# DEMONSTRATION OF A COMBINED ACTIVE-PASSIVE METHODOLOGY FOR THE DESIGN OF SOLID-STATE-FED MICROWAVE OVENS

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**Abstract** – This paper discusses a combined methodology for the design of solid-state-fed microwave ovens. The presented approach joins the design methodologies of both, active and passive component of the microwave oven to deliver to the heating system designers and manufacturers a full advantage of the opportunities brought by the solid-state technology. For the passive component design, new electromagnetic simulation regime is developed to accurately mimic the solid-state source operation and decrease computer effort required for the analysis, making the process more efficient. The combined active and passive methodology is experimentally validated in the industrial laboratory environment for dual-aperture microwave oven prototype and the results are discussed.

## I. Motivation and background

The 21st century is marked by a paradigmatic shift in the design strategies for domestic microwave ovens. Interests are devoted to the ovens fed by solid-state energy sources, facilitating control of power level, frequency, and relative phases [1]. This paves the way for higher quality cooking, e.g., enhanced energy efficiency as demonstrated in [2], where iterative electromagnetic (EM) simulations were run for multiple random source settings.

To take full advantage of the opportunities brought by the solid-state technology, novel design methodologies are needed, in respect of both the active and passive component of the microwave oven. Continuously growing interest in solid-state power sources observed among the heating systems' designers and manufacturers brings the need for a dedicated design methodology allowing for enhancing not only source output parameters but also its reliability. On the other hand, employing new type of microwave power sources in heating systems enforces the practical need for dedicated simulation regimes, allowing for modelling the physical behaviour of sources and therefore, higher practical and physical relevance of multiphysics design and analysis of a heating system. Herein, we report such a combined methodology composed of two steps:

1. Following our early research [3], two-stage solid-state amplifiers based on GaN HEMT transistors by CREE are designed. The output stage of amplifiers is based on a balanced configuration [4]. The proposed design delivers 53.9 dBm of output power over the 2.4 GHz to 2.5 GHz frequency range with power-added efficiency (PAE) exceeding 55%.
2. New FDTD simulation regimes are developed, which allow for dynamic switching of signal parameters of multiple sources, at predefined time-instants or in response to the monitored system behaviour. The heating patterns are accumulated without the need to re-run each simulation from EM zero state. The algorithms are implemented in QuickWave software, well-established in the AMPERE community [5][6].

Experimental validation of the combined active (1) and passive (2) methodology will be discussed based on the industrial laboratory prototype of a dual-aperture microwave oven after [6].

## II. Design methodology for active component

A block diagram of a multifunctional high-frequency-stability microwave high-power solid-state source designed for precise heating is shown in Fig. 1. A VCO/PLL synthesiser generates a low power, spectrally pure signal tuneable within the desired frequency range, e.g. ISM 2.45 GHz band. The amplitude and phase are controlled and set using a digital multi-bit attenuator and phase shifter cooperating with a power auto-levelling block under the microcontroller supervision. A circulator separates the incident and reflected waves, thereby providing the isolation between the source and its load. Together with detectors it further forms two loops – for power auto-levelling and for self-tuning to the frequency of minimum return loss (which varies for a typical time-varying load).

