Evaluation and consolidation of Additive Manufacturing processes and materials for the manufacturing of RF hardware

Executive Summary Report

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CONTRACT REPORT

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ABSTRACT

The present document reports a summary of all the activities performed under the contract Co-4000127300/19/NL/HK - Evaluation and consolidation of Additive Manufacturing processes and materials for the manufacturing of RF hardware and present the major outcomes.

Scope of the project has been to identify suitable Additive Manufacturing (AM) 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, for the above mentioned classes of materials, three different demonstrators were selected for being manufactured during Phase 2:
    - Demonstrator #1: Q/V-band antenna-feed chain components and subassemblies
    - Demonstrator #2: L-band bar-line 3-dB coupler
    - Demonstrator #3: miniaturized loaded filter at low frequency band
- 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.

In the following, section 1 gives an overview of the project organization while sections 2 and 3 briefly describe the two projects phases. Finally, section 4 reports the main project conclusions.

1. PROJECT OVERVIEW

Scope of the project has been to identify suitable Additive Manufacturing (AM) 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 through analytics and measurements. At conclusion of this assessment, for different categories of materials and processes, three demonstrators have been manufactured and their RF performances have been assessed with respect to the typical requirements of space applications.

The project has been carried out by a team of industries, universities and research centres with a strong and well-recognized expertise either in the field RF hardware for Space applications or additive manufacturing:

- Thales Alenia Space (TAS), in the role of Prime Contractor
- Consiglio Nazionale delle Ricerche – Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni (CNR-IEIIT) as partner,
- Politecnico di Torino (POLITO) as partner,
- Istituto Italiano di Tecnologia (IIT) as partner,
- BEAM-IT (BT) as partner.
- HB Technology (HBT).

The project has been conceived in two subsequent phases:

- Phase 1 aiming at investigating different materials, manufacturing processes and external treatments through design, production and test of multiple samples and test vehicles. Different class of materials (polymeric, metal and ceramic) were tested from a physical, mechanical, electrical, RF performances point of view. As conclusion of Phase 1, three different demonstrators were selected to be manufactured in Phase 2:
    - Demonstrator #1: Q/V-band antenna-feed chain components and subassemblies
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- Phase 2 focused on the finalization of the design of the abovementioned demonstrators, on their manufacturing and measurements of their RF performances and assessment with respect to the predicted ones.

The following milestones have been achieved during the project:

- Phase 1:
    - Baseline Design Review (BDR)
    - Test Readiness Review1 (TRR1)
    - Critical Design Review (CDR)
- Phase 2:
    - Design Review (DR)
    - Test Readiness Review2 (TRR2)
    - Final review (FR).

2. PHASE 1: END TO END MANUFACTURING ROUTES

Phase 1 of the current project focused on a comprehensive investigation of different materials, AM processes and post-process treatments in order to identify end-to-end manufacturing routes for the production of RF demonstrators to be assessed during the 2nd Phase of the study.

Primarily, a survey on the state of art of 3D-printed components based on IEEE papers published in 2017-2021 has been conducted. Due to the quite extensive number of papers, the microwave and sub-millimetre components realized in AM were subdivided in three main categories according to the employed material: all-metal (36%), polymer-based (57%) and ceramic-based (7%) components. In terms of operative frequency distribution of the devices the following percentages have been found: up to 5GHz (17%); 5-15 GHz (31%); 15-30 GHz (25%); 30-50 GHz (9%); over 50GHz (18%).

Metallic materials are often used for 3D-printed RF components, due to their mechanical and electrical properties; Selective Laser Melting (SLM), also known as Laser Powder Bed Fusion (LPBF) is the process mostly used for the AM of all-metal RF components. As concern the class of RF components realized in AM, the most common one concerns waveguide (straight or bents), then filters (mainly in Ku/Ka frequency range), and horn antennas (in the frequency range 12-50 GHz). Although few examples are present in literature, OMTs and polarizers have also been considered both as monolithic components or integrated in a feed system. The exploited frequency ranges are from C to Ka-band.

Polymers are referred in literature as the materials mostly used for RF components. The manufactured components are generally cheaper than all-metal or ceramic parts, but a metallization process is needed in most applications. Since the metallization of the internal channels is an issue, monolithic components have been rarely developed. Stereolithography SLA (38%) and Fused Deposition Modelling (FDM) (29%) technologies are the processes mainly used for polymer-based RF components.

