Imperial College London
Stepan Lucyszyn

Centre for EO Instrumentation
2019: RP10G0435A202

NPL National Physical Laboratory
Nick Ridler

Polymer-based 3D Printed Integrated Front-end Hardware for Atmospheric Science Observations Multi-channel Microwave Sounder Payloads (3DPAMS)

Fast Track Grant: 15 months

CENTRE FOR EARTH OBSERVATION INSTRUMENTATION
INSTRUMENTATION
TECHNOLOGY SHOWCASE
23RD & 24TH JUNE 2021
VIRTUAL MEETING

Overview:

3D-Printed Microwave-to-THz Technologies: ICL-NPL Landscape since 2015

Previous 15-month Pilot Study (UK Space Agency)

This CEOI-funded Project

Acknowledgements

Questions

3D-Printed Microwave-to-THz Technologies: ICL-NPL Landscape since 2015

J1. M. D'Auria, W. J. Otter, J. Hazell, B. T. W. Gillatt, C. Long-Collins, N. M. Ridler, and S. Lucyszyn, "3-D printed metal-pipe rectangular waveguides", *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 5, no. 9, pp. 1339-1349, Sep. 2015 **(Most Popular T-CPMT Article, Xplore® Usage Statistics, May. 2021)**.

C1. W. J. Otter and S. Lucyszyn, "3-D printing of microwave components for 21st century applications", *IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP 2016)*, Chengdu, China, Jul. 2016 **(Invited)**.

J2. B. T. W. Gillatt, M. D'Auria, W. J. Otter, N. M. Ridler, and S. Lucyszyn, "3-D printed variable phase shifter", *IEEE Microwave and Wireless Component Letters*, vol. 26, no.10, pp. 822-824, Oct. 2016.

J3a. W. J. Otter and S. Lucyszyn, "Printing: the future of THz", *IET Electronics Letters*, vol. 53, no. 7, p. 433, Mar. 2017 **(Invited Feature Article)**.

J3b. W. J. Otter, N. M. Ridler, H. Yasukochi, K. Soeda, K. Konishi, J. Yumoto, M. Kuwata-Gonokami, and S. Lucyszyn, "3D printed 1.1 THz waveguides", *IET Electronics Letters*, vol. 53, no. 7, pp. 471-473, Mar. 2017.

C2. W. J. Otter, N. M. Ridler, and S. Lucyszyn, "3D printed waveguides: A revolution in low volume manufacturing for the 21st century", *ARMMS RF & Microwave Society Conference*, Nr Thame, UK, pp. 1-6, Apr. 2017 **(Best Paper Award)**.

J4. W. J. Otter and S. Lucyszyn, "Hybrid 3-D-printing technology for tunable THz applications", *Proceedings of IEEE, Special Issue on Additive Manufacturing of Radio-Frequency Components*, vol. 105, no. 4, pp. 756-767, Apr. 2017 **(Invited)**.

C3. S. Lucyszyn, X. Shang, W. J. Otter, C. Myant, R. Cheng, and N. M. Ridler, "Polymer-based 3D printed millimeter-wave components for spacecraft payloads", *IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes (IMWS-AMP)*, Ann Arbor, USA, Jul. 2018 **(Invited)**.

J5. B. Al-Juboori, J. Zhou, Y. Huang, M. Hussein, A. Alieldin, W. J. Otter, D. Klugmann, and S. Lucyszyn, "Lightweight and low-loss 3-D printed millimeter-wave bandpass filter based on gap-waveguide", *IEEE Access*, vol. 7, no. 1, pp. 2624-2632, Jan. 2019.

J6. J. Sun, A. Dawood, W. J. Otter, N. M. Ridler, and S. Lucyszyn, "Microwave characterization of low-loss FDM 3-D printed ABS with dielectric-filled metal-pipe rectangular waveguide spectroscopy", *IEEE Access*, vol. 7, pp. 95455-95486, Jul. 2019.

C4. S.-H. Shin, D. Alyasiri, M. D'Auria, W. J. Otter, C. W. Myant, D. Stokes, Z. Tian, N. M. Ridler, and S. Lucyszyn, "Fully 3-D printed tunable microwave subsystem," *IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes (IMWS-AMP)*, Bochum, Germany, Jul. 2019 **(Invited and Best Student Paper Award)**.

J7. S.-H. Shin, D. Alyasiri, M. D'Auria, W. J. Otter, C. W. Myant, D. Stokes, Z. Tian, N. M. Ridler, and S. Lucyszyn, "Polymer-based 3-D printed Ku-band steerable phased-array antenna subsystem", *IEEE Access*, vol. 7, pp. 106662-106673, Aug. 2019.

