# Mode Picking and Algorithm Considerations in Solid State Microwave Development

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## Introduction

Many vendors of appliances have discovered by themselves, or through the pages of AMPERE and like publications, the basic hardware arrangement necessary to implement a solid-state microwave oven. In some cases, the struggle is with hiring the appropriate RF personnel and in other cases with the details of the implementation (and cost) of the Oven. In AMPERE-Newsletter's Issue 89, a number of articles appeared that gave the potential vendor a good look into development activities, particularly from RF-power transistor vendors. In that articles, the authors suggested various aspects of current magnetron ovens that could be improved, one of these being the consistency or evenness and this article deals with that topic.

Therefore, at NXP we have continued our R&D in this area, and have focused on the algorithm development in conjunction with hardware arrangements that may provide a suitable or superior basis for system development. A key part of this is the development of the algorithmic content that allows simplification of the system, or general purpose algorithmic solutions. The latter can then be used by the vendor to focus on the food science surrounding the cooking of dishes, using the algorithmic controls we have made available in solid-state arrangements. These include the precise setting of phase, frequency and amplitudes.

In our last article in Issue 89, we suggested that simply using a random number generator for the selection of phase and frequency could lead to improved evenness in the cooking result. This is true, but we have since focused on understanding how we can improve this further, particularly in near empty cooking cavities, that being the cooking of frozen or small items that loads the cavity little, and results in considerable reflected power. As a result, we modified our R&D processing software to look at:

(1) The mapping of the load conditions for various antenna launches.
(2) The use of parasitic elements such that we can reduce the need for a number of sources (and hence a costly system, something white goods vendors have had trouble with).[1-4]

Figure 1 displays the components that we typically program to effect R&D around this activity. We have internally developed sources to control phase, frequency and amplitude, along with computer software that makes modification and testing possible to try a number of avenues of thinking in this regard.

By mapping the phase vs. frequency behaviour of various loadings using various launch types, we can then begin to target a cavity and antenna system solution of interest to us. For example, if we directly couple our energy into the oven cavity via a linear antenna (i.e. a dipole or similar), we get considerably different loading properties than if we couple via an aperture (waveguide) or an array (i.e. patch) with multiple linear or circular line sources.

What we have found is that the use of some antennas like a patch antenna give us a phase frequency map under heavy loading that needs little consideration from the system controller with respect to improving efficiency. For example, under heavy loading, we may find that a patch-fed cavity may have a return loss of 15 dB or better across a large area of the phase-frequency space, suggesting a simplified system and possibly a large increase in the number of modes available to couple into. However, in near empty cavities we can look back at some basic analytical work with regard to modes and determine how many, and at what frequencies these should occur. Given this information, we can then go further and sum the electric fields for which we analyse for evenness. For example, if we analyse all modes in an empty cavity, there may be little point in picking some of them (especially degenerate modes) that may exacerbate an uneven cooking result. We want to focus on those modes under these conditions that yield a superior level of evenness.

Of course, this method of predicting an even cooking result can only hold true of empty cavities. Beyond that we must look at the experimental results obtained from a frequency vs. phase scan, as the derivation of an analytical result for complex loading (as seen in real food types) may be beyond that required (or possible).

