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Experimental Research Activity on Additive Manufacturing of Microwave Passive Waveguide Components

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***Abstract*— All metal passive waveguide components are key building-blocks of several RF systems used for telecommunications, navigation, imaging, radio-astronomy, and cosmology. The accurate manufacture of these devices in Additive Manufacturing (AM) technologies can open the way to a high integration level of microwave functionalities with a significant cost and mass reduction. In the paper, after an introduction on the most common AM technologies with particular detail on selective laser melting (SLM) and stereo-lithography apparatus (SLA) processes, the results on the on-going research activity are discussed. Measured performances are reported for AM prototypes of Ku/K/Ka-band rectangular and circular waveguide lines, microwave filters and a smooth wall horn.**

Keywords—3D printing, additive manufacturing, selective laser melting, stop band filter, smooth horn antennas.

I. Introduction

Additive Manufacturing (AM) technologies can represent a very good solution for system integration of complex microwave apparatus, as satellite antenna-feed chains. These systems are composed of different components (*e.g.*, horns, ortho-mode transducers, polarizers, filters) whose integration is often mandatory for not only issues related to mass, envelope and costs, but also for the risk reduction of spurious intermodulation product (PIM) generation in the contact surfaces of high-power handling systems. AM technologies present, in principle, an intrinsic feature that has to be still fully exploited by RF designers, i.e. there is a consistent increment of the degrees of freedom related to the internal shapes of microwave devices that permits to investigate solutions unachievable or too expensive by traditional subtractive techniques (like milling). This characteristic has already been exploited [1], [2] proving the advantages of AM-oriented layouts with respect to traditional architectures. Unfortunately, the successful application of additive manufacturing, in terms of mechanical accuracy and reasonable surface roughness, requires (in relation with the involved device architecture) a proper choice of the process of the materials and a tuning of machine parameters. In this framework, the present paper reports on the experimental research activities jointly carried out by CNR-IEIIT and IIT focused on the additive manufacturing of high-performance waveguide microwave devices. First, a description of additive manufacturing technologies, with particular detail on the Selective Laser Melting (SLM) and Stereo-Lithography Apparatus (SLA) processes, is reported. Then, the measured performances of AM prototypes of rectangular/circular waveguide lines, microwave filters and a smooth wall horn operating from Ku to Ka bands are shown, and the limits and bottlenecks of the AM processes are discussed.

II. Addittive manufacturing process

The ASTM F42 committee on Additive Manufacturing Technologies defines additive manufacturing as "a process of joining materials to make objects from three dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [3]. A generic AM process involves some steps from the design cad model to the final product. These stages, despite to the differences of the various technologies, can be summarized in the eight steps reported in Fig.1 [4].

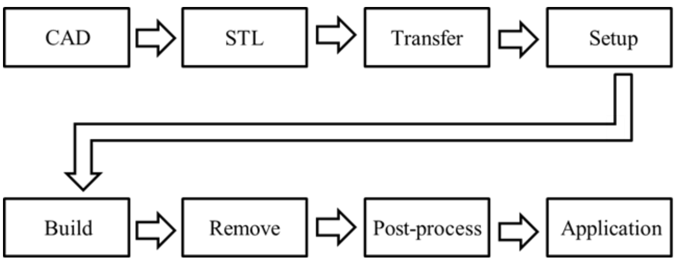

Fig. 1 Generic AM process.

Among the different AM technologies, Selective Laser Melting (SLM) is particularly suitable for waveguide components since it builds parts directly in metal. According to the scheme of Fig. 1 and the detail on the building system shown in Fig. 2, the part is created by a fusion process, where a metal powder is, layer by layer, deposited by a recoater on top of the building platform and selectively melted by a high-power laser. The maximum part dimension depends on the building machine; for instance, the EOS M270 Extended machine used in our research has a building volume of 250 mm x 250 mm x 215 mm. For microwave devices operating at Ku/K or higher frequencies, this volume corresponds to different wavelengths, and then different parts can be built in the same process with a significant saving in term of time leading. To reduce the effect of thermal stresses, which can create deformations of the device internal parts, the components undergo a high-temperature stress-relieving process. Finally, a post-processing, namely shot peening, is usually applied to reduce the surface roughness.

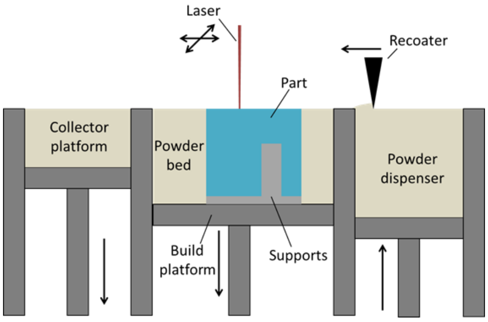

Fig. 2 Powder bed fusion process (e.g., selective laser melting).