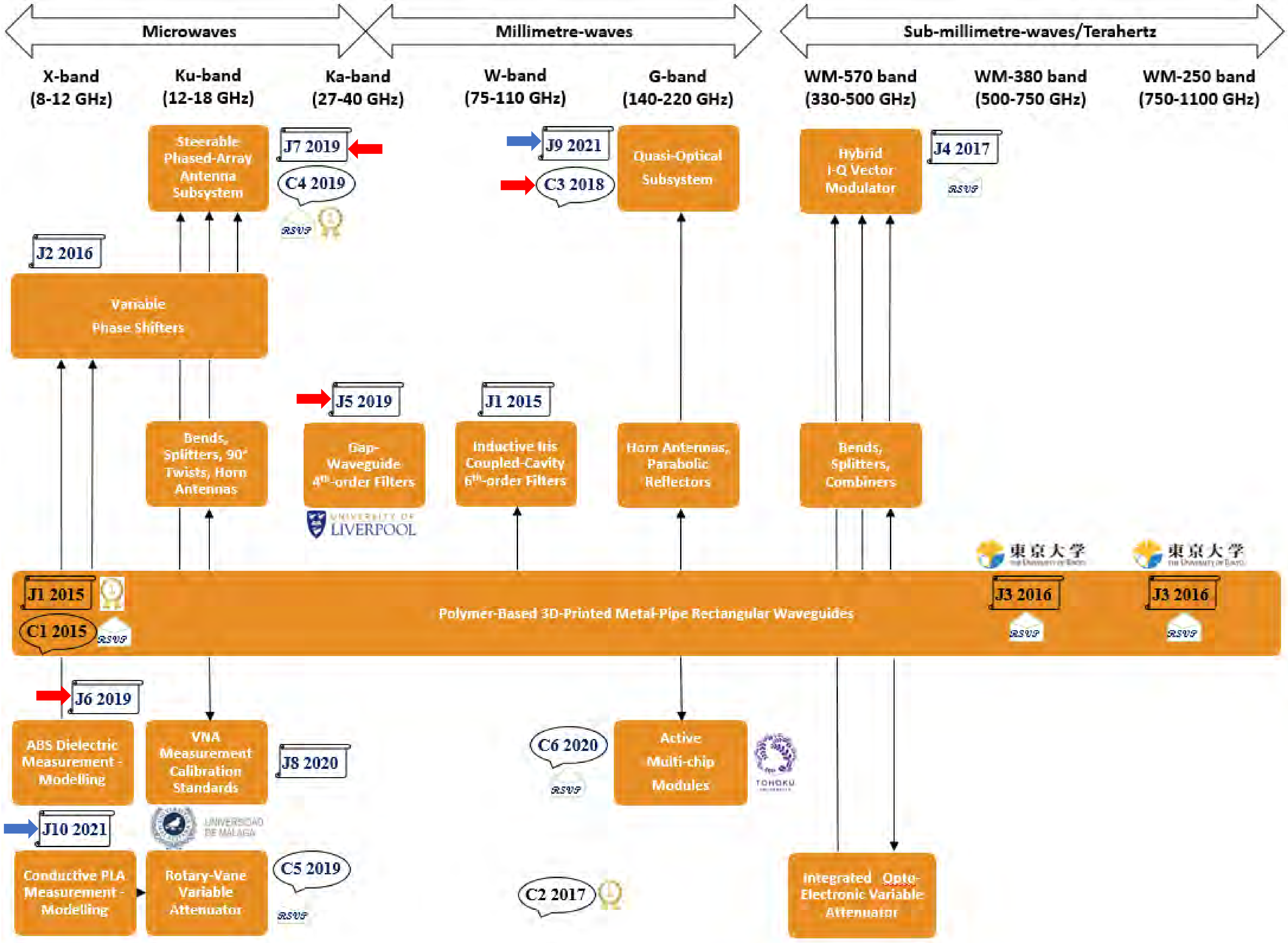
C5. E. Márquez-Segura, W. J. Otter, and S. Lucyszyn, N. Ridler, "Fabricationes aditiva de atenuadores variables de veleta rotatoria en guía de onda", *XXXIV Simposium Nacional de la Unión Científica Internacional de Radio (URSI 2019)*, Sevilla, Spain, Sep. 2019 **(Invited)**.

J8. A. Jones, S. Lucyszyn, E. Márquez-Segura, N. Ridler, J. Skinner, and D. Stokes, "3-D printed standards for calibration of microwave network analysers", *Measurement*, Elsevier, vol. 158, no. 107682, pp. 1-10, Jul. 2020

C6. S. Lucyszyn, L. Zhu, T. Machii, M. Motoyoshi and N. Suematsu, "Towards 3-D printed (sub-)THz active device packaging and multi-chip modules", *2020 IEEE International Symposium on Radio-Frequency Integrated Technology (RFIT2020)*, Hiroshima, Japan, Sep. 2020 **(Invited)**.

J9. S.-H. Shin, X. Shang, N. M. Ridler, and S. Lucyszyn, "Polymer-based 3-D printed 140-220 GHz low-cost quasi-optical components and integrated subsystem assembly", *IEEE Access*, vol. 9, pp. 28020-28038, Feb. 2021.

J10. E. Márquez-Segura, S.-H. Shin, A. Dawood, N. Ridler, and S. Lucyszyn, "Microwave characterization of conductive PLA and its application to a 12 to 18 GHz 3-D printed rotary vane attenuator" *IEEE Access*, vol. 9, pp. 84327- 84343, Jun. 2021.



Microwaves
Millimetre-waves
Sub-millimetre-waves/Terahertz
X-band (8-12 GHz)
Ku-band (12-18 GHz)
Ka-band (27-40 GHz)
W-band (75-110 GHz)
G-band (140-220 GHz)
WM-570 band (330-500 GHz)
WM-380 band (500-750 GHz)
WM-250 band (750-1100 GHz)
Steerable Phased-Array Antenna Subsystem
J7 2019
C4 2019
J9 2021
C3 2018
Quasi-Optical Subsystem
Hybrid I-Q Vector Modulator
J4 2017
J2 2016
Variable Phase Shifters
J5 2019
J1 2015
Bends, Splitters, 90° Twists, Horn Antennas
Gap-Waveguide 4th-order Filters
Inductive Iris Coupled-Cavity 6th-order Filters
Horn Antennas, Parabolic Reflectors
Bends, Splitters, Combiners
UNIVERSITY OF LIVERPOOL
J1 2015
C1 2015
Polymer-Based 3D-Printed Metal-Pipe Rectangular Waveguides
J3 2016
J3 2016
J6 2019
ABS Dielectric Measurement - Modelling
VNA Measurement Calibration Standards
J8 2020
C6 2020
Active Multi-chip Modules
TOHOKU
J10 2021
UNIVERSIDAD DE MÁLAGA
Conductive PLA Measurement - Modelling
Rotary-Vane Variable Attenuator
C5 2019
C2 2017
Integrated Opto-Electronic Variable Attenuator

Previous 15-month Pilot Study

2017 UK Space Agency grant NSTP3-FT-046:

3D Printed Millimetre-wave Components for
Guided-wave and Quasi-optical Systems for Spacecraft

This work was funded by the UK Space Agency under grant NSTP3-FT-046

IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications
(IMWS-AMP 2018), July 16-18, 2018, Ann Arbor, MI, USA

