EFFICIENCY OPTIMIZATION FOR PHASE CONTROLLED MULTI-SOURCE MICROWAVE OVEN

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ABSTRACT. A solid-state microwave generators system is considered as an alternative to the magnetron, in order to inject electromagnetic energy into the cavity of a microwave oven for domestic use. Over current devices, the use of solid state technology allows to control the frequency and phase of the electromagnetic field generated.

Considering a simplified cavity with 2 solid state sources, the influence of the electrical parameters on the maximum efficiency obtainable in the process of microwave heating is investigated. By varying the frequency, different values of optimal phases and different values of maximum efficiency are obtainable.

Moreover, the procedure is repeated varying the position of one source port and the influence of geometry on the system is evaluated.

The results demonstrate that the ability to control the electrical quantities of a microwave heating process, makes it possible to obtain better results in terms of energy efficiency over the current poorly controllable systems.

INTRODUCTION

Nowadays microwave ovens for household use and industrial installations at 2.45GHz frequency band use magnetrons as a high power sources of microwave energy. Those bulky and old-fashioned devices are characterized by a limited efficiency of energy conversion from power supply to microwaves. They are also difficult to control, which leads to mismatch losses due to significant changes in reflection characteristics of the resonant cavity caused by large variations of load parameters (permittivity, loss tangent) as a function of its temperature. New semiconductor technologies allow us for building innovative high power microwave sources. They exhibit great advantages over magnetrons like a precise frequency, phase and output power level control ability. The microwave field can easily be manipulated within an empty oven cavity using phased array control techniques, but when food is introduced in the cavity, the situation becomes complex due to many variables related to the load (position, type, weight, shape, dielectric constant).

The main goal of the work is to investigate on the control of phase shift and frequency, in order to introduce important innovations with regards to the energy transfer during a microwave heating process for household applications. Afterwards, the influence of the mutual waveguide position has been investigated: a matrix of simulations has been carried out to assess if there are any particularly promising solutions with regard to the optimal transfer of energy from the source to the load. A fixed load position has been assumed, without turntable because through further more complete investigation, the substitution of the mechanical movement will be evaluated considering the management of the electrical quantities.

Although traditionally extensive experimentation was the major technique exploited in the development of microwave applicators, it has been recently realized that advanced computer simulation could make the design of the microwave heating systems more intelligent and thoughtful, shorten the development time, and reduce the project's cost.

Two different commercial tools are used and compared during this analysis: QuickWave-3D and CST Microwave Studio.

QuickWave-3D is an electromagnetic simulator based on the conformal FDTD (finite difference time domain) method and supplemented with a range of unique models for curved boundaries, media interfaces, modal excitation, and parameter extraction. It can be applied to a variety of microwave problems and some new algorithms relevant to control multiple sources in terms of frequency, phase and amplitude tuning are already implemented.

CST Microwave Studio is a fully featured software package for electromagnetic analysis and design in high frequency range. The software contains several different simulation techniques (transient solver, frequency-domain solver, integral-equation solver, etc.) to best suit various applications. The frequency domain solver contains specialized methods for analyzing highly resonant structures.

EFFICIENCY DEFINITION

The solid-state microwave power generation technology offers the ability of precise frequency and phase-shift control for each source, which was not available in previous, magnetron based solutions [1][2]. This innovative technology needs a completely new approach in the microwave oven design process to fully benefit from the technology improvement. Future microwave ovens have the chance to be more compact, slighter and more efficient. To achieve those goals, a lot of research work must be performed. One of the tasks is a design of a system, which will be able to deliver microwave power to the load with a maximum efficiency [3].

In the most straight-forward understanding of the microwave heating process, the efficiency is a coefficient, which value equal to 100% means that all of the microwave energy delivered to the cavity has dissipated in the anticipated load (the efficiency of the microwave source is not in scope of this paper). This process usually results in the temperature increase of the heated object. Due to the standing wave phenomenon in cavity ovens, the temperature is not equal in a whole load's volume. Standing wave patterns in the cavity as well as in the heated load are very sensitive to excitation frequency and relative phases of each energy source, which results in high level of difficulty to predict load temperature patterns. In an environment of microwave electromagnetic simulation it is possible to calculate those patterns with a good accuracy [4]. However, it demands a lot of computational power (e.g. around 1 hour on a modern personal computer for a fine meshed scenario which includes waveguide details and rounded cavity embossments). It is completely unaffordable way to look for the solution and a much faster approach is necessary.

In a typical single-port microwave oven with a reasonably sized load, most of the energy is dissipated in that load or reflects back to the source. Only a very minor part heats-up the cavity walls and the turntable. When we neglect those wall losses, it is assumed, that all the energy injected into the cavity is dissipated in the load as heat or reflects back to the transmitter.

