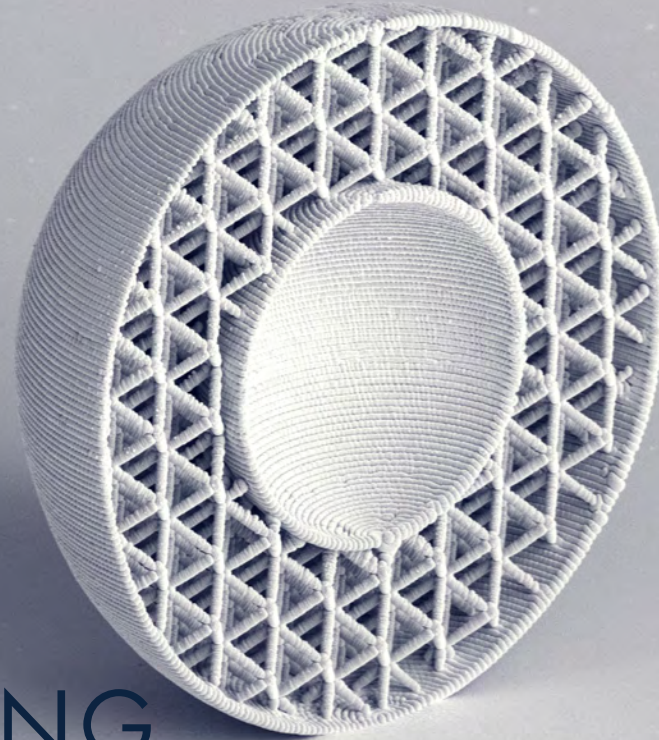


16.09.2021



ADDITIVE
MICRO-
MANUFACTURING
OF METALS
-EPHJ & Swiss Photonics-



Imagine the unseen

AGENDA

CERES Print System Overview

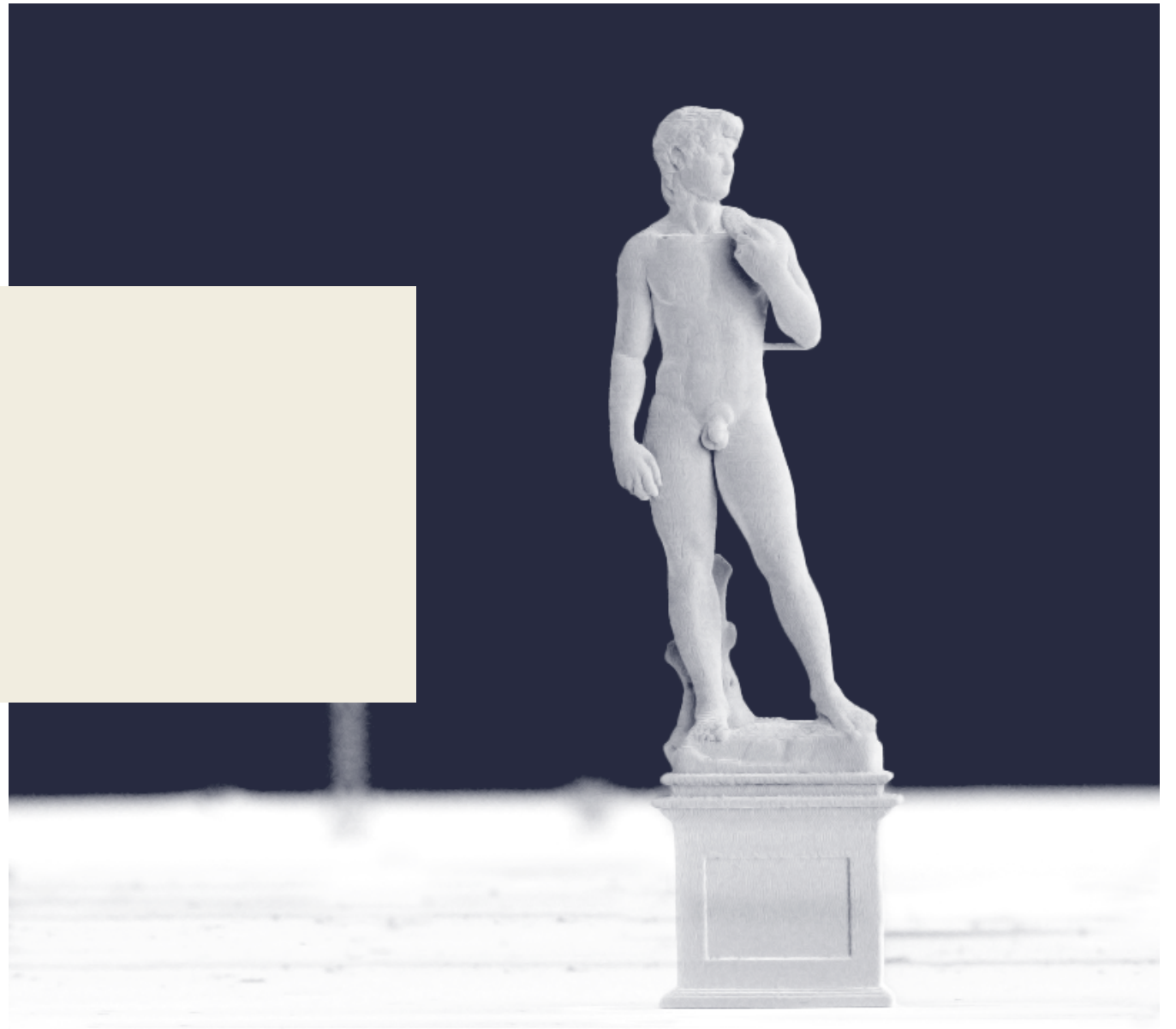
Print Process, Materials, Size Range

Material Properties

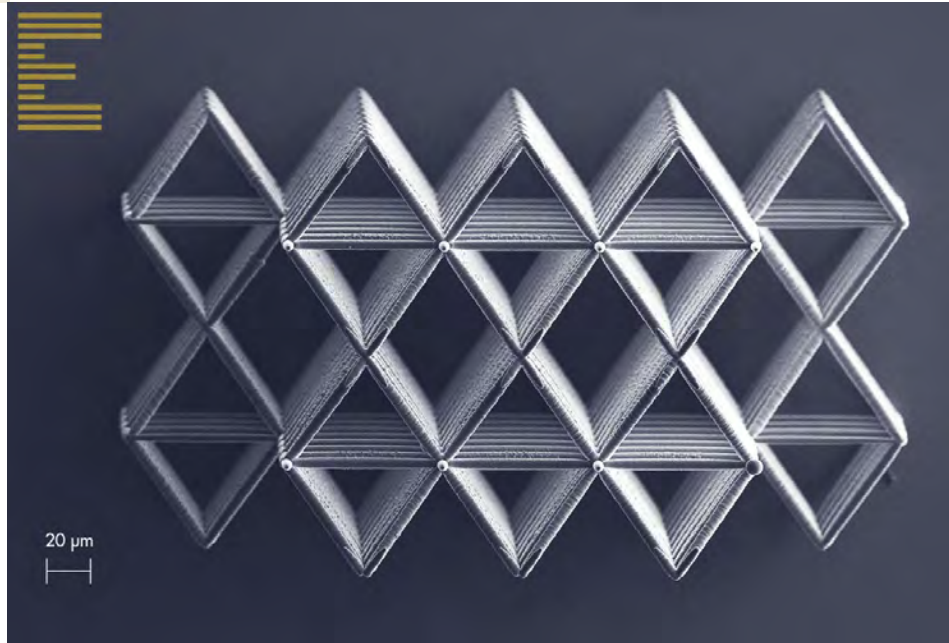
Typical Use Cases

Applications in Photonics

Q&A



EXADDON AG



- Formerly part of Cytosurge AG – developers of intra-nuclear cell-editing solutions (FluidFM)
- We have pioneered μ AM: additive micromanufacturing of metals
- Exaddon has ongoing research collaborations with respected academic institutions



PUBLISHED RESEARCH

- Well integrated into the science community
- High impact publications published frequently
- Focus on cooperation and know how exchange