Polymer-based 3D Printed Millimeter-wave Components for Spacecraft Payloads

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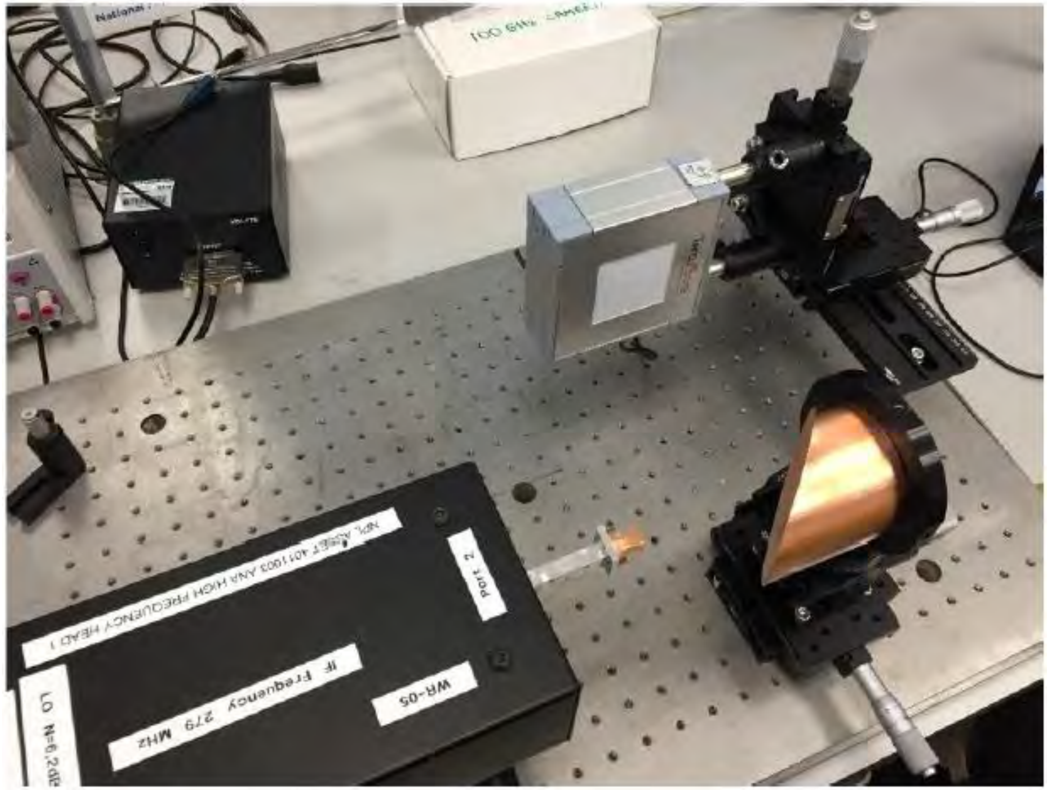
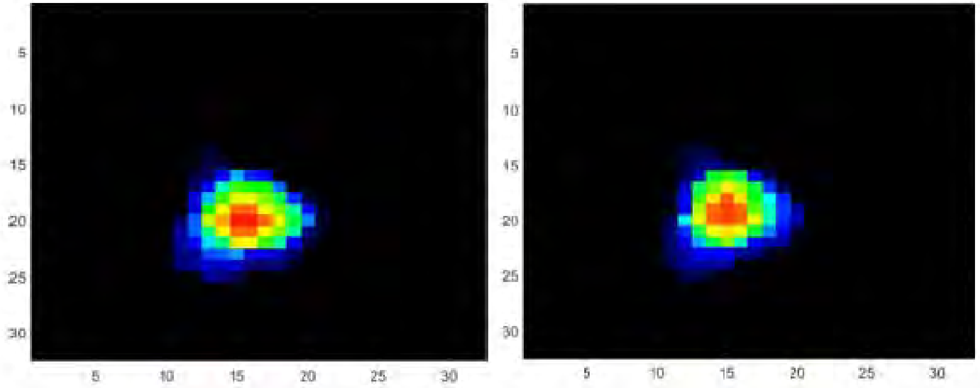


(a)



(b)

Quasi-optical measurement setup: (a) showing the G-band 3D printed rectangular horn antenna and parabolic mirror (after plating); and (b) preliminary field intensity plots at 160 GHz without background noise cancellation – (left) from commercial components, (right) from 3D printed components.

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Multidisciplinary | Rapid Review | Open Access Journal

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Lightweight and Low-Loss 3-D Printed Millimeter-Wave Bandpass Filter Based on Gap-Waveguide

