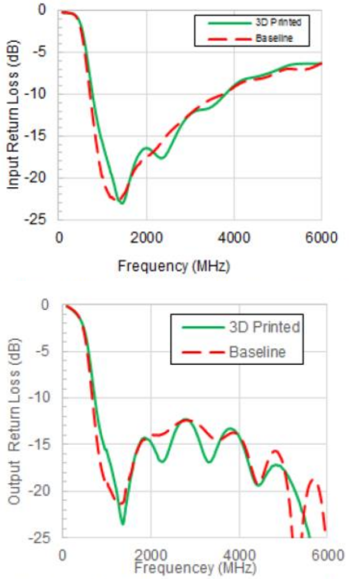


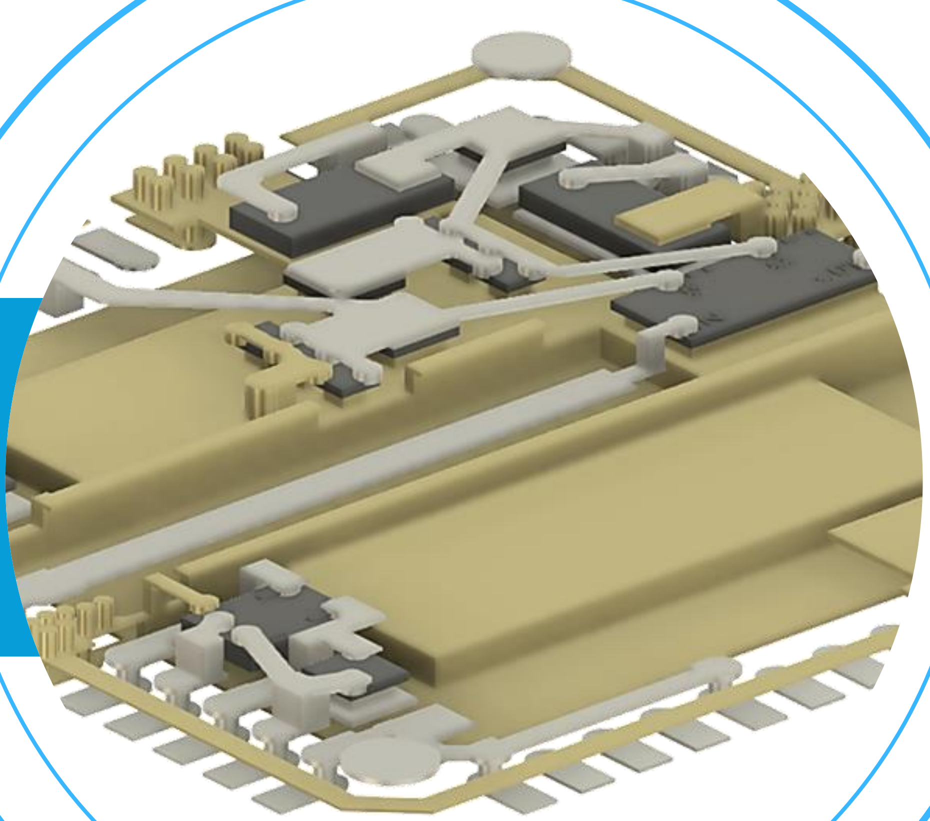
Figure 4. Amplifier return loss (output) comparison: 3-D printed and conventionally manufactured amplifiers.

Test results compared to conventional amplifiers

- No noticeable difference in the input or output return loss response over the frequency range from 10 MHz to 6 GHz.
- No noticeable difference detected in the gain of the 3D printed circuit and the conventionally manufactured amplifier. The gain difference between the 3-D printed circuit and the conventionally manufactured circuit was less than 1 dB up to 4.7 GHz and less than 1.3 dB up to 6 GHz.

> “The ability to manufacture RF systems in-house offers an exciting new means for rapid and affordable prototyping and volume manufacturing.”
>
> **- Dr. Arthur Paolella,**
> **Senior Scientist, Space and Intelligence Systems, L3Harris**

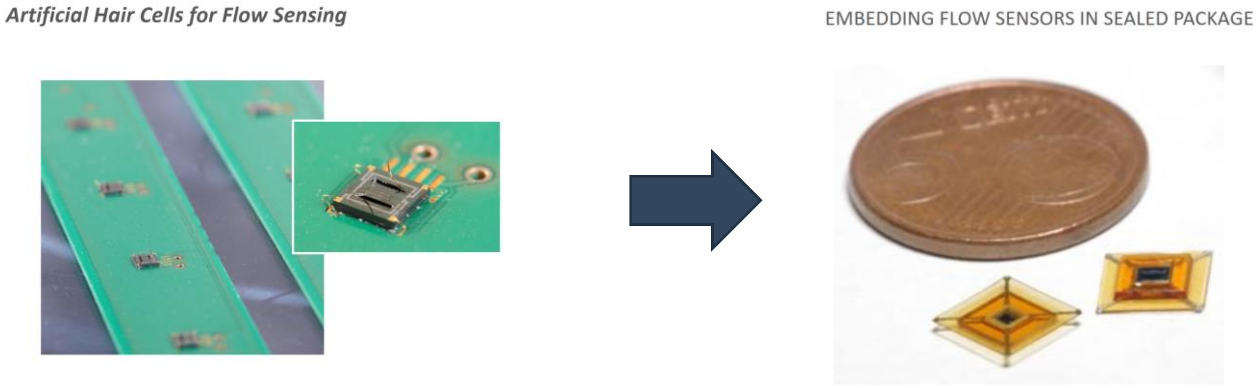
Pakaging & SiP development



ISTITUTO ITALIANO
DI TECNOLOGIA
CENTER FOR BIOMOLECULAR
NANOTECHNOLOGIES

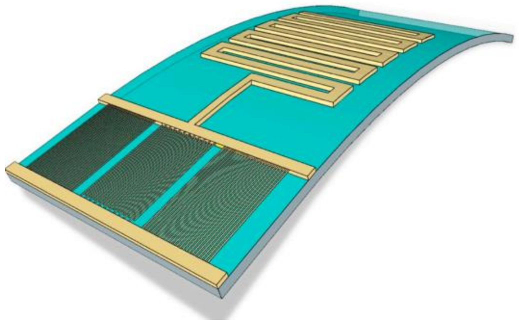
History (cont.)

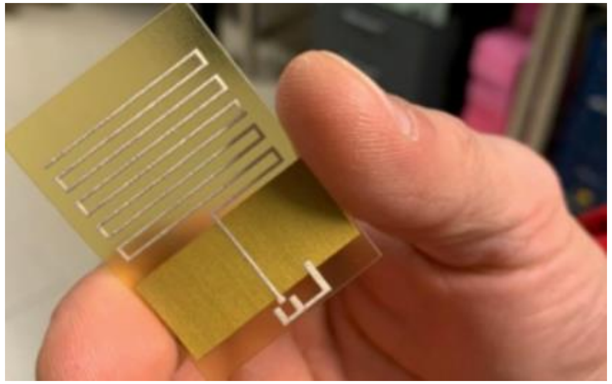
AME SENSOR APPLICATIONS

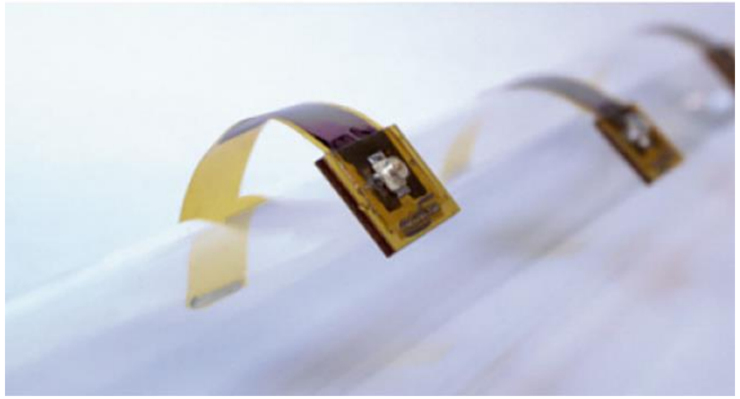

Artificial Hair Cells for Flow Sensing

EMBEDDING FLOW SENSORS IN SEALED PACKAGE

Sensor direct print packaging (3D printed wirebonding)



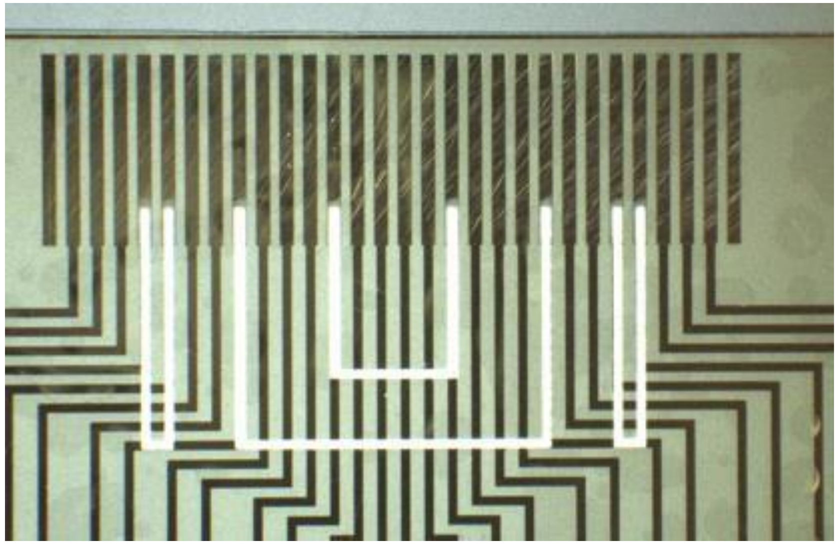

Compact and flexible meander antenna for Surface Acoustic Wave sensors


3D embedded sensor in electrical packaging


Optoelectronic Neural Surface

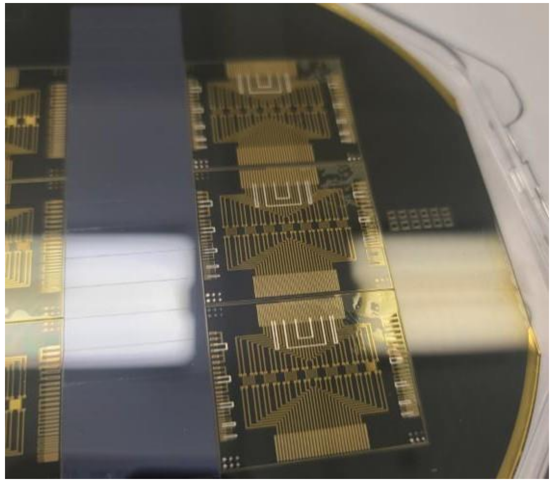
History (cont.)

