

Thermal and Solid-Mechanics FEM Simulation of a Microwave Spatial Power Combiner Amplifier

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Abstract: This paper describes the Thermal and structural combined simulation on COMSOL Multiphysics of a Microwave (MW) Fin Taper (FT) Spatial Power Combiner (SPC) Power Amplifier (PA), based on rectangular Waveguide (WG).

In the SPC based PA's, the captured power is feeded by microstrip transmission lines (μ STL's) to Monolithic Microwave Integrated Circuit (MMIC) Solid State Power Amplifier (SSPA's).

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, which can alter its desired Electromagnetic (EM) behavior. SSPA's are composed by driver and ended stage transistors which are been considered as different causes that contribute to the total effects, in order to estimate the reached temperatures in the different areas.

The model is organized by using Heat Transfer in solids (HT) and Solid Mechanics (SM) COMSOL modules. Temperature, stress and displacement under operative conditions have been computed.

Keywords: Finline structures, Rectangular Waveguide, Spatial Power Combiner, Heat Transfer in Solids, Structural Mechanics.

1. Introduction

POWER COMBINING represents an important issue in designing High Power Amplifiers in the High frequency range. The classical approach to combine power signal is the binary combining, it consists in a tree structure where the signals are added by binary combiners, such as Wilkinson power combiners. This solution is limited to the losses which each printed transmission-line combiner inserts, and limits the number of employed devices to a power of two. Conversely, spatial power combiners are based on the signal power combination in low loss

propagating modes within dielectric of transmission lines [1]. This principle offers several advantages as high device compactness, low combining losses, higher available power outputs and heat sinking facilitations [2].

1.1 Spatial Power Combiner Features

The typical SPC configuration is based on rectangular WG to microstrip Fin Line transitions [2].

The analyzed structure is a couple of cards which contain the Amplifiers and a quarter of the metallic walls of the WG, where it will be inserted. The Amplifiers are placed on a metallic slab called carrier, ensuring proper heat sinking and consequent small structural deformations.

In the described device, the power provided by a section of WG can be captured by a FT to microstrip transition and carried by microstrip transmission lines (μ STL's) to a Monolithic Microwave Integrated Circuit (MMIC) Solid State Power Amplifier (SSPA's) (included yet in the described card). The outgoing power from the amplifiers is sent to two opportune Fin Tapers, in order to be combined in the dielectric by low loss Transmission Line (TL) modes. A dual FT μ STL's to rectangular WG is shown in Figure 1.

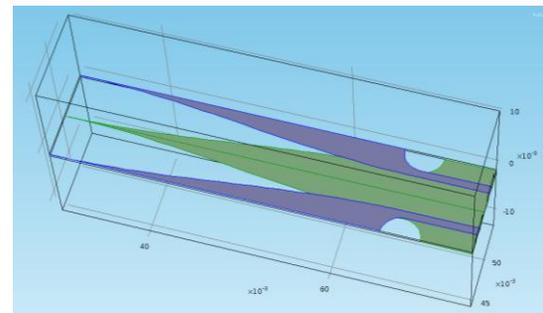


Figure 1. A dual FT μ STL's to rectangular WG.

This structure can be placed inside an air filled rectangular WG, by designing opportunely the

right FT profile referring to the target SPC TL features. Both μ STL's and FL are to be printed on a dielectric substrate which is to be placed near the support described in this paper and the μ STL's are to be connected to these SSPA's.

Several of these cards can be placed inside a single WG. This principle ensures low combing losses, easy integration and heat sinking, space saving and great output powers. Respect to both the kind of TL chosen to build the desired SPC, the described structure is doubly symmetric. If four of these ones are inserted in a rectangular WG, four dual FT in the WG can be obtained (that are four FT close to one of the WG long side with other four ones mirrored along the WG plane of symmetry which bisect the WG long side, close to the other WG long side). The analyzed structure, represented in Figure 2, is a quarter of rectangular WG which contains two carriers.

