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High-performance microwave waveguide devices produced by laser powder bed fusion process

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Abstract

Additive manufacturing technologies are currently envisaged to boost the development of a next generation of microwave devices intended for satellite telecommunications. Due to their excellent electromagnetic and mechanical properties, metal waveguide components are key building blocks of several radio frequency (RF) systems used in these applications. This article reports the perspectives deriving from the use of laser powder bed fusion (L-PBF) technology to the production of high-performance microwave waveguide devices. A robust design of filters has been implemented in several prototypes manufactured in AlSi10Mg alloy. The corresponding measured performance confirm the applicability of the L-PBF process to the intended applications

Keywords: Additive manufacturing; Laser powder bed fusion; Antenna-feed systems

1. Introduction

The waveguide components are a class of radio frequency (RF) components widely used in microwave and millimeter-wave antenna-feed chains developed for applications such as imaging, satellite communications (SatCom), scientific surveys, navigation and earth observation (Fig. 1). Nowadays, the design of the antenna-feed chains, that are the complex radio-frequency assemblies, requires a trade-off between the electromagnetic performance and mechanical constraints. Recently, the microwave community has shown interest for the Additive Manufacturing (AM) technologies in the production of waveguide due to the potential advantages in terms of mass reduction, cost, integration and design flexibility. Montejo-Garai et al. [1] investigated the application of the low-cost AM technique named Fused Filament Fabrication (FFF) to implement waveguide devices. Three filters with low-pass, high-pass, and band-pass responses respectively, designed in Ku band (12 - 18 GHz) satisfying classical specifications for satellite communication systems, have been designed, printed, metallized and measured. Laplanche et al [2] analyzed passive microwave components manufactured by polymer jetting, an AM process. Different types of components such as waveguides, couplers, power dividers, filters and antennas, can be designed to be made in a single part. Liu et al [3] used a stereolithography (SLA) AM process to create ta three-dimensional (3D) structures for high-frequency applications. Metal AM processes, such as laser powder bed fusion (L-PBF) and electron beam melting (EBM), permit to build all-metal parts without the use of a subsequent metal plating (depending on the metal powder used) that for components with complicated internal structures can be challenging to achieve. A comparative study by Le Sage [4] well illustrates the comparison between the SLA plating and direct metal laser sintering (DMLS), a trade name of EOS GmbH for L-PBF process, used to fabricate slotted waveguide arrays.

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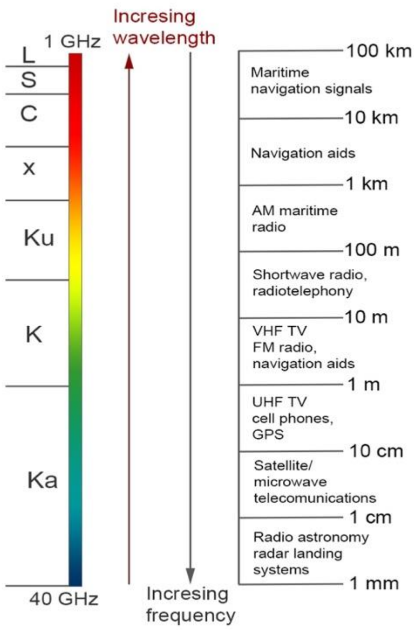

Fig. 1. Satellite frequency bands: L-band (1-2 GHz), S-band (2-4 GHz), C-band (4-8 GHz), X-band (8-12 GHz), Ku-band (12-18 GHz), K-band (18-26 GHz) and Ka-band (26-40 GHz).

