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Advances in manufacturing of 4×4 Butler matrices with inherent bandpass filter functions

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***Abstract*—In this paper is presented the process to build a 4×4 Butler matrix with inherent bandpass filter functions with additive manufacturing. Butler matrices are combination/splitting networks usually made by means of transmission line hybrid couplers. Here a design based on resonators is proposed and implemented in standard WR75 rectangular waveguide. The additive manufacturing technique is introduced as an effective way to overcome the complexities related to this geometry.**

***Index Terms*—Additive manufacturing, Butler matrix, rectangular waveguide.**

I. INTRODUCTION

Recent new satellite RF payloads require more capabilities in terms of performances in order to be competitive on the market. This is true for all the space domains (earth observation, navigation, telecom, etc.) but it is more evident in the satellite telecommunications industry. It is, by far, the most important space sector for the satellite manufacturing industry. The number of transponders has increased for the traditional frequency bands has increased in the last years. New frequency bands are now being extensively exploited to provide the traffic demand.

This puts a considerable challenge on the design of the RF hardware (filters, waveguides, amplifiers, multiplexers etc...) as they need to enhance the electrical properties in even more complex systems. The demand of higher throughput has been a stimulus to move to higher frequencies, such as Ka-band, because of the congestion of services registered at C and Ku-band. In this scenario, multi-beam satellites are so far the most effective implementation to efficiently guarantee an high level of throughput. The complexity associated to such payload configurations has a serious impact on the number of components required overall the payload and also for the different specifications for each beam subsystem [1]. However, the stringent requirements are not only linked to the electrical performance. The identified general needs across the different satellite system architectures are the reduction of costs, mass and lead time other than the flexibility in terms of bandwidth and power. Also it should be reduced the complexity of assemblies by the integration of numerous functions in one single design, in order to have less interfaces, mechanical stresses and testing. Additionally, programmes like CleanSAT aim to safeguard the terrestrial and space environment and consider new technologies devoted to cutting down on derelict satellites being abandoned, reducing the risk of orbital collisions from increasing debris while also reducing the threat posed by re-entering satellites.

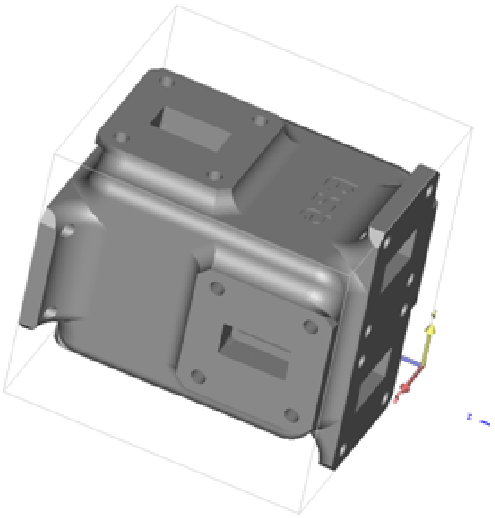

Fig. 1. Design of the 4×4 Butler matrix with filtering

The integration of several functions in the same piece that are normally separated, is an obvious solution to solve the problematic related to compactness, complexity of the assembly and mass. For example, in the recent years more emphasis has been given to all-resonator networks that can incorporate filtering functions as well as, but not limited, power splitting, multiplexing, phase distribution, etc... [2]–[4]. In this work it will be described the process of additive manufacturing (AM) a 4×4 Butler matrix based on resonators [5]. The proposed design is shown in Fig. 1.

Due to the inherent complexity of the resulting networks, the manufacturing applied with conventional methods is a challenging task. Additive manufacturing (AM) appears as a very promising solution which can at the same time provide some geometrical freedom to the RF design. AM is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods (milling, spark-erosion, turning, wire-erosion, etc...). It is used to build physical models, prototypes, patterns, tooling components and production parts in plastic, metal, ceramic, glass and composite materials. In general, AM can be considered as a manufacturing method capable to reduce lead time, improve product quality and reduce costs. From the RF point of view, there are parameters like surface roughness, mechanical tolerances, dimensional limitations in the fabrication etc..., which are deemed as drawbacks for the introduction of this technology for RF passive hardware. On the other hand, this technology can enable designs of complex structures which, until now, have been only manufactured joining multiple parts fabricated separately.

