CO-4000127300/19/NL/HK

EVALUATION AND CONSOLIDATION OF ADDITIVE MANUFACTURING PROCESSES AND MATERIALS FOR THE MANUFACTURING OF RF HARDWARE

FINAL PRESENTATION

TABLE OF CONTENTS

SCOPE OF THE STUDY

Scope of the project has been to **identify suitable Additive Manufacturing techniques** to be used for realising components and sub-systems for RF space applications.

Within this activity different AM processes, materials and post-processes for RF/microwave applications in space have been studied and characterized.

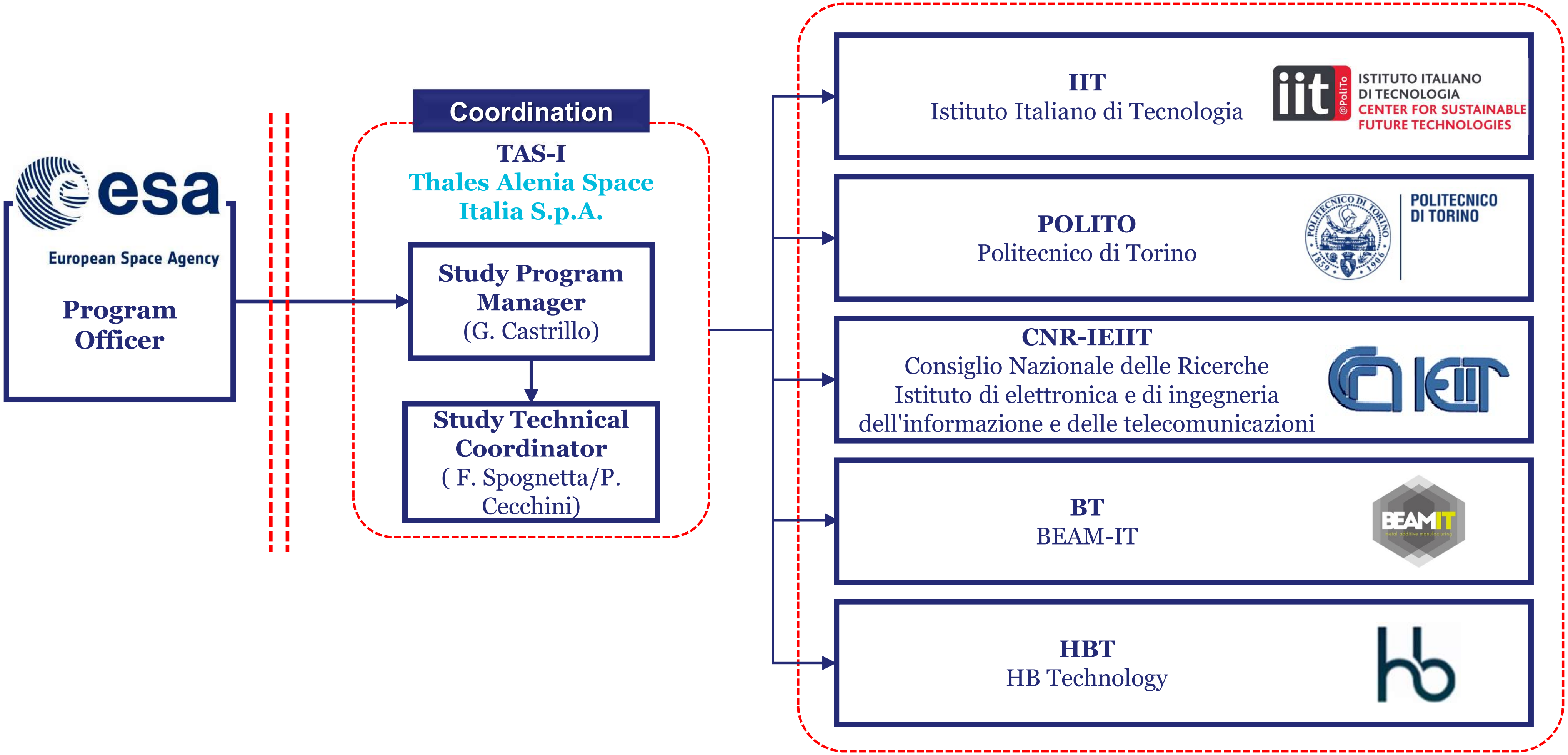
The Project has been conceived in **two phases**:

- **Phase 1** aiming at investigating different materials and manufacturing processes and external treatments through design, production and test of multiple samples and test vehicles (representative critical sections of RF concept).

  Different class of materials (polymeric, metallic and ceramic) were tested from a physical, mechanical, electrical, RF performances point of view. As conclusion of Phase 1, demonstrators were selected for being manufactured during Phase 2.

- **Phase 2** focused on the finalization of the design of the abovementioned demonstrators, on their manufacturing and post treatments and on the measurements of their RF performances and assessment with respect to the predicted ones.

PROJECT OVERVIEW: TEAM ORGANISATION



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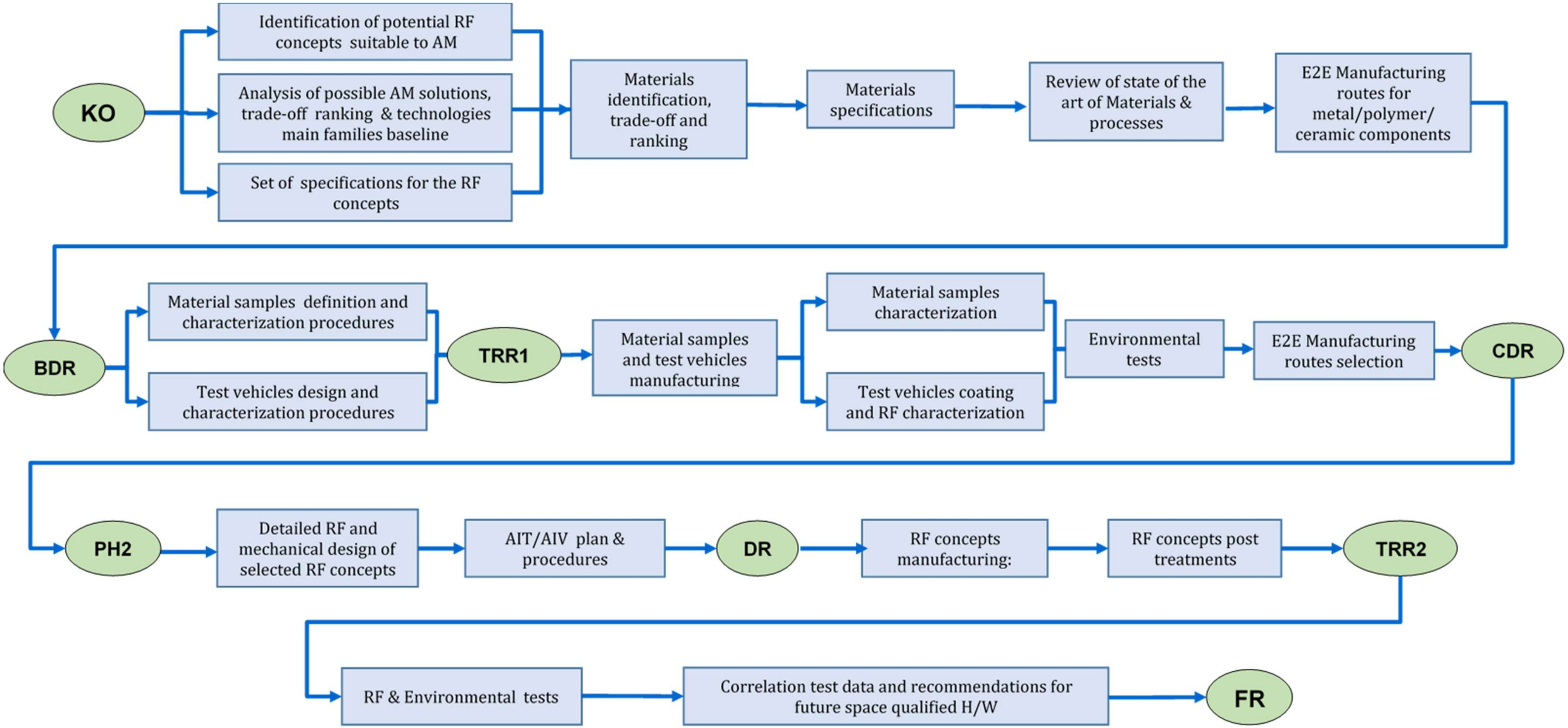
PROJECT OVERVIEW: STUDY LOGIC



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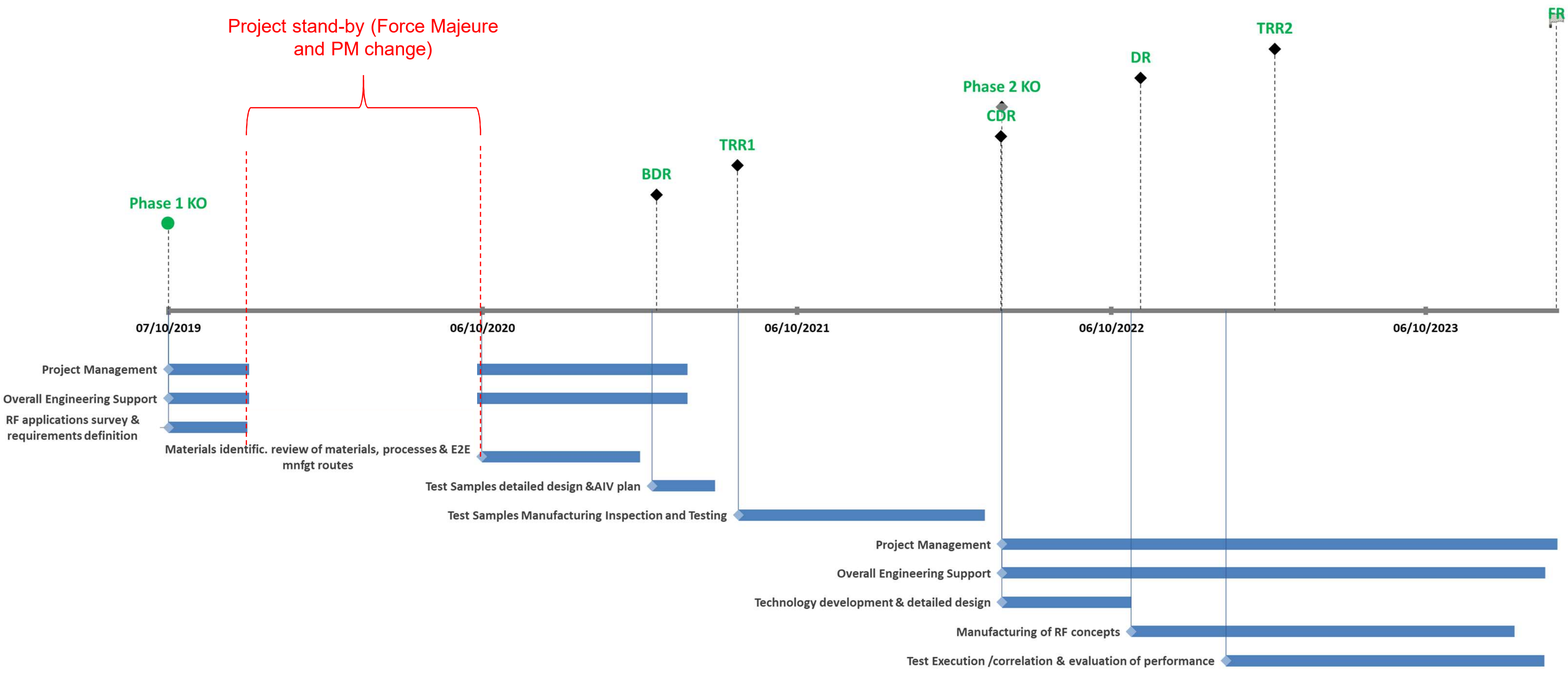
PROJECT OVERVIEW: MILESTONES

ML	Title	Actual date	Place
KO	Kick-Off	07/09/2019	videoconference
MS1	Baseline Design Review (BDR)	26/04/2021	videoconference
MS2	Test Readiness Review1 (TRR1)	29/07/2021	videoconference
MS3	Critical Design Review (CDR)	25-31/05/2022	videoconference
MS4	Design Review (DR)	09/11/2022	videoconference
MS5	Test Readiness Review2 (TRR2)	14/04/2023	POLITO premises
MS6	**Final Review (FR)**	**06/03/2024**	**videoconference**

- **Major delay events:**
  - ➢ COVID 19 pandemic during Q2/Q3 2020: CCN1 was approved by the Agency due to Force Majeure and PM Change
  - ➢ New COVID cluster in December 2021/January 2022 during manufacturing/test phase
  - ➢ Unexpected results on metal-plated polymers at the end of Phase 1
  - ➢ Unplanned extra-work on Demonstrator #3 manufacturing, design and characterization during Phase 2

PROJECT OVERVIEW: TIMELINE



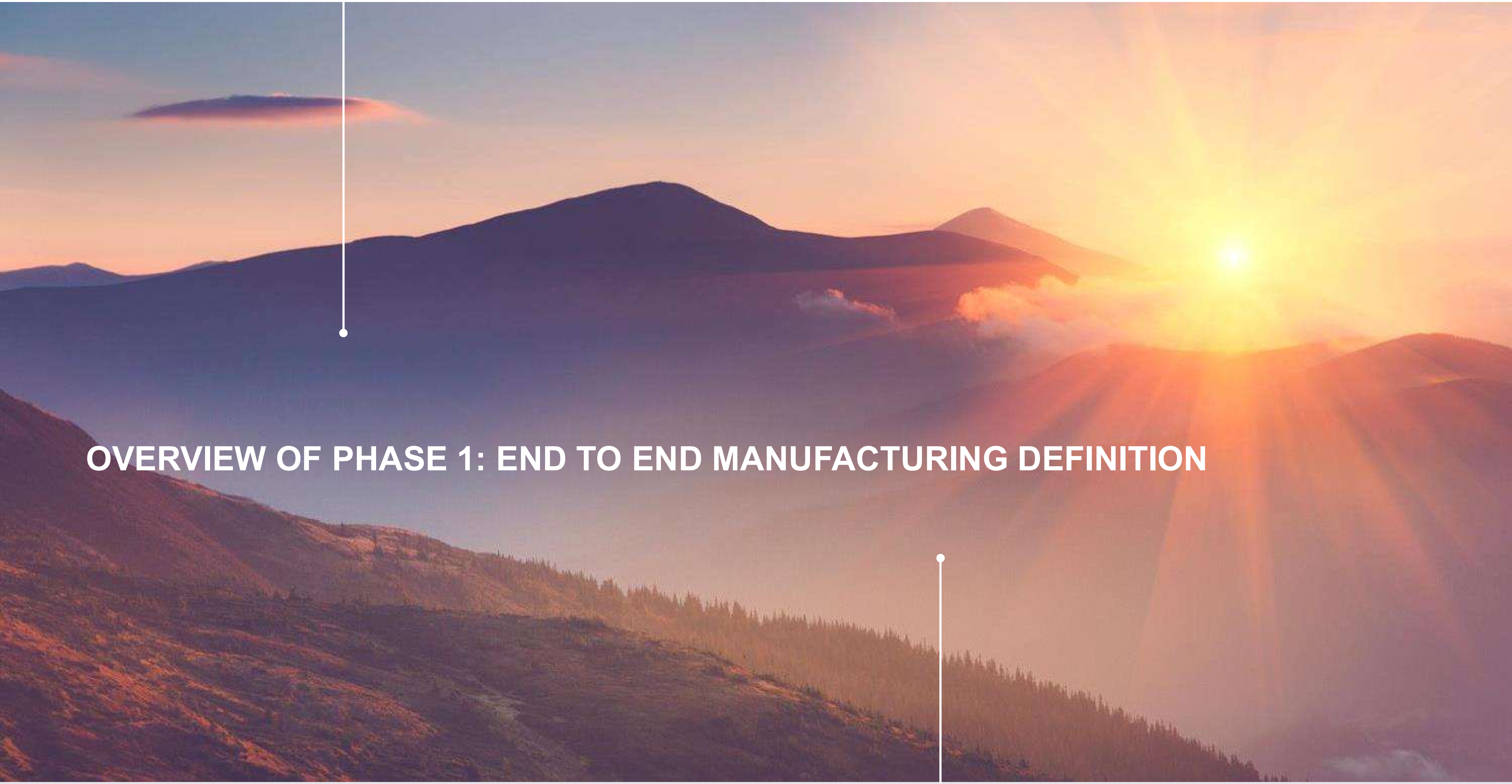
PROJECT OVERVIEW: DELIVERABLE LIST

	MS	ID Code	Document Title	Document No	Date	Issue	Remarks
PHASE 1	BR	TN-01	Potential RF concepts identification and justification	TASI-STLI-TNO-AMRF-0003	09/04/2021	02	Delivered
		TN-02	Set of specifications for the RF concepts	TASI-STLI-TNO-AMRF-0004	09/04/2021	02	Delivered
		TN-03	Materials identifiction	TASI-STLI-TNO-AMRF-0005	09/04/2021	02	Delivered
		TN-04	Specifications for materials	TASI-STLI-TNO-AMRF-0006	09/04/2021	02	Delivered
		TN-05	Review of State of Art of Materials and related Process in Additive Manufacturing including post processing	TASI-STLI-TNO-AMRF-0007	09/04/2021	01	Delivered
		TN-06	Identification of End-to-End Manufacturing Routes	TASI-STLI-TNO-AMRF-0008	09/04/2021	01	Delivered
	TRR1	TN-07	Test Vehicles and Test Samples Detailed Design and Verification Campaign Definition	TASI-STLI-TNO-AMRF-0009	02/07/2021	01	Delivered
	CDR	TN-08	Test Vehicles Manufacturing, Inspection and Testing	TASI-STLI-TNO-AMRF-0064	11/05/2022	01	Delivered
		TN-09	Manufacturing Process and Concept Selection	TASI-STLI-TNO-AMRF-0065	11/05/2022	01	Delivered
PHASE 2	DR	TN-10	**Detailed design report**	TASI-STLI-TNO-AMRF-0111	28/10/2022	01	Delivered
		TN-11	**Manufacturing file and manufacturing procedure for the RF concepts**	TASI-STLI-TNO-AMRF-0112	05/04/2022	02	Delivered
		TN-12	**Test plan and test procedures for the RF concepts**	TASI-STLI-TNO-AMRF-0113	28/10/2022	01	Delivered
	TRR2	TN-13	**Demonstrator manufacturing process evaluation and inspection results**	TASI-STLI-TNO-AMRF-0114	05/04/2022	01	Delivered
		TN-14	**Preliminary performance**	TASI-STLI-TNO-AMRF-0115	05/04/2022	01	Delivered
	FR	TN-15	**Concepts Test Report**	TASI-STLI-TNO-AMRF-0141	20/02/2024	01	Uploaded on Alfresco Repository
		TN-16	**Test evaluation and assessment of demonstrated performance improvements**	N/A			Agreed merge with TN-15
		TN-17	**Final report**	TASI-STLI-ORP-AMRF-0015	20/02/2024	01	Uploaded on Alfresco Repository

PROJECT OVERVIEW: HW LIST

	ML	Title	Description
Phase 1	HW1	Set of Test Vehicles and Material Samples	Test vehicles and materials samples produced during phase 1
	HW2	Concepts hardware 1	Dem. #1: Q/V-band antenna-feed chain components and subassemblies
	HW3	Concepts hardware 2	Dem. #2: L-band bar-line 3-dB coupler
Phase 2	HW4	Concepts hardware 3	Dem. #3: miniaturized loaded filter at low frequency band
	HW5	Concepts hardware 4	WR75 lines in metal-plated CF peek

AM4RF HW LIST



OVERVIEW OF PHASE 1: END TO END MANUFACTURING DEFINITION

PHASE 1 – STATE OF ART

3D printing vs standard machining of RF sub-systems/components for Space applications

PHASE 1 – STATE OF THE ART FOR AM MATERIALS FOR RF SPACE CONCEPTS

Demonstrator

- Lightweight
- Strength & Stiffness
- Low Outgassing under thermal vacuum
- Resistance in a wide T range

RF Applications

- Electrical properties: surface conductivity, dielectric constant and loss tangent
- Roughness for conducting surfaces
- Dimensional Accuracy

PHASE 1 – STATE OF THE ART FOR AM MATERIALS FOR RF SPACE CONCEPTS

A

- High dielectric constant
- Low loss tangent
- Resistance in a wide T range
- High dimensional accuracy
- Low outgassing

B

- Low dielectric constant
- Low loss tangent
- Resistance in a wide T range
- High dimensional accuracy
- Low outgassing

DIELECTRIC PROPERTIES

↓

Ceramics
Composites Polymers

C

- High electrical conductivity
- Low mass
- High strength and stiffness
- Resistance in a wide T range
- High dimensional accuracy
- Low roughness
- Low outgassing

CONDUCTIVE and STRUCTURAL PROPERTIES

↓

Metals
Metallized Polymers

→

- **Microwave Filters (A)**
- **Bar-Line Feeding Networks (B, C)**
- **Multi-Beam Antenna Feed Chains (C)**
- **Aperture Arrays (C)**

POTENTIAL DEMONSTRATOR CATEGORIES

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PHASE 1 – METALS AND AM TECHNOLOGY

LASER POWDER BED FUSION (LPBF)

AlSi7Mg

	Literature results	Experimental results	Acceptance criteria
Parameter	**Value**	**Value**	**Value**
Density [g/cm^3]	2.67 – 2.68	2.64 ± 0.01	2.60 – 2.68
CTE [K^{-1}]	$2.14\cdot10^{-5}$	$(2.23 \pm 0.02)\cdot10^{-5}$	$2.0\cdot10^{-5}$ - $2.2\cdot10^{-5}$
Thermal conductivity [W/m*K]	180 - 190	178 ± 5	120 – 190
E modulus [GPa]	75 - 76	68 ± 8	70 - 80
Eq. Surf. Elec. Res. [µΩ cm]		10 - 15	
Dim. Acc. [mm]		< 0.08	
Porosity	0.1% - 0.58%	0.8 ± 0.3% 1.3 ± 0.4%	<1%

AlSi10Mg

	Literature results	Experimental results	Acceptance criteria
Parameter	Value	Value	Value
Density [g/cm^3]	2.67 - 2.68	2.64 ± 0.01	2.60 – 2.68
CTE [K^{-1}]	$(1.9 – 2.5)\cdot10^{-5}$	$(2.19 \pm 0.03)\cdot10^{-5}$	$1.9\cdot10^{-5}$ – $2.5\cdot10^{-5}$
Thermal conductivity [W/m*K]	130 – 190	178 ± 3	100 - 170
E modulus [GPa]	60 - 78	71 ± 10	60 – 80
Eq. Surf. Elec. Res. [µΩ cm]		10 - 12	
Dim. Acc. [mm]		< 0.08	
Porosity	0.1 – 0.8%	0.5 ± 0.3% 1.1 ± 0.2%	<1%

Printing systems: SLM Solutions, Concept Laser, EOS
Thermal treatments: AB, SR, T5, T6
Ultrasonic cleaning + shot peening
Surface treatments: DryLite, chemical milling, acid pickling + SurTec650

PHASE 1 – METALS AND AM TECHNOLOGY

LASER POWDER BED FUSION (LPBF)

Scalmalloy®			
	Literature results	Experimental results	Acceptance criteria
Parameter	Value	Value	Value
Density [g/cm³]	2.7	2.66 ± 0.1	2.60 – 2.70
CTE [K^{-1}]	$(1.8 – 2.22)\cdot10^{-5}$	$(2.44 \pm 0.07)\cdot10^{-5}$	$1.9\cdot10^{-5} – 2.5\cdot10^{-5}$
Thermal conductivity [W/m*K]	86.9 – 129.5	127 ± 2	100 - 170
E modulus [GPa]	65 - 73	71 ± 4	60 – 80
Eq. Surf. Elec. Res. [μΩ cm]		30 - 60	
Dim. Acc. [mm]		< 0.16	
Porosity	0.1% – 0.7%	0.8 ± 0.3% 1.4 ± 0.2%	<1%