The SLA-plating technique requires the redesign of the slotted waveguide and a number of post-processes to achieve a good result. On the other hand, the DMLS process is more straightforward but the prototype is reported to be inferior in quality in terms of surface roughness. However, measured results in this study show that prototypes fabricated using both methods have no significant difference, even at the lower Ku-band. Booth et al [5] realized satellite feed chain and waveguide components using different AM processes (SLA, FFF, L-PBF, Material jetting) discussing the advantages and drawbacks. Good results have been achieved using powder bed fusion in Scalmalloy, an Airbus developed aluminum alloy. Microwave filters are being components present in any electromagnetic system. Their realization is particularly cumbersome, since their intrinsic sensitivity to producing tolerances makes their implementation particularly complicated. For this reason, in this study, an AM-oriented architecture is discussed and exploited for the L-PBF realization of high order filters. The manufacturing of filters is a challenging task because of the high standing waves developing inside the components. This phenomenon leads to high sensitivity to mechanical tolerances and high losses. Furthermore, stringent constraints apply to the mechanical design of filters aimed at high-power applications. For these reasons, filters are considered in this study as a highly relevant benchmark for the L-PBF fabrication of waveguide components. In particular, this study describes the development of Ku/K-band filters designed for L-PBF and that meet the typical electrical requirements of satellite communications.

2. Antenna-feed systems

Depending on the specific requirements and frequency plan, different configurations can be adopted to implement an antenna-feed chain. However, same basic building blocks are shared by all configurations, such as feed-horns (FH) for illuminating the reflector, ortho-mode transducers (OMTs) or junctions (OMJs) for polarization separation/combination, low/high-pass filters (LPFs, HPFs) for frequency discrimination/separation, and septum polarizers (SP) polarizers and phase-shifters for implementing differential phase-delays between two polarizations or signals in order to achieve the circular polarization. Fig. 2 shows an example of block diagram of a Ku/K-band dual-polarization antenna-feed systems aimed at fixed and broadcast satellite services. The FH is a wideband corrugated horn that illuminates a reflector antenna connected to an OMT. The OMT is used to inject the two left/right-hand circular polarizations (LHCP/RHCP) at the FH port in the K-transmitting (Tx) band. The vertical (VP) and horizontal (HP) polarizations in the Ku band are either routed toward or extracted from the waveguide through the Ku-band bandpass filter and OMT. A Ku-band waveguide diplexer is inserted in each polarization channel to separate the Tx and Rx (receiving) signals allocated to different frequency channels [6]. Generally, the antenna-feed chains are manufactured in several parts via conventional techniques (e.g., electrical discharge machining and milling) and subsequently assembled together. As a consequence, contacting flanges are inevitable, which in turn imposes stringent constraints in the electromagnetic design:

- oxidation of contacting flanges can generate high levels of passive intermodulation products that impairs the RX functionalities;
- mass and envelope, especially above 30 GHz, cannot be optimized because of the use of mounting screws that prevents miniaturization of components.

This aspect is particularly relevant in the case of applications based on the frequency-reuse factor and covering area where each spot is covered by a beam generated either by a dedicated antenna-feed system or by sharing adjacent feed horns [7] therefore a high number of compact and lightweight antenna-feed systems with complex geometries will have to be embarked on board satellites. L-PBF technology is expected to be a technological solution for the development of new antenna-feed systems as it could allow the manufacturing of monolithic systems with minimum mass and envelope. By exploiting the free-form fabrication of the L-PBF technology, microwave components could even be integrated in the supporting structures of satellites so that different functionalities (electromagnetic, thermal, and structural) could be implemented in a single part.

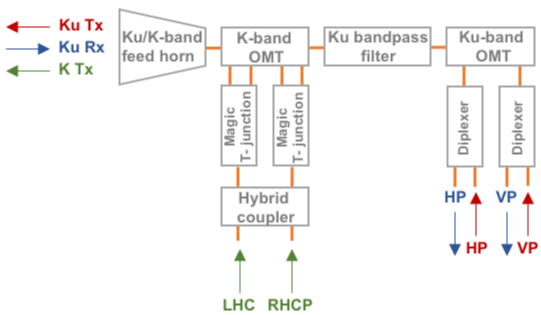

Fig. 2. Block diagram of the Ku/K-band antenna-feed chain.

