Design Optimization of Two Input Multimode Applicator for Efficient Microwave Heating

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Abstract. This paper presents a novel design, modeling and optimization of two input multimode applicator at 2.45 GHz for efficient microwave heating of materials. CST Microwave Studio 2012® commercial software is used to model a two input multimode applicator for coupling two low power sources to applicator chamber. Feeding microwave power at more than one location to a multimode applicator can result in improvement of field uniformity and the increase in heating power provided coupling is proper and polarization is chosen correctly. The model is simulated for different arrangements of waveguide ports and applicator is optimized to obtain low coupling between the input ports and uniform field distribution inside the applicator chamber. Minimum port to port coupling of -52 dB is achieved with two input ports arranged on adjacent face and in crosscurrent configuration. The electric field distribution in the empty cavity and cavity loaded with the wood sample is well uniform. Energy density and power loss density graphs show consistent microwave absorption inside the sample. Simulated results indicate that the microwave applicator design with this waveguide port arrangement is optimum for low port to port coupling and uniform microwave power absorption.

Keywords: Applicator, multimode, cavity, waveguide

1. Introduction

Microwave material processing offers advantages of penetrating radiation, controlled field distribution, reduced processing times, energy savings and volumetric heating [1, 2]. Industrial microwave heating equipment mainly consists of three major components: source for electromagnetic field generation, applicator where field interacts with material, and control circuitry to optimize and regulate the overall performance of the microwave heater [2]. The electromagnetic field distribution subjected to the heating load is determined by design of applicator and its feed. Effective material processing requires uniform electric field distribution and efficient absorption of microwave energy by the load.

Design of industrial microwave oven is complicated due to several considerations such as load type, heating uniformity and hot/cold spots. Varith et al. [3] presented a design of multimode circular microwave cavity at 2.45 GHz as a section of multimode microwave oven. Industrial microwave ovens are available both at 915 MHz and 2.45 GHz frequencies. Microwave oven at 915 MHz has an advantage of higher penetration depth than that of 2.45 GHz. The frequency of 2.45 GHz is increasingly applied in microwave processing because not only industrial ovens are available, domestic microwave ovens can also be modified for heating applications. The design of the applicator is critical to microwave heating because the microwave energy is transferred to materials through the applicator. The temperature fields within the material undergoing microwave heating are inherently linked to the distribution of the electric fields within the applicator [4].

Typical applicators used in microwave processing can be classified into non-resonant applicators like waveguides, travelling wave applicators, slow wave applicators, and resonant applicators like single mode cavities and multi-mode cavities. Applicator type is chosen for a processing system on the basis of application and material under processing. For heating and material processing applications, resonant applicators, such as single mode and multimode applicators and non-resonant waveguides are most familiar. Non-resonant applicators are travelling wave type and are primarily used for continuous processing. Resonant applicators are standing wave type and are mainly used for batch processing. Resonant cavities are commonly used because of their high field strengths. The single-mode resonant applicator is designed to support only one resonant mode, therefore resulting in highly localized heating. Single mode applicators are highly efficient but sometimes unable to heat large samples uniformly. Single-mode applicator finds use in specific applications such as ceramic joining and laboratory-scale studies of microwave materials processing. Multimode cavities can be used for processing large sized objects and are suitable for batch operations and therefore most industrial microwave processing systems employ multimode cavity [4-5].

Multimode applicator finds extensive use in material processing because of simple construction and suitability to heat different types of materials. Multi-input microwave applicators can be designed to achieve more uniform electric field distribution and higher heating power. Aside from improvement of uniformity, there are other reasons for feeding of microwave cavities at multiple points. Since magnetrons have limited lifetimes, in industrial applications it is often better to have more than one operating, so that if one fails the process would not shut down. An added advantage comes in very high power applications of more than tens of kilowatts, where single power sources are not available [6].

Modeling of multimode cavity applicators has been reported by various authors [7-11]. Few works have been reported about multiple input microwave cavities to achieve more uniform electric field distribution and higher heating power. Wieckowski et al. showed an improvement in power efficiency by optimizing frequency and phase of two solid state sources connected to the cavity [12].