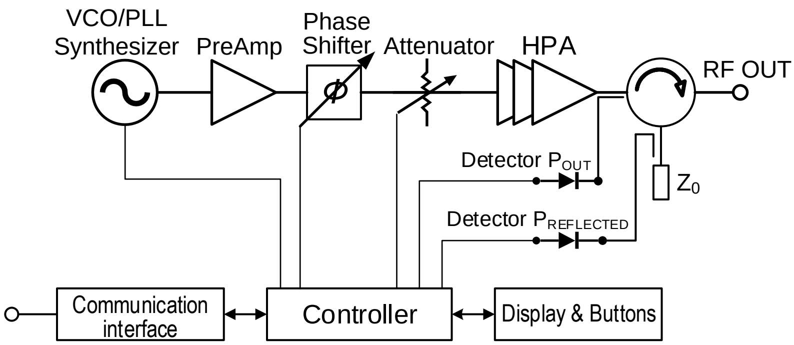



**Fig. 1.** Block diagram of a multifunctional microwave heating source.

The high power multistage amplifier (HPA) is considered a crucial component of the microwave heating source of Fig. 1, as it produces a high-power signal with an efficiency that determines power dissipation inside the active elements. Thus, via the internal temperature of transistors it directly affects the reliability of the amplifiers, and hence of the source. In addition, the amplifier is the most expensive element of the device, constituting ca. 80%÷90 % of the total value. In heating applications, due to the transistor operating in continuous-wave (cw) mode, being usually in class AB, the thermal requirements and restrictions are difficult to be fulfilled. Despite the rapid development of RF and microwave transistor technologies based on wide bandgap semiconductors, such as GaN HEMTs, particularly recommended for high-power microwave electronics, heat management remains a serious challenge [7]. It is worth noting that the output power levels for the transistors are desired to approach the performance of magnetrons classically installed in microwave ovens, and our design methodology presented herein meets this requirement.

For an HPA used in a microwave heating device, thermal effects and reliability are critical. On the other hand, in such applications an HPA does not have to meet stringent specifications critical elsewhere, e.g. linearity required for wireless communication. It is therefore reasonable to optimise the amplifier design primarily for maximum efficiency and output power. In this work, several relevant issues have been considered, including power-added efficiency (PAE), selection of transistors, and microstrip line substrate. This leads to the methodology based on the harmonic tuned method (HT), marked by continuously rising popularity and validated in our earlier research [8][9]. The HT method relies on proper harmonic terminations allowing for a significant increase in both, output power and efficiency.

We have performed design optimisation with a focus on minimising heat dissipation in the transistors, taking into account their availability on the market. The analysis at each iteration of the optimisation process has been run with the Keysight Advanced Design System (ADS) simulator together with nonlinear transistor models provided by the respective manufacturers. The optimisation process has led us to the design methodology based on the following observation (and methodological decisions):

A. GaN HEMT technology has been found favourable over Si LDMOSFET,
B. die transistors allow improving thermal transfer to a heatsink, when compared to package transistors,
C. a two-stage amplifier provides improved performance over a single-stage design.

Table 1 gathers key parameters of the selected GaN HEMT transistor dies. Specifically, Wolfspeed GaN HEMT chips CGH60040D and CGH60075D have been chosen, offering 40 W and 75 W of saturated output power, respectively. Besides the improved heat transfer, their source and load impedance changes within the desired frequency range are small making it easier to design the input and output matching networks.

The complete HPA architecture, together with the power budget, is presented in Fig. 2, while a photograph of the designed and manufactured real-life unit of the microwave heating source can be viewed in Fig. 3. The two-stage amplifier has a final stage in a double balanced configuration. The necessary 3dB/90° power combiners/dividers have been built using WireLine and WirePack sections [10]. The amplifier has been fabricated on the 0.762 mm-thick Rogers RT/Duroid 6035HTC substrate having dielectric constant of $\varepsilon_r = 3.5$, featuring a very high thermal conductivity, whereas the microstrip matching sections near the chip are made on the 0.635 mm-thick Rogers RT/Duroid 6010 substrate of $\varepsilon_r = 10.2$ on the copper plate, providing a significant reduction in the width of the microstrip line.

In order to validate the selected methodology, a more classical reference design has also been performed, based on the decisions opposite to those in bullets A, B, C above. Namely, a single-stage balanced amplifier with two Si LDMOSFETs BLF2425M6L180P (NXP) has been developed (with the use of the same HT method implemented in the ADS simulator), manufactured, and tested under the same conditions as our two-stage HPA with GaN HEMT dies postulated herein.