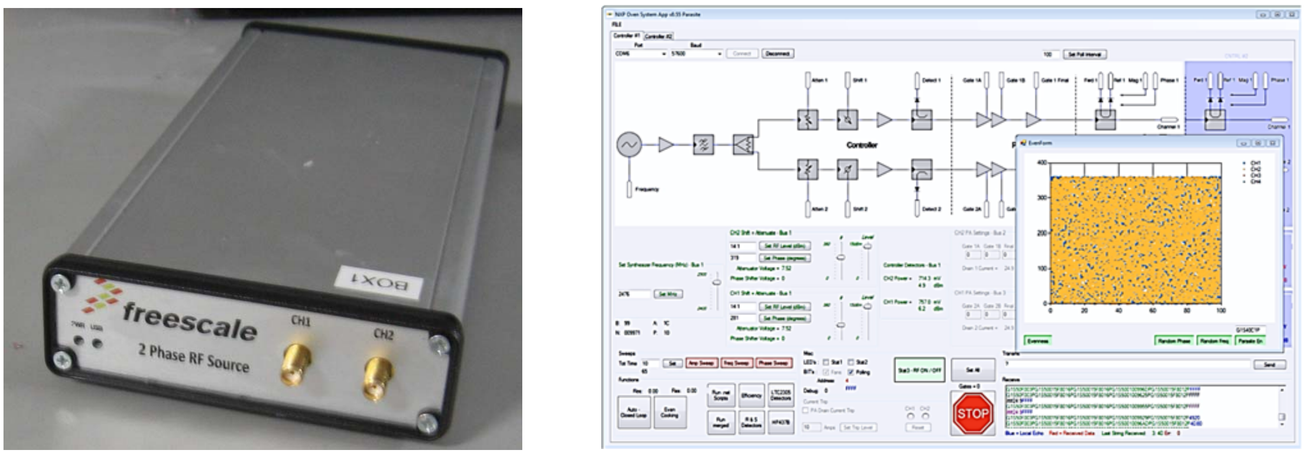


**Figure 1:** Experimental R&D Phase, frequency and Amplitude controller (left), and accompanying software (right).

## The basics of the empty or near empty cavity case

When the cavity is near empty (essentially lossless) we can rely on historical analytical work for their solution. The resonant modes can then be calculated as[5]

$$f_{res} = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{d}\right)^2}\,, \qquad (1)$$

where $c$ is free-space velocity of light, and $a$, $b$, and $d$ are the cavity's width, height and length, respectively. Typically, the size of cooking cavity dictates that these cavities are multimode by their nature and operation is well above fundamental or near-cutoff modes. Of most interest in dielectric heating are in-band (2.4 - 2.5 GHz) modes of operation. Typical expressions for the electric fields, $E_x$, $E_y$ and $E_z$, in TE and TM modes are given in the Appendix (Eqs. A1-A6, respectively).

For the purposes of this study, the author chose a cavity unit of dimensions, $a = 418$ mm, $b = 228$ mm and $d = 470$ mm, and counts 24 modes in the cavity. The fields generated by the sum of all modes can then be used to determine field distribution and evenness. The stored energy

$$W_{EM} = \varepsilon \int_{x=0}^{a} \int_{y=0}^{b} \int_{z=-d}^{0} \left( \left|\bar{E}_x\right|^2 + \left|\bar{E}_y\right|^2 \right) dxdydz\,, \qquad (2)$$

and the subsequent Q calculation can be used to predict efficiency,

$$Q_c = 2\pi f_{res} \frac{W_{EM}}{P_c}\,, \qquad (3)$$

where $P_c$ is the power loss due to heat in the cavity walls and other materials exposed to the cavity fields. These are not readily calculable and in practical terms we have available the IEC60705 heating test to determine power absorbed, knowing power input from the power amplifier and hence efficiency can be determined.

At this point, however, we are looking to knock out modes that do not contribute to the evenness of the result. For example, there may little point in exciting a degenerate mode, which may lead to over heating of that particular profile.

The modes can be calculated analytically as in the appendix, and then simulated. However, simulation does not necessarily show all the modes available to be excited in the cavity when looking at their reflection coefficients or return loss. This is because we may not be able to match (inject power into) all modes into the cavity at a given antenna location. Multiple antenna points may be advantageous in this regard (matching into 50 Ω for as many of the modes as possible).

To complicate the issue further, the scattered signal in a cavity of significant size (against wavelength) must be considered when look at the total electric field component and wave impedance at the feed point in the cavity,

$$E_{tot}\left(x,y,z\right)=E_{inc}\left(x,y,z\right)+E_{scat}\left(x,y,z\right), \quad (4)$$

leading to the interference pattern such that it generally leaves only the in-band matched modes remaining (and then only those modes that can provide a match at the antenna location). From that we may calculate the average power density at a given location

$$P_D=\sigma_{eff}\left|E_{tot}\right|^2 \qquad \left[\mathrm{W/m^2}\right], \quad (5)$$

where $\sigma_{eff}=\sigma+2\pi f\varepsilon_0\varepsilon_r'\tan\delta$ is the effective conductivity, $\varepsilon_r'$ is the relative dielectric permittivity of the material being heated, and $\varepsilon_o$ = 8.854 pF/m. The above was implemented in Matlab for the examination of even power patterns under light loading conditions and is generally approximated, however the author suspects cavity perturbations are somewhat affecting the results (due to losses/structures within the cavity).