3. Filters design for the L-PBF process

L-PBF process allows the manufacture of complex 3D parts by melting successive layers of metal powders on top of each layer, using a high energy laser computer-controlled [8]. The high values of energy that are used in the L-PBF process to melt the metal particles can give rise to problems like balling, residual stress development, and part deformation. The orientation of parts on the building platform and properly designing the supporting structures can reduce these phenomena [9]. Fig. 3 shows the fifth order filter geometry designed to operate in Ku/K bands and meet satellite telecommunications requirements, that is reflection coefficient lower than −30 dB in the pass-band (12.5 - 15.0 GHz) and transmission coefficient lower than -45 dB in the stop-band (17.5 - 21.2 GHz).

The geometry presents a classical straight orientation of the stub discontinuities designed to be manufactured via conventional technologies. In order to produce this filter with L-PBF technology, due to the orientation of the stub parallel to *xy*-plane, it is necessary to orient the filter on the building platform with different angles to the building direction, i.e. the *z*-axis, because the downward facing surface (Fig. 3a) could collapse during construction [9]. Indeed, inside the stub discontinuities, it is impossible to remove the support structures. Thus, the correct orientation of the filter for making by L-PBF is shown in Fig. 3b. However, this orientation produces an increase of the dross formation and a reduction in dimensional accuracy. A more effective solution to these problems is to design an AM-oriented RF layout so that the component can be built aligned along the *z*-axis without the use of internal supports. Indeed, this vertical part-orientation reduces the dross formation and leads to a better surface roughness. This approach has been applied to the sixth-order Ku/K-band low-pass filter shown in Fig. 4 [10].

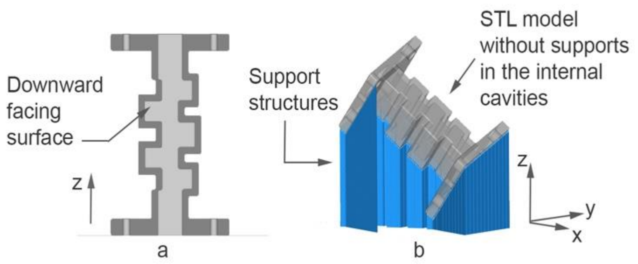

Fig. 3. Fifth-order Ku/K-band low-pass filter: (a) cross-section; (b) building orientation and support structures for the L-PBF process.

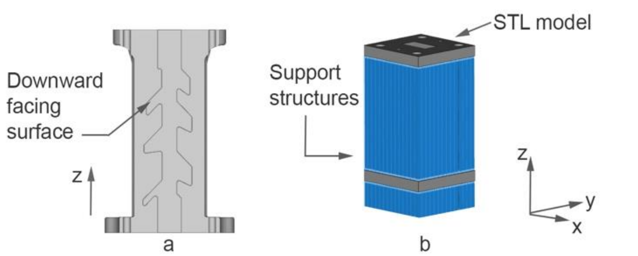

Fig. 4. Sixth-order Ku/K-band low-pass filter: (a) cross-section; (b) building orientation and support structures for the L-PBF process.

The waveguide propagation axis has been aligned with the building direction. To avoid using supports for the internal surfaces, the stubs have been tilted downwards. The minimum tilting angle of the downward facing surfaces has been set to 45° to minimize the risk of warping. Tilting of stubs by angles smaller than approximately 45° does not degrade the electrical performance of the stubs.

4. Equipment

The AlSi10Mg filters have been built through an EOSINT M270 Dual-mode system equipped with a Yb-fiber laser. The maximum laser power is equal to 200 W and the beam-spot size is 100 µm. The manufacturing process is carried out within a chamber filled with inert gas (argon), ensuring an oxygen content lower than 0.10 %. The building platform is heated at 100°C to reduce thermal stresses that arise during the process. The main L-PBF system parameters used: laser power of 195 W, scan speed of 800 mm/s, hatching distance (distance between two adjacent laser-beam traces) of 0.17 mm and layer thickness of 30 µm.

