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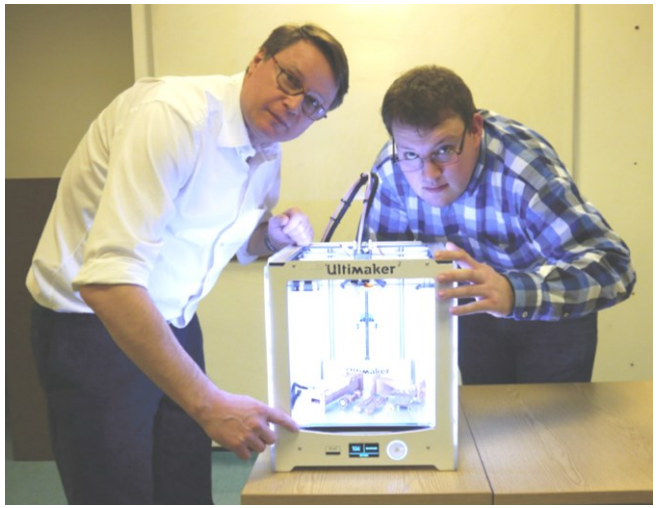
Building-Edge Additive Manufacturing Technologies: 3D Printing Landscape for Next Generation Radio Frequency Applications



Stepan Lucyszyn

August 2023

Imperial College London

Motivations

- Additive manufacturing minimizes material waste
- Polymer-based 3D-printing delivers dramatic mass reduction (saving transportation energy)
- Polylactic acid (PLA) is made from starch and so biodegradable
- Easily accessible technology to the general public (becoming more ubiquitous)
- Replacement part manufacture within isolated/remote communities
- Rapid prototyping and small-batch production saves time and money
- Promotes in-house innovation (securing intellectual property rights)
- Excellent pedagogical tool for hands-on students
- Enables tactile and visual observation of complex 3D geometries

Environmental

Social

Governance

Educational

Imperial College London

Impact

- Drones for agricultural monitoring (millimetre-wave radiometric imaging payloads)
- Earth observation satellites for pollution monitoring (millimetre-wave spectrometry payloads)
- +5G connectivity in remote locations using low-altitude balloons (communications payloads)
- Global +6G coverage with mega satellite constellations (communications payloads)
- Ubiquitous medical diagnostic equipment in GP surgeries and clinics (radiometric imaging of skin)
- Support emergency services using aerial vehicles (imaging and communications payloads)
- Ubiquitous security screening for weapons/contraband (radiometric imaging stand-off detection)
- Low-cost research infrastructure (avoiding expensive cleanroom facilities)
- Innovative technology transfer between academia and industry
- World-class research and highly skilled workforce for new spin-out SMEs

Environmental Social Governance Educational

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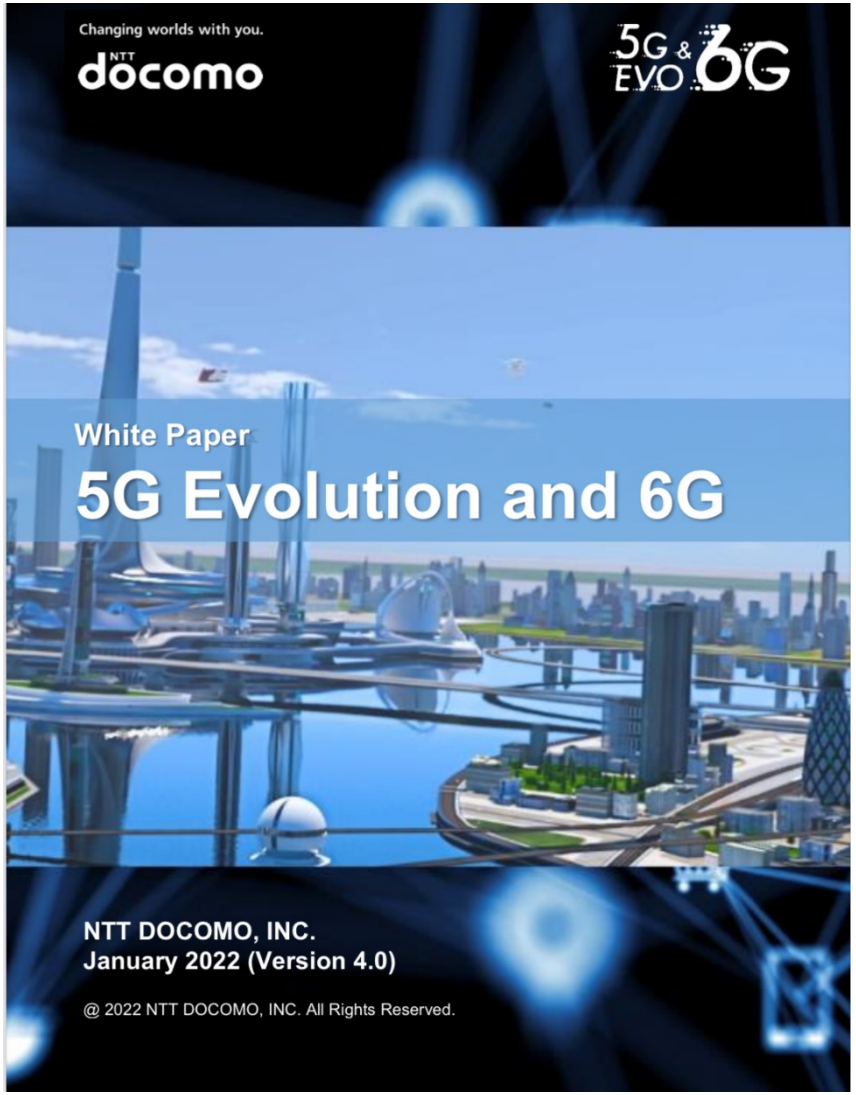
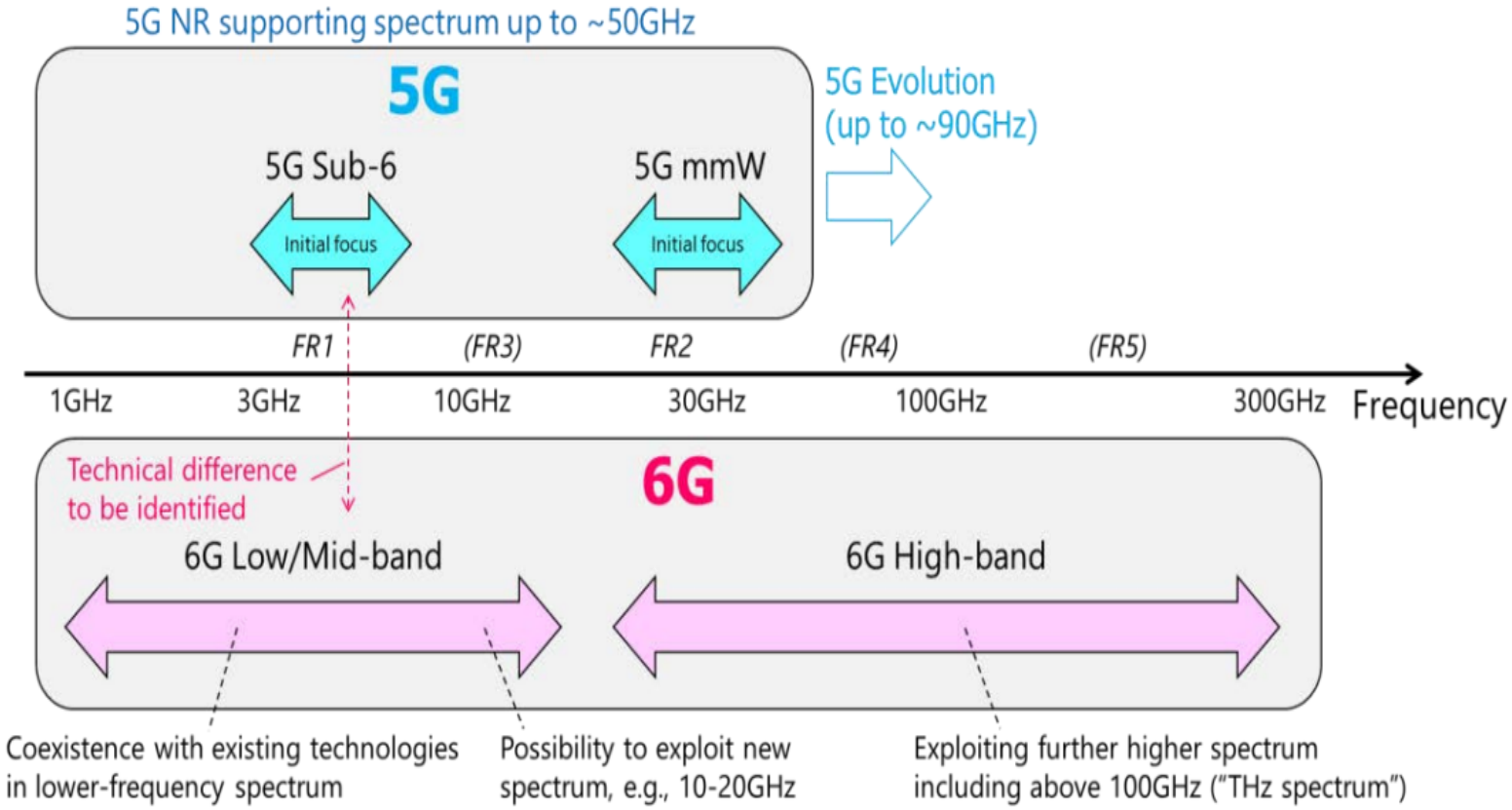
Motivations for G-band (140 to 220 GHz)



NTT to Pilot 6G Network at 2025 Osaka World Expo!



https://www.nttdocomo.co.jp/english/binary/pdf/corporate/technology/whitepaper_6g/DOCOMO_6G_White_PaperEN_v4.0.pdf

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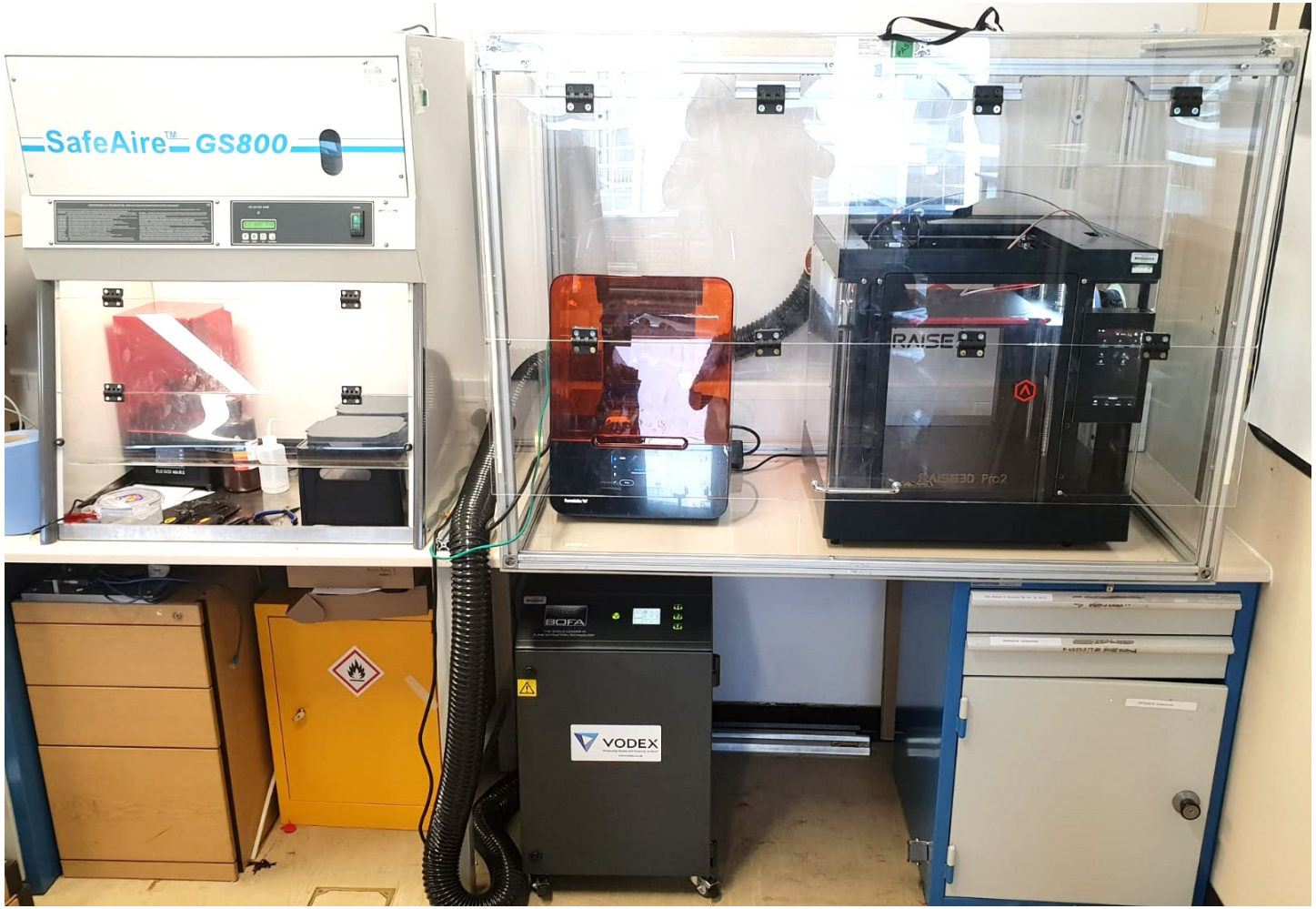
Low-cost 3D-printing Facilities

Formlabs Form 3 Laser SLA Raise3D Pro 2 FDM

Fume Hood With Elegoo Mars MSLA



Above: Ventilated Partial Enclosure
Below: Vodex Fume Extractor

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Our MSLA 3D Printers

£280 May 2021
Elegoo Mars 2 Pro:
50 µm resolution

Old Workhorse

£318 September 2021
Phrozen Sonic Mini 4k:
35 µm resolution

Current Workhorse

£592 January 2022
Phrozen Sonic Mini 8k:
22 µm resolution

New Arrival

Imperial College London

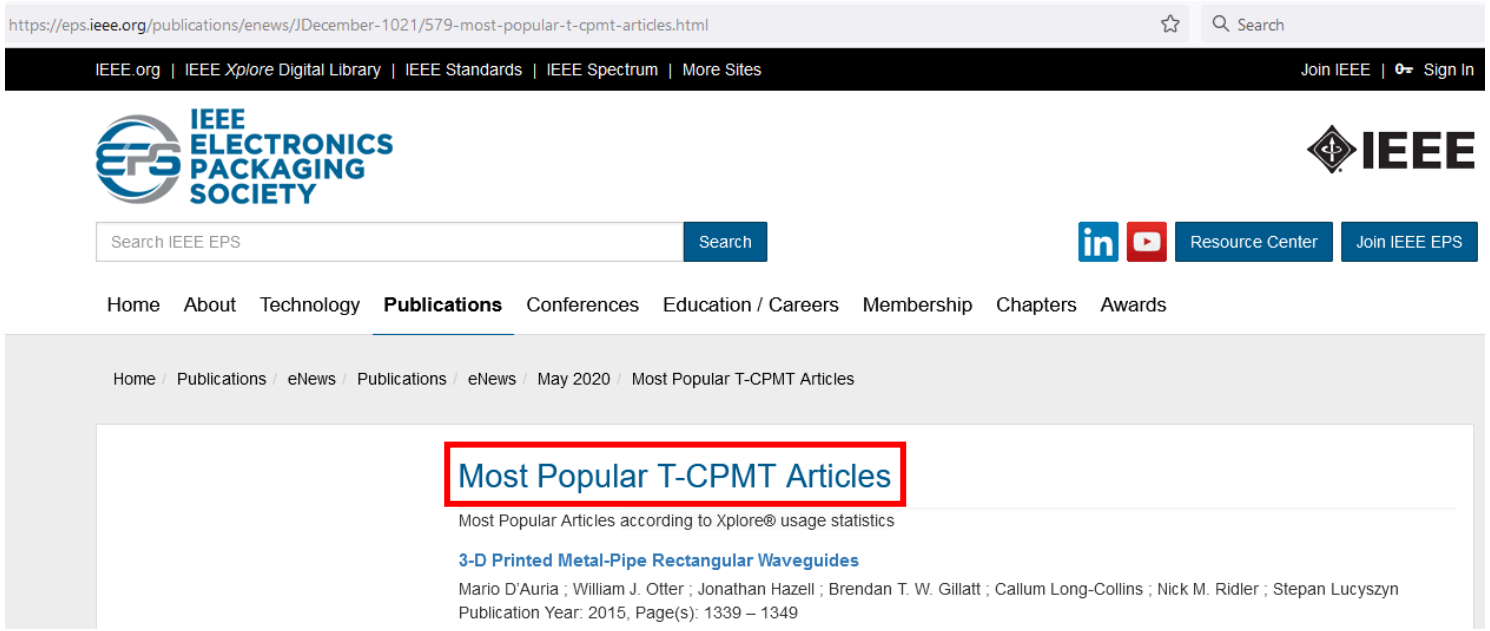
First Detailed Study of 3D-printed Waveguides

IEEE TRANSACTIONS ON COMPONENTS, PACKAGING AND MANUFACTURING TECHNOLOGY, VOL. 5, NO. 9, SEPTEMBER 2015 1339

3-D Printed Metal-Pipe Rectangular Waveguides

Mario D'Auria, *Student Member, IEEE*, William J. Otter, *Member, IEEE*, Jonathan Hazell, Brendan T. W. Gillatt, Callum Long-Collins, Nick M. Ridler, *Fellow, IEEE*, and Stepan Lucyszyn, *Fellow, IEEE*

2 Undergraduate Project Students



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Some Waveguide Components

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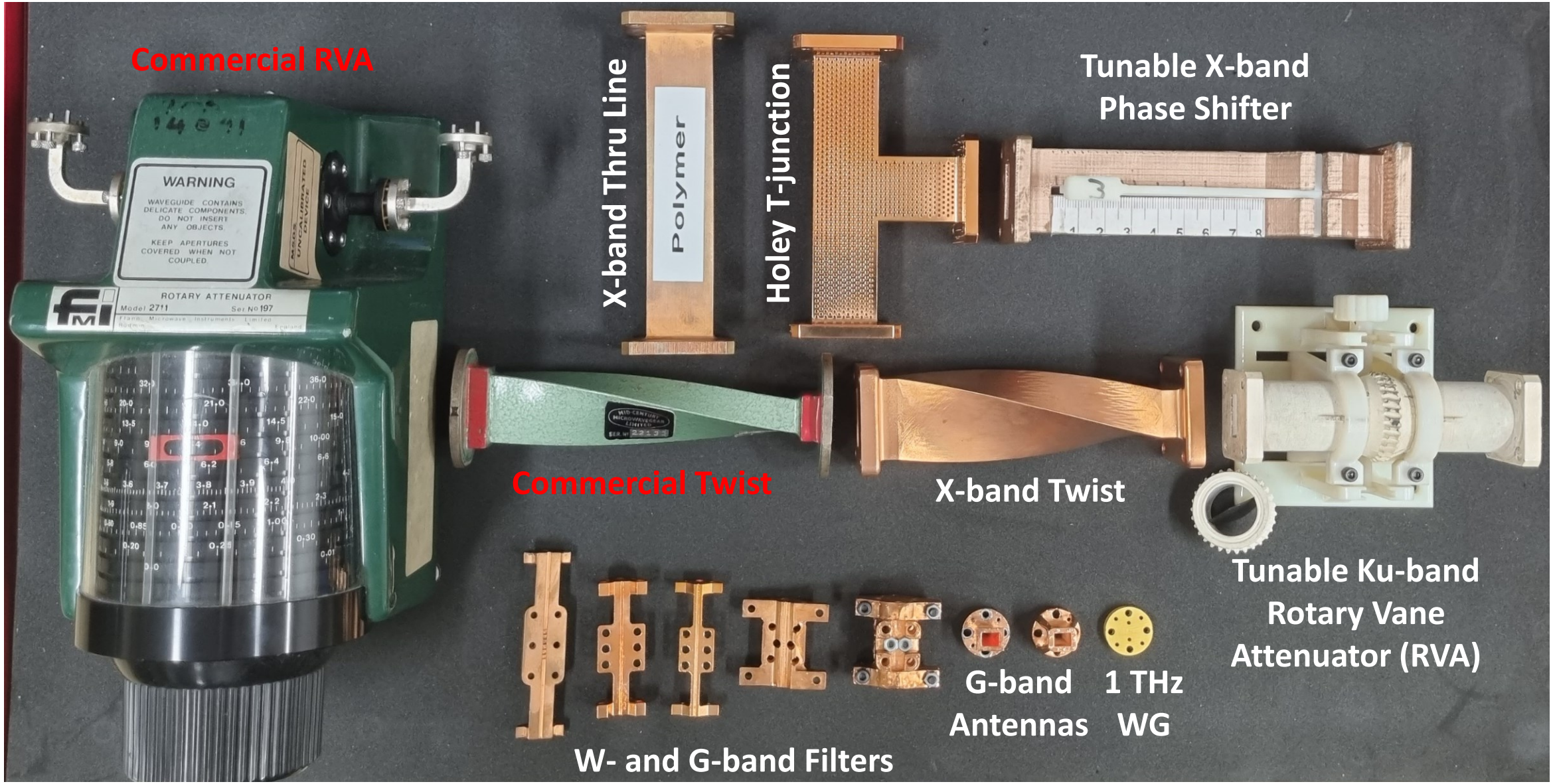