## Narrowing in even distributions of power

A key point we are trying to achieve in this work is the even distribution of energy over a given cooking zone. For this we may not necessarily want to use all 24 modes as calculated for this particular size of cavity. We therefore adjust $E_{tot}\left(x,y,z\right)$ so that we favour some modes over others, and avoid exciting frequencies (and modes) that produce an uneven result. This ongoing work at NXP is load dependent. Whilst we would like to believe that even small loads produce a near-lossless cavity, the reality is that even apparently small loading can introduce significant loss to the cavity.

## Providing access to all modes

Using a single feed, or perhaps two feed points within a cavity, we have found that it does not generally appear to allow us access to all modes within the cavity (i.e. we are unable to match efficiently at the appropriate mode frequency). However, there is considerable commercial advantage in reducing the number of solid-state amplifiers and hence to reduce the system cost. For this reason, recent work has concentrated on providing access to the excitation of all modes via the use of switched parasitic elements (undriven scatterers) rather than driven elements, and so we have attacked this problem on several fronts. These being:

a. The phase-frequency mapping of monopole antennas, located within the cavity
b. The phase-frequency mapping of patch antennas, located within the cavity
c. The phase-frequency mapping of waveguide driven cavities, attached to the cavity
d. The introduction of parasitic elements (scatterers) alongside a limited number of driven elements.

With respect to the mapping of monopole antennas, we found a very interesting result that was highly repeatable. Using a pair of bent monopole antenna's (naturally decoupled due to spacing under heavy loaded cavity or free space) we found that for a given phase offset (between the two antennas) we could essentially provide a fixed phase. Under heavy loading (where the number of modes increases substantially) as shown in Fig. 2 the frequency could simply be swept at that given phase offset in order to hit all the modes available. This has the possibility of somewhat reducing the required algorithmic complexity. Under light loading this then breaks down into a series of peaks, corresponding to mode positions (Fig. 3).