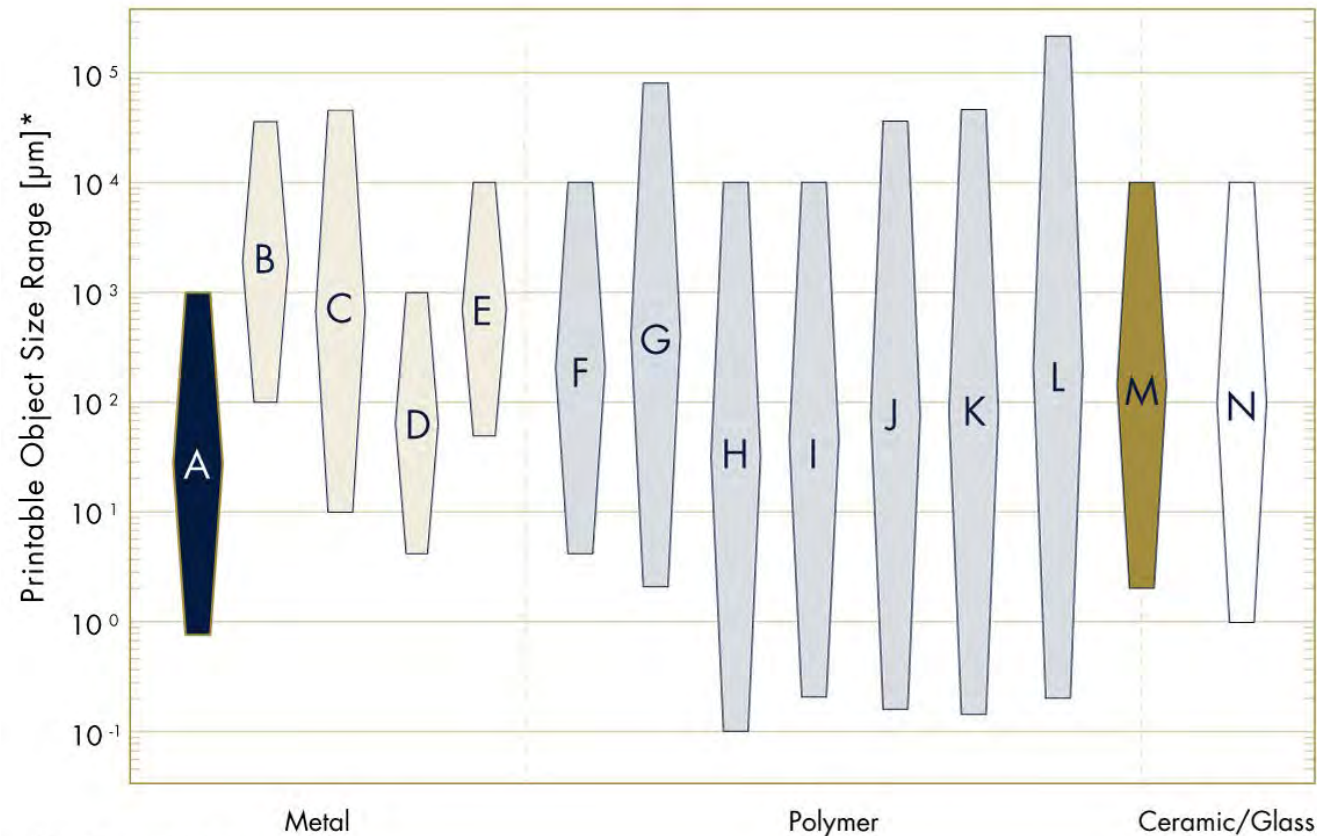


Browse complete publications list online

CERES - PRINT SYSTEM

COMPETITIVE LANDSCAPE POSITION

EXADDON μ AM COMPETITIVE LANDSCAPE 2021

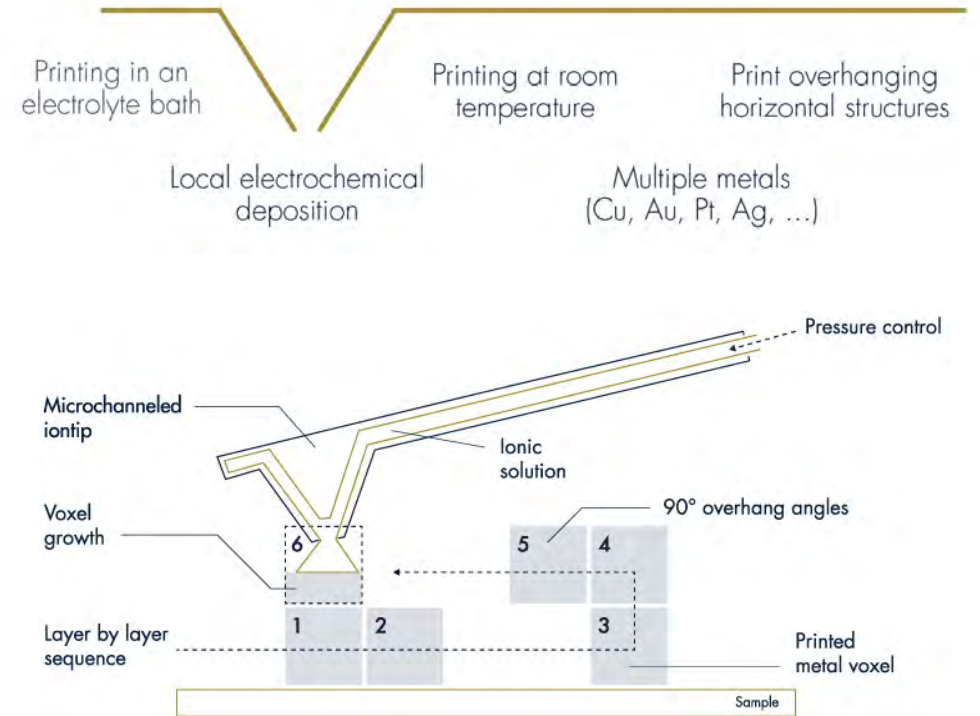
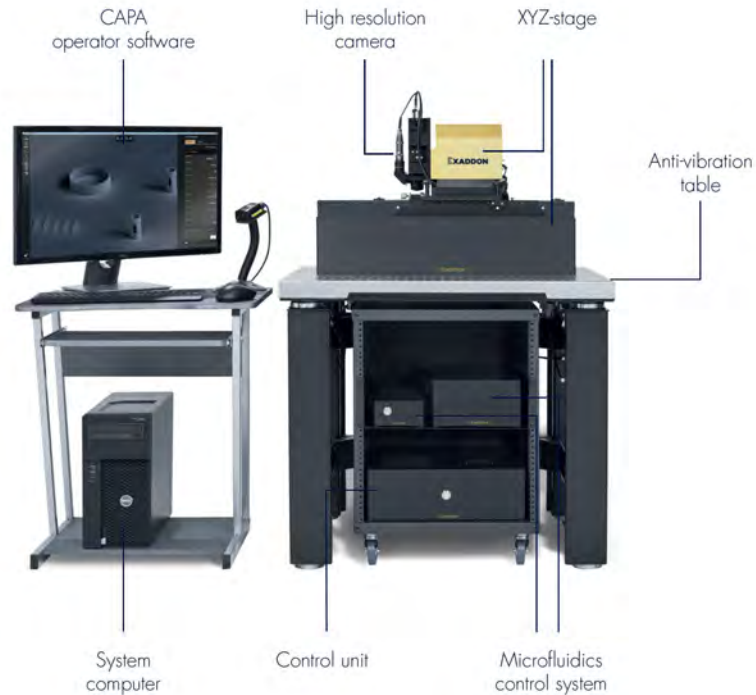


*Estimated, based on available data

- A** **EXADDON**
- B** **3D micro PRINT**
- C** **incus**
- D** **MICROFABRICA**
- E** **Mimotec**
Micro-fabrics pour grandes séries
- F** **MICROMAKER3D**
- G** **BMF**
BOSTON MICRO FABRICATION
- H** **Multiphoton Optics**
- I** **microlight3D**
- J** **UP nano**
- K** **nano scribe**
- L** **femtika**
- M** **NANOFABRICA**
- N** **FEMTOprint**

CERES - PRINT SYSTEM

UNIQUE PRINTING TECHNOLOGY



- Dispense liquids in 2D lines
- Print complex 3D structures out of metals
- **A system for innovators & visionaries in additive micromanufacturing**

ELECTRO-CHEMICAL DEPOSITION

WHAT CAN BE PRINTED?