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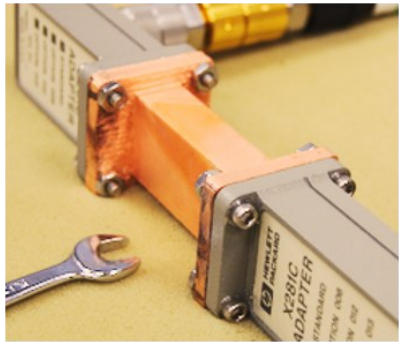
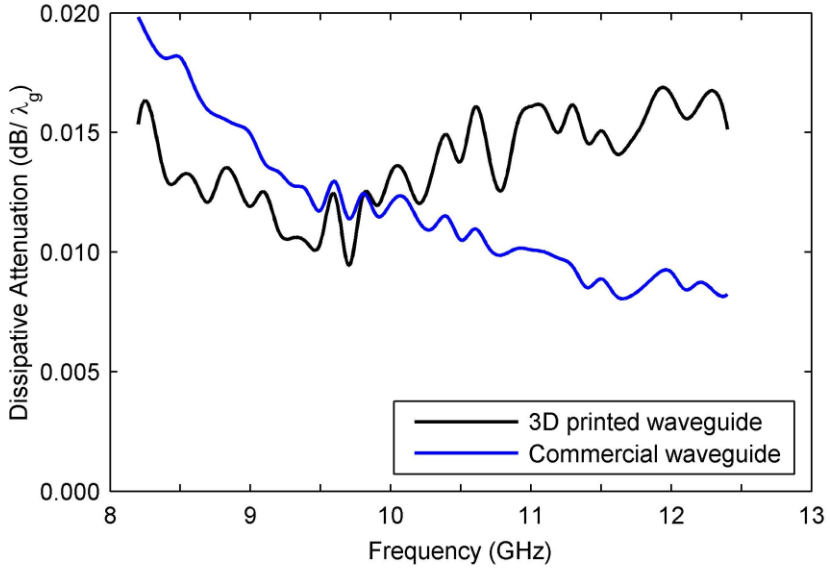
Waveguide Thru Lines

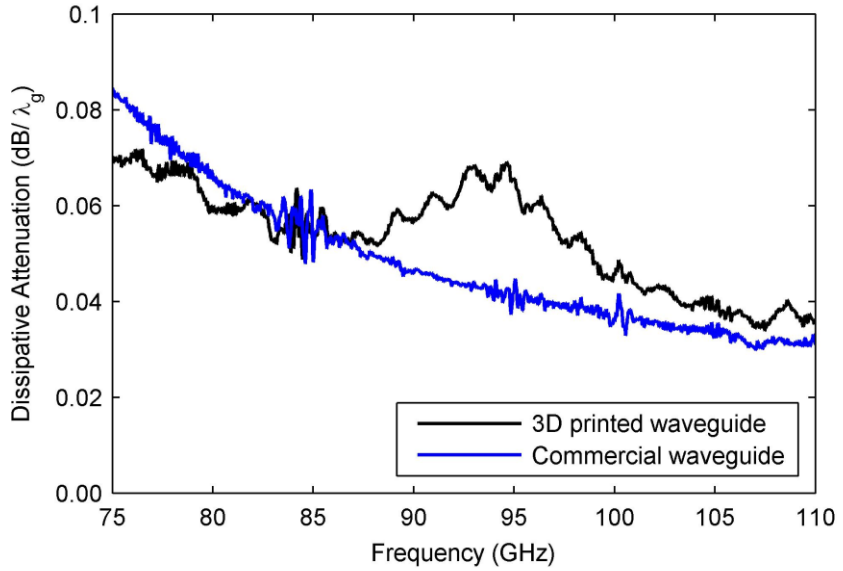
NPL National Physical Laboratory

X-band (8 to 12 GHz)

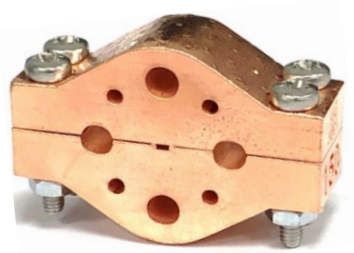


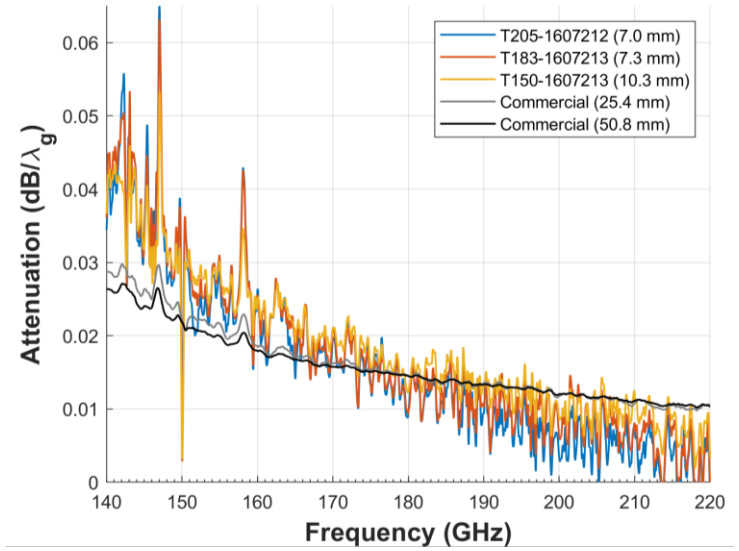


W-band (75 to 110 GHz)



G-band (140 to 220 GHz)





Waveguide Calibration Primary Standards

Measurement 158 (2020) 107682

Contents lists available at ScienceDirect

Measurement

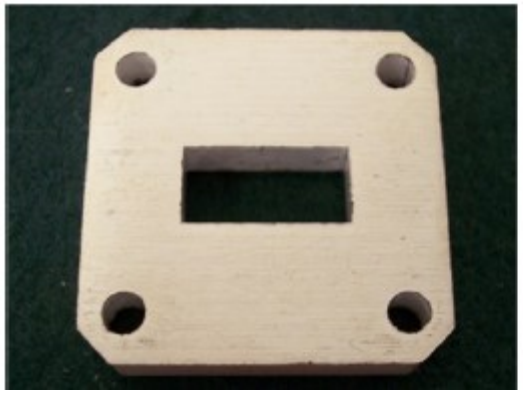
journal homepage: www.elsevier.com/locate/measurement

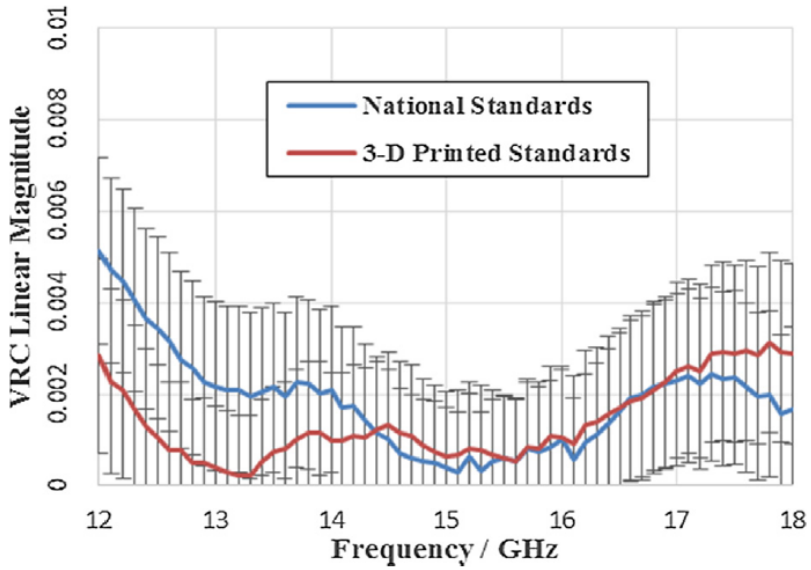
3-D printed primary standards for calibration of microwave network analysers

Adam Jones [a], Stepan Lucyszyn [b], Enrique Márquez-Segura [c], Nick Ridler [a,*], James Skinner [a], Daniel Stokes [a]

[a] National Physical Laboratory (NPL), Hampton Road, Teddington TW11 0LW, UK
[b] Imperial College London, Exhibition Road, London SW7 2AZ, UK
[c] Universidad de Málaga, Av. de Cervantes, 2, 29016 Málaga, Spain

Pre-university Apprentice





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Waveguide Filters

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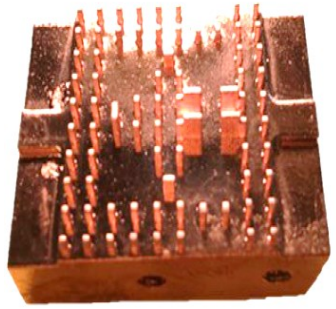
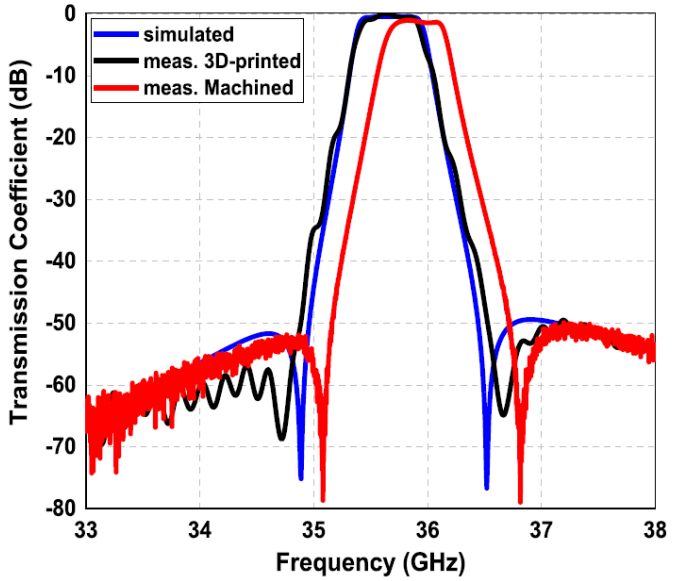
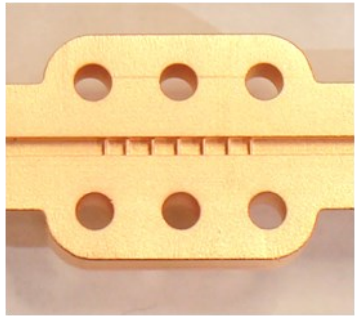
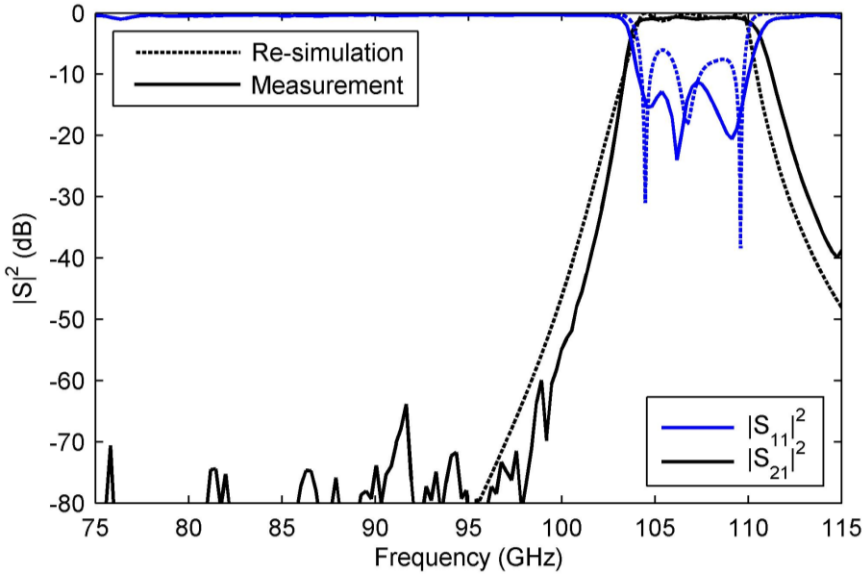
Ka-band



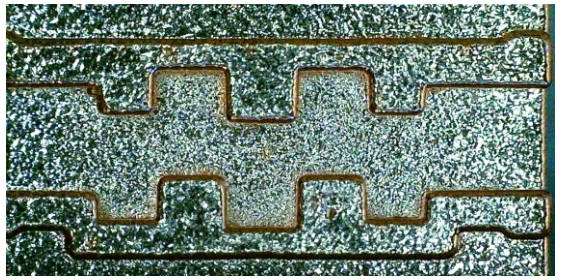


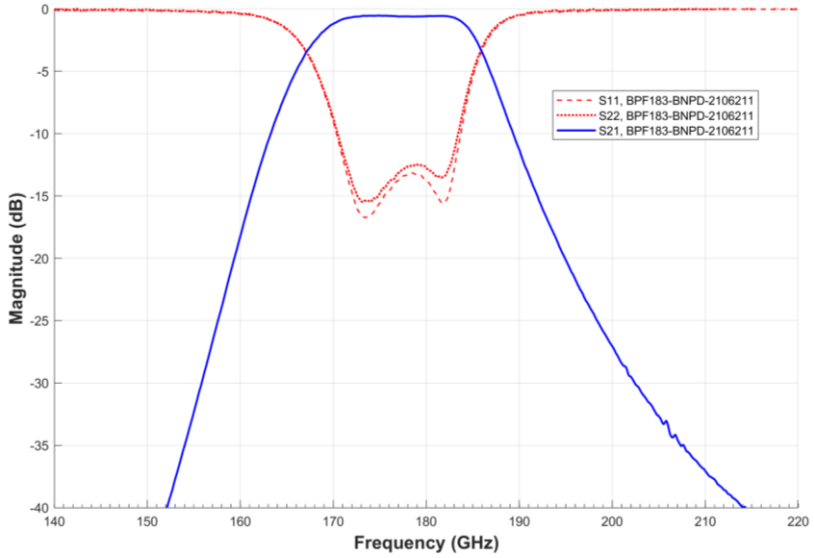
W-band





G-band





UNIVERSITY OF LIVERPOOL

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G-band (140 to 220 GHz) Manufacturing Limits

NPL National Physical Laboratory

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received January 24, 2022, accepted March 23, 2022, date of publication March 28, 2022, date of current version April 15, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3162586

3-D Printing Quantization Predistortion Applied to Sub-THz Chained-Function Filters

LIYAN ZHU[1], ROSHAN PAYAPULLI[1], SANG-HEE SHIN[1], (Member, IEEE), MANOJ STANLEY[2], (Member, IEEE), NICK M. RIDLER[2], (Fellow, IEEE), AND STEPAN LUCYSZYN[1], (Fellow, IEEE)

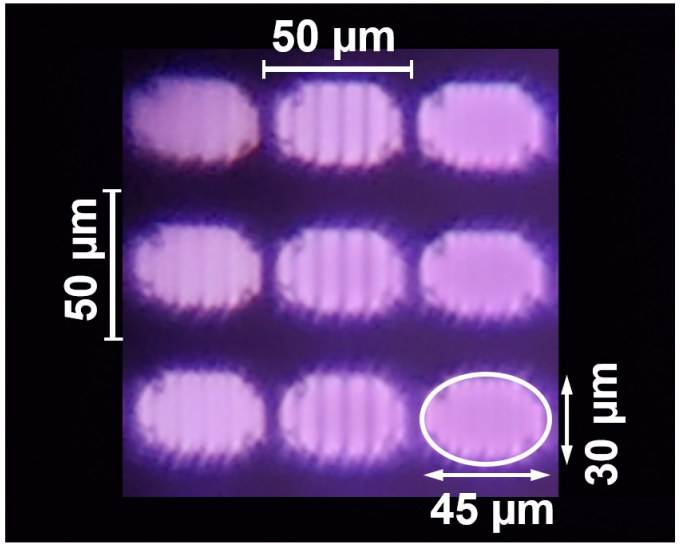
[1]Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2AZ, U.K.
[2]Department of Electromagnetic and Electrochemical Technologies, National Physical Laboratory, Teddington TW11 0LW, U.K.

Corresponding author: Stepan Lucyszyn (s.lucyszyn@imperial.ac.uk)

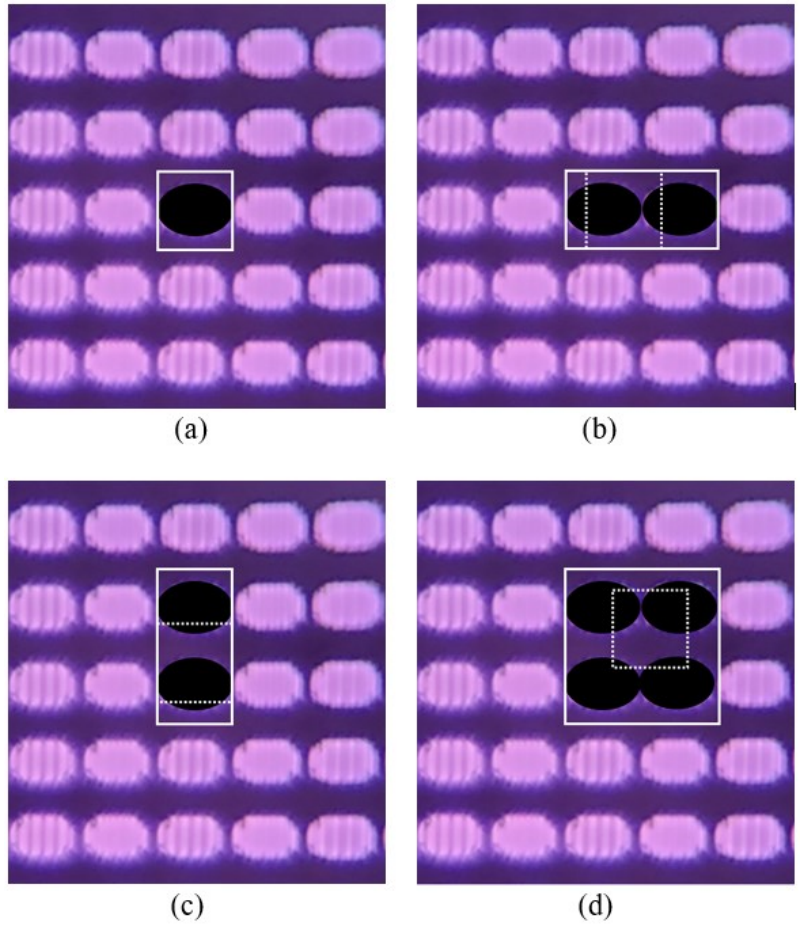
This work was supported by the U.K. Space Agency's Centre for Earth Observation Instrumentation (CEOI) under Grant RP10G0435A202.