Printing systems: SLM Solutions
Thermal treatments: T5
Ultrasonic cleaning + shot peening

PHASE 1 – POLYMERS AND AM TECHNOLOGY

MATERIAL EXTRUSION (MEX – FDM)

Carbon PEEK			
	Literature results	Experimental results	Acceptance criteria
Parameter	Value	Value	Value
Theoretical density [g/cm^3]	1.33-1.41	1.28 ± 0.01	1.25 – 1.40
CTE [K^{-1}]	(0.54-8.5)·10^{-5}	(2.7-8.3 ± 0.2)·10^{-5}	(0.54-8.5)·10^{-5}
E modulus [GPa]	6-27	5.2 ± 0.5	6-27
Eq. Surf. Elec. Res. ** [μΩ cm]		5 - 440	
Glass Transition Temperature [°C]	145-147	169 ± 6	>120

ULTEM™ 9085			
	Literature results	Experimental results	Acceptance criteria
Parameter	Value	Value	Value
Theoretical density [g/cm^3]	1.24 – 1.34	1.24 ± 0.01	1.24 – 1.34
CTE [K^{-1}]	5.3·10^{-5} – 6.5·10^{-5}	(6.7 ± 0.7)·10^{-5}	5.3·10^{-5} – 6.5·10^{-5}
E modulus [GPa]	1.8 – 2.6	2.6 ± 0.4	1.8 – 2.6
Eq. Surf. Elec. Res. ** [μΩ cm]		42 - 1000	
Glass Transition Temperature [°C]	171 - 186	180 ± 4	> 120

***for polymers metallized with copper*

PHASE 1 – POLYMERS AND AM TECHNOLOGY

SELECTIVE LASER SINTERING (SLS)

Alumide			
	Literature results	**Experimental results**	**Acceptance criteria**
Parameter	**Value**	**Value**	**Value**
Theoretical density [g/cm^3]	1.35 – 1.43	1.35 ± 0.01	1.3 - 1.6
CTE [K^{-1}]	-	$(17 \pm 2) \cdot 10^{-5}$	-
E modulus [GPa]	2.73 - 3.8	3.1 ± 0.3	2.5 - 3.9
Eq. Surf. Elec. Res. ** [μΩ cm]		POOR METALLIZATION	
Glass Transition Temperature [°C]	144	148 ± 1	> 120
Porosity	0.4%	0.8 ± 0.4%	< 1%

***Metallized polymer*

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PHASE 1 – CERAMICS AND AM TECHNOLOGY

VAT PHOTOPOLYMERIZATION (SLA-DLP)

Alumina (Al_2O_3)			
	Literature results	Experimental results	Acceptance criteria
Parameter	Value	Value	Value
Dielectric constant	9.8 – 10	8.75 ± 5%	9.8 – 10
Loss tangent	$<1\cdot10^{-3}$	$< 3.8\cdot10^{-3}$	$< 1\cdot10^{-2}$
Theoretical density [g/cm^3]	3.90 - 3.98	3.90 ± 0.02	3.70 – 3.98
CTE [K^{-1}]	$7 - 8\cdot10^{-6}$	$(6.62 \pm 0.07)\cdot10^{-6}$	$5\cdot10^{-6} - 10\cdot10^{-6}$
Thermal conductivity [W/m*K]	30 - 37	24 ± 1	30 - 40
Purity	> 99.8%	-	> 99.8%
Porosity	0.6 - 1.6%	1.7 ± 0.7% 2.0 ± 0.4%	< 5%

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PHASE 1 – CERAMICS AND AM TECHNOLOGY

VAT PHOTOPOLYMERIZATION (SLA-DLP)

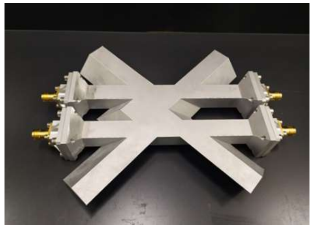
Zirconia (ZrO_2)			
	Literature results	Experimental results	Acceptance criteria
Parameter	Value	Value	Value
Dielectric constant	26 – 32	28.5 ± 15%	> 27
Loss tangent	$1 – 2 \cdot 10^{-3}$	$< 8.5 \cdot 10^{-3}$	$< \cdot 10^{-2}$
Theoretical density [g/cm^3]	5.71 - 6.09	6.01 ± 0.01	5.4 – 6.1
CTE [K^{-1}]	$10 \cdot 10^{-6}$	$(10.1 \pm 0.1) \cdot 10^{-6}$	$8 \cdot 10^{-6}$ - $12 \cdot 10^{-6}$
Thermal conductivity [W/m*K]	2 – 3	3.3 ± 0.1	2 - 3
Purity	3 – 9%mol Yttria	3%mol Yttria	3 – 9%mol Yttria
Porosity	0.6% - 2.9%	0.9 ± 0.5% 1.3 ± 0.3%	< 5%

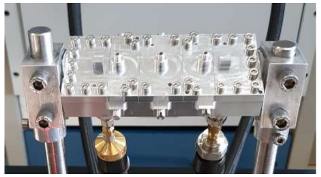
PHASE 1: CONCLUSIONS

- As outcome of the Phase 1, three demonstrators have been identified, to be manufactured and tested in the frame of Phase 2 of the Project.

SELECTED DEMONSTRATOR	MANUFACTURING
1. Q/V-Band Antenna Feed Chain	Laser powder-bed fusion on AlSi10Mg
2. L-band branch-line coupler in bar line technology	Laser powder-bed fusion on AlSi10Mg
3. Miniaturized loaded filter at low frequency band	LCM on Zirconia

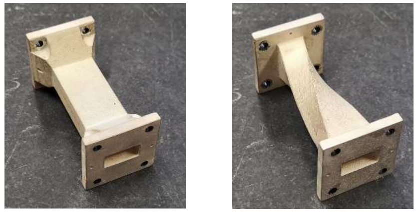

(1)

(2)



(3)

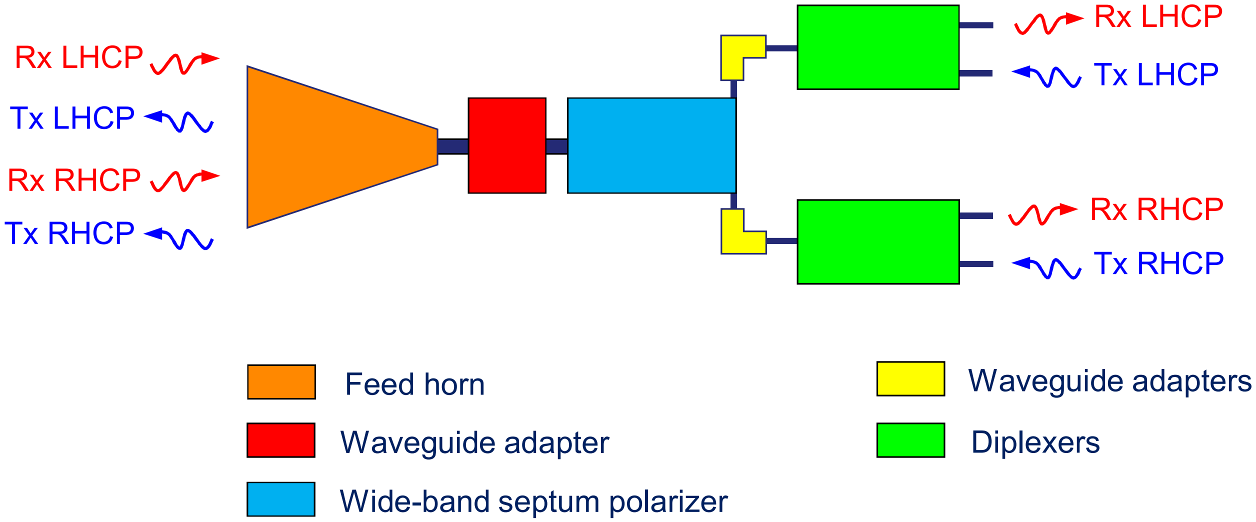
- Additionally, as a follow-on of Phase 1, an investigation activity on the metallization on structural polymers for the fabrication of RF parts has been carried out, in parallel to Phase 2.

SELECTED DEMONSTRATOR	MANUFACTURING
4. WR75 straight and twisted lines	FDM on PEEK-CF + DMP (silver plating)


(4)

DEMONSTRATOR #01: QV-BAND ANTENNA FEED CHAIN SUB-ASSEMBLY

DEMONSTRATOR #01: *Q/V-BAND ANTENNA-FEED CHAIN FOR MULTI-BEAM HTS PAYLOADS*



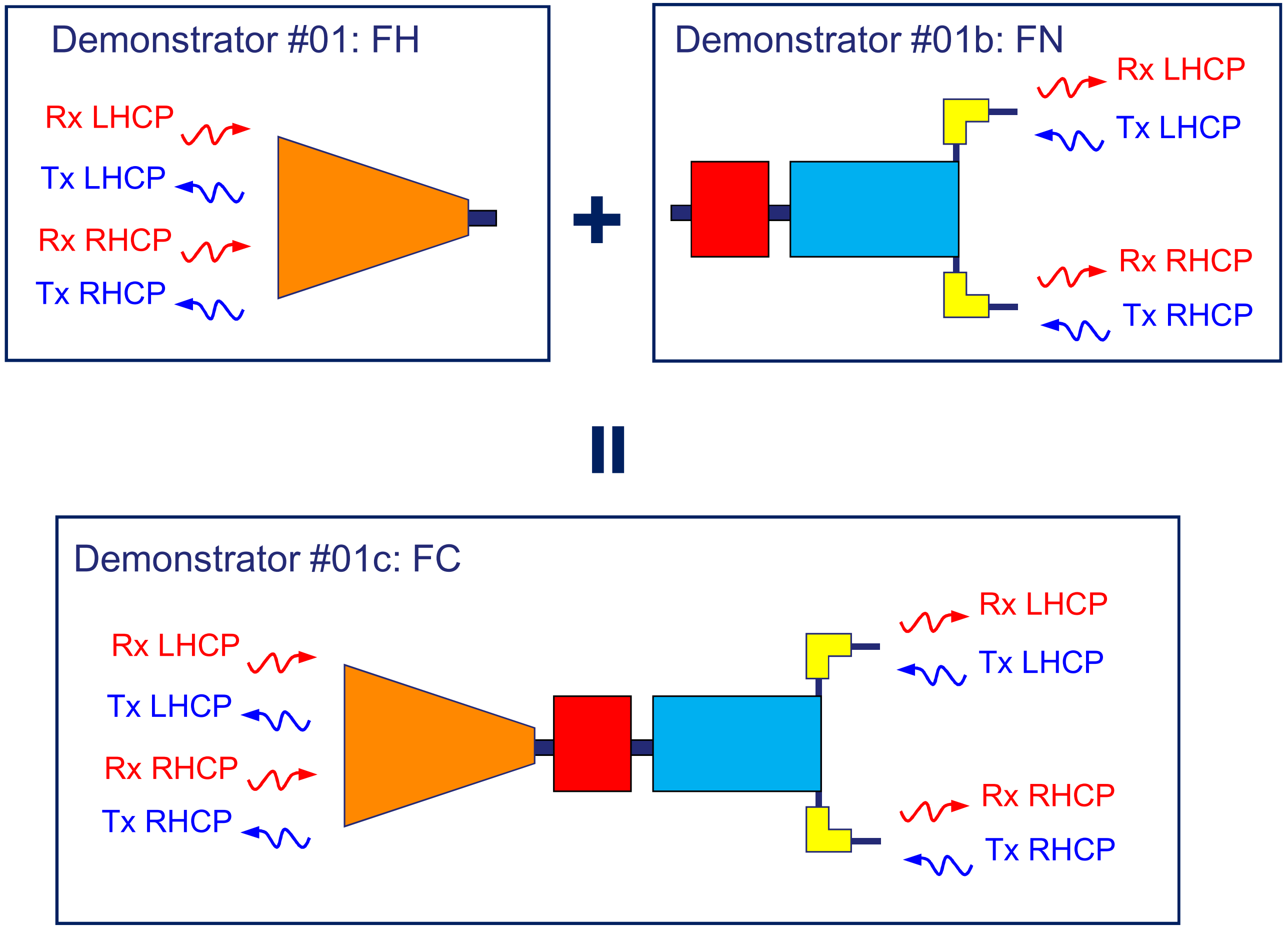
Reference requirements

Parameter	Q - Tx	V - Rx
Frequency band	37.5 - 42.5 GHz	47.2 - 51.4 GHz
Polarization	Dual Circular (RH/LH)	Dual Circular (RH/LH)
Cross-polarization	<-27 dB	<-27 dB
Return Loss	> 20 dB	> 20 dB
Insertion Loss	< 0.6 dB	< 0.6 dB
Port to Port isolation (in-band)	> 20 dB	> 20 dB
Port to Port isolation (out-of-band)	> 40 dB	> 40 dB
Power handling	30W + 6 dB margin	N.A.
Interfaces	WR22 (TBC)	WR22 (TBC)
Envelope	Diameter < 35 mm Length < 200 mm (depending on feed-horn aperture)	
Mass	< 100 g	
Temperature Range	Operative: -100 / +120 º C	

DEMONSTRATOR #01: *MANUFACTURING ROUTE*

Aluminum parts	
Material	AlSi10Mg
Process	Laser powder-bed fusion
System	EOSINT M270 Dual Mode
Post-Processing	1. Thermal treatment: stress release with components still attached to the platform. The treatment: 2 h at 300 °C 2. Flange machining and polishing: After the treatment, the support structures are manually removed. Subsequently, with a Wire-EDM machine, a thickness of 1.5 mm is cut from the flanges in order to obtain a suitable surface for coupling. 3. Ultrasonic cleaning: A further cleaning step is carried out through an ultrasonic bath. 4. Shot blasting: After removal from the platform and the ultrasonic cleaning, the components are placed in an oven at 80 °C for half an hour to dry. During Wire-EDM cutting, the component is constantly wetted by the dielectric. Subsequently, the surfaces of the flanges are coated to avoid damaging the finish and the internal and external surfaces are shot-blasted to clean the as-built parts from not completely melted powder. The parts are shot-blasted using glass microspheres at a pressure of 6 bar.

DEMONSTRATOR #01: *DEVELOPMENT PLAN*



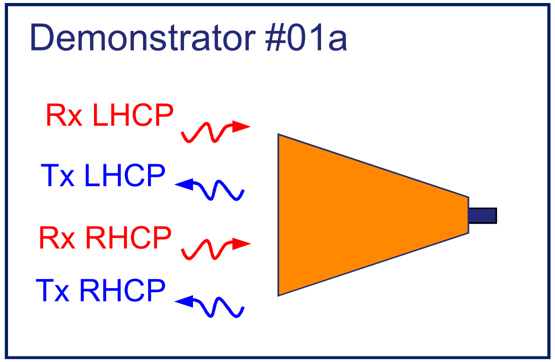
Feed horn

Waveguide adapter

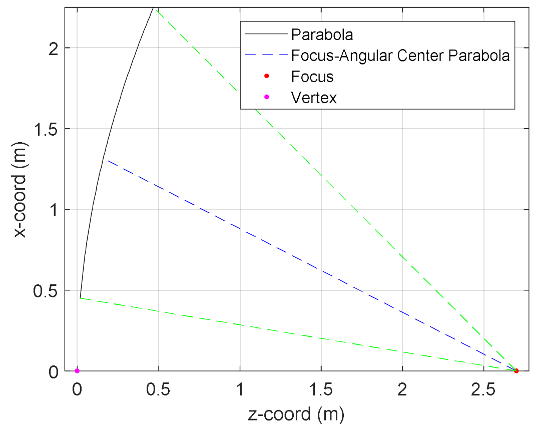
Wide-band septum polarizer

Waveguide adapters

DEMONSTRATOR #01A: *ELECTROMAGNETIC DESIGN*



Reference reflector



- Diameter: 1.8 m
- Focal distance: 2.7 m
- Illumination angle $\theta^*: 17.86^\circ$

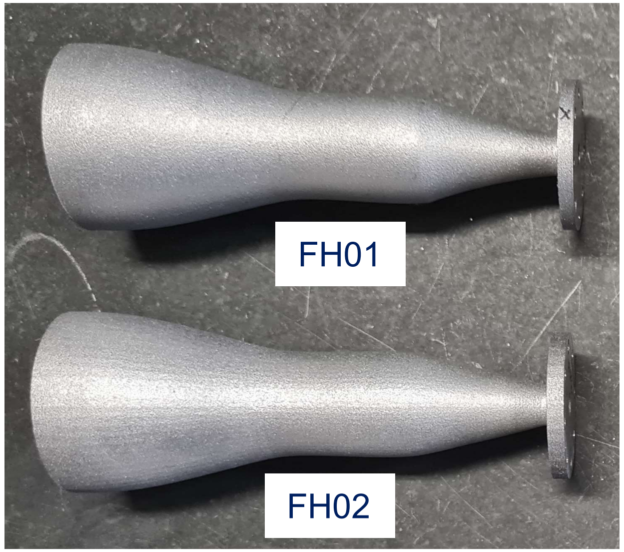
Smooth-wall profile architecture

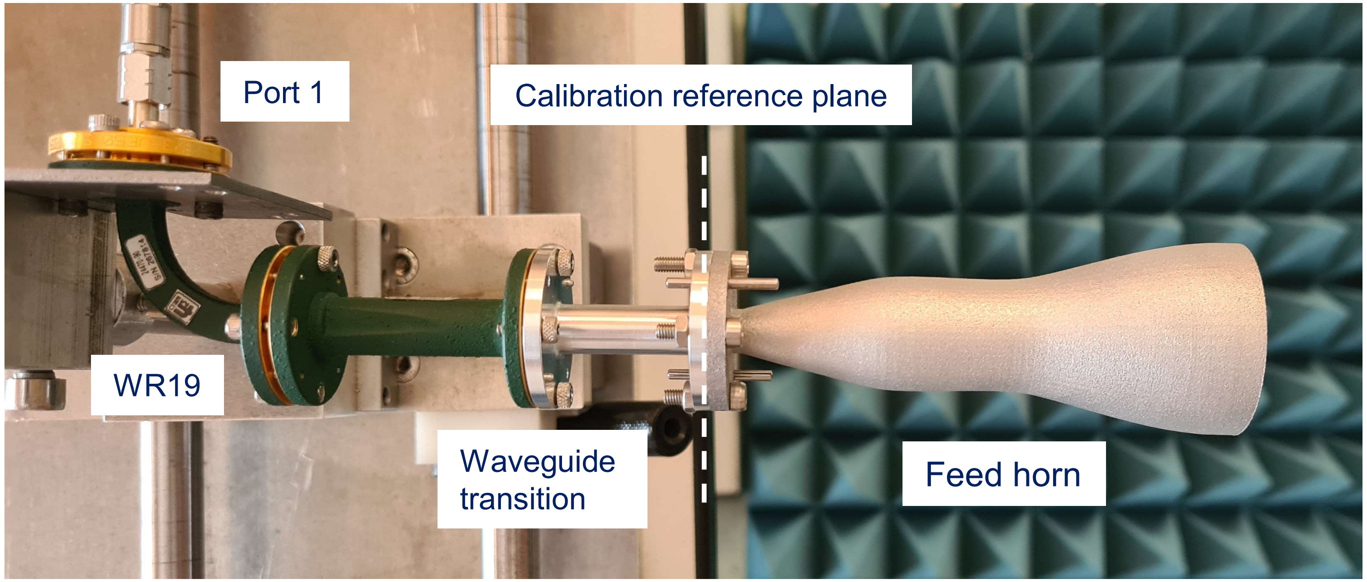
- Radiating aperture: 33.00 mm
- Input circular waveguide diameter: 5.200 mm
- Transverse envelope: 35.00 mm
- Length: 95.256 mm

Circular-waveguide port

Mode	Cut-off frequency (GHz)
TE11	33.57
TM01	43.85
TE21	55.69
TE01	69.89
TM11	69.89

DEMONSTRATOR #01A: *RF MEASUREMENT SETUP & PLAN*

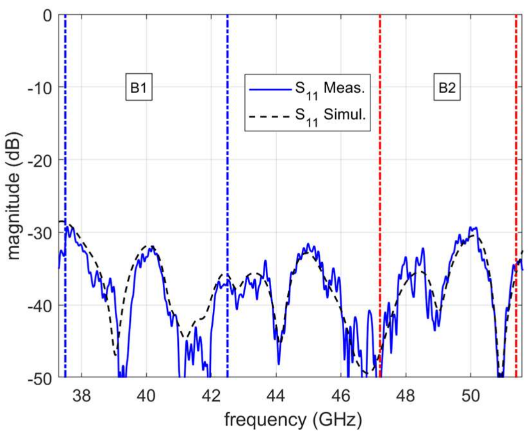


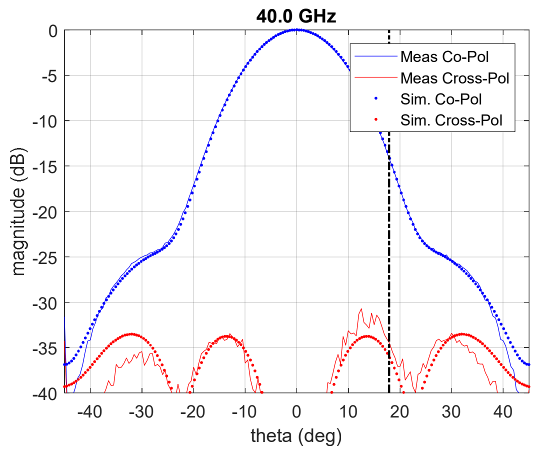


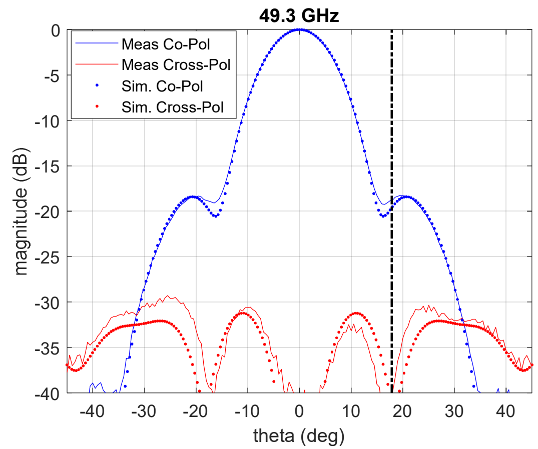
DEMONSTRATOR #01A: *RF TEST SUMMARY*

	Design values		Measured values for prototype FH01		Measured values for prototype FH02	
Parameter	**Q - Tx**	**V - Rx**	**Q - Tx**	**V - Rx**	**Q - Tx**	**V - Rx**
Frequency band (GHz)	37.5 - 42.5	47.2 - 51.4	37.5 - 42.5	47.2 - 51.4	37.5 - 42.5	47.2 - 51.4
Return Loss (dB)	> 29	> 30	> 24	> 29.5	> 29.5	> 29.5
Insertion Loss (dB)	< 0.05[(1)]	< 0.03[(1)]	< 0.05	< 0.03	< 0.05	< 0.03
Taper at illumination angle θ^*=17.86° (dB)	[-17.2, -12.0]	< -18	[-18, -12.4]	< -18	[-17.2, -12]	< -17.6
Cross polarization (in LP) (dB)	< -33	< -28	< -29	< -26	< -31	< -27

