The Squarax Amplifier: An Electromagnetic and Thermo-mechanical Innovation

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Abstract— This paper describes a novel broad band Spatial Power Combiner (SPC) Amplifier based on Square Coaxial (Squarax) Transmission Line (TL), able to tolerate the Thermo-Mechanical effects due to the transistor heating. In the proposed SPC, Fin Line to microstrip transitions (FLuS) are inserted into the Squarax TL, in order to connect many Monolithic Microwave Integrated Circuit (MMIC) Solid State Power Amplifier (SSPA) while maintaining an easy integration. The proposed structure has some advantages over the traditional SPC's. The Squarax SPC geometry allows the feeding of a higher number of MMIC than in a Waveguide SPC, and its straight profile allows to connect simple and low-cost square or rectangular heat-sink devices with high thermal dissipation attitude. Conversely, coaxial SPC needs apposite circular heat-sinkers that requires expensive custom production. Squarax structure ensures high power outputs and small sizes, together with theoretical DC frequency cut-off. In this work, a 16 cards Squarax SPC in the operative bandwidth 4–18 GHz has been designed, able to account for 32 MMIC SSPA's. The design Electromagnetic and Thermo-structural simulation of the proposed device are shown.

1. INTRODUCTION

Spatial power amplifiers (SPA) are high power amplifiers based on the Spatial Power Combining approach. In this case, power dividing and combining is performed in a parallel way. Actually, high power levels are obtained by Travelling Wave Tube Amplifiers. In comparing with such tubes, SSPA's based amplifiers offers short warm-up time, low standby mode power consumption and a reduced size [1]. The traditional approach to obtain a significant power output with SSPA's is the binary combining of many transistors through microstrip Transmission Lines [2, 3].

Binary combining of many transistors through microstrip Transmission Lines is limited to the losses which each printed transmission-line combiner inserts. Binary combining, in addition, limits the number of devices to a power of two.

In comparing to the binary combining, SPC approach offers high device compactness, low combining losses, higher available power outputs and losses are rather independent with the number of used PA's. In SPC the independent coupling of individual devices within the TL makes a little sensitivity to single-point failures, ensuring graceful degradation of output power. With a constant target output power, combining many devices by using the spatial approach allows to reduce size, weight, power draw, and cost [1, 4–10]. Since the loss is rather constant to the number of amplifiers, their size limits the combiner area with both the contributions of the active devices, the bias distribution and heat sink systems, which are especially important in order to avoid performance degradation and even device failure.

In this paper an innovative solution for SPC PA is shown. The proposed system is based on a Squarax TL [11], and use a Fin-Line [12] to microstrip (FLuS) transition to convert the energy of a square coaxial TEM fundamental mode to a microstrip quasi-TEM mode, which is then amplified by a SSPA. Many SSPA's outputs are recombined by the same principle. In order to maximize the useful space for energy dividing and combining in the SPC, the Squarax TL configuration has been adopted. Since the FLuS cards can be placed all around the inner conductor of Squarax TL, a high number of such structures can be driven: This provide a high power output when MMIC PA's will be employed. In order to hold up the inner conductor of the Squarax several metal cards are used, each one holding FLuS transitions, as will be shown later. A practical important aspect is the straightness of the Squarax SPC profile, which allows to be connected to a simple square or rectangular heat-sink devices, easily available in the market: it is completely different from the case of a Circular Coaxial SPC which needs apposite circular heat-sinker that require a custom production. Similarly, using a Circular Coaxial SPC there is the need of FLuS cards with a circular section of the lateral profile and with not planar faces, more expensive than simple rectangular cards as in the case of Squarax SPC.

Several circuital and technological solutions have been adopted. In order to reduce the combining loss and size, exponential FLuS transitions have been considered, using antipodal configuration. In order to improve the operative band, a parasitic void has been implemented by inserting an anti-resonance metal in the antipodal FLuS transitions [13]. Since electromagnetic characteristics depend on various factors, such as the FLuS shape and the number of cards, a computational electromagnetic model has been developed using HFSS version 15. The power dissipation of the MMIC SSPA's produces a considerable temperature increase and induces a thermal expansion of both the PA's and the connected structure. Transistor damage or an alteration of the desired electromagnetic behavior may occur. In order to inquire about these multiple aspects, a Thermo-mechanical model has been implemented on Comsol Multiphysic Version 4.