G-band Manufacturing Limits

Our masked stereolithography apparatus (MSLA)
Elegoo Mars 2 Pro, with 50 μm resolution and
print volume of 80 mm × 129 mm × 160 mm



λg/2 cavity resonator at 183.3 GHz has 8.5° change in electrical length from 50 μm quantization error → 3.5% frequency shift



Registration errors between the CAD drawing and slicing software

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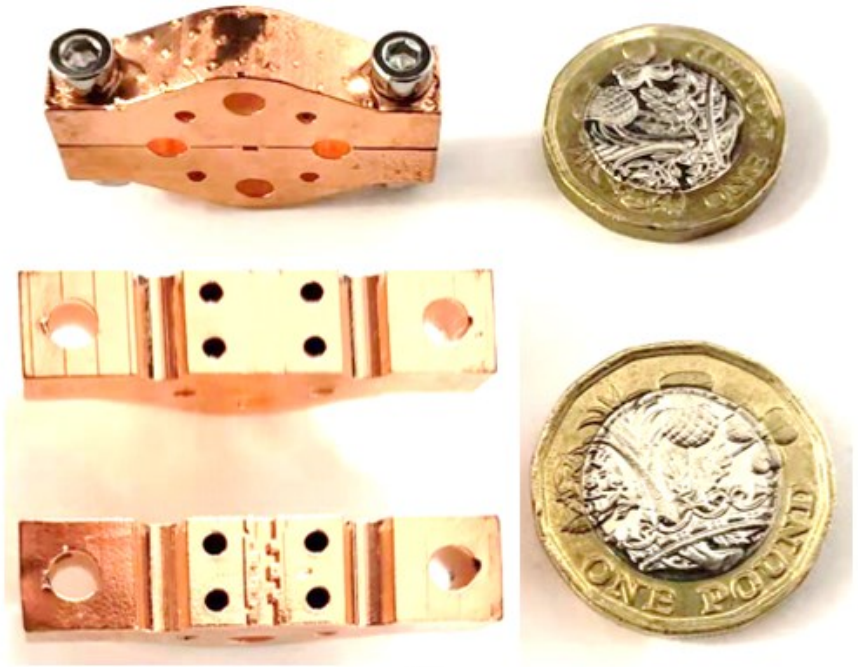
G-band Manufacturing Limits

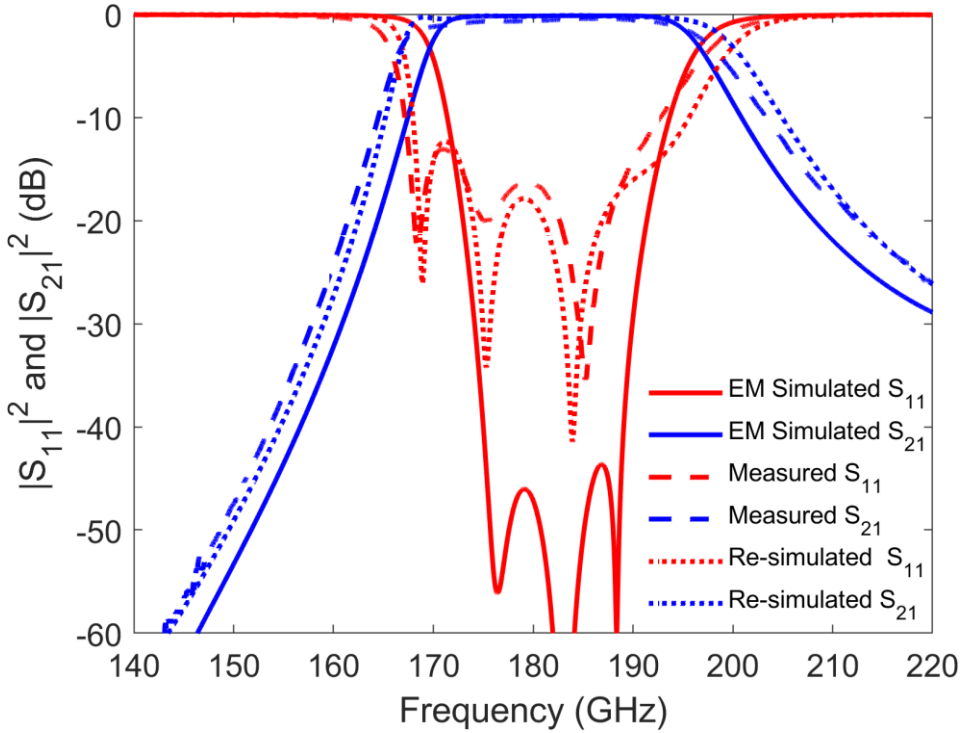
NPL National Physical Laboratory



(a)

(b)

Pre-distorted G-band 5th order chained-function filter



Imperial College London

Dielectrics

NPL National Physical Laboratory

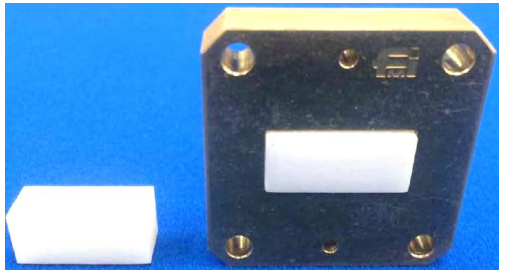
IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

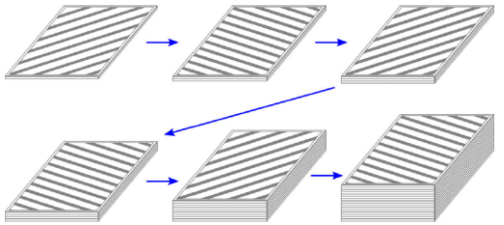
Received June 17, 2019, accepted June 29, 2019, date of publication July 4, 2019, date of current version August 1, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2926717

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)





IEEE Access
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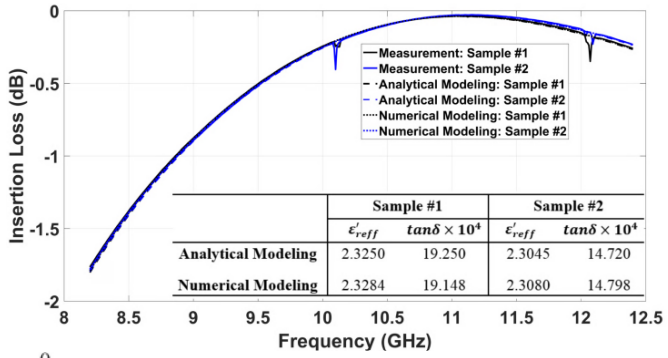
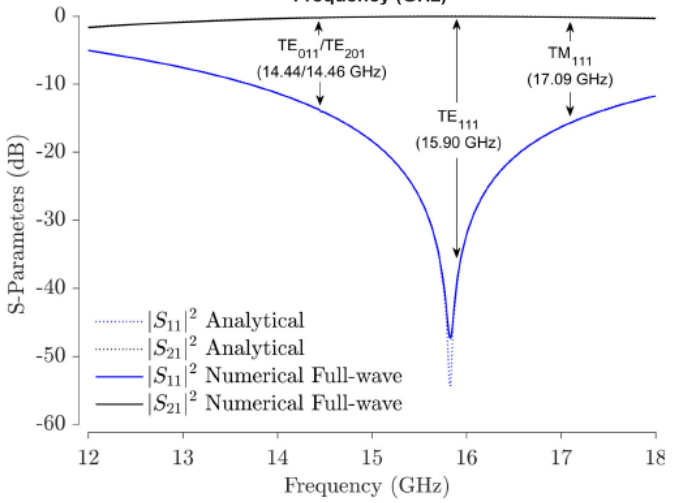


	Sample #1		Sample #2	
	ϵ'_{reff}	$tan\delta \times 10^4$	ϵ'_{reff}	$tan\delta \times 10^4$
Analytical Modeling	2.3250	19.250	2.3045	14.720
Numerical Modeling	2.3284	19.148	2.3080	14.798



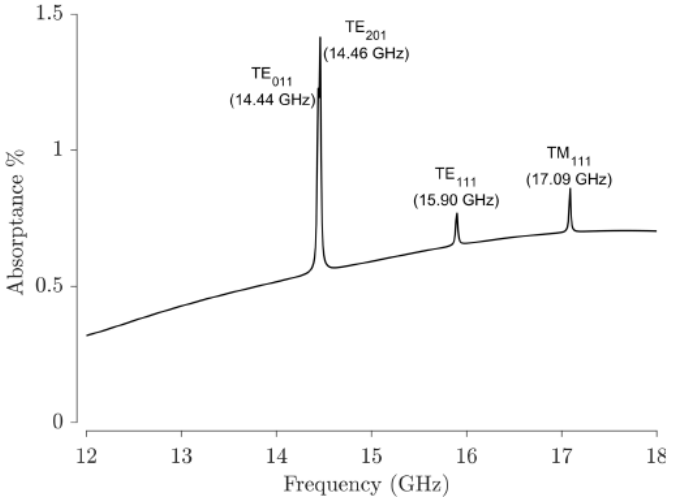
(a)

Received August 30, 2021, accepted September 8, 2021, date of publication September 10, 2021, date of current version October 6, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3111959

Parasitic High Q-Factor Open-Box Modes With 3-D Printed Dielectric-Filled Metal Waveguides

ATTIQUE DAWOOD AND STEPAN LUCYSZYN, (Fellow, IEEE)



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Variable Phase Shifter

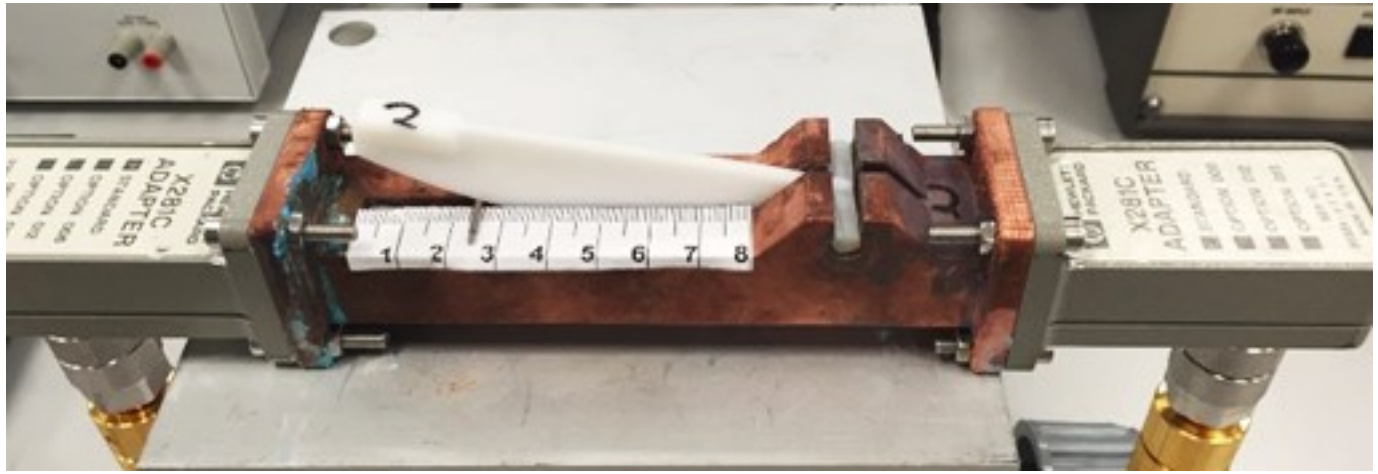
NPL National Physical Laboratory

822 IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 26, NO. 10, OCTOBER 2016

3-D Printed Variable Phase Shifter

Brendan T. W. Gillatt, Mario D'Auria, William J. Otter, *Member, IEEE*,
Nick M. Ridler, *Fellow, IEEE*, and Stepan Lucyszyn, *Fellow, IEEE*

Undergraduate Project Student



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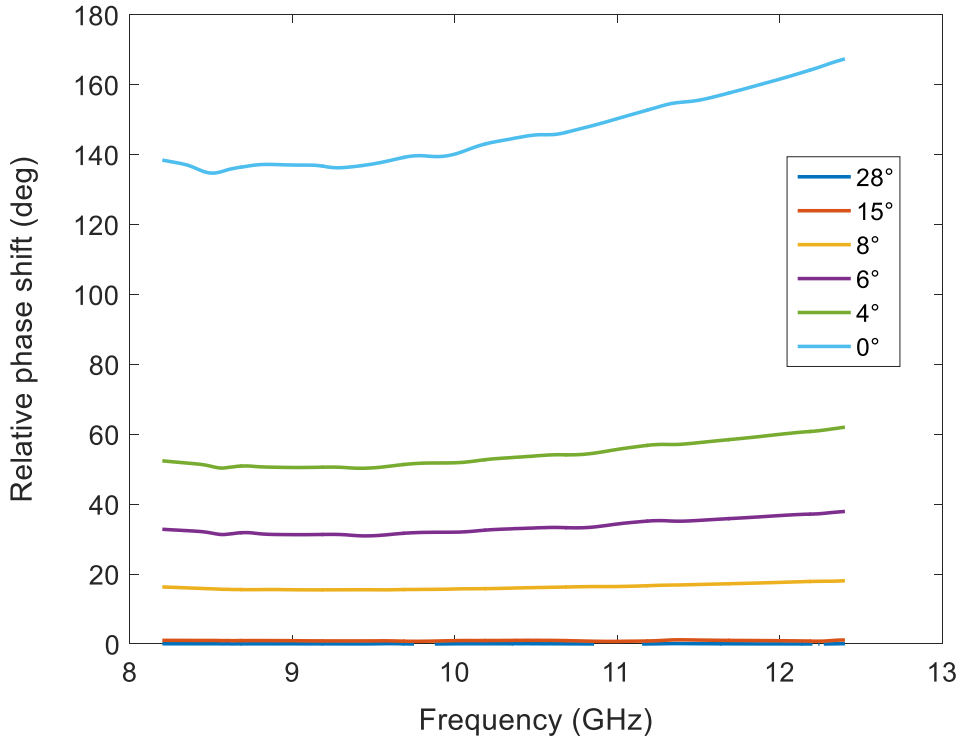


Ku-band Phased Array Antenna

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received June 21, 2019, accepted July 24, 2019, date of publication August 1, 2019, date of current version August 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2932431

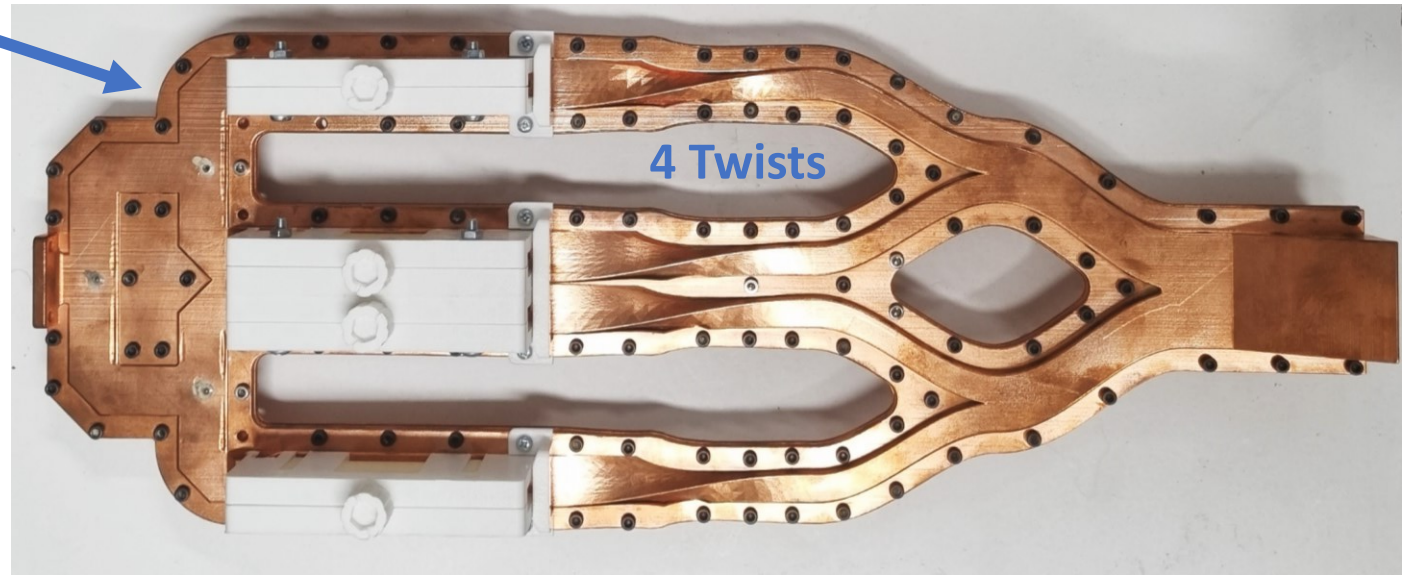
Polymer-Based 3-D Printed Ku-Band Steerable Phased-Array Antenna Subsystem

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)

Undergraduate Project Student

4-way Power Splitter

4 Tunable Phase Shifters



Waveguide Flange

4-element Antenna Arrays

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Ku-band Phased Array Antenna

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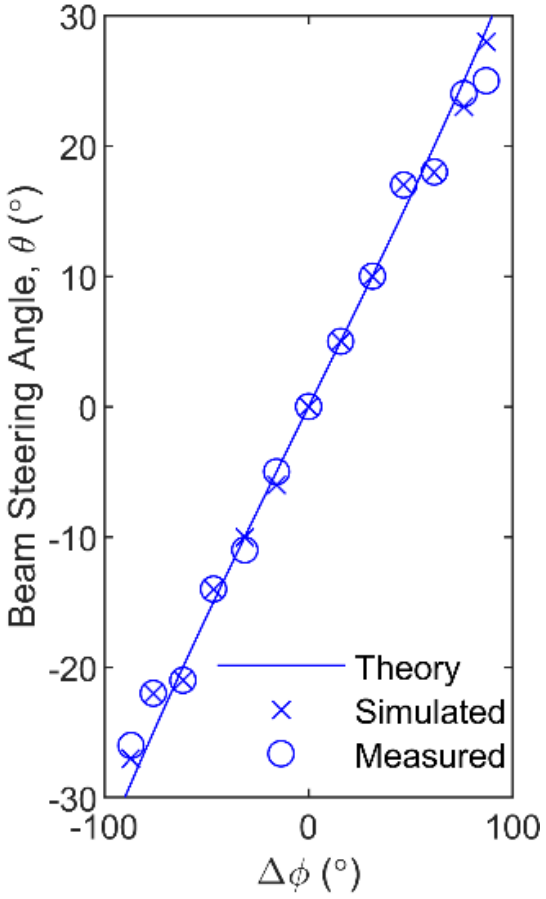
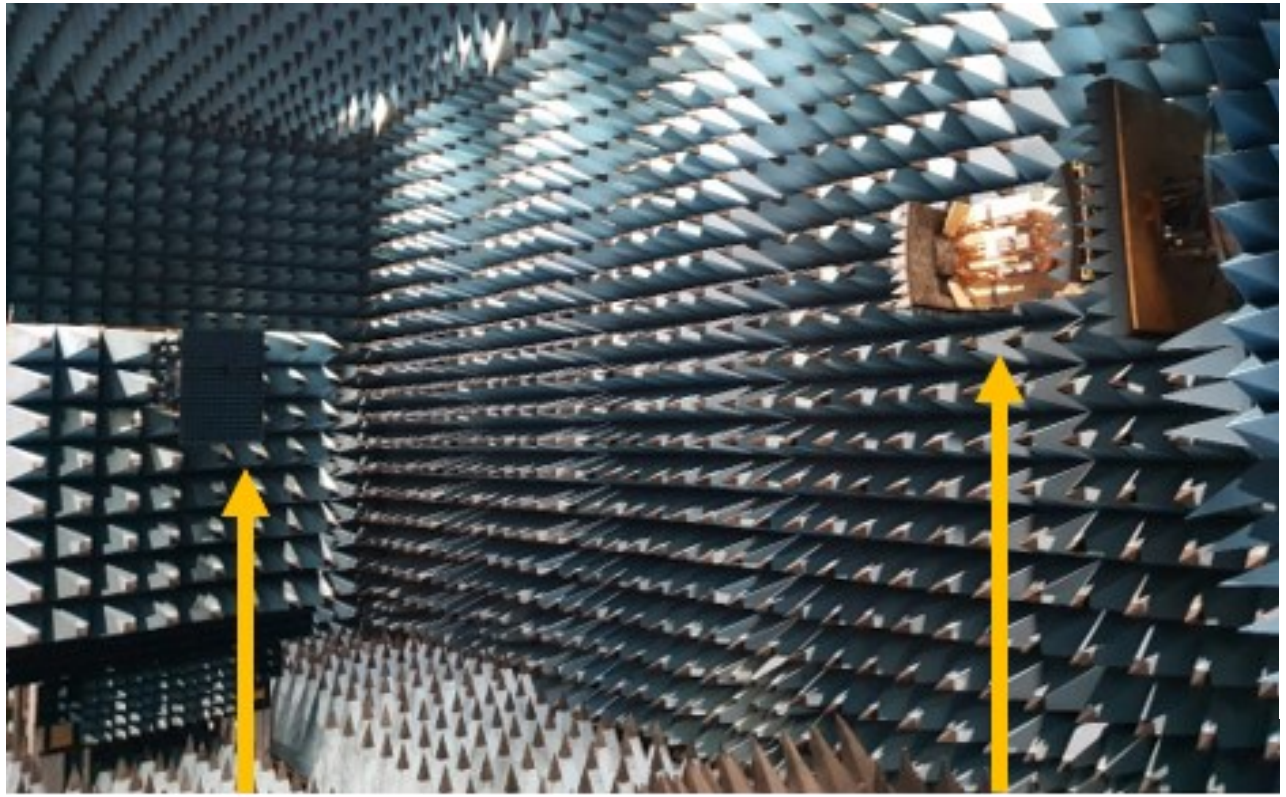
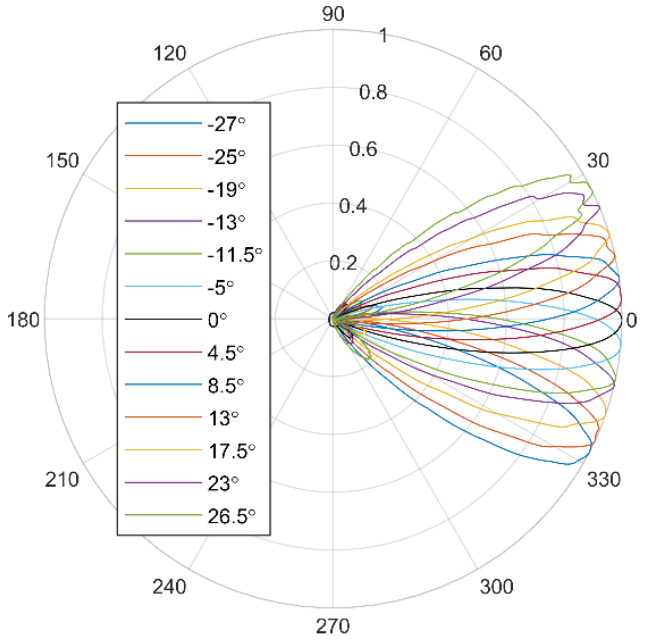