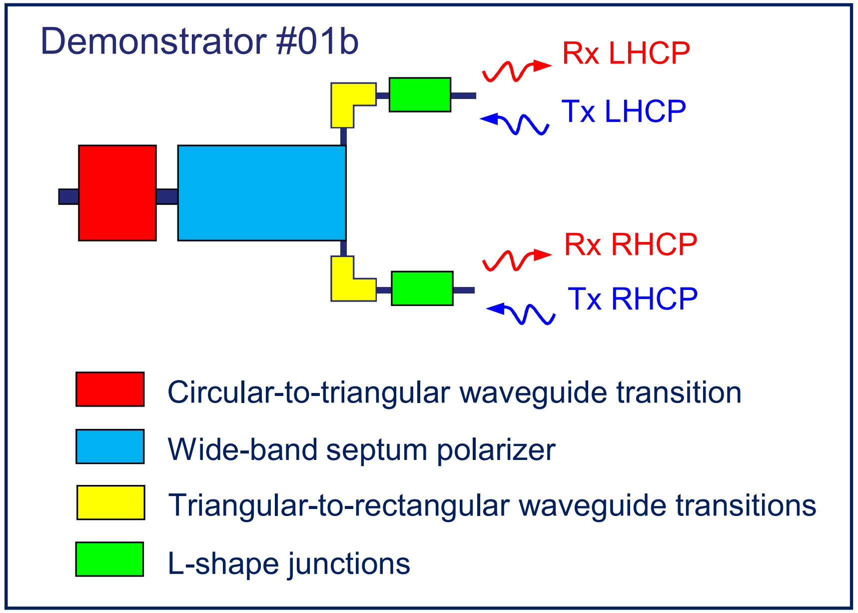
[(1)]: the values refer to an equivalent surface electric resistivity of 16 $\mu\Omega$cm







DEMONSTRATOR #01B: *ELECTROMAGNETIC DESIGN*



- Circular-waveguide diameter @ port 3: 5.200 mm
- Waveguide size @ ports 1 & 2: WR22-like (5.678 mm x 2.700 mm)
- AM-oriented architecture compatible with z-axis manufacturing
- Bending radius: 0.25 mm (curve-based CAE modeling)
- Length: 50.929 mm
- Transverse envelope: 20 mm

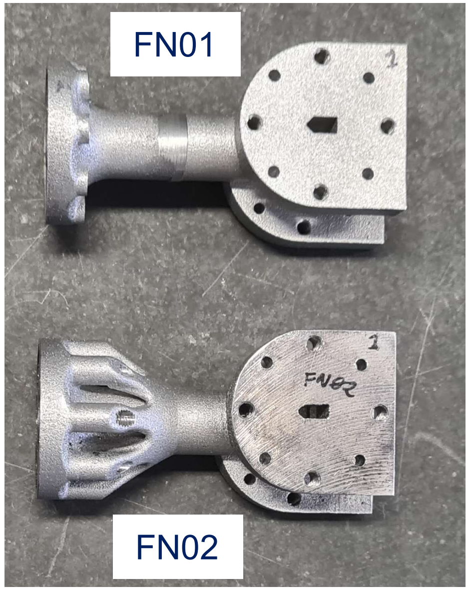
Ports 1 & 2

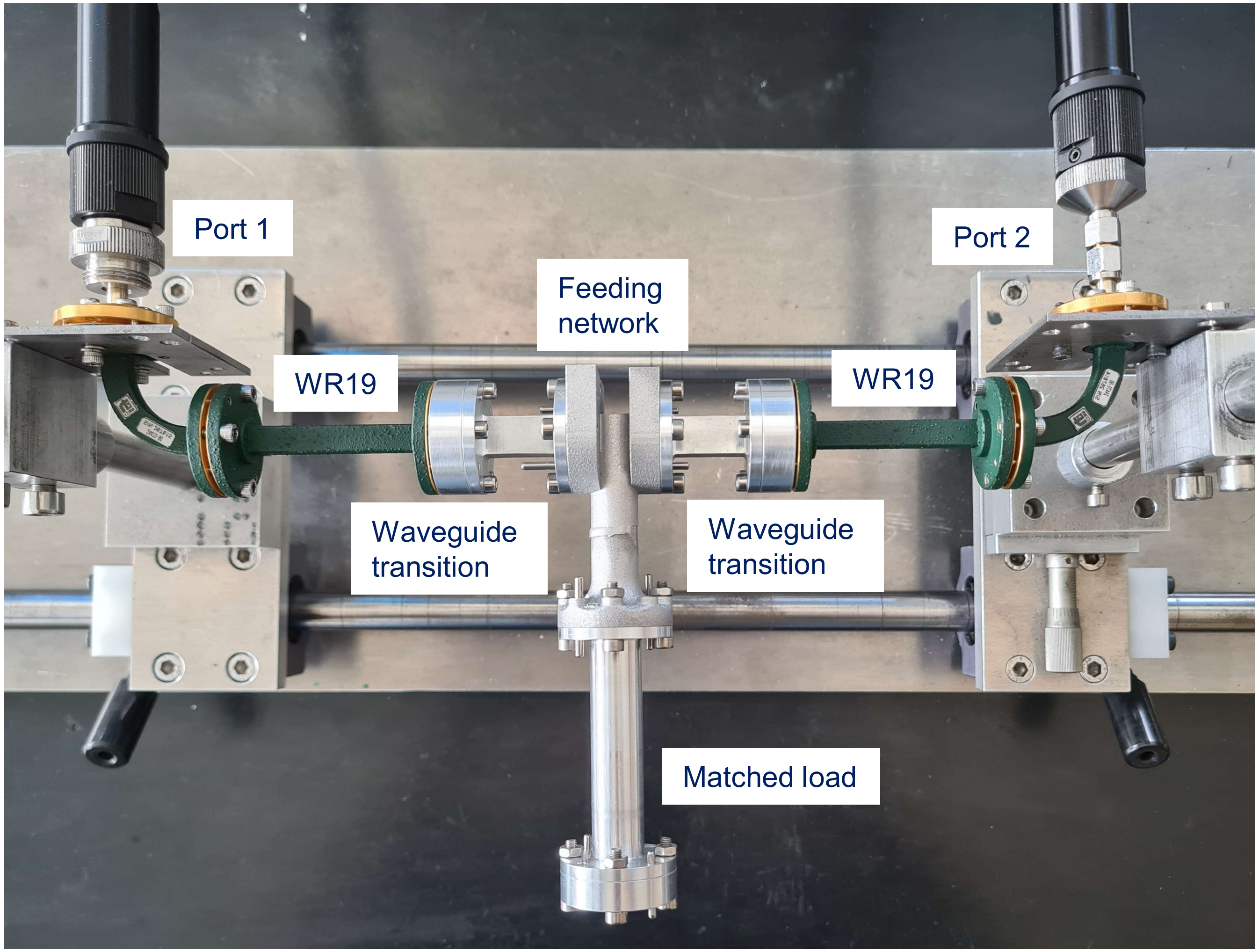
Mode	Cut-off frequency (GHz)
TE10-like	29.89
TE01-like	53.89
TE20-like	58.09

Port 3

Mode	Cut-off frequency (GHz)
TE11	33.57
TM01	43.85
TE21	55.69
TE01	69.89
TM11	69.89

DEMONSTRATOR #01B: *RF MEASUREMENT SETUP & PLAN*

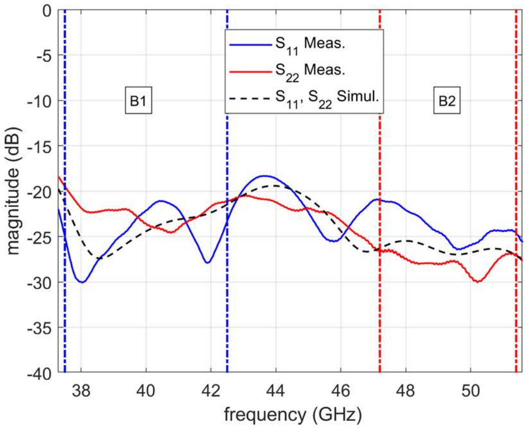


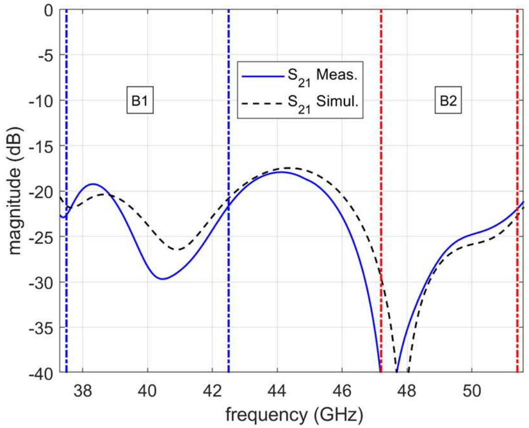


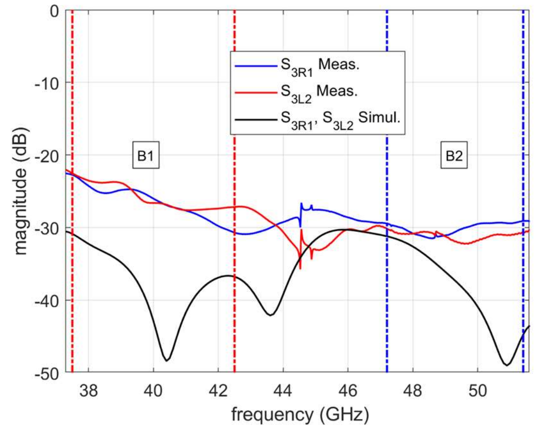
DEMONSTRATOR #01B: *RF TEST SUMMARY*

	Design values		Measured values for prototype FN01		Measured values for prototype FN02	
Parameter	**Q - Tx**	**V - Rx**	**Q - Tx**	**V - Rx**	**Q - Tx**	**V - Rx**
Frequency band (GHz)	37.5 - 42.5	47.2 - 51.4	37.5 - 42.5	47.2 – 51.4	37.5 - 42.5	47.2 – 51.4
Return Loss (dB)	> 21	> 25	> 19.5	>21	> 18.5	> 17.5
Port-to-port isolation (dB)	> 21	> 22	>19	> 22	> 19	> 24
Insertion Loss (dB)	< 0.32(1)	< 0.22(1)	< 0.50	< 0.35	< 0.40	< 0.3
Amplitude unbalance (dB)	< 0.14	< 0.07	< 1.0	< 0.6	< 2.8	< 1.5
Phase unbalance w.r.t -90 deg (deg)	< 3.5	< 3.5	< 6.0	< 1.5	< 3.5	< 2.0
Cross-polarization (in CP) (dB)	< -30	< -30	< -22.5	< -29.0	< -16	< -21

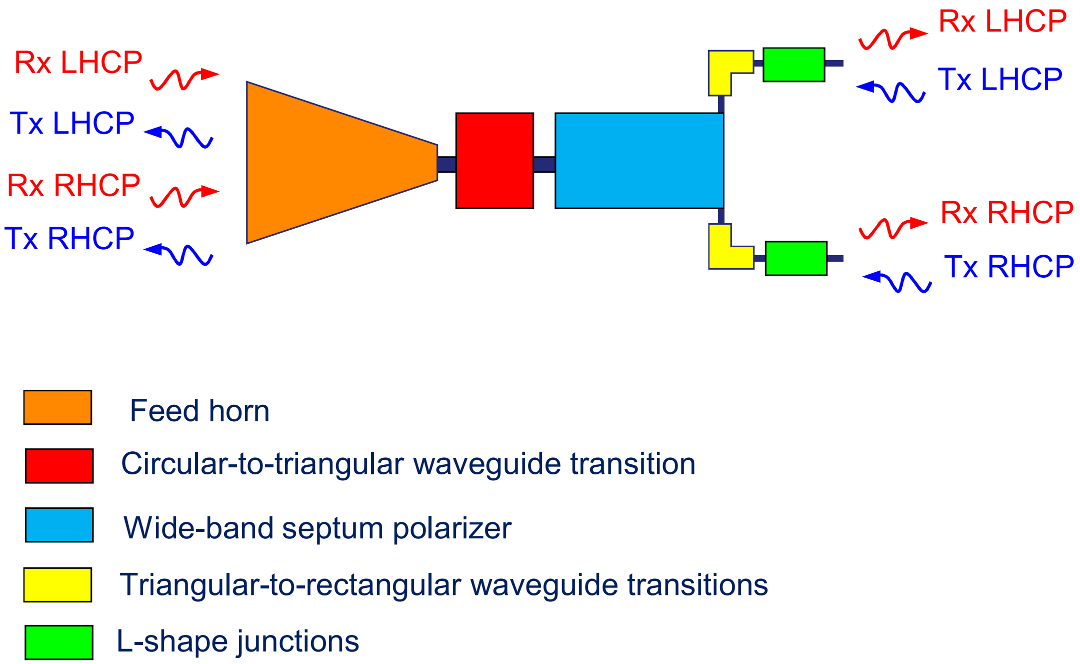
(1): the values refer to an equivalent surface electric resistivity of 16 μΩcm





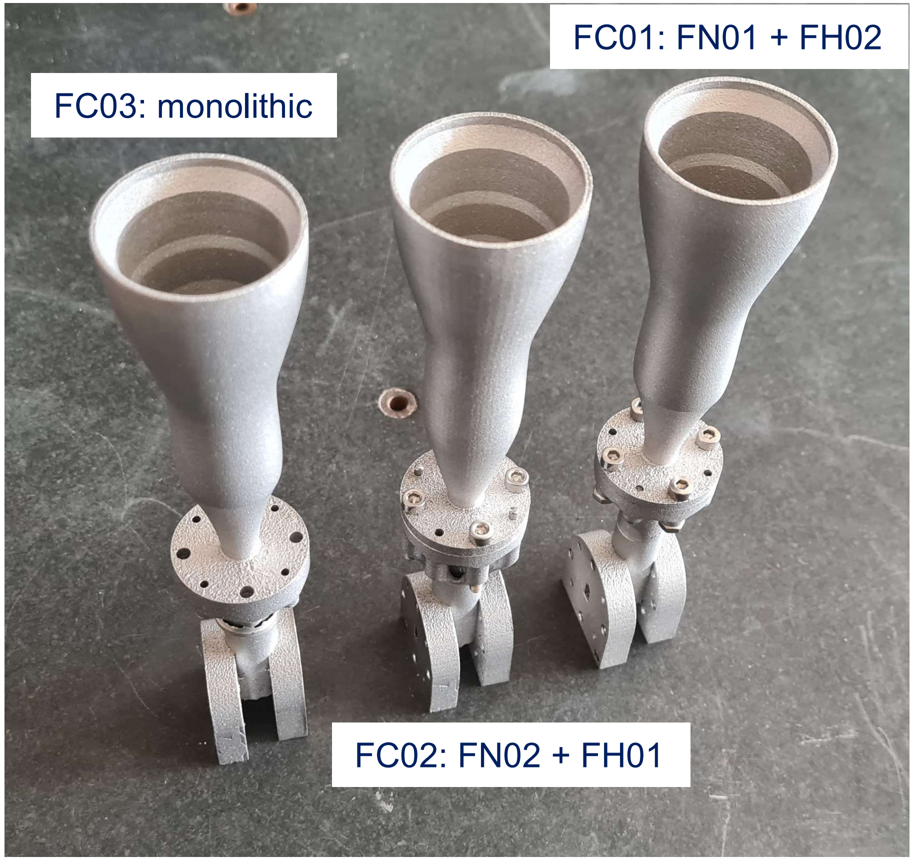


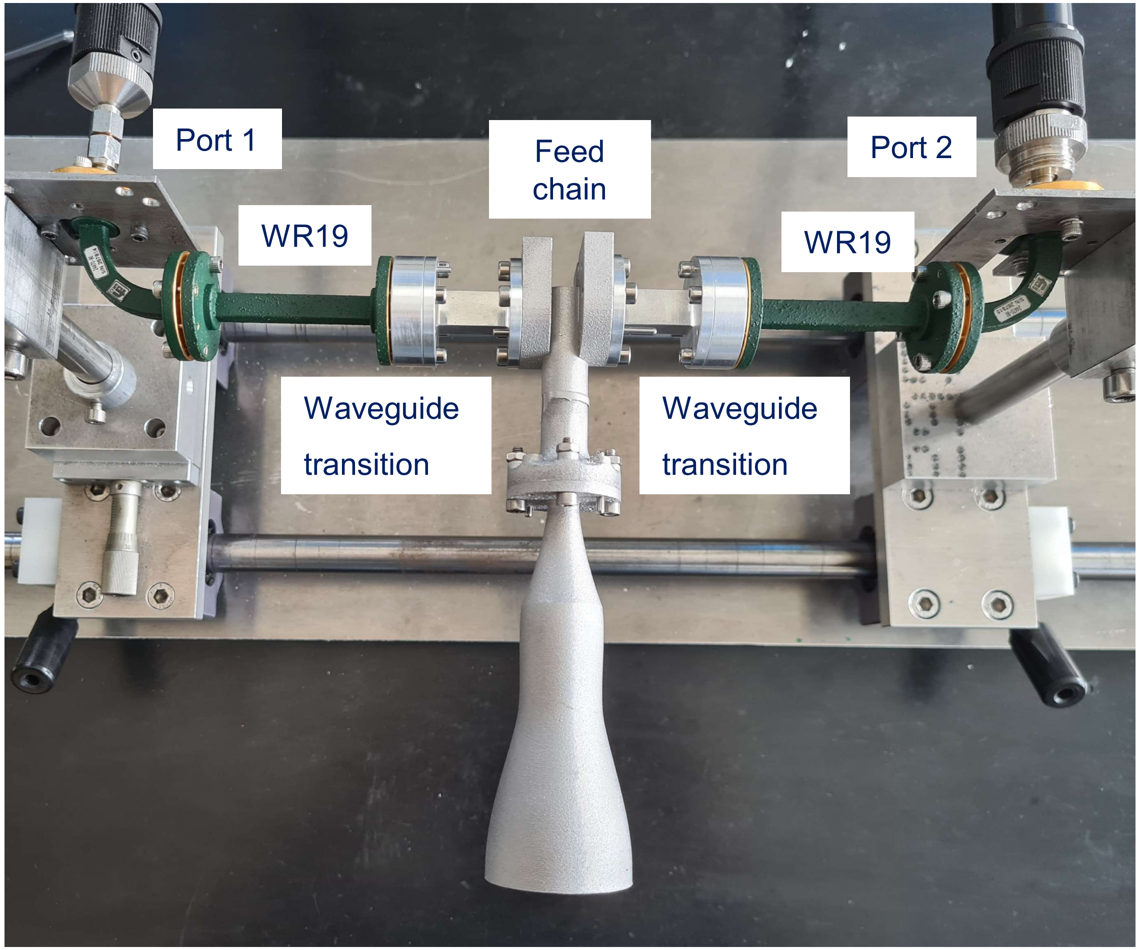
DEMONSTRATOR #01C: *ELECTROMAGNETIC DESIGN*



- Length: 158 mm < 180 mm (effective building-platform height)
- Transverse envelope: 36 mm (< 24 mm w/o feed-horn)
- AM-oriented architecture compatible with z-axis manufacturing

DEMONSTRATOR #01C: *RF MEASUREMENT SETUP & PLAN*

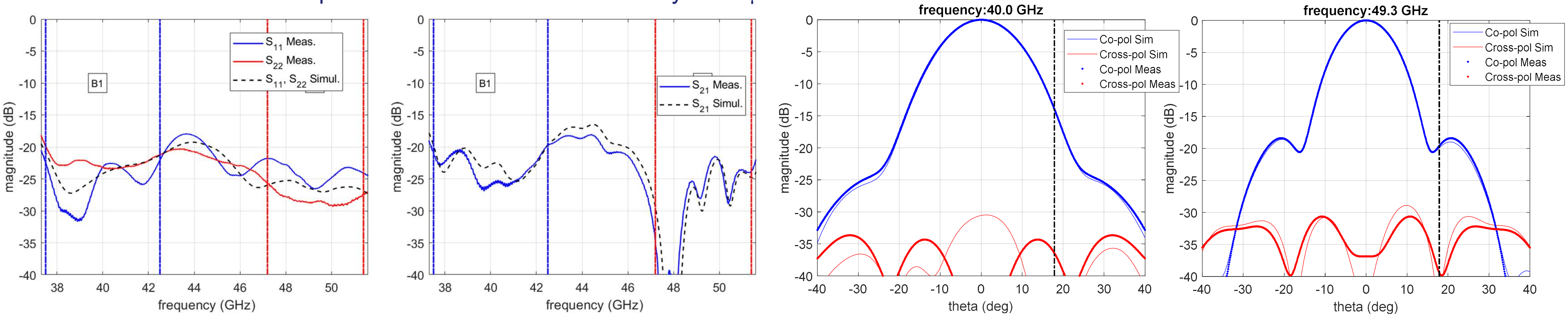




DEMONSTRATOR #01C: *RF TEST SUMMARY*

	Design values		Measured values for prototype FC01		Measured values for prototype FC02		Measured values for prototype FC03	
Parameter	**Q - Tx**	**V - Rx**	**Q – Tx**	**V - Rx**	**Q - Tx**	**V - Rx**	**Q - Tx**	**V - Rx**
Frequency band (GHz)	37.5 - 42.5	47.2 - 51.4	37.5 - 42.5	47.2 - 51.4	37.5 - 42.5	47.2 - 51.4	37.5 - 42.5	47.2 - 51.4
Return Loss (dB)	> 21	> 25	>20	> 21	> 17.5	> 18	>16	>16.5
Port-to-port isolation (dB)	> 20	> 22	>20	> 21	> 16	> 20	> 20	> 21.5
Insertion Loss (dB)	< 0.37[1]	< 0.25[1]	< 0.30 (0.55)	< 0.20 (0.40)	< 0.50	< 0.35	< 0.45	< 0.35
Taper at illumination angle θ*=17.86° (dB)	[-17.2, -12]	< -18	[-17, -12]	< -18	-	-	[-16, -12]	< -18
Cross polarization (in CP) (dB)	< -30	< -28	< -24.8	< -26.4	-	-	< -16.5	< -21

[1]: the values refer to an equivalent surface electric resistivity of 16 μΩcm



DEMONSTRATOR #01: *LESSONS LEARNT & WAY FORWARD*

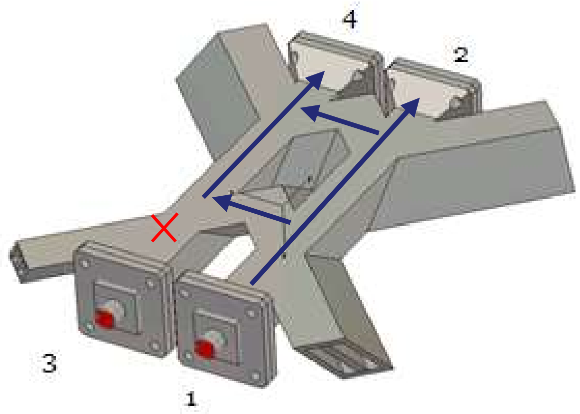
- Split-block assembly: Laser Powder-Bed Fusion in AlSi10Mg + Ag plating successfully applied
- Monolithic assembly: degraded RF performance
- Surface treatments (chemical milling, acid pickling, DryLyte) seem not viable at high-frequency Q-V bands
- Electrolytic Ag plating: significant reduction of IL w/o RF performance degradation

- Investigation on compensation strategy to manufacturing tolerances for high-frequency Q/V bands
- Development of a septet or larger cluster of Q/V-band antenna feed systems

DEMONSTRATOR #02: L BAND BRANCH-LINE COUPLER IN BAR LINE TECHNOLOGY

DEMONSTRATOR #02: L BAND BRANCH TYPE COUPLER

- Demonstrator #2 is a monolithic branch-type coupler in square coaxial waveguide technology (a non simply connected geometry), without dielectric supports for the suspended inner conductor.