Thus the energy delivery efficiency can be simply related to the reflection coefficient:

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

Where

$$\Gamma = \frac{b}{a}, \tag{2}$$

b – reflected wave amplitude
a – forward wave amplitude

In a multisource cavity the situation is similar, but a new reason of losses comes out. As it is well known, each transmitting antenna can act as receiving antenna with the same efficiency, thus part of the energy available in the cavity can be captured and dissipated in the output stage of an amplifier. We call this effect cross-talk losses, because the energy dissipated at each microwave source also comes from all of the other sources. The energy distribution between each port and the load is well described by S-parameters, so the efficiency can also be calculated on the S-matrix basis. In the *N*-port scenario the reflection coefficient at *i*-port is defined as follows [5]:

$$\Gamma_i = \frac{b_i}{a_i}, \tag{3}$$

where b_i is a sum of reflection and cross-talk waves at *i*-port:

$$b_i = \sum_{j=1}^{N} S_{ij} a_i \tag{4}$$

The efficiency can thus be defined as a relation between the sum of all returning waves to the incident waves:

$$\eta = \left(1 - \frac{1}{N}\sum_{i=1}^{N} |\Gamma_i|^2\right) \cdot 100\% \tag{5}$$

SIMPLE OPTIMIZATION ALGORITHM

Cross-talk losses can be minimized in the several ways, e.g. by carefully choosing position and polarization of each source. However, the fastest and most effective approach is to tune the relative phase-shift of each port to achieve the lowest vector sum of the waves, which come from the cavity. If only the S-matrix is available (simulated or measured), it is possible to quickly calculate optimal excitation parameters by multiple evaluation of the (5) formula.

This calculation is relatively simple and can be repeated thousands of times per second on a modern computer. We propose to use the following approach, which is based on a group of Monte-Carlo methods. The algorithm only needs the full matrix of scattering parameters in the considered frequency band as its input

The algorithm works in a loop iterated experimentally chosen number of times. At each iteration a common random discrete frequency for all sources and a random phase-shifts for each source independently are generated. The efficiency is stored in a table as minimum or maximum together with phase-shifts configuration for the given frequency. After the loop is done, the configuration which gives globally highest efficiency is returned.

SIMULATION RESULTS

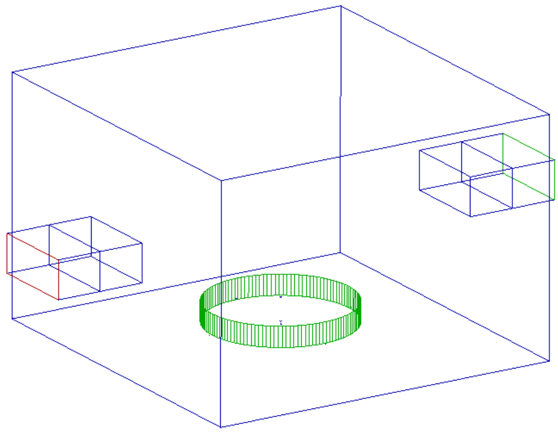

Figure 1. Simulated scenario.

Several simulations in QuickWave-3D and CST Microwave Studio have been performed to prove results achieved with this algorithm. The scenario consists of a rectangular metal cavity (343 mm wide, 266 mm high and 337 mm deep) with two waveguide apertures centered on their walls (cross-section 84x43 mm, 86 mm length) feeding with 250 watts each – Figure 1. The load is a cylinder of tap water, 20 mm above the bottom wall (diameter = 140 mm, height = 24mm, ε' = 69, σ = 0.735 S/m which is ε" = 5.4 at 2.45 GHz). Walls are made of Perfect Electric Conductor.

S-parameters obtained with QuickWave and CST Microwave Studio are shown in **Fig. 2**.