TESTPATCH AGCITE® BONDING



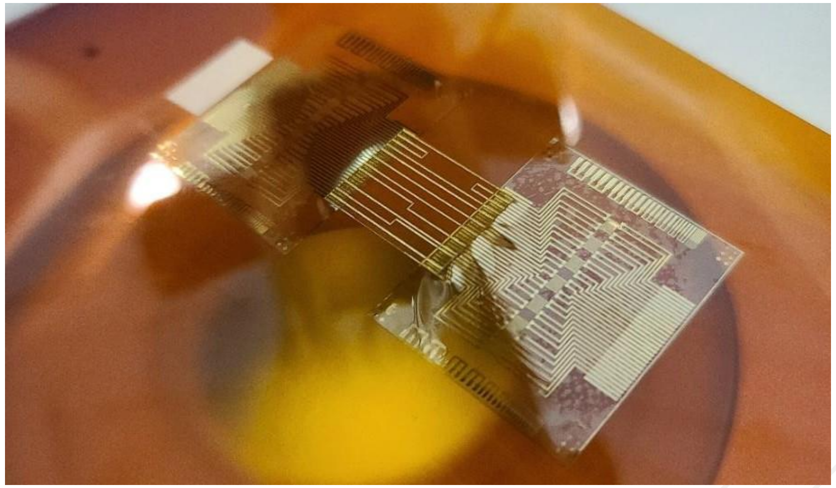
Print on foil

success



Print on wafer

success



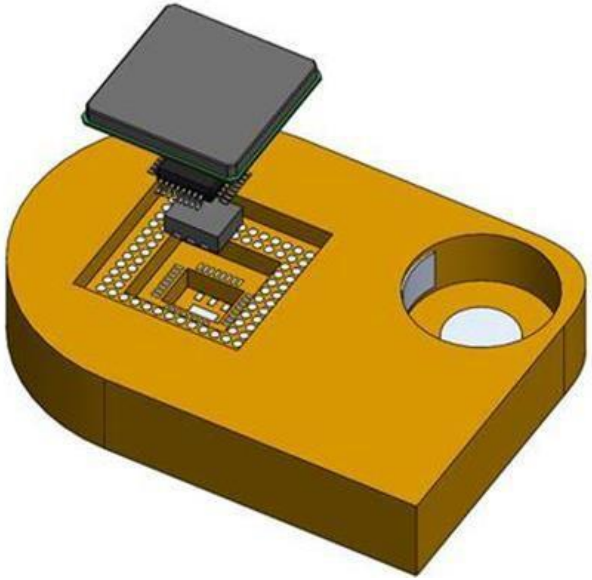
Connect two foil on flex substrate

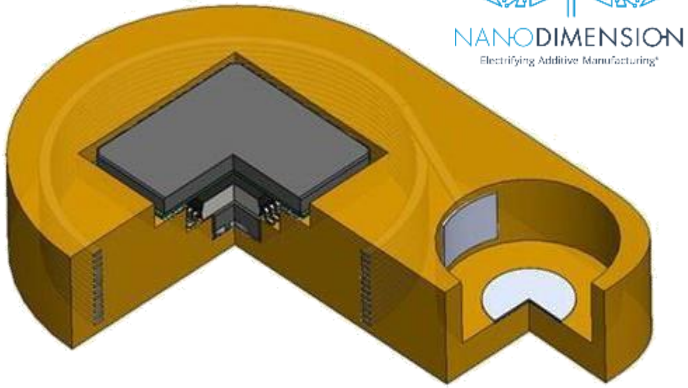
success

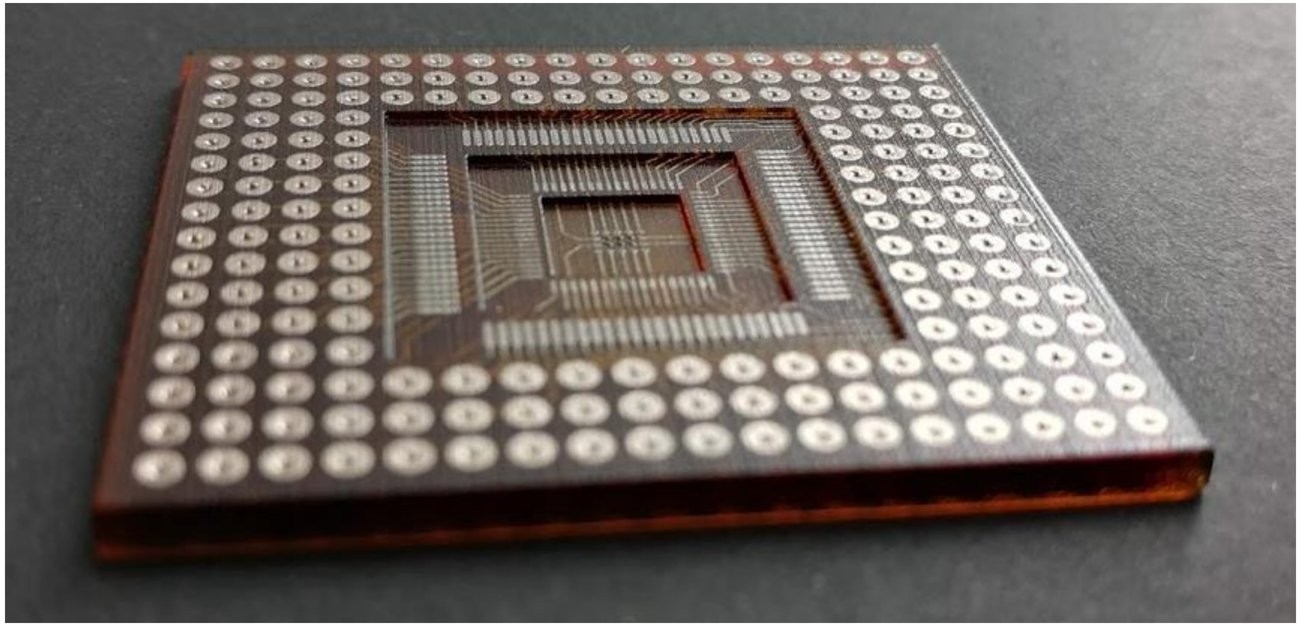
History

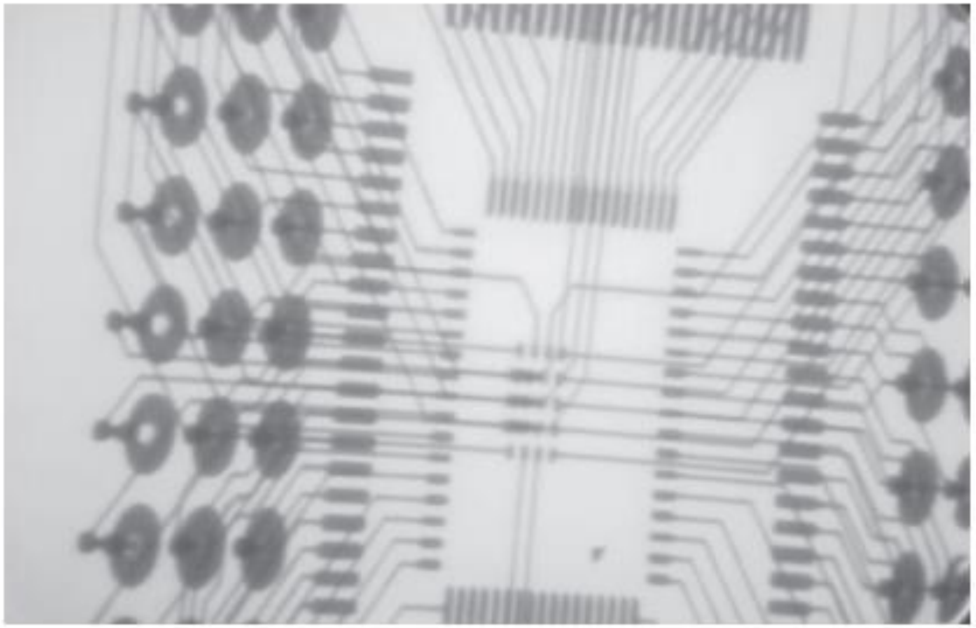
AME SOCKETS & INTERPOSERS

- Very first encapsulation concept: Stacking of packaged ICs and interposers





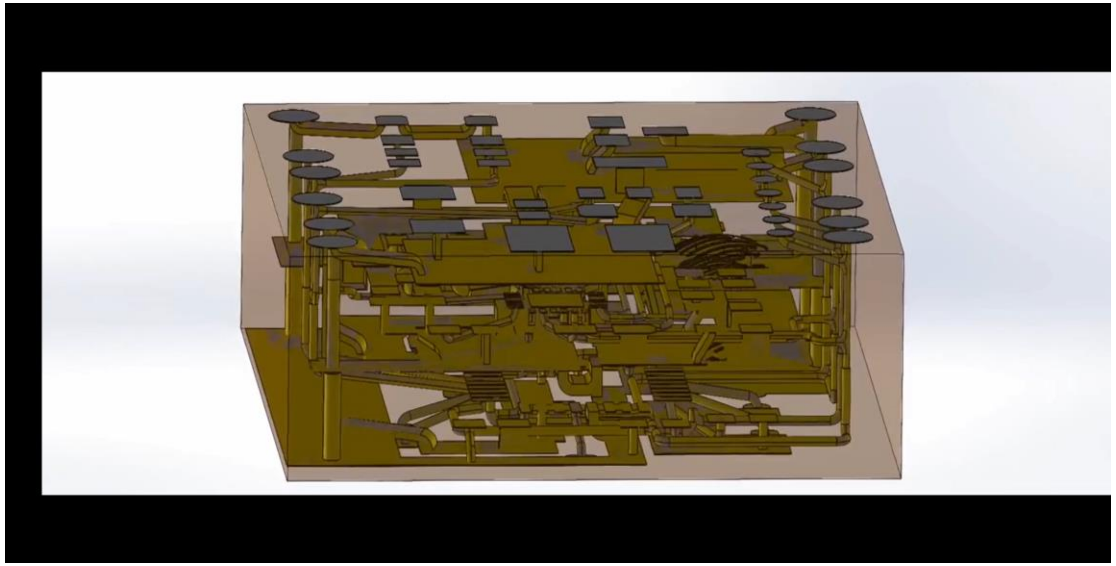