Standard Gain Horn

Phased Array Antenna



Rotary Vane Attenuator (RVA)

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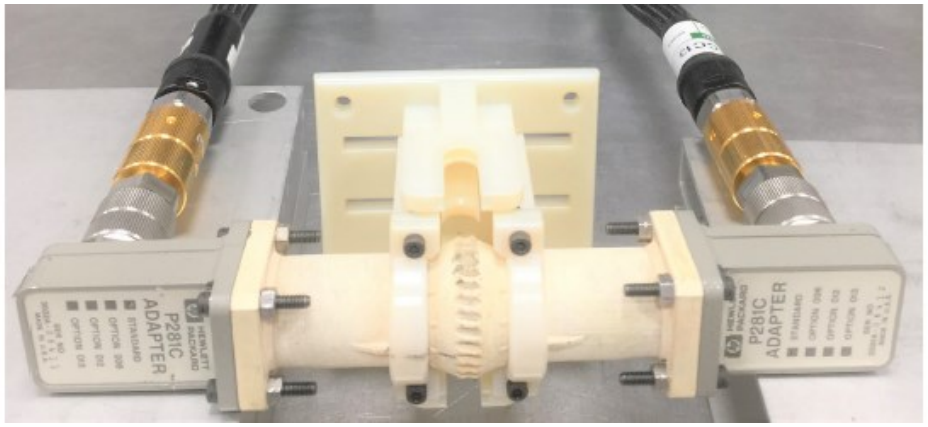
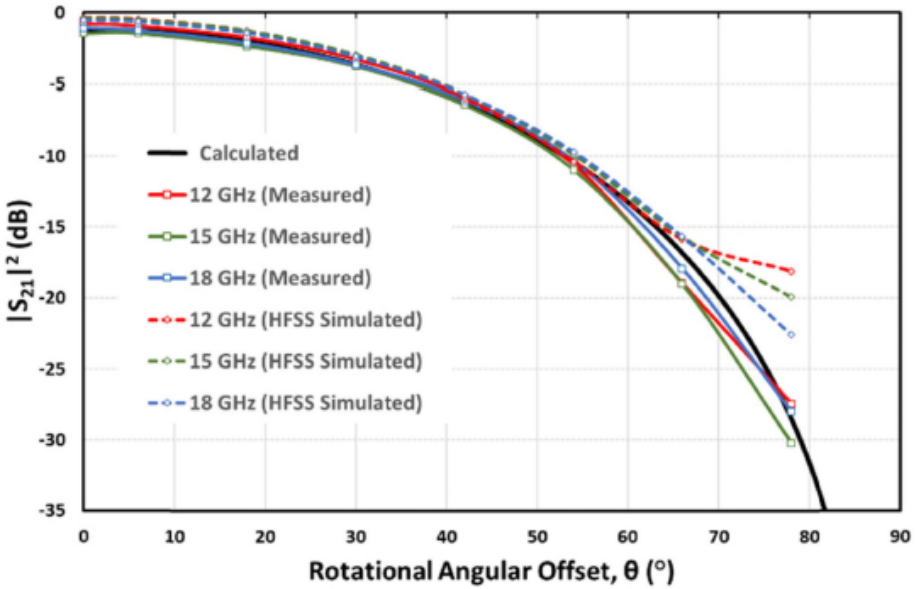
NPL National Physical Laboratory





IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

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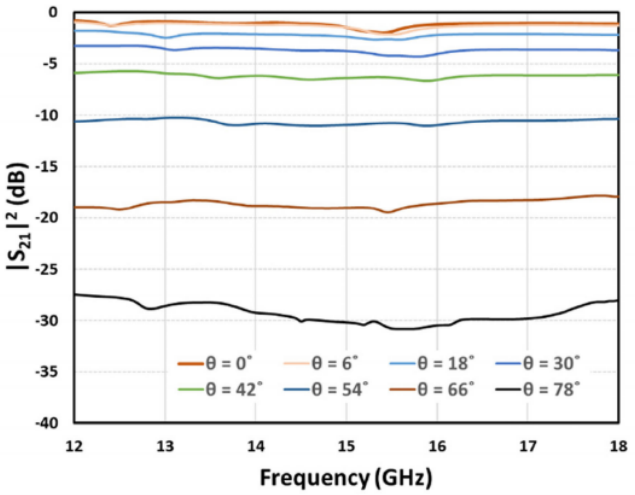
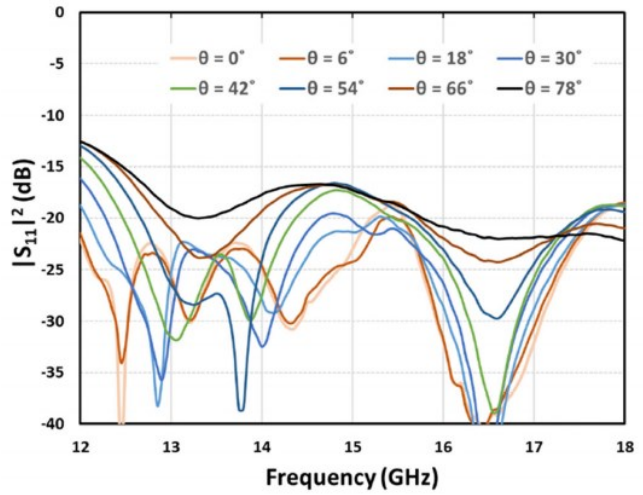
Digital Object Identifier 10.1109/ACCESS.2021.3087012

Microwave Characterization of Conductive PLA and Its Application to a 12 to 18 GHz 3-D Printed Rotary Vane Attenuator

ENRIQUE MÁRQUEZ-SEGURA[1,2], (Senior Member, IEEE), SANG-HEE SHIN[2], (Graduate Student Member, IEEE), ATTIQUE DAWOOD[2], NICK M. RIDLER[3], (Fellow, IEEE), AND STEPAN LUCYSZYN[2], (Fellow, IEEE)





UNIVERSIDAD DE MÁLAGA

Performance Parameter	This Work (3-D Printed)	Commercial (Machined)
Attenuation Range (dB)	0-27	0-60
Maximum Insertion Loss (dB)	1.2	0.3
Worst-Case Return Loss (dB)	17 (12.7 to 18 GHz)	23
Mass (kg)	0.050	3.4

Imperial College London

G-band Quasi-optics

NPL National Physical Laboratory

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

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Digital Object Identifier 10.1109/ACCESS.2021.3057606

Polymer-Based 3-D Printed 140-220 GHz Low-Cost Quasi-Optical Components and Integrated Subsystem Assembly

SANG-HEE SHIN[1], (Graduate Student Member, IEEE), XIAOBANG SHANG[2], (Senior Member, IEEE), NICK M. RIDLER[2], (Fellow, IEEE), AND STEPAN LUCYSZYN[1], (Fellow, IEEE)

[1]Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2AZ, U.K.
[2]National Physical Laboratory, Department of Electromagnetic and Electrochemical Technologies, Teddington TW11 0LW, U.K.

Corresponding author: Stepan Lucyszyn (s.lucyszyn@imperial.ac.uk)

This work was supported by the U.K. Space Agency's Centre for Earth Observation Instrumentation (CEOI) under Grant RP10G0435A202, and in part by the U.K. Space Agency under Grant NSTP3-FT-046.

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G-band Subsystems

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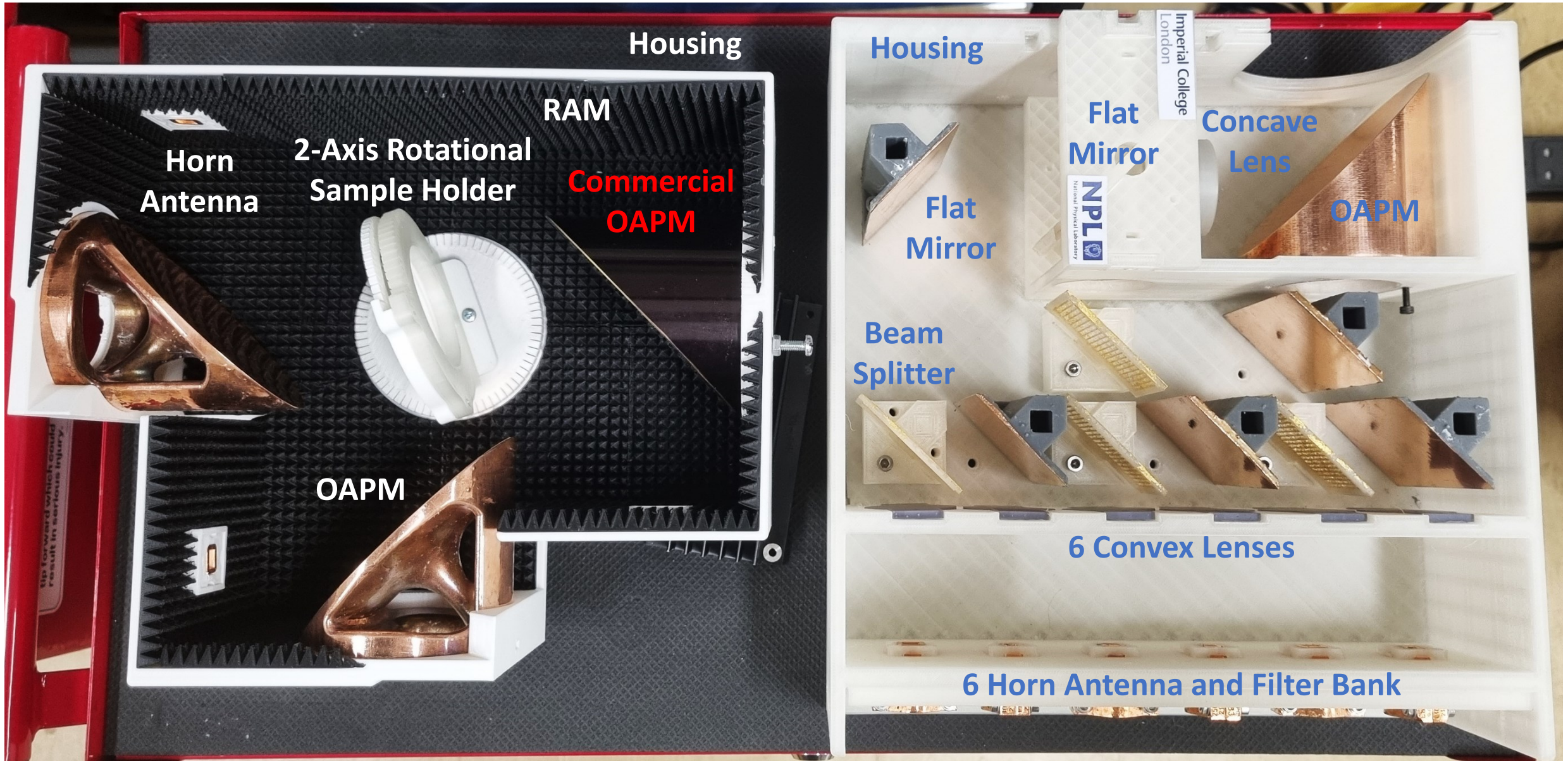

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90° Off-axis Parabolic Mirrors (OAPMs)

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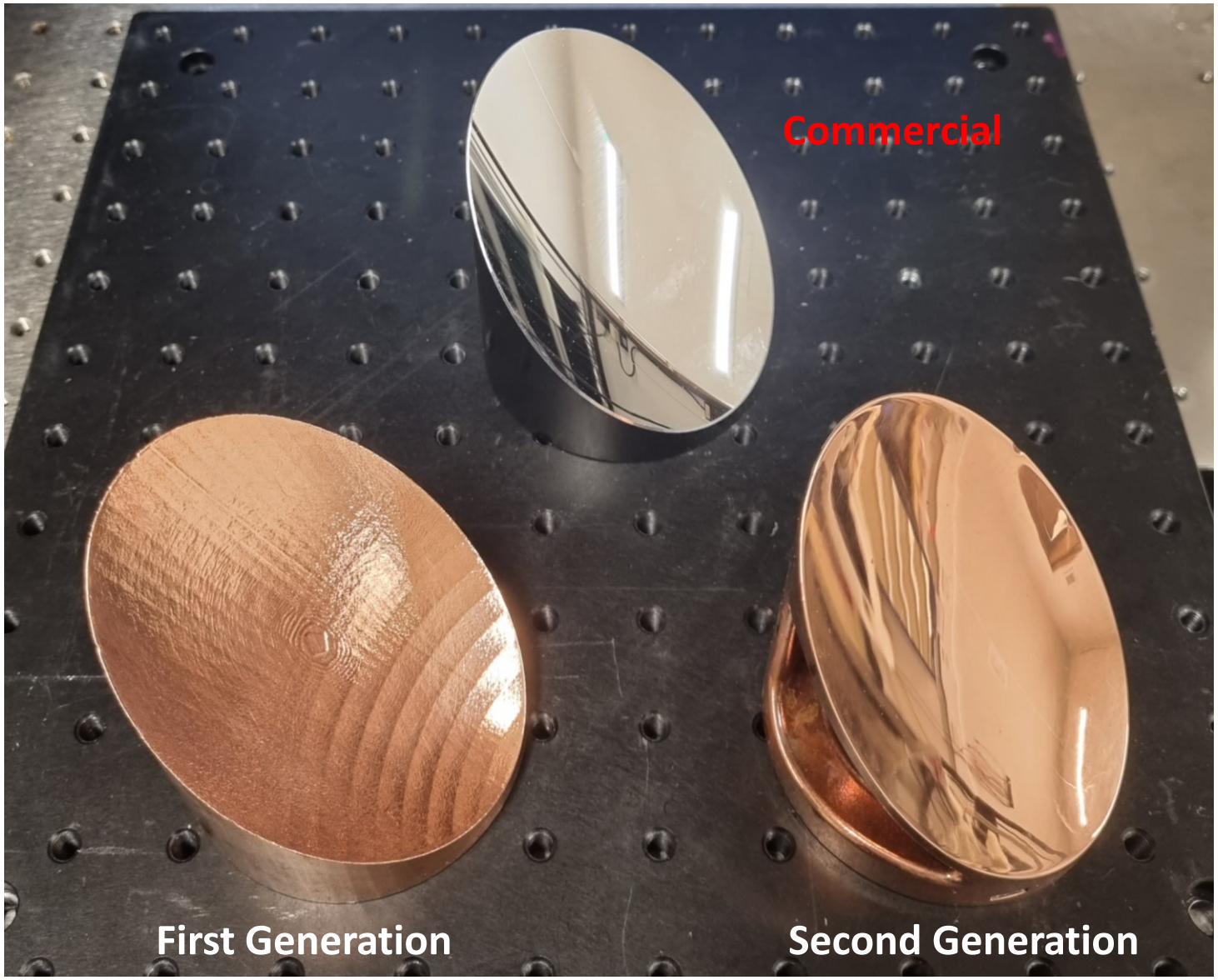

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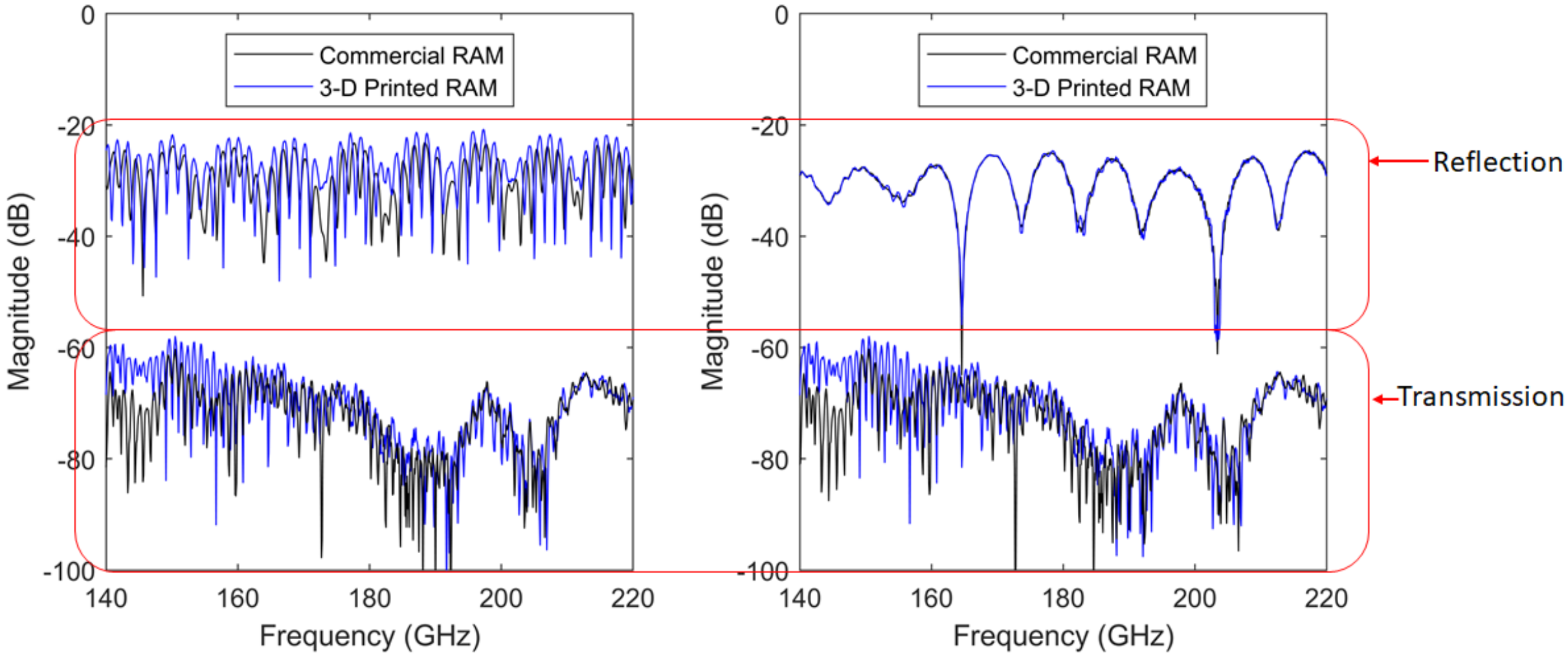
Pyramidal Radiation Absorbent Material (RAM)



