Power Combining Techniques for Space-Borne GaN SSPA in Ka-Band

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***Abstract*—Highly Efficient power combining techniques are mandatory for developing solid state power amplifiers (SSPAs) for high frequency space applications. Indeed, SSPAs are designed starting from medium power components, in the range of few watts, that are combined in such a way that the equipment efficiency is kept as maximum as possible. Planar structures such as branchlines or Wilkinson provide good isolation between ports but their losses become prohibitive when both peak power and frequency are in the range of hundreds of watt and tens of GHz, respectively. In these cases, waveguide structures result to be the most appropriate. On this way, the paper presents the design and experimental characterization of two distinctive structures conceived for spatially combine sixteen 10 W Gallium nitride monolithic microwave integrated circuit for realizing a Ka-band (17.3 GHz-20.2 GHz) SSPA with more than 125 W of saturated output power.**

***Index Terms*—Spatial Combiner, GaN, Ka-Band, PA.**

I. Introduction

Future Very High Throughput Satellites (vHTS) satellites will make use of Ka/Q/V gateways where the forward payload link will operate in K-band. Although the downlink band is known as K-band (i.e., 17.3-20.2 GHz), at satellite payload level it is normally referred as to Ka-band [1], [2]. The required RF power capability in such a band is about 110 W at saturation. Radio-frequency (RF) power amplifiers (PAs) are one of the key components on-board of communication satellites consuming roughly the 80–90% of the spacecraft bus power. Therefore, its efficiency is of utmost importance. Traditionally, demand for power at high frequencies has resulted in travelling wave tube amplifiers (TWTAs) as the logical amplifier of choice; however, the availability of reliable and powerful materials such as Gallium Nitride (GaN) and the adoption of innovative power combining techniques, have levelled the playing field for Solid State PAs (SSPAs).

This paper discusses the first prototypes of two highly efficient power combiners conceived for the implementation of a Space-borne GaN SSPA for vHTS applications in Ka-Band, i.e., 17.3 GHz-20.2 GHz. Both designs will be detailed together with their experimental characterizations, after having provided an overview of the SSPA under development.

II. SSPA Requirements

The main requirements of the SSPA under development are listed in Table I, whereas Fig. 1 reports the power budget of its radio frequency tray (RFT).

TABLE I
Requirements of the SSPA

Feature	Value	Unit
Frequency	17.3-20.2	GHz
Saturated Power	125	W
Max gain	70	dB
Power Added Efficiency	>30	%
Weight	<2	Kg
Base Plate Temperature	-5 to 85	°C

Fig. 1 reports the power budget of its radio frequency tray (RFT). In order to attain 125 W at SSPA level, the idea is to combine, in the last stage named high-power section (HPS), sixteen high efficiency 10 W GaN MMICs by using innovative and low losses power combining solutions. This subunit will be driven by a single MMIC with a gain of 22 dB and an output power of 10 W, i.e., the same MMIC used in the HPS. An analogue linearizer will be placed in front of the driver to improve the linearity of the chain, whereas a gain control unit (GCU), embedding analogue variable attenuators to properly implement the foreseen operating conditions and thermal/aging compensation, will be considered as input stage, with a gain of at least 30 dB.

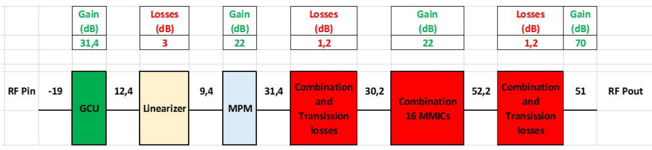

Fig. 1. Power budget of the RFT of the SSPA.

III. Power Combining Techniques

Considering the required output power and the 10 W expected from the single GaN MMIC under development, combing techniques based on waveguide structures have been investigated to implement the HPS of the SSPA, since planar solutions at this frequency and power level are characterized by unacceptable losses. In particular, among the possible solutions [3], the cavity-based Radial Combiner (RC) and the single waveguide longitudinal probe Spatial Combiner (SC) have been selected as the most suitable ones.

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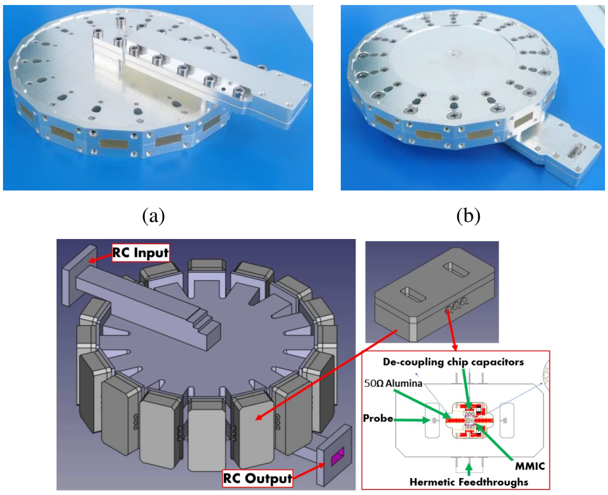
A. *Cavity-based RC*