Monolithic branch line coupler in barline coaxial technology (AM)

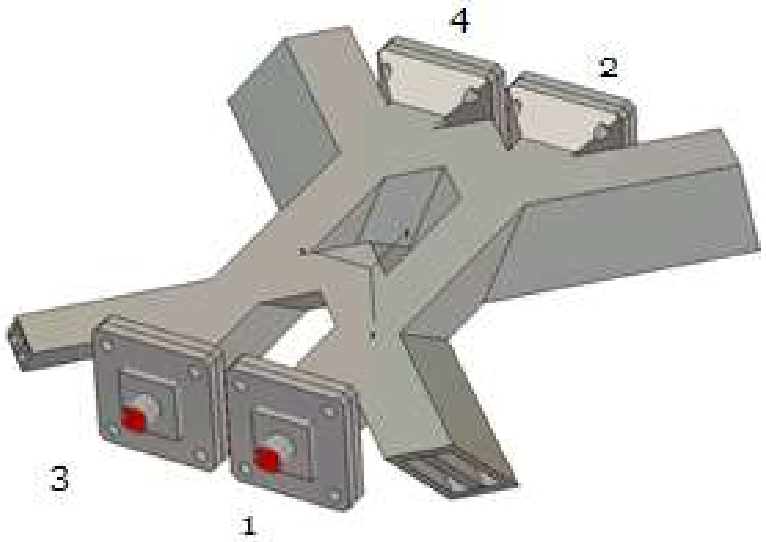
Typical responses (from port 1):
- Port 2: direct port
- Port 4: coupled port (90deg delay w.r.t. 2)
- Port 3: isolated port
- All ports matched

REQUIREMENTS

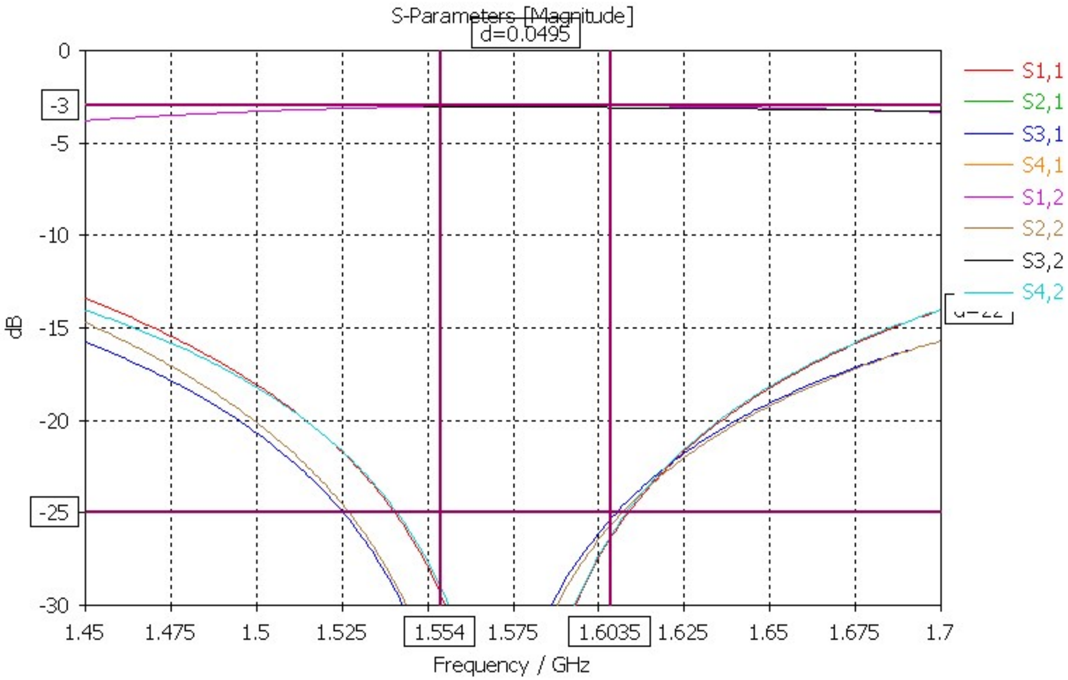
PARAMETER	VALUE
Frequency band	1.55-1.60 GHz (L1 band)
Number of ports	4
Return Loss at all ports	>25 dB
Output coefficients (from any input port)	Direct port : -3dB / 0deg Coupled port: -3dB / -90deg
Output coefficients unbalance	±0.1 dB amplitude ±0.5° phase
Isolation between ports 1,3 and 2,4	>25 dB
Temperature range	-100 / +120 º C
RF I/F	TNC coaxial female
Power Handling	30+30W (by analysis)
Mass	To be minimized

DEMONSTRATOR #02: RF DESIGN

- End to end predicted S-parameters of the designed 3dB branch coupler, including custom test jig adapters and TNC connectors (fullwave CST model in Frequency Domain)



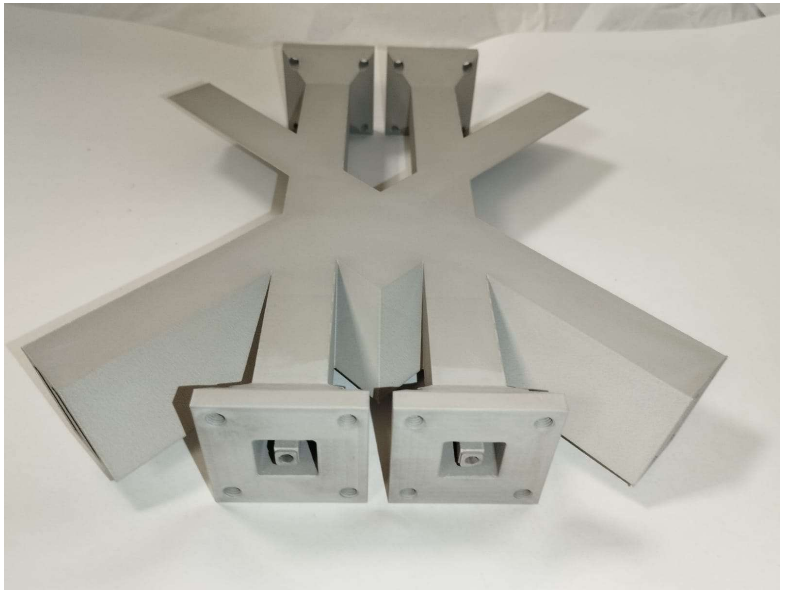
Branch line 3dB coupler demonstrator #2 assembled with TNC test jig adapters



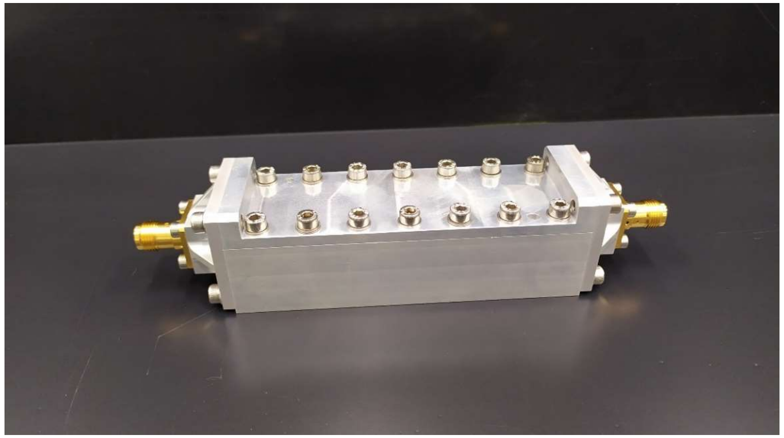
End to end predicted S parameters at TNC interfaces (behavior of ports 3 and 4 is symmetric)

DEMONSTRATOR #02: MANUFACTURED HARDWARE

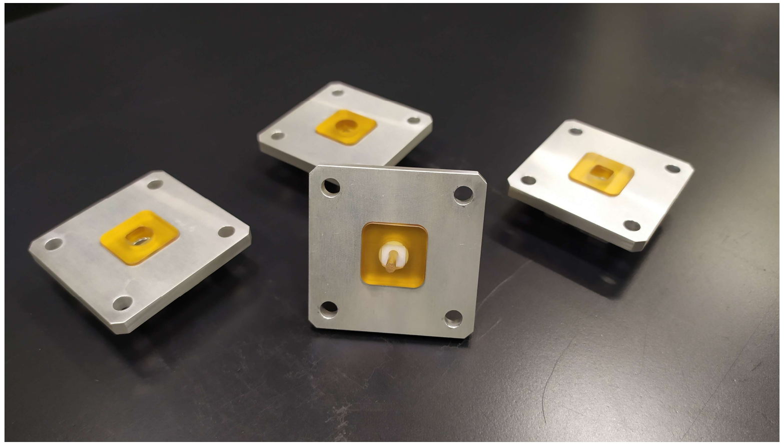
Straight line sample in AM



L-band 3dB coupler in AM



Straight line sample in CNC



Test jigs adapters to TNC

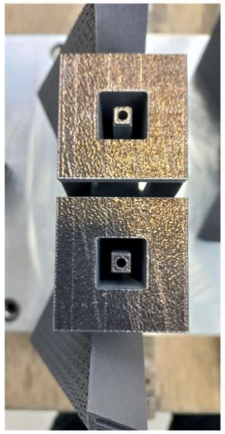
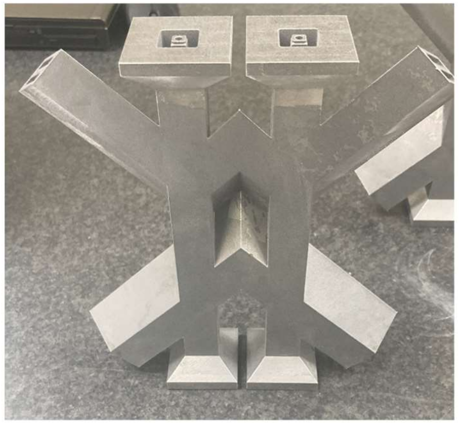
DEMONSTRATOR #02: MANUFACTURING PROCESS

Aluminum parts	
Material	AlSi10Mg
Process	Laser powder-bed fusion (powder layer thickness 30μm)
System	SLM 500 HL
Post-Processing	1. **Depowdering**: the operation is performed after printing with a dedicated equipment (vibratory equipment). 2. **Thermal treatment**: stress relieve heat treatment is performed with components still attached to the platform. (2 h at 300 °C) 3. **Platform detachment**: an EDM wire cutting operation is performed to detach the component from the build platform. 4. **Surface finishing**: After the treatment and EDM operation the support structures are manually removed. 5. **Flange machining**: The connection flanges have been machined in order to obtain a suitable surface for coupling.

DEMONSTRATOR #02: STRAIGHT LINE MANUFACTURING

- Build job preparation and positioning of support structure
- Detachment from the build platform using EDM
- Removal of support structure and IF finishig using CNC
- Mass reduction of conductors using inner lattice: >30%



L Band coupler manufacturing

DEMONSTRATOR #02: PERFORMED TEST ACTIVITIES

The following test activities have been performed:

1. **S parameter measurement on the two straight lines in aluminum**, manufactured in CNC and AM respectively, for model correlation of RF losses VS surface roughness

2. **Tests of the 3dB coupler**, for performance verification and electromagnetic model correlation:
    1. S parameters
    2. RF losses: losses have been measured both before and after surface finishing with SURTEC and compared. The purpose is to verify possible benefit related to the roughness reduction through the acid pickling (performed before the chemical conversion)

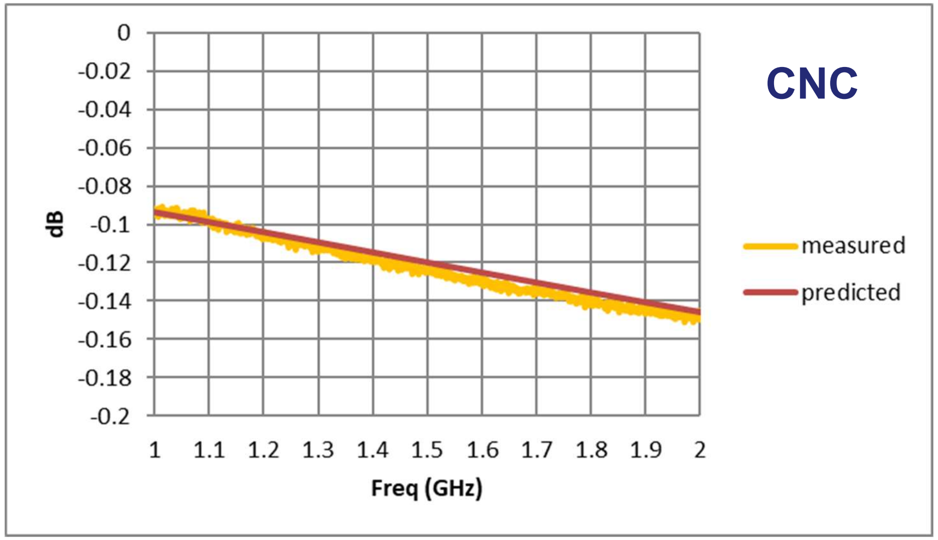
3. **Thermal cycling of the 3dB coupler** on -130/+130°C

4. **Final S parameters check**

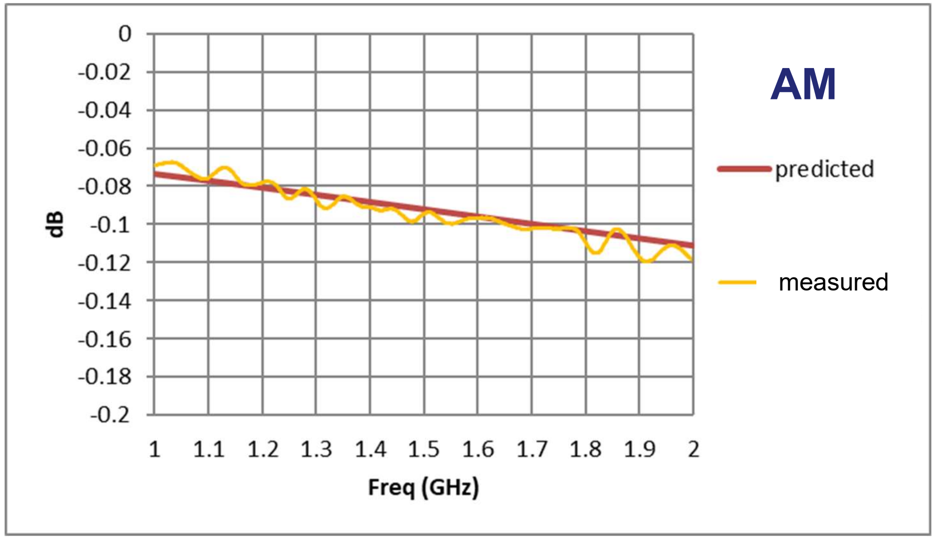
DEMONSTRATOR #02: RF TESTING ON STRAIGHT LINE SAMPLES

- **Best fitting of losses of the two samples vs frequency (wide band measurement) is achieved through a fullwave CST model, by considering the following values of surface roughness:**
  - ρ = 8μm for the AM parts (to be used in the coupler model)
  - ρ = 1.2μm for the CNC parts

- **The absolute value and the slope vs frequency (due to roughness) are well fitted**



Measured Losses VS frequency and correlation with prediction for the straight line in ***AM***

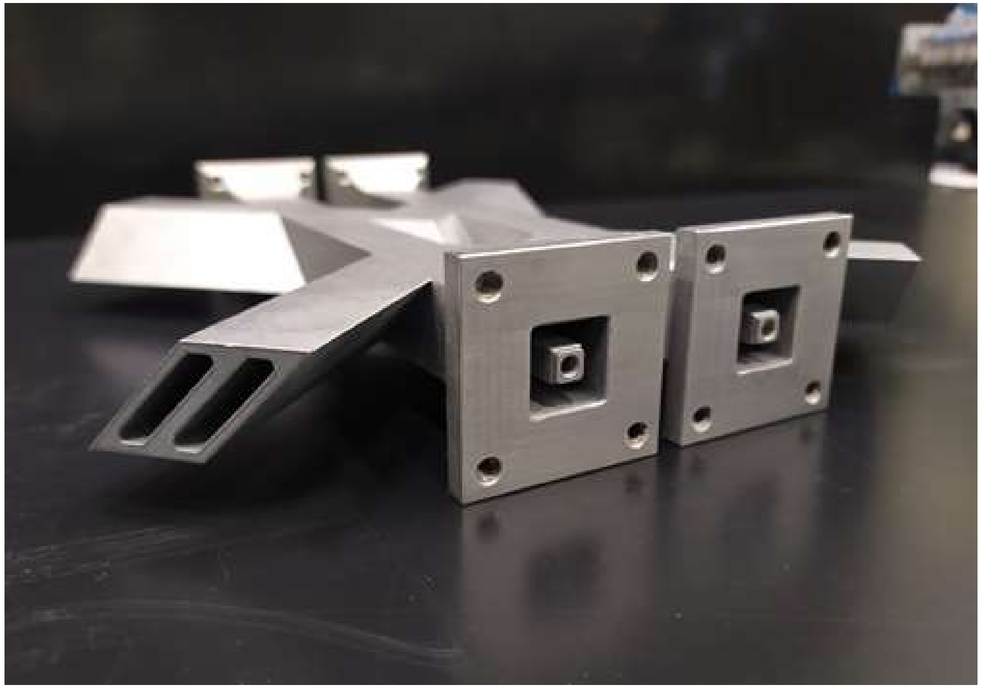


Measured Losses VS frequency and correlation with prediction for the straight line in ***CNC***

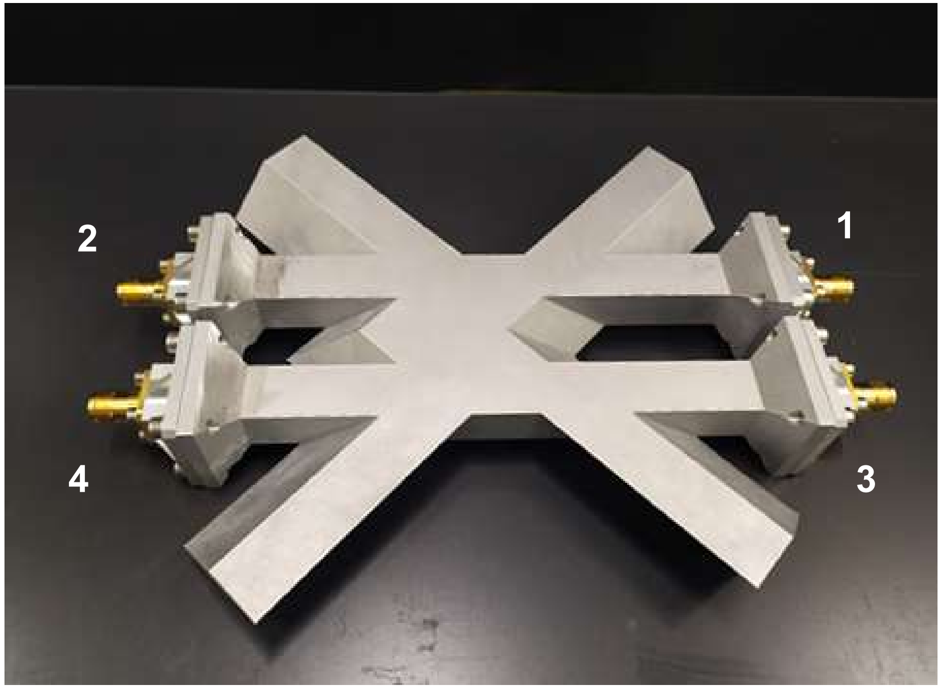
NOTE: the RF losses of the two samples are calculated from the S21 parameter, by excluding the reflection coefficient (S11) at the input port

DEMONSTRATOR #02: RF TESTS ON L-BAND COUPLER

- The L band coupler printed in AM has been integrated with TNC connectors and tested for S parameter through a calibrated VNA
- S parameters have been compared to fullwave predictions (RF losses included in the model)



L band coupler in AM (details of RF interfaces)



L band coupler assembled with TNC connectors and port identification for RF testing

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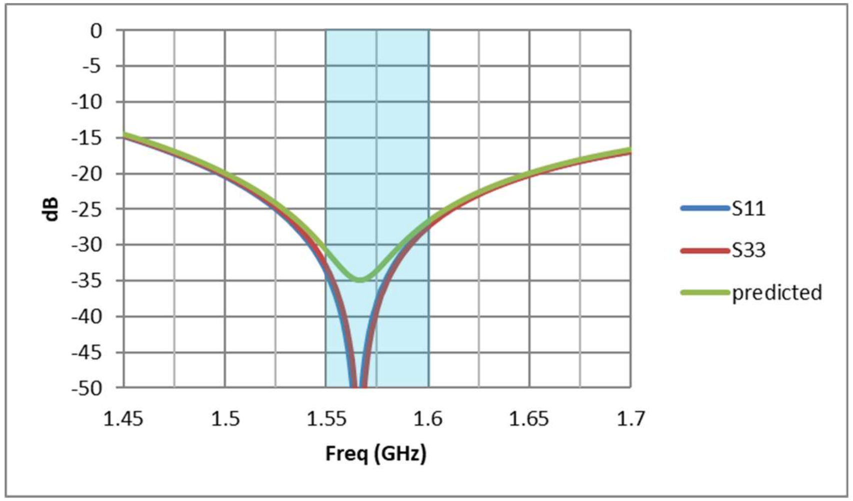
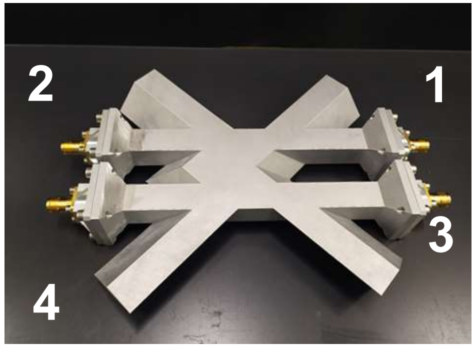
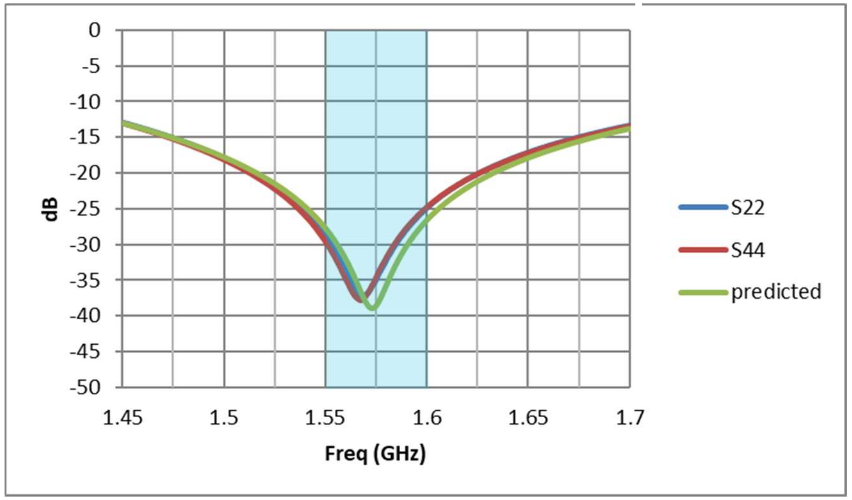
DEMONSTRATOR #02: RF TESTS ON L-BAND COUPLER

- **Reflection coefficients at input ports and comparison with predictions**
  The nominal bandwidth of 1.55-1.60GHz is highlighted



