# Solid-State Heating with Advanced RF-Power Solutions

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## Introduction and background

NXP (until recently the Freescale RF power division) has been involved for a number of years in examining and nurturing the transition of the heating industry from magnetron-sourced RF power to what we consider to be a more rugged and flexible solid-state alternative. Initially, this consisted of a number of magnetron replacement amplifiers and self oscillating sources[1-3]. At that time, with the then current LDMOS processes and devices, we were achieving respectable results of 46% efficiency for a 310W dual device magnetron replacement solid-state oscillator. Since that time we have continued to engage with the industry while incrementally improving both device offerings and adding systems and applications support functions. At the 2014 International Microwave Symposium, then Freescale announced the "RF Power Tool", which consisted of a synthesized source, PC software and digitally controlled 2.45-GHz power amplifier that was designed to replace a slew of bench equipment that would normally be required to control and assess the performance of a single amplifier lineup. At the time, we also demonstrated a consumer microwave oven modified with this technology. At the 2015 Freescale Technology Forum, we presented our technical efforts[4], and at the 2015 Int'l Microwave Symposium we went a step further and presented a touch screen driven consumer oven with accompanying cooking demonstrations. At the recent Int'l Microwave Symposium[5] in 2016, we demonstrated one of our current customer engagements by showing our technology integrated into the Wayv Adventurer portable battery powered RF food heater[6,7]. At present, interested parties can assess the current device lineup on the NXP website[8]. Current component offerings consist of the plastic packaged LDMOS MHT1003N with typical PAE of 59% at 250W, and the MHT1004N with typical PAE of 57.9% at 300W. To complement these final devices, the MHT1006N (P1dB compression of 10W), and MHT1008N (P1dB of 12.5W) driver devices are available. Lineup's and application fixture data are also available. We are also demonstrating integrated solutions using the above parts and the MKW40Z Kinetis wireless micro-controller (MCU) combining RF source and MCU with a MMA25312 low power pre-driver.

## The solid-state design solution

At the recent 2016 Int'l Microwave Symposium, NXP and competitors displayed a number of oven concepts integrating their various RF transistor technologies. This year, as opposed to previous years, all demonstrations displayed were portable in nature, presenting physical form factors that would be difficult to achieve with magnetron systems in addition to the ability to operate under battery power. These physical attributes define some of the immediate applications that solid state lends itself well to. But the promise of solid state also revolves around an ability to improve some of the aspects of microwave ovens that frustrate their use. That aspect list would likely be topped by the often inconsistency in heat distribution - that is some food parts cooking well, and others remaining undercooked. To counteract this, microwave manufactures have various technologies in play, including turntables and oven cavity shapes - for example rounded cavity corners and oven wall pressings. An examination of patent filings will show the creativity in this area. Most oven manufacturers today seem to have abandoned the use and expense of additional mode stirrers. In solid state ovens, however, it is possible to affect active mode stirring without the expense of mechanical stirrers through the use of both frequency and phase adjustment of a number of sources. The exact number and placement of sources for stirring is best determined by the electromagnetic modeling of the desired cavity and/or by experimental validation. With good application of the above methods NXP has been able to show considerable improvements in even cooking.