Antenna Pointing at Back-Side of RAM

Antenna Pointing at Front-Side of RAM

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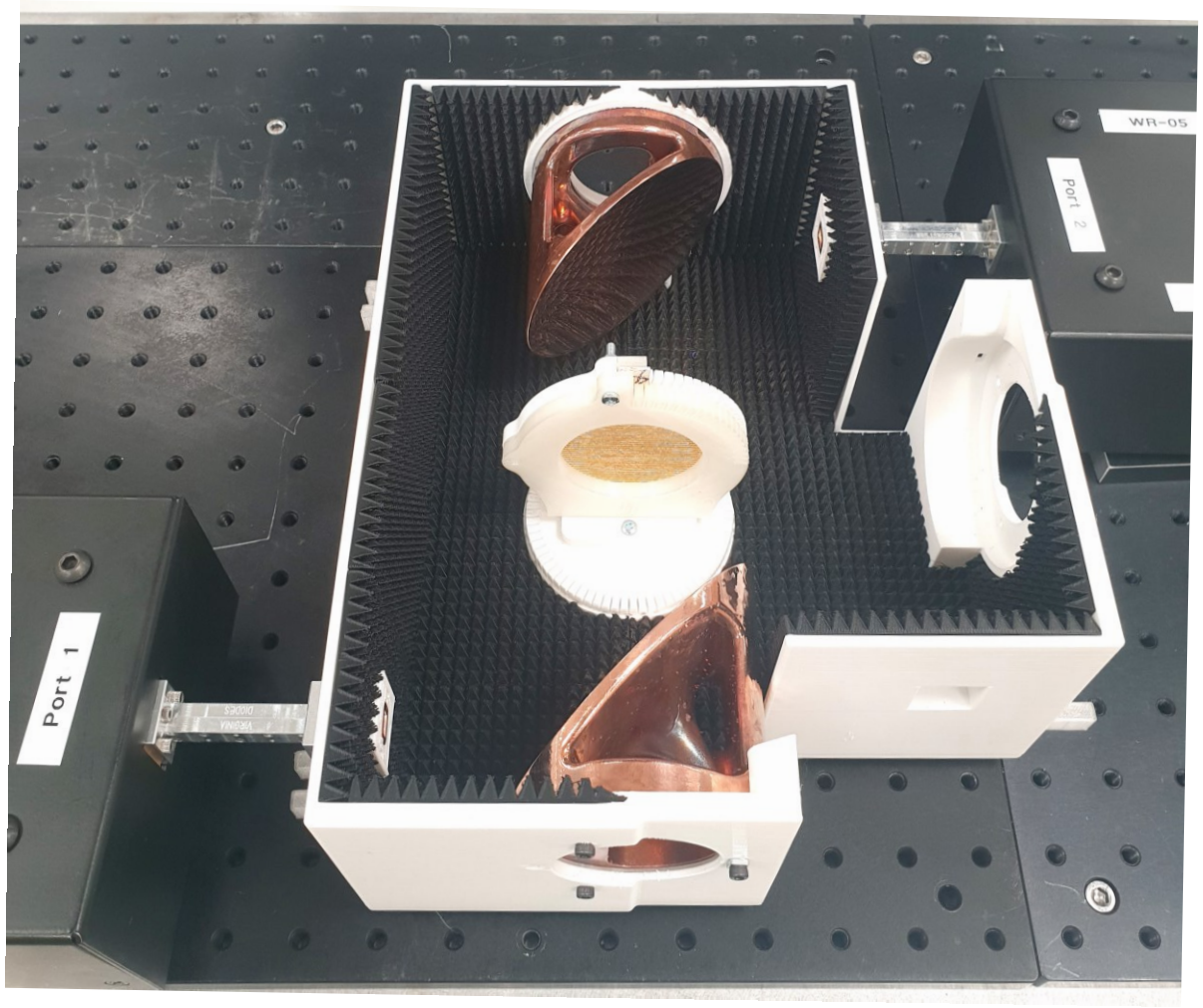
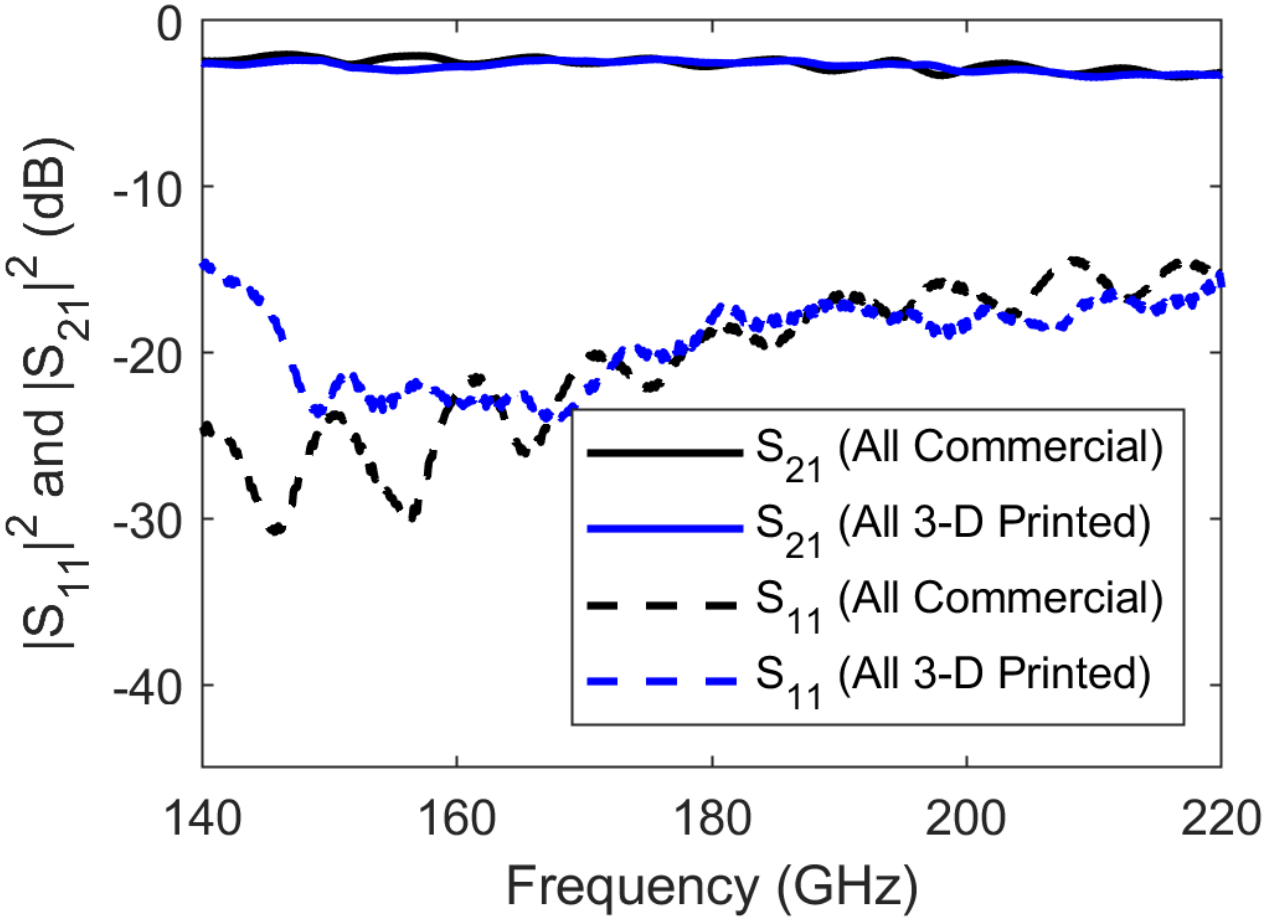
G-band Quasi-optical Thru

NPL National Physical Laboratory





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G-band Multi-channel Front-end

NPL National Physical Laboratory

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3-D Printed Plug and Play Prototyping for Low-Cost Sub-THz Subsystems

SANG-HEE SHIN[1], (Member, IEEE), ROSHAN PAYAPULLI[1], LIYAN ZHU[1], MANOJ STANLEY[2], (Member, IEEE), XIAOBANG SHANG[2], (Senior Member, IEEE), NICK M. RIDLER[2], (Fellow, IEEE), AND STEPAN LUCYSZYN[1], (Fellow, IEEE)

[1]Department of Electrical and Electronic Engineering, Imperial College London, London SW7 2AZ, U.K.
[2]Department of Electromagnetic and Electrochemical Technologies, National Physical Laboratory, Teddington TW11 0LW, U.K.

Corresponding author: Stepan Lucyszyn (s.lucyszyn@imperial.ac.uk)

This work was supported by the U.K. Space Agency's Centre for Earth Observation Instrumentation (CEOI) under Grant RP10G0435A202.

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G-band Multi-channel Front-end

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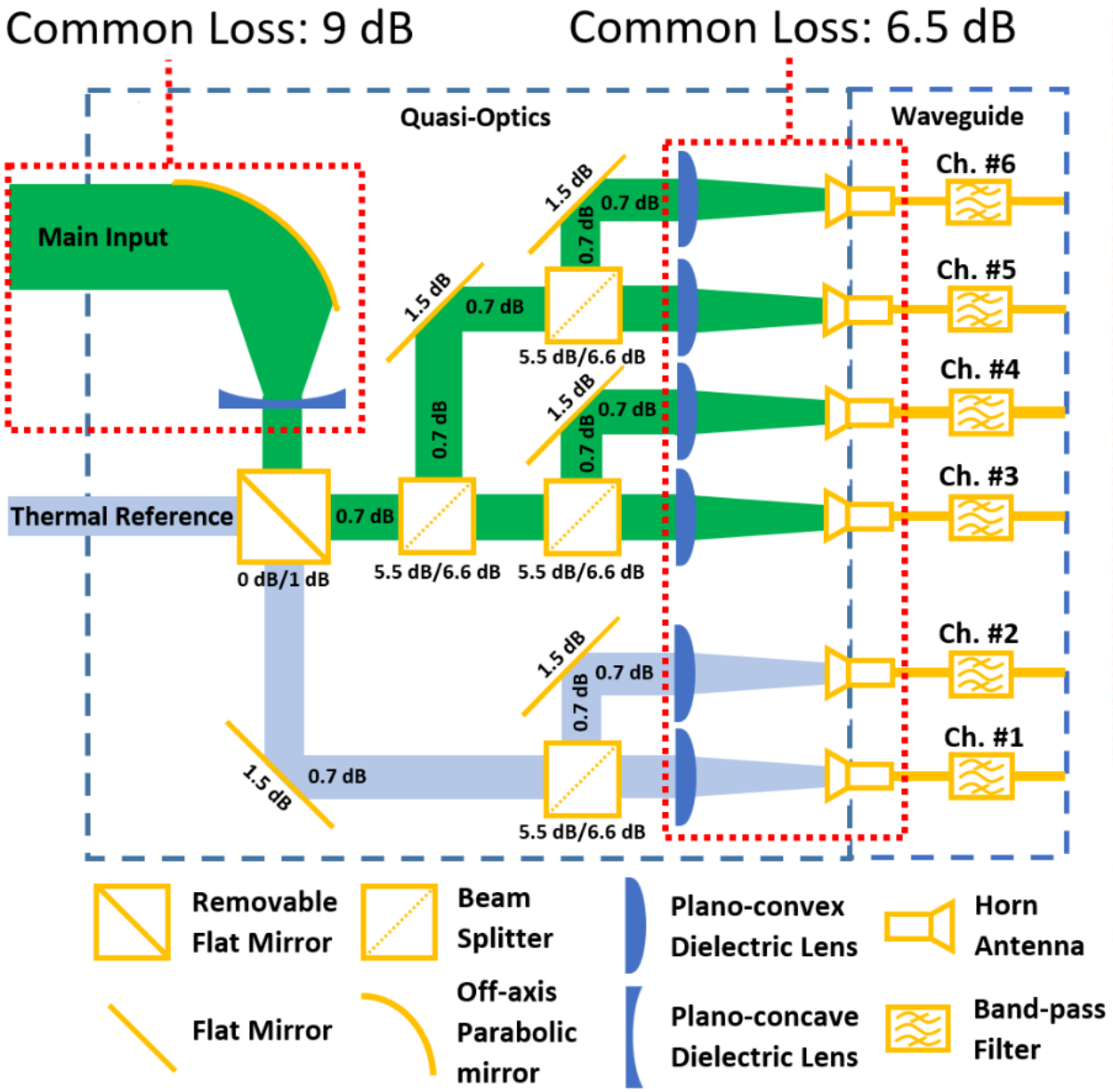
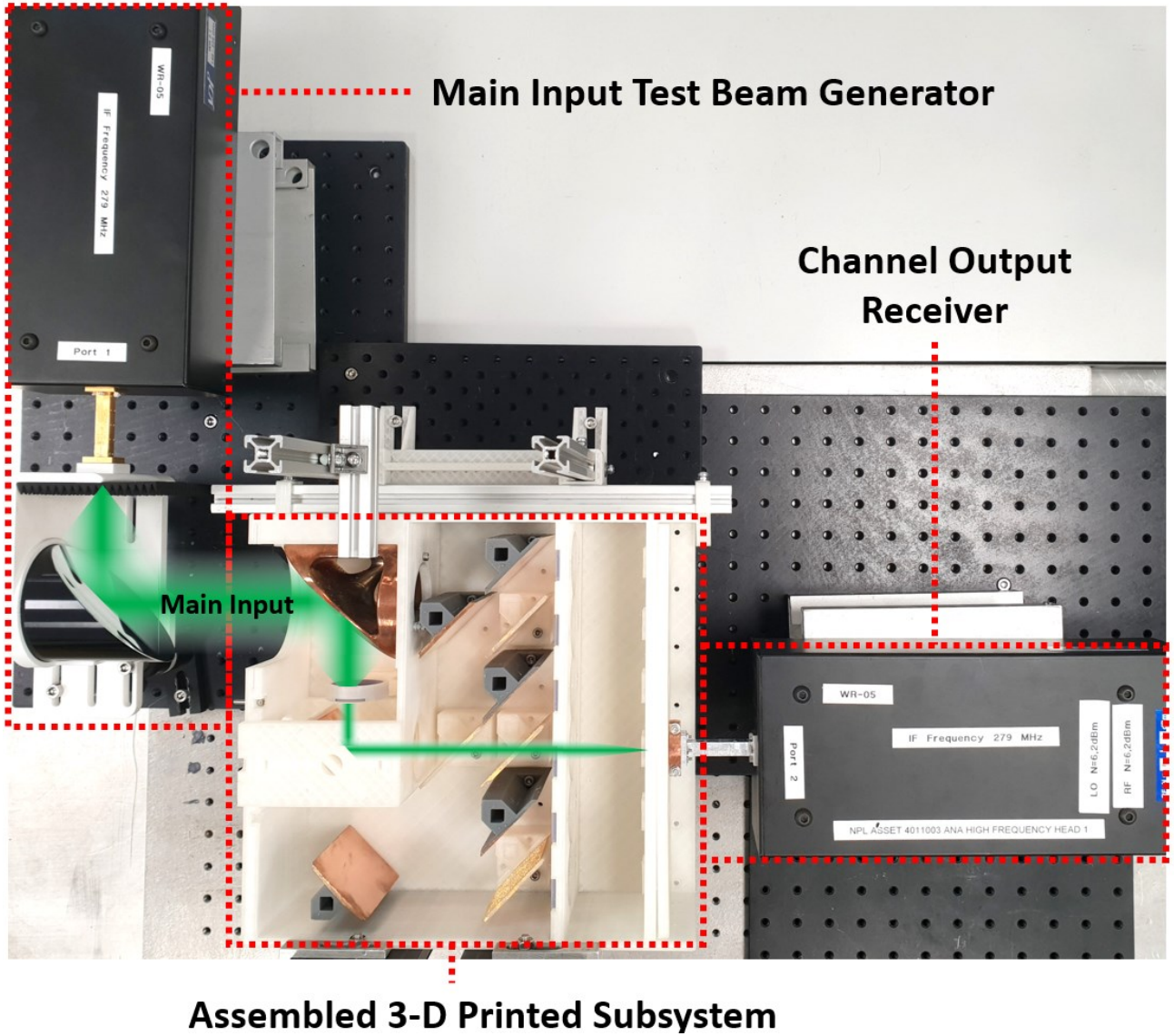
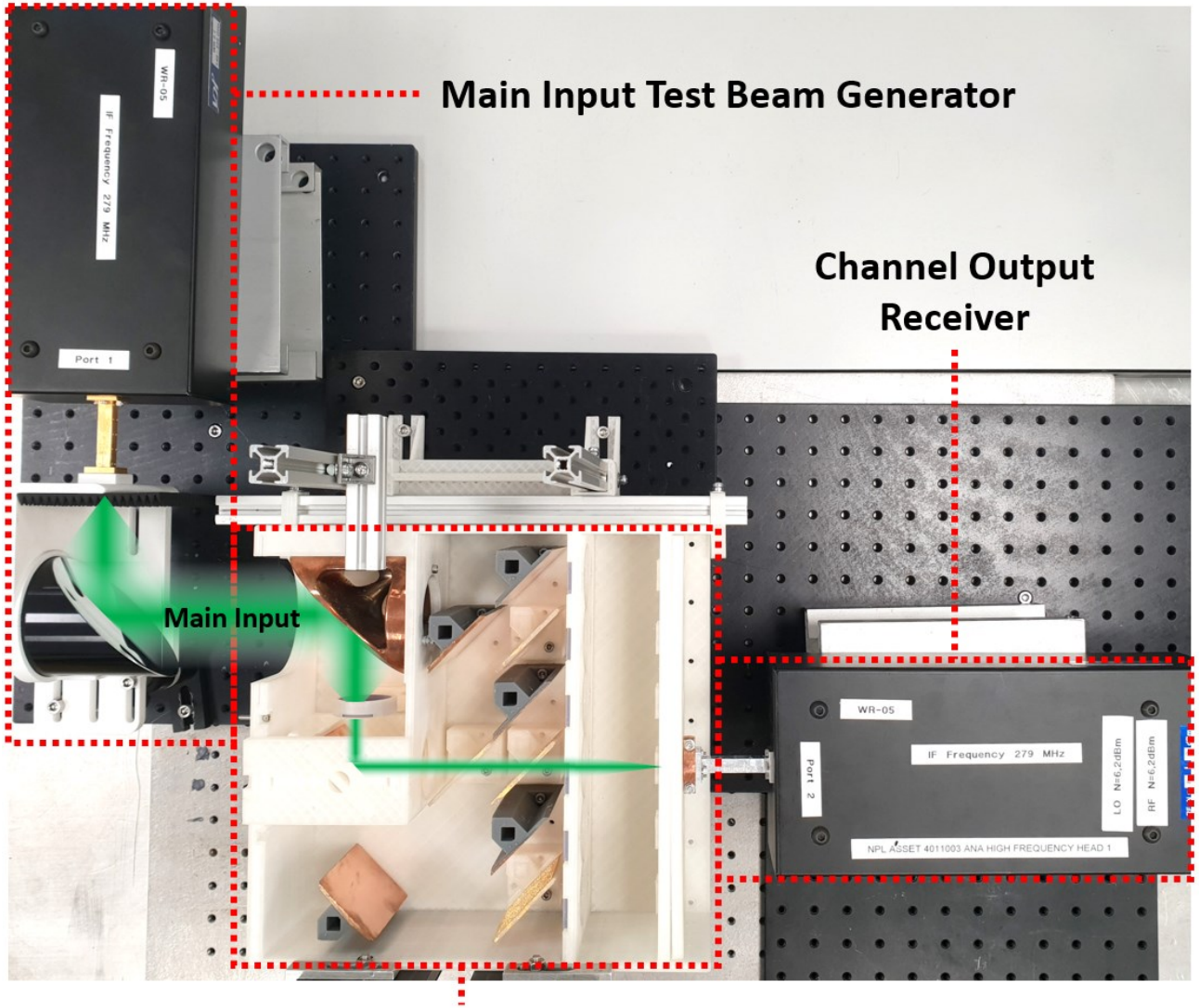
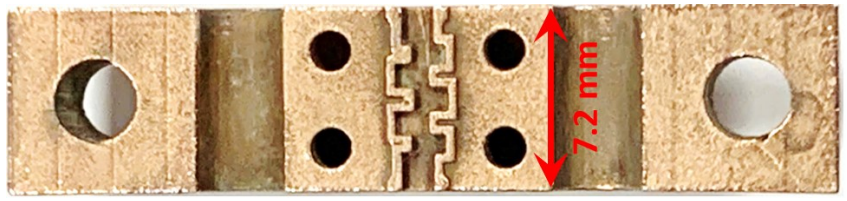