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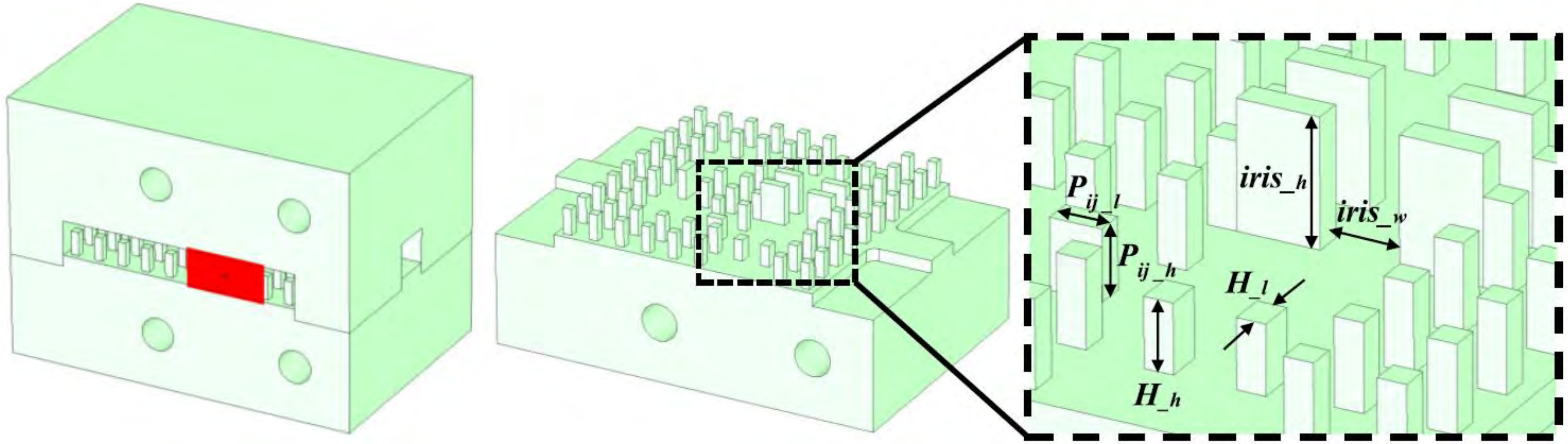
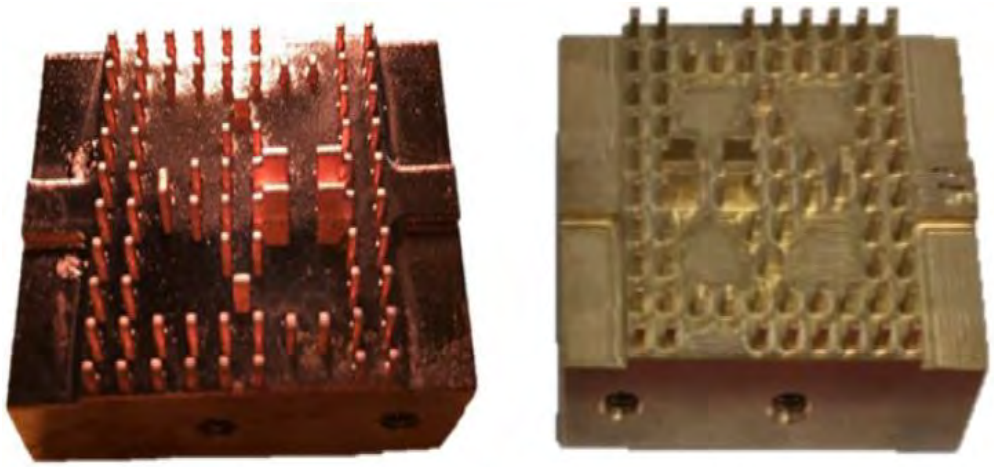
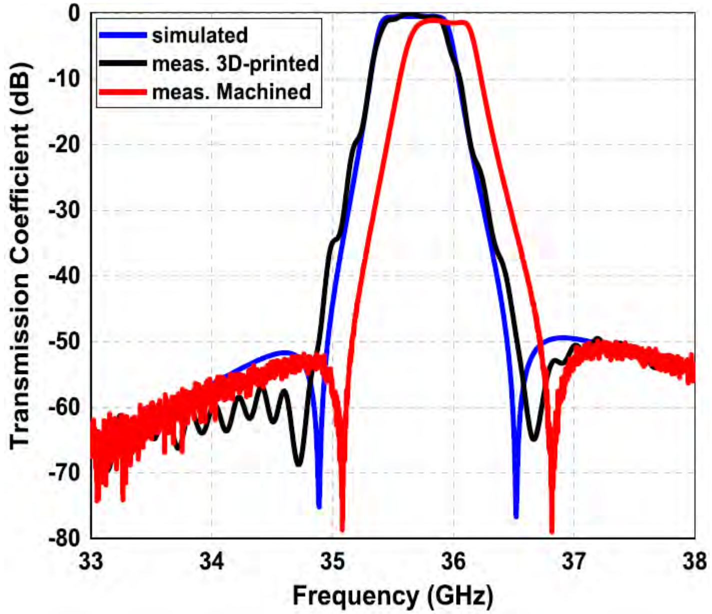
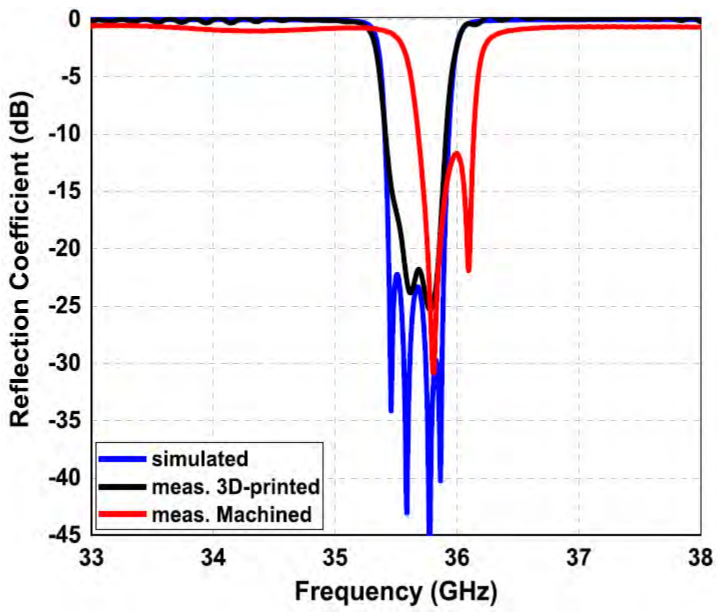




(a) (b)





Prototype Ka-band BPFs: (a) Polyjet 3-D printed (weighing 17 g); and (b) CNC machined (weighing 112 g).

This work was funded by the UK Space Agency under grant NSTP3-FT-046

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Multidisciplinary : Rapid Review : Open Access Journal

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Microwave Characterization of Low-Loss FDM 3-D Printed ABS With Dielectric-Filled Metal-Pipe Rectangular Waveguide Spectroscopy

JINGYE SUN[1], ATTIQUE DAWOOD[1], WILLIAM J. OTTER[1], NICK M. RIDLER[2], (Fellow, IEEE), AND STEPAN LUCYSZYN[1], (Fellow, IEEE)
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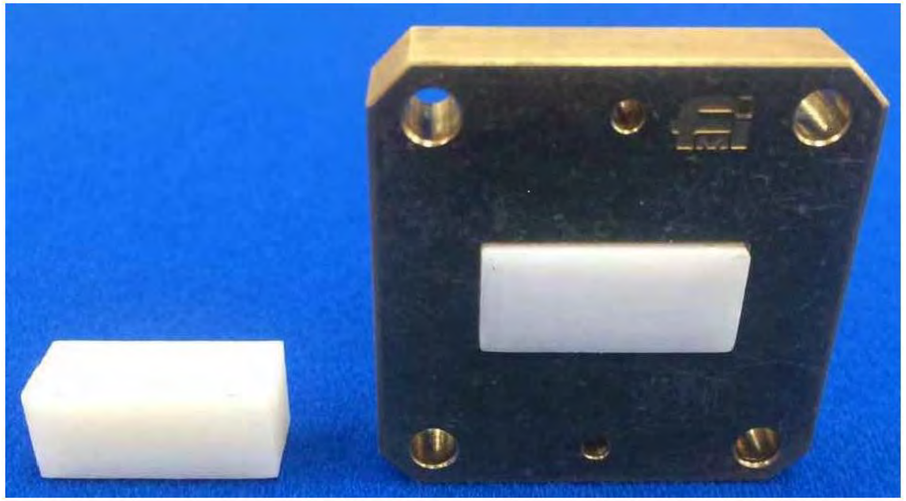

