An Optimization Method for the Control of Efficiency in Two-ports Microwave Ovens

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***Abstract*— 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. Those new features give a chance for improving total efficiency of microwave heating by means of a good design of the oven, taking into account the possibility of two independently controlled sources for a two ports configuration.**

The original contribution of the paper is the systematic approach to the optimal design of a microwave oven, based on the link between an algorithm of evolutionary computing and a finite-element solver. In particular, the electromagnetic parameters are modeled by means of the complex valued S-matrix of the oven, while the geometrical parameters (i.e. position and orientation of the ports) are modeled by a finite-element analysis in 3D.

***Index Terms*—Microwave ovens, optimization, product design**

I. 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 characterize with 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.

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It is clear that the absorption of microwave energy in foods is dependent on both the electromagnetic fields and the microwave penetration pattern in the food material. The field distribution is in turn strongly influenced both by the type of cavity, the waveguide system, as well as by the type, shape and distribution of the food inside the oven [1].

Although trial-and-error approach was the major technique exploited in the development of microwave (MW) applicators, it has been recently realized that advanced computer simulation could make the design of the MW heating systems more intelligent and thoughtful, shorten the development time, and reduce the project's cost [2].

In this work the efficiency represents the objective of the optimization, where efficiency means the ratio between the volumetric power in the load and the power supplied to the cavity. Considering the walls ideal conductors and not having introduced elements with losses in the model, the input power can only be absorbed by the load or reflected back.

II. Definition of the Direct Problem

Given a field region Ω, wave equations can be derived from Maxwell's equations and expressed in the time domain; the knowledge of electric fields intensity leads to the magnetic field intensity and vice versa. For simplicity, we can consider sinusoidal time-varying fields and Maxwell's equations can be rewritten in the frequency domain in the form:

$$\nabla^2 \mathbf{E} = \gamma^2\, \mathbf{E} \quad (1)$$

$$\nabla^2 \mathbf{H} = \gamma^2\, \mathbf{H} \quad (2)$$

with **E** (V/m) the electric field, **H** (A/m) the magnetic field, and γ is the propagation constant

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} = \alpha + j\beta \quad (3)$$

It is possible to define the energetic behavior of a microwave oven by means of the efficiency parameter (η), which represents the relationship between the incident and reflected power at the feeding ports. With reasonably small losses on the walls of the oven, can be expressed by:

$$\eta = (\mathbf{I} - \mathbf{S}^{\intercal}\mathbf{S}) \quad (4)$$

with **I** the identity and **S** the complex scattering matrix [3].

III. Definition of the Inverse Problem

The microwave power absorbed by the load can be related to the average temperature rise of the load itself: having prescribed the input power, η will be maximum when the average temperature increment in the load is maximum. The device model is shown in Fig.1: it consists of a rectangular metal cavity (343mm wide, 266mm high and 337mm deep), with two waveguide apertures (section 84x43mm , 86 mm deep) supplying the microwave energy inside.

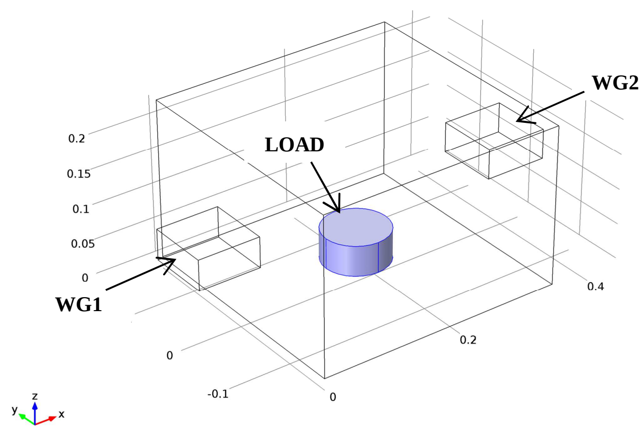

Fig. 1. Geometric model of the oven for the analysis problem

Perfect electric conductors have been assumed (infinite electrical conductivity) in the numerical model. Therefore, PEC boundary condition has been adopted on the side walls, while electric field's TE10 mode is imposed on the entrances of waveguides by using a rectangular ports. The total maximum power is 500 W for each supply input with fixed working frequency 2.45 GHz.