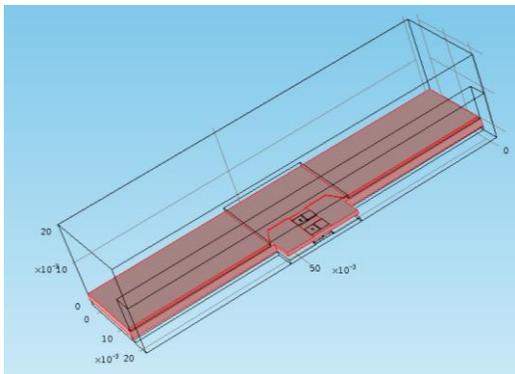


Figure 2. Two cards main carriers: One carrier is highlighted in red. In the center are placed two MMIC SSPA's. The combing structure has to be inserted, parallel to the carrier, in the smallest parallelepiped which, in this figure, represents the air in the WG.

1.1 Thermal and stress analysis

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. The thermal expansion of the materials may also induce significant stresses and strains with consequent displacement of the guiding and combining structures, which alter the desired

Electromagnetic (EM) behavior of the SPC. Stresses and strains are thus needed to be computed.

Power amplifiers are composed by a driver stage and a ended stage transistors, but actually thermal power dissipation analysis are performed considering the amplifiers as heat sources, which dissipate the total lose power in all their volumes [3]. The problem of this approach is that it doesn't allow understanding if a determined area of the integrated circuit exceeds the maximum rated temperature.

The innovation manifested in this study is the analysis of the thermal effects induced by the single transistors channel in which power is dissipated, by considering separately the power dissipation of the driver transistors and of the ended stage transistors inside an integrated circuit.

This accurate analysis can ensure the right thermal power dissipation representation of the specific device inside the SSPA's, since the power consumption and the consequent dissipation are unequally distributed in the SSPA's volume. The difference of heat power distributions between the two amplification stages determines a different path of the heat generated by the driver and the heat generated by the ended transistor.

These energies, in the form of heat, combine and induce heat in several points of the material, and only with this driver-ended dedicated analysis is possible to determine if the transistor channels can be cooled. The driver devices are typically smaller than the ended and have a typical power dissipation which is generally estimated as the total power dissipation multiplied for the ratio of the driver volume and the ended volume. The remaining one is dissipated by the ended transistor.

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.

2. Use of COMSOL Multiphysics

Thermal stationary analysis allows to determine the temperature when the heat generated by the MMIC's power dissipation has been diffused on

all the reachable SPC components and the system has become thermally stable, since the external temperature is by then steady over all the SPC outer boundaries which are exposed to the external environment.

A Structural Mechanics stationary analysis can be employed to estimate the deformation induced by the thermal expansion of the material induced by the heat generated by the SSPA's power dissipation.

A Finite Element Method (FEM) based Multiphysics simulation using COMSOL can couple Thermal and Structural analysis by storing thermodynamics information. In order to decrease computational time and resources maintaining accuracy, the device model is organized by using several strategies allowed by COMSOL.

The mesh is set at minimum edge of the SSPA's domain which is 10^{-4} m long. By using the default normal settings of COMSOL mesh interface for other mesh features, an accurate discretization has been reached with moderate computational cost.

In order to ensure great model reliability, all the materials are temperature dependent and characterized in the temperature range of simulation, which is from 20°C to 140°C.

The model is organized by using Heat Transfer in solids (HT) and Solid Mechanics (SM) COMSOL modules.

Since has been assumed that the temperatures are independent of the displacements, a separate computation has been adopted, for temperature, using the HT module and for the displacement using the SM.

2.1 Heat transfer

The HT module is employed to describe the Thermal formulation of the problem by using the following features [4]:

- Heat transfer in Solids, default: The SSPA's, with its copper support slab, and the wall of the WG are modeled in the heat transfer formulation referring to solid material type.
- Heat Sources: The MMIC SSPA's Drivers and Ended transistors are represented as constant volume heat sources. The heat power density is calculated from the SSPA's

Power Added Efficiency (PAE) at its maximum power output, and scaled in function of each specific transistor volume.