**Table. 1.** Typical performance of considered GaN HEMT transistors.

| Part number | CGH60040D | CGH60075D |
|---|---|---|
| Frequency range | DC ÷ 6 GHz | |
| Maximum drain-to-source voltage $V_{DSmax}$ | 150V | |
| Maximum channel temperature $T_{ch}$ | 225°C | |
| Thermal resistance $R_{thJC}$ | 3.27°C/W | 1.66°C/W |
| Operating point $V_{DS}$ , $I_{DQ}$ | 50 V, 65 mA | 50V, 0.125A |
| Test frequency | 4 GHz | |
| Saturated output power $P_{SAT}$ | 40W | 75W |
| Power-added efficiency *PAE* | 65% | 65% |
| Small signal gain *G* | 18dB | 19dB |

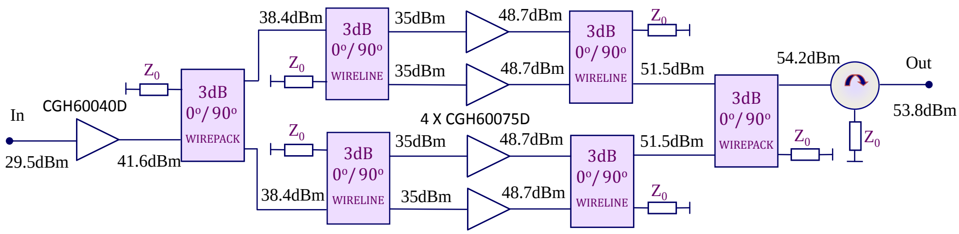



**Fig. 2**. HPA architecture with the power budget (at saturation).

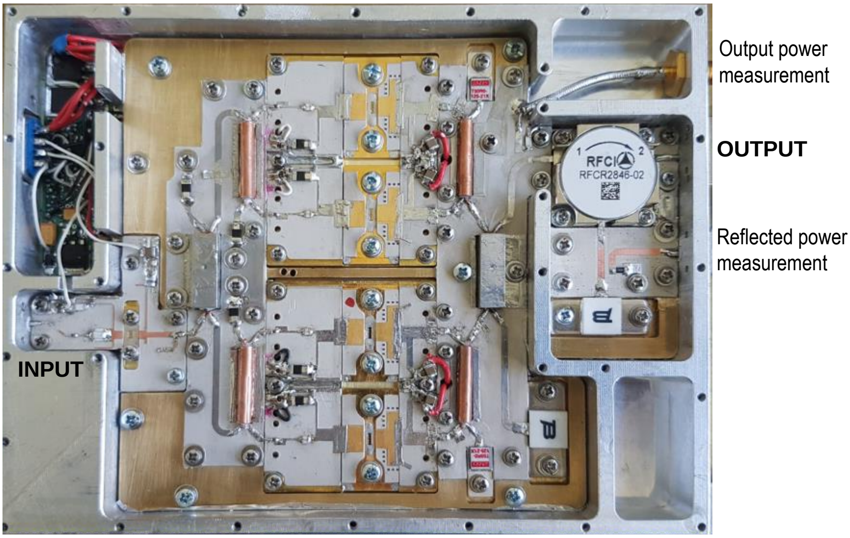



**Fig. 3.** Two-stage double-balanced GaN HEMT HPA for a microwave heating source.

Both HPA units have been subject to a range of laboratory measurements. Two operation parameters have been evaluated: output power ($P_{OUT}$) as a function of input power ($P_{IN}$) and power-added efficiency (PAE) versus output power, within ±50 MHz of the nominal 2.45 GHz frequency. For the reference single-stage Si LDMOSFET HPA, the PAE does not exceed 50% and varies significantly with frequency (by more than 1.5 dB at the saturated output power of 54 dBm in the considered frequency range). The PAE of the entire microwave source designed herein, based on the two-stage GaN HEMT HPA (and including feedback loops with circulator, Fig. 3), is always higher, by as much as 10 percenatge points at saturation. Moreover, gain changes over the considered frequency range are less than 0.5 dB (under similar operating conditions). The measurement results for the two-stage amplifier at three frequencies and for the single-stage HPA at the centre frequency are plotted in Fig. 4.

