Numerical Analysis of Cylindrical Cavities Used for Microwave Heating, Employing the Mode Matching Technique

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Abstract — The analysis and design of a cylindrical cavity for microwave heating applications, including the feeding mechanism is proposed in this paper. The cylindrical cavity design aims at the production of a uniform field distribution, avoiding non-uniform heating and thermal runaway. The analysis of the device is based on the Mode Matching Technique. This has been proved to be an efficient and robust technique for the analysis of multiple discontinuities. The feeding structures maybe a circular, rectangular or coaxial waveguide. All quantities involved in the analysis are evaluated analytically achieving a fast and accurate method.

1. INTRODUCTION

The application of high power microwaves for thermal processing of dielectric materials, has received a great attention in the past. The benefits of using microwaves instead of conventional heating mechanisms are mainly due to the fact that microwave energy can penetrate the material achieving rapid internal heating. The main disadvantages are non-uniform heating and thermal runaway [1].

As rectangular cross-section cavities are mainly used, the amplitude field distribution depends on the cavity dimensions and the modes excited in the cavity. Even for a high order modes cavity there is a great fluctuation of the field distribution, resulting in non uniform heating of the material under process. Many techniques have been proposed to overcome this problem, such as the frequency variation and the field disturbance using a metallic blade. Frequency variation can be used only in relatively low power or small size devices, since high power microwave generators cannot alter their frequency. Moreover, the use of a metallic blade in a high power microwave cavity will produce high voltage arcs with unpredictable results.

The main strength of rectangular and in particular cubic cavities is the possibility of high order mode degeneration. Namely, up to 12 modes can be made to resonate at the frequency of operation. The always challenging question is, what is the appropriate excitation which optimally excites all modes, in order to achieve homogeneous heating energy deposition. Instead of working toward this direction, the present work tries to examine the possibility of producing uniform fields using cylindrical cavities either ordinary or with corrugated walls. The corrugations aim at the establishment of a hybrid HE$_{11}$ mode which is expected to present a more homogeneous field distribution. The exact analysis of the cavity as well as the feeding mechanism will be performed using a closed-form mode matching technique. Since all the involved coupling integrals are evaluated analytically, this results in a very fast and compact technique without numerical instabilities. The dimensions of the cavity and the feeding source section will be designed aiming at the higher possible uniformity of the field amplitude. The feeding structure can be a circular, rectangular, coaxial waveguide or a combination of them. Its position will be optimized for the proper excitation of all necessary modes in the cavity. The material to be heated will be inserted to the cavity with the aid of a moving belt, since the device aims at industrial applications, as shown in Fig. 1. For this purpose, two openings will be included in the cavity, while $\lambda/4$ chokes will prevent microwave leakage [2].

2. GEOMETRY OF THE MICROWAVE HEATING STRUCTURE

A three dimensional view of the structure to be used for microwave heating is shown in Fig. 1(a). The structure is simplified for electromagnetic simulation convenience reasons. A vertical cross section of the simplified structure is shown in Fig. 1(b). In order to apply the Mode Matching technique the latter structure can be identified as comprised of waveguide sections as shown in Fig. 1(b). The purpose of the Mode Matching technique is to characterize each discontinuity between different waveguides through a generalized scattering matrix. In turn, all the discontinuity scattering matrices along with those of the waveguide section are combined together to yield a system matrix representing the whole structure.
3. MODE MATCHING ANALYSIS OF A CYLINDRICAL CAVITY

The electromagnetic analysis of the device is based on a closed-form Mode Matching-Generalized Scattering Matrix method. The analysis of the feeding mechanism consists of a discontinuity between a circular waveguide and a smaller offset rectangular (Fig. 2(a)), circular or coaxial one (Fig. 2(b)). The best way to achieve this task is the analytical evaluation of the quantities involved in the analysis instead of any numerical integration. A mode matching technique handling offset circular and offset coaxial waveguides has been established in our previous work, [3]. Concerning, the offset rectangular-to-circular waveguide discontinuity, a similar mode matching is developed for the needs of the present work, as proposed in [4]. Let us briefly describe the basic ideas implemented in this technique.