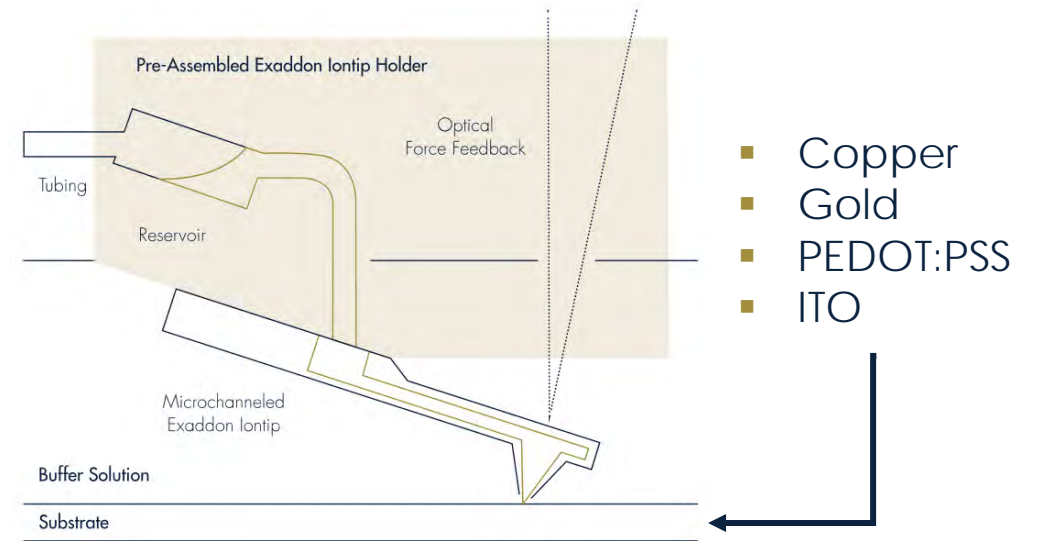
Possible Print Materials

Hydrogen 1 H 1.0079																	Helium 2 He 4.0026						
Lithium 3 Li 6.941	Beryllium 4 Be 9.0122																	Boron 5 B 10.811	Carbon 6 C 12.011	Nitrogen 7 N 14.007	Oxygen 8 O 15.999	Fluorine 9 F 18.998	Neon 10 Ne 20.180
Sodium 11 Na 22.990	Magnesium 12 Mg 24.305																	Aluminum 13 Al 26.982	Silicon 14 Si 28.086	Phosphorus 15 P 30.974	Sulfur 16 S 32.065	Chlorine 17 Cl 35.453	Argon 18 Ar 39.948
Potassium 19 K 39.098	Calcium 20 Ca 40.078	Scandium 21 Sc 44.956	Titanium 22 Ti 47.883	Vanadium 23 V 50.942	Chromium 24 Cr 51.996	Manganese 25 Mn 54.938	Iron 26 Fe 55.845	Cobalt 27 Co 58.933	Nickel 28 Ni 58.693	Copper 29 Cu 63.546	Zinc 30 Zn 65.38	Gallium 31 Ga 69.723	Germanium 32 Ge 72.63	Arsenic 33 As 74.922	Selenium 34 Se 78.96	Bromine 35 Br 79.904	Krypton 36 Kr 83.80						
Rubidium 37 Rb 85.468	Sr 87.62	Yttrium 39 Y 88.906	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.906	Molybdenum 42 Mo 95.94	Technetium 43 Tc [98]	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.91	Palladium 46 Pd 106.42	Silver 47 Ag 107.87	Cadmium 48 Cd 112.41	Indium 49 In 114.82	Sn 118.71	Sb 121.76	Te 127.60	Iodine 53 I 126.90	Xenon 54 Xe 131.29						
Cesium 55 Cs 132.91	Ba 137.33	* 57-70	Lanthanum 57 Lu 174.97	Hafnium 72 Hf 178.49	Tantalum 73 Ta 180.95	Tungsten 74 W 183.84	Rhenium 75 Re 186.21	Osmium 76 Os 190.23	Iridium 77 Ir 192.22	Pt 195.08	Au 196.97	Hg 200.59	Tl 204.38	Pb 207.2	Bi 208.98	Po [209]	At [210]	Rn [222]					
Francium 87 Fr [223]	Ra [226]	* 89-102	Actinium 89 Ac [227]	Rf [261]	Db [262]	Sg [263]	Bh [264]	Hs [265]	Mt [266]	Uun [267]	Uuu [268]	Uub [269]	Uuq [270]										

Falola et al. *Curr. Op. in Solid State and Mat. Sci.* 2015

Metals that can be electrodeposited from aqueous solution

Substrate/Print Surface

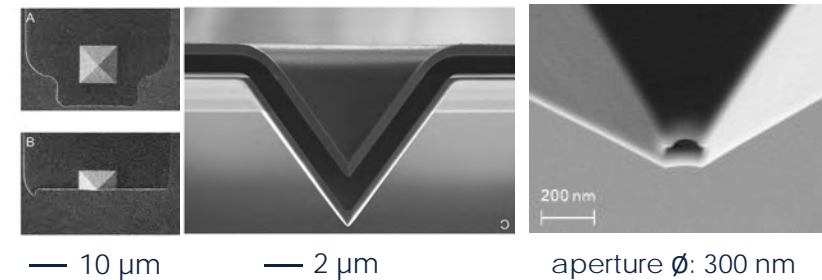
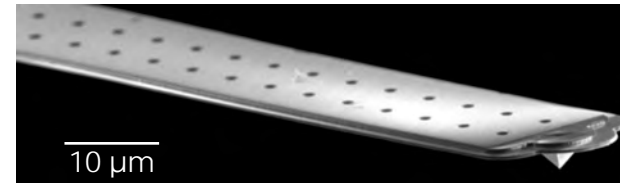
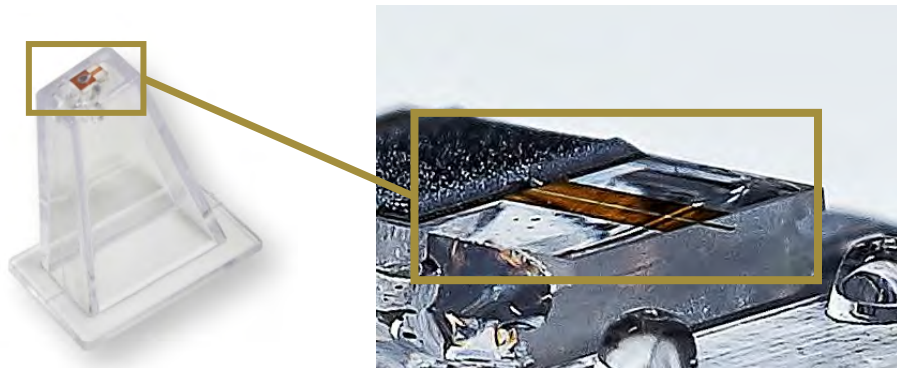


We have experience 3D printing Cu, Au, Ag, Pt, Ni

EXADDON IONTIP

IONTIP PRINTING PROBE

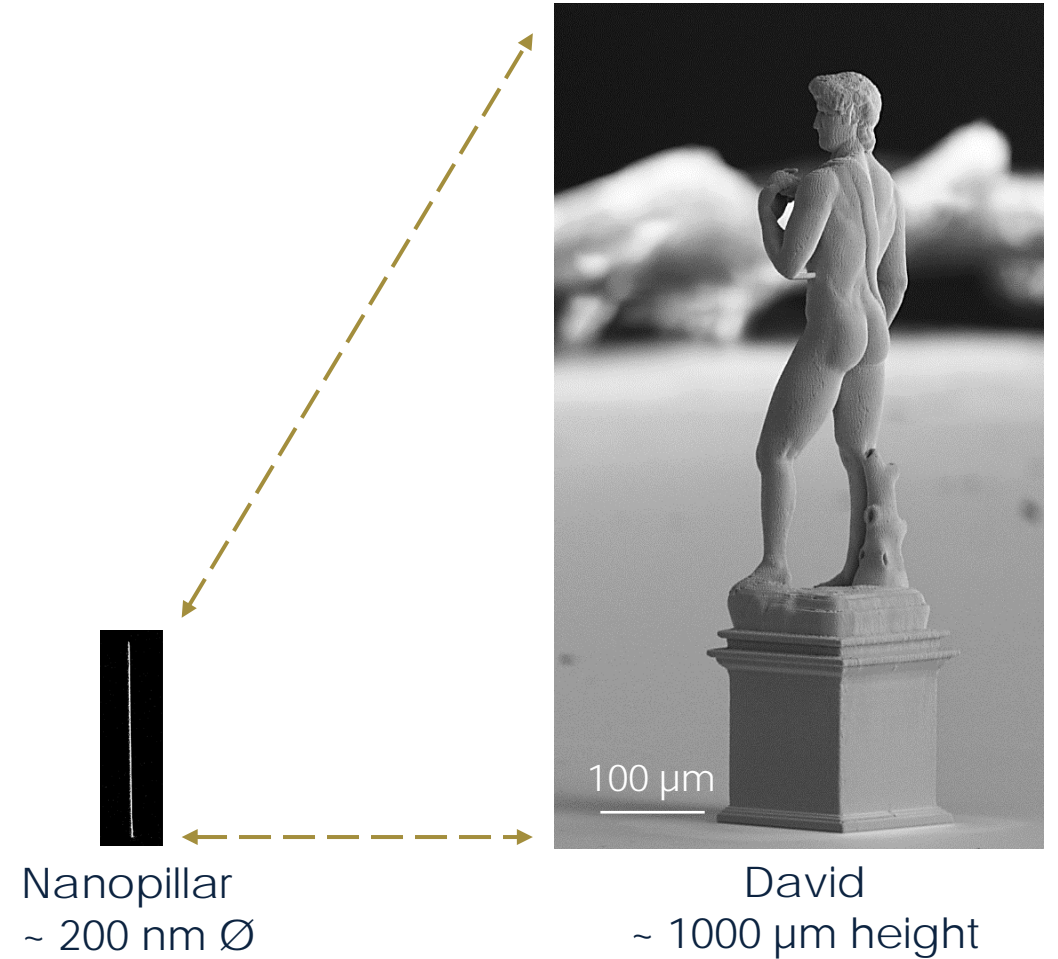
- A hollow, micro-channeled cantilever mounted to a user-friendly plastic housing containing the ink reservoir (1 μl capacity)
- Ink reservoir (circled) is filled before printing with a micropipette
- Iontip aperture diameter is just 300 nm