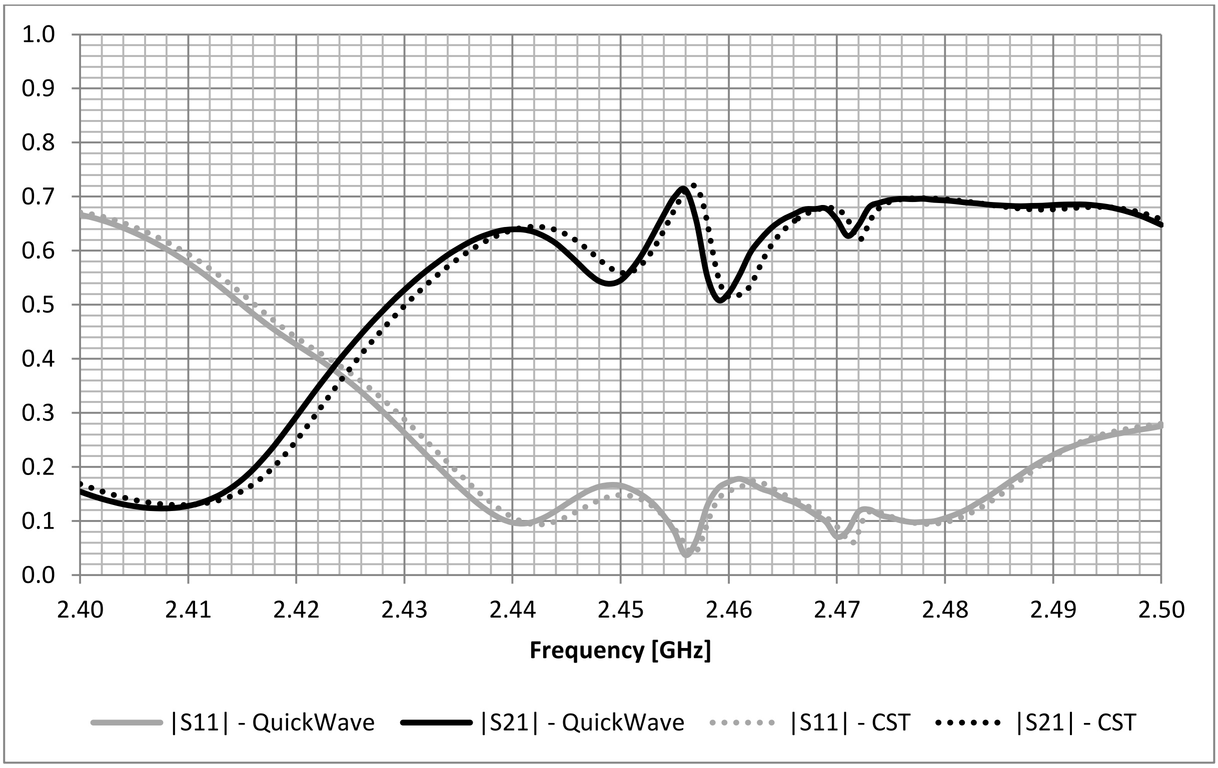

Figure. 2. Scattering parameters

Optimization algorithm has been used to find excitation parameters (the same frequency for all sources and different phase-shifts for each one), which give best and worst efficiency.

Results of optimization are presented in **Fig 3** and **Table 1**.