2. THE SQUARAX AMPLIFIER

In TL active SPC architecture each amplifier is connected to a probe, in order to couple its input port mode with the energy of the TL propagating mode. Several amplifiers, usually MMIC's, are mounted in metallic cards containing their related functional circuitry, like probes, transitions, biasing: such cards are placed in parallel inside the TL. Input probes, printed on each card, receive a portion of the input power so that many lower amplitude signals are obtained, which are then amplified by PA's and routed to output probes [11]. As much, these outputs are recombined coherently in an output TL by using the same principle, so the circuit consists of a back-to-back configuration of splitting and combining structure used as through elements.

In TL SPC architecture, the energy is distributed in low loss electromagnetic modes and combined in the TL dielectric, for example in a closed waveguide and, above all, using a single stage of power combining; this reduces the ohmic combining losses and makes it quite independent to the number of devices [9].

The Squarax TL is a coaxial line having square inner and outer conductors [14]. In order to maximize the useful space of mode combining of the SPC, the same FLuS structures can be implemented to couple a quasi TEM mode driven by a microstrip to a portion of the TEM mode of the Squarax. Circular Coaxial Transmission Lines (CCTL's) have been used extensively in the past, but square coaxial lines may be preferable since the presence of flat rather than circular surfaces offers mechanical advantages [15]. The Squarax constant ratio of the outer to inner conductors was chosen to 3 : 1 so that the characteristic impedance of the SCTL is as close as possible to the $50\,\Omega$ that is $61\,\Omega$ [15, 16]. An example of an 8 carriers, each with two FLuS's, inside the central part of the SCTL is depicted in Figure 1. The two pyramidal tapers allows for the connection with N type connectors.

Electromagnetic design of the Squarax SPC Amplifier proposed in this work is widely described in [11], we report only a briefly description of its main features. In this paper we mostly provide useful details on the thermo mechanical features of such device.

A microstrip taper has been used as a broad-band impedance transformer between the tapered-slot antenna and MMIC amplifier, since the characteristic impedance at the taper end of the probe can be different to the impedance required by the PA input port matching condition [10]. In order to reduce the combining loss, the shape of the antenna taper has to be chosen properly so that return loss can be minimized within the frequency band of interest. Several spatial profiles of FL can be implemented: exponential, parabolic, sine, sine squared, cosine and cosine squared taper [12]. The former is chosen to ensure the smoothness of the taper, whereby very good matched-load is readily available for the Squarax, because this transition indeed reflects a small amount of incident power. From Riccati's equation it is possible to find the reflection coefficient trend with respect the

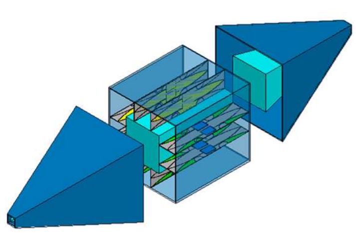


Figure 1: Example of an 8 carriers, each with two FLuS's, inside the central part of the Squarax SPC.

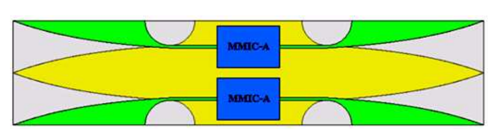


Figure 2: The carrier, holding FLuS's and two MMIC-PA's.

product βl is given by (1) [17] and Microstrip Lines were designed following Hammerstad formulas reported in [18].

$$\Gamma = \frac{1}{2} e^{-j\beta l} \ln\left(\frac{z_1}{z_2}\right) \frac{\sin(\beta l)}{\beta l} \tag{1}$$

In order to obtain great system integration, Antipodal configuration of Fin-Line to microstrip transition is an attractive solution [13], but presents evanescent modes inducing resonances. In order to solve this problem, the Fin-Line discontinuities can be designed so as to break the slot electric field lines. An useful solution has been applied; it consists to model a circular section through the metal sheet in the area where the parasitic slot might create [13].

In order to improve the return loss, a dielectric Quarter Wave Transformer (QWT) has also been provided.

More cards can be inserted by proper impedance matching between the central section and the input/outputs ports. Each cards is composed with input and output dual FLuS transitions, two MMIC's, together with their bias circuitry, and a carrier holding all these components. The carrier is made with copper, to assure high thermal conductivity, and an interface sheet composed with CuMo compound, is placed under the MMIC to assure thermo-mechanical compatibility between GaAs MMIC and the carrier. A picture of the carrier is reported in Figure 2.