Most of the passive RF hardware embarked on satellites are made of metals. This is due to the needs of good electrical and thermal conductivity together with the mass/envelope minimization while maintaining mechanical performances (e.g. stiffness). At the same time the metallic parts create a shielding which avoid undesired RF leakage. Additionally, due to the increasing complexity of communication payloads, it is required a miniaturization for all the units in order to reduce total mass and allow the accommodation of a high number of units. It shall be stressed out that some post-processing may be needed once the parts have been manufactured by AM means. Typically, post-processing is needed to overcome some limitations of the AM or/and to achieve certain properties that the AM process cannot achieve and are required for Ka-band passive RF hardware. Depending on the AM technique used, the required post-processing will vary. Some of the processes are mandatory while others can be applied to achieve specific requirements such as surface finishing. This has a high associated cost, therefore the number of steps should be minimized so that AM keeps being an attractive manufacturing solution. A correct selection of the AM technique will reduce the cost of the post-processing tasks. Some of these methods may include machining, abrasive blasting or polishing.

In order to develop precision components made by aluminium, the following process is carried out:

1) analysis and optimization of parts,
2) design to adapt them to additive manufacturing,
3) manufacturing of the parts with metal technology,
4) post-processing of the parts (improving of surfaces).

The mentioned steps will be performed to implement the Butler matrix in order to simplify the complex geometry of the design shown in Fig. 1.

II. BUTLER MATRIX DESIGN

The Butler matrix to be implemented is a 4 × 4 device capable to split the input power equally among the outputs. This circuit provides an input to output phase distribution by means of combination of several 2 × 2 hybrids [6]. Normally the hybrids are based on pieces of transmission lines with different characteristic impedances in order to provide the desired electrical behaviour. The same power splitting characteristics and phase distribution can also be obtained through a circuit based on 16 resonators and electromagnetic couplings [5]. Fig. 2 shows the topology of this network with the input and output ports I_k and O_q shown. Like any other all-resonant circuit, the electrical properties are conveniently expressed through its coupling matrix [7]. In Fig. 2 the 16 synchronously tuned resonators are shown with circles, while the line between them are the electromagnetic couplings whose values are given by the different coloured lines [5].

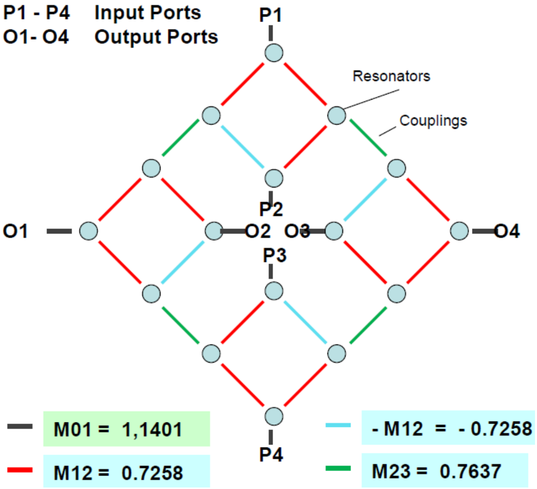

Fig. 2. Topology and couplings of the 4 × 4 Butler matrix with filtering [5]

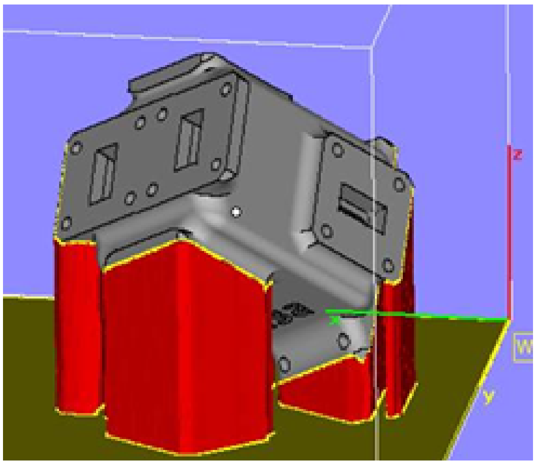

Fig. 3. Geometry placed on material supports in red

The circuit is implemented in standard WR75 rectangular waveguide. The topology of Fig. 2 can be also seen as formed by 4 blocks of 4-resonator: each block includes an input and output port and two couplings towards a pair of adjacent blocks. All blocks are the same and it is possible to use the values of the couplings of Fig. 2 in order to calculate the initial dimensions. Then, the blocks of 4 resonators are connected orthogonally (2 horizontals and 2 verticals) in order to create the model of Fig. 1. At this stage the dimensions are further optimised and the standard WR75 flanges are included in the final design [8]. Due to the complexity of the model,