While SLM permits to build parts directly in metal, the STereoLithography Apparatus (SLA) technology is a vat-photo polymerization process based on the solidification of a photosensitive liquid resin. The machine consists of a vat full of liquid resin, a platform that can be moved up and down in the vat and a radiation source that activates polymerization (see Fig. 3) Laser and UV light are common radiation sources. For waveguide components, a subsequent chemical metal plating is mandatory. Recently, SLA has been exploited in the realization of open structures, like antennas, periodic structures, and lenses [5], [6]. The main advantages of SLA are better accuracy (as low as 0.02 mm for small parts) and very good surface finish. Conversely, in the case of waveguide components the metallization process a critical aspect, since a non-uniform metallization of the polymeric internal channels can significantly degrade the device performance.

III. EXPERIMENTAL RF INVESTIGATION ON ADDITIVELY MANUFACTURED PARTS

In order to evaluate the manufacturing accuracy, repeatability, surface roughness and electrical conductivity of the SLM process, we started considering a resonant cavity in a WR51 rectangular waveguide. To increase the sensitivity of the cavity electrical response to the SLM process parameters (such as metal losses and mechanical uncertainties), the cavity has been designed to present a very narrow pass-band.

Two prototypes, shown in Fig. 4, have been built by SLM: one in AlSi10Mg aluminium alloy, the other in Ti6Al4V titanium alloy. Figure 5 shows the simulated and measured magnitude of the transmission coefficient S_{21}. The differences between simulation and measurements are related to both mechanical accuracy and different values of equivalent surface resistivity ρ. In the simulation, the equivalent surface resistivity has been set to the reference value of 10 μΩcm, that is commonly provided by aluminium parts manufactured through electrical discharge machining (EDM) or milling. A non-linear best-fitting procedure carried out on the measured data provides, instead, an equivalent ρ of 250 μΩcm and 40 μΩcm for the Ti- and Al-samples, respectively. After silver plating, the measurement of the prototypes has been repeated (see Fig. 5). By applying the same best-fitting procedure, the equivalent geometry and surface resistivity have been deduced. The AlSi10Mg prototype exhibits a dimensional accuracy within ±0.1 mm, which is the typical tolerance for the material; on the other hand, the Ti6Al4V devices shows a better manufacturing accuracy, in the order of ±0.05 mm. In both devices, after silver plating, the equivalent surface resistivity reduces to 8 μΩcm.

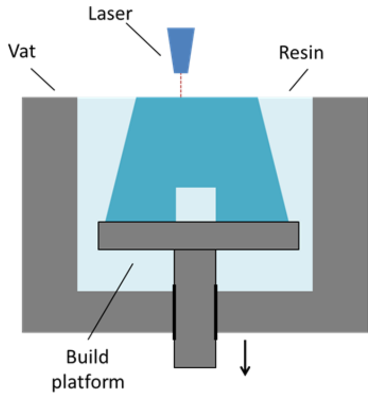

Fig. 3 Vat photo-polymerization process (e.g., stereo-litography).

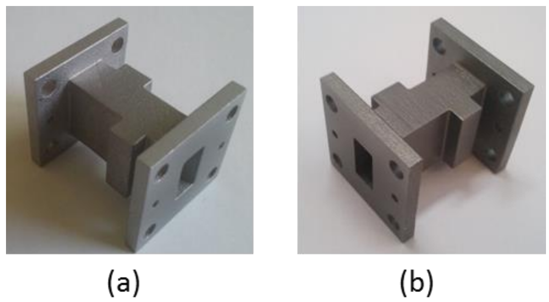

Fig. 4 Picture of the two test SLM cavity prototypes.
(a): prototype made in AlSi10Mg alloy powder.
(b): prototype made in Ti6Al4V allow powder.

On the basis of these experimental results, the design of a filter operating in Ku/K band for satellite communication systems has been considered with pass-band [12.5,15] GHz and stop-band [17.5,21.2] GHz. Among the different architectures, a fifth-order composite step/stub-resonator architecture has been selected [7]. Three different samples in SLM with ALSi10Mg, Ti6Al4V and maraging steel have been manufactured and silver plating (see Fig. 7). For a comparative analysis of the SLA technology, a prototype in ABS-like material has been built and, then, copper plated. Table 1 reports the measured performances of the different prototypes in terms of return loss, isolation and insertion loss in the pass-band. Remarkable results have been found for all the prototypes with a return loss and an isolation in the stop band greater than 20 and 35 dB versus the simulated values of 30 and 45 dB.