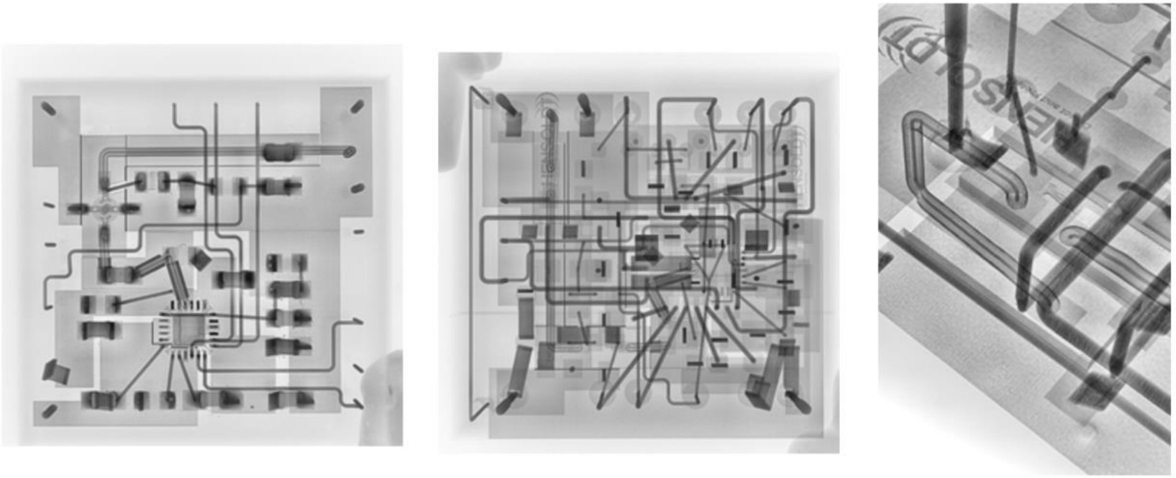


New Design Thinking

RF SYNTHESIZER

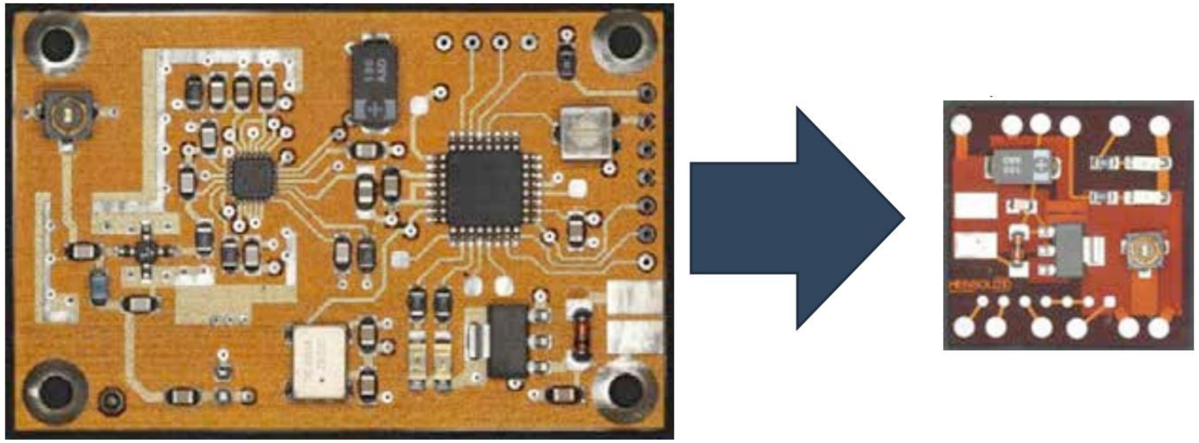
- 3D Heterogeneous Integration
- Includes DC, digital signals and also RF
- Shielded coaxial lines to keep signal integrity/Impedance controlled interface
- Printed passive components (coils, capacitors)
- Miniaturization





High Resolution X-ray Views

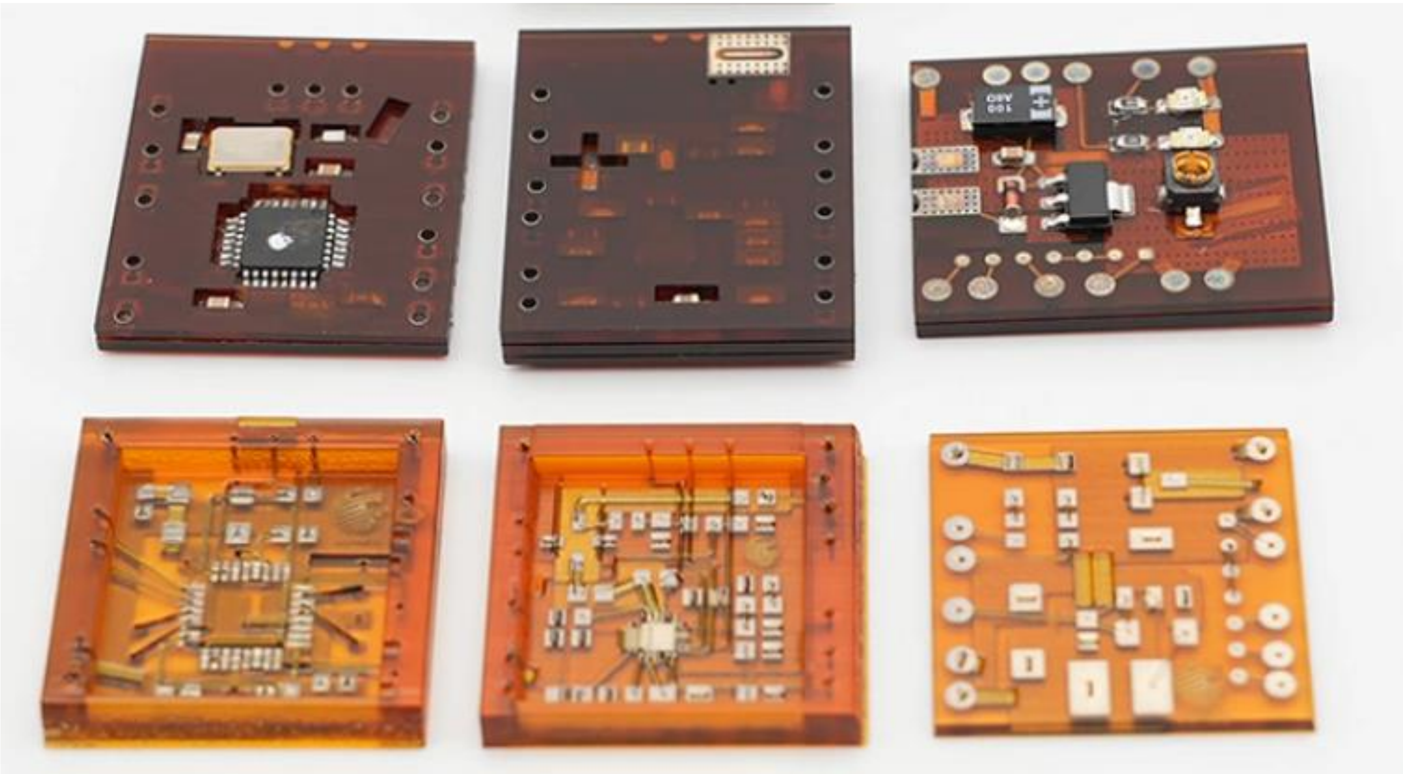
Original PLL board



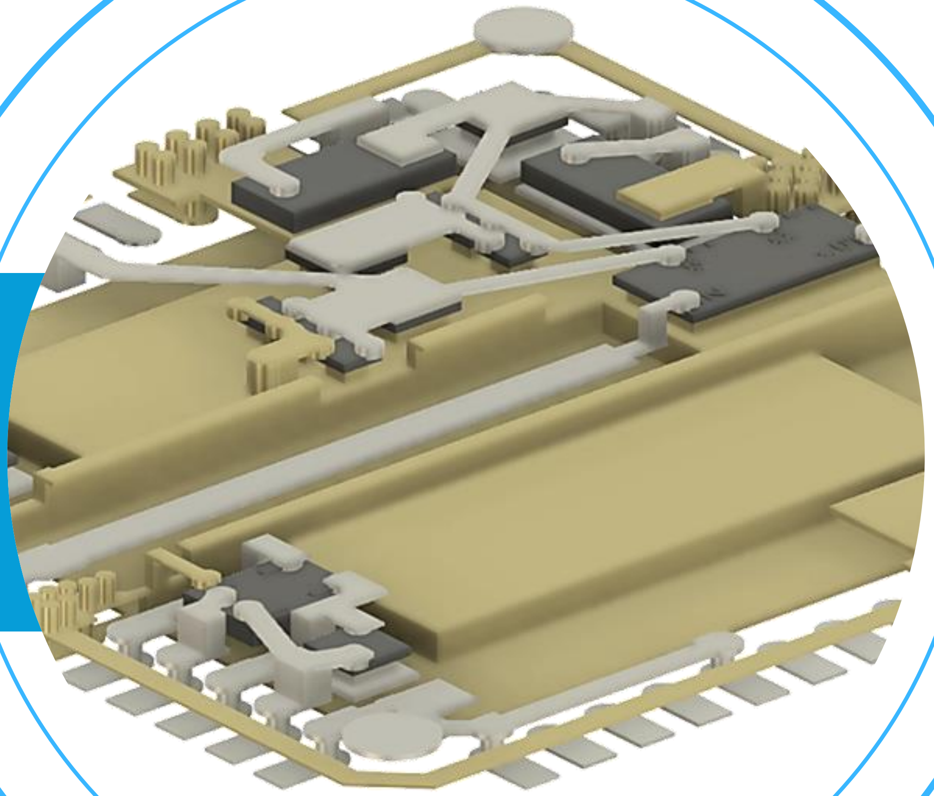
New Design Thinking

RF SYNTHESIZER –CONT'