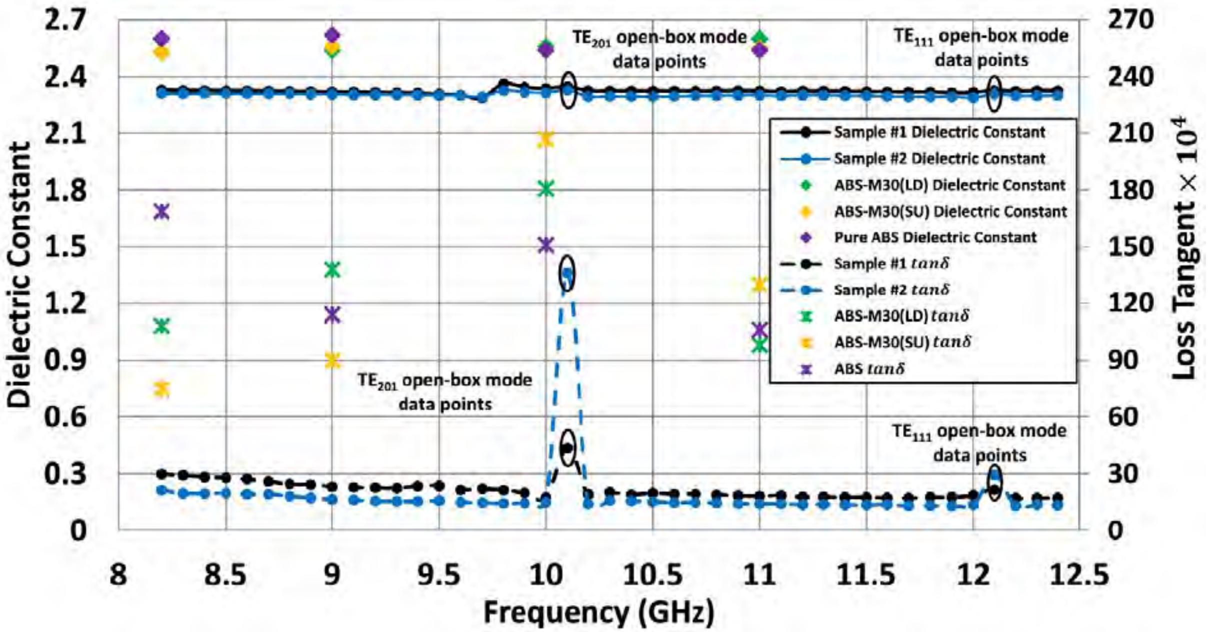

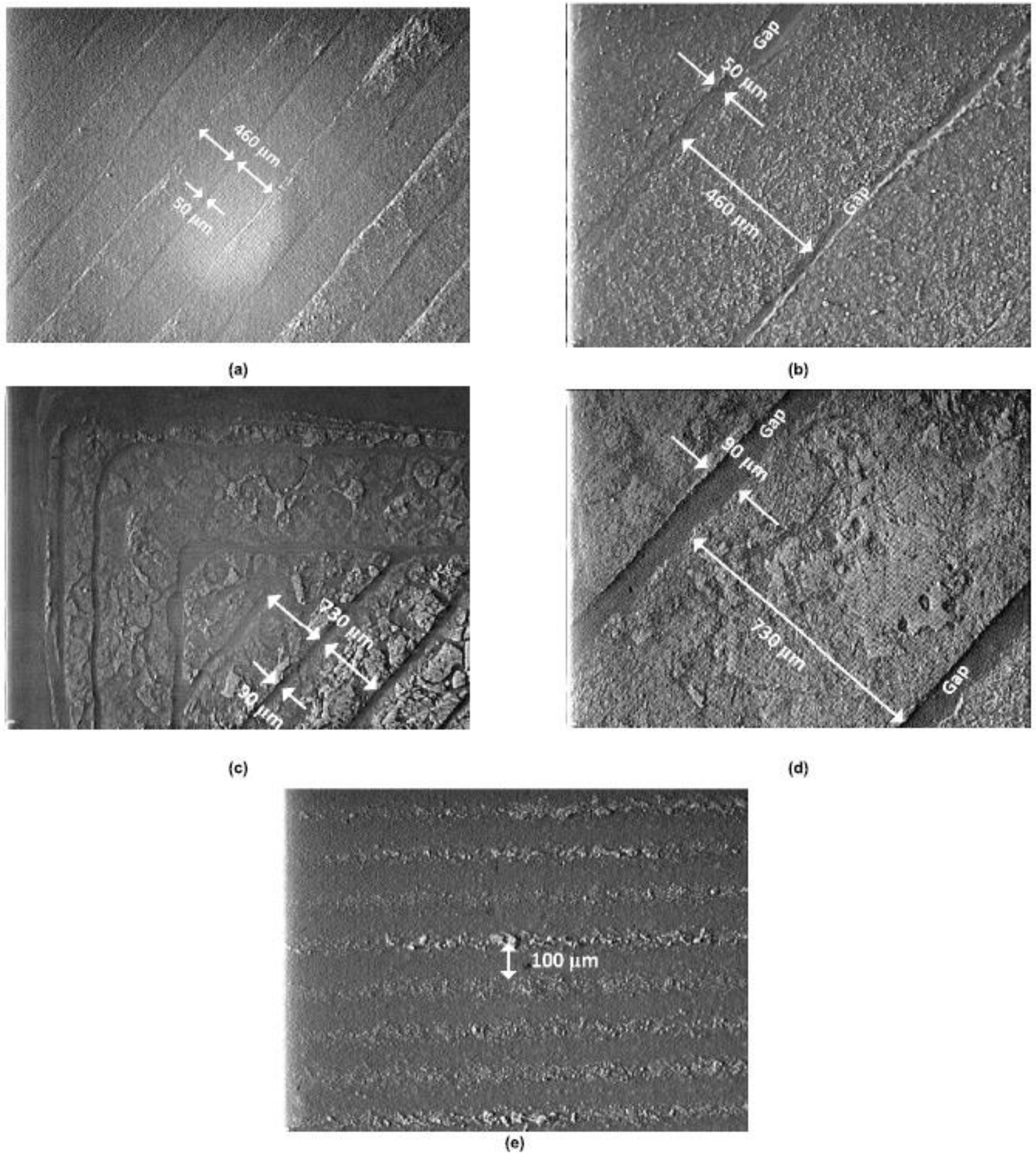

Photomicrographs of an FDM 3-D printed ABS sample under test with nominal 100 m layer height and 100% infill printer settings: (a) top layer *x-y* plane view; (b) top layer *x-y* plane close-in view; (c) bottom layer *x-y* plane view of a corner; (d) bottom layer *x-y* plane close-in view; and (e) vertical build *x-z* plane view.