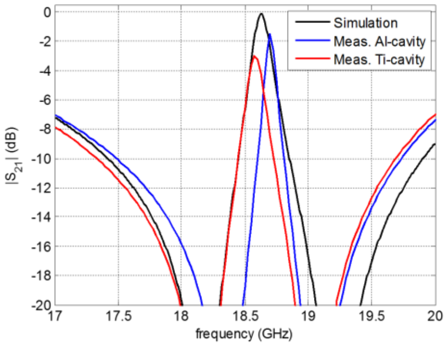

Fig. 5 Comparison between simulated (black line) and measured transmission coefficients of the test cavities in AlSi10Mg and Ti6Al4V (blue and red lines, respectively).

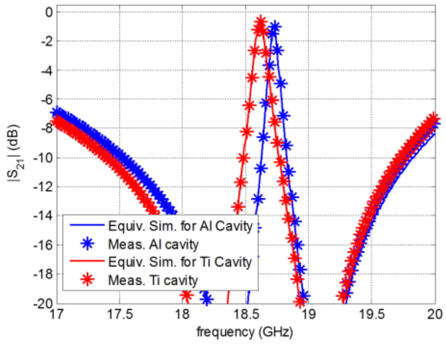

Fig. 6 Test cavity transmission coefficients after silver plating. The continuous lines refer to the best-fitting geometry for AlSi10Mg and Ti6Al4V prototypes (in blue and red, respectively).

TABLE I. MEASURED PERFORMANCES OF THE FIFTH ORDER FILTERS OF FIGURE 7 AFTER SILVER PLATING OF SLM SAMPLES.

	Prototype			
	SLM in AlSi10Mg	SLM in Ti6A14V	SLM in Steel	SLA in ABS
Return Loss	23 dB	20 dB	29 dB	27 dB
Isolation	45 dB	35 dB	35 dB	35 dB
Insertion Loss	0.08 dB	0.08 dB	0.08 dB	0.25 dB

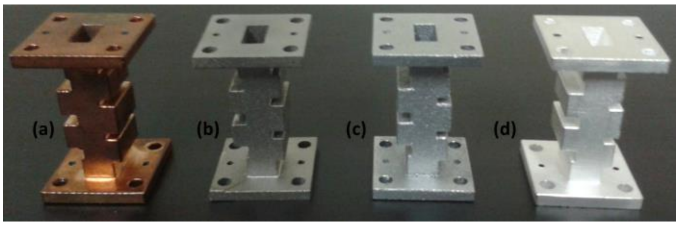

Fig. 7 Fifth-order stop-band filter prototypes manufactured through SLA and SLM.
(a) SLA, copper-plated ABS-like polymer, (b) SLM, maraging steel. (c) SLM, AlSi10Mg. (d) SLM, Ti6Al4V.

The SLM machine process parameters (e.g. beam-offset, hatching and scan speed) have been optimized for the AlSi10Mg alloy powder by manufacturing and testing a series of waveguide lines in WR51 (see Fig. 8). Their nominal length is 5.84 mm. Figure 9 shows the envelope of the measured reflection and transmission coefficients for nine prototypes. The mechanical accuracy, estimated by best-fitting procedure on the measurement data, has shown to be of the order of 0.05 mm.

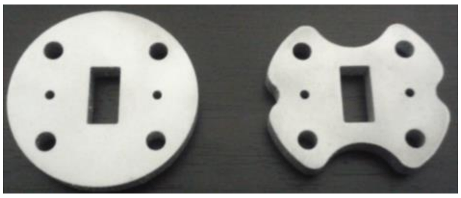

Fig. 8 Two of the nine prototypes of the WR51 waveguide lines manufactured in AlSi10Mg alloy to optimize the AM process parameter.