To summarise, high-power solid-state microwave sources designed with the proposed methodology have been demonstrated beneficial over an alternative design. When tested in laboratory conditions, they also appear a promising alternative for commonly used magnetrons in the field of precise microwave heating. Their practical use further requires a synchronised design of the passive part of the microwave applicator, for which a multiphysics-simulation-based methodology is described in the following section.

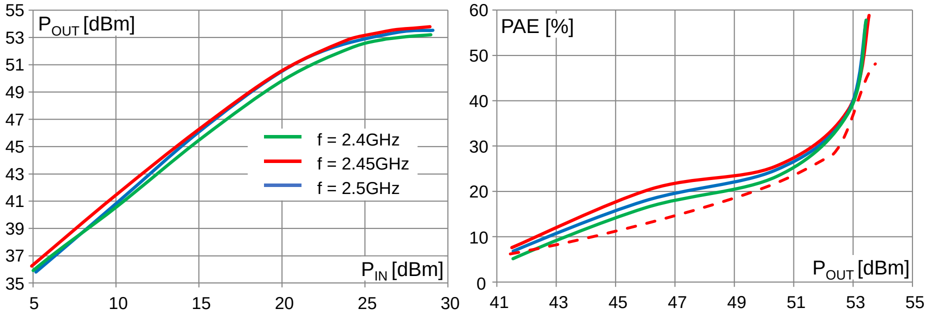



**Fig. 4** Measured $P_{OUT}$ ($P_{IN}$) and PAE ($P_{OUT}$) of the designed two-stage GaN HEMT HPA at three frequencies (solid lines) and PAE of the single-stage Si LDMOSFET HPA at the centre frequency of 2.45 GHz (red dashed line).

## III. Advanced simulation methodology for passive part

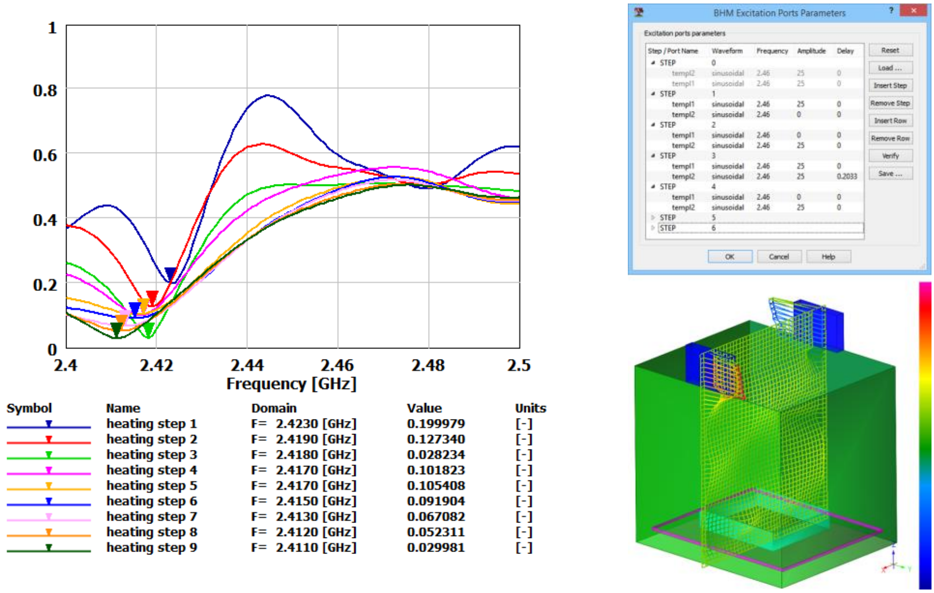
Advances in microwave heating technology require parallel advances in the modelling technologies, in order to take full advantage of new degrees of freedom and new control options. Computational electromagnetics is a core modelling tool. Borrowed in its basic form from common applications to the design of telecommunication systems, it has reached a position of a virtual microwave power laboratory, by means of linking and coupling to different physics solvers relevant to materials heating. Among them, bilateral coupling between electromagnetics and thermodynamics has been proven crucial, especially while considering phase changes. Heat transfer and load movement modelling have also been developed and applied, depending on the system characteristics, e.g. [11].