Input reflection coefficient at ports 1 and 3

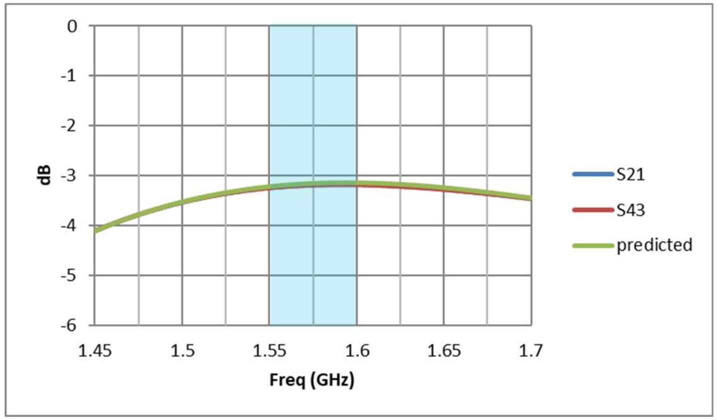




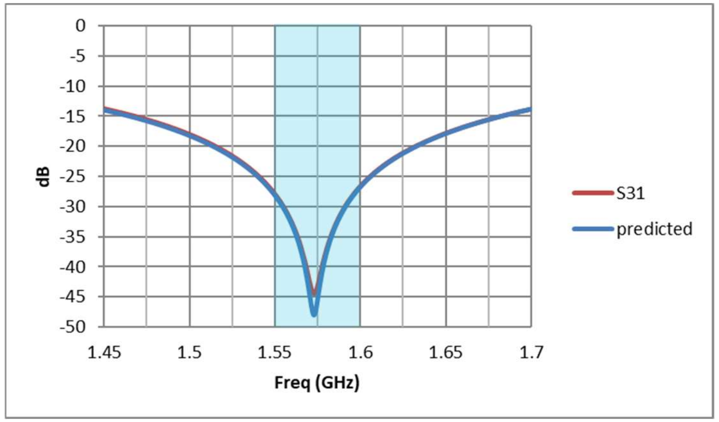
Input reflection coefficient at ports 2 and 4

DEMONSTRATOR #02: RF TESTS ON L-BAND COUPLER

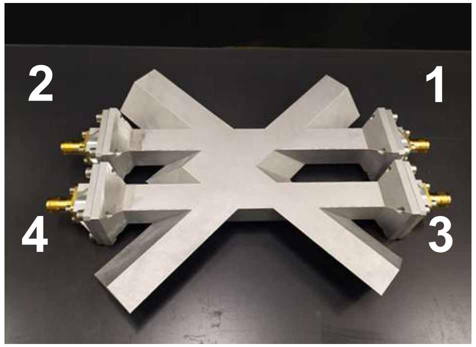
- **Transmission coefficients between the ports and comparison with predictions**

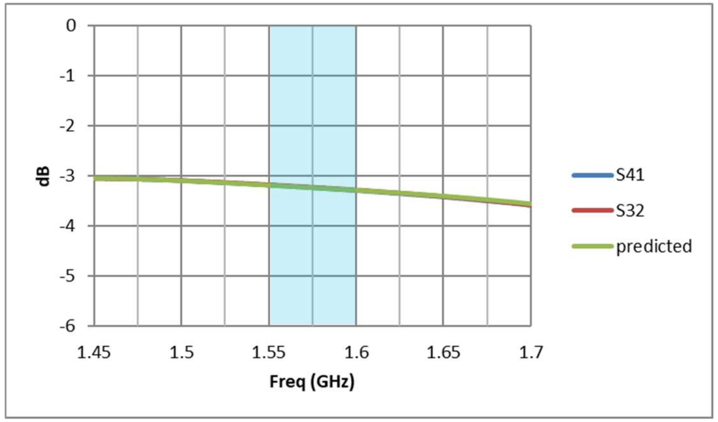


Direct path: port 1-> 2 and 3->4

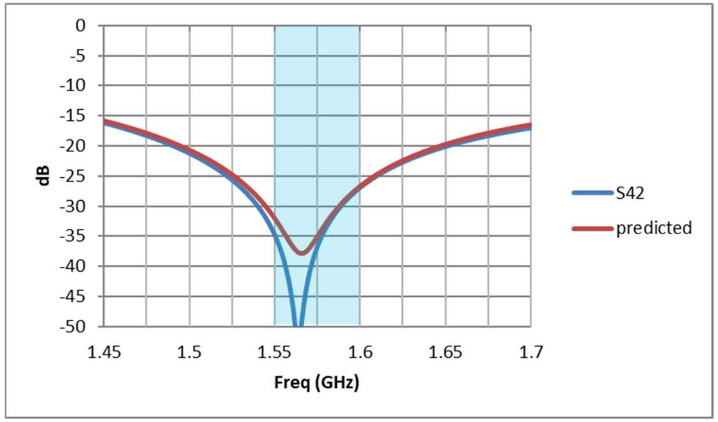


Isolated path: port 1->3





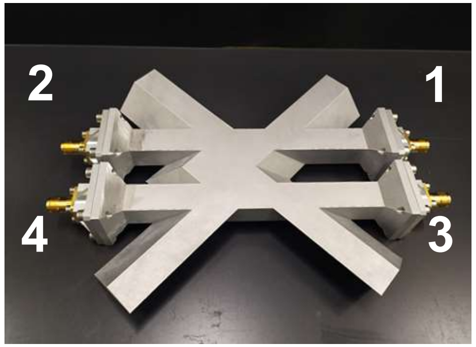
Coupled path: port 1-> 4 and 3->2

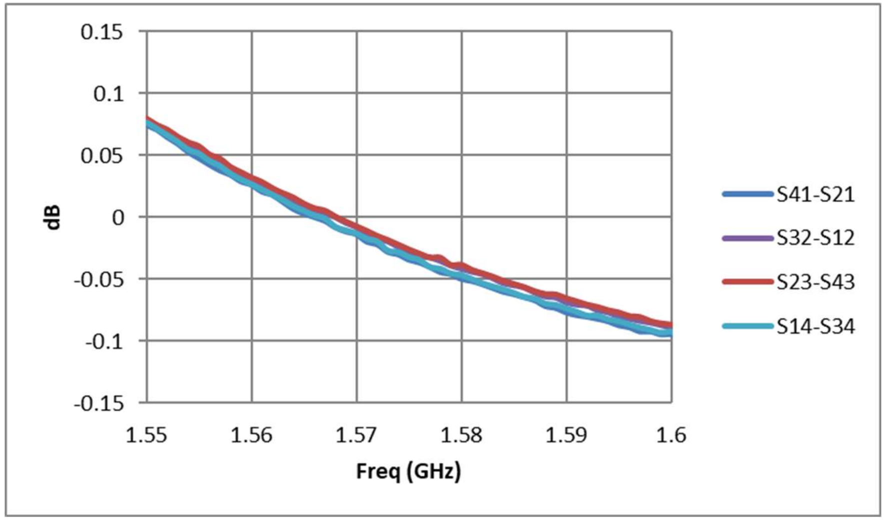


Isolated path: port 2->4

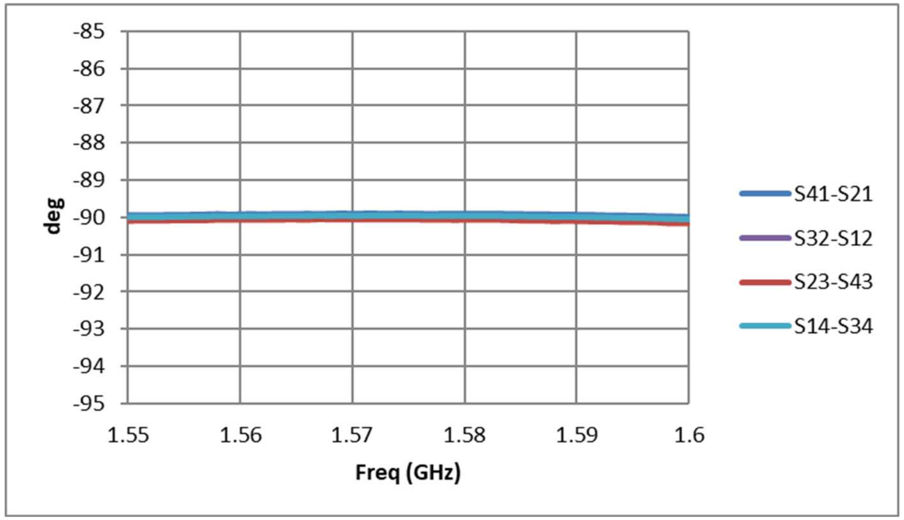
DEMONSTRATOR #02: RF TESTS ON L-BAND COUPLER

- **Detail of measured amplitude unbalance (nominally 0dB) and phase difference (nominally -90deg) between coupled and direct output ports, for each of the input ports:**
  - from **port 1** to **ports 4** (coupled) / **2** (direct)
  - from **port 2** to **ports 3** (coupled) / **1** (direct)
  - from **port 3** to **ports 2** (coupled) / **4** (direct)
  - from **port 4** to **ports 1** (coupled) / **3** (direct)





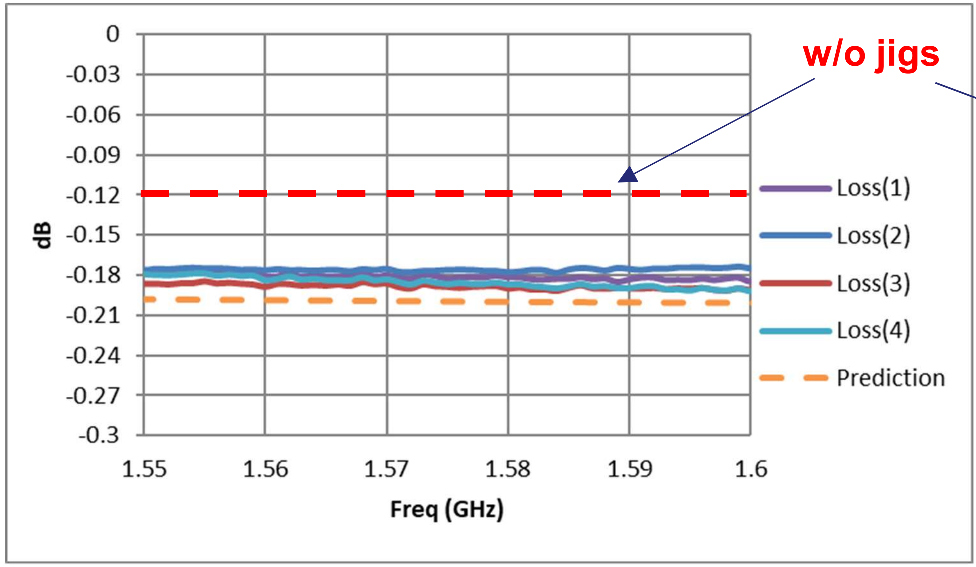
Amplitude unbalance between coupled and direct ports (for each input port)



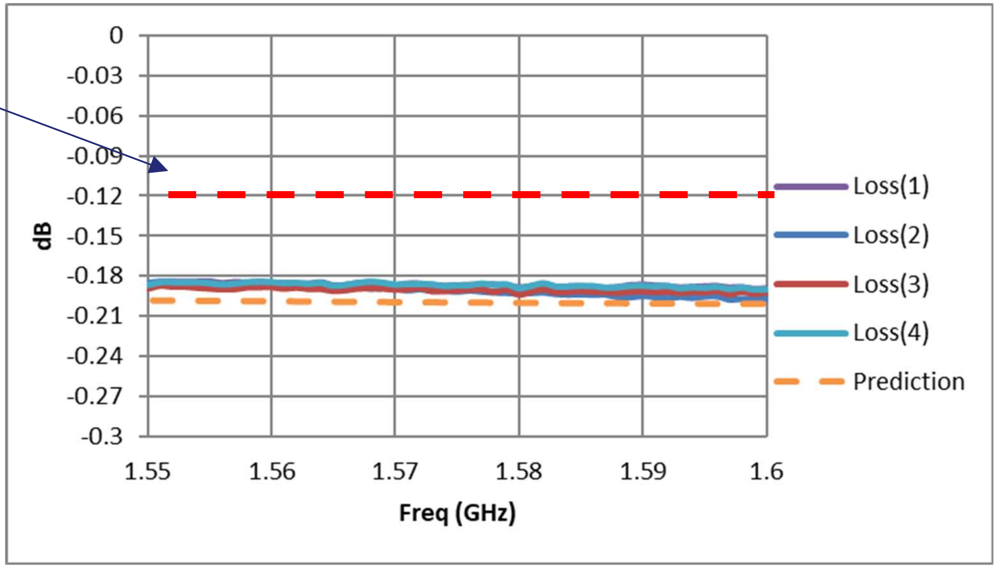
Phase difference between coupled and direct ports (for each input port)

DEMONSTRATOR #02: RF TESTS ON L-BAND COUPLER

- Measured end to end RF losses of the coupler (by S parameters balance) for all ports, compared to predicted values achieved with best fitted parameters σ=2 10^7 *Si m* and ρ=8μ*m* in the CST model
- Total loss of the assembly, including test jigs and connector, is in the range of 0.18dB. The standalone coupler (no jigs and connectors) ohmic loss is in the range of 0.12dB.
- The comparison between the losses measured on bare aluminum surfaces and after SURTEC treatment does not show significant variation due to acid pickling.



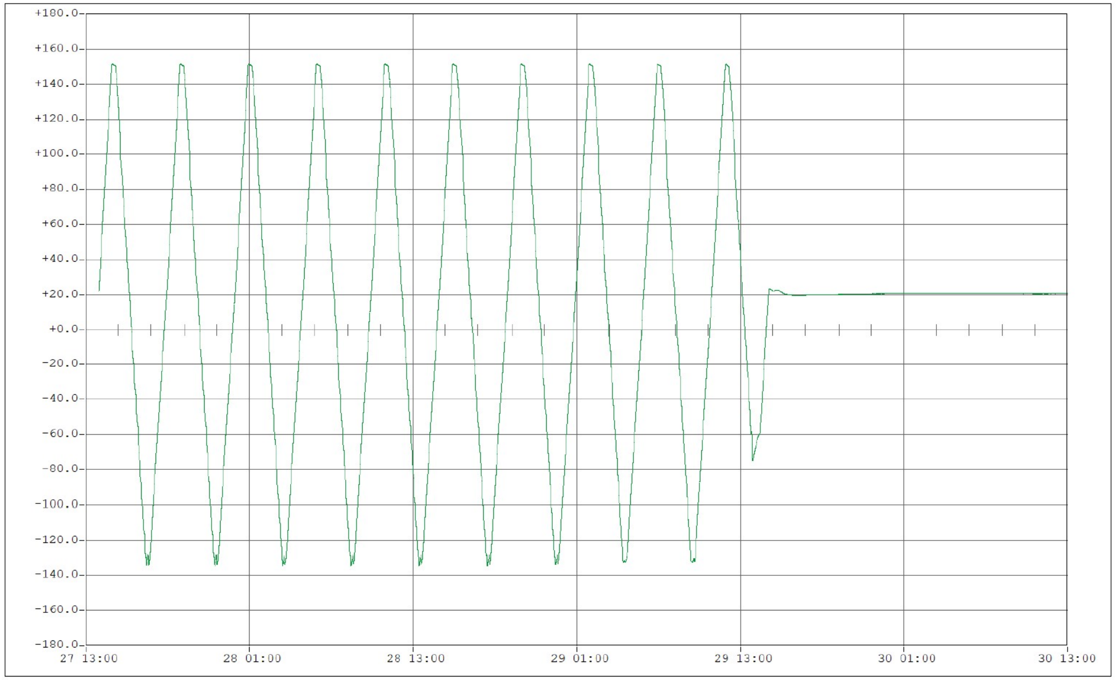
RF losses (including jigs and connectors) before SURTEC



RF losses (including jigs and connectors) after SURTEC

DEMONSTRATOR #02: THERMAL CYCLING

- The L-band coupler has been subjected to thermal cycling in nitrogen
- The S parameters have been verified before and after the cycle, to verify the repeatability of the RF performance and confirm the stability of the geometry in a realistic in orbit thermal environment.
- High repeatability of S parameters is demonstrated

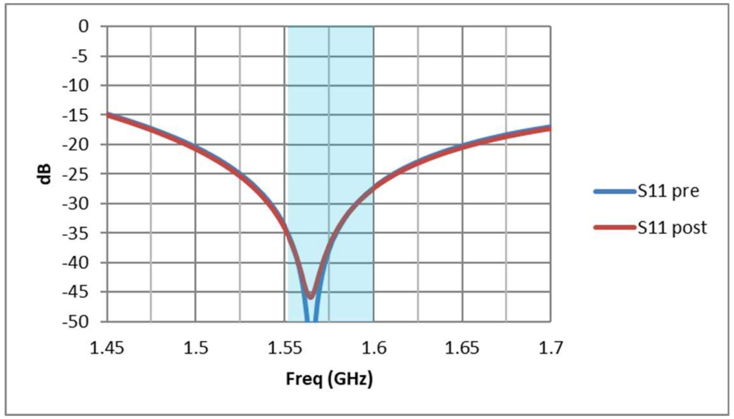


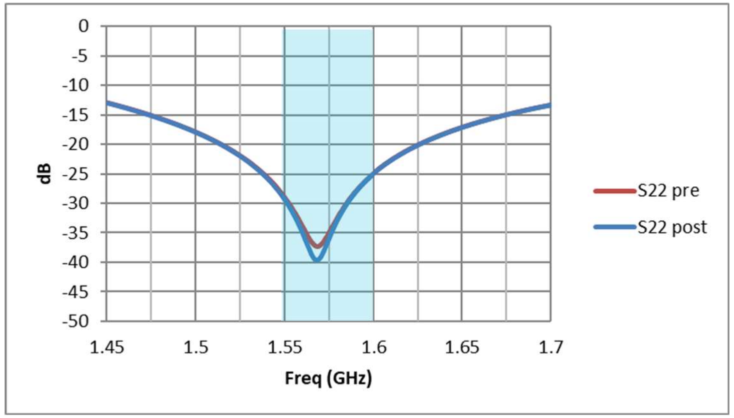
TEMPERATURE PROFILE

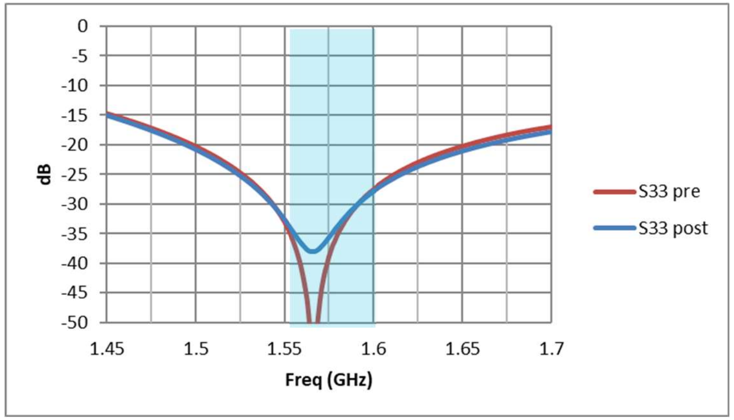
- 10 cycles between -130/+150°C
- 15minutes plateau at extreme temperatures
- temperature gradient is 2°C/min

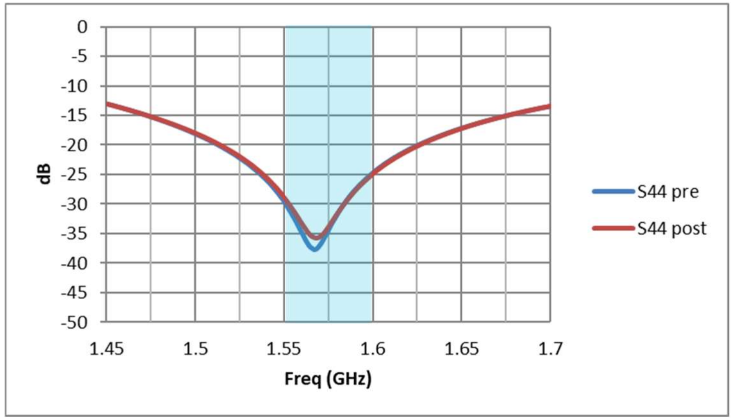
DEMONSTRATOR #02: FINAL RF TESTS ON L-BAND COUPLER

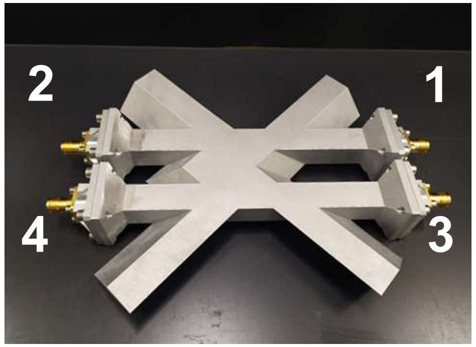
- **Input reflection coefficients at all ports pre/post Thermal Cycling**











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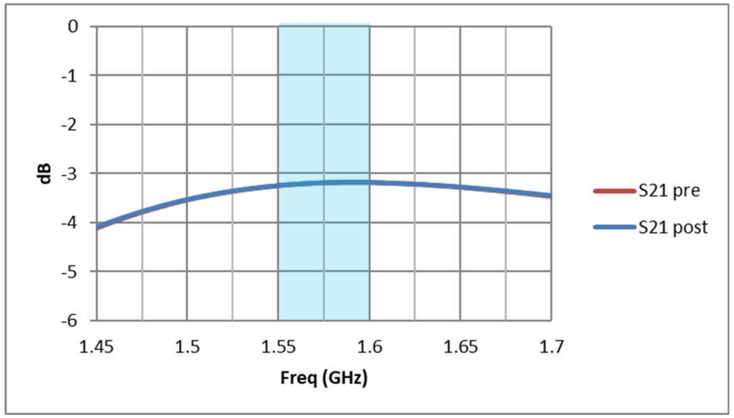
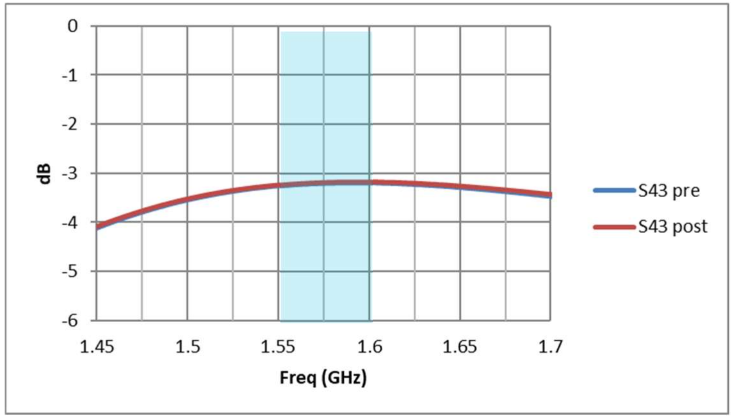
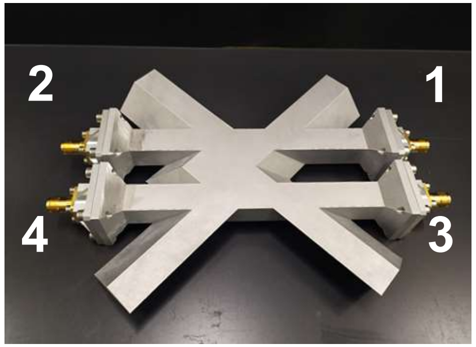
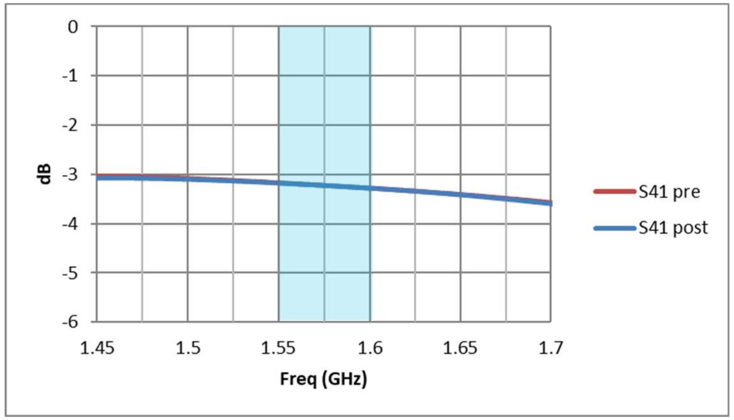
DEMONSTRATOR #02: FINAL RF TESTS ON L-BAND COUPLER