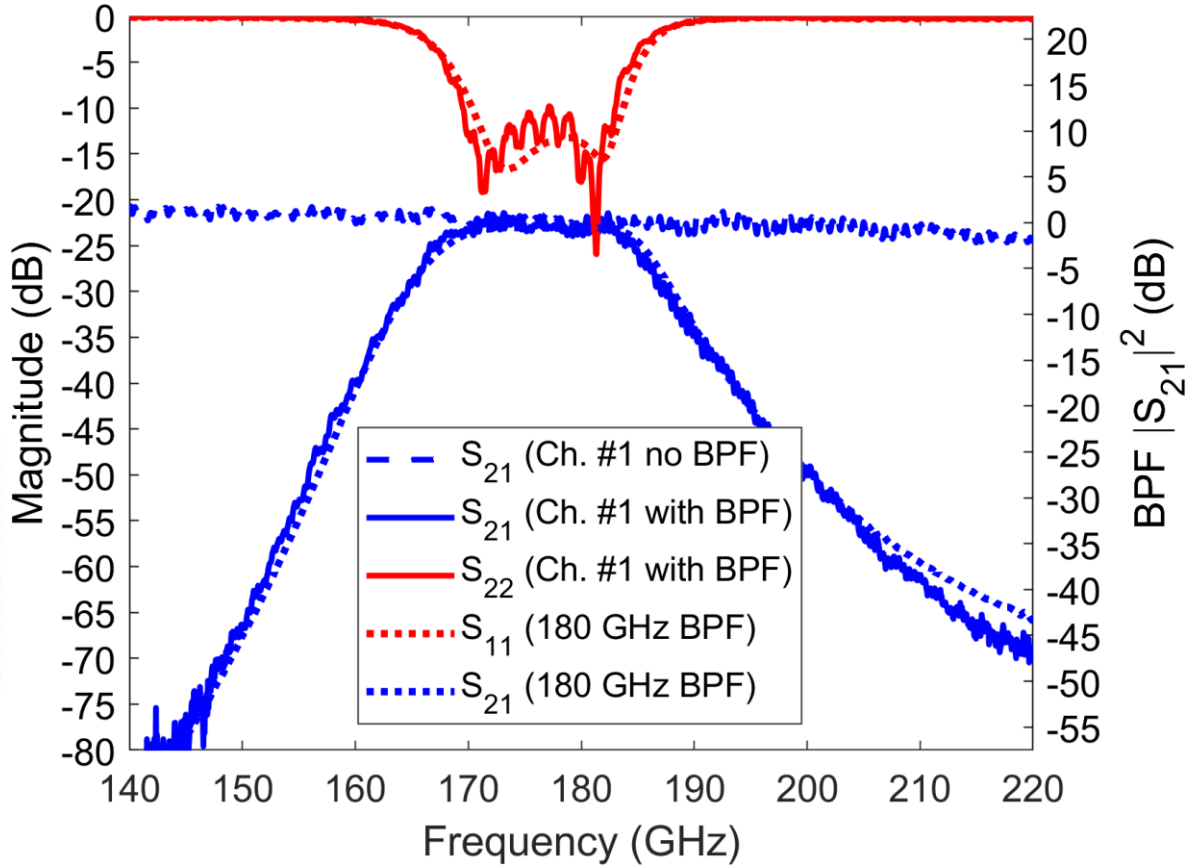


Assembled 3-D Printed Subsystem

G-band Multi-channel Front-end







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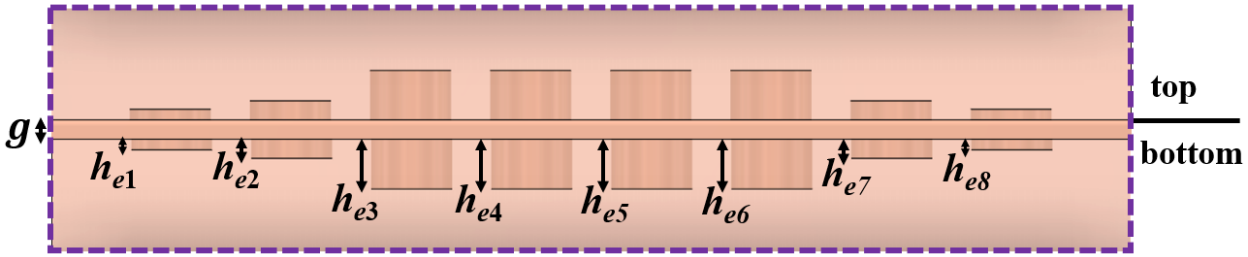
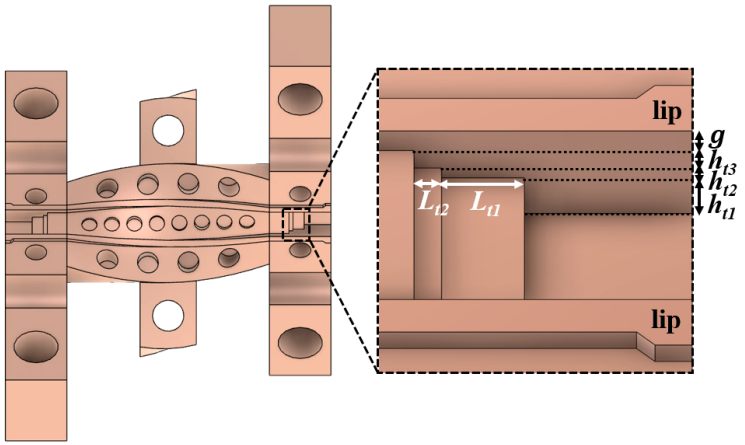
W-band 90° Twist with Integrated Filtering

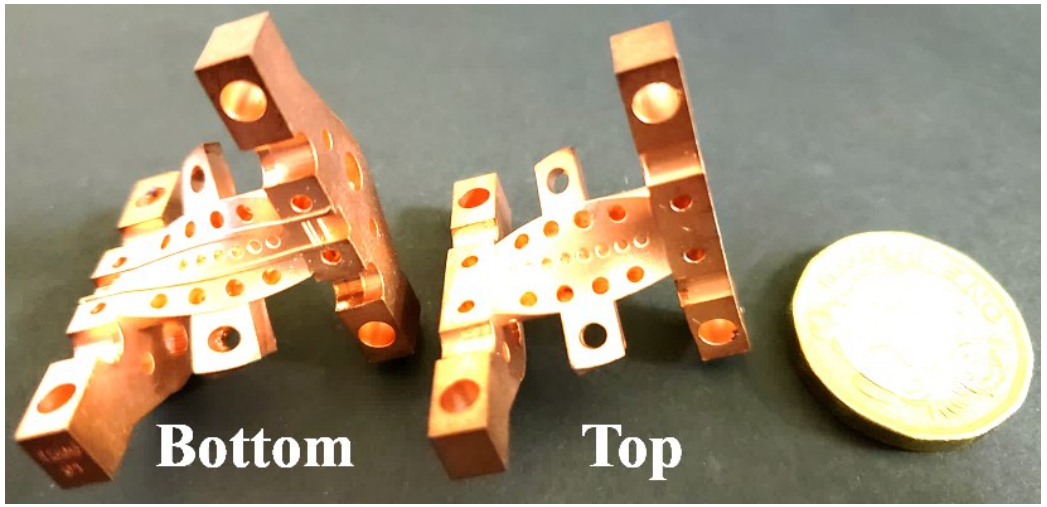
IEEE MICROWAVE AND WIRELESS TECHNOLOGY LETTERS, VOL. 33, NO. 6, JUNE 2023

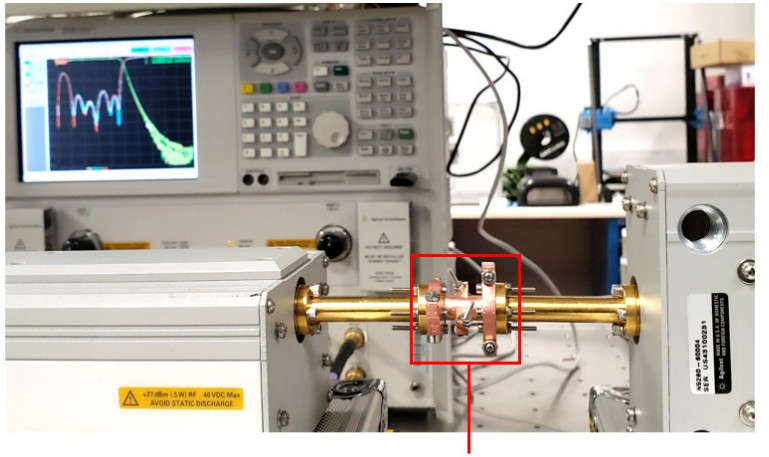
3-D Printed *W*-Band Waveguide Twist With Integrated Filtering

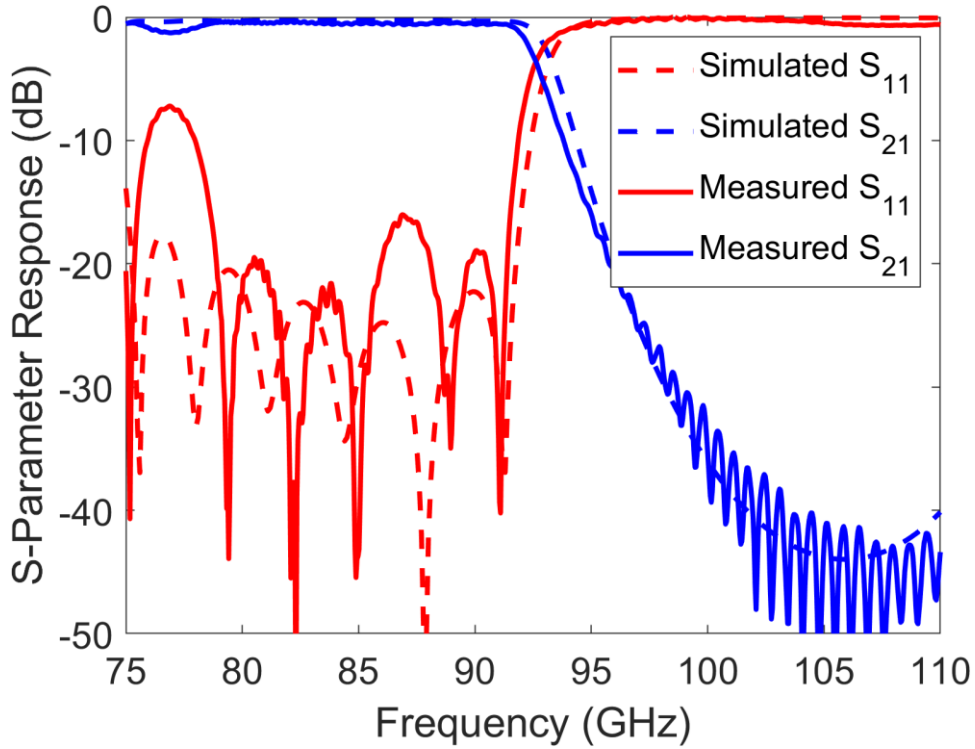
Liyan Zhu, Ian W. Rossuck, Roshan Payapulli, Sang-Hee Shin, *Member, IEEE*, and Stepan Lucyszyn, *Fellow, IEEE*


g
h_{e1}
h_{e2}
h_{e3}
h_{e4}
h_{e5}
h_{e6}
h_{e7}
h_{e8}
top
bottom


lip
lip
g
h_{t3}
h_{t2}
h_{t1}
L_{t2}
L_{t1}


Bottom
Top


VNA extension head (port 1)
VNA extension head (port 2)
3-D printed waveguide twist-filter


S-Parameter Response (dB)
Frequency (GHz)
0
-10
-20
-30
-40
-50
75
80
85
90
95
100
105
110
Simulated S_{11}
Simulated S_{21}
Measured S_{11}
Measured S_{21}

Imperial College London

D-band Multi-chip Modules

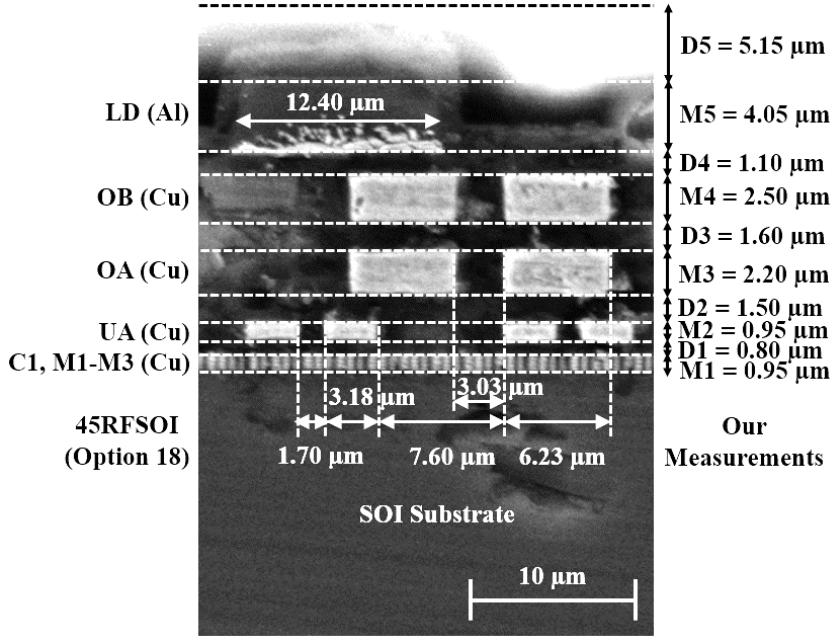
NPL National Physical Laboratory

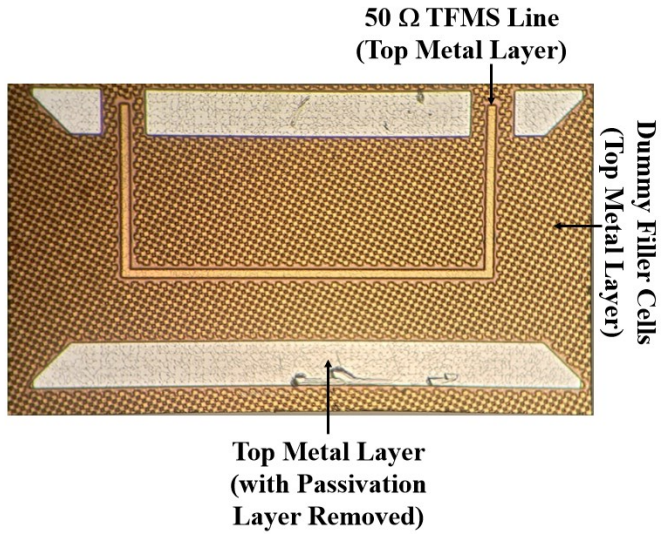
IEEE MICROWAVE AND WIRELESS TECHNOLOGY LETTERS, VOL. 33, NO. 2, FEBRUARY 2023 157

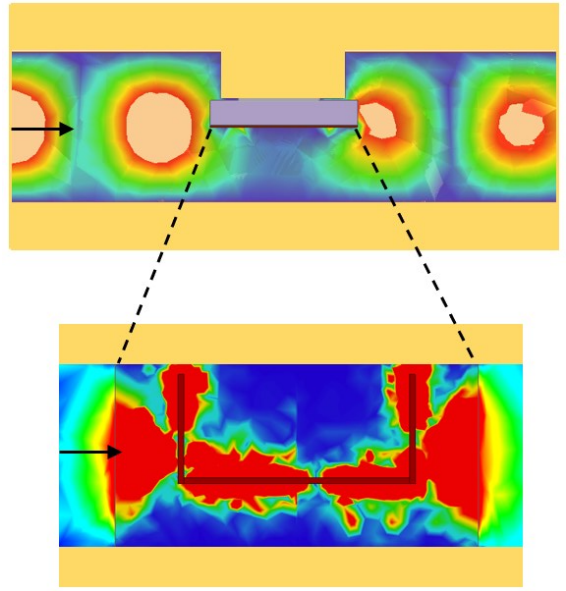
3-D Printed Rectangular Waveguide 123–129 GHz Packaging for Commercial CMOS RFICs

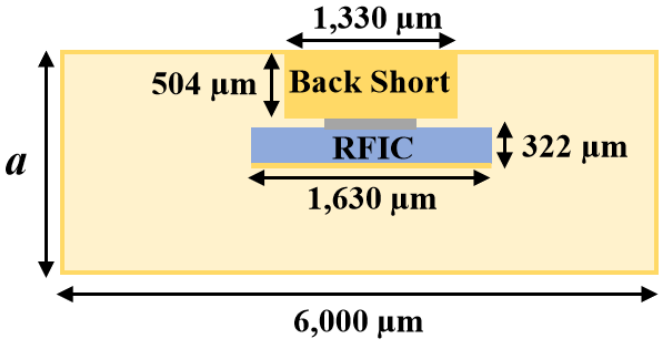
Liyan Zhu, Sang-Hee Shin, *Member, IEEE*, Roshan Payapulli, Taiki Machii, Mizuki Motoyoshi, *Member, IEEE*, Noriharu Suematsu, *Senior Member, IEEE*, Nick M. Ridler, *Fellow, IEEE*, and Stepan Lucyszyn, *Fellow, IEEE*

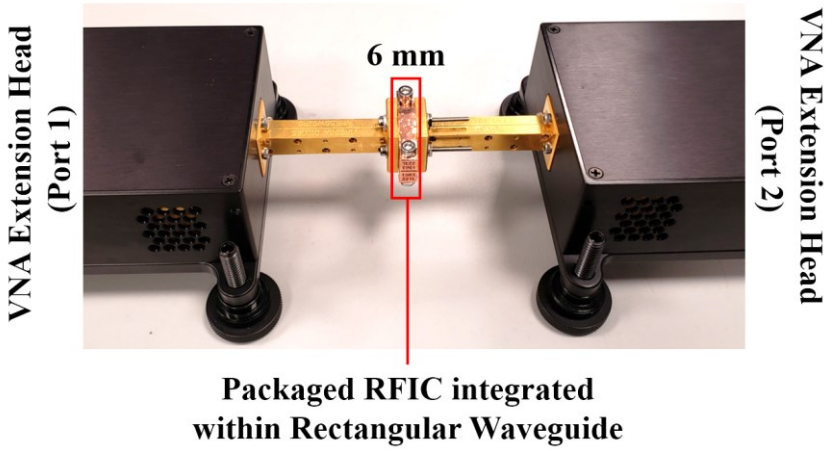
TOHOKU UNIVERSITY

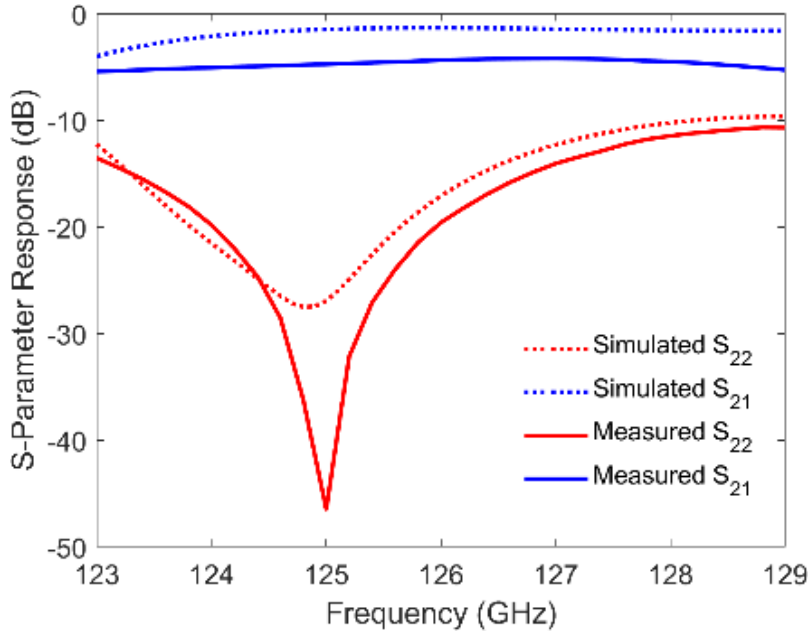












GlobalFoundries® 45 nm CMOS RFIC: SEM microphotograph and optical microphotograph showing 20-µm wide 50 Ω TFMS line

Imperial College London

Low-cost G-band Waveguides

NPL National Physical Laboratory

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RESEARCH ARTICLE

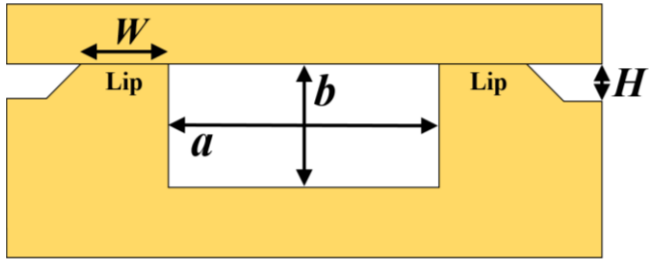
Polymer-Based 3-D Printed 140 to 220 GHz Metal Waveguide Thru Lines, Twist and Filters

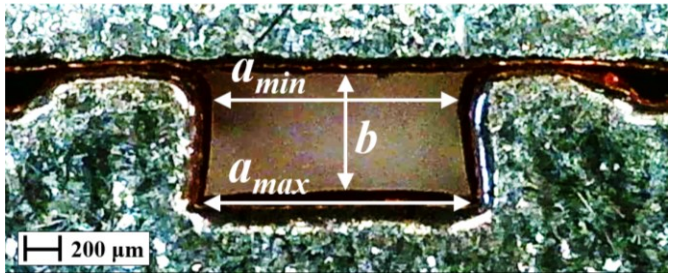
ROSHAN PAYAPULLI[1], LIYAN ZHU[1], SANG-HEE SHIN[1,2], (Member, IEEE), MANOJ STANLEY[2], (Member, IEEE), NICK M. RIDLER[2], (Fellow, IEEE), AND STEPAN LUCYSZYN[1], (Fellow, IEEE)

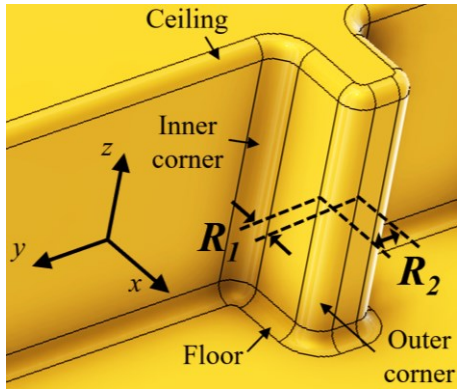
[1]Department of Electrical and Electronic Engineering, Imperial College London, SW7 2AZ London, U.K.
[2]National Physical Laboratory, Department of Electromagnetic and Electrochemical Technologies, TW11 0LW Teddington, U.K.

