Phase-Shift-Based Efficiency Optimization in Microwave Processing of Materials with Solid-State Sources

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Abstract – The paper describes an efficient way to maximize the power level delivered to a multi-source cavity fed by solid-state generators. While maximum output power of semiconductor-based RF sources is still insufficient for various applications related to microwave processing of materials, summation of signals from several sources is often performed at dedicated power adders. A different approach is demonstrated in this paper: here, power is summed directly on the load inside the multiport cavity. A smart selection of operating frequency and relative phase shifts enables minimization of power loss due to impedance mismatch and cross-talk. An example of a two-port cavity with a sequentially shifted waterload is provided to explain why this approach should be useful for material processing applications.

Introduction

For many years a magnetron was the only widely-used RF source for microwave heating applications working in 2.45 GHz band. Now new semiconductor technologies allow us to build high-power microwave sources. They exhibit great advantages over magnetrons like a precise frequency, phase, and output power level control ability, which can be used for electronic manipulation of the electromagnetic field inside the cavity. However, solid-state sources still have some drawbacks like high price, not-so-competitive efficiency levels, and limited maximum output power (e.g. 100 watts for Emblation ISYS245 devices [1], 200 watts for SAIREM devices [2]). While it is believed that the first drawback will be significantly reduced after mass production of transistors begins, the two others are still a subject for technology improvement.

What can be done today is a decrease of power loss due to the impedance mismatch at cavity entries. In traditional, magnetron-based systems, input reflection coefficient of the heating device (oven cavity, chemical reactor, etc.) is significantly affected by several parameters of the heated material (its geometry, position, electromagnetic properties) and uncontrolled, may result in an additional efficiency loss. Some improvements can be achieved by precise positioning of the load [3], but it is not always possible. In other cases, where input reflection coefficient characteristics cannot be predicted due to a wide variety of user-dependent variables (like in domestic microwave ovens), solid-state RF sources driven with the help of a smart control algorithm can exhibit their potential to minimize losses caused by impedance mismatch and cross-talk between feeding apertures. Moreover, higher power levels can be achieved inside the cavity by feeding it with more than a single source keeping the power loss due to coupling between antennas at a minimized level.

Architecture and Algorithm

An architecture of the microwave heating system based on semiconductor power sources evaluated in this paper is presented in Fig. 1. It consists of two partially independent channels, both operating at the same frequency, but with the ability to separately control relative phase shift and output power levels. This approach allows electronic alteration of the

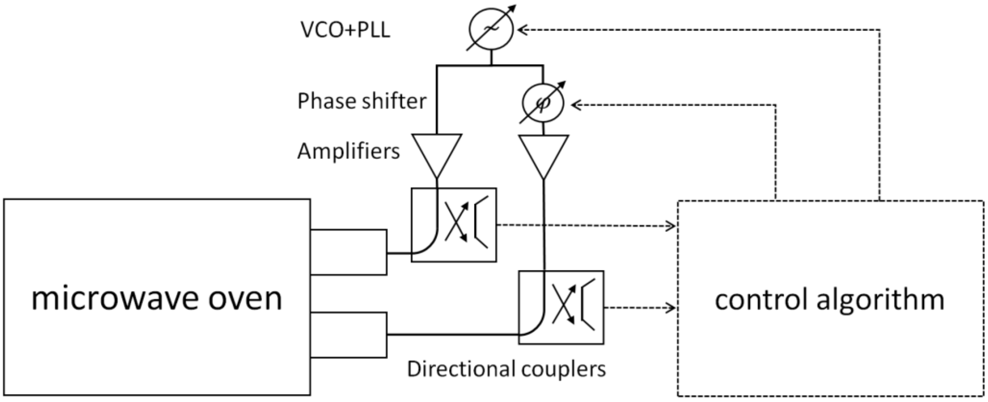


Fig. 1. Architecture of the solid-state microwave oven.

electromagnetic field pattern inside the cavity – a feature unavailable in magnetron-based ovens.

A much more powerful feature is the ability to maximize the efficiency of energy injection (up to near 100%) into the cavity, in the case of multisource feeding. Due to a smart selection of operating frequency and phase shifts between channels, it is possible to minimize losses caused by impedance mismatch and crosstalk between the feeding apertures.

The algorithm takes at its input a full *S*-matrix (it can be simulated in a numerical environment, e.g., in FDTD-based tools, or measured in a hardware implementation) and calculates the expected efficiency for several random combinations of frequency and phase-shift values. Thus the concept is similar to Monte-Carlo methods. Calculations are very fast, so thousands of combinations can be evaluated in a second resulting in a curve of best available efficiency for each considered frequency [4, 5]. The one with the highest efficiency value, together with the phase shift that results in this extreme, is selected as output value of the optimal frequency together with the optimal phase shift.