Since the two waveguides of Fig. 2 are offset, their eigenfunctions are expressed with respect to a coordinate system having a z-axis coinciding with the waveguide axis of symmetry. These eigenfunctions must be expressed in a common coordinate system. Since the integration limits are described by the coaxial waveguide aperture, it was found more convenient to transform the eigenfunctions of the circular waveguide to the offset coordinate system of the coaxial one using the Graff’s formula [5, p.363]. Then by properly transforming the eigenfunctions of the two waveguides from the cylindrical to rectangular coordinate system, the coupling integrals take the form of a product of Bessel functions with the same order. This expression is known as the Lommel integral and can be evaluated analytically, e.g., Abramowitz and Stegun [5, p.484]. In this way, the coupling integrals involved in the mode matching technique are evaluated analytically and finally the junction generalized scattering parameters are given in closed form.

Regarding the two apertures at the side walls of the cavity aiming at the introduction of the material to be heated in the cavity, these are also analyzed using the same method as proposed in [6]. It consists of a T-junction between a cylindrical and a rectangular waveguide, while the suppression of the energy leakage is made using $\lambda/4$ rectangular waveguide chokes.
4. NUMERICAL RESULTS

The first device analyzed was a circular cavity loaded with a dielectric disk at the middle of the cavity (see Fig. 1(b)). The excitation is made by a stepped concentric circular waveguide, while the two side wall openings were omitted for simplification reasons. The device consists of a cavity having $R = 268.7\, \text{mm}$, $l = 61.78\, \text{mm}$, a feeding waveguide with $R = 35\, \text{mm}$ and a circular dielectric disk with thickness $t = 10\, \text{mm}$, $\varepsilon_r = 4.0$ located at the center of the cavity. The analysis was made at $f_0 = 2.45\, \text{GHz}$, and the field distribution taking into account all the modes (propagating and evanescent) in the dielectric is shown in Fig. 3(a). It is obvious that the field distribution is far from being homogeneous. Next, in order to achieve a uniform transition between the feeding waveguide and the cavity, a taper section forming a conical section with taper angle $\alpha = 75^\circ$ was included. This is approximated by of a number of waveguides with stepped increasing radius. The resulting field distribution at the dielectric disk is shown in Fig. 3(b). Since higher order modes are excited in the cavity, the field maxima retains the form of concentric rings. This geometry can be used only in conjunction with a moving belt, in order to heat the material uniformly.

Since the analysis involves offset waveguide discontinuities, multiple waveguides can be used in order to excite the cavity. Aiming at the generation of a more uniform field distribution at the material to be heated, the cavity was excited by two identical offset circular waveguides, located $240\, \text{mm}$ apart, as shown in Fig. 4(a). The resulting field distribution at the dielectric disk is presented in Fig. 4(b). This geometry produces a uniform field distribution along the axis where the excitation is located. Hence, this is compatible with the moving belt structure of Fig. 1(a). Furthermore, a four waveguide excitation can produce a uniform distribution at two perpendicular axes.

Figure 3: Field distribution for cylindrical cavity excited by a circular waveguide, a) Step excitation, b) Taper excitation.

Figure 4: Cylindrical cavity excited by two circular waveguides, a) Geometry, b) Field distribution.
In the last geometry studied, the excitation of a HE_{11} hybrid mode is expected to yield a more uniform field distribution. For this purpose a TE_{11} to HE_{11} transformer was introduced, which consists of a corrugated circular waveguide section, as shown in Fig. 5(a). Ten corrugations were introduced, having a length of \( \lambda/4 \) at \( f_0 = 915 \text{ MHz} \), width \( w = 16.39 \text{ mm} \), spaced at \( t = 32.78 \text{ mm} \), while the radius of the feeding waveguide and the cavity are 98 mm and 122 mm respectively. The length of the cavity is \( l = 327.86 \text{ mm} \). The resulting field distribution is described in Fig. 5(b) and it presents relatively good homogeneity, except a small region at the center.

![Figure 5: Cylindrical cavity excited by HE_{11} hybrid mode, a) Geometry, b) Field distribution.](image)

5. CONCLUSIONS
The analysis of a cylindrical cavity structure used for heating purposes was presented in this paper. This is based on a closed form Mode Matching technique. The overmoded cylindrical cavity excited by a step or a tapered circular waveguide produces a non-uniform field distribution. To overcome this problem, multiple excitations must be used (multi-furcated circular waveguide) in order to achieve a uniform heating of the material. A single mode cylindrical cavity can produce a uniform field, if the HE_{11} mode is excited using a cylindrical corrugated section.

REFERENCES