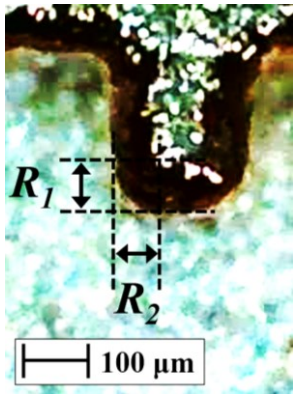
Corresponding author: Stepan Lucyszyn (s.lucyszyn@imperial.ac.uk)

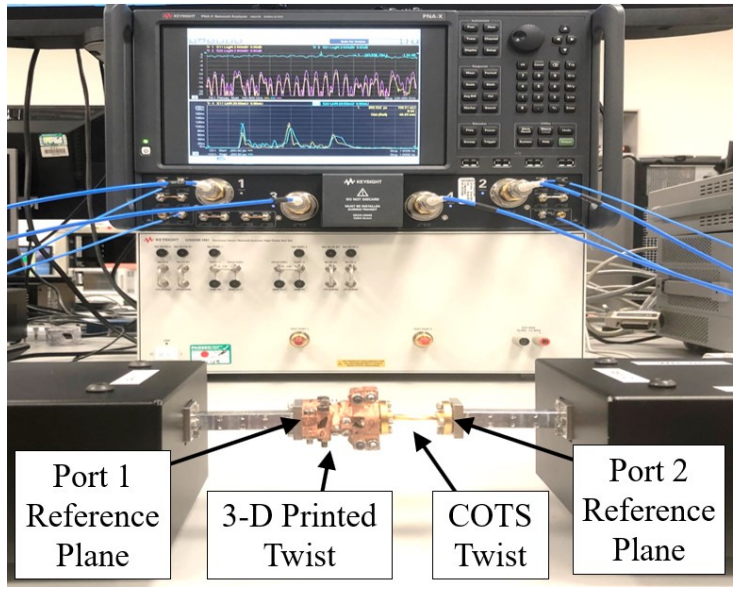
This work was supported by the U.K. Space Agency's Centre for Earth Observation Instrumentation (CEOI) under Grant RP10G0435A202.

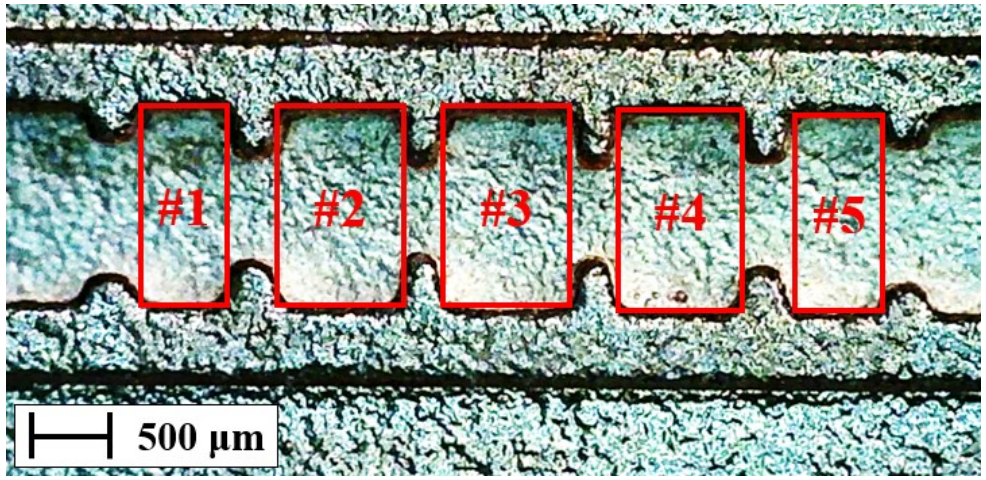

W
Lip
b
a
Lip
H

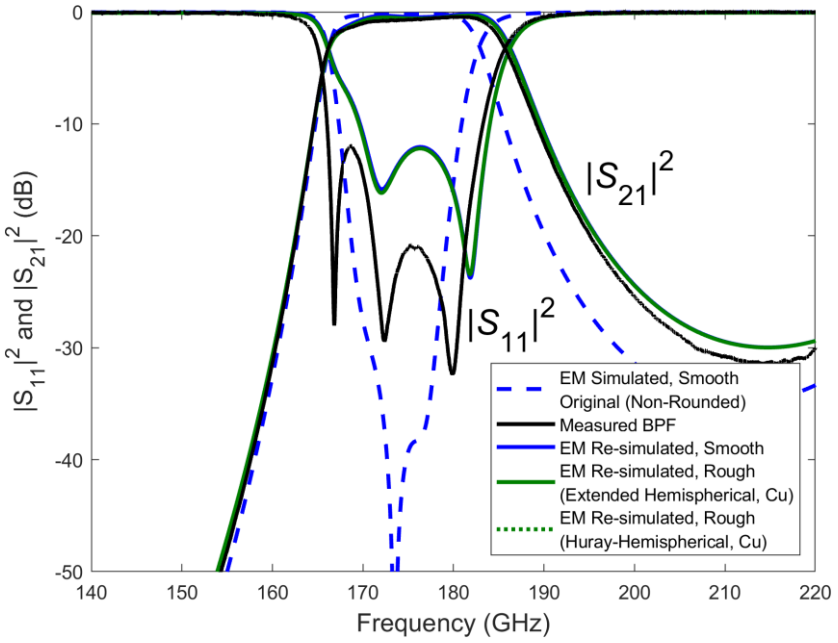

a min
b
a max
200 µm


Ceiling
Inner corner
z
y
x
R1
R2
Floor
Outer corner


R1
R2
100 µm


Port 1 Reference Plane
3-D Printed Twist
COTS Twist
Port 2 Reference Plane


#1
#2
#3
#4
#5
500 µm


0
-10
-20
-30
-40
-50
140
150
160
170
180
190
200
210
220
Frequency (GHz)
|S11|2 and |S21|2 (dB)
|S21|2
|S11|2
EM Simulated, Smooth Original (Non-Rounded)
Measured BPF
EM Re-simulated, Smooth
EM Re-simulated, Rough (Extended Hemispherical, Cu)
EM Re-simulated, Rough (Huray-Hemispherical, Cu)

Imperial College London

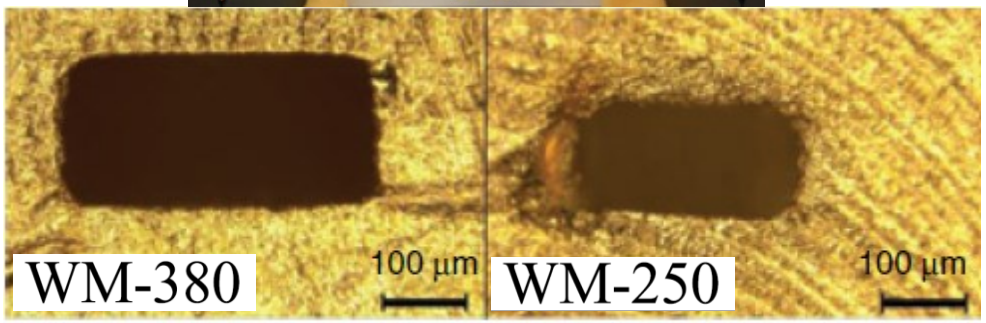
Terahertz (300 GHz to 3 THz)

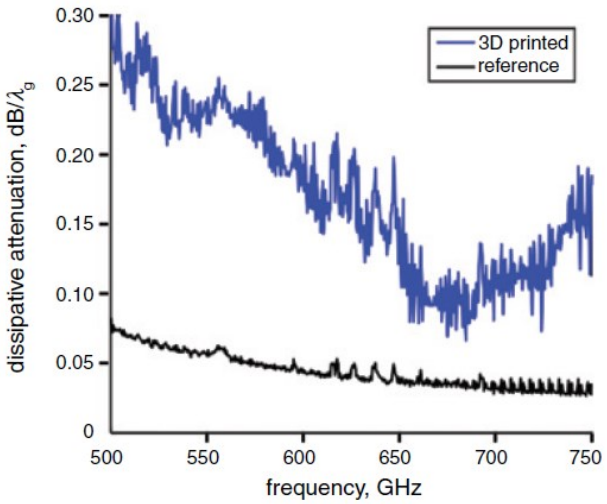
NPL National Physical Laboratory

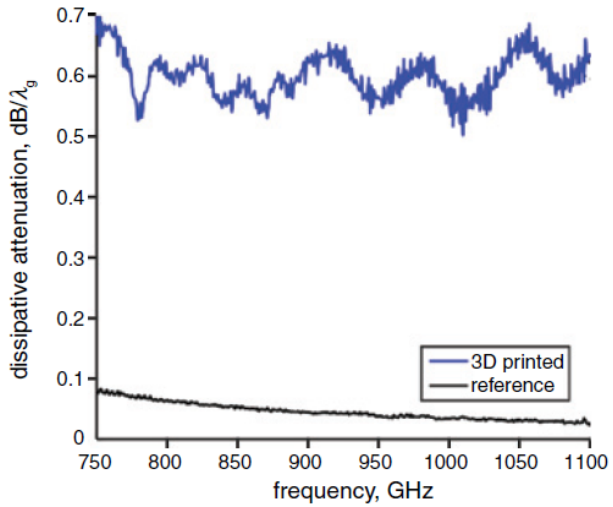
3D printed 1.1 THz waveguides

W.J. Otter, N.M. Ridler, H. Yasukochi, K. Soeda, K. Konishi, J. Yumoto, M. Kuwata-Gonokami and S. Lucyszyn✉

東京大学 THE UNIVERSITY OF TOKYO





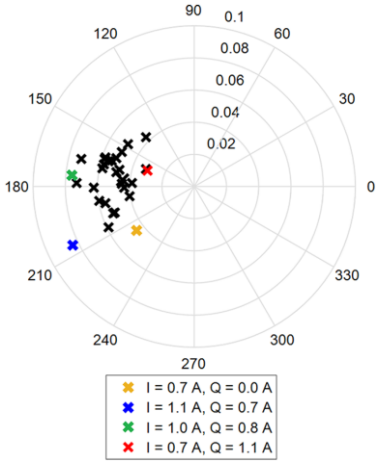


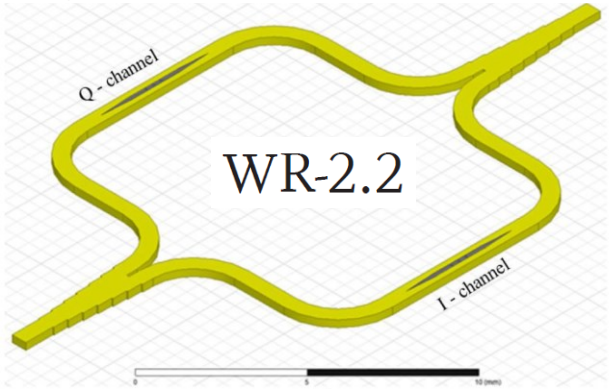
INVITED PAPER

Hybrid 3-D-Printing Technology for Tunable THz Applications

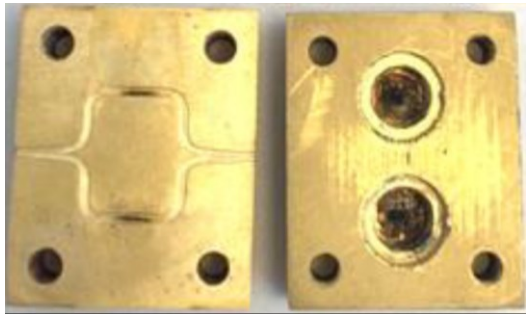
In this paper, a hybrid manufacturing approach is presented that combines metallized passive components produced through the polymer-jetting process with active semiconductor devices. The potential for producing low-cost THz communication systems using this methodology is demonstrated with the successful development of a THz I-Q vector modulator.

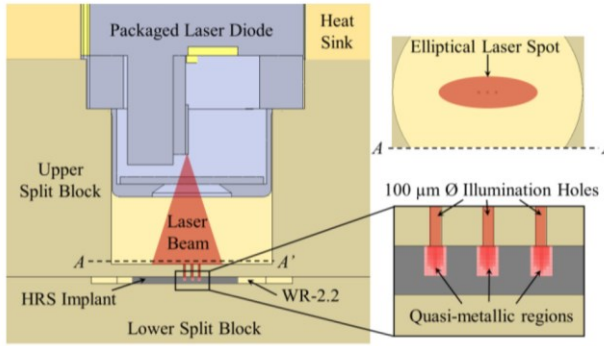
By William J. Otter *Member, IEEE,* and Stepan Lucyszyn *Fellow, IEEE*





(a)





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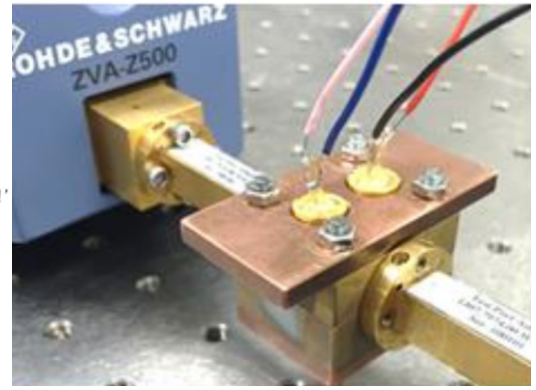

Imperial College London

Low-cost THz Waveguides

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RESEARCH ARTICLE

3-D Printed THz Waveguide Components

LIYAN ZHU[1], SANG-HEE SHIN[2], (Member, IEEE), ROSHAN PAYAPULLI[1], IAN W. ROSSUCK[1], NORBERT KLEIN[3], NICK M. RIDLER[2], (Fellow, IEEE), AND STEPAN LUCYSZYN[1], (Fellow, IEEE)

[1]Department of Electrical and Electronic Engineering, Imperial College London, SW7 2AZ London, U.K.
[2]Department of Electromagnetic and Electrochemical Technologies, National Physical Laboratory, TW11 0LW Teddington, U.K.
[3]Department of Materials, Imperial College London, SW7 2AZ London, U.K.

Corresponding author: Stepan Lucyszyn (s.lucyszyn@imperial.ac.uk)

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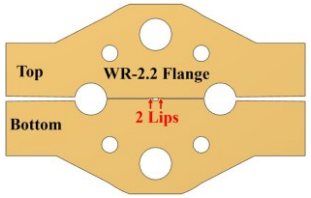
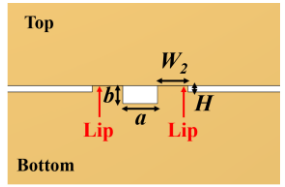
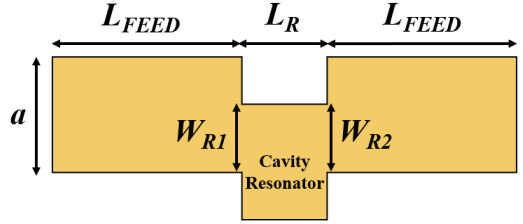
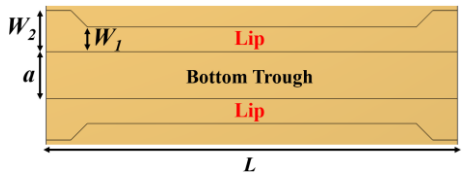
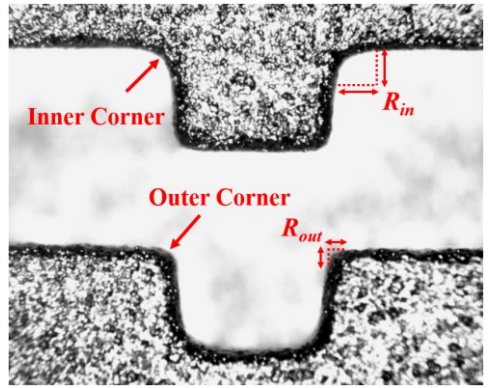
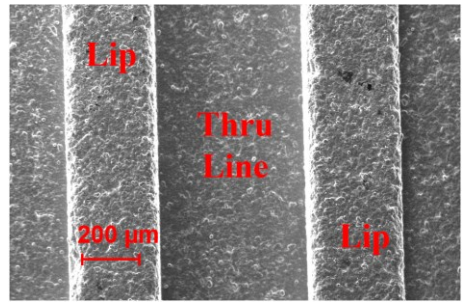


