Solid-State Microwave Cooking

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Cooking by solid-state microwave systems has been proposed and discussed over many years. A number of patents from the 1970's present the concept of using RF amplifiers to heat food in a solid-state microwave oven. As often happens, the imagination of the global community of inventors has been working out the exciting possibilities of this new field well ahead of the decades of hard work in semiconductor processes that has been required to make it a practical reality.

RF-power amplifiers are not the subject of Moore's famous extrapolation, which has predicted the exponential growth in processing power of the last fifty years. Making transistors ever smaller with lower operating voltage is great for digital circuit density, but for high power amplifiers, big is beautiful. A single high-power RF transistor can handle peak currents large enough to start a small car.

Communications and radar applications have been the big driving forces behind transistor development, which are both high value applications with (typically) high peak to average power ratios. Solid-state cooking (SSC), by contrast, has a peak to average power ratio of 1, and, to be successful, must be compatible with pricing of consumer ovens.

Generation after generation of LDMOS transistor technology has been optimized for current markets, leading to an LDMOS-law of around 3% of efficiency improvement every 2-3 years. Like Moore's law, this will slow as physical limitations become apparent, but it has been broadly valid for a decade. Through this steady incremental increase in efficiency, and accompanying power delivery capability, semiconductor companies can now supply devices that make good on the hopes of those early inventors. History shows how quickly transistors can completely replace valves when such a tipping point is reached.

Technical capability is of course only half of the story; cost targets must also be met to reach a tipping point for new technology. As consumers, we could all estimate for ourselves what we would be willing to pay for a better oven. While this of course depends on how much better the appliance is, and what difference it makes to our lives, it is bounded in practice. If a breakthrough technology costs ten times as much as an incumbent technology, a few systems may be sold to soccer stars. If the cost is double, perhaps we might expect single digit percent market penetration could be achieved. To corner a significant fraction of the volume of the magnetron equipped oven market, we might estimate that the cost at point of sale must be somewhere between parity and double, benefit dependent.

A virtual shopping exercise can be performed on different segments of today's microwave market, the countertop and built-in segments. Based on cumulative density function (CDF) price analysis of 100 each type of oven (Fig. 1), countertop microwave ovens today range from sub $100 at the low end to a high end in the range $500-$800. Prices for built-in systems can exceed $8K. If SSC system solution is compatible with an oven sales price of $1000, we can assume that the full countertop market is excluded but more than 80% of the built-in oven types are theoretically accessible.

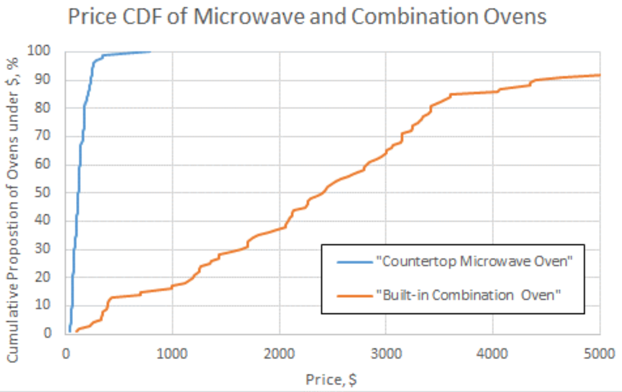

Figure 1. Price CDF's of two market sub-segments for subsystem cost target estimation

Considering the fact that oven ex-works prices can be 1/3 of the high street price, and allowing the SSC system to comprise 1/3 of the manufacturing cost of the oven, we can make a working estimate target cost of ~$100 for the whole RF subsystem.

Of course, every consumer will make their own estimates of acceptable cost for a better cooking solution, and each manufacturer will devise its own targets for subsystem cost based on how much of which segments they wish to enable with the new technology. The estimation process undertaken here simply gives an indication that even if the RF power transistor was free, a lot of other cost optimization work needs to be done to make the volume SSC market a reality.

Cost, efficiency and thermal performance are three key parameters for solid-state devices for this new market. The lower the electrical efficiency, the greater the thermal design challenge, which is relevant at all stages from the die to the kitchen. Lower cost transistors with lower cost materials must have high peak efficiency and excellent thermal properties. However, it does not stop there. The RF heating amplifier must dissipate many times the heat energy of a comparable base-station amplifier, as shown by comparing the estimates in Tables 1 and 2.

