Application Study of New Solid-State High-Power Microwave Sources for Efficiency Improvement of Commercial Domestic Ovens

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The work is concerned with an emerging technology of microwave ovens fed by several independently controlled solid state power sources. Its advantages are summarized and a computational method for adjusting individual amplitudes, positions, and relative phases of the multiple sources is presented in general terms. While mathematical details will be published elsewhere, here - for the first time - the optimization algorithm is applied to a commercially available domestic oven cavity. To this end, it has already been linked to one popular commercial software package but benefits are predicted for the modeling community as a whole, helping its products gain in adequacy for microwave heating applications. With a soon expected advent of economically affordable semiconductor high-power amplifiers, the proposed multi-source optimization technique will pave the way towards "green" domestic ovens with energy consumption reduced by up to 25%, enriched functionalities, and enhanced safety of foods prepared in a fully controlled environment. It is thus relevant to microwave oven designers, microwavable food manufactures, and thereby to the society The target audience for this presentation is broad and encompasses both newcomers and pioneering specialists in the field of solid state sources for microwave processing.

Keywords: electromagnetic modeling, computer-aided efficiency optimization, energy efficiency, microwave heating, microwave ovens, solid state microwave power sources.

INTRODUCTION

After roughly 70 years of proliferation, microwave ovens have become essential household equipment worldwide. While diverse in functionality, mechanical design, and even color, they all share one feature; namely, they are all fed by bulky magnetrons that have reached their limits of performance and energy efficiency. Only in Europe domestic microwave ovens consume some 12.8 TWh of energy a year, with relatively poor efficiency of 50% or less [1]. A promising alternative in the form of solid state sources based on transistor amplifiers has been under discussion for over a decade, see e.g. [2]. Industrial implementation, developments, and validation of this emerging technology are subject of the on-going High Efficiency Electronics Cooking System (HEECS) project [3] within the European ENIAC JU (Joint Undertaking) public-private partnership. The key target of the project is 25% efficiency enhancement.

Solid state sources also offer other advantages that are being explored. Their frequency of operation and available power can be precisely controlled [2], possibly by a computer system using feedback signals from sensors placed in the heating environment. Thereby they become immune to "pushing" and "pulling" effects, which lead to erratic frequency jumps and spectrum spread over some 50 MHz in magnetron-fed domestic ovens [4][5][6]. It has been shown that such changes in the operating frequency may lead to substantial changes in the overall heating patterns [7], especially in small loads [8]. Hence uncertainties as to the frequency currently set a limit to the practical relevance of computer modeling of microwave power processes, where a fixed nominal ISM (Industry, Science, Medical) frequency of 2.45 GHz is assumed by most researchers without validation - see e.g. articles in [9]. Advanced modeling regimes with automatic frequency changes during the heating have been developed [9, Ch.17][10], but they are time consuming and based on intuitive criteria of predominant "pulling" by the load.

Finally, due to compact sizes and much smaller weight of semiconductor amplifiers with respect to magnetrons, one may envisage cavities with several apertures fed by several independently controlled sources. It is known that additional apertures facilitate excitation of different modes, for example, a combination of cavity modes for volumetric heating of the load with an underheating mode trapped under the glass plate and responsible for crisping and popping [11]. Currently, two-aperture ovens are available on the market, such as the one discussed further in this paper (Fig.1), however, due to space and weight limitations both apertures are fed by the same magnetron.

As of today, high-power microwave transistors are too expensive to be incorporated into domestic ovens. A single 180W GaN HEMT unit (CGH40180PP from Cree) comes at 450 USD [12]. Nevertheless, it is wise to explore their possible applications in advance, so as to have one's computer aided design (CAD) workshop ready by the time the affordable hardware technology arrives.

Microwave oven design is a complex task, with various optimization goals, many degrees of freedom and constraints. Here, we aim to maximize energy efficiency, which is a goal common for all applications. We focus on two-aperture cavities as such are already in domestic use. We pose the following question: Will such available cavities (often designed with a high investment of resources and validated throughout their often significant lifetime on the market) remain compatible with the new feeding systems? - and we provide a positive, cautiously validated answer.