Ceramic materials are not widely used in AM, due to the some criticalities in the manufacturing and post-processing (e.g., anisotropic shrinkage during sintering, metal plating). However, in some applications, the dielectric characteristics of the materials have been exploited, without a metal coating of the parts. SLA is the main technology used with 67%, while 20% refers to extrusion-based processes (FDM). The application in the RF range relates to filters and planar components operating in the frequency range up to 90 GHz.

On the basis of the review of the state-of-the-art, a trade-off between different categories of RF components have been performed to identify RF concepts of interest in space applications:

- Microwave filters
- Aperture arrays
- Multi-beam antenna-feed chains
- BFN (Beam Forming Network) in bar-line technology or, more in general, in shielded suspended transmission line.

Several AM technologies, such as FDM, Selective Laser Sintering (SLS), Digital Light Processing (DLP), LPBF and Electron Beam Melting (EBM) have been compared in terms of dimensional tolerance, surface roughness (as-built), minimum wall thickness, support structures, and maximum build size. For each material, End-to-End manufacturing routes have been selected.

For each class of materials, multiple samples and test vehicles (representative of possible critical sections of the RF concepts) were designed, printed and tested in terms of mechanical and physical properties and RF performances.

- Metals - Several test cavities in WR75, WR51, WR42, WR28, and WR22 operating from 10 GHz to 50 GHz were manufactured in AlSi7Mg, AlSi10Mg, and Scalmalloy through powder bed fusion process. Three different LPBF printing systems were used, namely SLM solutions 280 Dual, Concept Laser M2, and EOSINT M270 Dual Mode. In the case of Al-Si alloys four thermal treatments were also investigated. All samples were subjected to ultrasonic cleaning and shot peening. After a first manufacturing batch, AlSi7Mg by SLM solutions and AlSi10Mg by EOS were envisaged as the two most promising LPBF systems. For these processes and for the most accurate test cavities, three different additional surface-finishing treatments were investigated, namely DryLyte, chemical milling and acid pickling + SurTec 650 passivation. Additionally, a second batch of selected test cavities (WR51, WR42, WR28) was built through these two manufacturing routes with the aim of improving printing quality. All samples were subjected to RF testing by measuring the corresponding 2 x 2 scattering matrix through a VNA calibrated at the reference rectangular-waveguide ports by means of the thru-reflection-line technique. The measured data were used to de-embed the manufactured geometry and the resulting equivalent electrical surface resistivity (combination of bulk resistivity and surface roughness).

- Metal-plated Polymeric test vehicles - Polymeric metal-plated test-vehicles were developed in Ku band (10 – 15 GHz), by considering three dielectrics exhibiting structural proprieties compatible with typical space environment requirements:
    - Alumide printed through SLS
    - CF-PEEK printed through FDM
    - ULTEM printed through FDM.

  For each material, WR75 waveguide straight lines and single-cavity resonators were manufactured, metal plated, and tested. Monolithic and E-plane split-block layouts were adopted for due comparison.

  The Alumide samples fabricated through the SLS process were covered by an Aluminium thin film. The coating was performed by an Ultra-Low-Vacuum Thermal Evaporation (Physical Vapour Deposition). The CF-PEEK and ULTEM samples were printed through the FDM process. The samples were post-processed with an electroless deposition of a silver primer and with a subsequent copper-based electroplating.

- Dielectric Samples (Polymeric and Ceramic) - A ridge-waveguide setup consisting of a line loaded with the sample under test placed within two irises was used to de-embed the dielectric properties in L/S band of the following materials: ULTEM, PEEK, Alumina, and Zirconia. A couple of CF-PEEK and Alumide samples were also measured to confirm the non-applicability of these materials as dielectrics because of the very high loss tangent caused by the inclusions of carbon-fiber or aluminium in the polymeric matrix.

In conclusion of Phase 1, three RF demonstrators to be manufactured and tested during Phase 2 have been identified and the end to end manufacturing routes have been consolidate:

- Demonstrator #1: Q/V-band antenna-feed chain components and subassemblies in AlSi10Mg;
- Demonstrator #2: L-band 3-dB coupler in square coaxial technology in AlSi10Mg;
- Demonstrator #3: miniaturized loaded filter at S band in Zirconia.