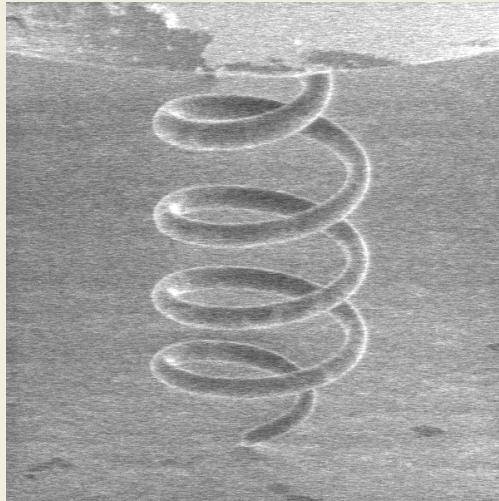
3D OBJECT PRINTING SIZE

NANOMETER ↔ MILLIMETER OBJECTS

- Possible object dimensions:
 - Starts at nanometer sizes
 - Up to 1 mm
- Printing speed up to 4 $\mu\text{m/s}$
- Changing print parameters changes minimum feature size (through tuning voxel diameter)
- Voxel size tunable on-the-fly
- 15 x 15 mm / 25 x 25 mm substrates (standard sizes)
- Substrate thickness is 0.4 - 1 mm



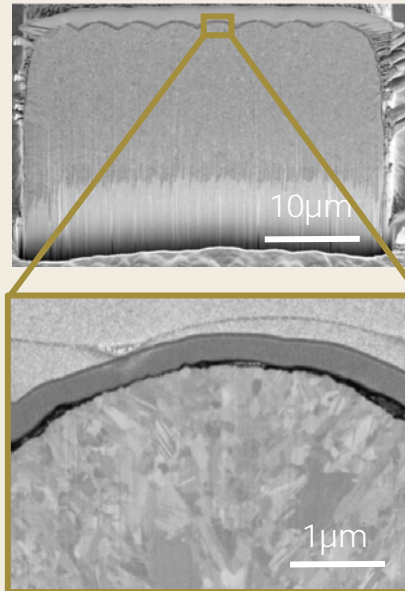
Mechanical hysteresis testing



(Click video to play)

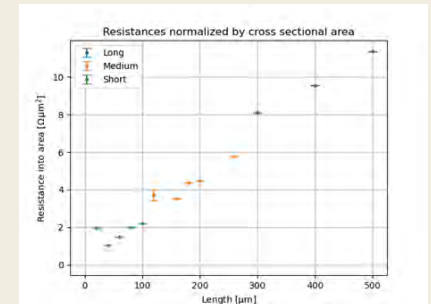
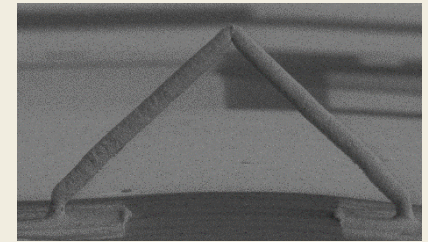
- The copper is mechanically stable
- The copper behaves elastically
- There is a good adhesion to the gold substrate

Material density inspection (FIB)



- The deposited material has >99% density
- Homogeneous grain structure - no visible traces of individual voxels

Electrical resistivity measurement

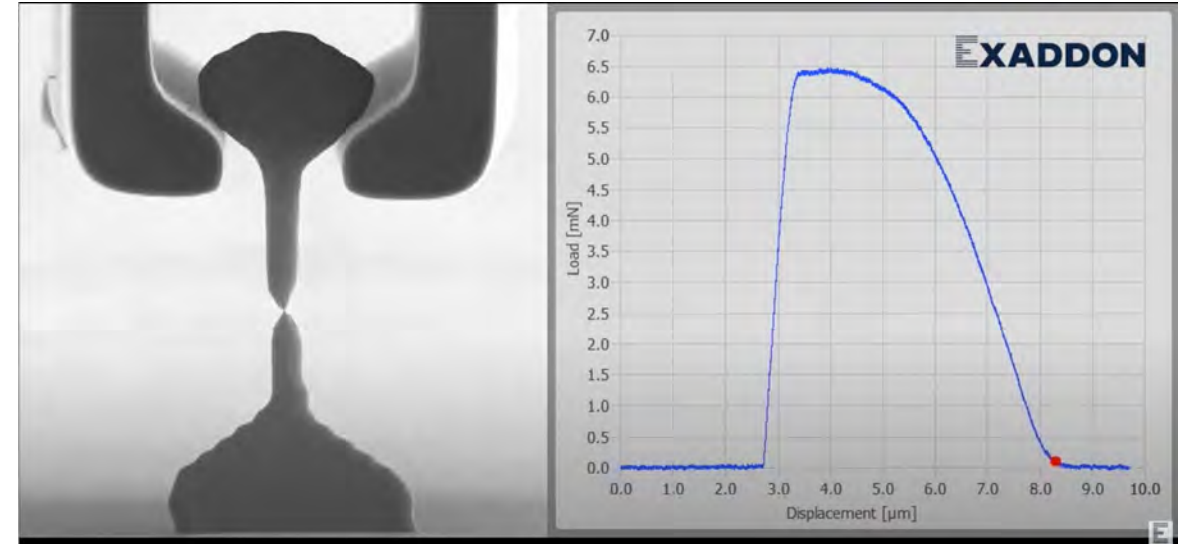


- Resistivity of printed structures:
 $\rho_{\text{copper}} = 2.2\text{E-}8 \text{ } \Omega \cdot \text{m}$
- This equals 75% of the conductivity of bulk copper

MATERIAL PROPERTIES

TENSILE STRENGTH & YIELD STRENGTH

- Conducted on 5 μm \varnothing copper test pieces printed with CERES
- Test pieces subjected to constant elongation using specialized nanoscale test platform (Alemnis AG, Switzerland)
- Behavior as expected; i.e. like a macroscale sample produced with conventional manufacturing techniques
- See more at:
exaddon.com/material-properties



Tensile strength of μAM structures = **342.5 MPa**
Comparison: cold-drawn copper = 344 MPa*

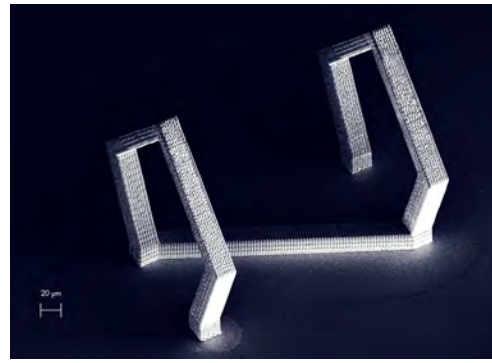
Yield strength of μAM structures: **320 MPa**
Comparison: cold-drawn copper = 333.4 MPa*

*[Copper, Cu; Cold Drawn \(matweb.com\)](http://Copper, Cu; Cold Drawn (matweb.com))

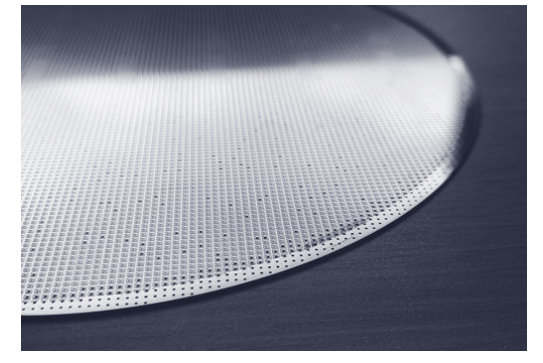
EXADDON USE CASE INDUSTRIES



HF Receivers
& Antennas

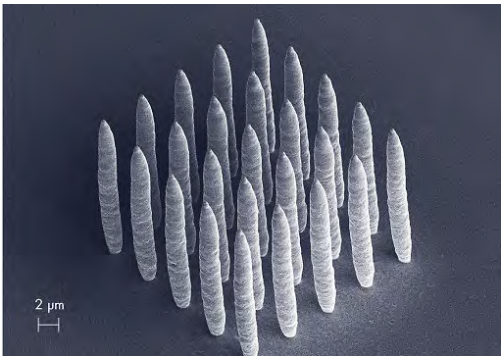


5G/THz
Communications

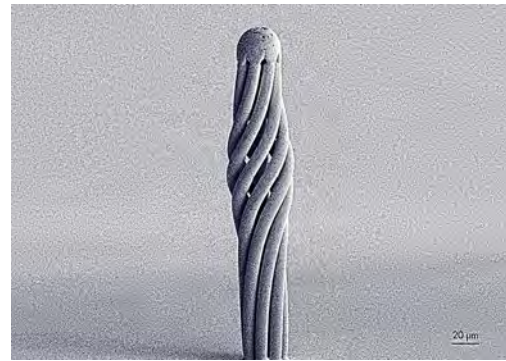


Semiconductor
Modification

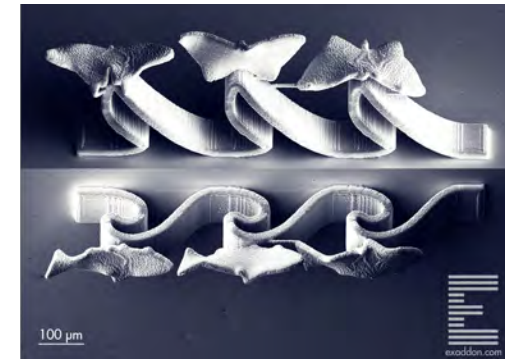
Neural Interfaces
& Electrodes



Microelectronics



Watchmaking



POTENTIAL APPLICATIONS IN PHOTONICS

Existing uses of 3DP in photonics

Helices & lattices

2D line printing

Micro object arrays



EXISTING USES OF μ 3DP IN PHOTONICS

Waveguides

Bertoncini A., Liberale C. "3D printed waveguides based on photonic crystal fiber designs for complex fiber-end photonic devices," *Optica* 7, 1487-1494 (2020)