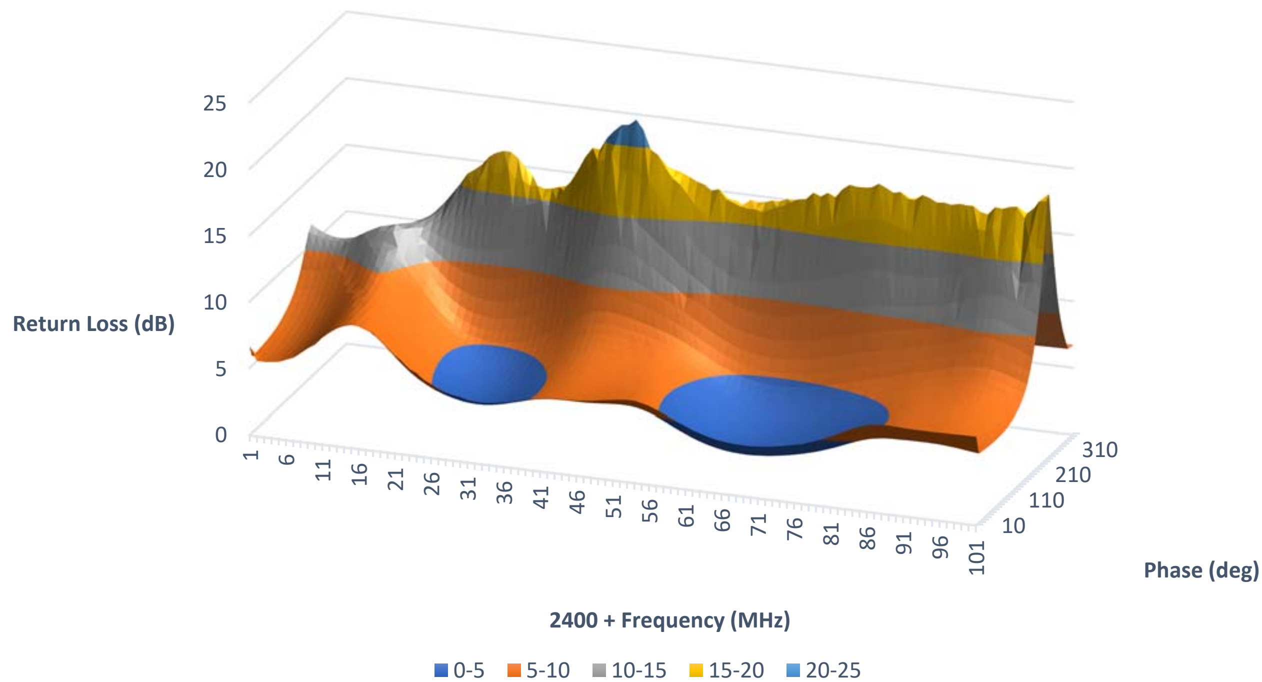


**Figure 2:** A phase-frequency scan of a IEC 1 Liter water load driven by a bent monopole antenna.

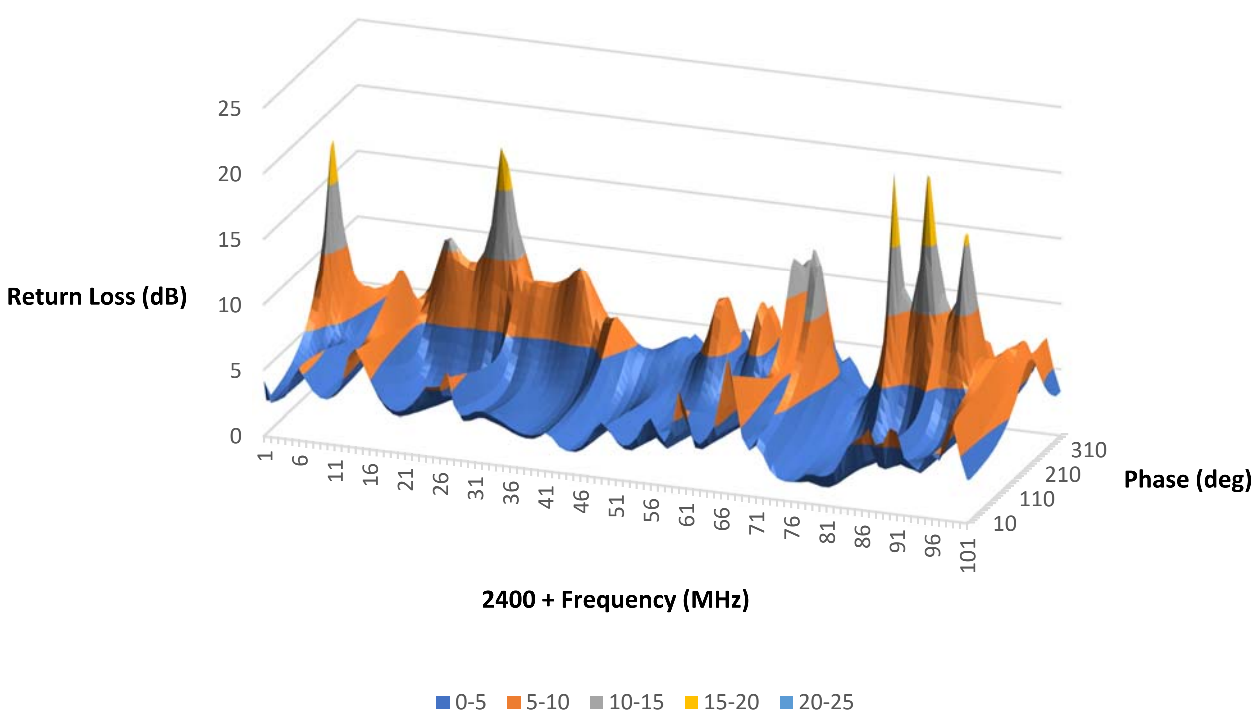


**Figure 3:** A phase-frequency scan of an empty cavity driven by a bent monopole antenna.

We find a similar result for patch driven cavities (Figures 4 and 5). However, it is interesting to note that there is a higher average return loss over the phase-frequency space, suggesting that in some configurations such antennas could be advantageous. The results presented here are for pairs of antennas located on the side wall of the microwave oven in much the same position as the magnetron is presently mounted. However, with experimentation and modeling we have found that if form factor is changed, there are other positions for one of the patch antenna's that lead to even superior results. For the sake of brevity, we have not included the data for waveguide launches as these were generally found to be patch like (although with slightly lower average return loss in our configuration).