- 3 steps process

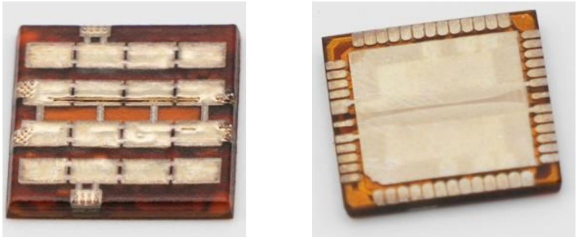


RF SiP

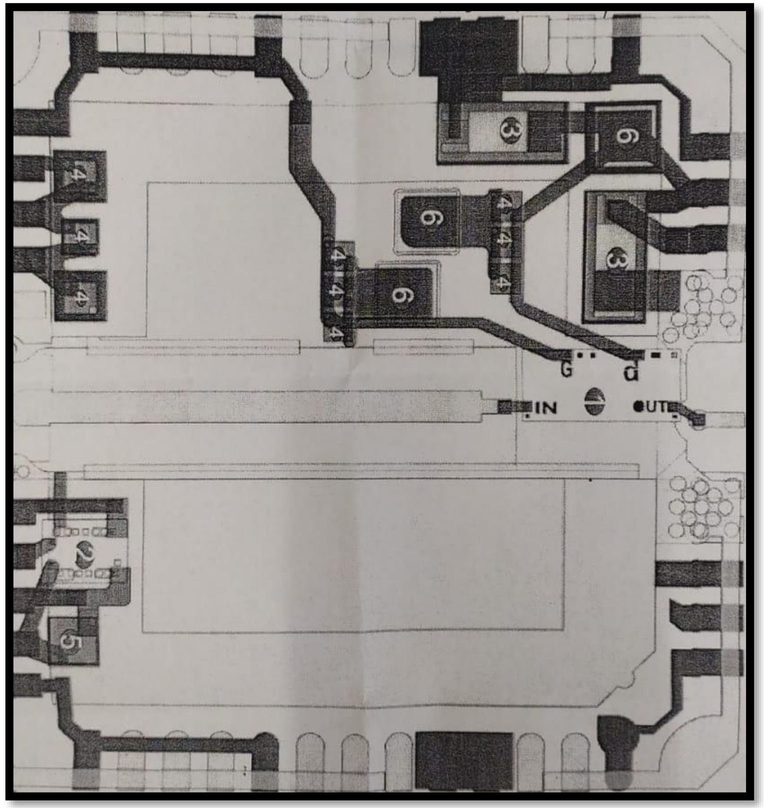


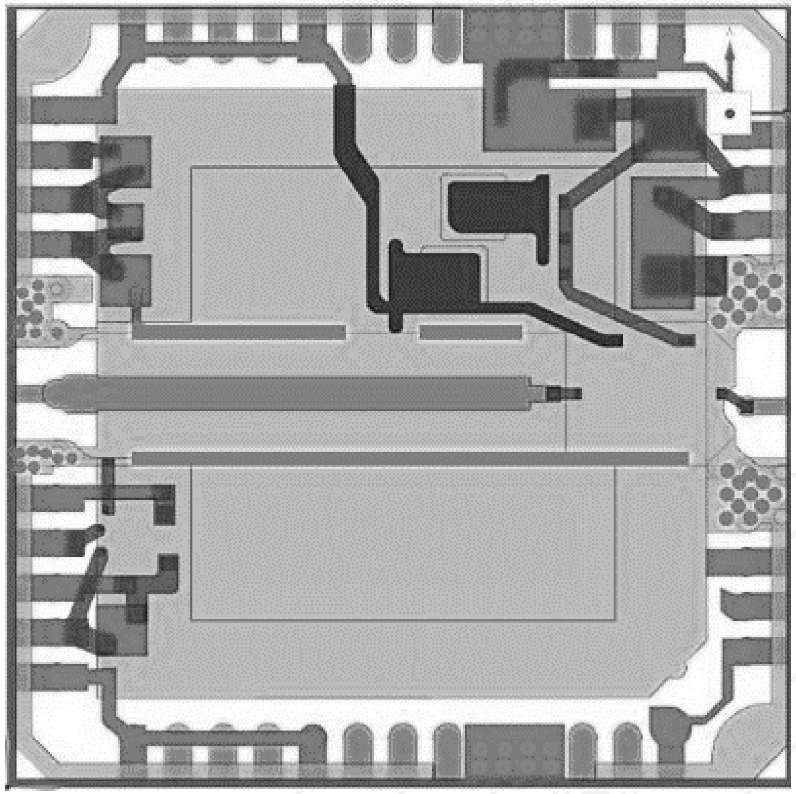
Schematic

- Main component:
    - MMIC 4W X-band die (QPA1022D)
- Other: Resistors (6), capacitors (3) and MOSFET dies.



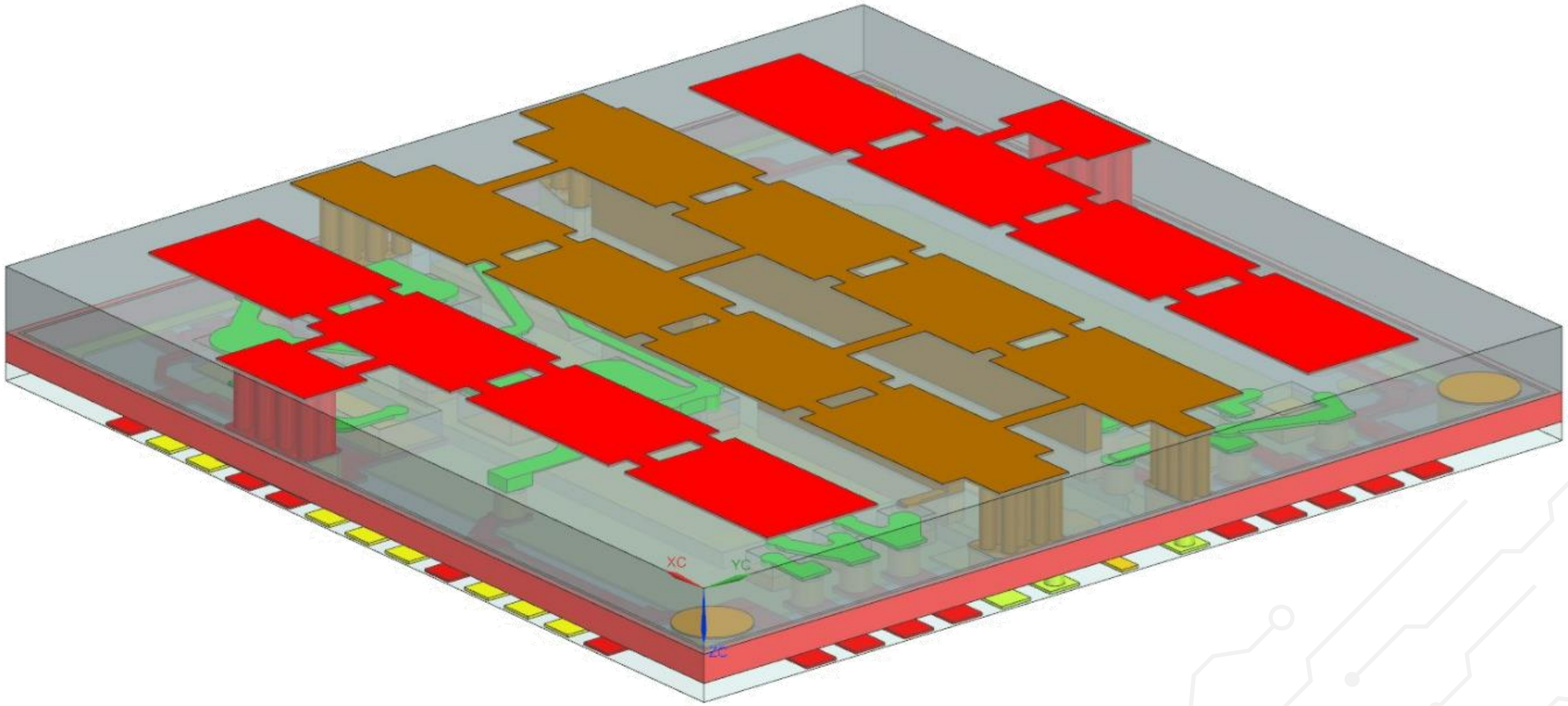
13.2x13.2x1.5mm



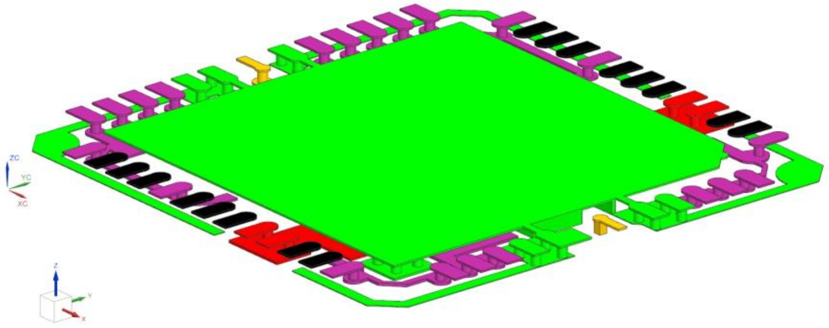


Layout and BOM

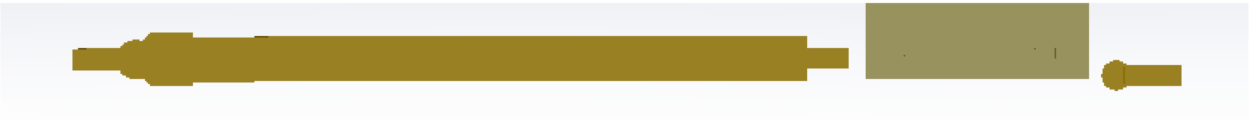
- Main component:
  - MMIC 4W X-band die (QPA1022D)
- Other: Resistors (6), capacitors (3) and MOSFET dies.
- Overall physical dimensions:
  - 13.2x13.2x1.5mm
- Minimum pad size on die 80um.



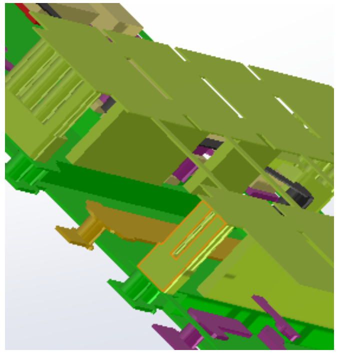
Layout and BOM –cont’



- QFN on bottom side.