Table 1: Thermal and efficiency characteristics of a typical base-station PA

P-out	40	W
Frequency	2,140	MHz
Peak to average power ratio (PAPR)	8	dB
Peak efficiency	-	
Efficiency at average power	45	%
Peak power	252	W
Thermal dissipation	49	W

The requirement for high efficiency at average power levels for complex amplitude and phase modulated communication wave-forms has driven semiconductor device optimization towards efficiency in load modulation architectures, such as the Doherty or Outphasing PA, with low average power dissipation being more important than low peak power dissipation.

Table 2. Thermal and efficiency characteristics of a typical RF-energy PA

P-out	250	W
Frequency	2,450	MHz
PAPR	0	dB
Peak efficiency	60	%
Efficiency at average power	-	
Peak power	250	W
Thermal dissipation	167	W

RF power delivery applications have very different requirements including higher frequency, emphasis on efficiency at peak power (rather than average power), and significantly increased thermal transfer capability, all at lower cost.

Lower cost, higher efficiency and improved thermal capability are all being delivered at the device level, as semiconductor companies push towards 65% efficient 250W low-cost solutions, but what of the rest of the system?

Power amplifiers

The power amplifier (PA) must also be low cost. Many of the standard design and construction techniques used in base-stations are likely to be too expensive for truly low cost amplifier production. High performance substrates are almost universally used in power amplifiers, and copper heatsink ‘coins’ are used to spread the heat from the power device into a thermally poorer aluminum heatsink. Low cost circuit boards are typically multiple layer FR4 assemblies with high functional density, but poorly controlled impedances. Coins require an extra assembly step that reduces yield, takes a lot of time (thermal mass), and requires an extra assembly station. Further, todays PA’s are often tuned in production with many ‘soft-pot’ settings used to configure gain ranges and bias settings during production, and parametric test stations are needed to verify correct assembly. Both steps require interface hardware to be included in the design, and add significantly to the production minutes for every module produced.

One body of knowledge exists today relating to production of high volume low cost electronics. Another body of knowledge is available on high performance PA design and production, but today these two have, to the best of our knowledge, never truly been mixed. A new way of producing PA's is needed to enable consumer high-power RF market opportunities (at least for the non-footballers amongst us). Without access to a crystal ball, we can only try to predict some of the key focus areas for effort:

- High power PA assembly without a coin
- Zero tuning PA production
- Zero test PA production
- Minimizing high performance substrate content
- Maximizing use of high density multi-layer FR4 technology
- Minimum use of expensive metals like copper and gold
- Smaller PA modules to reduce materials cost

All of which must be achieved while improving thermal dissipation behavior compared to today's PA modules for pulsed or high peak to average signals.

Power supplies

Today's microwave ovens use a stepped up AC power arrangement, which requires a heavy but simple transformer-based power supply. Power amplifiers need DC supplies that must be generated using high efficiency AC to DC converters. The efficiency of the PA is multiplied by the efficiency of the converter, so both should be high performance and low cost.

Microwave ovens today are rated by the power they can deliver into a 1-liter water load. Both the wattage and the efficiency of the microwave are advertised at point of sale and are derived from the same simple IEC-705 heating test. A common power rating of 1,000W means 1,000W can actually be delivered into a good load in the oven. This typically equates to around 1,150W at the output of the magnetron, and ~1,600W AC. Overall system efficiency is impacted by the efficiency of energy transfer to the load, inherent magnetron efficiency and power supply efficiency. RF amplifiers with 1,150W RF output power and 60% efficiency need a DC supply capable of supplying 60A at 32V. Power supply (PS) efficiency of 90% reduces the efficiency of RF power generation to 54%. At these example levels, increasing the PS efficiency by 1.5% achieves the same system efficiency enhancement as 1% of RF power transistor efficiency. High efficiency switched-mode power supplies also require high performance power transistors, demonstrating that the SSC market is truly being enabled by big transistors with high efficiency at low cost.

Excitation and Control

Systems will also need RF small signal generators and control circuitry, which are generally compatible with high density PCB assembly, and should not be a significant barrier to market development in the new field. The control algorithms may vary dramatically in complexity from application to application, and may require more digital processing power than today's microwave ovens due to the enhanced control variables and sensor complexity.

Cavities

An oven cavity, arbitrary food load included, is a passive structure and can be analyzed like any other passive structure. S-parameters are used for optimizing microwave filters and other small signal RF circuits, and so they can be useful for understanding a cavity design. The same techniques can also be used to track the evolution of the cooking process as the food, and therefore cavity behavior, is modified by the cooking process. The S-parameter plots in Fig. 2a,b,c show the same two port cavity measured with a vector network analyzer (VNA) with three different load states from 2,300 to 2,600 MHz. The load is an integral part of the cavity, and the port characteristics and field patterns change significantly when the load is increased. A broad de-Qing of the cavity occurs when a lossy load is incorporated into the structure, and it can be clearly seen that when cavity insertion loss (S_{21}) is highest, port reflection (S_{11}, S_{22}) is high also, suggesting that cavity retained power management is a key dimension of system operation.