An RC is a radial waveguide structure with N input and one output port, in which the power available at the N input ports is summed in one step at the output one [4]. The same structure can work as a *1-to-N* power splitter also, by swapping the input with the output ports. Considering the operating frequency, the most appropriate size of the waveguide to be used would have been the WR-51, which has an operative band from 15 GHz to 22 GHz. However, with such a waveguide the volume and size of the overall combiner/splitter resulted to be unacceptable. For this reason, the design was moved on WR-42 that, even if it has a nominal operative band from 18 GHz to 26.5 GHz, has shown the best trade-off between combiner's geometry and electrical performance. Moreover, the final RC is made in aluminium to ensure a good compromise between strength, lightness and heat transfer. Fig. 2(a) and Fig. 2(b) show a picture of the realized splitter and combiner (sizes and weight for each are 105x133x26.8 mm^3 and 233 g), respectively, whereas Fig. 2(c) is a 3D representation of the final HPS. In the latter is also shown how the MMICs will be integrated in the structure. The idea is to realize an hermetic module (HM) for each MMIC and to fix it at the splitter/combiner in vertical mode. The waveguide to coaxial transition in the HM (Probe in Fig. 2(c)) will be realized exploiting hermetic glass-bead. Simulation results of such a transition have shown insertion and return losses better than 24 dB and 0.05 dB, respectively, in the overall frequency band.

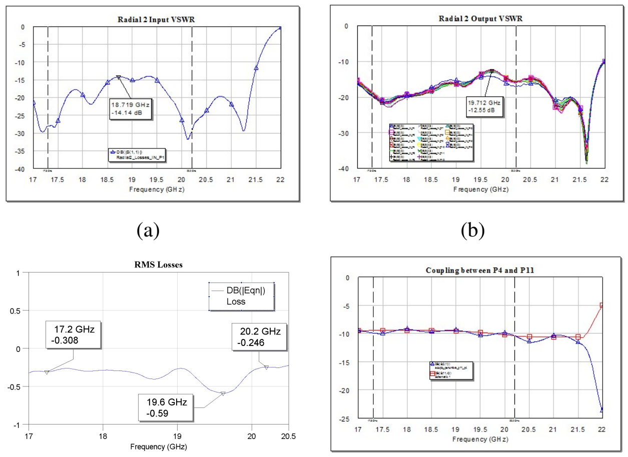


(a) (b)

(c)

Fig. 2. Realized RC splitter (a) and combiner (b) together with a 3D representation of the final HPS of the SSPA (c).

The structures in Fig. 2(a) and Fig. 2(b) have been tested by using a 2-ports vector network analyser, thus terminating each of the remaining 15 ports with a WR-42 50 Ω load. Being identical, both structures have shown very similar behaviour. The measured results as a splitter (i.e., 1-to-16 configuration) of one of these structure in the operative band are shown in Fig. 3(a)- 3(d). The return loss at the common port (Fig. 3(a)) is better than 16 dB, whereas it is better than 13 dB at each of the output ports (Fig. 3(b)). The rms value of the insertion loss between the common port and one of the output port (Fig. 3(c)) has an average value of 0.4 dB, whereas the worst isolation between two output ports is better than 10 dB (Fig. 3(d)). By combining the 2-ports measurements and accounting for the simulation results of the HM, the overall losses of the HPS based on the RC (i.e., the cascade of 1-to-16 RC, the HM and the 16-to-1 RC) were estimated in 1 dB, meaning 0.5 dB for the output combiner alone.



(a) (b)

(c) (d)

Fig. 3. Measurements of half RC: input (a) and output (b) return losses, rms of the insertion loss (c) and isolation between output ports (d).