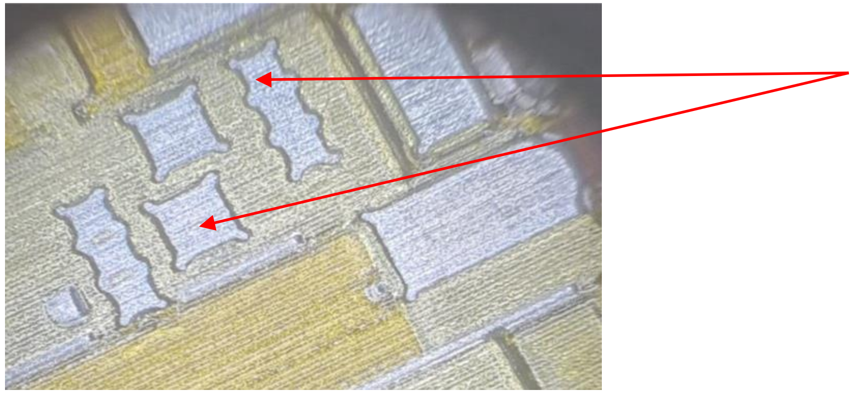
- Main 50-Ohm line



- Shielding for the RF line (walls)

Layout and BOM –cont’

- CAVITIES

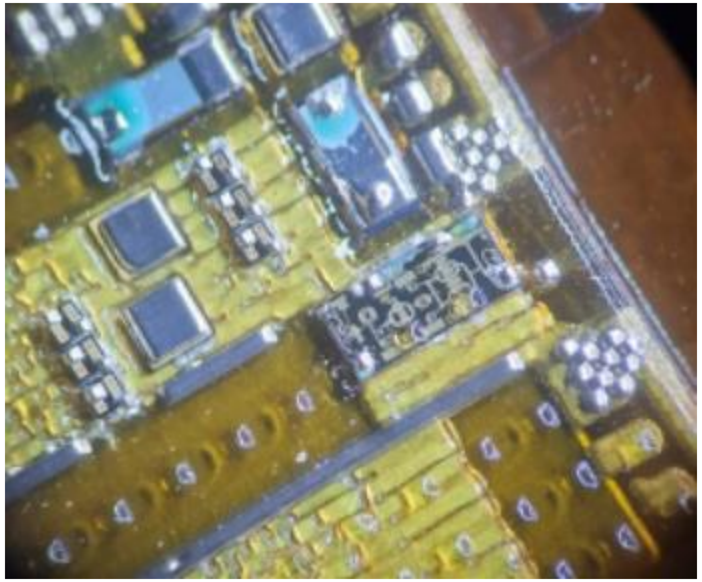


Cavities

- Before components placement

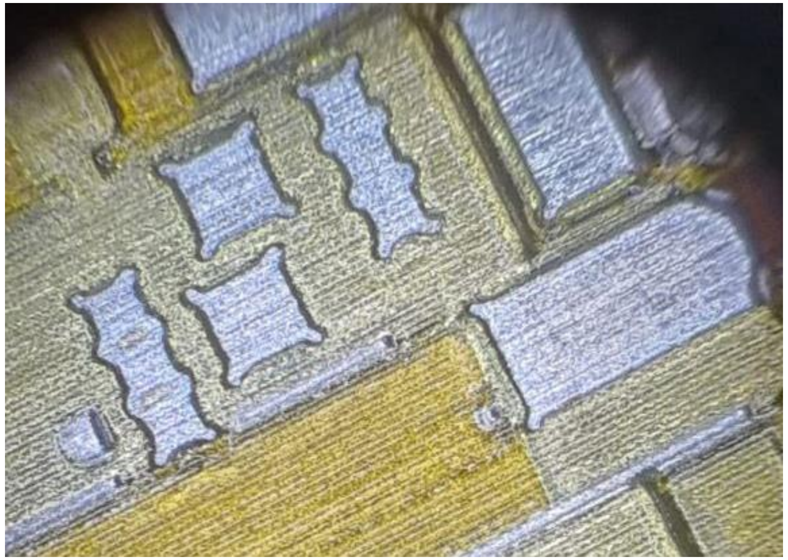
Layout and BOM –cont’

- COMPONENTS PLACEMENT

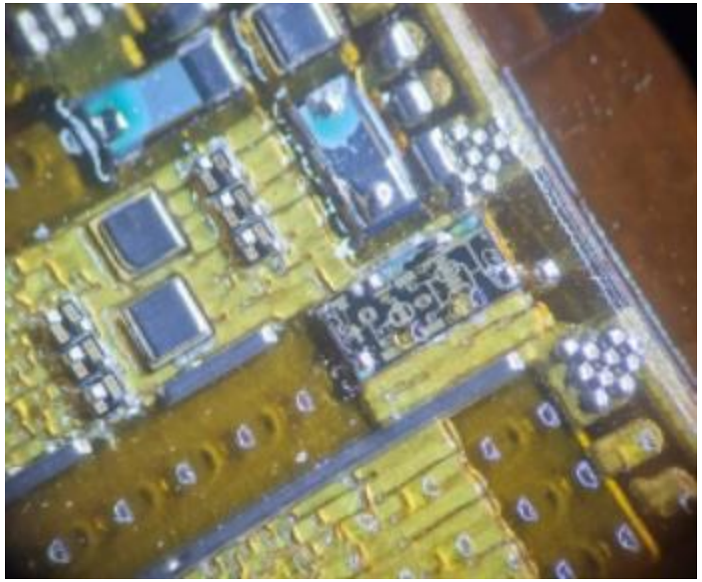


- After components placement

Layout and BOM –cont’



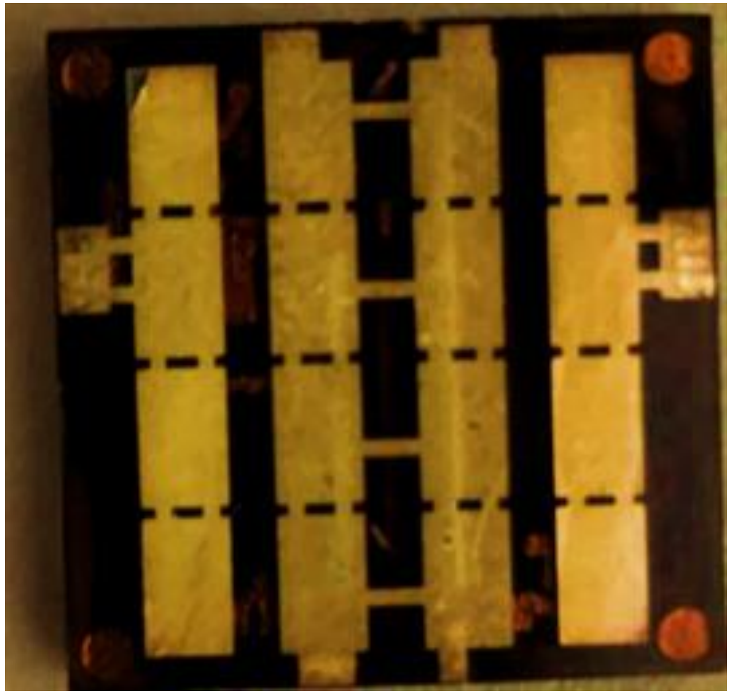
- Before components placement

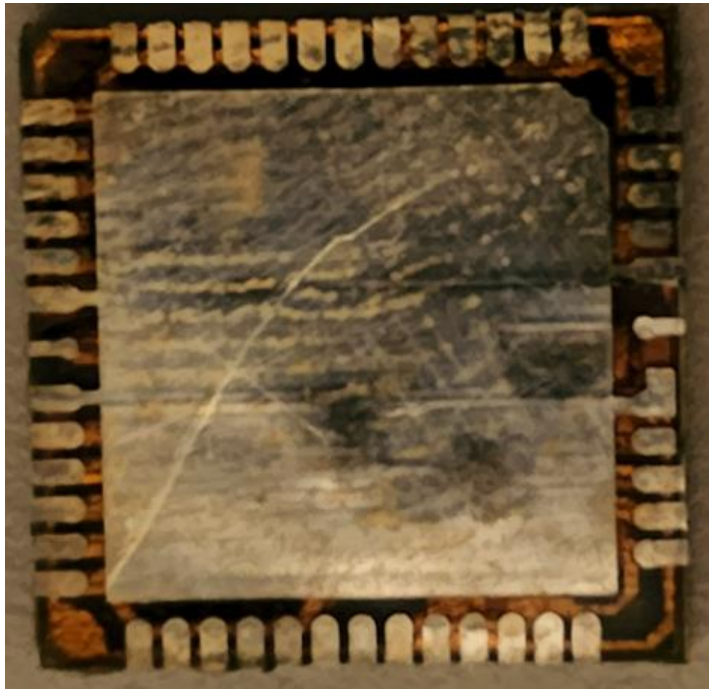


- After components placement.

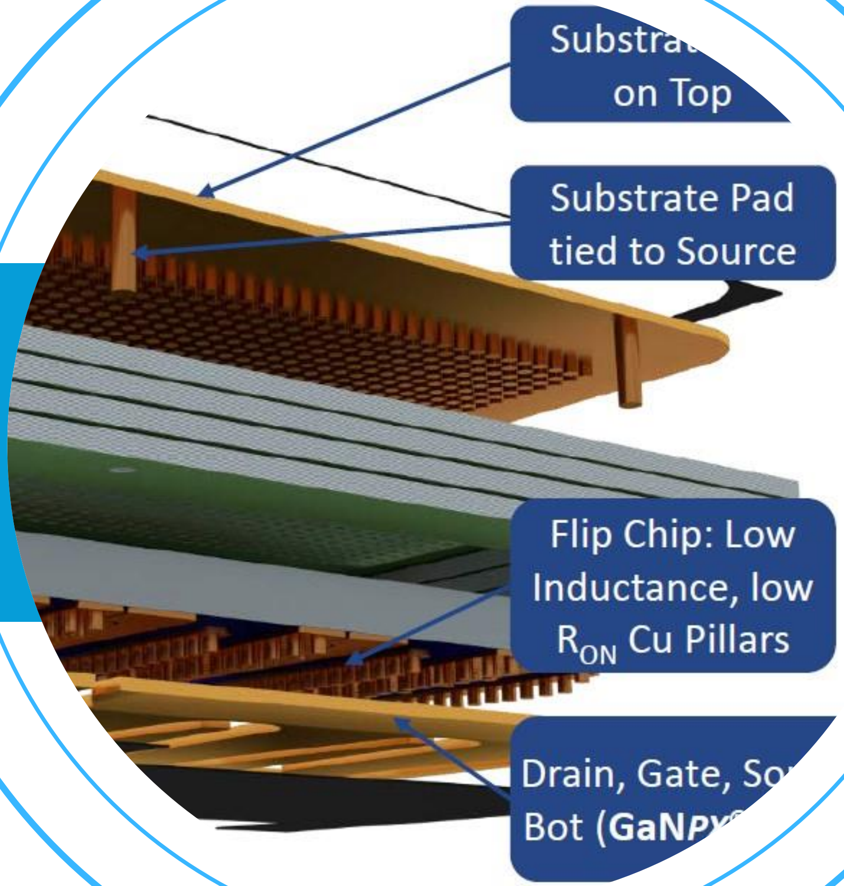
Layout and BOM –cont’