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Digital Object Identifier 10.1109/ACCESS.2019.2932431

Polymer-Based 3-D Printed Ku-Band Steerable Phased-Array Antenna Subsystem

SANG-HEE SHIN[1], (Student Member, IEEE), DIYAR F. ALYASIRI[1], MARIO D'AURIA[1], WILLIAM J. OTTER[1], CONNOR W. MYANT[2], DANIEL STOKES[3], ZHENGRONG TIAN[3], NICK M. RIDLER[3], (Fellow, IEEE), AND STEPAN LUCYSZYN[1], (Fellow, IEEE)

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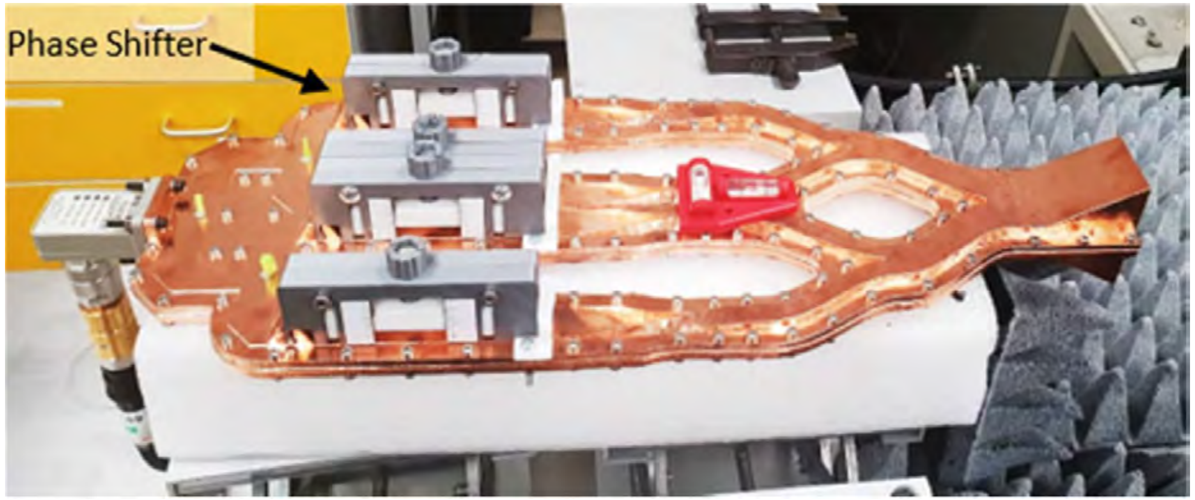
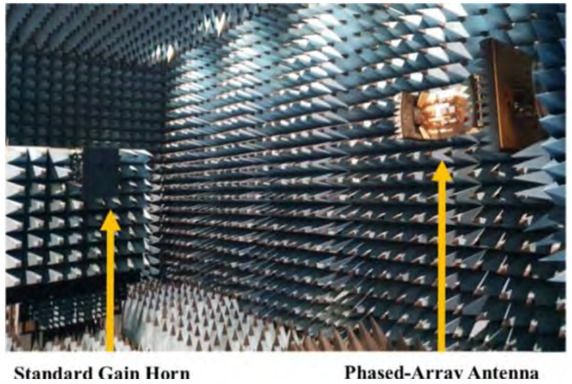
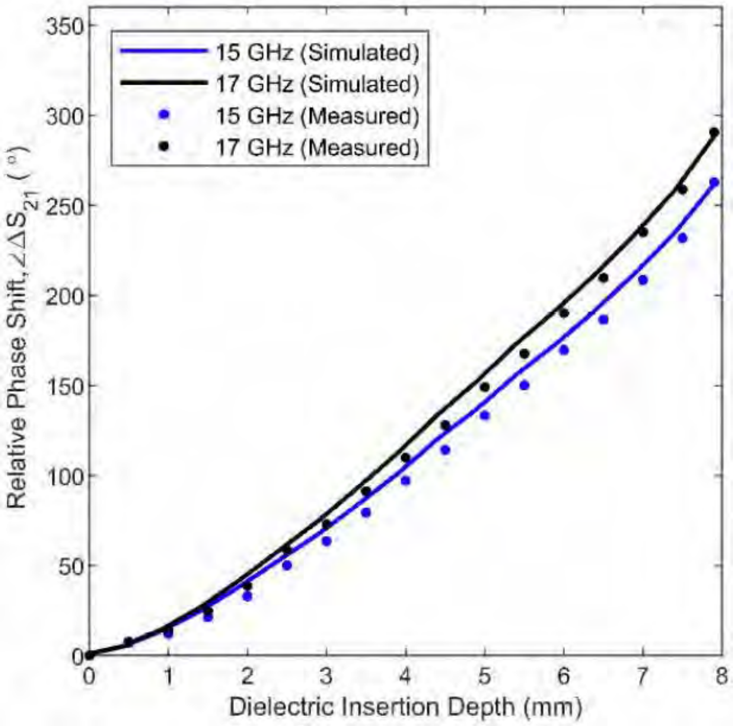
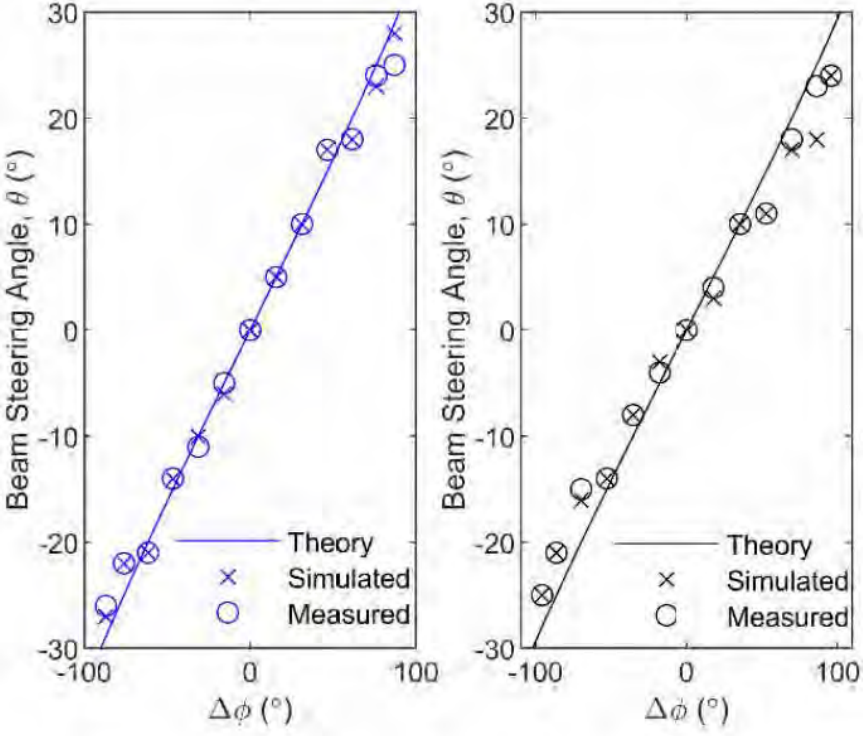