Scenario

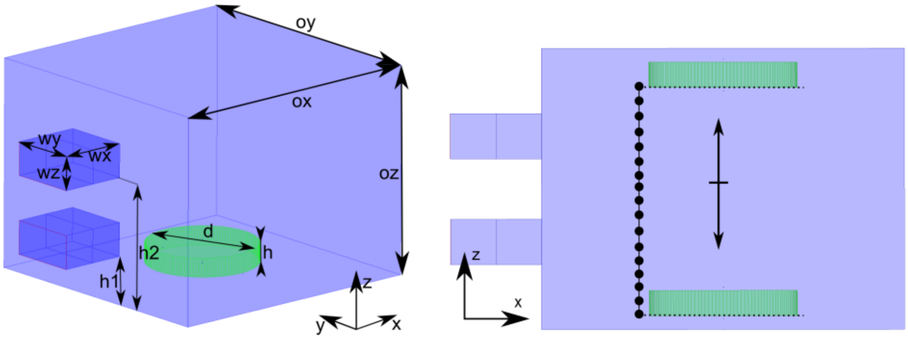
The scenario proposed for algorithm evaluation consists of a rectangular metal cavity (a very simplified model of a domestic-like microwave oven) – Fig. 2. Inside the cavity a cylindrical water load is placed in the center of the bottom wall (water parameters: $\varepsilon' = 69$, $\sigma = 0.735$ S/m, $\varepsilon'' = 5.4$ at 2.45 GHz).

Adaptivity properties of the proposed control method have been already presented in a few papers. Demonstration of the influence of load dimensions has been presented in [5] and influence of the feeding aperture position has been explored in [6]. Another approach is presented in this paper: the algorithm is evaluated for a series of simulations, which differ in vertical position of the load. Its z-position is changed from the cavity bottom ($z = 13$ mm) up to the ceiling ($z = 229$ mm) with a 24 mm step.

Results

Each FDTD simulation returns a full 2-port S-matrix in the frequency band 2.4 – 2.5 GHz. The efficiency optimization algorithm has been applied to each *S*-matrix separately. As a result of testing thousands of phase-shift and frequency combinations, curves of best available efficiency have been created for each load position. The highest value represents optimal excitation parameters (frequency and phase-shift) – Fig. 3.

Name	Value [mm]
ox	343
oy	337
oz	266
wx	86
wy	86
wz	43
h1	61,5
h2	161,5
d	140
h	24



(a) (b) (c)

Fig. 2. Scenario overview: (a) dimensions, (b) definitions, (c) cavity side view showing two extreme positions of the load.

It can be noticed that in most cases it is possible to find a high efficiency condition (efficiency over 90 %) – black dots in Fig. 3. It is a very powerful feature of the system, because it allows adaptation to several positions of the load keeping mismatch losses at low levels.

What seems more surprising at first sight is that the best efficiency curves presented in Fig. 3(b) are exactly mutually covered in pairs. This happens due to geometrical symmetry between cases z =13…109 and z =229…133. The algorithm exhibits this fact, resulting in exact available efficiency values, which confirms adaptive properties of our approach.

Conclusions

The adaptive control method presented in this paper can be implemented in microwave heating systems based on solid-state RF sources. It can result in improvement of heating efficiency due to minimization of losses caused by impedance mismatch and cross-talk between feeding apertures. Moreover, the system can adapt to *a priori* unknown load position and its other properties (dimensions, permittivity, conductivity), which can be useful in situations where those variables are difficult to predict.

Acknowledgement

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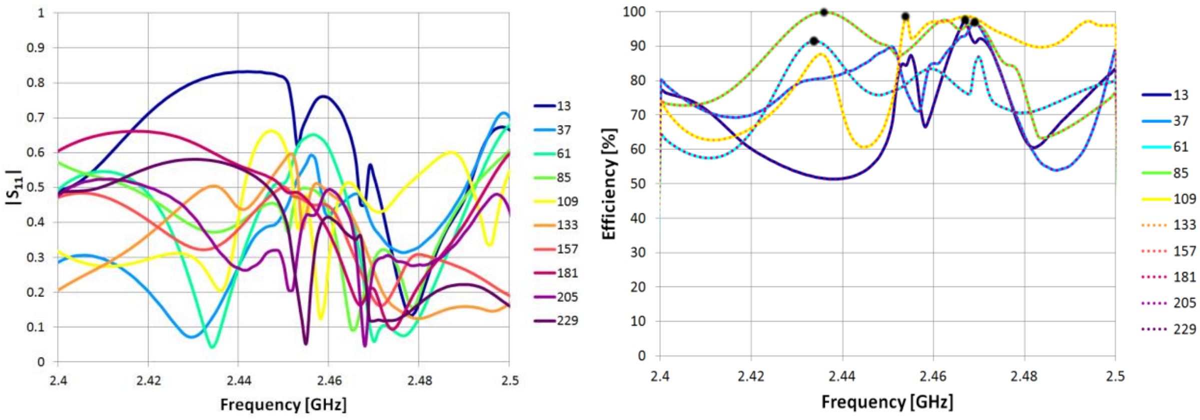

(a) (b)

Fig. 3. Evaluation of the efficiency optimization algorithm for different *z*-position of the load: (a) input reflection coefficient at port 1, (b) best efficiency curves obtained with the optimization algorithm.

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