- Temperature: The temperature of the SPC outer boundaries is constant and equals the external temperature, in order to model the thermal steady state.
- Heat transfer in Fluids: The air inside the WG is used to model only the heat transfer from the combining structure to the external environment. The formulation refers to the Gas-Liquid fluid type.
- Heat flux: All external boundaries are used to compute the inward heat flux, in order to simplify the surface cooling a heat transfer coefficient to the air external environment of $5 \text{ Wm}^{-2}\text{K}^{-1}$ has been adopted. This feature allows furthermore to decrease computational cost.
- Symmetry: The analyzed geometry is a quarter of the entire SPC main structure. Symmetry constraints are included on the boundaries which are been connected to the mirrored ones, in order to solve for the same geometrical and Thermal conditions, along both y and x directions.

2.2 Solid Mechanics

The SM module is employed to give the rules on how compute the displacements in function of the temperatures computed by the HT analysis [5]. The mechanical boundary conditions have been chosen in order to leave the WG external walls free from any constriction, ensuring the boundaries ability to swell. This condition avoids any normal force on the WG walls and any rotation, allowing to compute the complete deformation of the SSPA's induced by the thermal expansion of the materials. This behavior can be implemented inserting a Roller and Prescribed Boundary Displacement conditions with particular settings [6], as explained below.

In order to perform the structural analysis on the heated structure, the SM module uses the following features:

- Linear Elastic Material Model, default: The combining structure and the SSPA's are modeled in this feature in order to compute all the linear elastic dynamics over its constituent materials. The solid model is intended as isotropic and the structural transient behavior as quasi-static.
- Thermal expansion sub-node: the temperature computed by the HT module is inserted in this sub-node in order to induce, by thermal linear elastic formulation, stresses and strains on the materials.
- Symmetry: The thermal expansion induced forces have symmetric application points, due to the geometric symmetry. The surfaces which lie on xy and xz planes, and not assigned to WG walls, are symmetry surfaces. For such reason are assigned to symmetry boundary conditions.
- Roller: this condition has been inserted to specify that the left external surface of the WG can't move along its normal, that is the x direction.
- Prescribed Point Displacement: In order to compute the structural modification, a point has been set with locked displacement over the x coordinate, it can move only on y and x directions.
- Prescribed Boundary Displacement: The combining structure and the SSPA's boundaries are subjected to deformation. The displacement vectors (u, v, w) computed by the TS module are employed to specify this superficial displacement.
- Each WG external wall needs a constant displacement in its normal direction. The right side external lateral surface, laid on the yz plane, can move only on the x direction. The rear lateral surface, which lies on the xz plane, can move only on the y direction. These displacements are unknown and have been computed by adding two Ordinary Differential Equations (ODE's), as described below.
- Global equations: this feature is used to add two ODE additional global equations,

independent to the space coordinates, in order to calculate the unknown displacement of the external boundaries described above. This feature adds two further degrees of freedom to the FEM model. Initial conditions for ODEs first time derivative and for the second time derivative are set to zero.

2.3 Analysis

Since the HT problem is independent of the displacements, the study has been solved by adopting two separated steps: the first stationary step has been employed to calculate the temperature distribution, by the HT module, and the second stationary step to solve for the displacements, by the SM module.

In order to consider the computed temperature resulted from the HT analysis, the information has been inserted as the temperature in the Thermal Expansion sub-node of the Linear Elastic Material feature in the SM module.

By the SM module the meshes of the model has been moved in function of the displacement computed by the Thermal Expansion analysis.

The solver is organized in performing two separated steps: First, a stationary analysis to compute the temperature by using the HT conditions, then a stationary analysis which calculates stresses and displacements by the SM features.

3. Results

3.1 Temperature and Heat Flux

We have imposed a power dissipation of 20 W for each of the 16 MMIC's, considering the conversion efficiency of the used MMIC's.