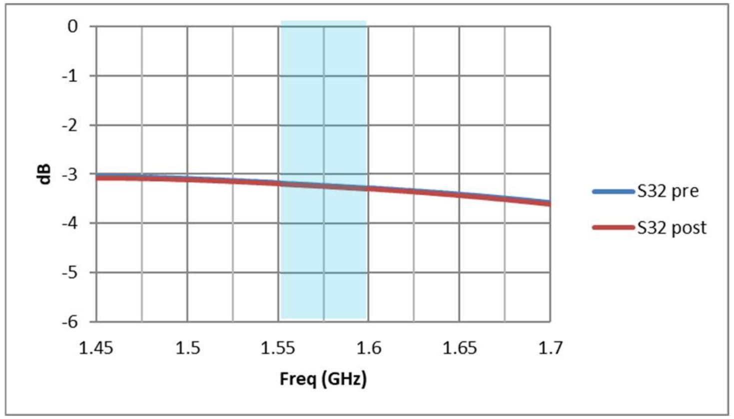
- Direct (S21,S43) and coupled (S41,S32) coefficients pre/post Thermal Cycling





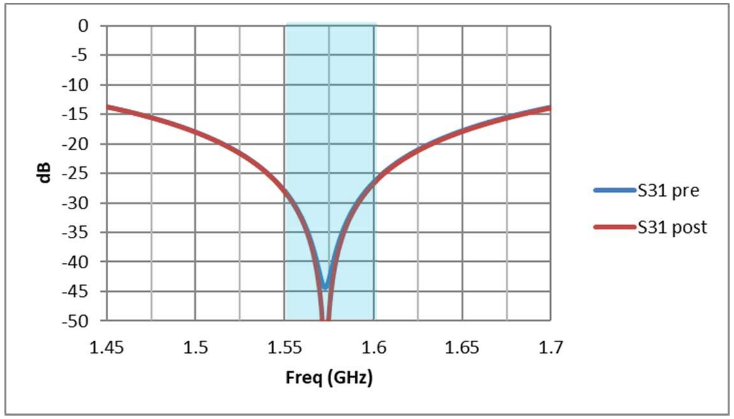


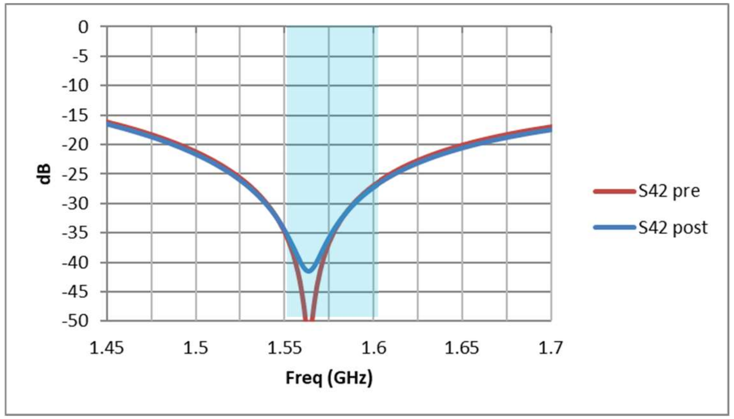


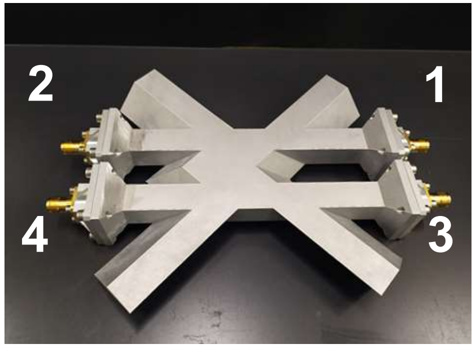


DEMONSTRATOR #02: FINAL RF TESTS ON L-BAND COUPLER

- Isolation (S31,S42) pre/post Thermal Cycling







DEMONSTRATOR #02: LESSON LEARNT

In conclusion of the Study, the lesson learnt from the activity on Demonstrator #2 can be summarized in the following points:

- **Successful monolithic construction of a non-simply connected transmission line devices**, introducing RF-transparent shunt stubs as mechanical supports for inner conductor (which also provide DC-grounding and serve as thermal shunt between conductors). On the other hand, it has to be considered that the monolithic device cannot be inspected or dimensionally checked inside. For this reason, high confidence of the design predictions and manufacturing process must be guaranteed. This goal has been demonstrated to be achievable by the present demonstrator.

- **Measured RF performance of the component in AM match very well the fullwave predictions**. The achieved tolerances appear well suitable for the application in the selected frequency band (L band, E1).

- **Higher ohmic losses than with conventional CNC**, related to higher inner surface roughness (8-10um for AM VS 1.2um typical for CNC). The electromagnetic model accounts for roughness and fits very well the measured losses, providing an accurate tool for prediction. Due to the geometry of the component it is not possible to reduce the roughness by post-processing. It has been verified that non aggressive acid pickling and SURTEC application do not change the losses.

- **Mass of the device is not significantly increased in comparison to the conventional approach**, thanks to the absence of screws and to the possibility of printing lattice inside the metal. Anyhow the concept does not seems yet applicable with advantages to more complex BFNs with significantly long RF paths. Firstly due to the limitations of printers volume, and further due to the need of a significant number of shunt stubs when long inner conductor has to be kept suspended, under mechanical load.X

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DEMONSTRATOR #02: FUTURE DEVELOPMENTS

As future steps, the following activities can be envisaged:

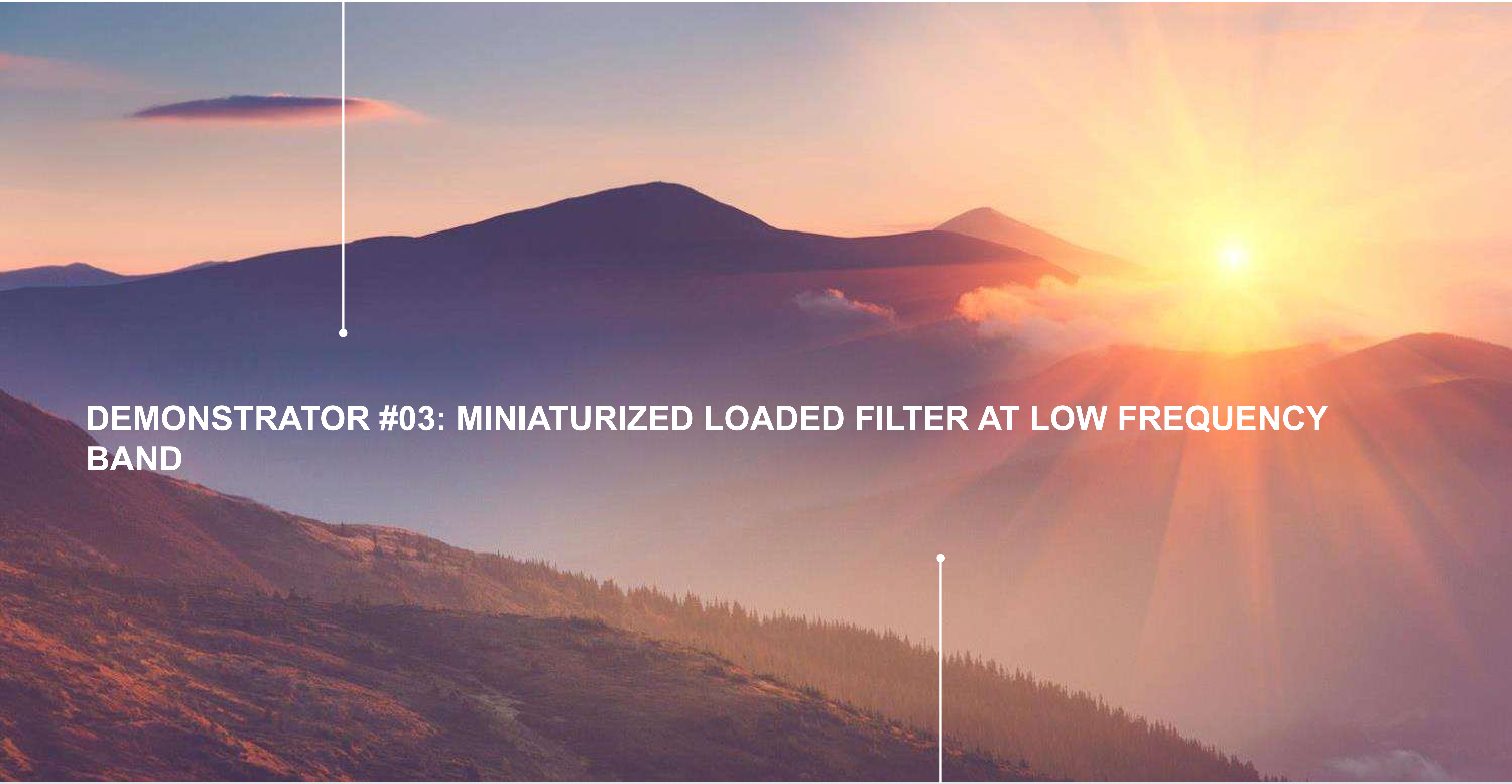
1. **To investigate other solutions for roughness (and ohmic loss) reduction**, as for example:
   - more aggressive acid pickling of the surfaces, to be tuned in order to not alter significantly the geometrical dimensions
   - silver plating, feasibility to be verified depending on the accessibility for electrodes into the folded geometry

1. **Analyses and tests of the geometry toward mechanical loads**, in order to define suitable criteria for the minimization of shunt stubs to be used, especially in view of possibly longer paths.

2. **Further optimization of the lattice structure inside the waveguide walls for mass minimization**, still fulfilling mechanical requirements

3. **Possible application of the concept to more complex devices**:
   - multiple-layer / folded components for room saving, where coaxial vias between the different layers could be avoided and monolithically implemented
   - integration of radiating elements (e.g. an all metal patch) to be printed monolithically with the coupler, in order to achieve a full-metal dual circularly polarized radiator to be used in array, without the need of welded or screwed joints between the BFN and the patches.

DEMONSTRATOR #03: MINIATURIZED LOADED FILTER AT LOW FREQUENCY BAND

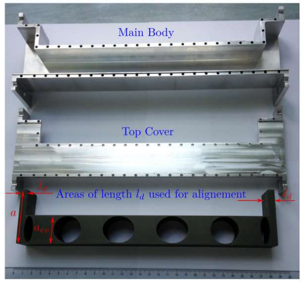


DEMONSTRATOR #3: *CERAMIC-LOADED FILTER*

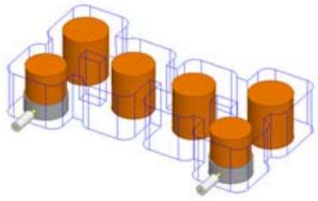
- Frequency band: S band (2.5 GHz)
- High permittivity dielectric: ZrO_2
- High miniaturization: dielectrically loaded ridge waveguide resonators (f_{cutoff} in the range of 1.6 - 1.9 GHz)
- Compatible with ZrO_2 printing dimensional constraints
- Applicable in Space programs: metallic waveguide housing (no direct painting of dielectric core)
- RF and mechanical design to mitigate effects induced by air gaps, dimensional tolerances, planarity & parallelism of dielectric parts, permittivity variability

DEMONSTRATOR #3: *STATE OF THE ART*

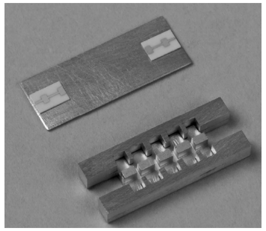
Pons-Abenza, et al. 2020



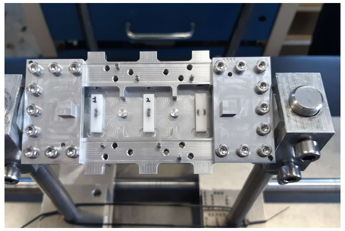
Pelliccia et al 2019



Rauscher et al 2006



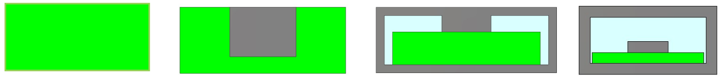
Present activity



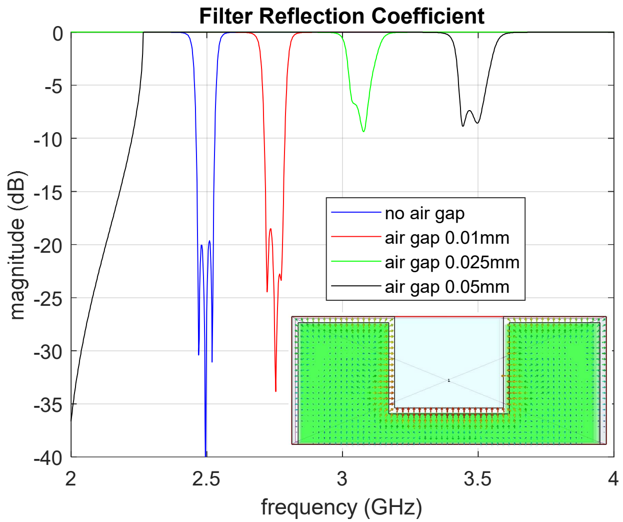
Center Freq (GHz)	**3.65**	**1.6**	**6.4**	**2.5**
Material	ABSPlus	Maruwa	Eccostock-CK	Zirconia
Permittivity	2.55	45	9.5	27-28
Number of cavities	5	6	5	3
Inserion Loss (dB)	4.3	0.5	1.3	2
Waveguide Type	Completely filled rect	Partial filled rect	Completely filled ridge	Partially filled ridge
Waveguide side (mm)	30	30	5.0	20
Resonator length (mm)	23	30	1.7	5
Discontinuity length (mm)	30 (evanescent)	2 (iris)	0.6 (evanescent)	20 (evanescent)

DEMONSTRATOR #3: *DEVELOPMENT PLAN*

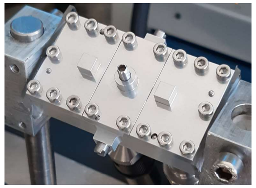
1. Resonator waveguide trade-off through preliminary RF designs

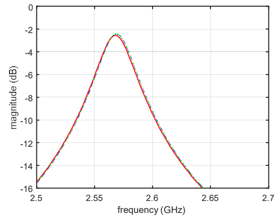


2. Spurious effect analysis and waveguide selection

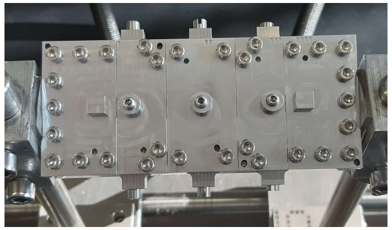


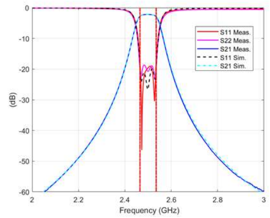
3. Dielectric sample manufacturing, characterization and mechanical investigation through test cavity





4. Filter design, manufacturing and testing

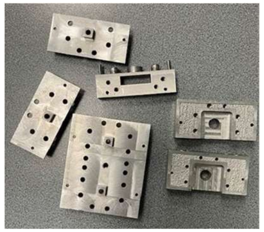




DEMONSTRATOR #3: *MANUFACTURING ROUTE*

Ceramic parts	
Material	Zirconia (LithaCon 3Y 210)
Process	Ceramic Vat Photo Polymerization (CerAM VPP)
System	Lithoz LCM
Post-Processing	The printed green components are thermally treated in two consecutive steps comparable to the standard ceramic processing steps of de-binding and sintering.
Remarks	Mass loading can be used during sintering to guarantee higher parallelism and planarity of the top and bottom surfaces of the ceramic elements (goal value < 0.02 mm).

	Metal housing - Test Cavity #01	Metal housing - Test cavity #02 & Filter
Material	AlSi10Mg	Al 6082
Process	Laser powder bed fusion	CNC milling
System	EOSINT M270	-
Post-processing	• Thermal treatment: Stress release with components still attached to the platform for 2 h at 300 °C • Milling	None
Remarks	• Dimensional tolerances < 0.05 mm • Surface roughness = 0.4 ÷ 0.8 micron	• Dimensional tolerances < 0.02 mm • Surface roughness = 0.2 ÷ 0.4 micron



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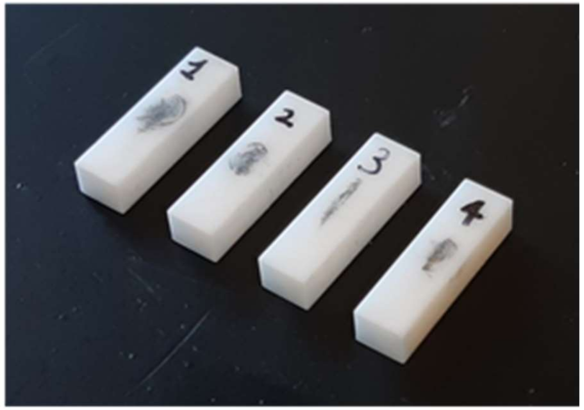
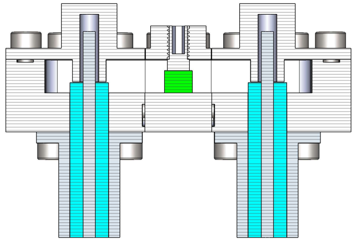
DEMONSTRATOR #03: *ZIRCONIA SAMPLES*

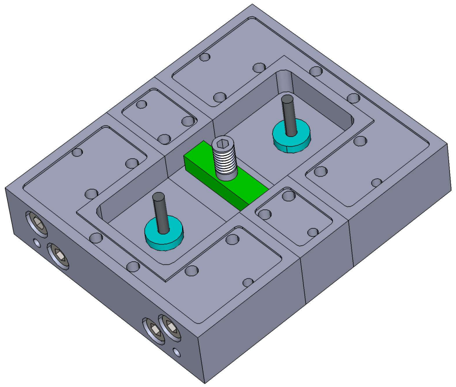
- Four ceramic samples have been manufactured through Lithoz LCM technology
- Two of these samples (#1 and #2) have been subjected to mass loading during sintering to guarantee higher parallelism and planarity
- The samples have been firstly measured with a 3D coordinate measuring machine, using 40 points for each plane

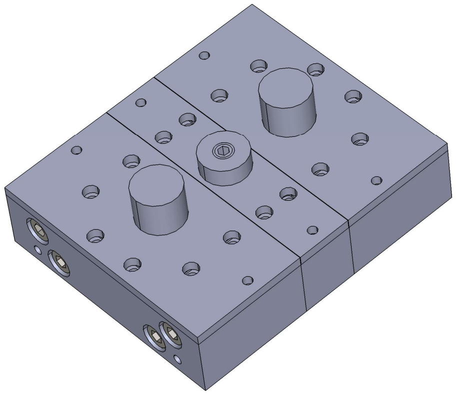


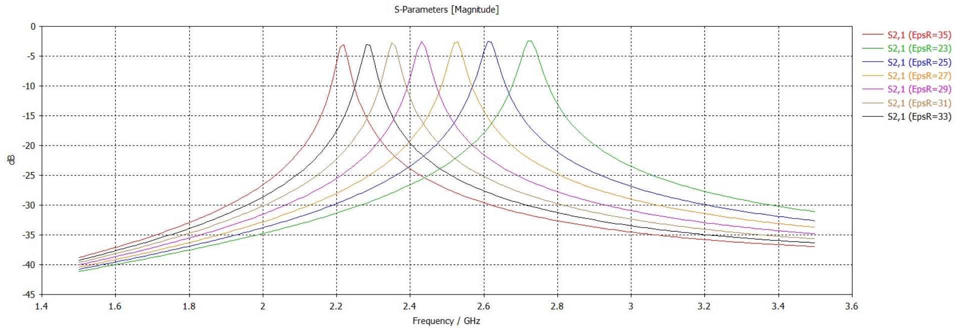
Sample	Width (mm)	Height (mm)	Length (mm)	Planarity (mm)	Parallelism (mm)
Nominal	18.00	4.00	5.00	-	-
CLZ5-1	17.87	4.03	4.97	0.02 ÷ 0.03	0.03 ÷ 0.04
CLZ5- 2	17.88	4.04	4.96	0.02 ÷ 0.03	0.03 ÷ 0.04
CLZ5- 3	17.84	4.04	4.96	0.02 ÷ 0.04	0.04 ÷ 0.05
CLZ5- 4	17.85	4.05	4.95	0.02 ÷ 0.03	0.03 ÷ 0.04

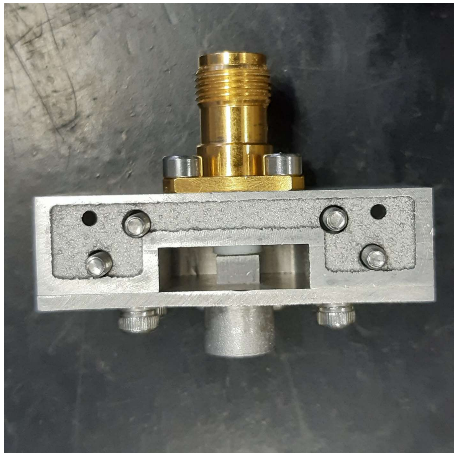
DEMONSTRATOR #03: *TEST CAVITY #01*

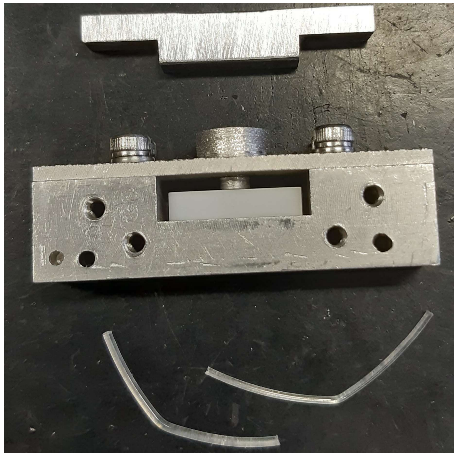


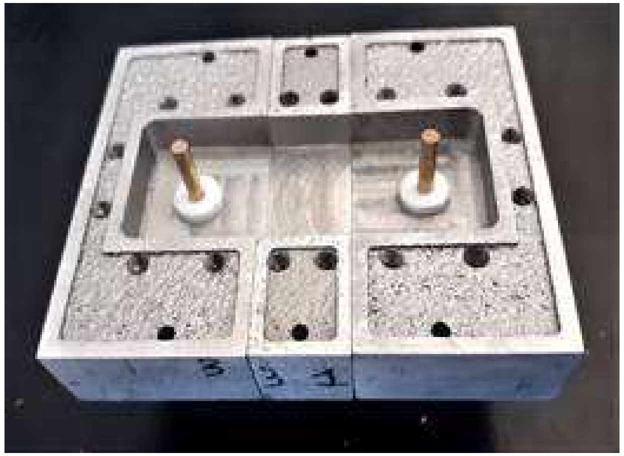


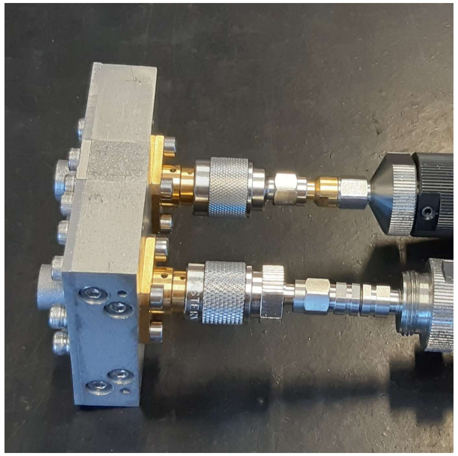




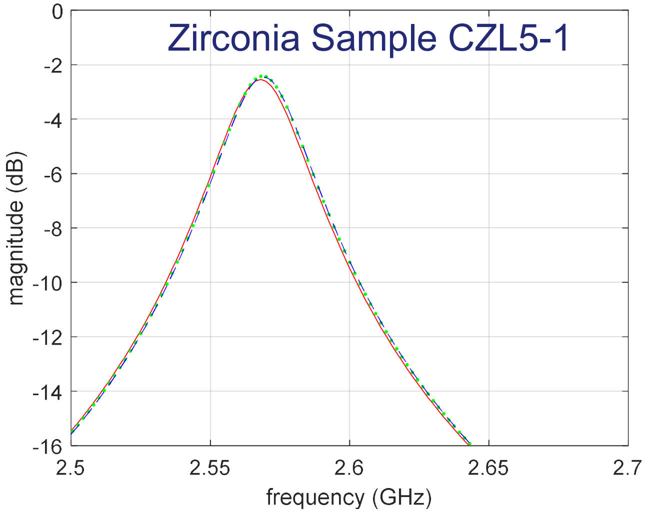








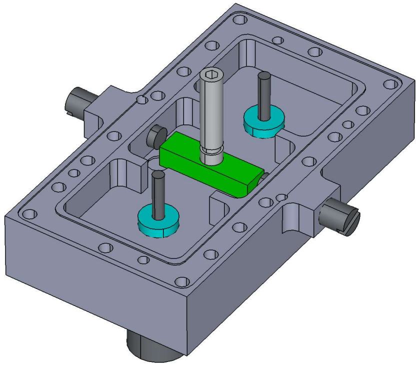
DEMONSTRATOR #03: *TEST CAVITY #01*

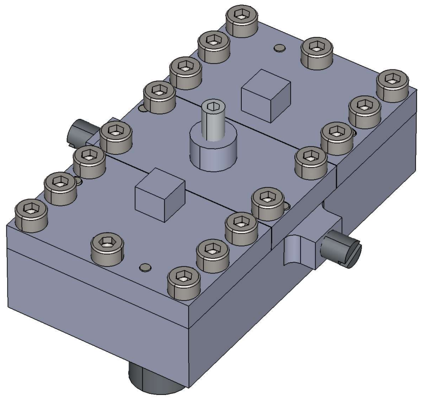


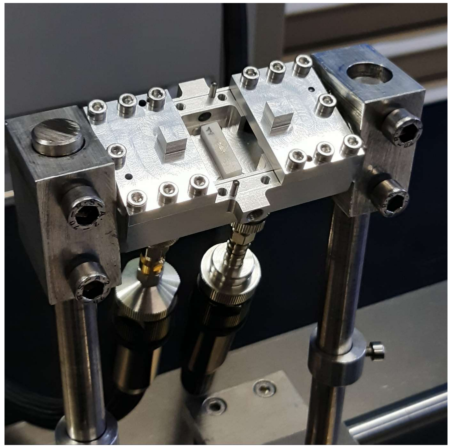
Measurement	#1		#2		#3	
	f_0 (GHz)	BW-3dB (MHZ)	f_0 (GHz)	BW-3dB (MHz)	f_0 (GHz)	BW-3dB (MHz)
Sample CZL5-1	2.568	31.9	2.569	31.5	2.568	31.6
Sample CZL5-2	2.546	32.1	2.546	32.0	2.546	31.6
Sample CZL5-3	2.533	33.0	2.532	32.9	2.532	33.3
Sample CZL5-4	2.529	31.1	2.529	31.2	2.529	31.6