Micro lenses

Thomas R., Li J., *et al.* "In situ fabricated 3D micro-lenses for photonic integrated circuits," *Opt. Express* 26, 13436-13442 (2018)

Gold helices

Gansel J.K., M. Thiel M., *et al.* "Gold Helix Photonic Metamaterial as Broadband Circular Polarizer" *Science*, Vol 325, Issue 5947 pp. 1513-1515 (2009)

Photonic Crystals

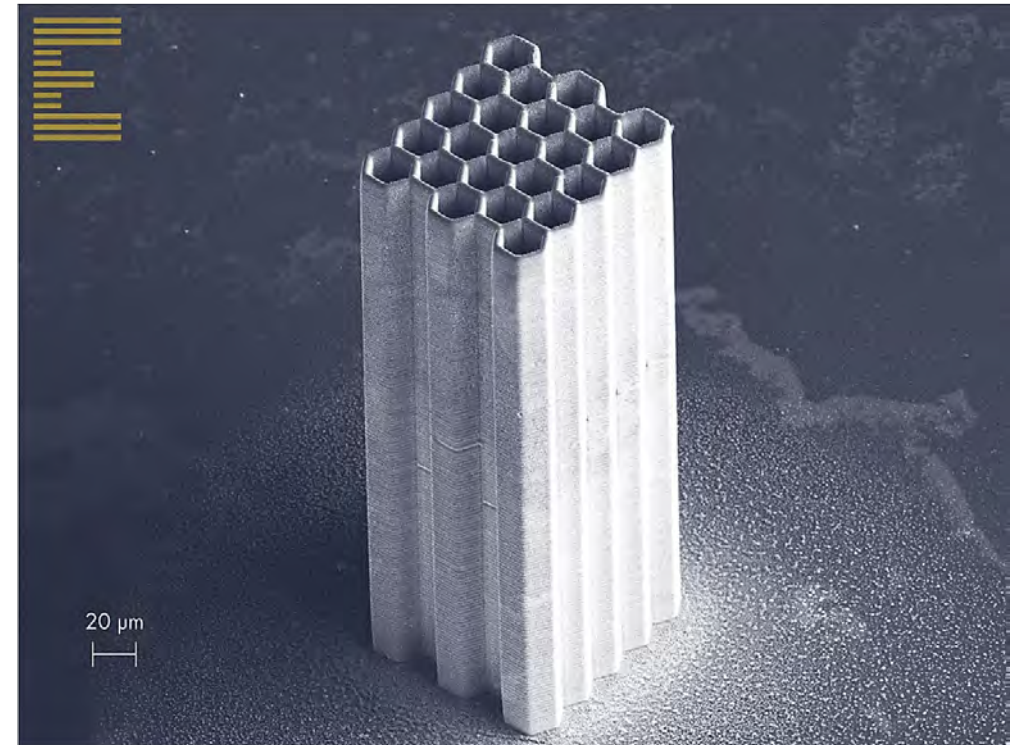
Tubio C., Nóvoa López J.A., *et al.* "3D printing of Al₂O₃ photonic crystals for terahertz frequencies." *RSC Adv.* 6. 2450. (2016)

How could CERES be used to used for such applications?

3D PRINTED HOLLOW OBJECTS

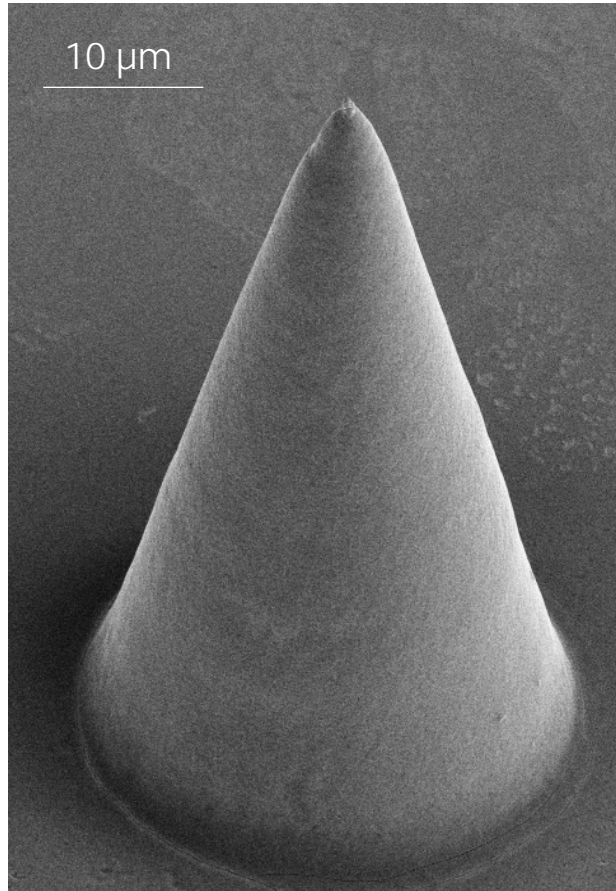


Organic, non-linear geometries are possible

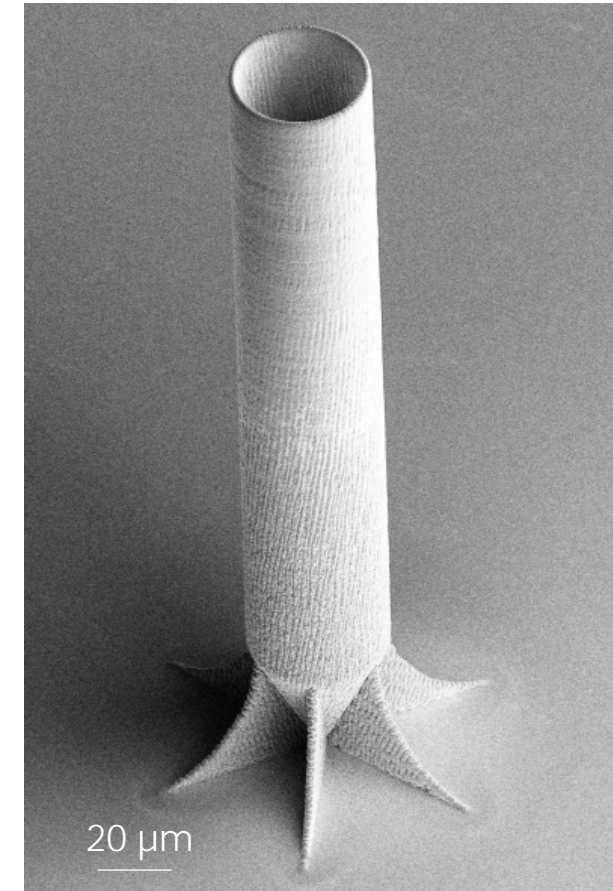
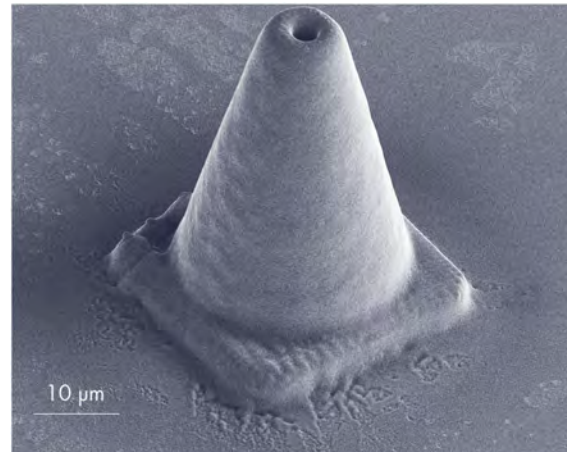
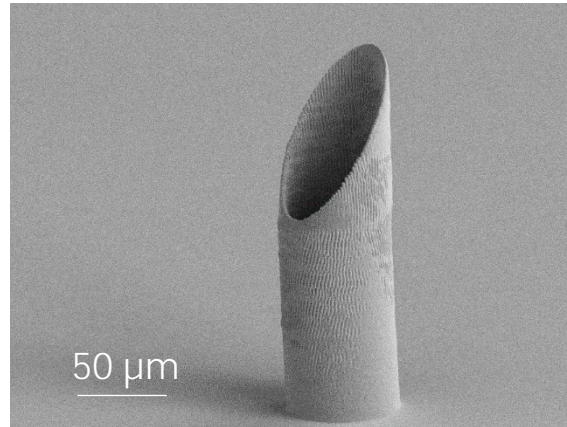