For the selected SSPA's, 16W are dissipated by the Ended and 4W By the driver. The Ended transistor volume is of $1.3e-11 \text{ m}^3$ and the volume of the driver is $4e-12 \text{ m}^3$. The resulting heat power densities are $Q_{\text{driver}}=1e12 \text{ Wm}^{-3}$ and $Q_{\text{ended}}=1.23e12 \text{ Wm}^{-3}$.

We have in first simulated the temperature at the channels of the MMIC's when the carrier is realized with aluminum; the result is shown in Figure 3.

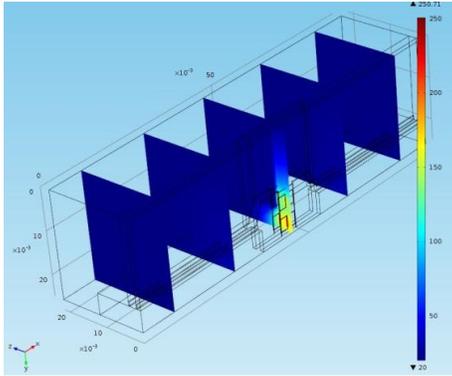


Figure 3. Temperature, with Aluminum carriers.

Note that the temperature in the channel of the final stage is around 250 °C, well above the maximum MMIC allowed temperature. So, we have repeated the thermal simulation when using Copper carriers, and the results are given in Figure 4.

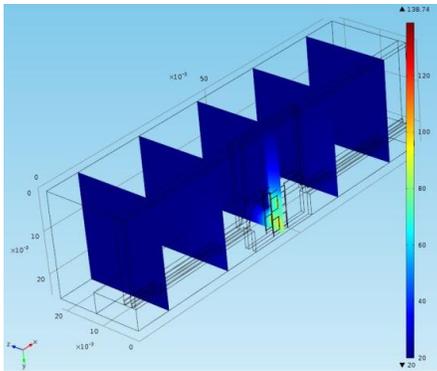


Figure 4. Temperature, with Copper carriers.

In this case, the channel temperature arrives at a maximum of 140°C, which is inside the maximum allowed temperature. The external temperature profile is shown in Figure 5.

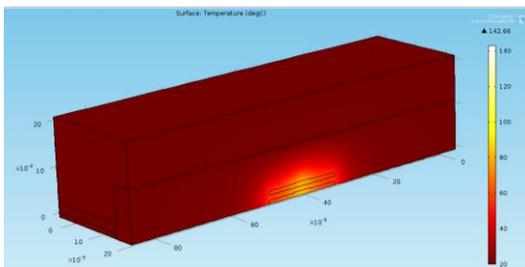


Figure 5. Temperature, with Copper carriers: External profile of the main structure. The highlighted area is the hottest part of the carrier and the air close to it.

It is important to show that assuming an uniform power dissipation throughout the MMIC result in a highly underestimated temperature: in fact, in Figure 6 we have the result for temperature when MMIC power dissipation is assigned to the whole MMIC volume, i.e. an uniform power distribution.

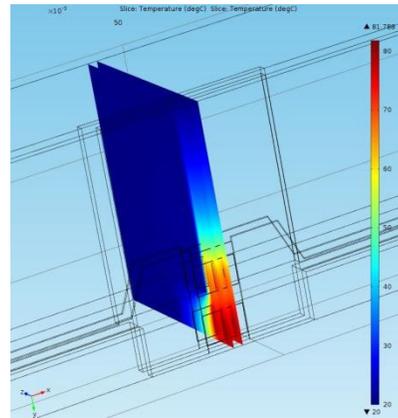


Figure 6. Temperature, with Copper carriers and uniform power distribution: zoom view.

Note that in figure 6 a maximum temperature of 81.5°C is estimated, well below the 140°C simulated in the channel when power dissipation is concentrated in the active device channels. The temperature at the center of driver and ended transistors has been represented besides by using cut planes which bisects the transistors. Results are reported in Figures 7 and 8. The heat flux lines are shown in Figure 9.