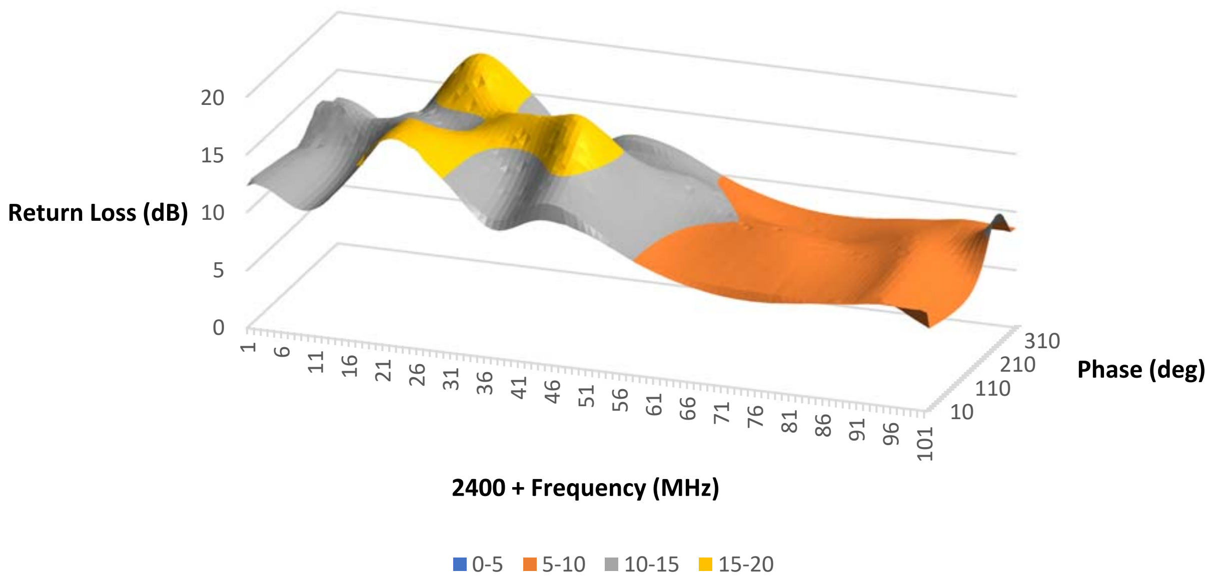


**Figure 4:** A phase-frequency scan of a IEC 1 Liter water load driven by a patch antenna.

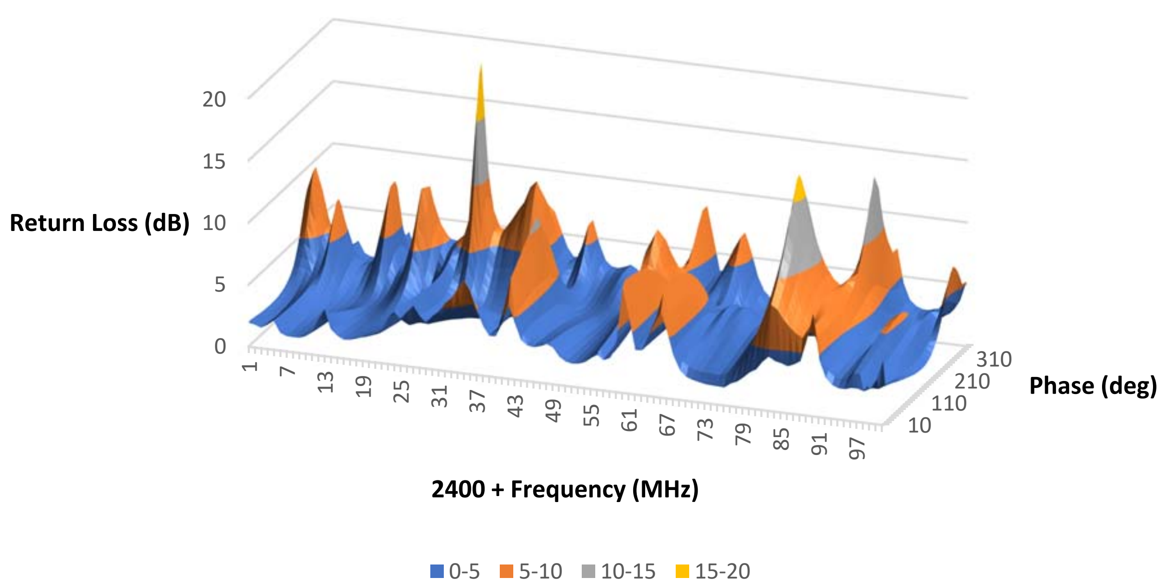


**Figure 5:** A phase-frequency scan of an empty cavity driven by a patch antenna.

### The addition of parasitic elements

Parasitic antenna elements (or scatterers) are not actively driven and may be either passively placed or accompanied with a controllable pin diode element so as to short the element to ground (the cavity chassis) and detune it so that it plays no scattering role. Selecting the patch as the element of choice we were able to provide for a simulation (CST) of the role that scatterers may play in improving uniformity. By comparing these simulations with a single fed case, we clearly see improved electric field distribution around the perimeter of the 1 Liter IEC water load compared to an equivalent simulation with only one feed point (Fig. 6).