It is worth mentioning that, while metals and ceramics have been selected for the manufacturing of the three demonstrators in Phase 2, the metallized polymers technology has been judged not yet mature for the application.

For this reason, it has been agreed to continue the investigations on polymers in a follow-on of Phase 1, parallel to Phase 2, to review the metallization process and verify its functionality through further test vehicles in waveguide in WR75. Basing on the outcomes of Phase 1, Direct Metallization Plating (DMP) on silver has been selected as metallization process. The metallization has been applied first on PEEK-CF and ULTEM specimens, which have been subjected to thermal cycling and adhesion tests. At the end of this phase, PEEK-CF has been selected by virtue of better adhesion proprieties. In addition, as an outcome of the activity, the DMP process parameters have been further tuned.

The activity continued with the production and test of RF test vehicles, consisting in two sets of straight and twisted WR75 waveguides, as shown in Figure 1. The samples have been measured for S parameter, both before and after thermal cycling.

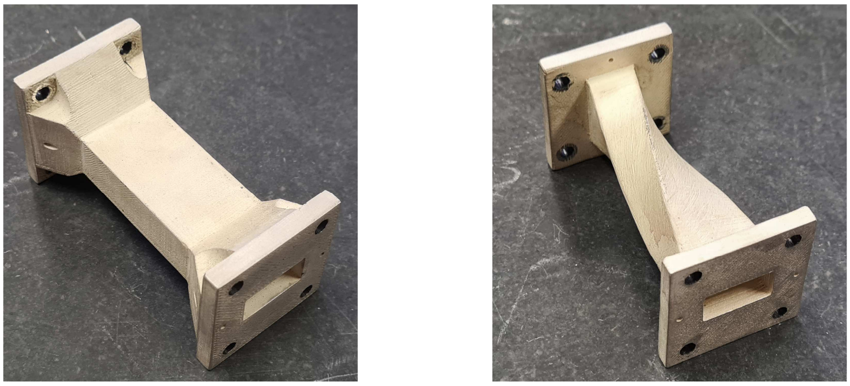

Figure 1: WR-75 straight and twisted lines in silver plated PEEK-CF

Typical measured S parameters (reflection and transmission) of straight and twisted lines have been found through RF tests.

3. PHASE 2: MANUFACTURING AND ASSESSMENT OF THE SELECETD DEMONSTRATORS

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. A very brief introduction of each demonstrator is given hereafter.

DEMONSTRATOR #1: Q/V-BAND ANTENNA-FEED CHAIN COMPONENTS AND SUBASSEMBLIES

The Demonstrator #1 consists of a dual-band antenna-feed chain for SatCom feeder links operating in Q/V bands. The block diagram of the reference antenna-feed chain is shown in Figure 2, which is aimed at diplexing in frequency and polarization the Q/V-band circularly-polarized signals entering the feed-horn that is used to illuminate the reflector. The reference configuration for the demonstrator consists of a feed-horn connected to a wide-band septum polarizer through a waveguide transition. Indeed, the wide-band septum polarizer is based on a triangular-waveguide configuration, whereas the feed-horn configuration most suitable for multi-beam antennas is a circular-waveguide smooth-wall architecture. The Q- and V-band signals at the output ports of the wide-band septum-polarizer are split by means of a diplexer inserted in each of the two polarization arms. The two diplexers provide the four ports in rectangular waveguide Rx-LHCP, Tx-LHCP, Rx-RHCP, Tx-RHCP.

The development plan identified for the antenna-feed chain consisted of two phases:

1. Development of the following stand-alone components:
    a. the feed-horn,

   b. the wide-band septum polarizer with integrated waveguide adapters.