In the actual case, FLuS uses the rigid Al_2O_3 substrate, brazed on Cu carrier. The square profile of the Squarax determines the defined plane of polarization and the wave can travel down to the FLuS transitions to coherently couple their energy to the microstrips. Since such transitions can be placed all around the inner conductor of the Squarax, a higher number of FLuS transitions can be illuminated than in other TL, for example a rectangular WG [1, 8, 10]. Therefore a high power output can be reached, because the power output of a SPC amplifier increases with the number of its internal coupled active devices.

In order to have high power output, in every SPC, SSPA's may be employed at maximum efficiency and they produce significant power dissipations. A thermo-mechanical modification of the carrier shape, induced by such power dissipation, may induce significant modification on the electromagnetic behavior of the guiding and combining SPC structures. For this reason a good heat-sinking subsystem is recommended.

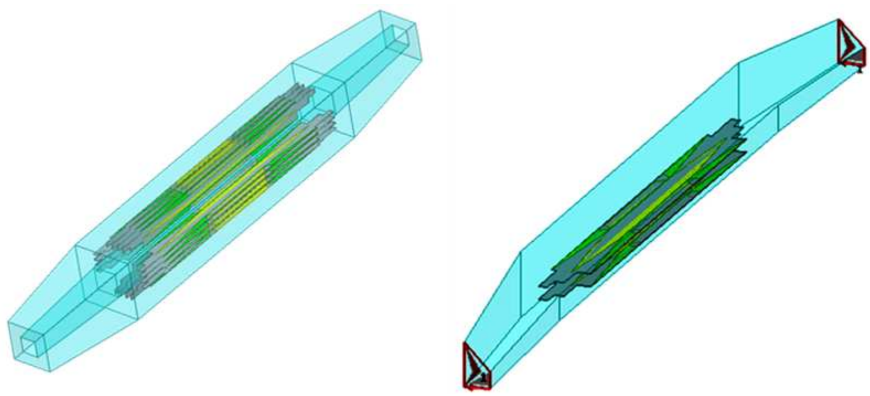
Due to the straightness of its profile, the Squarax SPC can be connected to a simple square or rectangular heat-sink devices, which is easily available with a low cost. A classical circular CCTL needs a heat-sink with a semicircular cross section which has to be specially designed, requiring higher cost. Moreover, when using a CCTL as a SPC, cards with a circular section of the lateral profile of the substrate are required; this further increases the manufacturing costs.

In a Squarax TL, in addition to the TEM fundamental mode, higher order modes can propagate. The higher order mode spectrum of circular coaxial lines is very well known and, as described in [15], a SCTL can be used alternatively to a CCTL with its technological advantages, maintaining great wave-guiding properties as for the CCTL. However, when the CCTL is loaded with the FLuS, ε_r changes, and a numerical optimization is mandatory.

3. COMPUTATIONAL DESIGN AND SIMULATIONS OF A 16 CARDS SQUARAX SPC

3.1. Computational Electromagnetic Model and Analysis

Return loss characteristic of the passive structure SPC depends also on the number of inserted cards. In order to meet the operating power goals with the fewest possible devices, to minimize the insertion loss and to maximize the return loss, the better configuration can be found selecting the profile shape of the FLuS (including the microstrip transformer and the anti-resonance circular section) which allows to accommodate the optimum number of cards and the number of devices per card to insert in the target Squarax. A 16 cards Squarax SPC in the operative bandwidth 4–18 GHz has been designed, able to account for 32 MMIC SSPA's. The inner part has the cross sections $a = 13.524\,\text{mm}$ $b = 33.524\,\text{mm}$, while the tapered transition from coaxial input and output sections to the inner part is 60 mm long. Exponential tapered FL transitions are mounted on 16 cards placed at each side of the Squarax. The FLuS are made on Al_2O_3 substrate, with a thickness of 0.254 mm. Each card contains two FLuS connected back to back with double asymmetrical QWT sections. The Squarax conductors have been considered as copper, which has excellent thermal conductivity. The simulation of the proposed device has been performed, using HFSS version 15 of Ansys-Ansoft. The 3D simulated structure is shown in Figure 3. Simulation setup has been developed in order to reach the desired high performances which distinguish the proposed device from the classical spatial power combiner-dividers.