EFFICIENCY OPTIMIZATION ALGORITHM

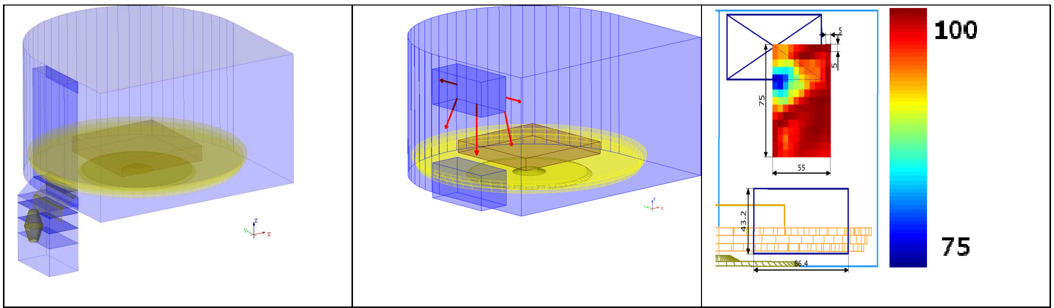
Efficiency is a key figure of merit for microwave ovens. Its value equal to 100% means that all of the microwave energy injected into the cavity is dissipated in the anticipated load. If we neglect losses in oven walls or a glass plate, the efficiency η for a single-port structure is directly related to the input reflection coefficient Γ:

$$\eta = \left(1 - \left|\Gamma\right|^2\right) \cdot 100\% \tag{1}$$

It has been shown in [13] that for *N*-port ovens the formula extends to:

$$\eta = \left(1 - \frac{1}{N}\sum_{i=1}^{N}\left|\Gamma_i\right|^2\right) \cdot 100\% \tag{2}$$

In [13] an algorithm based on the Monte-Carlo approach has been proposed for choosing a common frequency, individual amplitudes, and a relative phase shift for the two ports. It has been applied to a fictitious and simplistic cuboidal cavity, providing a solution with at least 80% efficiency. Interestingly, sensitivity to relative positions of the apertures could be compensated the relative phase shift.



a) b) c)

Figure 1. The Whirlpool MAX oven: its original model (a), the model under optimization (b), and the highest-efficiency map for the top waveguide scanned across the side cavity wall (each square marks one of the considered 165 positions of the aperture center).

EXAMPLE OF COMMERCIAL CAVITY OPTIMIZATION

A Whirlpool MAX microwave oven (Fig. 1a) has been chosen for validation of the proposed methodology. It is fed through two apertures, as this study requires. In the present commercial version, both apertures are excited by the same magnetron, its power being split by a septum. In the model under optimization, the two apertures are assumed to be excited by two independent sources. The lower waveguide is fixed at the original position while the top one is scanned across the whole available surface on the same wall (Fig.1b), with 5mm resolution (Fig.1c). QuickWave-3D [10], an FDTD (finite-difference time-domain) -based electromagnetic simulator, is applied as an engine for calculating the oven's 2x2 scattering matrix (whose '11' and '22' entries correspond to Γ_1, Γ_2 in equation (2)). A grid search regime [10] facilitates automatic simulation of 165 scenarios (with different top waveguide positions) and for each position a common frequency, independent amplitudes, and a relative phase shift between the apertures are optimized. Fig.1c shows that even for the least advisable positions of the upper waveguide (upper-left region of the wall, blue color in Fig.1c) efficiency of over 75% is reached, that is, much better than 40-50% in the case of magnetron feeding in traditional ovens. For more promising positions (brown regions in Fig.1c) efficiency approaches 100%.

CONCLUSIONS

The paper has been concerned with an emerging technology of high-power solid-state sources for microwave heating applications. A recently proposed algorithm for optimizing frequency, amplitudes, and phases of two sources, with the goal of maximizing the oven's efficiency, has been linked to a popular software package and executed in a grid search regime with sweep over possible positions of one aperture. For the first time, the algorithm has been applied to a realistic, commercially available domestic oven. It has led to a stimulating conclusion that the oven's efficiency can be increased to nearly 100%, without a need for re-designing the cavity.

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