2. Integration of the feed-horn and the wide-band septum polarizer in a single mechanical part.

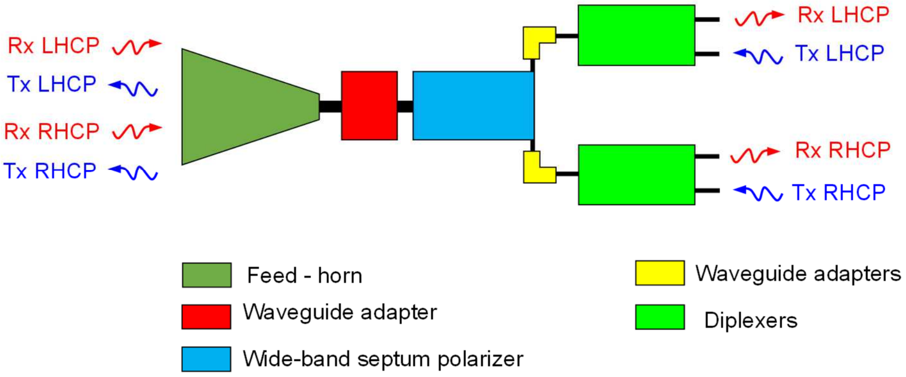

Figure 2: Block diagram of the reference antenna-feed chain for Demonstrator #1.

The two diplexers have not been included in the final configuration.

All the breadboards shown in Figure 3 have been manufactured in AlSi10Mg through an EOSINT M270 Dual Mode system:

- nr. 2 Q/V-band feed horns (prototypes FH01 and FH02).
- nr. 2 Q/V-band feeding networks (prototypes FN01 and FN02).
- nr. 1 Q/V-band monolithic feed chain assembly (prototype FC03).

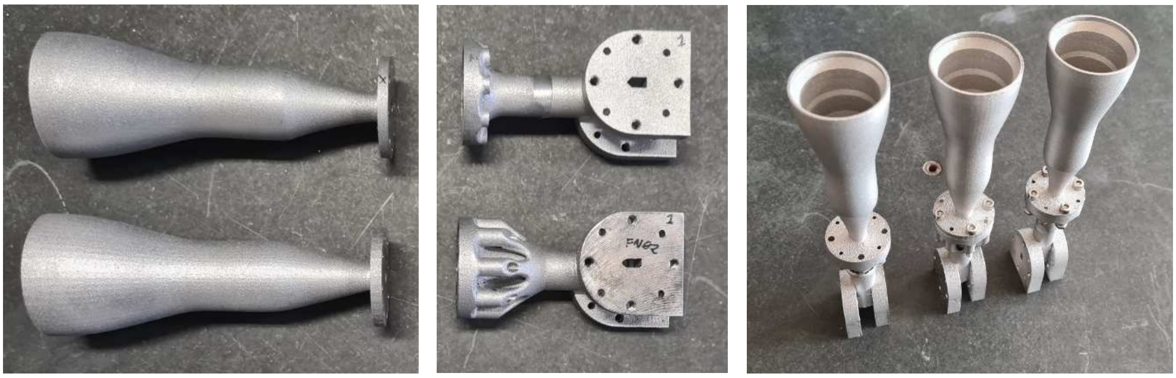

Figure 3: AM components of the QV feed: horn (a), polarizer (b), feed assembly (c).

The RF testing of Demonstrator #01 has been carried out in the full frequency range 37.5 – 51.4 GHz and it has included measurements of scattering coefficients and radiation patterns of the stand-alone components and of the three Q/V-band feed-chain assemblies FC01 (FH02+FN01), FC02 (FH01 + FN02), and FC03 (monolithic prototype). Since the Q/V-band split-block feed-chain assembly FC01 has exhibited the best RF performance, its two building blocks (FH02 and FN01) have been subsequently subjected to silver-plating. All the other parts have been subjected to Surtec650 passivation to prevent surface oxidation. The comparison between the design and the measured performance of the feed-chain assembly FC01 after silver-plating is reported in the following table.

DEMONSTRATOR #2: L-BAND BAR-LINE 3-DB COUPLER

The selected demonstrator #2 is a 3-dB coupler in bar-line technology operating in E1 band, a typical key building brick of L-band beam-forming networks. The coupler is of branch-line type, with two input ports and two output ports, generating two signals of equal amplitude and in phase quadrature. For each input port, the coupled port has a phase delay of 90° with respect to the direct one.