Different cylindrical volumes (according to the typical household use of a microwave oven) of water were used as heated loads: the load, which does not move, is centered 20 mm above the down wall. After the electromagnetic simulation (that takes into account reflections and cross-talks between sources) the S-matrix of the oven was obtained; then an optimization strategy procedure (defined in the next Section) was applied to identify source settings (position of ports, amplitude and phase of power supply) for achieving optimal efficiency.

IV. EStra: An Evolution Strategy of Lowest Order

Darwinian evolution is intrinsically a robust search and has become the model of a class of optimization methods for the solution of real-life problems in engineering. For the latter, the natural law of survival of the fittest in a given environment is the model to find the best design configuration fulfilling given constraints. As a matter of fact, the principle of natural evolution inspired a large family of algorithms that, through a procedure of self-adaptation in an intelligent way, lead to an optimal result. The evolutionary algorithm, if successful in finding a point better than the current one, covers a larger region of search in order to see if there would be another good candidate in the neighbourhood, and then does the opposite when this is not believed possible. This way, there is a non-zero probability of finding the region where the global optimum of the objective function is located. EStra is a low-cost algorithm which has proven to be successful to identify the region of global optimum of non-convex and numerically ill-conditioned objective functions: The mutation operator is emphasized: at each generation the fittest individual between parent and offspring does survive [4],[5].

V. Optimization Results

The optimization algorithm EStra, coded in the MATLAB environment, has been coupled to Comsol Multiphysics (a FEM commercial software) in order to shift the position of the ports in the domain and the parameters of electromagnetic sources. This allows a completely automatic design of the oven looking for the highest efficiency (see TABLE I).

The main assumption of the analysis model is that the electromagnetic properties of the load are constant, thus resulting in a linear analysis problem and allowing a faster procedure for the optimization, not affecting reasonably the final solution if the load temperature increase is small.

A convenient manipulation of the complex S-matrix is done by varying phase and amplitude of supplying inputs. Moreover, the optimization algorithm considers the rotation of both the waveguides (two configuration: horizontal or vertical), the position of the center of both the apertures along the relevant lateral walls (shift of 1,5 cm both in Y and Z direction), thus resulting in 6 geometrical parameters and 4 circuital parameters.

TABLE I – Geometric and physical data

Load dimension			
Load type	**Volume (ml)**	**Radius (mm)**	**Height (mm)**
Small	275	45	43
Medium	350	70	23
Large	1000	95	35
***Physical properties* (*working frequency 2.45 GHz*)**			
Material	**Dielectric relative constant**	**Magnetic relative permeability**	**Electrical conductivity (S/m)**
Air	1	1	0
Water	70-j8	1	5.5e-6
Metal walls	Assumed to be Perfect Electric Conductor (PEC)		

As an example, in Fig. 2 the evolution of the oven's efficiency as a function of the optimizer's iterations for the small load is shown (overall calculation time: 8 hours on a workstation with 96GB RAM and 12 processors @ 2.96GHz): the optimization results are summarized in Table II.

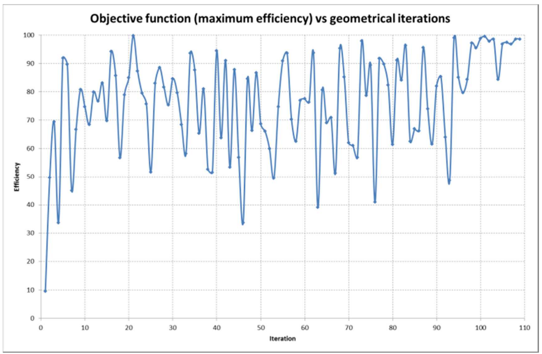

Fig. 2. Objective function vs iterations

TABLE II

***Optimization results* (*small load*)**					
	***Rotation* (deg)**	***ΔY* (cm)***	***ΔZ* (cm)***	***Input Phase* (deg)**	***Input Power* (W)**
WG1	0	12	-3	0	225
WG2	0	-9	-4.5	307	350
*Shift from the geometrical centre of the relevant lateral wall					

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