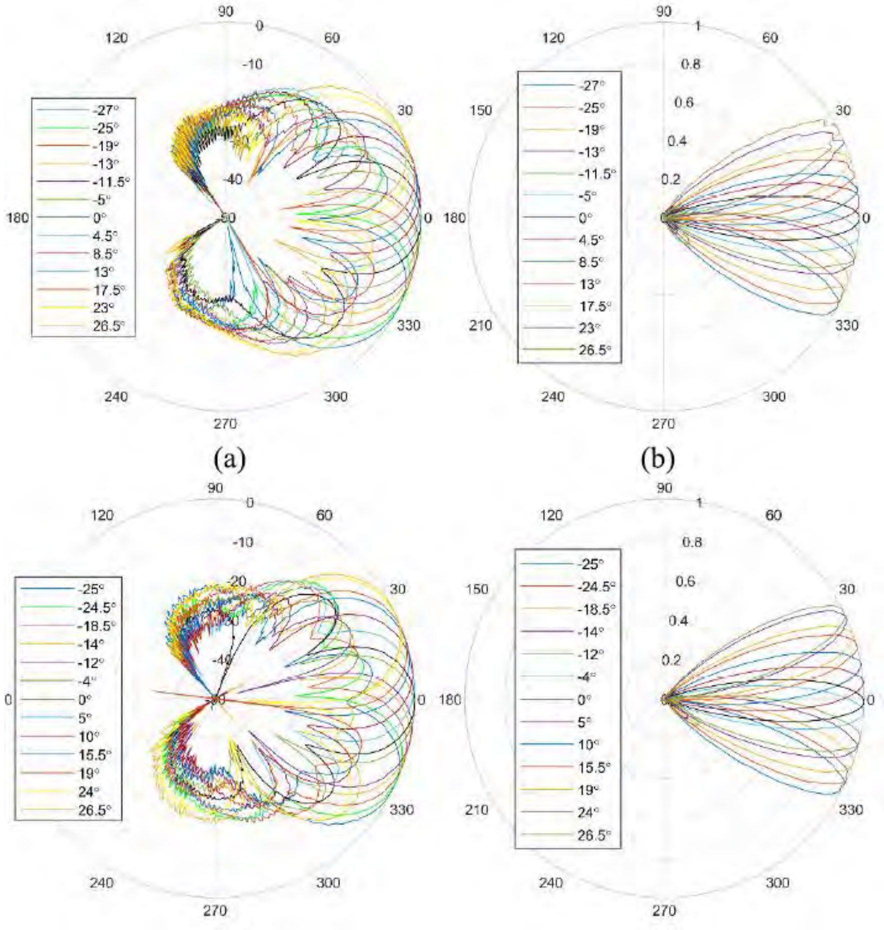






(a) (b)

Theoretical, EM simulated and measured performances: (a) 15 GHz; and (b) 17 GHz.



(a) (b) (c) (d)

This CEOI-funded Project Aims to Deliver:

- Models of complex waveguide components for 3D printing to TRL 5
- Methodologies and a UK facility for characterisation of 3D printed mm-wave components traceable to the International System of units