The technology for this component is the suspended barline (square coaxial waveguide), where the inner conductor is held in position by means of four one-quarter wavelength stubs (RF transparent) short circuited onto the outer conductor. The 3D printing allows to manufacture monolithically the device, avoiding to integrate different parts (outer/inner conductors and cover) with screws/rivets and does not require dielectric supports for the suspended inner conductor. The stubs also serve as DC grounding and thermal shunts. The printed demonstrator, integrated with TNC coaxial connectors IFs, is shown in Figure **4**. The geometry of the coupler has been adapted to the 3D printing process, by suitably inclining the transverse RF paths, including the shunt stubs, and the unsupported waveguide walls. A suitable study of the printing angles has been done and RF design iterations have been necessary to optimize the RF performance of the printed geometry. Lattice structure has been printed inside the inner conductor for mass reduction.

The demonstrator has been printed through the SLM 500 HL system in AlSi10Mg. Post-production procedures encompassed depowering using specialized vibratory equipment, stress-relief heat treatment conducted while components were still attached to the platform at 2 hours and 300°C, detachment of the platform using EDM wire cutting, and removal of support structures. CNC machining was used to refine the IF flanges for the RF connectors. The device surfaces have been treated with SURTEC.

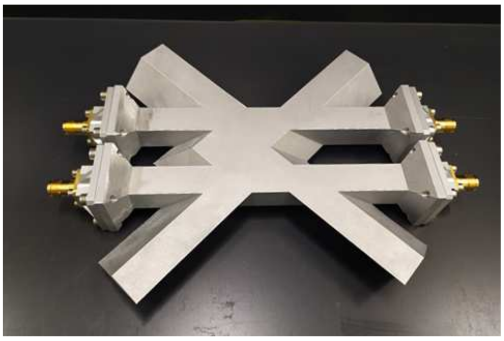

Figure 4: L band 3dB coupler in AM

The RF characterization of the coupler has been performed through S parameters measurement and comparisons with predictions. In particular the ohmic losses have been accurately predicted taking into account both the bulk conductivity of aluminum and effect of surface roughness typical of the printing process.

To finely tune the loss model, a dedicated test vehicle (a simple straight 50ohm line with identical transverse section as the coupler) has been produced with the same printing parameters. This device has been measured in comparison to an identical one, realized through accurate CNC milling at very low surface roughness, as a reference for losses and dimensional accuracy achievable with conventional technique. By comparing the two devices, and considering the measured roughness on the HW, an accurate predictive model for the losses has been finely tuned. Very satisfactory agreement between measurements and predictions has been found both on S parameters and losses.

Finally the device has been subjected to thermal cycling between -130/+150°C and then re-tested for final verification. The correlation with predictions and the performance repeatability after the thermal cycle are very satisfactory, demonstrating the stability of the printed coupler geometry in presence of large temperature variations. The demonstrator confirms the feasibility of monolithic construction of non-simply connected transmission line devices, avoiding the integration of several parts (housing, cover, inner bar and dielectric supports). The developed solution does not increase the mass of the device significantly in comparison to the conventional approach, thanks to the absence of screws and to the possibility of printing lattice inside the metal.

DEMONSTRATOR #3: MINIATURIZED LOADED FILTER AT LOW FREQUENCY BAND

The Demonstrator #3 is a third-order ceramic-loaded waveguide microwave filter operating at 2.470 - 2.530 GHz. To achieve a high rate of miniaturization (the overall envelope of the filter is 50 mm (W) x 30 mm (H) x 110 mm (L)), ridge waveguide resonators loaded with zirconia elements have been considered. A typical solution reported in literature for realizing 3D-printed ceramic filters is to apply metallization directly on ceramics. However, this solution does not seem viable in space programs because of mechanical reasons, especially when low frequency filters of remarkable dimensions are considered. In this activity, the 3D printed zirconia elements have been inserted in a structural metallic waveguide housing. A preliminary deep investigation on the dielectric properties of zirconia and on the mechanical housing have been carried out in order to minimize spurious effects, such as the presence of air gaps due to the non-perfect planarity of the zirconia elements. Figure 5 shows the manufactured demonstrator under testing. The measured performances of the demonstrator well agree with the predicted ones in terms of return loss (> 19 dB), bandwidth (2.470 - 2.530 GHz) and out-of-band isolation (> 20 dB at 2.4 GHz and 2.6 GHz). A detailed investigation has been carried out in order to understand the reasons for the high insertion losses and to identify possible solutions to improve this figure-of-merit.