(a) (b)

Figure 3: (a) 3D view of the 16 Cards-32 MMIC's designed Squarax and (b) the simulated octave of the device.

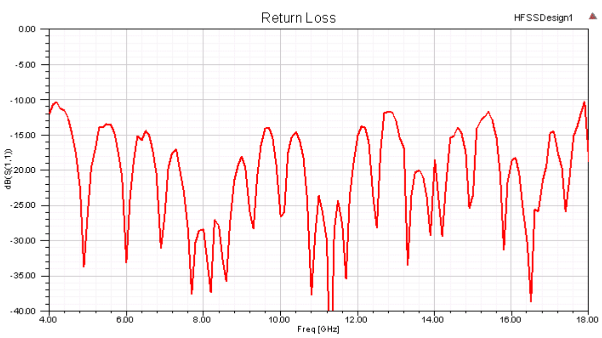


Figure 4: Reflection coefficient, in dB, of the Squarax SPC. Return losses are better than 10 dB in the whole bandwidth.

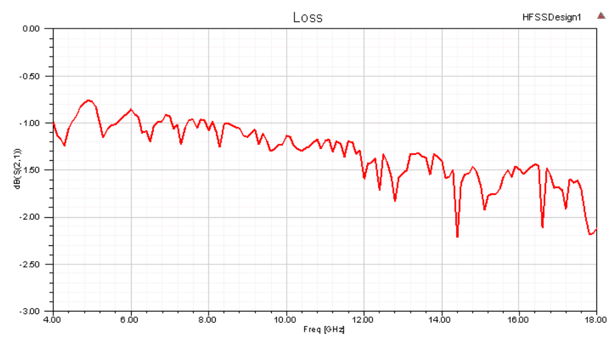


Figure 5: Transmission coefficient, in dB, of the Squarax SPC. Insertion losses are less than 2.5 dB.

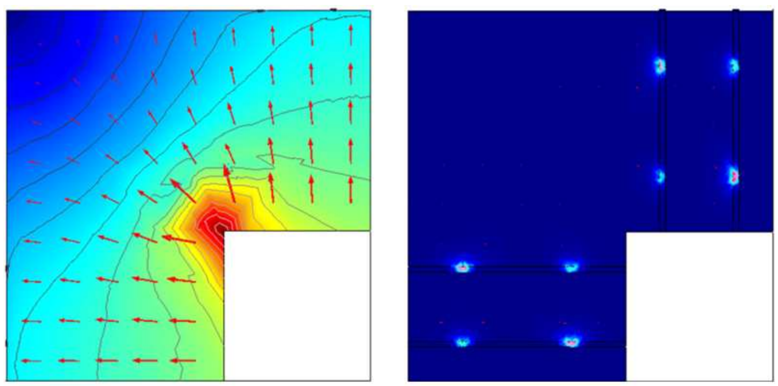
Since the Squarax SPC is willing to be interfaced with external devices, such as front-end, back end modules or phase shifter, isolator and other passive devices, commonly with circular coaxial ports, two wave ports with such shape have been needed. Circular coaxial ports have been assigned to the Squarax model by defining two integration lines: one for each port, like a circular coaxial. Since the Squarax is a TEM structure, ports are introduced by employing an Electric Filed Arrow, from inner conductor to outer one. Ports have been assumed as matched with interconnected outer devices, thus a port renormalization hasn't been necessary. Losses of copper waveguide walls and gold metallization of the micro-strip lines and dielectric losses on the alumina slabs have been considered. The Squarax internal volume is filled by air, in such medium the stationary solution of the wave equation in the frequency domain (2) [17] has been solved with HFSS.

$$\nabla \times \mu_r^{-1}(\nabla \times \bar{E}) - k_0^2 \left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right) \bar{E} = 0 \tag{2}$$

where μ_r is the magnetic permeability, ε_r the electrical permittivity and σ the electrical conductivity of the material; ε_0 is the electrical permittivity of the vacuum, k_0 the wave number in free space, ω the wave angular frequency and $\bar{E}$ the electric field.

Driven modal analysis has been performed with a 18 GHz solution frequency and a standard 0.02 Maximum Delta S has been adopted. In the adaptive options tab a 20% maximum refinement per pass has been choice, in order to reduce probability to get an unneeded large amount of tetrahedrons. Moreover, in order to ensure a good solution quality, a minimum converged passes has been set to 2 and an iterative solver with mixed order basis function has been employed. The simulated S-parameters are given in Figure 4 for s_{11}, and Figure 5 for s_{21}.