- FINAL TOP & BOTTOM VIEW





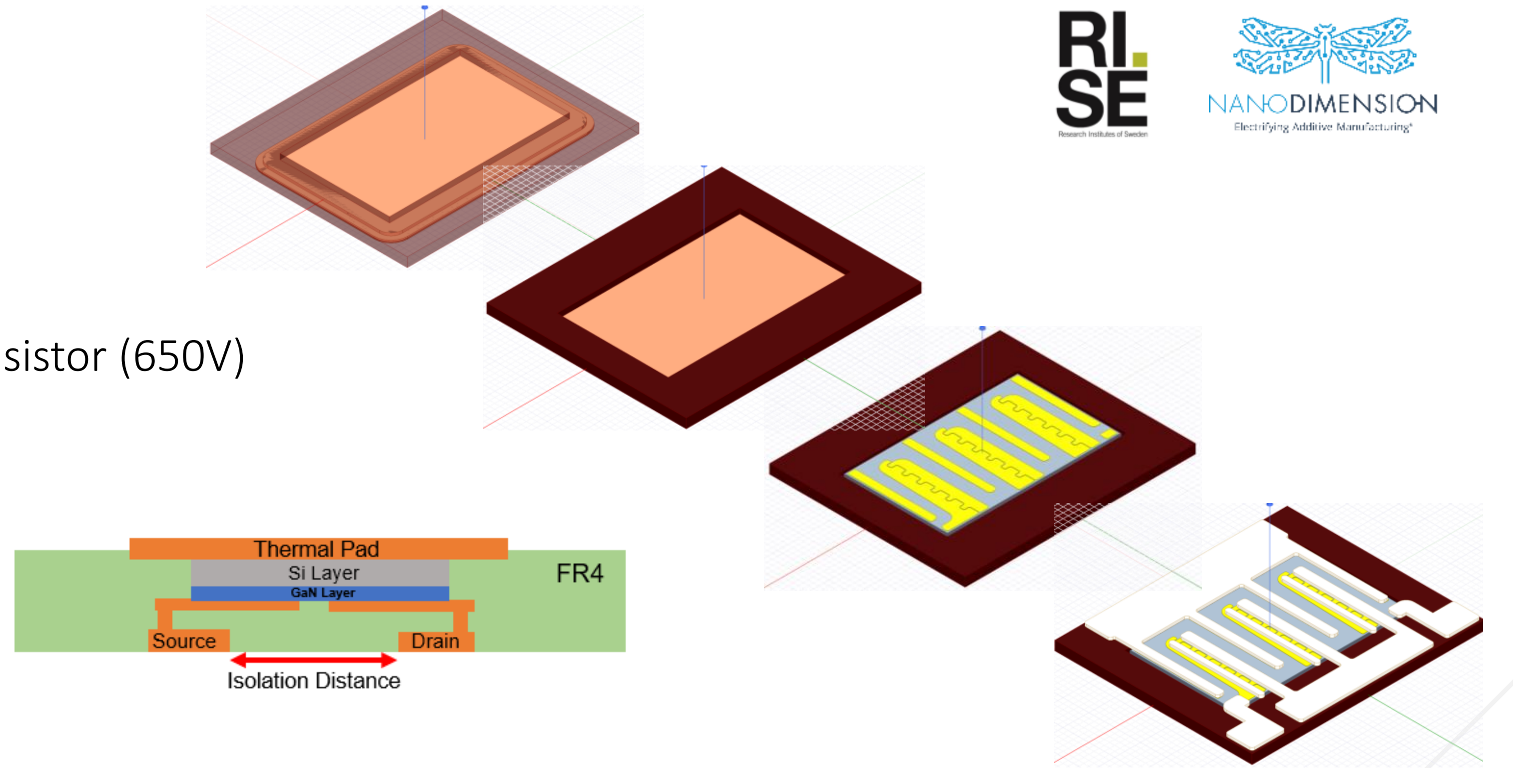
Power Transistor AME Packaging

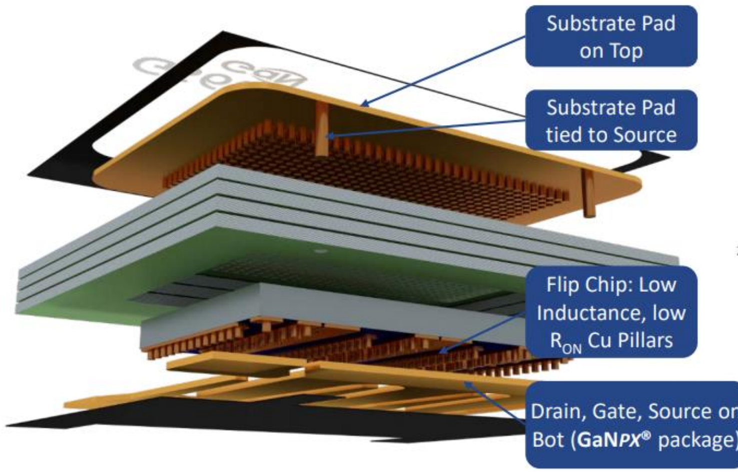


Power Transistor SiP

GAN-ON-SILICON

- Enhancement mode GaN-on-silicon power transistor (650V)
- Top-side cooled configuration
- High current $\mathrm{Ids}(max) = 60A$
- $\mathrm{Rds}(on) = 25m\Omega$
- Very high switching frequency (> 100MHz)
- Small 9 X 7.6 mm PCB footprint



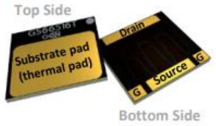


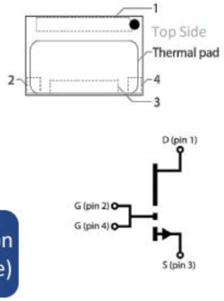
Substrate Pad on Top

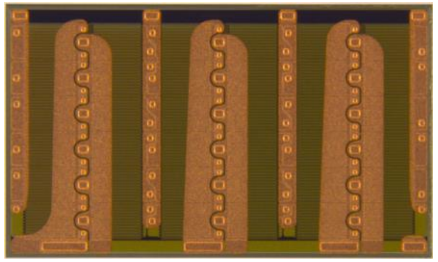
Substrate Pad tied to Source

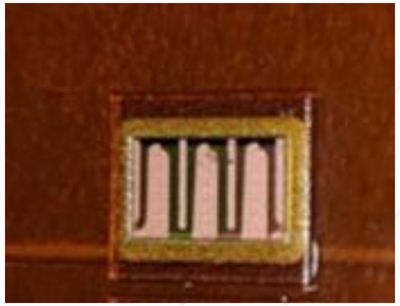
Flip Chip: Low Inductance, low R_{ON} Cu Pillars

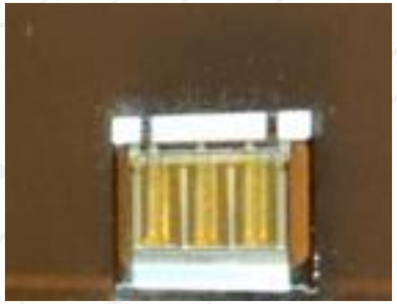
Drain, Gate, Source on Bot (**GaN*PX*®** package)









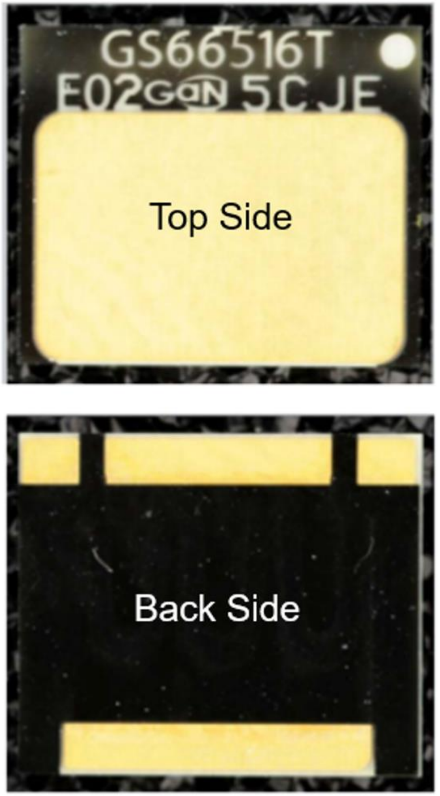


Commercial package: complicated manufacturing process: lamination, drilling, electro-plating, etc.