Now, the solid-state technology brings new control opportunities for microwave heating, as sources can be accurately steered by a computer. This calls for new simulation regimes, where not only load parameters would vary with temperature, but also source parameters would vary over time, either in a pre-defined manner or in response to the monitored system behaviour. In other words, enthalpy pattern in the load should be simulated with high accuracy, by integrating the dissipated power over time. With a view to the different time scales of the electromagnetic process, the thermal process, and the source switching, the overall strongly nonlinear heating process can be approximated by a parametric one and solved iteratively in the time domain, following the approach of [13]. Hence, we utilise the EM-thermal simulations regimes of [11][12] incorporated into QuickWave [13] software and supplement them with new functionalities for source switching at each so-called heating step. Our extended passive methodology provides two options:

1. Dynamic and automatic switching of source operation frequency in response to system behaviour related to varying load conditions (material parameters changing as a function of varying temperature or load movement). For example, the operating frequency in consecutive heating iterations may be automatically tuned to the one of the lowest reflection coefficient (within user-defined frequency range) at current process conditions (Fig. 5 a), hence maximising the power delivered by the source to the load.
2. Dynamic switching of source signal parameters at user-defined time-instants during the heating process, to user-predefined parameters' specification (Fig. 5 b).

This option is prepared to handle all signal parameters controllable in solid-state technology: amplitude, frequency, and also, in case of multiple solid-state sources, relative phase shifts between the sources. The amplitude control mechanism additionally allows for switching off the microwave power delivery, which enables the modelling of heat transfer and temperature equalisation within the load after the heating.

An advantage of the time-domain approach in our methodology is the accumulation of both the thermal and electromagnetic states of the system, with a suppression of numerical spurious solutions [12]. This enables starting each consecutive heating step, before which material parameters are updated with reference to the accumulated enthalpy and calculated temperature change, from non-zero EM steady state reached in the previous heating step. Such an approach eliminates the need for re-running the EM analysis from EM zero state and typically provides an order of magnitude reduction in computing time.




(a) (b)

**Fig. 5.** (a) Reflection coefficient of a cavity representative of a domestic microwave oven loaded with a slice of beef, with temperature-dependent beef. (b) Exemplary user-defined specification of sources' parameters for consecutive simulation heating steps and electric field distribution in the related microwave oven after heating *Step 3*.

## IV. Experimental validation

The combined active and passive methodology has been favourably validated in a sequence of industrial experiments. Due to industrial confidentiality, only one experiment is released for publication [11]. It concerns a dual-aperture microwave oven prototype (designed by the algorithms of Section III) loaded with mashed potato cookies and fed with two computer-controlled solid-state sources (designed as in Section II). The settings of sources are computer-controlled, taking into account a feedback information about the reflection coefficient. In the considered case, both sources have been set to operate at 2.45 GHz and 155 W output power. The mashed potato cookies were heated for 60 s and after completing each test, temperature distribution was measured with the use of infrared camera.

A computational model of the oven has been prepared in QuickWave software using its dedicated plug-in for industrially acknowledged CAD environment, Autodesk Inventor Software. Electromagnetic and thermal parameters of mashed potatoes were set based on our previous experience to $\varepsilon_r$=51.09, $\sigma$=3.012 S/m, specific heat 3.581 J/gK, density 1.01 g/cm$^3$, thermal conductivity 0.005 W/cmK, convective heat transfer coefficient between potato and air 0.001 W/cm$^2$K (approximation of cooling in the oven). Coupled EM-thermal analysis was performed following the simulation methodology discussed in Section III, including phase shift between the sources.