Algorithms

Knowing how to operate an SSC system is critical to results. Taking a reverse look at the problem, a solid-state system is capable of much greater stability of power delivery into a single cavity mode which means a more stable pattern of hotspots in the food. Much worse cooking is possible with the added control of solid-state systems than with legacy magnetron systems with unstable frequency of operation can ever achieve.

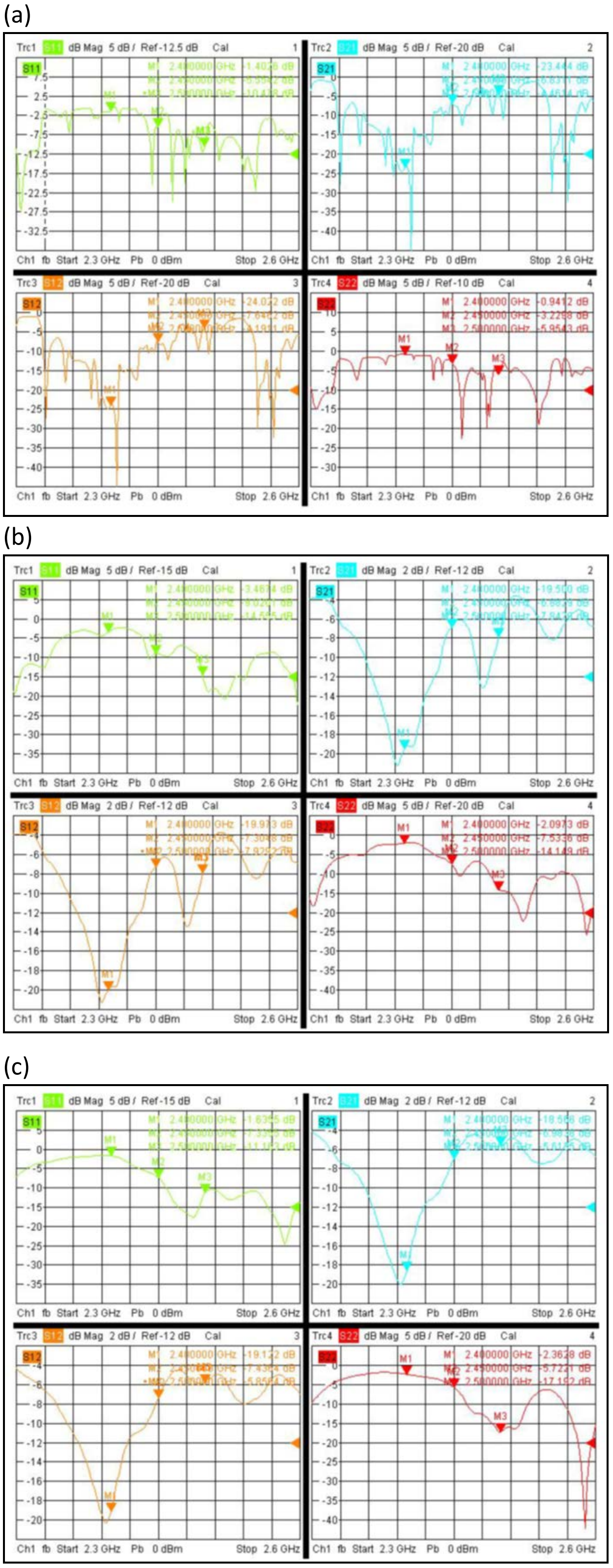

Figure 2. S-parameter measurements for an empty (a), partially loaded (b), and heavily loaded (c) cavity

The reverse example above demonstrates why it is not meaningful to evaluate the SSC performance without considering the effect of the algorithm used, and why good algorithms will be vital for product differentiation in future.

Algorithms can be categorized along various axes, as follows:

- Deterministic / Adaptive
- Coherent / Multi-frequency
- Sweep or S-parameter based learning
- Efficiency or diversity optimized

When considering algorithms for SSC, an early question to ask is whether the food is repeatable or variable. For well controlled foods located in a repeatable position within a cavity, it is possible to create a fixed-frequency phase and power sequence that delivers an optimum result. The enhanced stability and repeatability of RF energy delivery compared to the free running magnetron oscillator is the key enabler in this scenario, along with the added control variables that allow more field patterns to be generated and evaluated for inclusion.