(a)

(b)

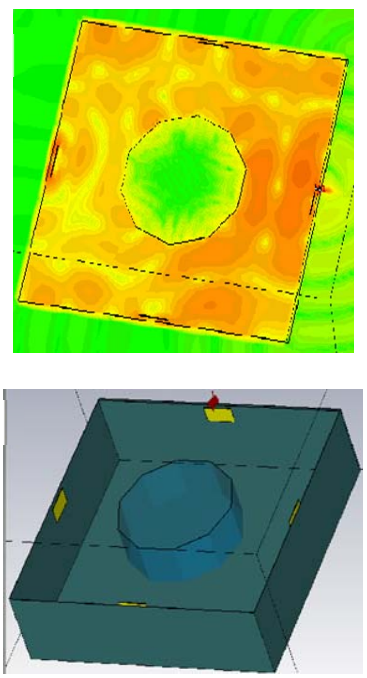

**Figure 6:** (a) CST simulation and (b) model of a single patch feed with multiple parasitics.

In order to experimentally examine this, we modified a cavity of the same dimensions as previously stated and then attempted to look at color changing desiccant placed on the turntable of the oven (in order to provide a light load). The results (Figure 7) show that compared to a regular oven with turn table operating, we are achieving a better distribution of power throughout the oven (it should be noted we were able to provide only 2 parasites in addition to the driven element due to our inability to add one to the oven door).

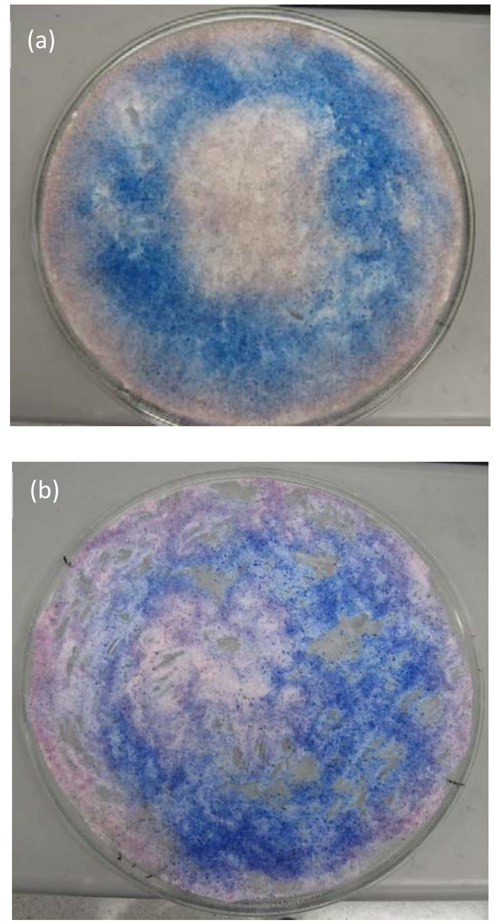


**Figure 7:** (a) Experimental result of a standard magnetron oven with a turntable on, and (b) result with a solid-state oven using switched parasites as an inclusion in the cooking algorithm (turntable off).