Copper microchannels printed on a flexible polymer substrate (PEDOT:PSS)

3D PRINTED HOLLOW OBJECTS

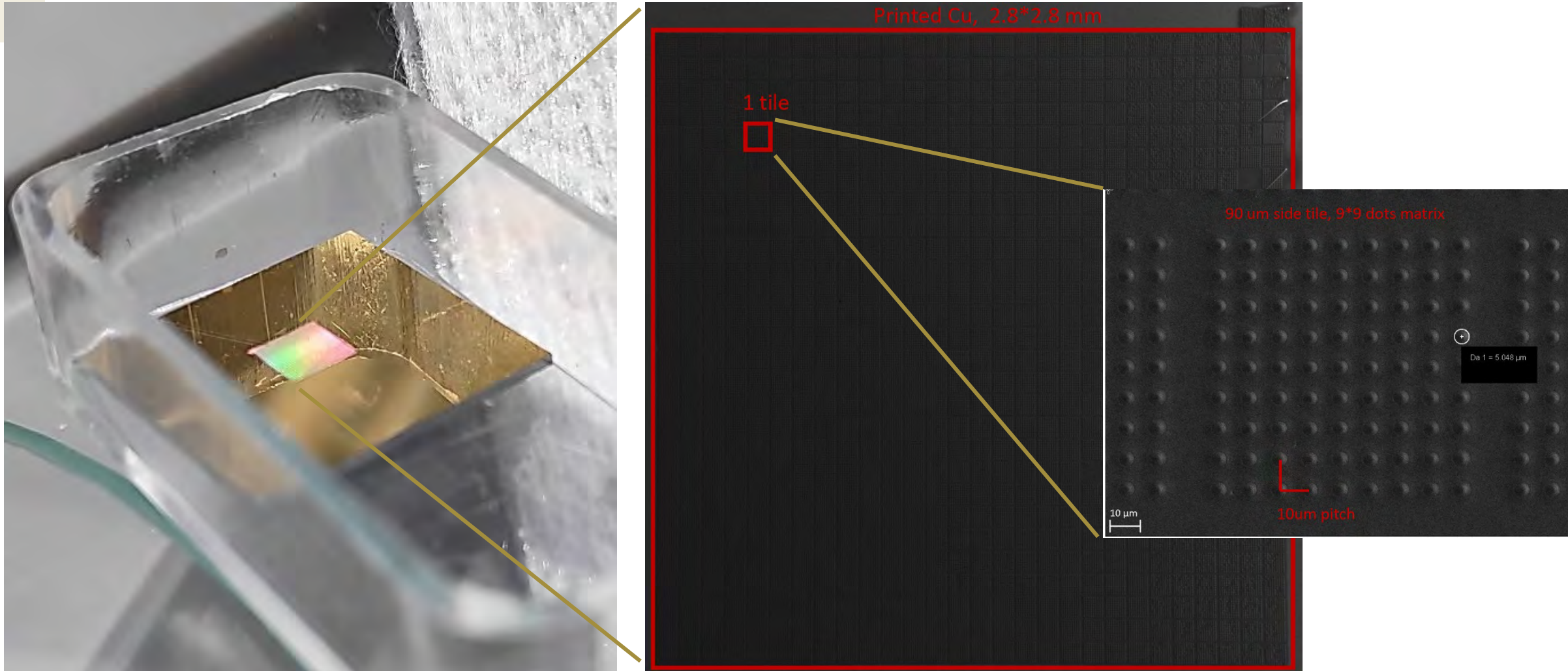


Hollow cone (aperture could be created by FIB milling)

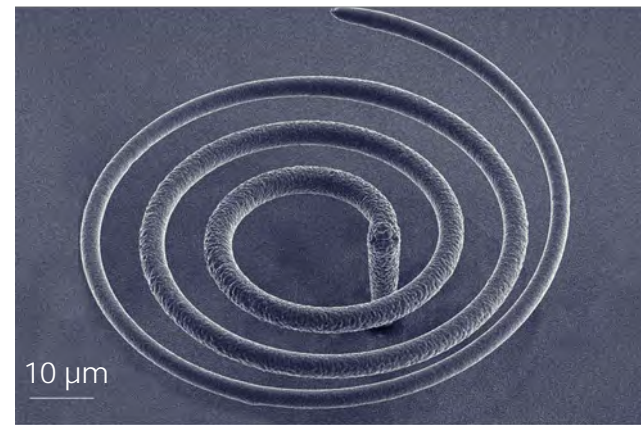
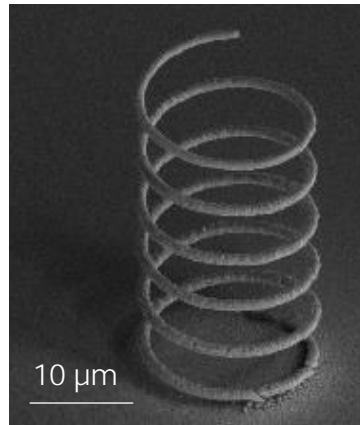
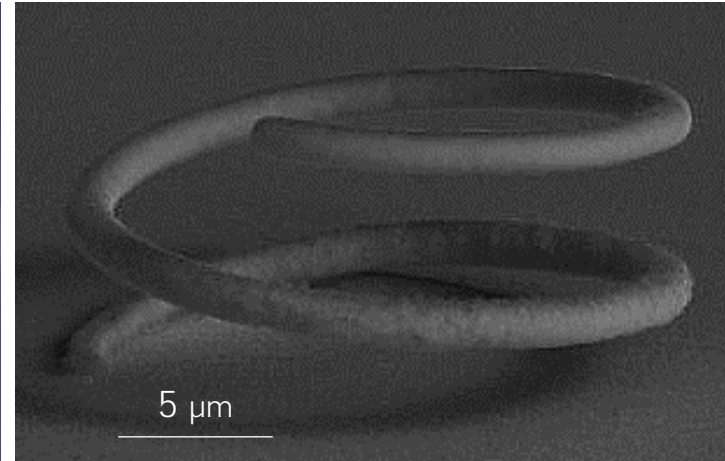