For general cooking purposes, the food is not well controlled in shape, size and material content, so it is not possible to pre-prepare an optimal heating sequence in the lab. Generalized algorithms must be created for general cooking purposes. Generalized algorithms can still follow a prescribed sequence, hardcoded in the oven firmware, but it can be advantageous to integrate input from all sensor channels to create an adaptive heating sequence that responds to the cavity environment for any food type.

The plots in Fig. 2 were taken with a VNA, but Ampleon’s demo systems integrate the measurements of cavity power delivery into an oven. Detailed ‘fingerprints’ of the load can be sensed in this way, which provide feedback from the changing dielectric and structural properties of the food as cooking proceeds.

Optimizing heating algorithms for a food type is primarily an empirical affair, extending the techniques used for optimizing magnetron oven cooking with the extra dimensions of control available. Magnetron based ovens are optimized by tuning the port match and location by ‘metal shaping’ methods. Each configuration is tested with a range of food types, and the performance is quantified to allow results to be compared. SSC systems still require antennae, which also need tuning into the cavity, and the antenna placement still affects the range of possible field configurations. However, instead of (typically) only one feed point with poor frequency control, the system can have multiple feed points with accurate frequency and phase control, as well as accurate, repeatable power control. Power amplifiers, just like magnetrons, suffer from a small loss of power output as the internal temperatures increase during extended use. However, the magnetron can only run ‘flat out’ whereas incorporation of power sensors and linear power control allow a power amplifier to be operated just below peak power. As the amplifier heats up, perhaps when multiple ready meals are heated sequentially, there is margin left to continue to deliver the rated power of the oven. The system is able to cook more repeatedly from test to test simply because the power is controlled.

In addition to the metal shaping techniques that the current magnetron oven optimization process is based on, solid-state ovens will perform differently, depending on how the power is used. This dimension of system tuning simply does not exist for the incumbent technology. In the future, multi-physical models of food may be developed that allow a simulator to predict the cooking quality of a prototype cavity design and algorithm.

To achieve this, the simulator needs to be able to convert EM-field patterns to thermal input, and allow for heat flow in complex structures comprising lossy non-homogenous dielectric materials. Changes in both parameters and structure of the food must be taken into account such as a cake rising as bubbles form in the batter. Such a familiar process is physically quite complex, involving structural changes, fluid flow, phase transitions and chemical changes.

Once libraries of food models are available with all the right processes incorporated, the capabilities of EM simulators will need to be modified. Solving a structure for field distribution at one frequency is just the beginning, as the simulator must be able to predict the heating effect of the algorithm in the form of multiple constantly changing variables affecting cavity field excitation over time. Further, variable cavity port impedances can affect each amplifiers power delivery which in turn affects the cavity fields and port impedances. Simulating this requires power amplifier load pull simulation to be integrated with food and cavity simulation.

Until a single simulation platform is capable of all of this, solid-state oven development will remain a mixture of theoretical insight with practical experience and, like so much of RF – something of a black art.

Demo system

To help explore new RF Energy applications, Ampleon has developed a demo system (Fig. 3) controlled via TCP/IP from high level software such as Matlab or LabVIEW. This way of working, along with a number of example demonstration algorithms that can be used as a start point for heating investigations, ensures a rapid learning curve for teams interested in evaluating these new and exciting techniques.

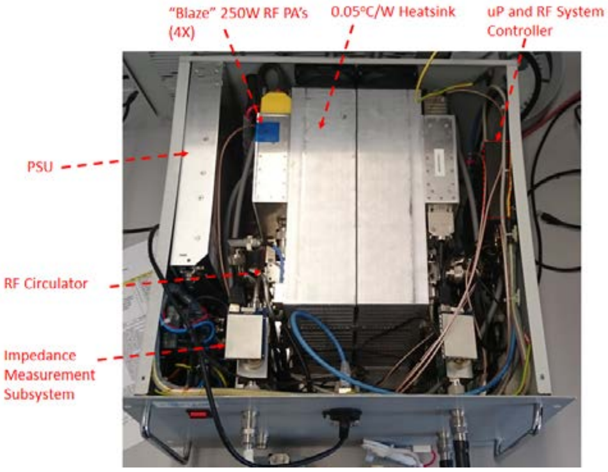

Figure 3. RF-energy demo system for R&D purposes

While it is not designed for low cost production (Fig. 4), or to facilitate integration into a cavity, more than twenty of these units have been built, supporting the necessary boot-strapping of an entire new industry. However, when the ‘replacement value’ of a solid state RF system is taken into account, comparisons should not be made with low volume demo systems being used for R&D, even in terms of system architecture. Future systems may need to fit the model developed in the current microwave market, which has implications for module level functionality but also the shape of the supply chain.