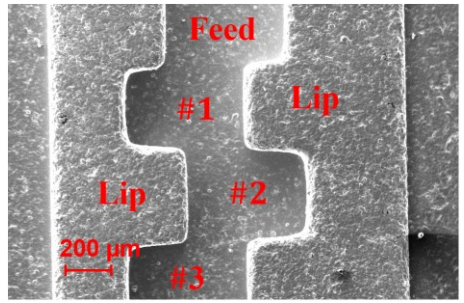


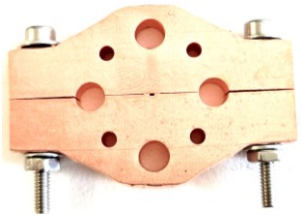


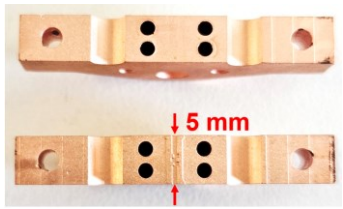


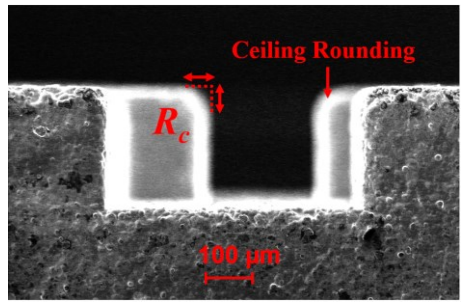


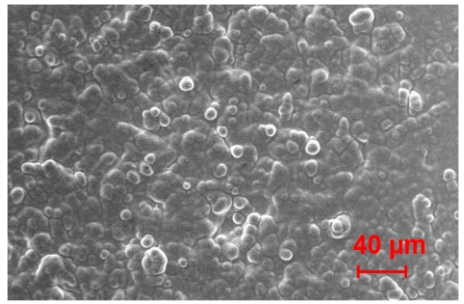


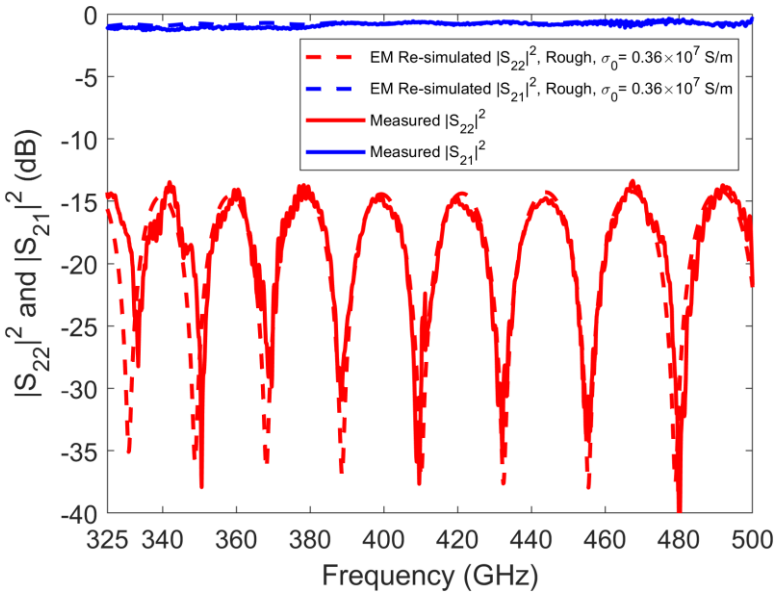


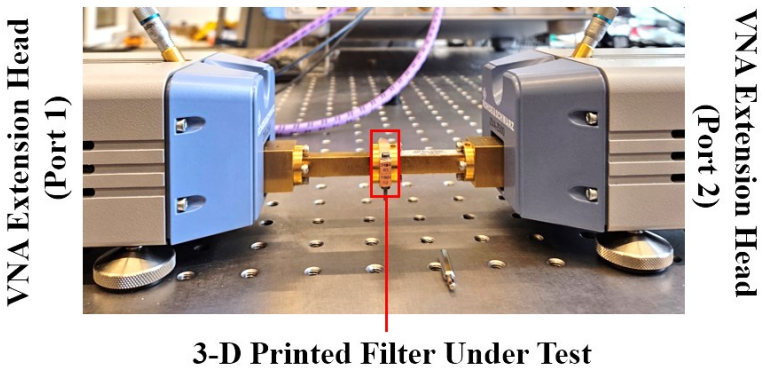




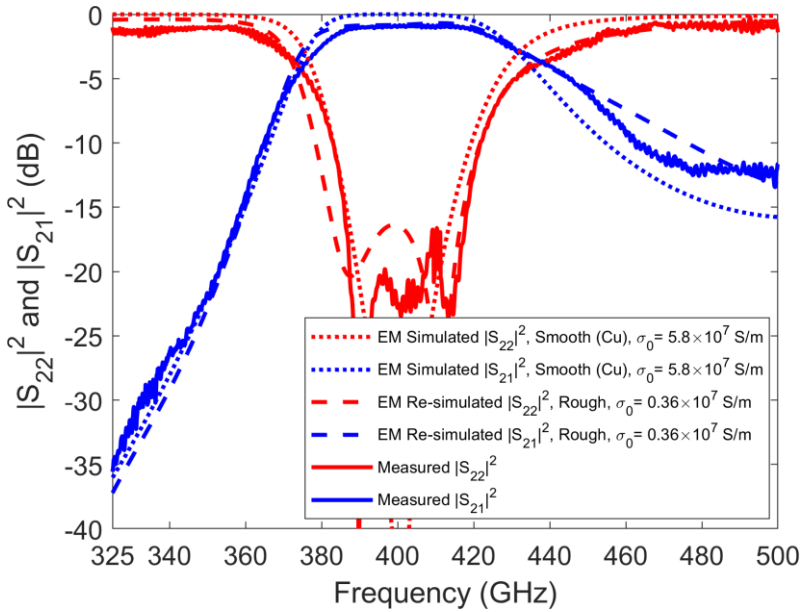








3-D Printed Filter Under Test



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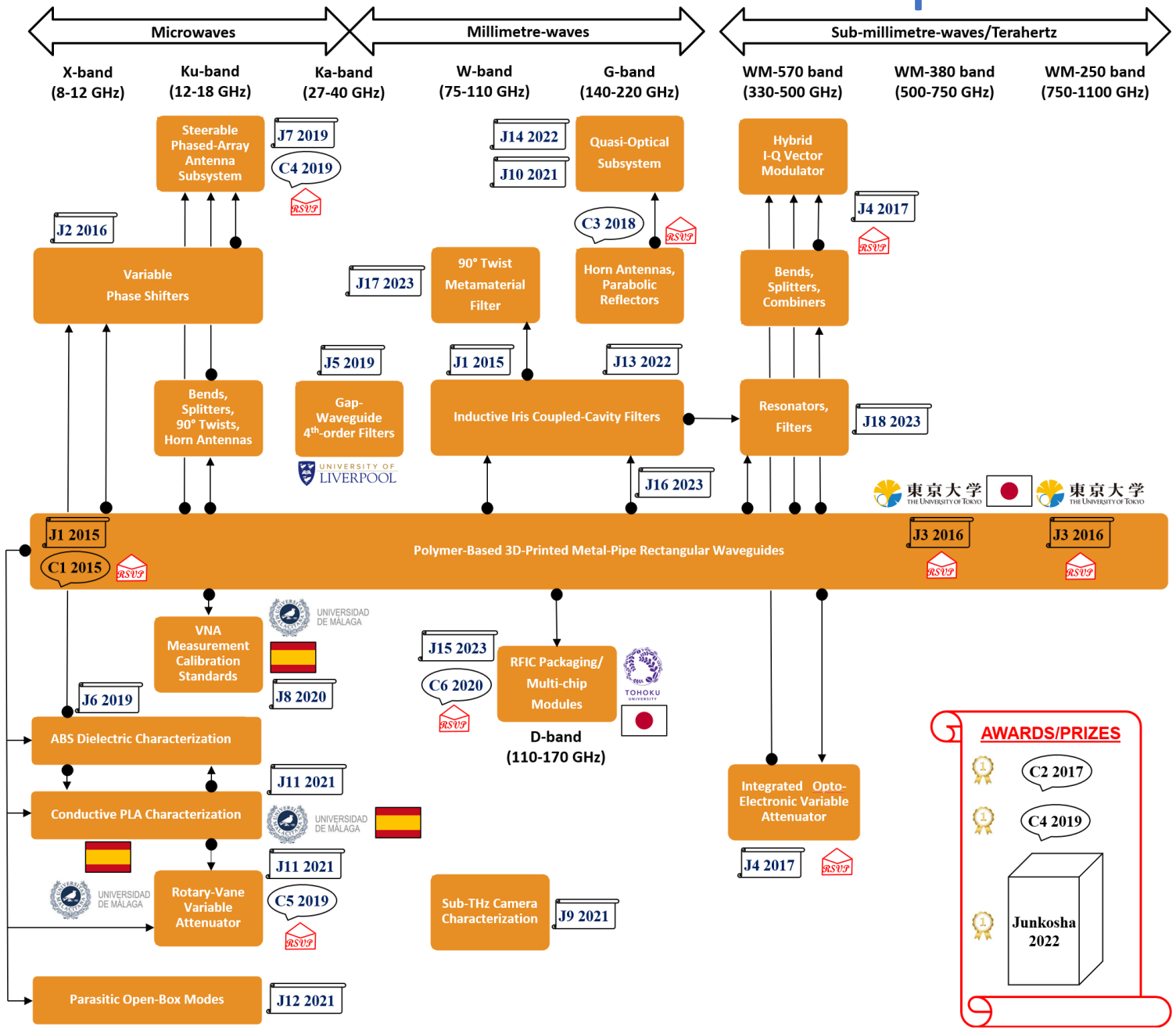
Publications Landscape



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Publications

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, Nov. 2019)**.

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, "Fabrications 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 primary 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)**.

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J9. S.-H. Shin and S. Lucyszyn, “Benchmarking a commercial (sub-)THz focal plane array against a custom-built millimeter-wave single-pixel camera”, IEEE Access, vol. 8, pp. 191174-191190, Oct. 2020.

J10. 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.

J11. 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.

J12. A. Dawood and S. Lucyszyn, “Parasitic high Q-factor open-box modes with 3-D printed dielectric-filled metal waveguides”, IEEE Access, vol. 9, pp. 134319-134334, Oct. 2021.

J13. L. Zhu, R. Payapulli, S.-H. Shin, S-H, M. Stanley, N. M. Ridler, S. Lucyszyn, “3-D printing quantization predistortion applied to sub-THz chained-function filters”, IEEE Access, vol. 10, pp. 38944-38963, Mar. 2022.

J14. S.-H. Shin, R. Payapulli, L. Zhu, M. Stanley, X. Shang, N. M. Ridler, and S. Lucyszyn, “3-D printed plug and play prototyping for low-cost sub-THz subsystems”, IEEE Access, vol. 10, pp. 41708-41719, Apr. 2022.

J15. L. Zhu, S.-H. Shin, R. Payapulli, T. Machii, M. Motoyoshi, N. Suematsu, N. M. Ridler, and S. Lucyszyn, “3-D printed rectangular waveguide 123-129 GHz packaging for commercial CMOS RFICs”, IEEE Microwave and Wireless Technology Letters, vol. 33, no. 2, pp. 157-160, Feb. 2023.

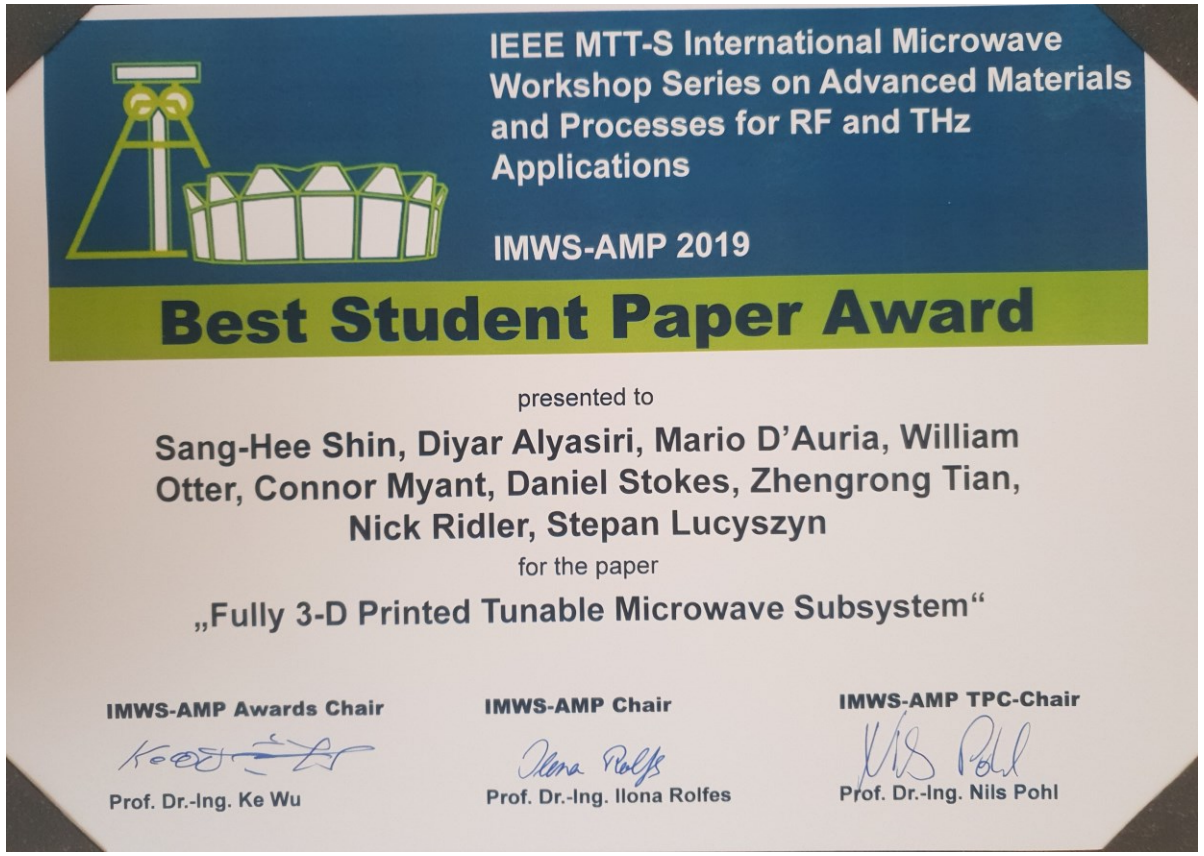
J16. R. Payapulli, L. Zhu, S.-H. Shin, M. Stanley, N. M. Ridler, and S. Lucyszyn, “Polymer-based 3-D printed 140 to 220 GHz metal waveguide thru lines, twist and filters”, IEEE Access, vol. 11, pp. 32272-32295, Apr. 2023.

J17. L. Zhu, I. Rossuck, R. Payapulli, S.-H. Shin, and S. Lucyszyn, “3-D printed W-band waveguide twist with integrated filtering”, IEEE Microwave and Wireless Technology Letters, vol. 33, no. 6, pp. 659-662, Jun. 2023.

J18. L. Zhu, S.-H. Shin, R. Payapulli, I. W. Rossuck, N. Klein, N. M. Ridler, and S. Lucyszyn, “3-D Printed THz Waveguide Components”, IEEE Access, vol. 11, pp. 79073-79086, Aug. 2023.

Prizes

William Otter receives the Steve Evans-Pughe Memorial Prize for the best paper from John Crute, ARRMS Chairman, 2017



Stepan Lucyszyn receives the category winner (Microwave and Millimeter Wave) of its inaugural Technology Innovator of the Year Awards from Joe Rowan, President and CEO of Junkosha USA Inc., 2022

Our Student Training at NPL

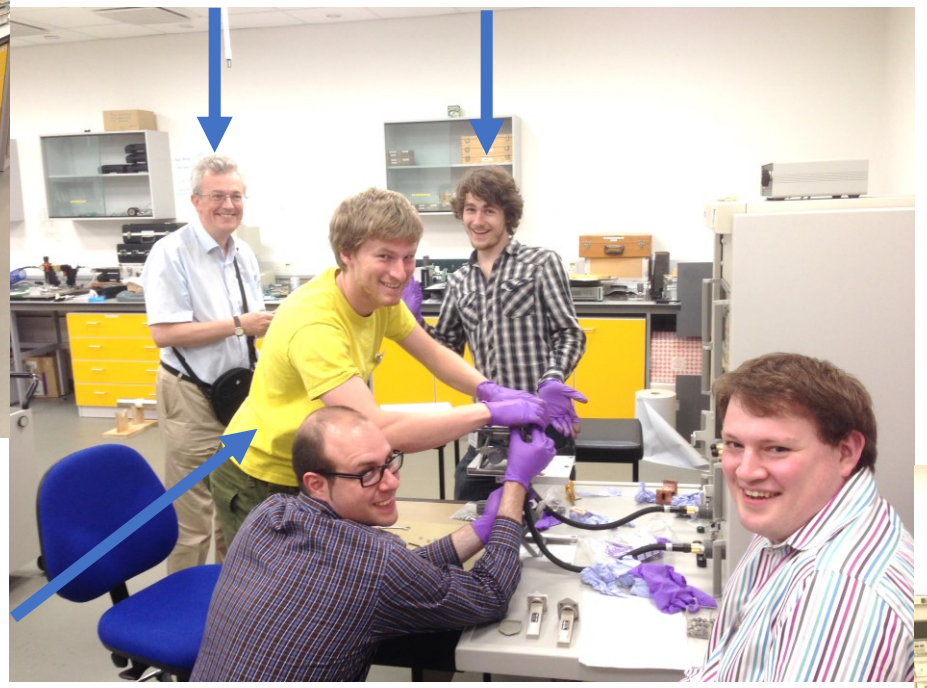
Imperial College London

NPL National Physical Laboratory

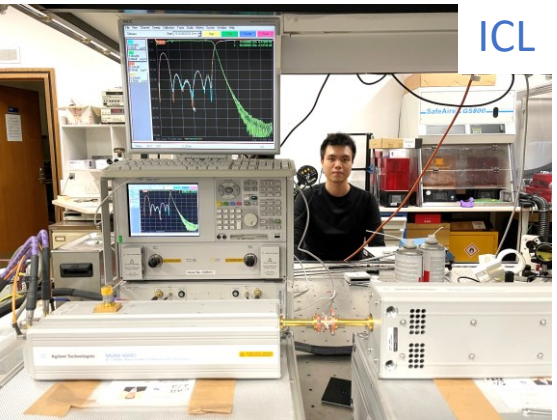
Callum Long-Collins
(Undergraduate Student)

Nick Ridler
(NPL)

Brendan Gillatt
(Undergraduate Student)



Jonathan Hazell
(PhD Student)
ICL



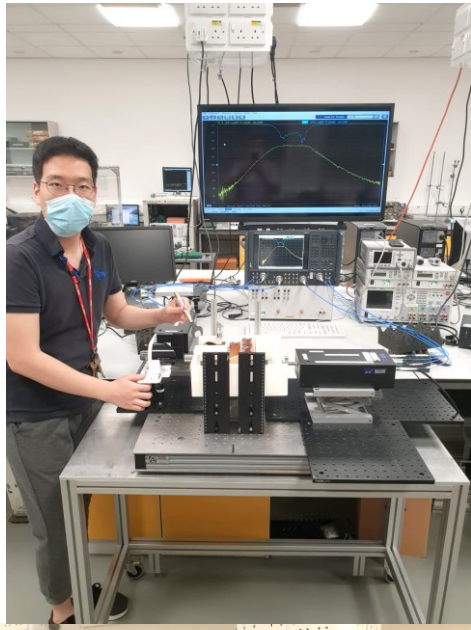
Liyan Zhu
(PhD Student)

Mario D'Auria
(PhD Student)
(NPL Spin-out)

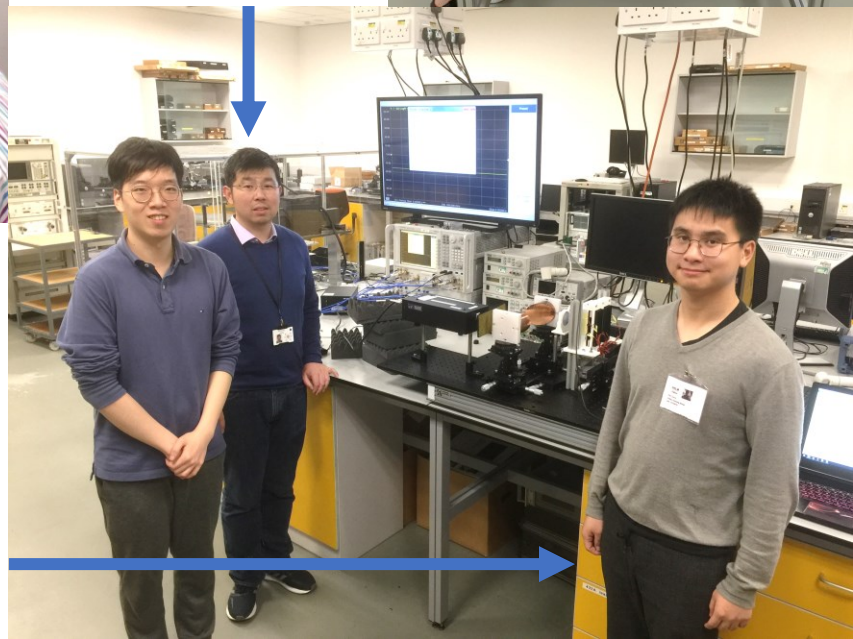
William Otter
(PhD Student)

Ran Cheng
(PhD Student)

Sang-Hee Shin
(PhD Student)
(now at NPL)



Xiaobang Shang
(NPL)



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J. Sun

A. Dawood

S.-H. Shin

R. Payapulli

L. Zhu

I. W. Rossuck

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C. Long-Collins

D. Alyasiri

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R. Wang

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NPL National Physical Laboratory

Nick M. Ridler

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X. Shang

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J. Skinner

D. Stokes

Z. Tian

A. Jones (apprentice)

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President, 2015-2021


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