We note that the Squarax SPC ensures a maximum insertion loss of 2.3 dB and a minimum Return Loss of 10 dB in the whole 4–18 GHz. Several problems were solved, such as a large amount of tetrahedrons in meshing steps and several resonance occurrences. At last about 980 thousands tetrahedrons versus 8 million ones have been obtained, resulting in a reliable modeling which has ensured correct results. This improvement was achieved by defining two Perfect Magnetic Conductors (PMC) within the Squarax SPC. Furthermore, since a good discretization of the Fin taper profile was of fundamental importance, the exponential profile was approximated with a discrete number of points such that the different segment obtained were smaller than $\lambda/20$ at the highest frequency of the operative band. In this way the discretization doesn't affect the performance but reduces the computational complexity. By adopting these strategies and by enabling the Iterative Solver of HFSS, 9.7 GB of memory have been employed, instead of 32 GB ones necessary without this reduction. A dimensioning optimization of the Squarax SPC length has been needed to cut out the resonances. In order to improve the lower band return loss and to extend the operative bandwidth, longer FLuS can be used, with negligible insertion loss degradation. A group QWT's, tuned to different frequencies from the actual, can be a preferable solution. A triple QWT's may be also designed. In Figure 6 we report the result of the electromagnetic simulation of the Squarax SPC, obtained by using COMSOL Multiphysics Version 4: this is a front view of the central section of a quarter of the structure depicted in Figure 3, representing the intensity of the electric field at the microstrips after the FLuS.



(a) (b)

Figure 6: E-field intensity (a) at the TEM interfaces and (b) at the microstrips between the FLuS's. The blank part is the inner conductor.

3.2. Thermo-structural Model and Simulation

The power dissipation of the MMIC SSPA's produces a considerable temperature increase and induces a thermal expansion of both the PA's and the connected structure. If the SSPA's temperature exceeds the maximum allowed value (specified by the SSPA's vendor), an amplification failure or device damage may occur. After the main electromagnetic design, a thermo-structural analysis has been performed in order to define the carrier profiles and its proper materials. As for the electromagnetic simulation, since the structure is doubly symmetric respect two longitudinal orthogonal planes, one quarter of the complete structure has been simulated.

To inquire about the Heat Management Capability of this new SPC, we have performed a Thermal Simulation step linked to a Structural Mechanics analysis totally dependent. This analysis has been performed by supposing to use one of the most powerful GaAs MMIC available on the market, i.e., the TGA9083 produced by Triquint. For such simulation we have used the software Comsol Multiphysic Version 4. The Squarax has been supposed to be held at a constant temperature at its outside, equal to 27°C.

An innovation respect to the Thermo-mechanical simulation approach is represented by the proposed approach, described below. Many MMIC SSPA's are composed by a driver stage and a final stage FET's, but quite often thermal analysis are performed considering the amplifiers as a unique heat sources, which dissipate the total power in all their volumes [6, 10]. The problem of this thermal approach is that it doesn't allow understanding if a determined area of the integrated circuit exceeds the maximum rated temperature, as the channel temperature. The total power dissipation can be evaluated by the ratio between the maximum power output and the Power

Added Efficiency of the MMIC. The driver devices are smaller than the final, and have typical power dissipation P_{Driver} which is generally estimated, when the exact values are not available, as the total power dissipation P_{outMax} multiplied for the ratio of the driver volume V_{Driver} and the final volume V_{Final}: the remaining one is dissipated by the final stage. The power dissipation of the driver is expressed in (6). The Heat power density related to such dissipation can be expressed by the (7).