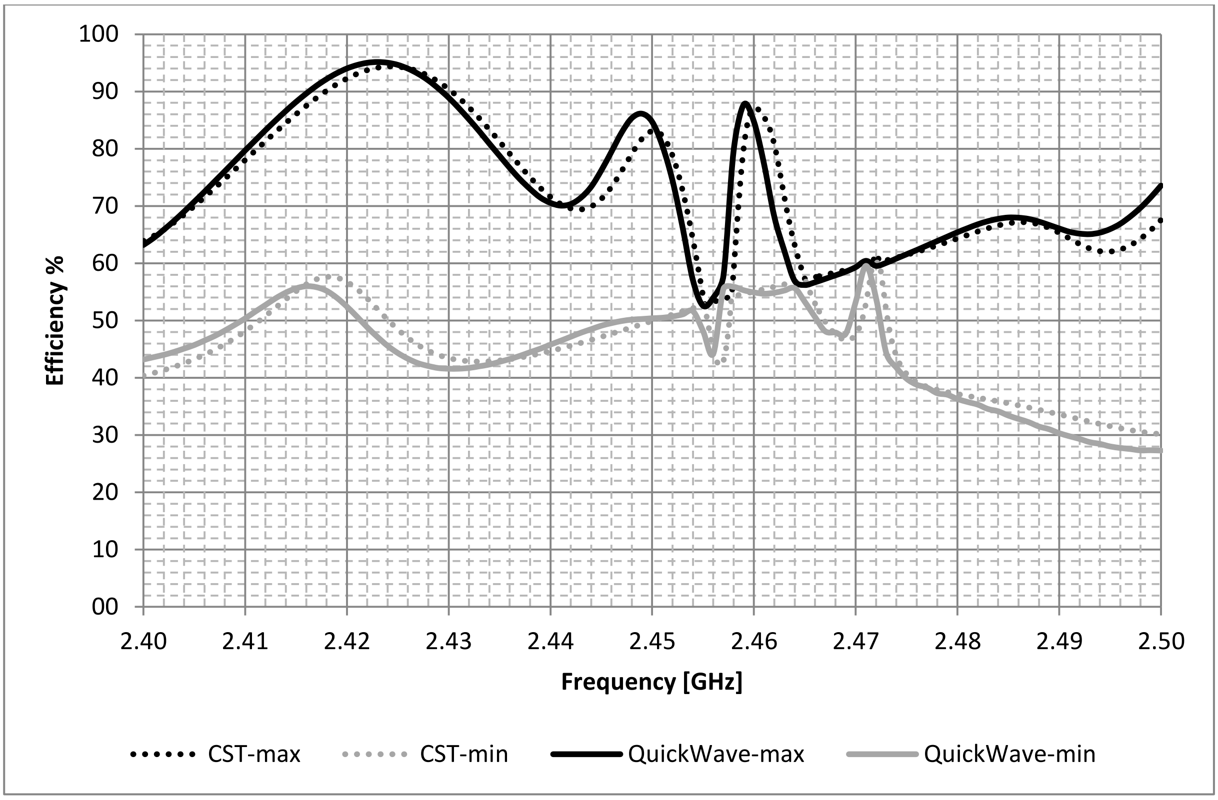

Figure 3. Results of optimization – comparison of results.

Table 1. Optimization results – comparison of results.

Simulator	Output Power [W]	*Maximum efficiency*			*Minimum Efficiency*		
		Freq. [GHz]	Phases [deg]	Efficiency [%]	Freq. [GHz]	Phases [deg]	Efficiency [%]
QW3D	2×250	2.423	0,180	95.1	2.500	0,180	27.3
CST	2×250	2.424	0,180	94.4	2.500	0,180	30.2

APERTURES POSITION OPTIMIZATION

Another aspect of the efficiency optimization is the positioning of the feeding apertures. This is a very complex task and several approaches are available, like genetic optimization algorithms [7]. However, scattering parameters are very sensitive to details of the cavity geometry and this applies also to apertures positions. This observation leads us to the question: how much a proper positioning of apertures is critical to achieve best possible efficiency? A series of simulations have been performed in QuickWave-3D to come closer to an answer. Considered scenario is the same as described in previous section, but with an additional variable: one of the waveguide apertures is scanned across the whole wall – **Fig. 4.**

With a dedicated data analysis software it has been found that even though S-parameters are highly dependent on aperture position, but after applying the optimization algorithm it is possible to achieve high level of efficiency (over 80%) at each position and more than 95% in most of them by setting phase-shifts appropriately.

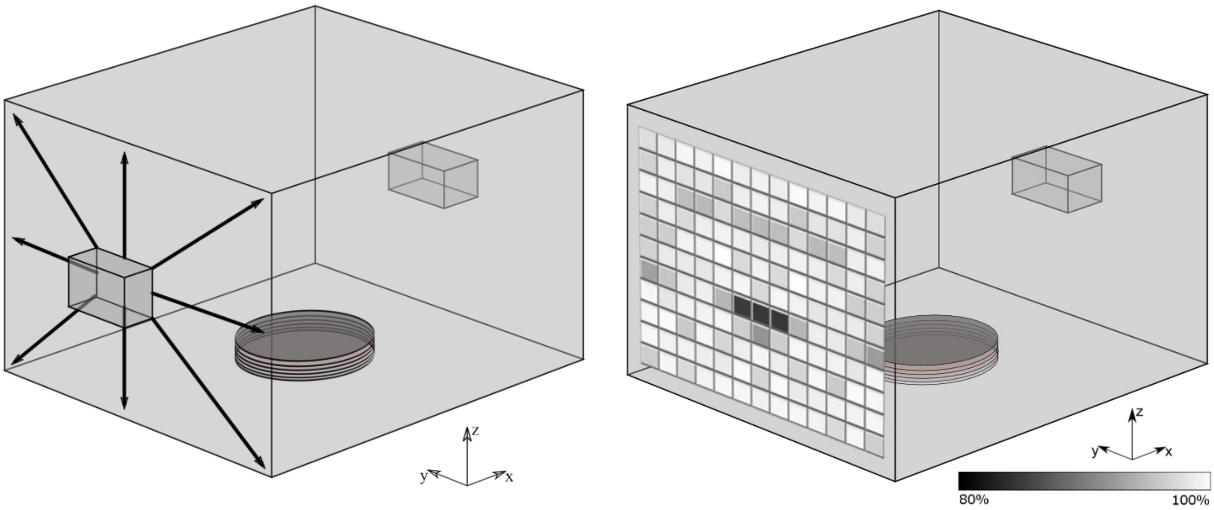

Figure 4. Apertures position optimization: (a) the idea, (b) optimal efficiency results.

CONCLUSIONS

It has been shown that, in a multisource cavity the level of power dissipated in the load can be estimated on the basis of complex scattering parameters. Cross-talk phenomenon between different antennas can reduce efficiency in general, but this effect can be minimized by precise selection of frequency and relative phase-shifts set for each source.

Positions of apertures does not seem to be very critical for the considered two-port cavity, since for most of tested configurations the best efficiency achievable after the optimization algorithm was over 94%.

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