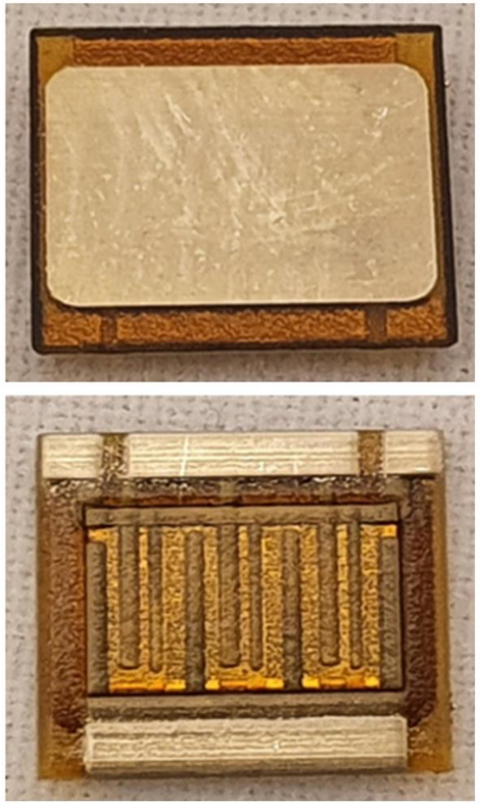
Power Transistor SiP

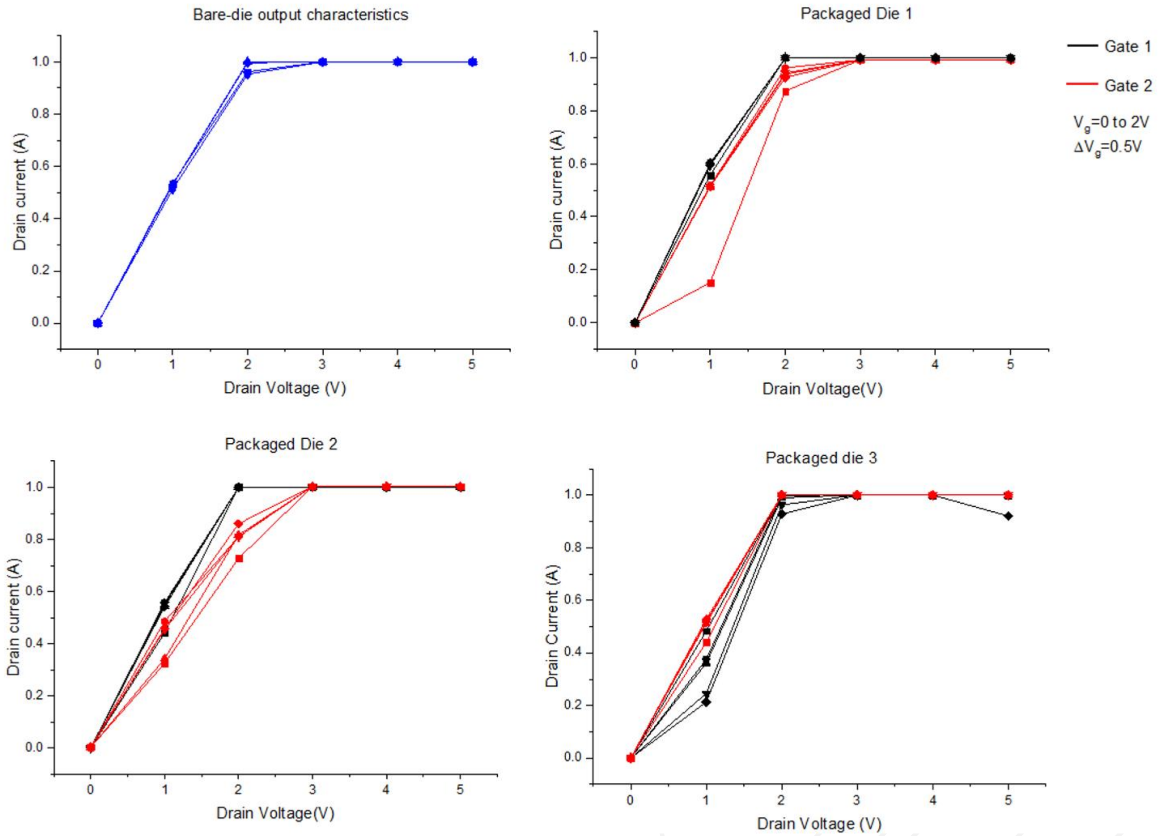
GAN SYSTEMS (GS66516T)

Commercial Package



Printed Package





Power Transistor SiP

GAN-ON-SILICON

Process:

a) Printing dielectric cavities & pause the print (keeping chuck at 100°C)

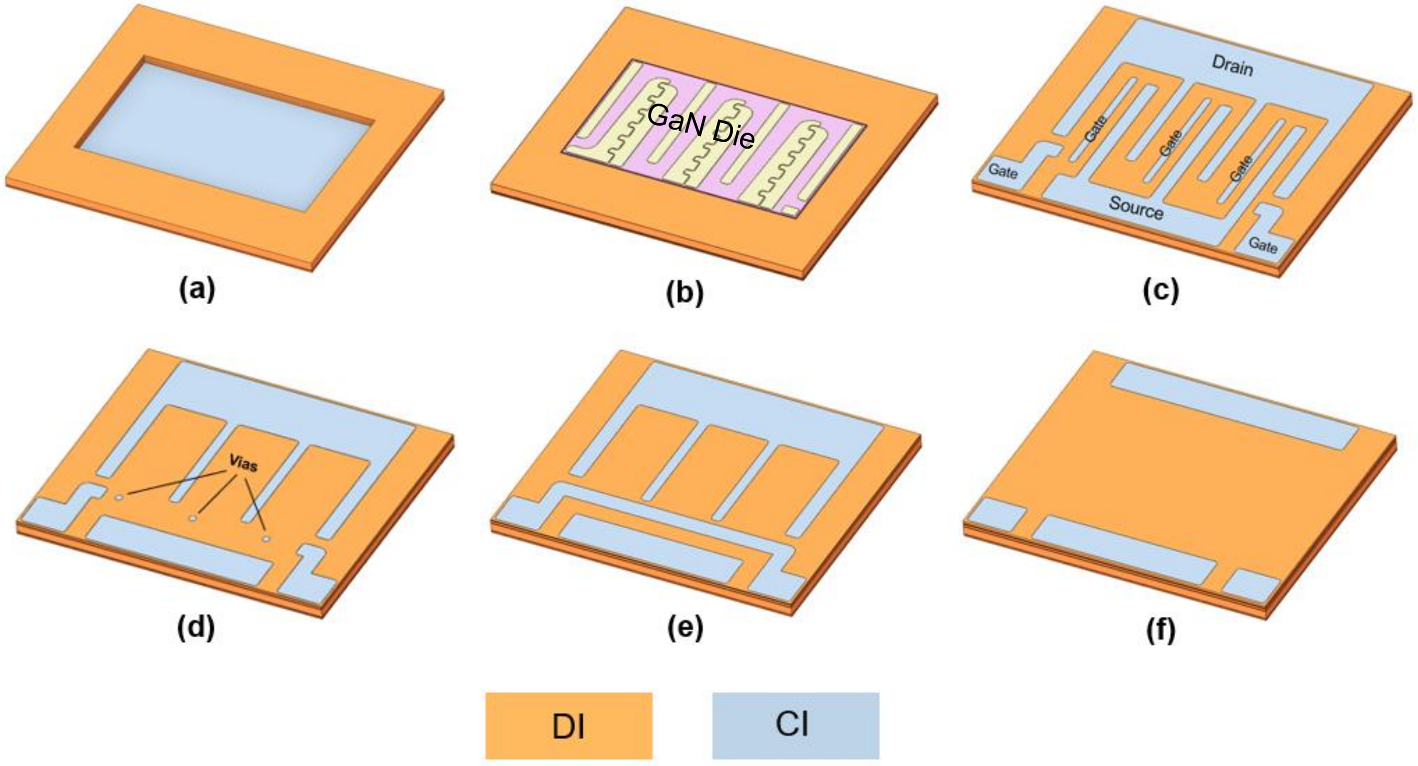
b) Placing the silicon dies and adding Epotek conductive glue on the bare pads

c) Print DI “soldermask alike” and fill gaps

d) Print CI pads connection

e) Print interconnecting tracks

f) Print cover layer



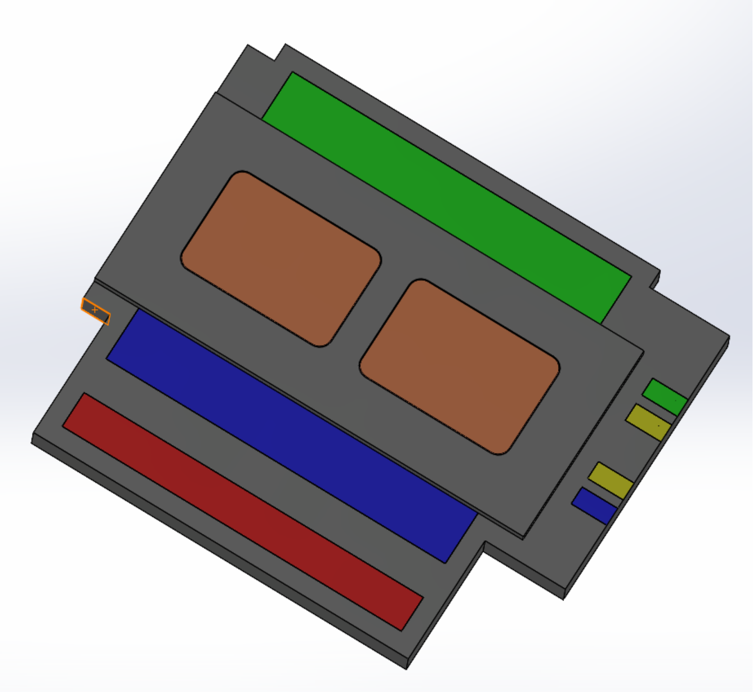
Power Transistor SiP

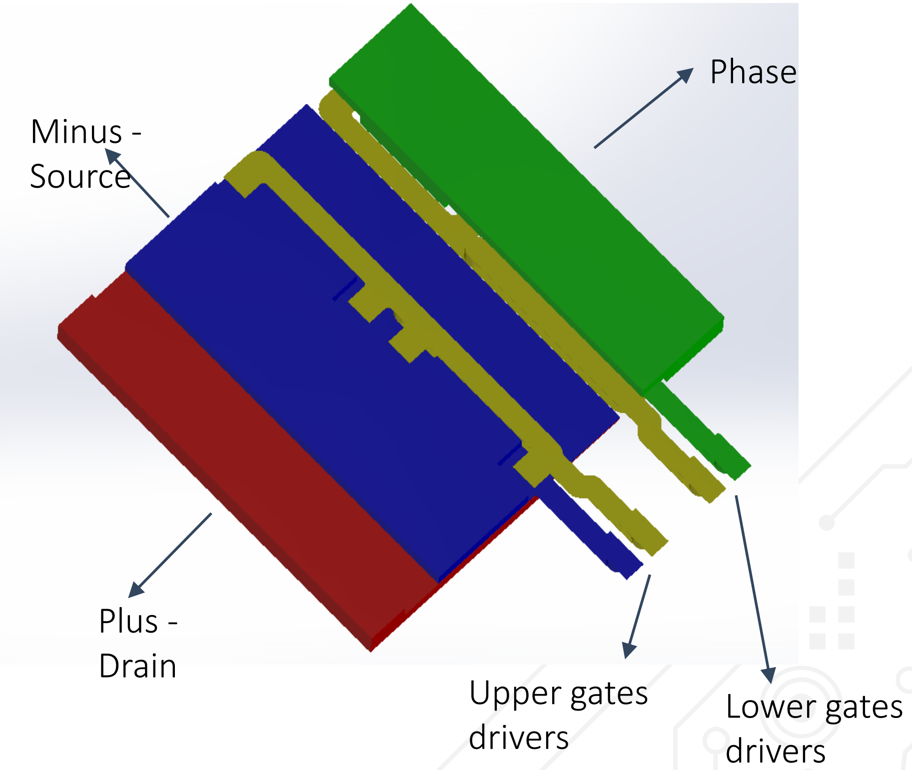
RI.SE DESIGN FOR AME

- A very compact module with four GaN discretes was designed.