Height 400 μm

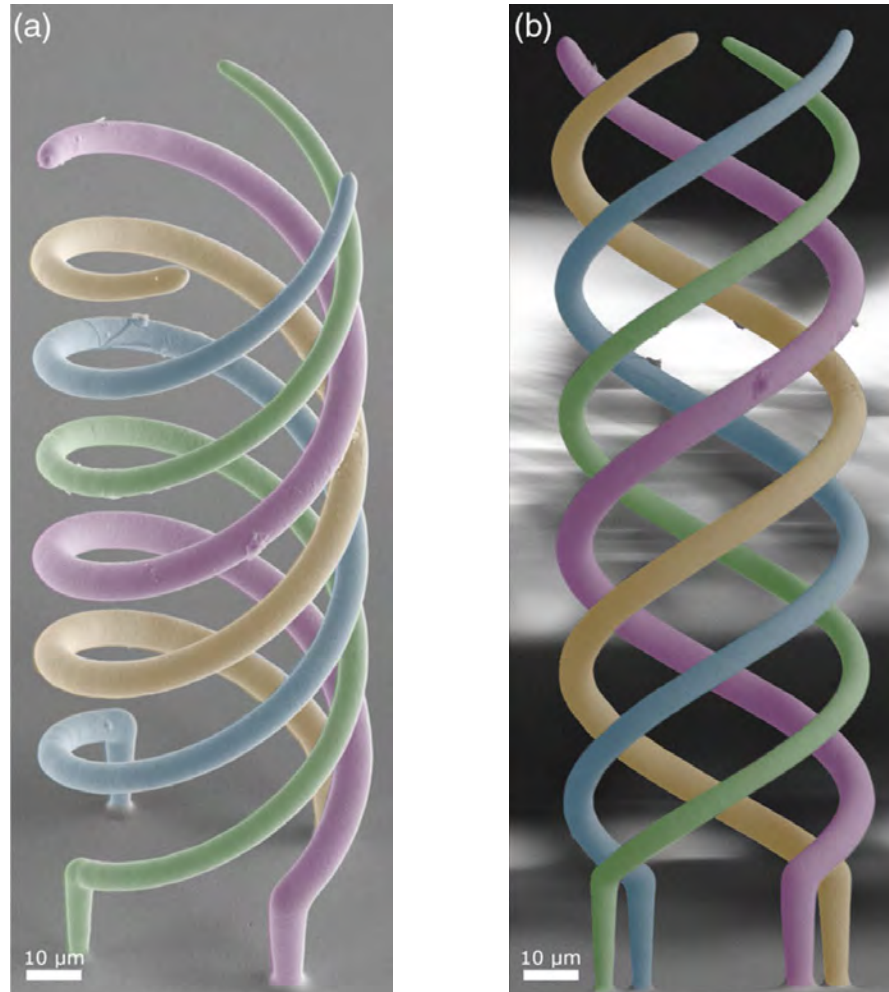
MICRO DOTS @ LARGE AREA



HELICES AND COIL STRUCTURES



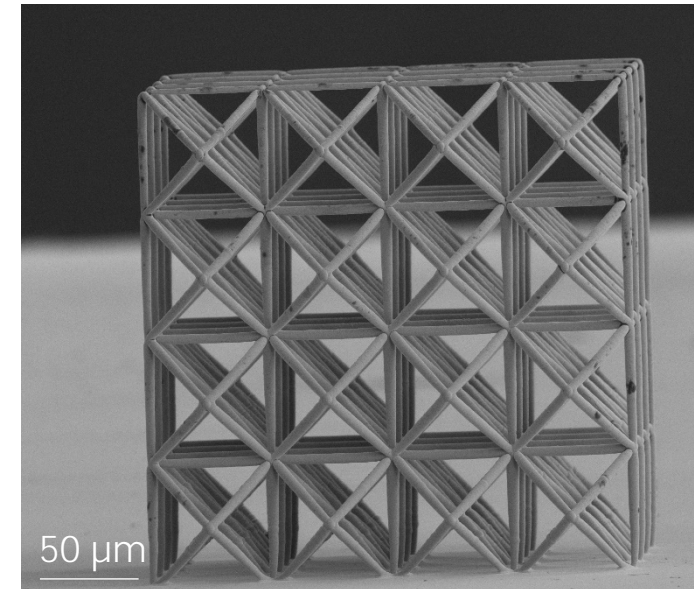
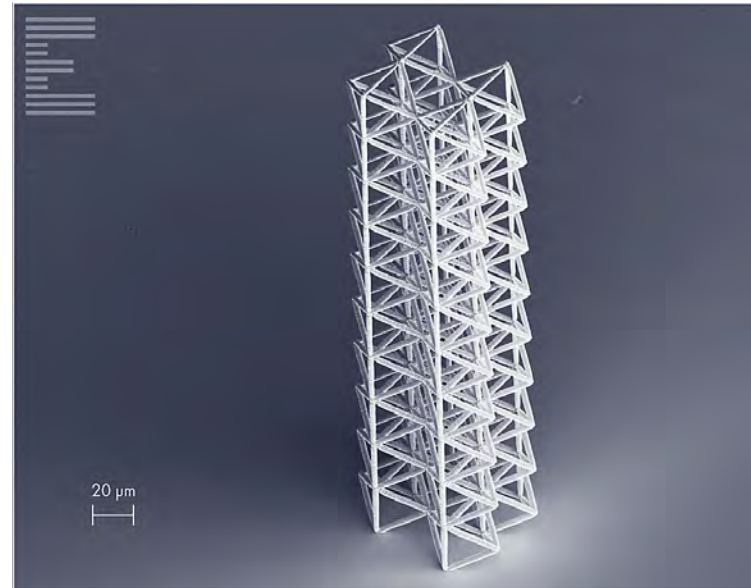
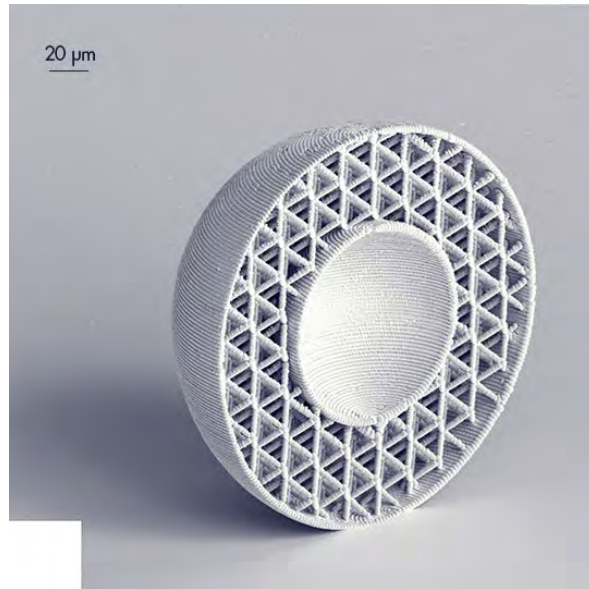
TUNING PRINT PARAMETERS



Ercolano et al. *Adv. Eng. Mater.* 2019

- CERES offers tunable print parameters on-the-fly
- Voxel diameter changed by adjusting the applied pressure of print ink through the tip
- Same print tip throughout
- Each strand is a different diameter
- Strands printed layer-by-layer
- Unique technology; unrivalled at these dimensions in metal printing

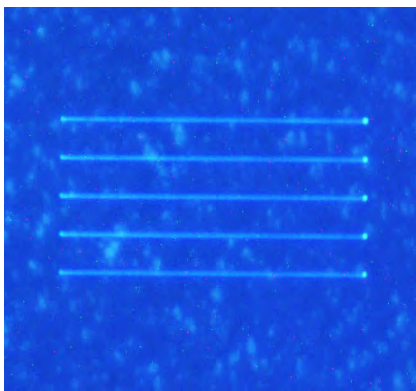
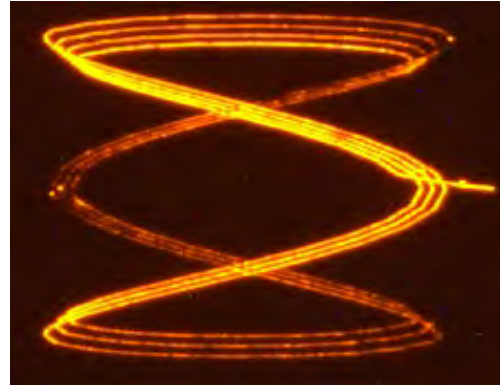
LATTICES FOR FUNDAMENTAL RESEARCH