$$P_{Driver} \approx P_{outMax} \frac{V_{Driver}}{V_{Ended}}, \tag{3}$$

$$Q_{Driver} \approx \frac{P_{Driver}}{V_{Driver}} \tag{4}$$

The difference of heat power distributions between the two active stages determines a different path of the heat generated by the driver and the heat generated by the final transistor. These energies, in the form of heat, combine and induce heat in several points of the material, and only with this driver-final dedicated analysis is possible to determine if the transistor channels can be cooled. The specific heat flux paths determine specific thermal expansion of the materials in different portions of the SSPA volume, which induce specific compressive forces distribute in the subjected areas. Stresses and strains are thus applied to the device, and need to be computed, because consequent displacement of the guiding and combining structures may alter the desired electromagnetic behavior of the structure in different manners, depending on these heat paths. WG walls are intended as in a stationary temperature regime, cooled by the external environment, so they are non deformable by thermal stress and consists in virtual fixed constraints. Solid model is isotropic and the structural transient behavior is quasi-static. For this analysis we have considered the temperatures dependent of the displacements and a coupled computation has been adopted. The Comsol TS module is employed to solve the system of steady state Equation (3) [19]:

$$-\nabla \cdot \sigma = \bar{F}_V \qquad \rho C_p \bar{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \tag{5}$$

where σ is the stress and $\bar{F}_V$ is the force per unit volume; ρ is the density, Cp the heat capacity

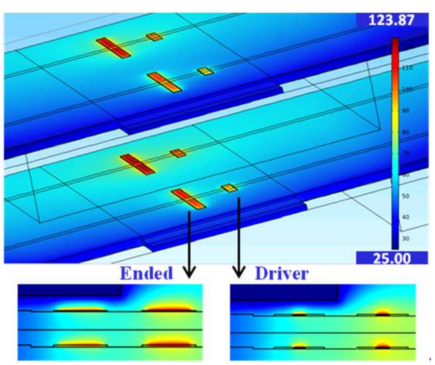


Figure 7: Simulated temperature (°C) inside the GaAs FET channels.

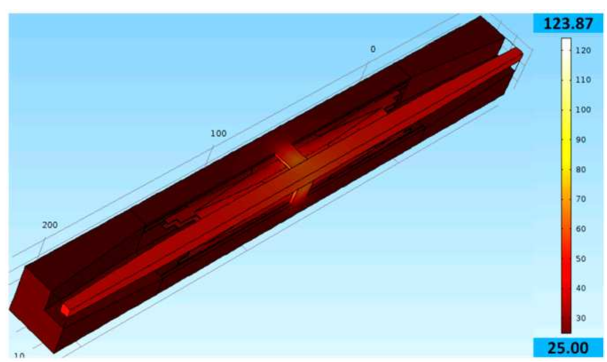


Figure 8: Simulation of the temperature (°C) inside the Squarax volume.

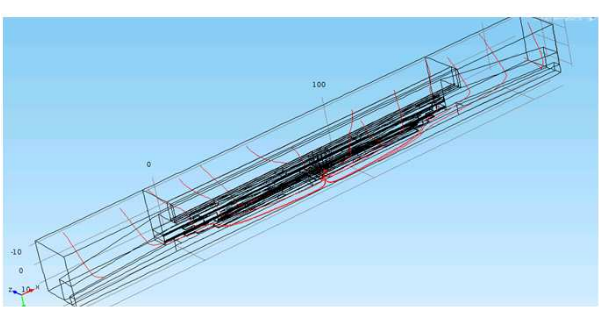


Figure 9: Heat flux streamlines described in a quarter of the SPC.

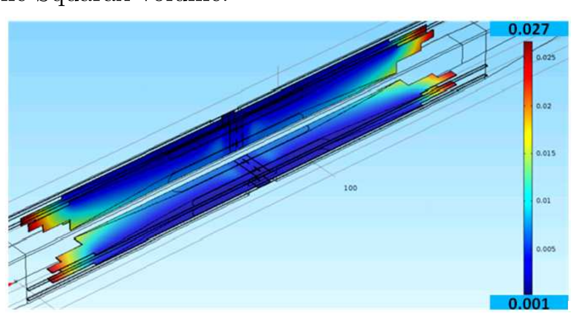


Figure 10: Total displacement (mm) in the Squarax SPC volume, due to heat generation inside the MMIC SSPA's.

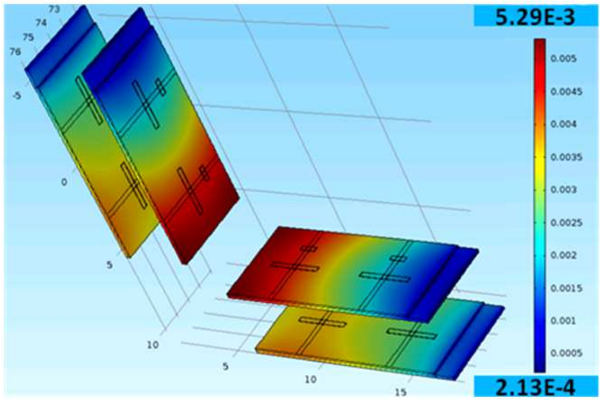


Figure 11: Representation of the displacement (mm) on the SSPA's.