B. *Single waveguide longitudinal probe SC*

The block diagram of the second spatial combiner is shown in Fig. 4(a). It is a single waveguide longitudinal Probe type developed in WR-51. The division/combination by sixteen is realized by cascading a waveguide division by 2, a Fin-Line [3] division by 4 and a Wilkinson division by 2, as shown in Fig. 4(b). The former, a Tee-junction in E-plane, splits the signals in two WR-51 arms and was designed with four-step Chebyshev transformer in order to obtain small reflections at the input port. The Fin-Line transition with exponential shape was printed on 254 um Al_2O_3 substrate, preceded by a dielectric quarter-wave transformers. In particular, for each waveguide arm, the TE_{10} fundamental mode entering inside the WR-51 waveguide couples with two Al_2O_3 substrate cards, each one carrying two antipodal Fin-Lines and placed symmetrically with respect to the center of the waveguide. Consequently, each Fin-Line transforms the TE_{10} waveguide field in a q-TEM microstrip mode that, after the splitting realized through the Wilkinson divider, is ready to be captured and amplified by the MMICs. As a result, each waveguide arm holds a total of 8 MMICs, 4 on top and 4 on the bottom side. It worthily noting that Wilkinson networks are not strictly necessary, and same number of outputs can be realized using Quad Fins [3]. However, it was proved that the use of Wilkinson results in a much better graceful degradation, at the expense of an increase in the insertion loss of nearly 0.8 dB. Fig. 4(c) shows a 3D representation of half shell of the SC. Each MMIC has a dedicated Feedthrough (FT) to bias its gate, whereas all the MMICs drains are connected together at the same drain bias. Due to the amount of required drain current, 8 FTs in parallel will be used to accomplish this task. Therefore, a total number of 24 FTs are required to bias the whole HPS, as shown in Fig. 4(a). On the other hand, four biasing boards (i.e., Bias board 1-4 in Fig. 4(a)) realized on alumina will carry out the bias routing inside the SC. Fig. 5(a) shows a picture of the realized passive SC, in which the MMICs have been replaced with transmission lines realized on 254 um Al_2O_3, in order to be able to test the behaviour of the combiner alone. Measured Scattering parameters from J1 to J2 coaxial interfaces (see Fig 4(a)) are shown in Fig. 5(b). The overall losses of the HPS based on SPC are 2.74 dB, meaning 1.38 dB at the output side.

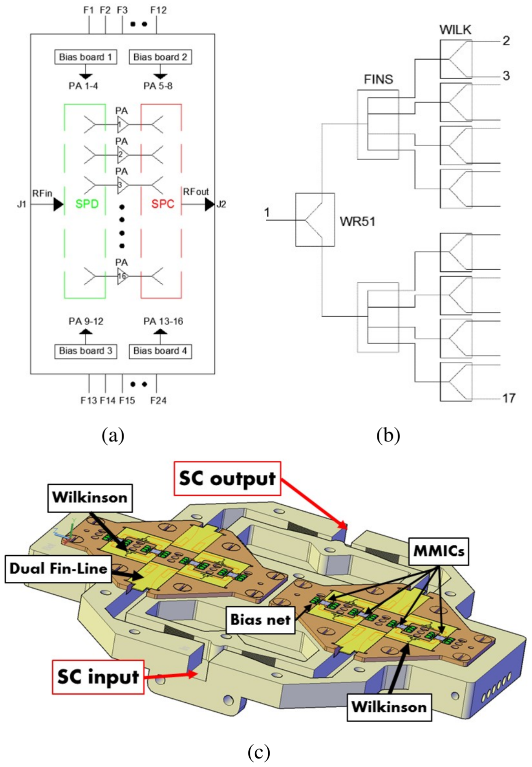


Fig. 4. SC: (a) block diagram, (b) splitter/combiner topology, and (c) 3D representation.

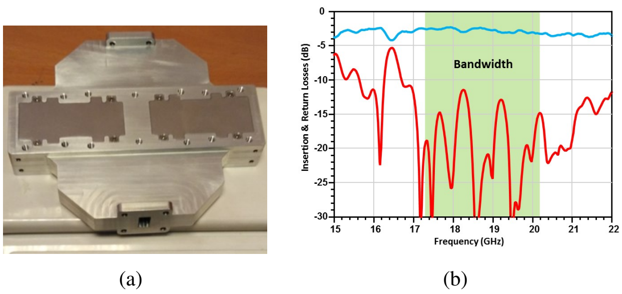


Fig. 5. Realized passive SC (a) together with the measured scattering parameters (b). Weight of the overall SC is 490 g.

C. Comparison

Table II summarizes the results of the two solutions. As expected due to the presence of the Wilkinson structures, the losses of the SC are higher than those of the RC, leading to a lower combining efficiency, i.e., 73% for the SC with respect to 89% of the RC. On the other hand, even if not explicitly reported in the previous sections, simulation results have shown that with four MMICs off, the insertion losses of the SC degrade of about 0.5 dB only, whereas in the same condition, that of the RC degrade of about 3 dB. Additionally, the SC is lighter and more compact with respect to the RC comprising the 16 HMs. Finally, it is worthily noting that, through a detailed thermal-mechanical design, both solutions have been made multipaction free and able to dissipate the generated heat, while assuring a safe thermal working condition for the MMICs keeping their junction temperature lower than 160 °C.

TABLE II
COMPARISON BETWEEN RC & SC

Feature	RC	SPC
Insertion Loss	0.5 dB	1.37 dB
Combining Efficiency	89%	73%
Size (mm^3)	160x122x63	123x146x21
Weight	1060 g	490 g
Graceful degradation	poor	good
Multipaction Free	yes	yes
Thermally Compliance	yes	yes

IV. CONCLUSION

This contribution presented the design and characterization of two highly efficient spatial power combiners conceived for the implementation of a Space-borne GaN SSPA for vHTSs in Ka-Band. Comparing them, it was highlighted that each structure has its pros and cons with respect to the other. The RC is more efficient as compared to the SC but it has a poorer graceful degradation. On the other hand, the SC is lighter and more compact with respect to the RC.

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