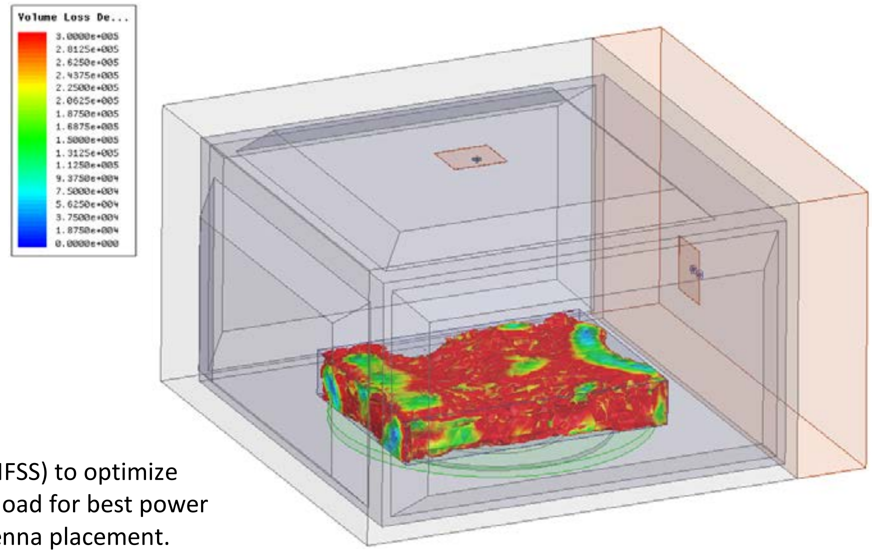


**Figure 1.** Using a simulator (HFSS) to optimize (for highest loss) a pan sized load for best power distribution by adjusting antenna placement.

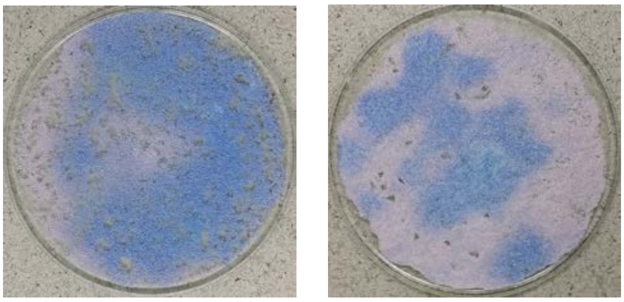

**Figure 2.** Colour changing desiccant identifying power distribution with (a) solid-state mode stirring enabled (left), and (b) no mode-stirring in a magnetron system (right). The Blue areas have had water boiled out of desiccant.

The second common issue with ovens is the variable nature of cooking time, and is also somewhat related to mode stirring. If the food item is placed in a low electric-field point (a heating cold spot) on the turn table, then most likely it will take a different amount of time to cook than the same item placed differently. In addition, most consumer microwave ovens are setup to pass the Int'l Electrotechnical Commission IEC-60705 standard efficiency test to an overall system efficiency number that is currently approximately 56%, via a method which consists of a large water load that presents a good match to the waveguide coupled magnetron. In practice, as shown in Table 1, it is possible to repeatedly achieve ~90% or greater simulated and measured cavity efficiency (from antenna to water test).

In almost all other loading conditions, i.e. most food cooked, the loading conditions are somewhat inferior in power coupling to the cavity and hence efficiency of the system drops, sometimes drastically for example in the case of frozen food. So to summarize this point, there are two predominant technical issues in play:

(1) Spatial consistency of heating, or in technical terms – mode stirring for an even distribution of power.

(2) Variable efficiency of heating, or in technical terms – adjusting source parameters for load matching.

Spatial consistency can be fixed in the solid state application as discussed above. In its crudest form this may simply be a random number generator picking frequencies and phases at will, in order to create as much mode chaos as possible in as many sources, and hence as many modes as possible. The quality of the random number generator is of utmost importance here.

Variable efficiency of heating can also be improved for loads other than well matched. Basically we are looking to match our solid-state PA's into the cavity launches (antennas or waveguide transitions) without the use of discrete auto-tuners. This is possible again by using the precise frequency and phase agility of the solid-state source in combination with return-loss measurements. This leads to the need for optimization algorithms.

**Table 1. Measured Efficiency for a cavity driven by two RF power sources**

| Test | To (C) | Tf (C) | | delta_T | | Time (sec) | Pabsorb (W) | P_RFin (W) | | Cavity Eff. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 25 | 43 | = | 18 | | 240 | 314.0 | 362 | | 86.7% |
| 2 | 25 | 43 | = | 18 | | 240 | 314.0 | 361 | | 87.0% |
| 3 | 24 | 42 | = | 18 | | 240 | 314.0 | 351 | | 89.5% |
| 4 | 24 | 43 | = | 19 | | 240 | 331.5 | 366 | | 90.6% |
| **Avg 4 test** | 24.5 | 42.8 | | **18.3** | | 240 | **318.4** | 360 | | **88.4%** |

### Algorithmic pressures

Essentially when you have a microwave oven with a number of sources, each with a phase, frequency and amplitude parameter that needs to be adjusted, you end up with a large simultaneous system of equations with each system row solving for return loss. Overall, you are looking to solve and minimize the system for low total average return loss and high power transfer into all sources. With only one solid-state source your simultaneous system breaks down and the chances of clear parameter convergence, that is the chances of all parameters being mutually inclusive, is high. As the number of sources increases, or cavity loading level decreases, then some mutual exclusivity may come into play, and we end up with a compromised solution. For best compromise we can address standard methods of optimization for these types of problems[9] as considered in Table 2.