### Conclusion

As mentioned in the introduction, NXP has continued to work to understand ways to better achieve a technical solution by focusing on the electromagnetic fundamentals at play. It is important to note that the cost of the final systems, particularly in the consumer space has been a major concern in looking at ways to provide even cooking by keeping the number of amplifiers to a minimum. As LDMOS and GaN devices improve, it is reasonable to expect that we may achieve usable power levels from a pair of power amplifiers operating into the cavity providing a cheaper solution than is the case by using three or four amplifiers. In addition, we paid considerable attention to the type of feed and placement of the antenna in the cavity. We found in our experiments (given our cavity size) that the patch antennas provided a good workable solution, slightly better than that of a waveguide feed and a monopole feed, however all are usable, dependent on modification of the algorithm. With the use of mode picking, we have been working on the improvement of evenness, however this requires lengthy assessment in an experimental environment, for example under loaded conditions.

## Appendix

The electric fields for an arbitrary TE mode in Cartesian coordinates are typically given in text books by expression such as:

$$\bar{E}_x = \frac{2\omega\mu}{k^2}\frac{n\pi}{b}\bar{H}_0 \cos\left(\frac{m\pi}{a}x\right)\sin\left(\frac{n\pi}{b}y\right)\sin\left(\frac{p\pi}{d}z\right)$$
$$\bar{E}_y = \frac{2\omega\mu}{k^2}\frac{m\pi}{a}\bar{H}_0 \sin\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)\sin\left(\frac{p\pi}{d}z\right)$$
$$\bar{E}_z = 0\,. \qquad \text{(A1, 2, 3)}$$

For TM modes of operation, the electric field vectors in Cartesian coordinates are given as:

$$\bar{E}_x = -\frac{2}{k^2}\frac{m\pi}{a}\frac{p\pi}{d}\bar{E}_0 \cos\left(\frac{m\pi}{a}x\right)\sin\left(\frac{n\pi}{b}y\right)\sin\left(\frac{p\pi}{d}z\right), \qquad \text{(A4)}$$

$$\bar{E}_y = -\frac{2}{k^2}\frac{n\pi}{b}\frac{p\pi}{d}\bar{E}_0 \sin\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)\sin\left(\frac{p\pi}{d}z\right), \qquad \text{(A5)}$$

and

$$\bar{E}_z = 2\bar{E}_0 \sin\left(\frac{m\pi}{a}x\right)\sin\left(\frac{n\pi}{b}y\right)\sin\left(\frac{p\pi}{d}z\right). \qquad \text{(A6)}$$

## For Further Reading:


1. D. V. Thiel and S. Smith, *Switched Parasitic Antennas for Cellular Communications*, Artech House, MA, 2002.
2. G. J. Durnan, D. V. Thiel, S. G. O'Keefe, "Switched parasitic feeds for parabolic antenna angle diversity," *Microwave and Optical Technology Letters*, Vol. 23, pp. 200-203, 1999
3. E. J. Kajewski, Litton Industries, *Microwave Heating Apparatus*, US Patent 3271552, Sept. 6, 1966.
4. H. C. Anderson, Litter Systems, *Mode-Shifting System for Microwave Ovens*, US Patent 3740514, June 19, 1973.
5. R. F. B. Turner, W. A. G. Voss, W. R. Tinga and H. P. Baltes, "On the counting of modes in rectangular cavities," *Jour. Microwave Power and Electromagnetic Energy*, Vol. 19, pp. 199–208, 1984.


## About the Author

**Dr. 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 25 published and presented works and holds a first-class honors 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.