5. Results and discussion

Two prototypes have been manufactured in AlSi10Mg alloy to assess repeatability of the manufacturing process. The measured scattering coefficients are shown in Fig. 5a: the green and violet solid lines correspond to the measured parameters; the yellow and black solid lines correspond to the predicted parameters; the red and blue vertical solid lines mark the passband (12.5 - 15.0 GHz) and stopband (17.5 - 21.2) GHz.

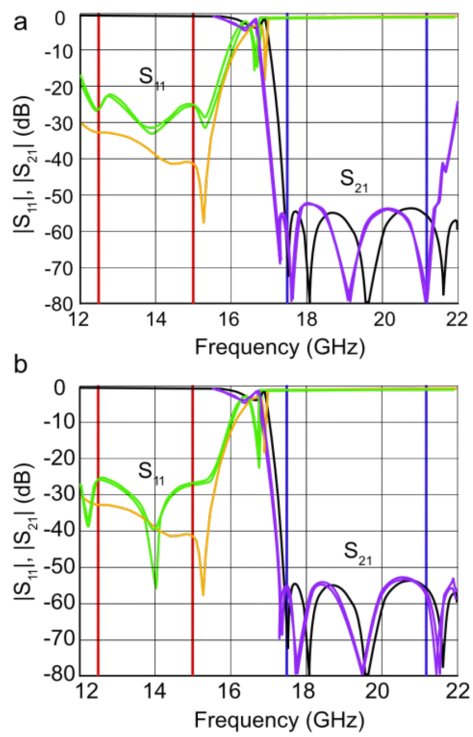

Fig. 5. Reflection coefficient S_{11} and transmission coefficient S_{21} of the sixth-order filter shown in Fig. 4. (a) Prototypes manufactured before process parameter tuning; (b) Prototypes manufactured after process-parameter tuning.

The prototypes provide almost identical performance, but both show a frequency shift caused mainly by a non-optimum laser beam-offset during the L-PBF manufacturing process. For this reason, a tuning of the L-PBF process parameters has been carried out: beam-offset (BO) and scanning options [11] have been adjusted in order to minimize the difference between the measured and theoretical values of the phase shift introduced by the lines. The tuning process has been repeated until reaching a manufacturing error lower than 0.08 mm. The measured performance reported in Fig. 5b prove the effectiveness of the process tuning procedure, although a residual systematic enlargement of the waveguide dimensions has still to be compensated. Nevertheless, all the filter prototypes, as they are, meet typical requirements set in satellite communications, specifically $S_{11} \leqslant -25$ dB and $S_{21} \leqslant -50$ dB. In order to reduce the support structures also for the external profile (Fig. 4b), the filter has been modified externally as shown in Fig. 6a [12]. However, despite this redesigning has led to an improvement in mechanical accuracy (0.04 - 0.06 mm), this geometric choice has led to an increase in weight: from 27 g to 76 g. Therefore, the external profile was modified in order to obtain lighter L-PBF prototypes maintaining the self-supporting feature in the stubs region (Fig. 6b). It can be deduced that the prototype provides RF performance in line with those of the previous filter prototype (Fig. 7) while exhibiting a mass reduction of the order of 50% (40 g).

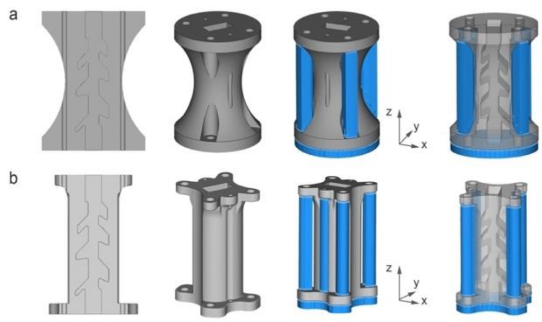

Fig. 6. Sixth-order Ku/K-band low-pass filter (a) first external optimized profile; (b) second external optimized profile.