Today, most microwave manufacturers source their magnetrons from only a handful of suppliers, and these modules are very low cost. The production and test of magnetrons has been pared down to the minimum number of steps by decades of competition.

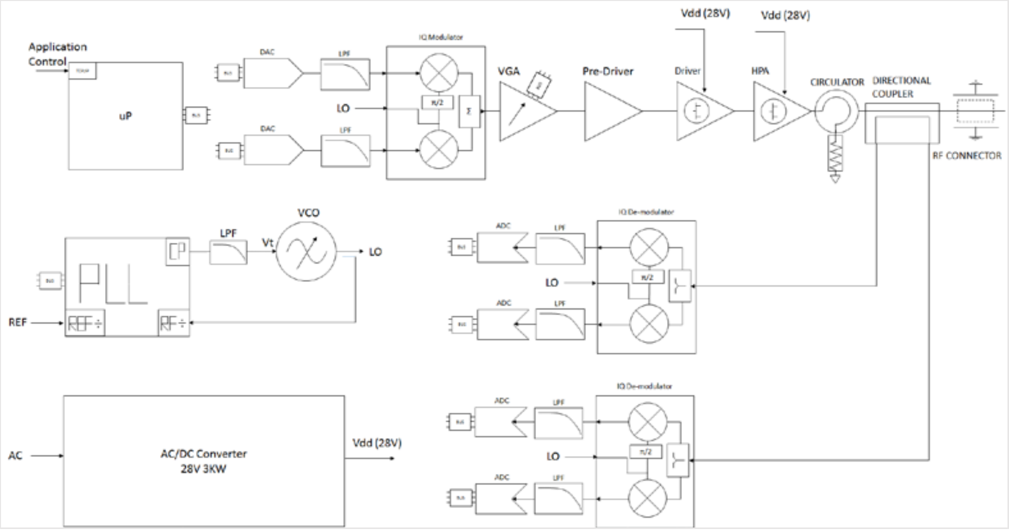

Figure 4. The demo system block diagram

Whilst it is unlikely that solid-state will compete with the magnetron on absolute cost terms in the near future, it is increasingly clear that the control availability brings true breakthrough potential in this industry, a view supported by the number of R&D hours being put in by teams in lab-kitchens around the world.

If the supply chain for SSC does follow the supply chain for magnetrons, huge volumes can be the prize for the organization willing to learn the necessary lessons to produce low cost ‘magnetrons’ by embedding a highly accurate solid-state RF engine into a form factor familiar to oven manufacturers today. Semiconductor companies play an important initial role in this, to ensure their products deliver the right performance at a suitable price point. They can also go above and beyond this by helping create the key knowledge required in adjacent areas such as system architecture, operational algorithms and low-cost manufacture, but ultimately all these choices will fall in the domain of the manufacturer.

Conclusions

SSC is no longer an abstract future concept, as it was when those first patents were drafted in the 1970’s. It is happening in a lab near you, and momentum is gathering for the first volume product launches. Two key pillars are involved. Firstly, research into how to best use the enhanced precision, additional control variables and integrated measurement capabilities of solid state technology. Secondly, cost down investigations into mass production of electronics that were in the past the preserve of seldom seen applications and high-tech companies.

For further reading:

Several manufacturers have developed oven prototypes, but no information yet in the public domain. However, early market entrants are:

1. *Midea Inc.* recently announced the launch of its first product: www.everythingrf.com/News/details/2330-ampleon-and-midea-develop-first-commercially-available-rf-energy-oven
2. *Ampleon Inc.* has a white paper with more technical background on the solid state cooking application, available at: www.ampleon.com/white-paper-solid-state-cooking

About the author

Robin Wesson is an RF System Architect with Ampleon’s RF-Power Innovation team. He has worked as an RF circuit and system designer for twenty years in the UK, US and Netherlands. During that time he has designed Private Mobile Radio handsets and infrastructure, ISM short range communication systems, RF over fiber distribution systems, RF location systems, 3G/4G Base-stations, and Satellite TV receivers amongst others. He is currently active in RF-energy systems and switched-mode out-phasing PA’s.