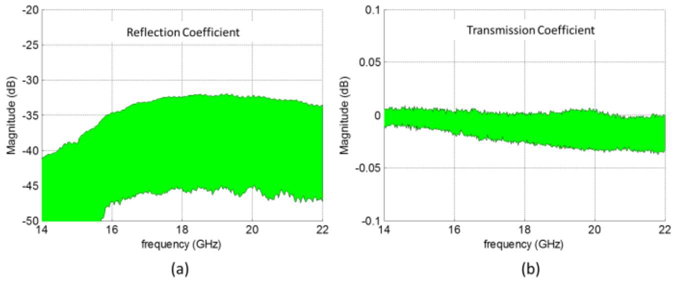

Fig. 9 Envelope of the measured reflection and transmission coefficient of the SLM WR51 waveguide lines of Fig.8

Then, the design of a new Ku/K stopband filter with more demanding requirement has been considered [2]. In this case, an AM-oriented architecture based on slanted stubs has been conceived in order to avoid, in the manufacturing process, the presence of supporting structures both for both the internal and external faces. Different samples in the same metal powders have been realized and tested (see Fig. 10). Table 2 reports the measured performances of the different samples in terms of return loss, isolation and insertion loss. Subsequently, the design of a high-performance feed-horn for satellite communication in the Ku band (operative band [14, 18] GHz) has been considered. A smooth-wall solution has been preferred to the classical corrugated horn design in order to simplify the manufacturing process and avoiding the presence of supporting structures for overhanging surfaces. The measured performance versus the simulated ones are summarized in Table 3.

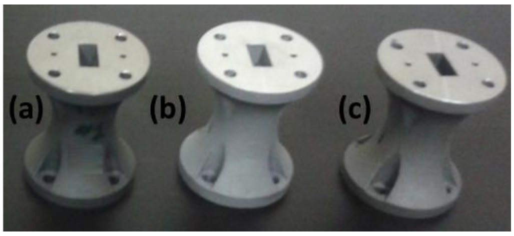

Fig. 10 Sixth-order stop-band filter prototypes with optimized design for the SLM process. (a) AlSi10Mg alloy. (b) Ti6Al4V alloy. (c) Maraging steel.

TABLE II. MEASURED PERFORMANCES OF THE SIXTH-ORDER FILTER OF FIGURE 10

SLM Prototype	Return Loss	Isolation	Insertion Loss
AlSi10Mg	25 dB	52 dB	0.08 dB
Ti6A14V	27 dB	52 dB	0.45 dB
Mararging Steel	30 dB	49 dB	1 dB

TABLE III. SIMULATED AND MEASURED PERFORMANCES OF THE SMOOTH PROFILE FEED HORN IN KU BAND

	Simulation	Measurements
Return Loss (dB)	>30dB	>28dB
Cross Polarization (dB)	>37dB	>33dB
Gain (dB)	>17.5dB	>17dB

Finally, the Ka-band has been started to be considered and some preliminary tests have been carried out by manufacturing and measuring two prototypes of circular waveguide operating in the frequency range [28,40] GHz (see Fig. 11). The two prototypes, whose nominal radius and length are 4.69 mm and 50 mm, respectively, differ on the external profile. In one case, the external profile traces the internal part, whereas in the other it has been conceived to avoid supports, as in the realization of the filter of Fig. 10.

In order to understand the feasibility of the SLM process for dual-polarization systems, the co-polar and the spurious cross-polar transmission coefficients have been measured. The latter have been obtained through a 90-deg rotation of one of the two coaxial-to-circular transitions used to connected the DUT to the VNA setup. The results of this experimental activity are shown in Fig. 12, where the envelopes have been obtained by collecting the different measurements corresponding to eight different angular mounting orientations of the circular waveguide (thanks to the eight dowel holes). The reflection coefficient is in the order of -35 dB, while the cross-polarization, not shown in the plot, is in the order of -30dB. These experimental results prove that additively manufactured components can be developed to meet communication satellite requirements, even if further investigations are necessary in order to increase the technological readiness level.

Fig. 11 AlSi10Mg prototypes of Ka-band circular waveguides manufactured through SLM.

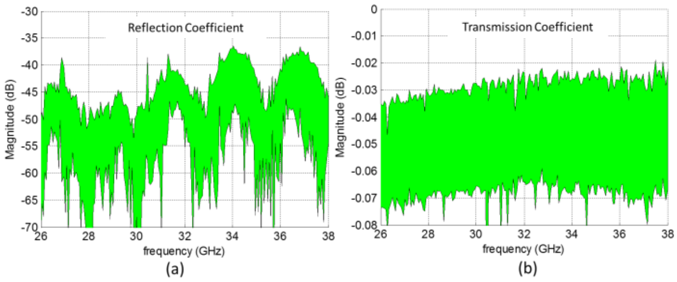

Fig. 12 Measured values of the reflection (a) and transmission (b) coefficients of the Ka-band SLM circular waveguides shown in Fig.11.

IV. CONCLUSIONS

The results of an on-going experimental research activity on the application of AM technologies to the realization of high-performance Ku/K/Ka devices has been described. Further tests and devices are under consideration and the relevant results will be presented at the conference.

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