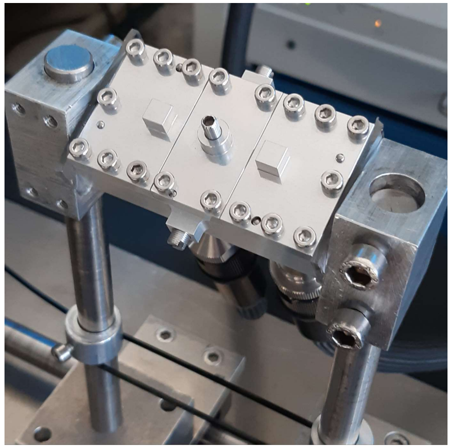
Measurement	#1		#2		#3	
	ϵ_R	$tan\ \delta$	ϵ_R	$tan\ \delta$	ϵ_R	$tan\ \delta$
Sample CZL5-1	27.02	1.4E-3	27.01	1.2E-3	27.01	1.3E-3
Sample CZL5-2	27.54	1.7E-3	27.54	1.6E-3	27.54	1.5E-3
Sample CZL5-3	27.90	2.2E-3	27.90	2.2E-3	27.90	2.4E-3
Sample CZL5-4	28.10	1.5E-3	28.10	1.5E-3	28.10	1.6E-3

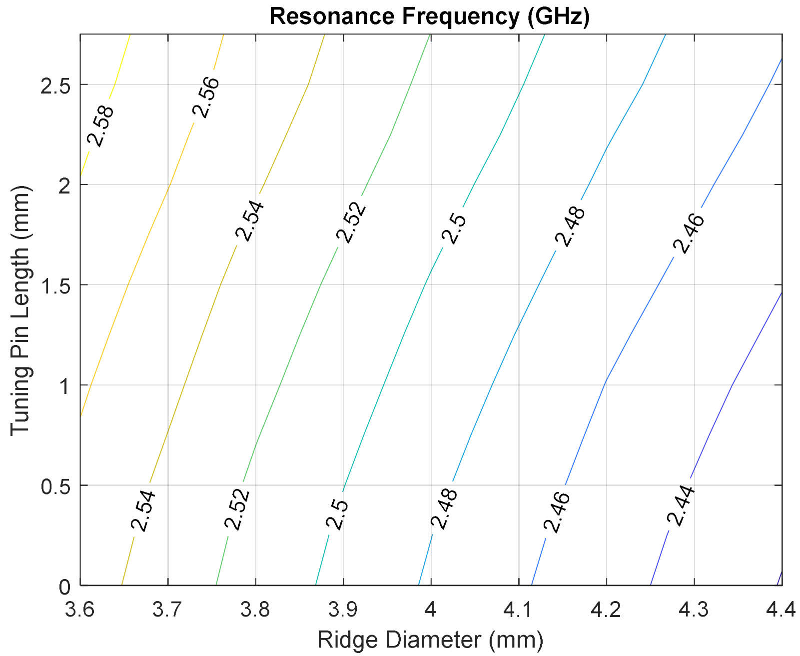
DEMONSTRATOR #03: *TEST CAVITY #02*











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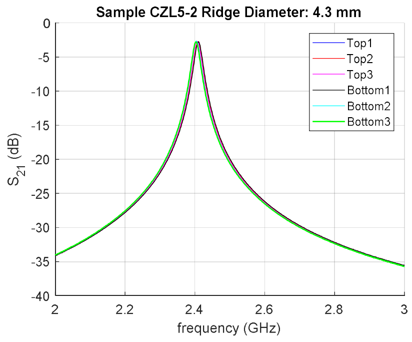
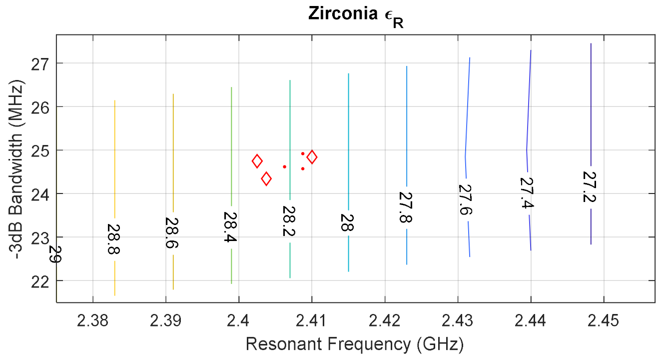
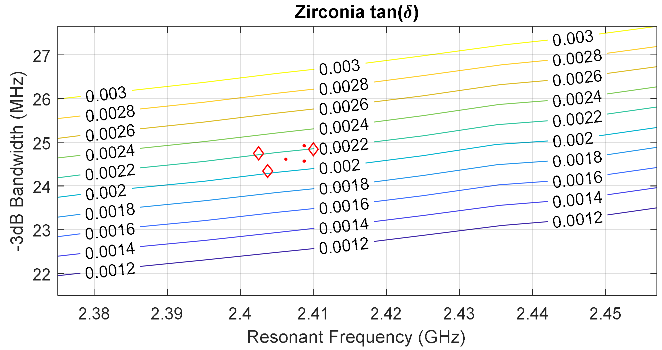
DEMONSTRATOR #03: *TEST CAVITY #02*

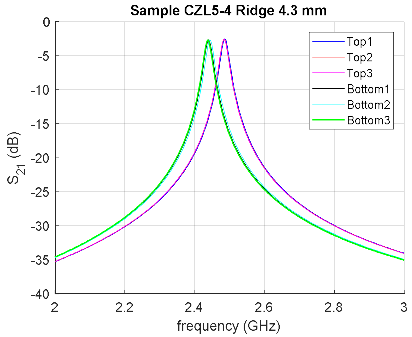
CZL5-2

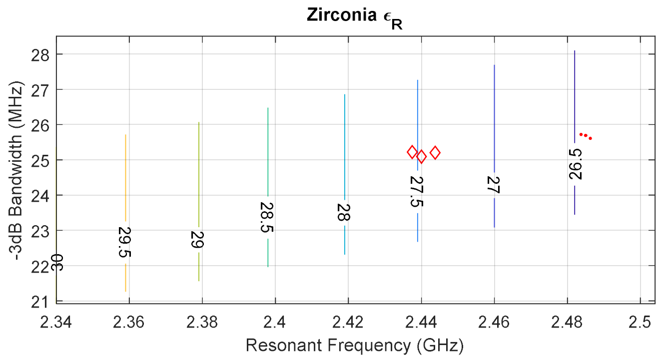


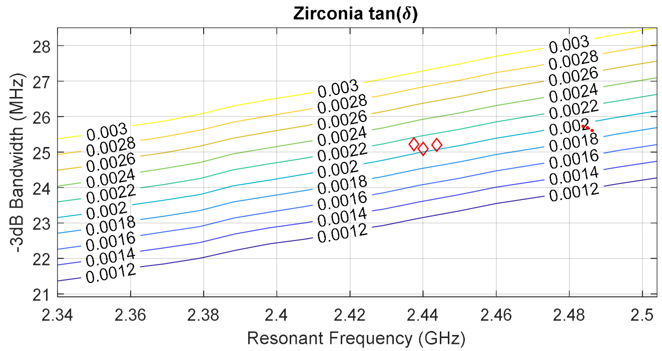




CZL5-4

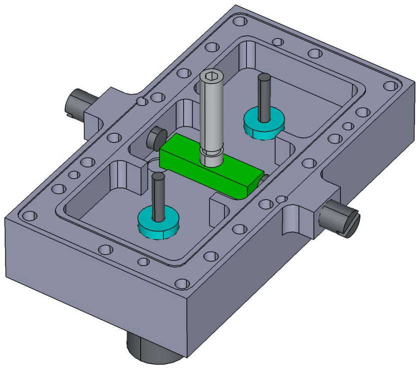


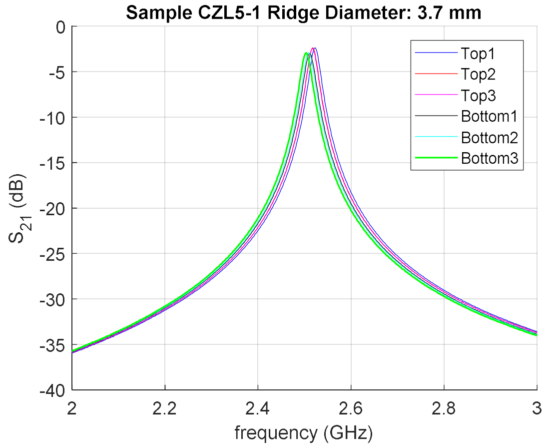


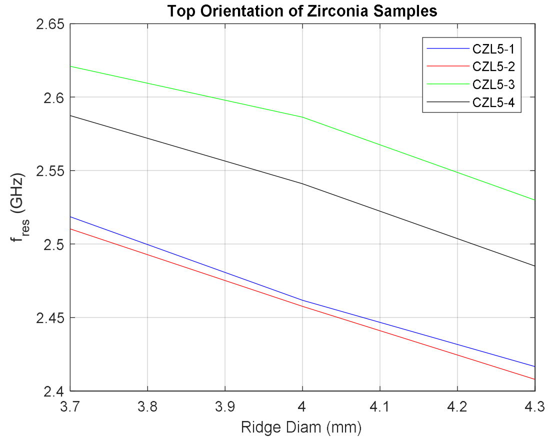


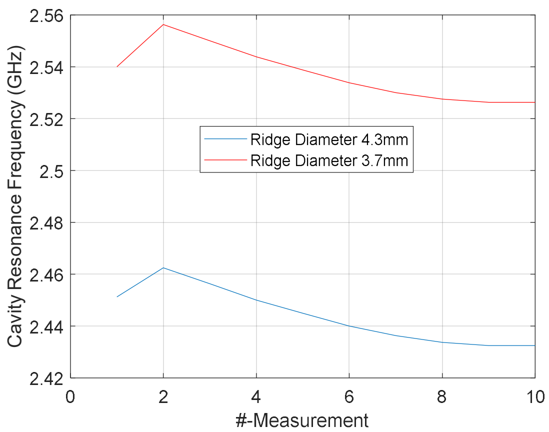
DEMONSTRATOR #03: *TEST CAVITY #02*

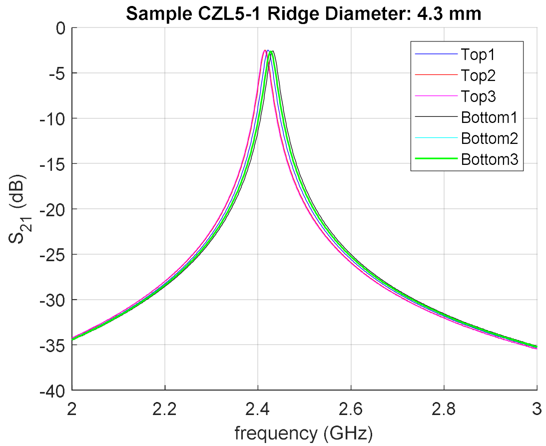
CZL5-1

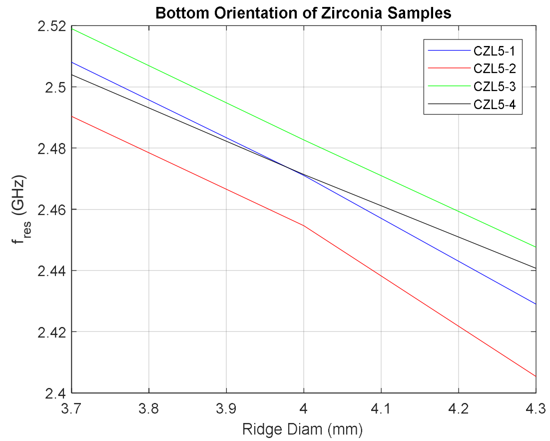




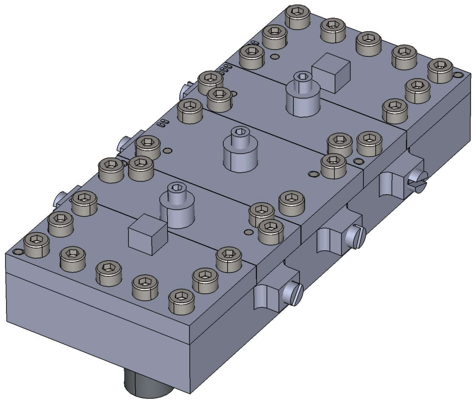








DEMONSTRATOR #03: *S-BAND THREE-CAVITY FILTER*

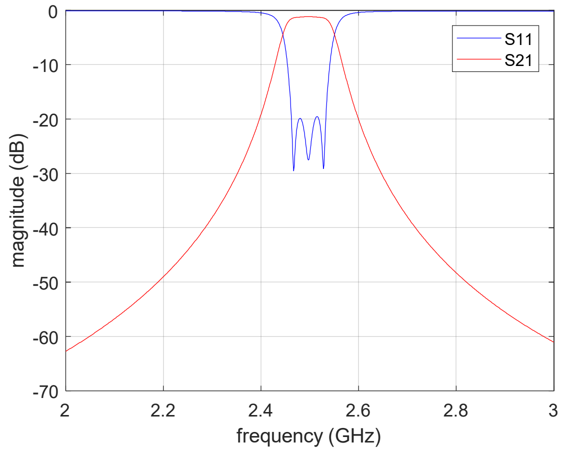


	ϵ_R	
Measurement	**Top**	**Bottom**
Sample CZL5-1	27.85	27.7
Sample CZL5-2	28.1	28.22
Sample CZL5-3	<25	27.5
Sample CZL5-4	26.25	27.7

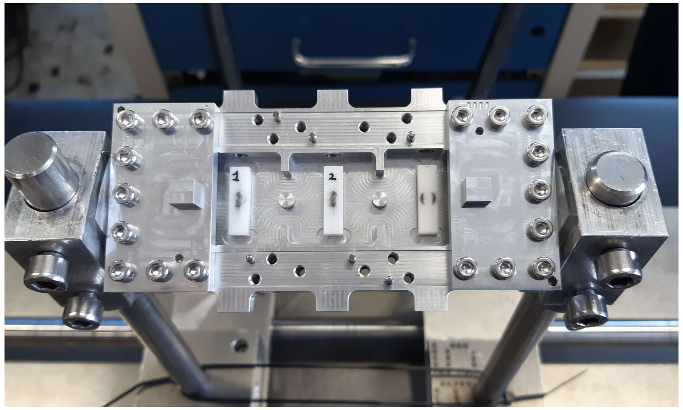
tan δ ~ 2E-3

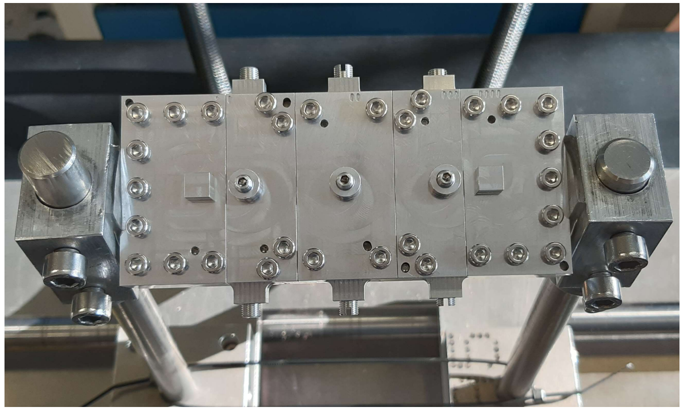
Reference requirements

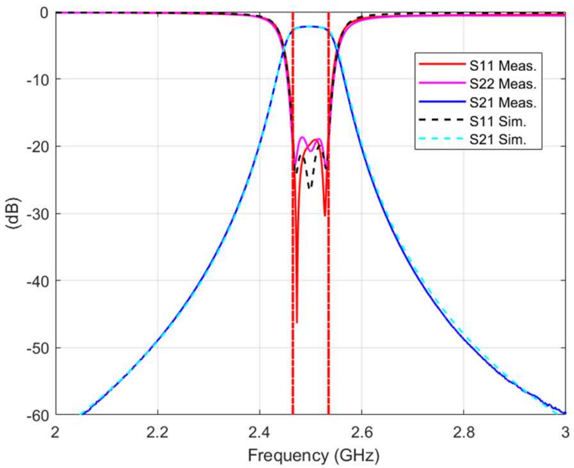
Parameter	Value
Passband	2470 - 2530 MHz
Return Loss in passband	> 17 dB
Insertion Loss in passband	< 0.4 dB
Rejection in (2000,2300) MHz	> 37 dB
Rejection in (2700,3000) MHz	> 37 dB
Envelope	< 50 x 30 x 110 mm

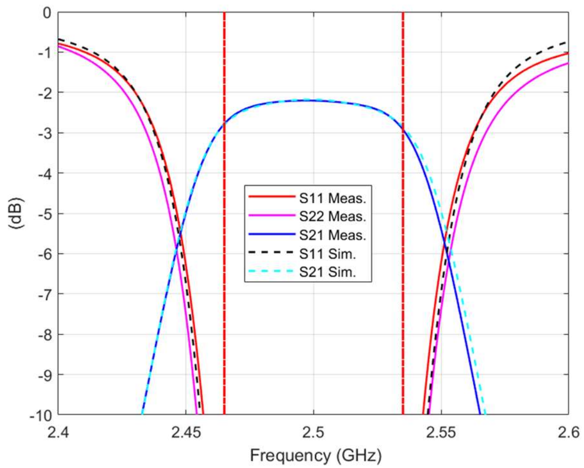


DEMONSTRATOR #03: *S-BAND THREE-CAVITY FILTER*





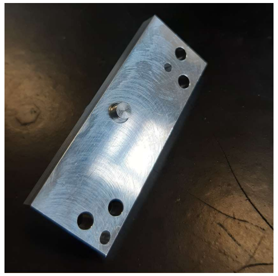


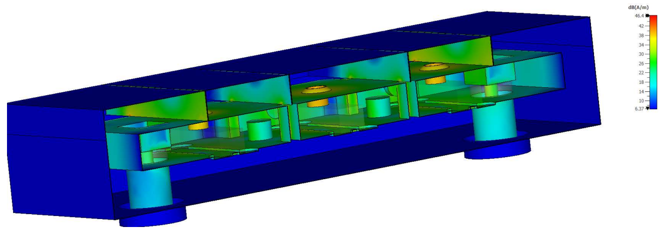


Equivalent tan δ ~ 4E-3

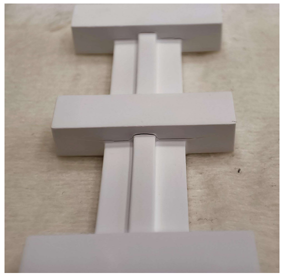
DEMONSTRATOR #03: *LESSONS LEARNT & WAY FORWARD*

- High miniaturization is achievable
- Effects induced by air gaps, dielectric variability, samples' planarity can be compensated for
- High IL can be caused by countersunk holes & standard thread pitch of the ridged pins





- Optimization of ZrO2 printing process vs losses
- New mechanical solutions to implement ridges on top of ZrO2 resonators
- Investigation on Ag-plating of metallic housing
- More complex shapes to exploit AM flexibility



DESCRIPTION OF SIDE ACTIVITY ON METAL-PLATED POLYMERS

METALLIZED POLYMERS (PHASE 1 FOLLOW ON ACTIVITY 1)

- Dielectric properties of polymers have been measured at L/S and Ku frequency bands. The relatively low ε and good tgδ ($10^{-4} \div 10^{-3}$) confirm the applicability of such materials to the manufacturing of RF dielectric parts (dielectric lenses, substrates, supports...)

- In the frame of the Study, the use of **polymers with structural proprieties**, such as **ULTEM** or **PEEK CF**, for fabrication of electrically conductive RF parts through surface **metallization** process was judged of higher interest

- The metallization of polymers have been attempted on PEEK CF and ULTEM. Waveguide cavities printed through FDM have been metallized with a double coating process, consisting of an electro-less silver substrate and a copper electroplating on top.

- Measured conductivity of the metallized surfaces appeared not satisfactory, metallization is not sufficiently thick or even absent in some areas, especially on closed and complex geometries. In addition, the final test results have showed large data dispersion, highlighting that the applied metallization processes are not consolidated yet.