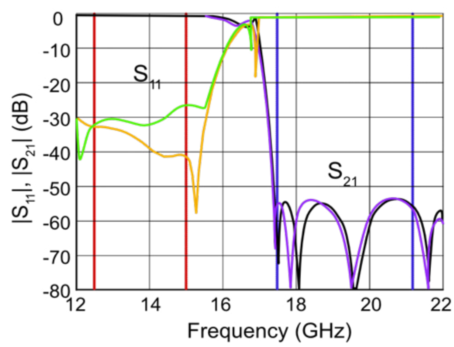

Fig. 7. Measured scattering coefficients of the weight-optimized L-PBF prototype of the sixth-order Ku/K-band low-pass filter.

6. Conclusion

The results reported show that that an AM-oriented RF design can enhance the RF performance exhibited by the prototypes. In particular, the optimization of both the internal shape of the filters and AM machine parameters has been considered in order to achieve electromagnetic performances in line with those exhibited by components manufactured via standard machining (milling or electrical discharge machining). a good agreement between measured and theoretical values is achieved. In particular, all the three main figure-of-merits (i.e., return loss, insertion loss, and rejection) meet the standard specifications of SatCom applications.

References

[1] Montejo-Garai JR, Saracho-Pantoja IO, Leal-Sevillano CA, Ruiz-Cruz JA, Rebollar JM. Design of microwave waveguide devices for space and ground application implemented by Additive Manufacturing. Proc. of 2015 International Conference on Electromagnetics in Advanced Applications (ICEAA), Torino, Italy, 2015.

[2] Laplanche E, Feuray W, Sence J, Perigaud A, Tantot O et al.Additive manufacturing of low cost and efficient proof of concepts for microwave passive components. IET Microwaves, Antennas & Propagation, 2017; 11:1997-2004

[3] Liu B, Gong X, Chappell WJ. Applications of layer-by-layer polymer stereolithography for three dimensional high-frequency components. IEEE Trans. Microw. Theory and Techn., 2004; 52: 2567-2575

[4] Le Sage GP. 3D printed waveguide slot array antennas. IEEE Access, 2016; 4: 1258–1265

[5] Booth P, Roberts R, Szymkiewicz M, Hartwanger C. Using additive manufacturing for feed chain and other passive microwave component. Proc. of 11th Eur. Conf. Antennas Propag. (EUCAP), Paris, France, 2017; 558-562.

[6] Cecchini P, Mizzoni R, Ravanelli R, Addamo G, Peverini O, Tascone R, Virone G. Wideband diplexed feed chains for FSS + BSS applications. Proc. 3rd Eur. Conf. Antennas Propag. (EuCAP), Berlin, Germany, Mar. 2009, pp. 3095–3099.

[7] Schneider M, Hartwanger C, Wolf H. Antennas for multiple spot beam satellites. CEAS Space J., 2011; 2: 59–66.

[8] Calignano F, Cattano G, Manfredi D. Manufacturing of thin wall structures in AlSi10Mg alloy by laser powder bed fusion through process parameters. Journal of Materials Processing Technology, 2018: 255:773-783.

[9] Calignano F. Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting. Mater. Design, 2014; 64: 203–213.

[10]Peverini OA, Lumia M, Calignano F, Addamo G, Lorusso M, Ambrosio EP, Manfredi D, Virone G. Selective laser melting manufacturing of microwave waveguide devices.Proceedings of the IEEE, 2017:105:620-631.

[11] Calignano F, Manfredi D, Ambrosio EP, Iuliano L, Fino P. Influence of process parameters on surface roughness of aluminum parts produced by DMLS. Int. J. Adv. Manuf. Technol., 2013; 67: 2743–2751.

[12] Peverini OA, Addamo G, Lumia M, Virone G, Calignano F, Lorusso M, Manfredi D. Additive manufacturing of Ku/K-band waveguide filters: a comparative analysis among selective-laser melting and stereo-litography. IET Microw. Antennas Propag., 2017; 11:1936-194