An antenna measurement of the frequency vs. return loss into a poorly loaded cavity, i.e. empty or near empty, shows many narrow modes of resonance separated by poor return losses. Basically we need to find all the reasonably well matched cases if we are going to ensure good power transfer into the cavity, such as implementing a 1-bit threshold detector. Newton or Gradient methods that simply assess curve slope and look for a minimum are not going to be suitable as they will likely lock into a local minimum. The Random method, which basically suggests that we run a random number generator for as long as reasonable, and try to pick out the well matched cases, has a chance of looking at every phase, frequency combination for each source but will likely take a long time and require a lot of data handling. For this reason, conversion rate is poor.

This of course is only a small list of possible methods in a very large area of research, but the key point to note here is to some extent conversion rate. With a good number of sources (with each likely 250W or perhaps 500W) collecting return loss data for every phase and frequency setting of a source will take considerable time. So it is a tradeoff between complexity, data bandwidth, and usability. If the user of an oven is going to place food in an oven for 30 seconds, how long will that user tolerate the oven looking for a best match and evenness parameter setting condition before doing the business of real cooking? So it needs to be fast.

**Table 2: A comparison of global iterative methods for optimization problems[9]**

| Method | Global Capability | Discontinuous Function | Nondifferentiable Function | Conversion Rate |
|---|---|---|---|---|
| Gradient | Poor | Poor | Poor | Good |
| Random | Fair | Good | Good | Poor |
| GA | Good | Good | Good | Poor |
| PSO | Good | Good | Good | Fair |
| Taguchi | Good | Good | Good | Good |
| SA | Good | Good | Good | Fair |

## Active load-pulling and circulators

For cost conscious systems design, it could be desirable to operate a PA without the use of circulators that protect the final stage transistor from being load pulled. The issue here is that due to the highly reflective nature of the cavity, if significant mutual coupling exists between sources, then it's certainly possible to actively load pull one PA from another (or itself), and therefore we would need to de-embed the load pull contour from our detector power measurements (in order to correct measurement data). As the number of sources goes up, this becomes increasingly compromised.

At NXP we have managed to successfully run circulator-free systems into a two source cavity, however these were into more or less perfect loading condition's (IEC test) whereupon the sources were also naturally decoupled and resistively matched. Using the algorithm to decouple the sources, ensure maximum power transfer, and affect some evenness, adds additional complexity and compromise, which in many cases defeats the optimizer. It is an area of continued interest however and certainly not beyond the realms of possibility that it can be solved via topology or similar investigations.

This brings into view scalar vs. vector detection of forward and reflected power for each source, but within the scope of this article we have defined the optimization problem essentially as return-loss minimization at a resonant point (or points) which are naturally resistive in nature, and have low enough return losses (which being lost on a reactive SWR circle is not of prime concern). But a look at the load pulling relation will show that information is being missed that may be necessary to de-embed in certain demanding situations, particularly poorly loaded (reactive) conditions. Of course, ideally you can combine all of the features in this article so far and attempt to optimize it as a complete unit using linked circuit and field simulators as in Fig. 4.