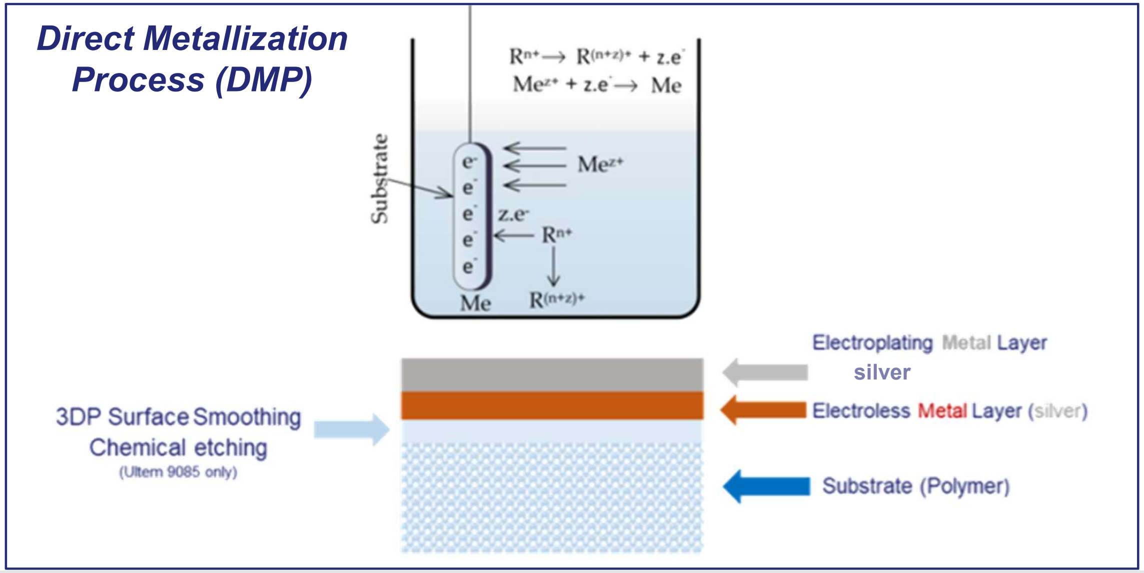
- For these reasons, as a follow-on of Phase 1 of the Study, it has been agreed to further investigate the metallization process on **PEEK CF** and **ULTEM** using **Direct Metallization Plating (DMP)** in silver, and to verify its effectiveness through the manufacturing and tests of waveguide samples in WR75.

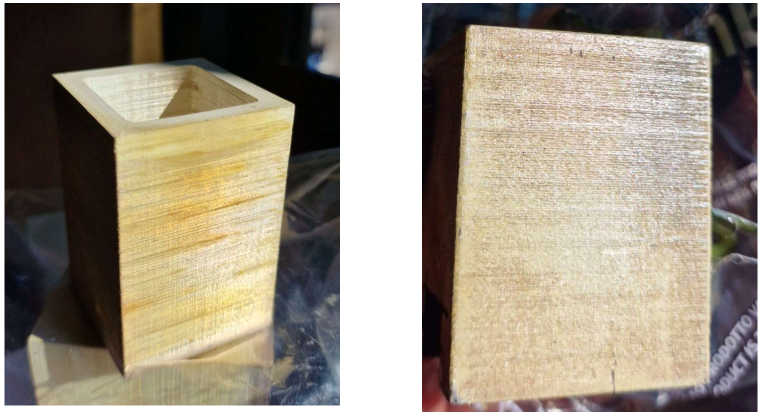
METALLIZED POLYMERS (PHASE 1 FOLLOW ON ACTIVITY 1)

- **The Direct Metallization Process has been verified on 5 PEEK-CF and 5 ULTEM specimens, which have been subjected to:**
  - Adhesion test
  - DC resistance measurement
  - Thermal cycling (-100/+100°C) and further adhesion test

- **At the end of this preliminary investigation phase:**
  - PEEK-CF has been selected, by virtue of better adhesion proprieties
  - The DMP parameters have been further tuned to improve metallization thickness and adhesion

Direct Metallization Process (DMP)

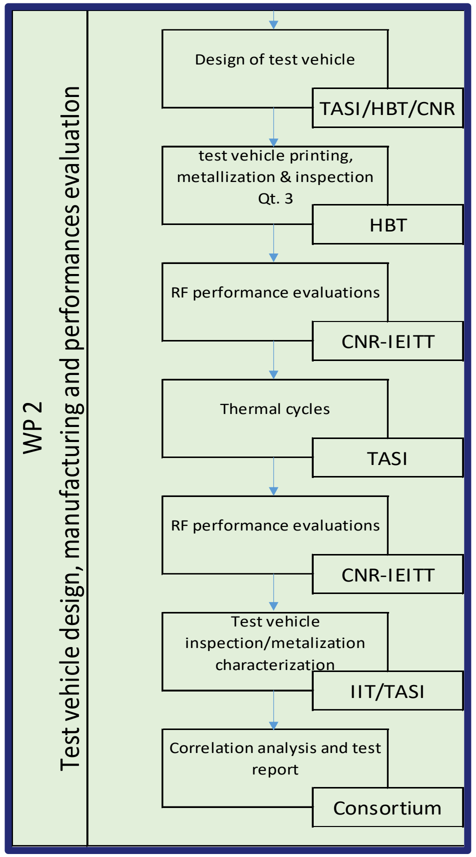


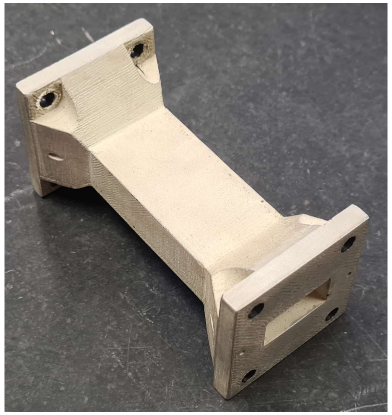


Metallized specimen in PEEK-CF and ULTEM

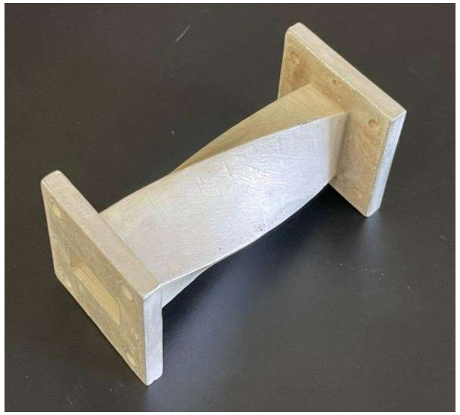
METALLIZED POLYMERS (PHASE 1 FOLLOW ON ACTIVITY 1)

- **The refined DMP has been applied to dedicated test vehicles, consisting in N=3 straight and N=3 twisted WR75 waveguides**





Straight WR75 line sample, printed in PEEK CF (FDM) and metallized through DMP in silver

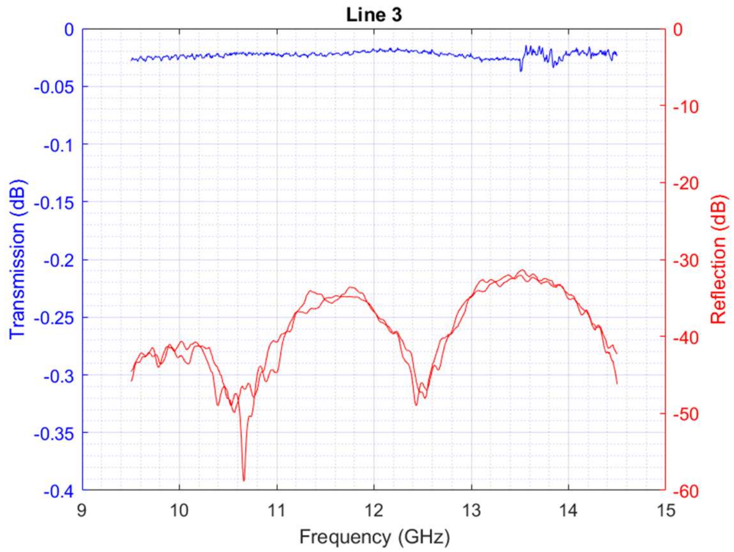


Twisted WR75 line sample, printed in PEEK CF (FDM) and metallized through DMP in silver

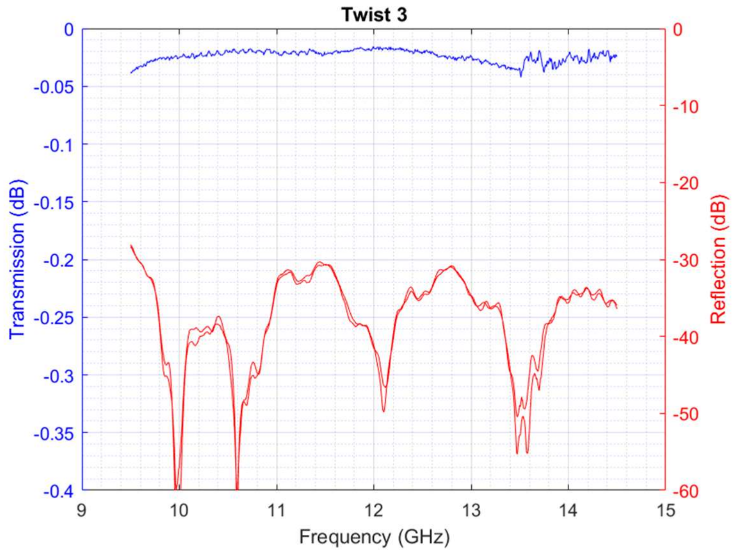
- **FDM printing**
- **DMP (Direct Metallization Plating)**
- **S parameters and losses**
- **Thermal cycling by incremental temperature steps up to ±80°C**
- **S parameter verification**

METALLIZED POLYMERS (PHASE 1 FOLLOW ON ACTIVITY 1)

- **Typical measured S parameters on the two types of samples**

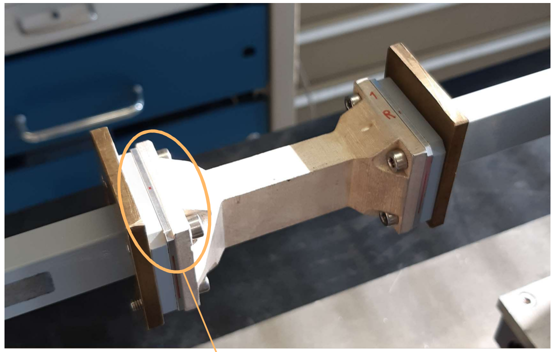


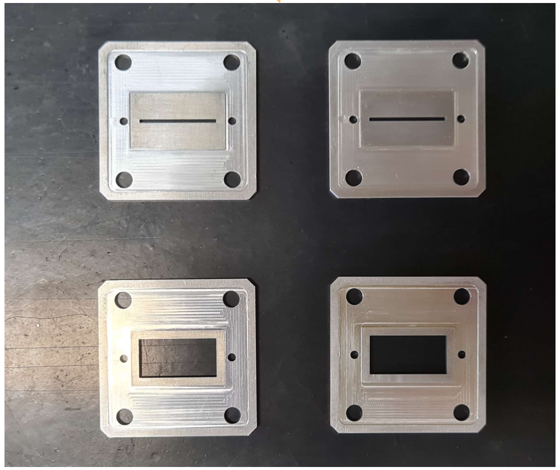
S parameters (reflection and transmission) on a straight line sample in WR75



S parameters (reflection and transmission) on a twisted line sample in WR75

S parameters measurement setup





WR75 thru and irises (with anti-cooking flanges, to enhance measurement repeatibility)

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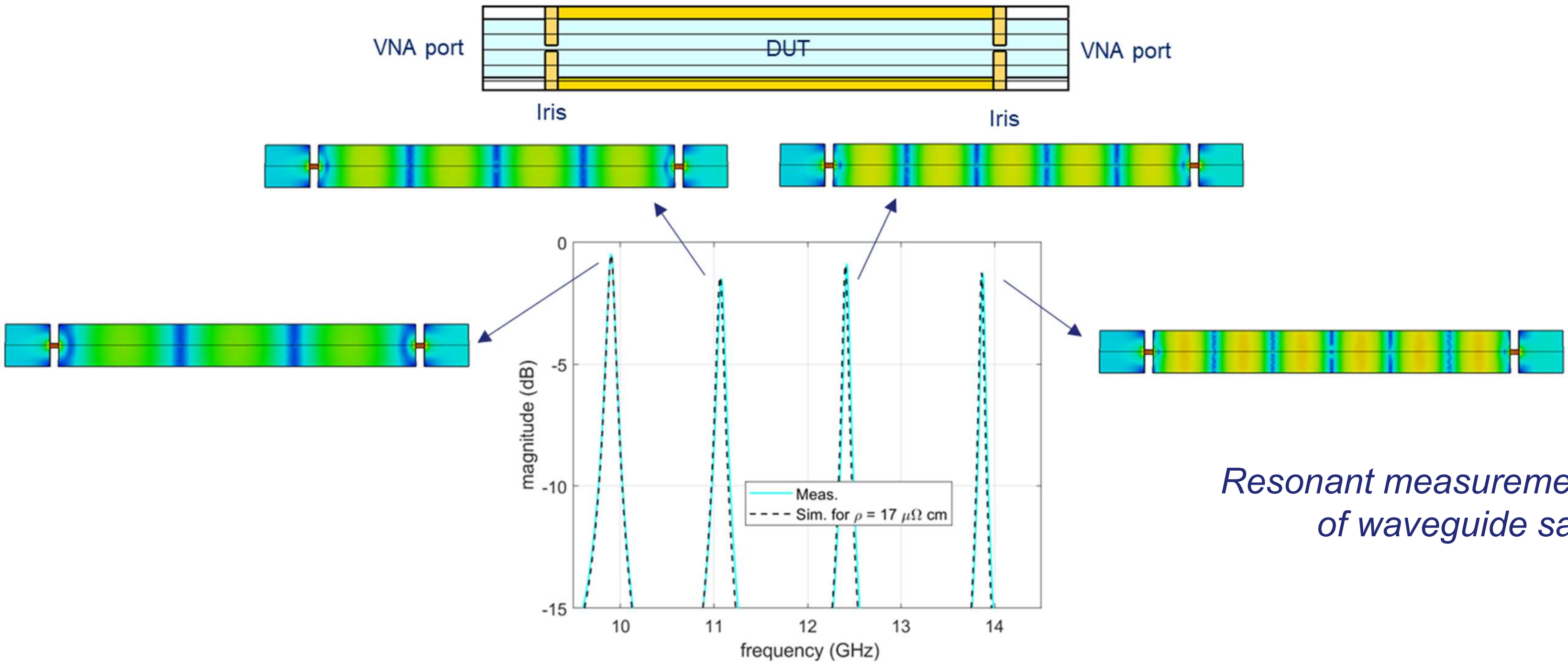
METALLIZED POLYMERS (PHASE 1 FOLLOW ON ACTIVITY 1)

- Resonant setup has also been used to emphasize losses, by inserting the waveguide samples between two irises
- The resonant peaks in the frequency response, corresponding to resonances of different orders, have been correlated with the electromagnetic model deriving equivalent resistivity over frequency for the metal plated polymer surface (10-20 μΩcm)



Resonant measurement technique of waveguide samples

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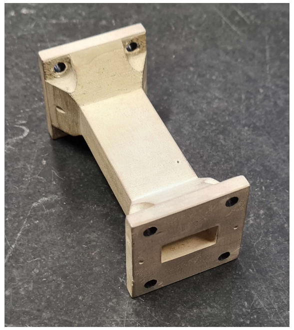
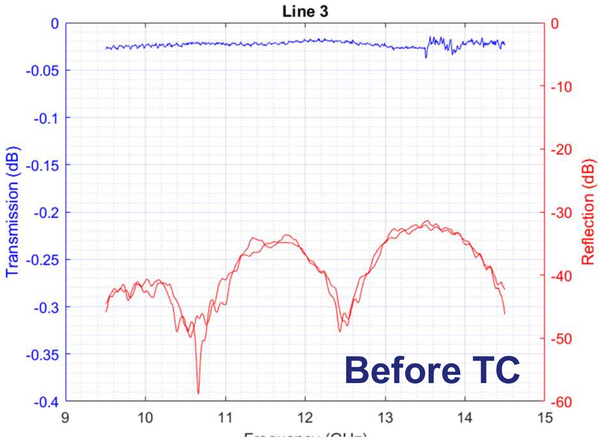
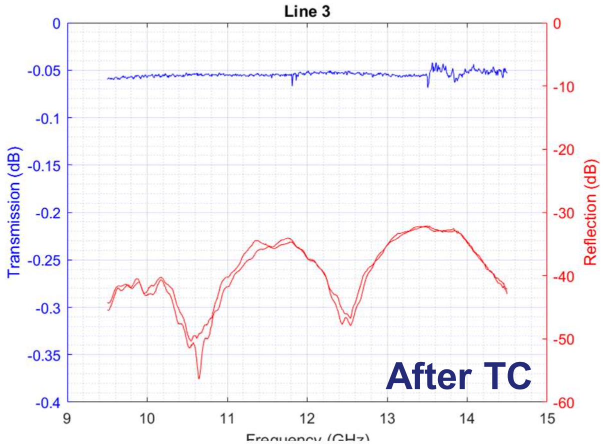
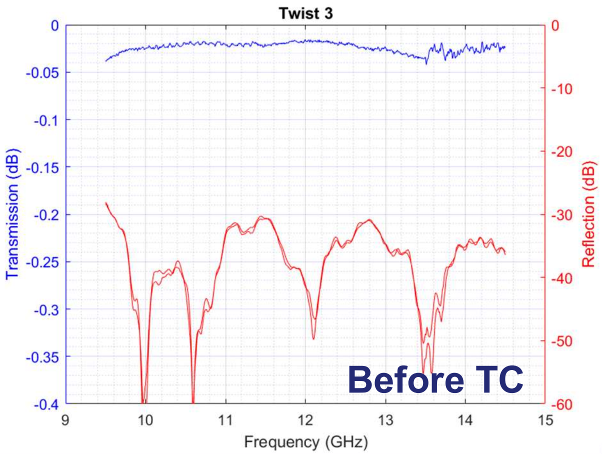
METALLIZED POLYMERS (PHASE 1 FOLLOW ON ACTIVITY 1)

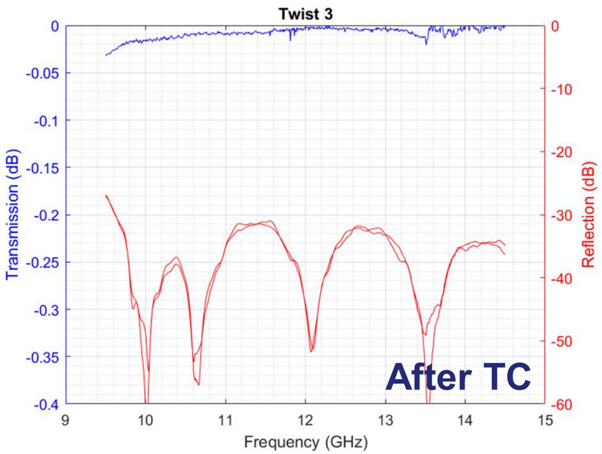
- The samples have been subjected to thermal cycling between -80/+80°C
- The comparison of the S parameters before and after the TC demonstrated a good repeatability











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METALLIZED POLYMERS (PHASE 1 FOLLOW ON ACTIVITY 1)

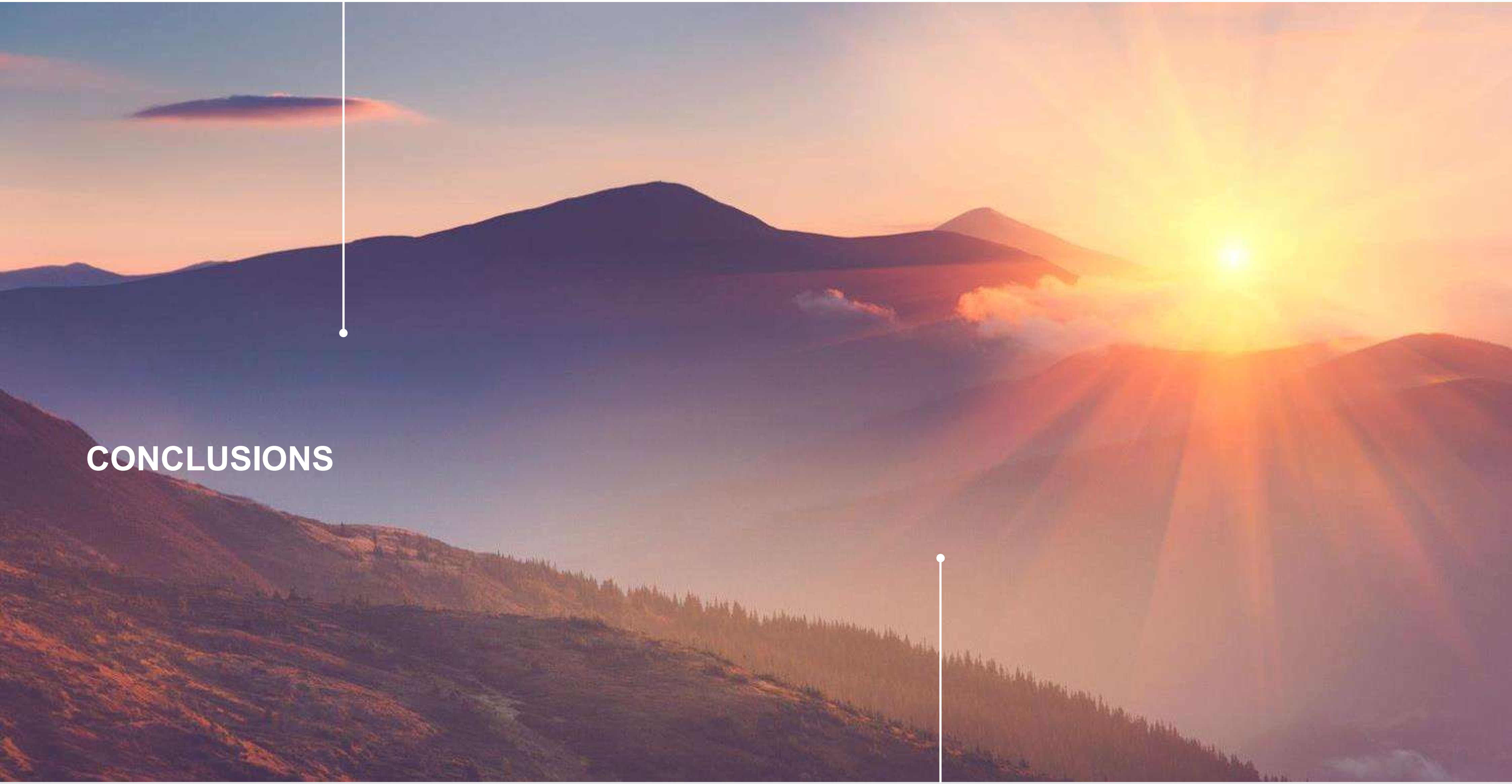
- **The metallization of polymer with good structural proprieties (PEEK CF) has been implemented through DPM**

- **The process could be then applicable to the fabrication of polymeric RF components with the following key characteristics:**
  - electrically conductive surfaces
  - compliant to space environment requirements (extreme temperature ranges, high mechanical loads, low outgassing…)

- **The process still needs some refinements to improve the adhesion, uniformity and thickness of the metallization. Anyhow the repeatability of RF performance vs thermal cycling already demonstrates suitable robustness of the metallization**

- **Possible future applications of the technology:**
  - Slot array antennas (ranging from C to Ku band)
  - Waveguide routings components

CONCLUSIONS



CONCLUSIONS

- **The project aimed at identifying additive manufacturing (AM) techniques suitable for RF space applications**
- **Phase 1 involved rigorous evaluations to select candidate materials and technologies meeting stringent space application requirements**
- **Materials investigated included metals, metallized polymers and ceramics, considering electric, mechanical, and environmental properties**
- **In Phase 1 three candidate demonstrators, representing different categories of microwave components usable in space missions, have been identified and designed:**
  - Aluminum AlSi10Mg printed through SLM was selected for a high frequency feed systems at Q/V band and a monolithic coaxial transmission line BFN component at L band
  - Zirconia ceramic printed through Lithoz LCM technology was chosen for a miniaturized filter at S band in ridged waveguide technology
  - Metallized polymeric materials with good structural proprieties (such as PEEK-CF and ULTEM) printed through FDM and metallized with DMP were considered to print waveguide test vehicles at Ku band
- **Phase 2 involved tests on RF demonstrators to evaluate performance and correlate results with predictions, which is general satisfactory**
- **The study highlighted the potential of AM in the production of microwave component for space applications. Lesson learnt and possible way forward activities have been presented for each demonstrator**

End of Presentation