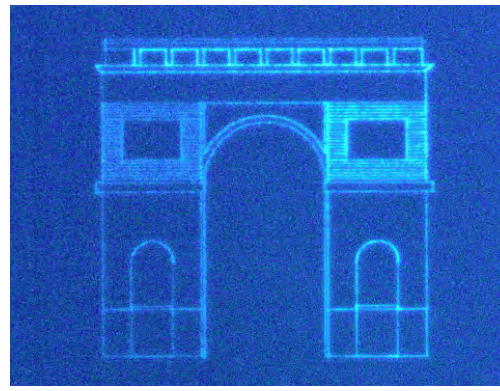
2D SURFACE PATTERNING



Fluorescently labeled polystyrene beads (20nm) on glass

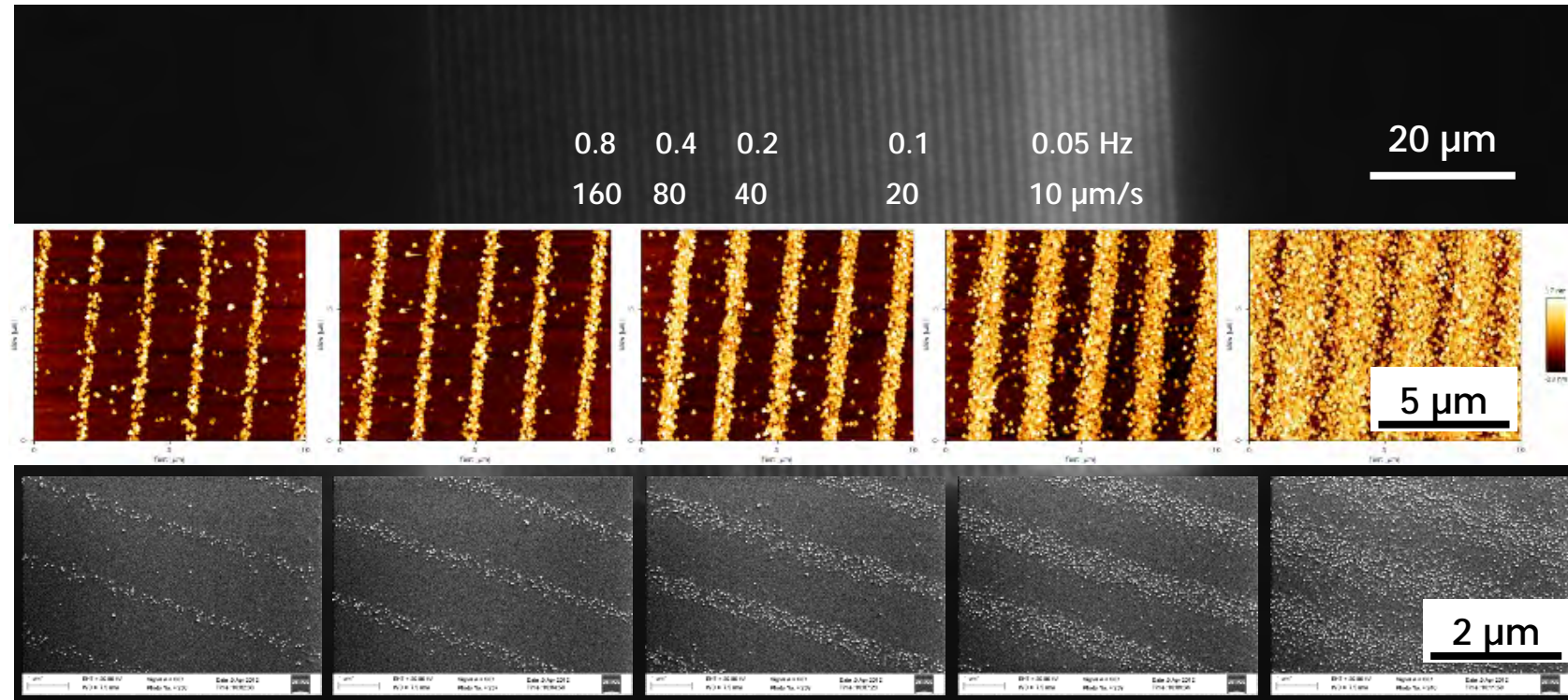


DAPI in glycerol (1mg/ml) on coated glass



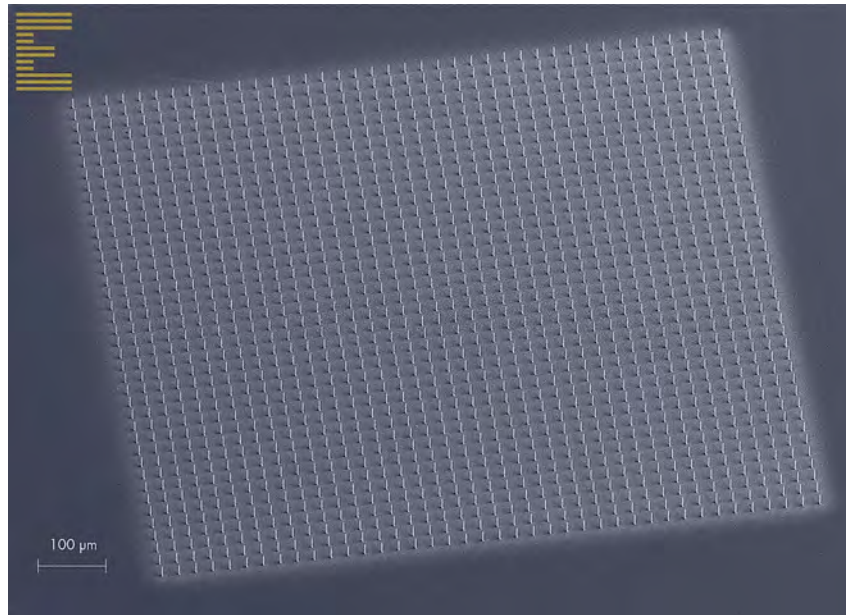
- Microscopic nanolithography printer
- Printing of vectors and complex structures
- Dispensing liquids enables printing of
 - Metals
 - Alloys
 - Polymers
 - Nanoparticles
 - In general, particle sizes ≤ 200 nm, suitable viscosity
- Up to $100 \mu\text{m/s}$ writing speed
- Precision liquid/particle control
- μm to cm lines and movements
- Fluid rate as low as femtoliters/s

2D SURFACE PATTERNING

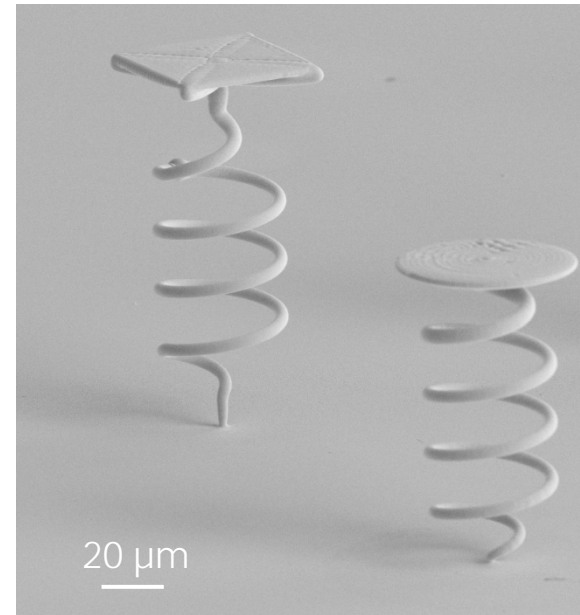


Grüter et al., Nanoscale (2013)

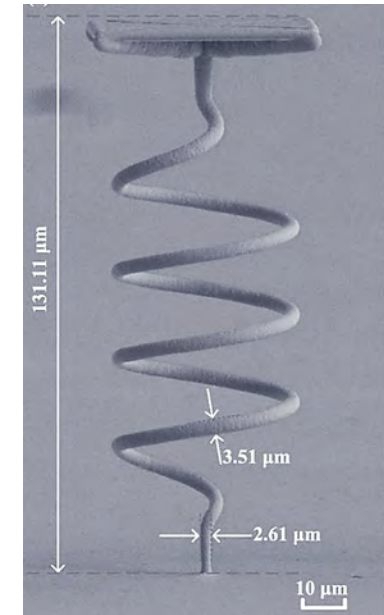
MICROSCALE OBJECT ARRAYS



1600 pillars printed on a 1mm x 1mm grid.
Each pillar is ~1.6 μm Ø

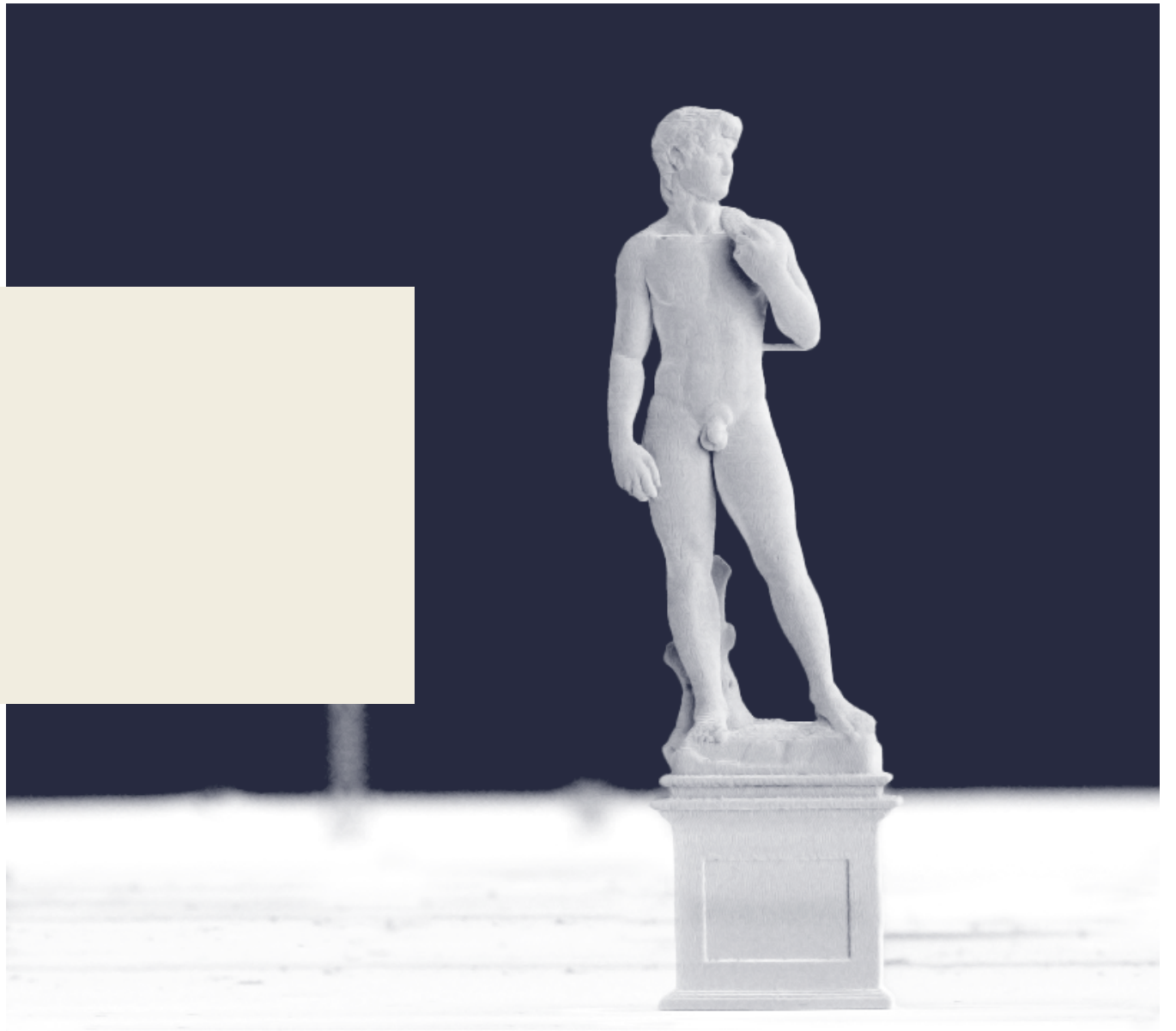


Printed objects



Ren W., *et al.* Materials. 2020

Q&A



THANK
YOU FOR
YOUR
ATTENTION



Edgar Hepp
CEO



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hello@exaddon.com

exaddon.com