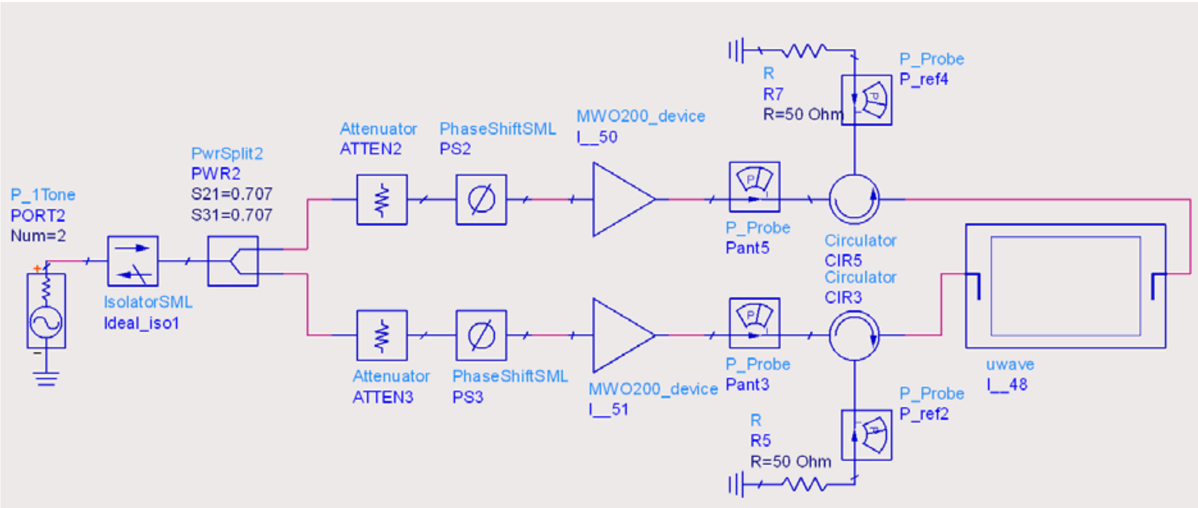


**Figure 4.** Simulating both system and cavity using the inbuilt optimizer and implementing all system phase and frequency functions (ADS & HFSS).

## Conclusions

An attempt has been made in this article to present somewhat of a roadmap for enterprises and research organizations when considering a move to solid-state RF heating and when faced with system architecture issues by leveraging the NXP/Freescale experience thus far. As in any system development activity, one tries to align cost and time targets, internal tool chains, and technical capabilities. An internal processor platform preference and software tool chain investment, together with vendor flexibility and high operating margins, may lead one to select the safer modular architecture and in other cases costs may dictate integration at the expense of risk and development time cycles. These are questions for the seasoned systems architect.

One possible approach to start is selection and optimization of the cavity efficiency and evenness for a given load condition, ideally using one of a number of excellent simulation tools available today. Overall power levels can be chosen based on desired cooking times and scale more or less linearly (as long as food phase state changes are avoided i.e. boiling conditions), as follows:

$$P_{new}\Delta t_{new} \simeq P_{known}\Delta t_{known}$$

Once the location and number of sources for a cavity shape has been determined for a desired overall power level and evenness and efficiency, it is possible to make decisions regarding transistor device selection. If we ignore ancillary losses in the system and assume that when well matched the antenna or transition is operating at close to maximum efficiency (typically better than 95% for an air loaded basic antenna element), then we can break the system problem into a straight forward efficiency calculation consisting of (a) cavity efficiency, (b) PA efficiency, and (c) power supply efficiency, as follows:

$$\eta_{Total} = \eta_{Cavity}\eta_{PA}\eta_{PSU}$$

In one example, if we achieve 59% PA efficiency and use a 95% switch-mode power supply, and achieve 95% cavity efficiency under very good loading to IEC test specifications, we achieve an efficiency of $\eta_{Total} = 53\%$, not that far from consumer regulatory limits, and more than suitable for many commercial and industrial applications.

Whilst this article has provided somewhat of a roadmap, details of implementation are wide open to selection, from cavity size, structure, source placement, specific improvements to optimization methods, not to mention hardware modularity, additional sensors, and food recipe development. All of these provide prospective vendors opportunity for IP protection and differentiation.

## For Further Reading:


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## About the Author

**Gregory Durnan** is a member of the NXP RF-Systems and Solutions group engaged in R&D to enable and demonstrate solid-state RF power devices in the consumer, commercial and industrial spaces. He has a varied industrial electromagnetics and RF design background having worked in the defense, cellular, GPS, scientific NMR and medical fields from R&D conception through to product release and manufacture in Australia, Japan and the US. He has approximately 20 published and presented works and holds a first-class honours degree and PhD in RF and Electromagnetics from the Radio Science Laboratory at Griffith University, Australia. He graduated with distinction in Electrical and Electronics Engineering from the Australian Maritime College (University of Tasmania) and holds a MBA from the University of London.