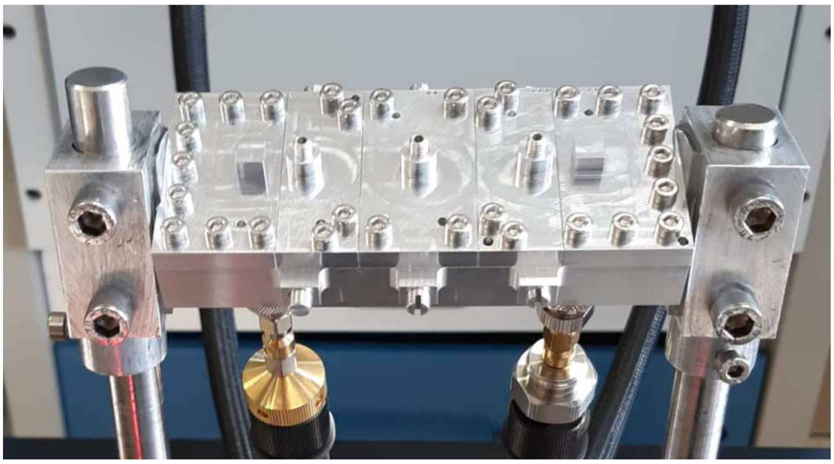

Figure 5. Miniaturized Loaded Filter Design (Demonstrator #3)

4. CONCLUSIONS

A comprehensive study of different materials and Additive Manufacturing process has been carried out in order to identify the most promising materials and printing techniques for producing microwave components suitable for space applications, characterized by stringent requirements and high reliability.

During the first part of the project, namely Phase 1, multiple samples and test vehicles in metals, polymers or ceramic materials have been tested from a physical, mechanical, electrical, RF performances point of view. As a conclusion, three different demonstrators have beene chosen to be manufactured during Phase 2 in order to represent a range of microwave components commonly used in space missions, allowing to assess the feasibility and effectiveness of additive manufacturing for each application. In particular, the aluminium AlSi10Mg printed through SLM has been selected for the fabrication of: a) high frequency feed system, operating in the very high frequency range of 40/50GHz; b) non-simply connected and monolithic transmission line components operating at L band. Zirconia ceramic, printed through Lithoz LCM technology has been selected for the fabrication of a miniaturized filter at S band combining ridged waveguide technology and electric loading using printed ceramic elements. During Phase 2, tests have been conducted on the RF demonstrators to evaluate their performance and correlate the results with predictions.

In Phase 1, metalized polymeric materials with structural proprieties (such as ULTEM and PEEK CF) have also been considered as a possible alternative to metal for producing RF components compatible with the space environment typical requirements, including large temperature ranges, high mechanical loads and low outgassing. However, the investigated metallization process, based on copper plating, did not provide satisfactory and repeatable results. As a follow on of the Phase 1, in parallel to Phase 2, an alternative process based on electro-less silver plating (Direct Metallization Process) followed by electrolytic silver deposition has been used to successfully metallize waveguide samples printed in PEEK CF, showing promising RF performance and good repeatability after thermal cycling.

The study has highlighted some interesting potentiality of additive manufacturing in the production of microwave components for space applications. Moving forward, further research and development efforts will be needed to refine some aspects of the manufacturing processes. In particular, for metals, surface roughness and manufacturing tolerances achievable through SLM on AlSi10Mg appeared adequate to the challenging design of a feed operating in very high frequency range (up to 40/50GHz). RF losses, due to surface roughness, have been mitigated by silver plating. A direct way-forward of the activity is envisaged to be the development of septets or larger clusters of Q/V-band radiators for multi beam antenna feeding systems. Feasibility of monolithic non-simply connected geometries, based on coaxial waveguide, has been demonstrated as well. Very good correlation between measurements and predictions have been achieved. The design and tuning of the ceramic loaded filter in ridged waveguide is based on accurate RF characterization of Zirconia parts and filter tuning process, which has been elaborated and improved during the study and provided satisfactory tuning of the response and good correlation with prediction within the operative band. Nevertheless insertion loss is still quite high. At the moment, relatively high dielectric losses and mechanical issues in the filter assembly are identified as the causes for this undesirable behaviour and deserve some further investigations. Repeatability and planarity of Zirconia printed parts have been improved through dedicated mechanical solutions, such for instance mass loading.