A very good agreement is observed between the results of the physical measurement (Fig. 6) and computer simulation (Fig. 7). It is clearly seen, in both sets of the results, that a change in relative phase shift between the sources significantly influences the heating pattern in the considered oven, modifying the distribution of the hot and cold spots within the heated cookies. They validate our methodology and demonstrate the need for advanced simulation regimes dedicated to the modelling of solid-state sources, in order to develop new technologies enhancing the performance and efficiency of microwave heating systems.

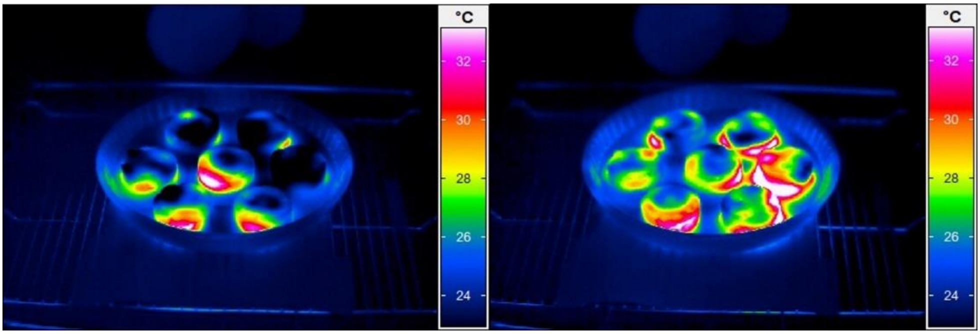



**Fig. 6.** Temperature distribution in mashed potato cookies, measured with infrared camera, after 60 s of heating in the considered oven prototype, for different values of relative phase shifts between the employed solid-state sources. Phase shift between the two presented cases differs by 110 degrees. Photos courtesy of BSH HAUSGERATE GMBH, Traunreut, Germany. Originally published in [6].

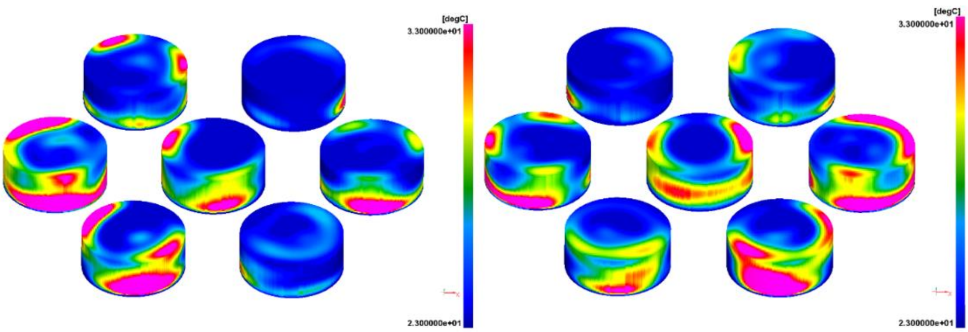



**Fig. 7.** 3D display of temperature distribution in mashed potatoes cookies obtained with QuickWave 3D coupled EM-thermal analysis for the model of the dual-aperture microwave oven prototype: phase shift between presented scenarios differ by 110 degrees, as in Fig. 6. Originally published in [6].

## V. Conclusions

In this work, a combined active-passive methodology for the design of solid-state-fed microwave ovens is presented. A new approach to the design of solid-state microwave power sources, based on GaN HEMT transistors in a two-stage balanced configuration, is discussed and its advantages over a more classical single-stage SiC-based solution are presented, in terms of output parameters and device reliability. Furthermore, advanced simulation regimes dedicated to the modelling solid-state sources behaviour in application to microwave heating systems are developed and implemented in the FDTD-based coupled EM—thermal solver of QuickWave software. The new simulation tools allow taking full advantage of the solid-state technology. The active and passive methodologies have been validated, first independently and then jointly in an industrial experiment.

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