Challenges:

- Meeting the application targets – High voltage, high current
- Effective heat dissipation – High current





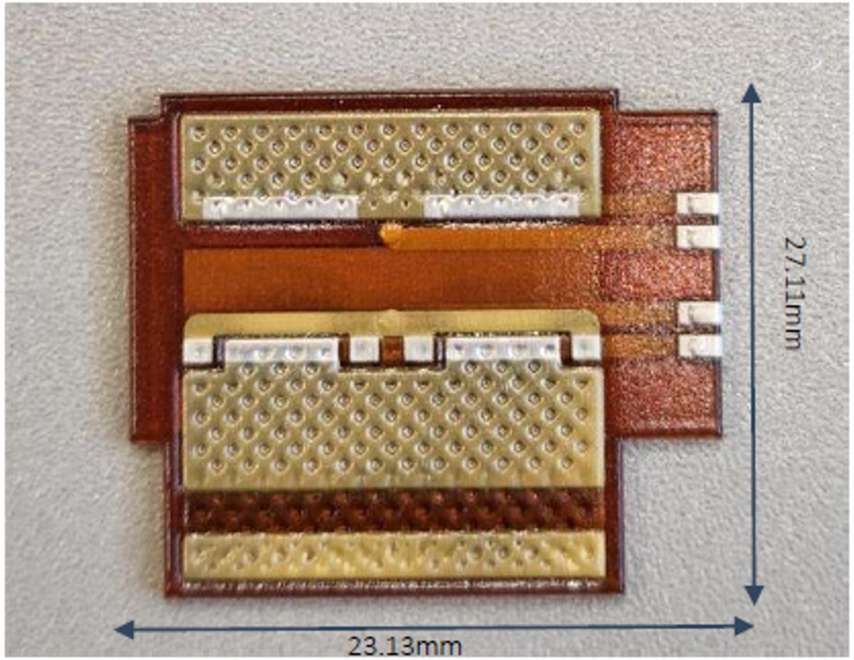
Power Transistor SiP

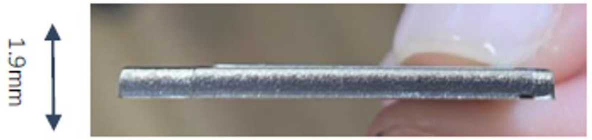
GAN-ON-SILICON

Power Transistor SiP

GAN-ON-SILICON

Module with four GaN HEMTS (V_{DS}= 650 V, I_{DS}= 60 A, $R_{DS(ON)}$= 25 mΩ)





- The AME method have proven to be very time efficient!
  - 2-3 complete packaging iterations within 2-3 months – this normally takes years

The Smallest High Power Module of its Kind

Printed with AME technology

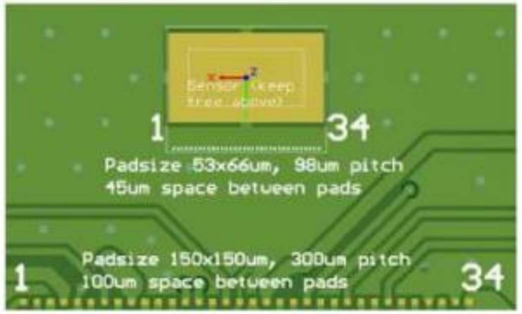
“ The device’s mechanical characteristics are approximately 64% smaller than the smallest similar functional devices existing in the market and will create the highest power density for this kind of device.

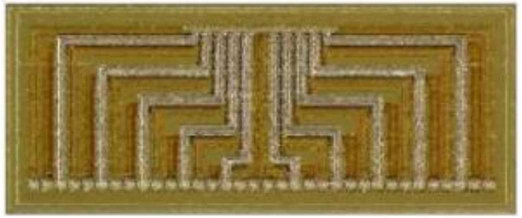
Furthermore, this is the first attempt to use 3D AME technology to reduce size, reduce manufacturing time and improve power density in this kind of circuit.”

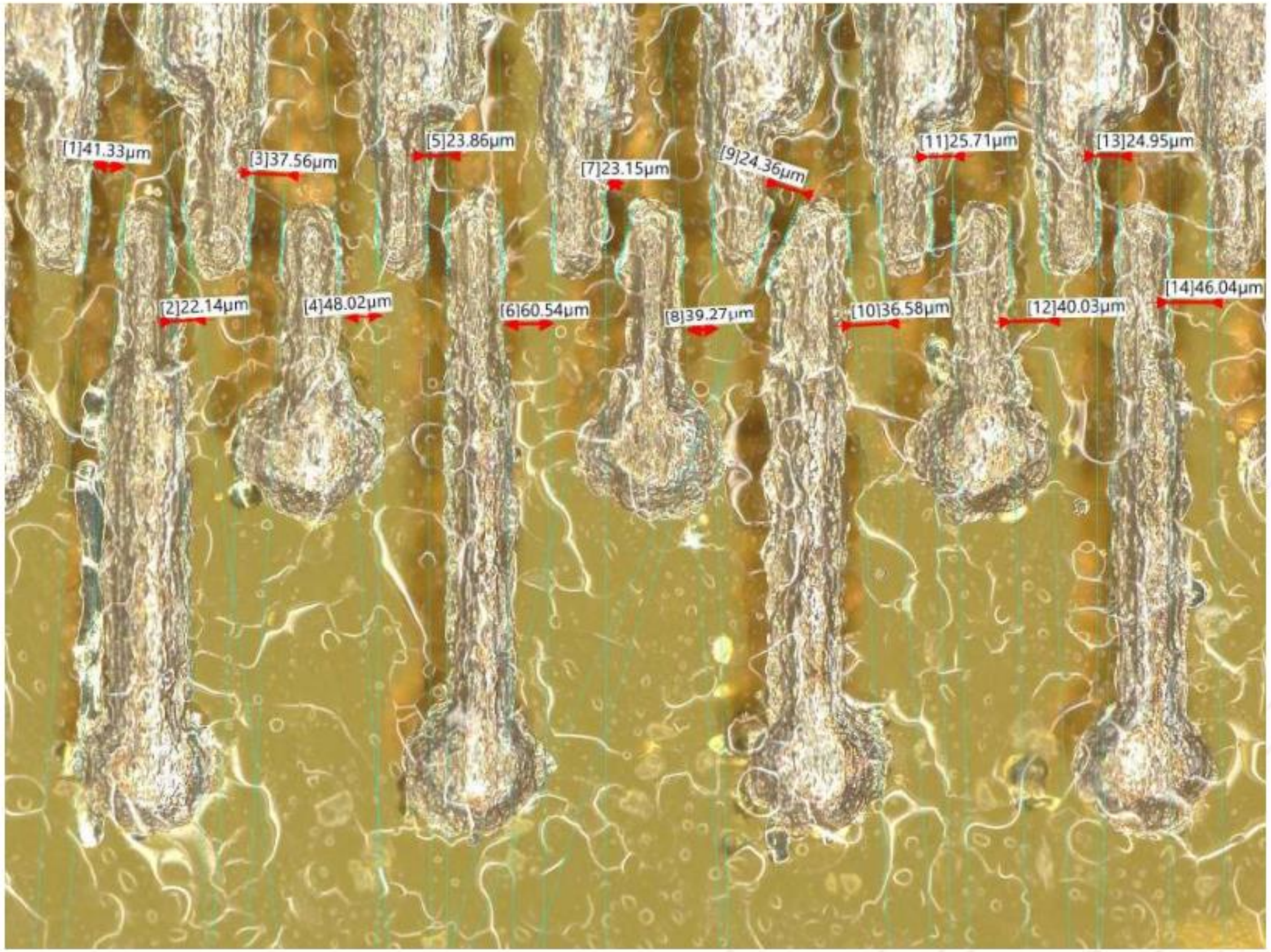
New Design Thinking

EMBEDDING & ENCAPSULATION

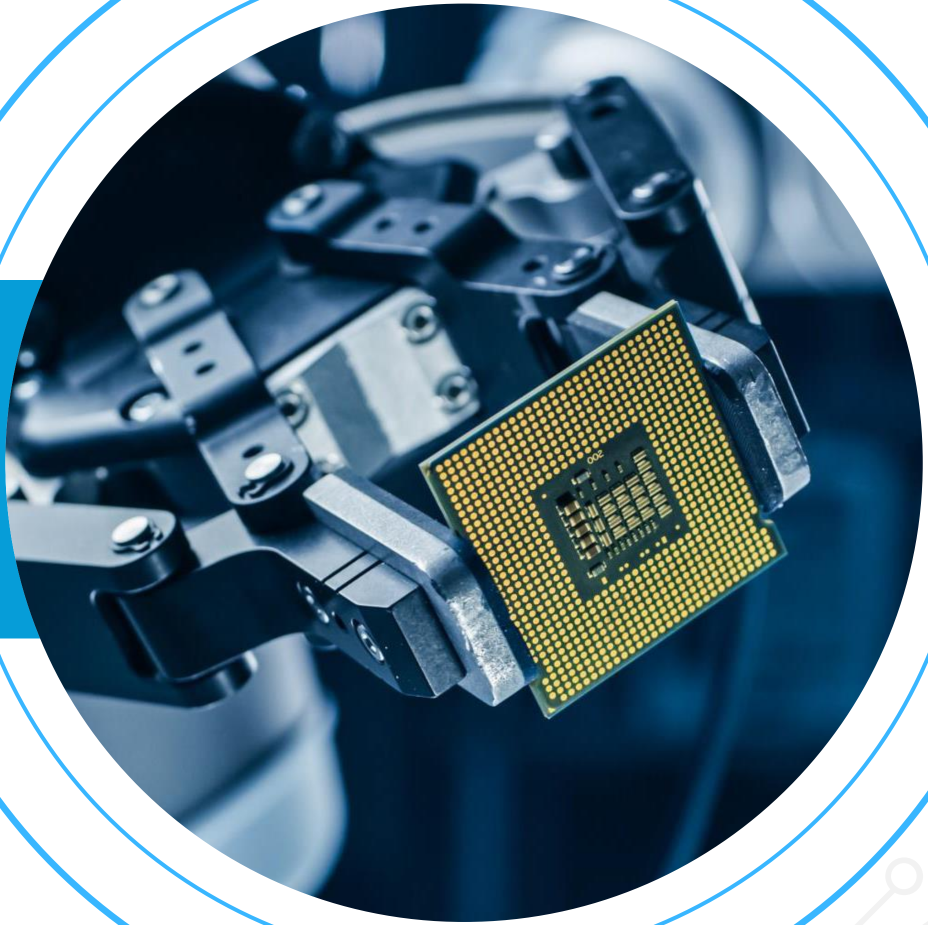
- Image sensor Die
  3D printed wire bonding







Summary



Solving Large and Growing Challenges

Providing Solutions that Industry, OEMs, and Researchers Need Now

Problems

- Supply chain disruptions
- IP theft
- Limits of mass production
- Ongoing environmental disaster

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