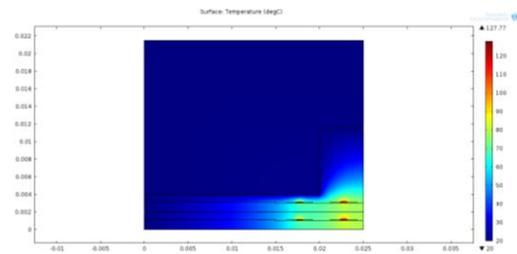


Figure 7. Driver, center temperature – Max 128°C

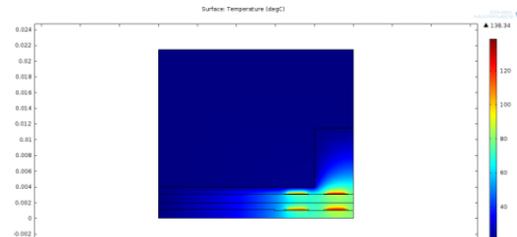


Figure 8. Ended, center temperature – Max 138°C

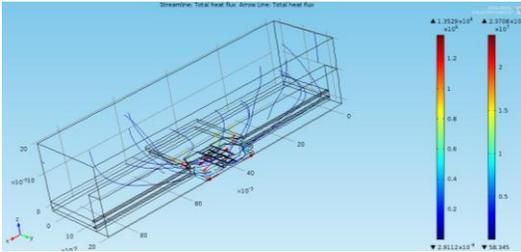


Figure 9. Heat Flux Lines: Power dissipations is ensured by proper copper carriers. The Heat is directed towards the external WG walls.

3.2 Stress and Displacement

By receiving the Temperature computation from the HT analysis, the SM study give us the possibility to evaluate the stress and strain in any part of the structure. Copper carriers are used. In figure 10 we report the maximum stress: it is located near the oblique angles of the cards and locally reaches 0.66 GN/m^2 .

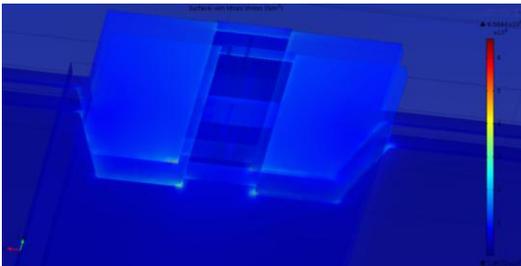


Figure 10. The maximum stress inside the structure.

The maximum displacement is located near the interface between the innermost SSPA's and the slab copper support, which is of $4.9 \mu\text{m}$, enough negligible from the RF guiding properties of the structure but critical for the GaAs MMIC survivability: this is shown in figure 12.

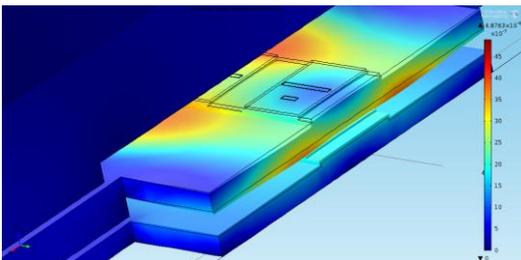


Figure 12. The maximum displacement inside the structure: Black outlines represent the original conformation, stained volume the deformed structure.

This result is very useful, since this displacement value is completely incompatible with the GaAs survivability to displacement: for such reason, an interface layer is needed between the back of the GaAs MMIC and the copper carrier: used materials are CuW or CuMo.

7. Conclusions

The FL SPC technology has been studied using FEM HT and SM simulation with COMSOL Multiphysics. Temperature and consequent stress and displacement under operative conditions are been estimated. This study allows the proper thermo-mechanical design for such amplifiers, so that proper materials for carriers and interfaces between them and MMIC's can be chosen.

8. References

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