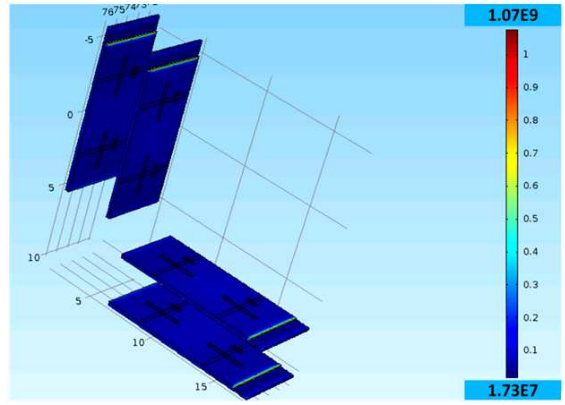


Figure 12: Representation of the Stress (N/m^2) suffered by the SSPA's.

and k the thermal conductivity of the material. Q is the heat source, $\bar{u}$ is the spatial displacement vector.

We have evaluated the thermo-mechanical features of the 16 cards Squarax SPC, where 32 MMIC SSPA's type TGA 9083 are used. We have imposed a total power dissipation of 23 W distributed in the driver and final transistors of each MMIC. Heat power densities have been evaluated, as explained above, basing on the volumes of the transistors. In Figure 7 we have the result of the thermal simulation of the transistors and Figure 8 we report the temperature distribution inside the whole structure.

Driver channels reach 107°C and Final 124°C. We note that Maximum temperature is perfectly respecting the maximum ratings reported by the SSPA vendor. In Figure 9 we report the total Heat Flux Streamlines derived in a quarter of the SPC structure. Heat Flux is directed towards the Sqaurax TL walls, ensuring the correct heat sinking. In Figure 10 the result we obtained for the total displacement, due the thermal stress induced by the heat dissipation is described. We can note, by observing this result, that the maximum displacement is about 27 µm. From Figure 10 we note that the displacement maximum due to temperature, which is obviously obtained at the end of the QWT, is in any case negligible due to low Temperature Expansion Coefficient of the Alumina substrate. The Maximum displacement on the whole SPC surfaces is 27 µm and, since is located on the end of the QWT, is in any case negligible. However, on the MMIC surface we have a maximum displacement of 5.3 µm, as shown in Figure 11: The problem is that GaAs is not very resistant to this displacement values. For this reason, CuMo or CuW layers can be inserted between the back of the GaAs MMIC and the copper carrier. We have adopted the following solution: The carrier is made with copper, to assure high thermal conductivity, and an interface sheet composed with CuMo compound, is placed under the MMIC to assure thermo-mechanical compatibility between GaAs MMIC and the carrier. In Figure 12 we report the Stress on the MMIC devices. Maximum stress, which is less than 1.1 GN/m^2, is located on the GaAs SSPA near the connection between the copper carrier and the Squarax walls.

4. CONCLUSIONS

The Squarax SPC technology has been studied and several circuital and technological solutions have been adopted. The Squarax SPC represents an innovative solution, in order to increase available power outputs and low cost.

By using this solution, optimal results have been achieved. A 16 cards Squarax SPC has been designed with great performance: The model presents gain variation of ±0.4 dB, and 10 dB minimum for Return Loss for the whole 4–18 GHz.

The average insertion Loss of the whole SPC is $IL = 1.5$ dB and, by taking into account such losses, and considering that each TGA9083 can reach a maximum power of 37.4 dBm, the proposed SPA can reach a maximum power output of 51 dBm.

The structure offers 14 GHz of Operative Band with about 230 cm^3 of volume. A thermo-structural simulation has been also performed, showing good results in term of heat management and structural stability.

The maximum power dissipation of the transistors produces a maximum temperature of 124°C locally on the ended transistors and induces a maximum displacement of about 27 μm. According to this study, the appropriate materials have been chosen in order to ensure the correct operation of the device in thermal stress affected working conditions.

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