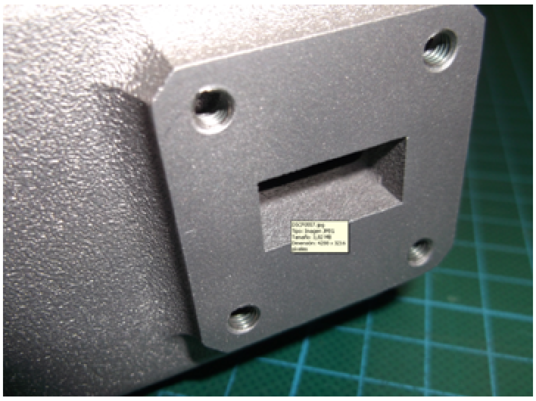

Fig. 4. Detail of the external surface interface

the process of additive manufacturing has to consider the symmetries and the internal parallel surfaces. The prototype is built in aluminium AlSi10Mg.

The entire structure is to be positioned on an inclined plane in order to efficiently deposit the material and to apply the laser siltering. This is due to the two lateral vertical walls and the two horizontal planes, all respectively parallel. Hence the model is then positioned over *supports* of the same material and the 3D software design adjusted accordingly. Fig. 3 shows the view of the model put over same material supports, here indicated in red. The supports are all placed in correspondence to the external interfaces, so as a faster laser siltering can create the structure. The piece has been made in an EOS M280 machine equipped with a 400 W laser with a layer thickness of 30 μm. The build chamber of this system is $250\times250\times300$ mm and the tolerances are in the range ±0.05 mm. The prototype also received a thermal treatment stress relieve, corresponding to 2 hours at 300 C. At the end of the process the supports are removed in two steps: firstly by hand to remove the majority of the material and then through automated machine tools (machining centres etc...). Fig. 4 shows the result of the final removal and refinement of the surface of one of the external flanges. It is crucial to have this surface as flat as possible in order to improve the contact with waveguide flanges.

III. RESULTS

The measurements of the scattering parameters are shown in Fig. 5 for an input source at port 1. The design specifications are: central frequency $f_0 = 12.5$ GHz, bandwidth of 500 MHz, return loss of 25 dB and isolation better than 30 dB. The measurements show that the entire frequency response is shifted down in frequency of about 180 MHz and that return loss is 11 dB for the worst case. The bandwidth is confirmed for all the pass-bands as well as the equal 6 dB power splitting ratio. The isolation is in agreement with specifications for the S_{31} and S_{41} while it is 18 dB for S_{21}.

IV. CONCLUSIONS

In this paper the design of a 4×4 Butler matrix has been presented and the device built with additive manufacturing techniques. In recent satellite RF payloads the demand for higher throughputs is merged with the need for more compact equipments. Hence, devices incorporating multiple components are often required. This is the case of the Butler matrix based on resonators, where the traditional power splitting and phase distribution are included with a filtering transfer function. However, the geometry implementing this topology is challenging in terms of manufacturing for its multiple layers. Thus, additive manufacturing is used to build this kind of device in a single piece. The manufacturing process is described and proves its feasibility for a complex Butler matrix with filter transfer functions included. The RF measurements also show that the internal dimensions have been enlarged of a constant factor during building as the overall response is shifted down in frequency of 180 MHz.

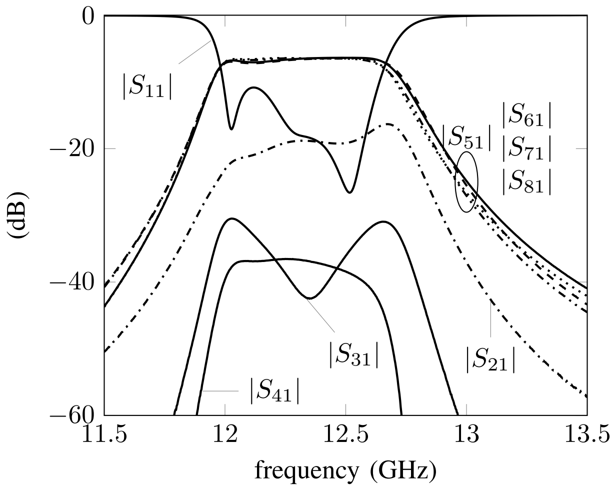

Fig. 5. Magnitude of scattering parameters at port 1

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