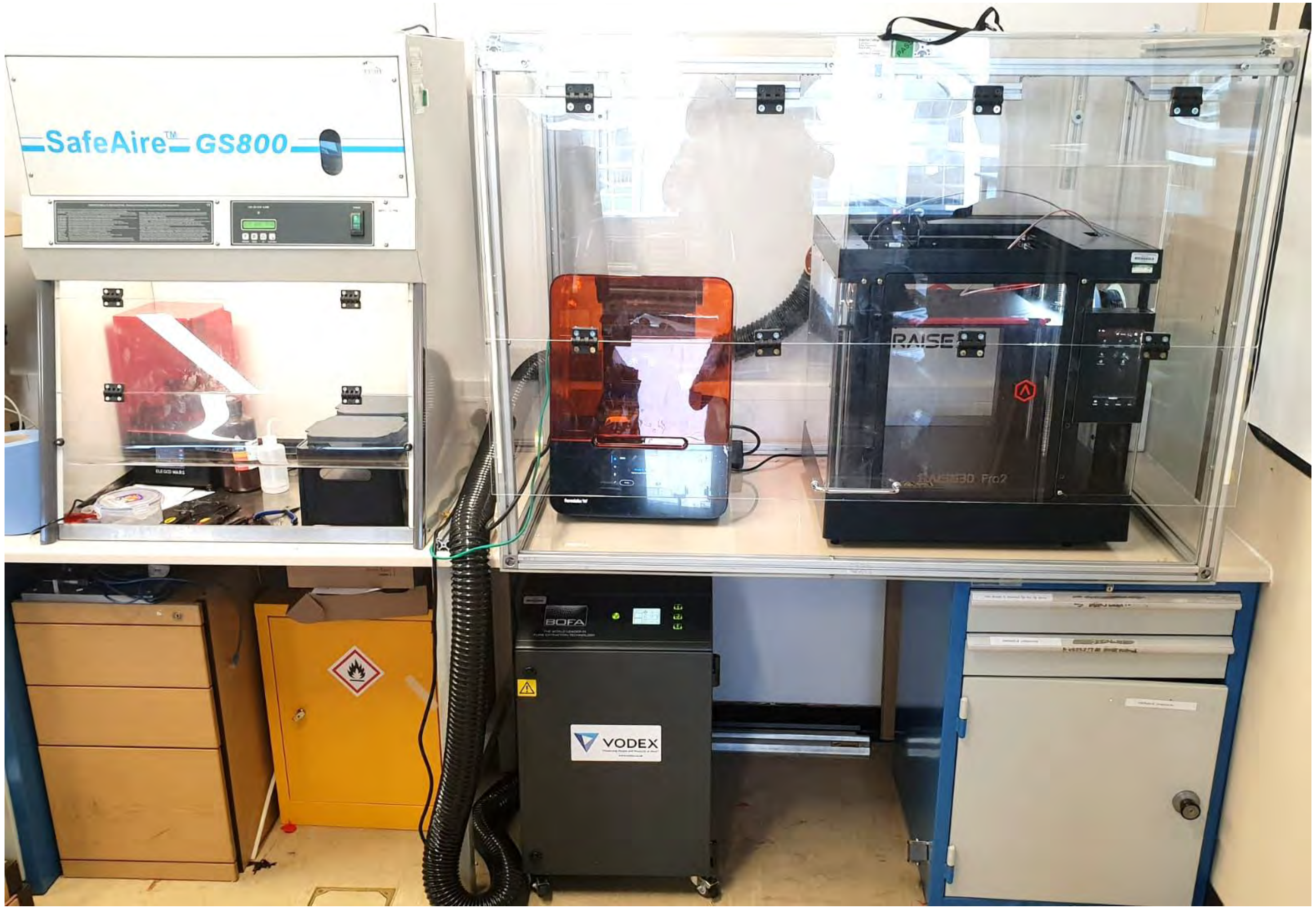
TRL 5 Definitions:

- Technology Development/Demonstration
- Laboratory Testing of Integrated System
- Component and/or Breadboard Validation in Relevant Environment

CEOI-funded 3D-printing Facilities at Imperial

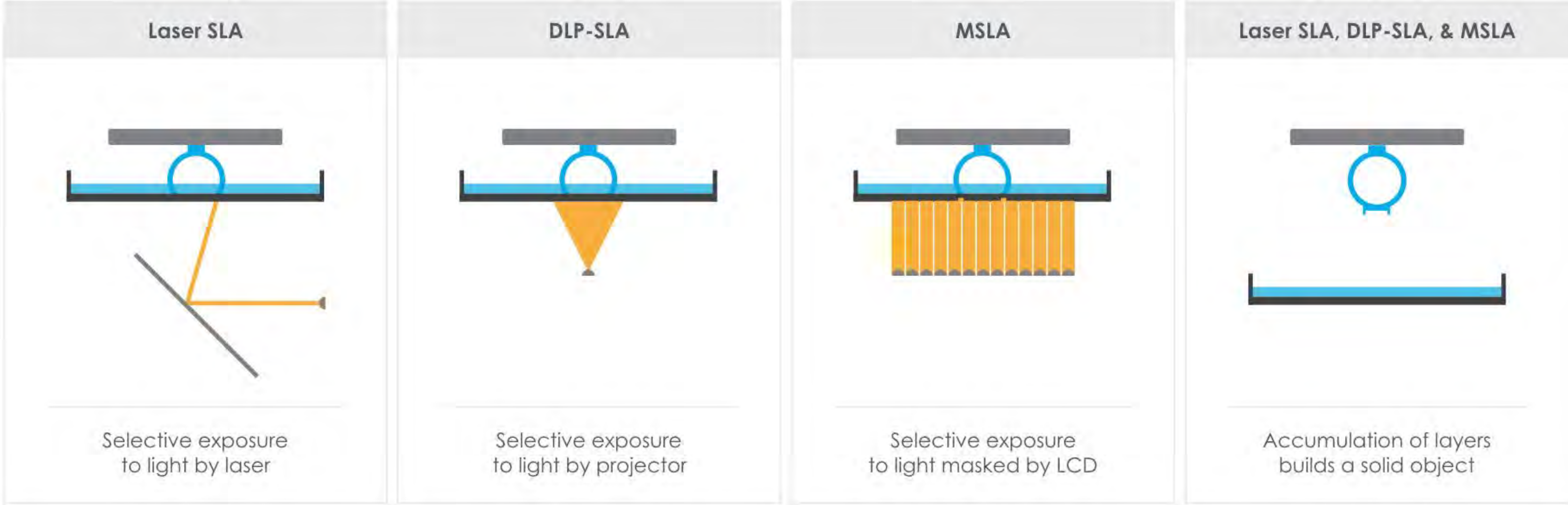
Formlabs Form 3 Laser SLA   Raise3D Pro 2 FDM

Fume hood with
Elegoo Mars MSLA



Above: Ventilated partial enclosure
Below: Vodex fume extractor

SLA (Stereolithography)



Laser SLA

- Formlabs Form3 (current technology)
- Grey Resin (version 4, current technology)
- Layer Height : 25 μm (specification)
- Printed Parts: Off-axis parabolic mirror

Masked SLA

- Elegoo Mars (current technology)
- Upgrades:
  - Linear Rail
  - Ball Bearings
- Water washable ceramic grey resin
- Layer Height: 20 µm
- Printed Parts: Waveguides, Horn, FSS, Lens

FDM (Fused Deposition Modelling)

- Raise 3D Pro 2 (current technology)
- RS Components White PLA (1.75 mm)
- ProtoPasta Conductive PLA (1.75 mm)
- Layer Height: 100 µm - 250µm
- Printed Parts: Quasi-optical test assembly, Adapters, RAM, Polarizers

FDM (Fused Deposition Modelling)

- Original Prusa MK3s (current technology)
- Various PLA materials
- Printed Parts: Various alignment tools and adapters