This paper presents a novel design, modeling and optimization of two input multimode applicator at 2.45 GHz for efficient microwave heating of materials. Feeding microwave power at more than one location to a multimode applicator can result in improvement of field uniformity and increase in heating power provided coupling is proper and polarization is chosen correctly. The model was simulated for different arrangements of waveguide ports and applicator was optimized to obtain low coupling between the input ports and uniform field distribution inside the applicator chamber.

2. Theory of microwave cavity

Resonant cavities are metal-enclosed resonant structures where the dimensions are comparable with, or larger than, the operating wavelength. As such, practical cavities are almost exclusively operated at microwave frequencies (300 MHz to 30 GHz), where wavelengths are of the order of 1 cm to 1 meter. The operating frequency of a cavity, when properly used, is the same as one of the resonant modes.

Consider a generic cavity, shown schematically in Figure 1, where there are four potential modes of operation with designations 1, 2, 3, and 4. Each of these modes has a distinct standing-wave field pattern as shown, and each has a resonant frequency, designated as *f*1, *f*2, *f*3, and *f*4, shown in a frequency domain spectrum.

A frequency source that generates stimulant frequency *fs*, can be fed to the cavity through a coupling structure. When this stimulant frequency is set to equal the resonant frequency of mode 2 (*f*s = *f*2), the cavity will form a field pattern that matches that of mode 2 in Figure 1. In this example case, among the four potential modes, mode 2 has become the only operating mode. If the frequency of the source does not match any of the mode resonant frequencies, there would be no operating cavity modes, and power emitted from the source would be reflected [6].

Figure 2 shows electric field propagation from antenna of λ/4 length in a microwave oven cavity consisting of a magnetron source for electric field generation. The electric field lines curls at both ends of the antenna.

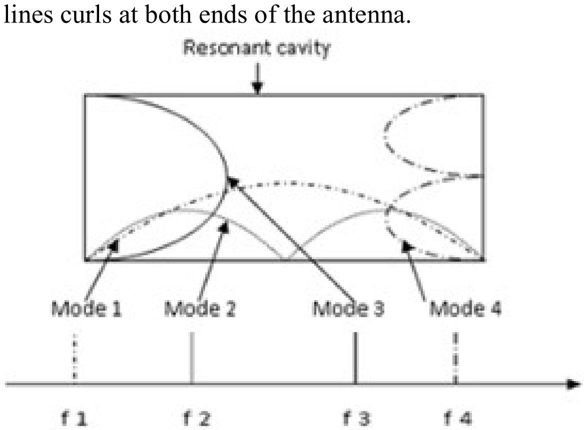


Fig.1. Potential operating cavity modes and their respective resonant frequencies.

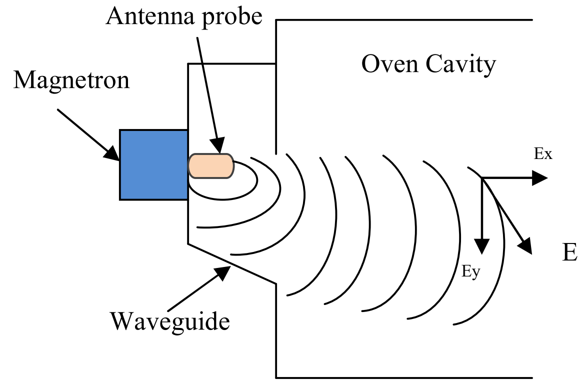


Fig.2. Electric field components are generated from antenna and carried to oven cavity through waveguide

Electric field components are generated from antenna and carried to oven cavity through waveguide attached to the microwave oven wall. The resultant electric field E at a given location in the oven cavity is given by [13]

$$E = \sqrt{E_x^2 + E_y^2} \tag{1}$$

where *Ex* and *Ey* are the components of the electric fields in the *x* and *y* directions. The solution of the three-dimensional wave equation with prescribed boundary conditions gives standing waves in the three dimensions *x*, *y* and *z*, which altogether follow the equation

$$\frac{1}{\lambda^2} = \frac{1}{\lambda_x^2} + \frac{1}{\lambda_y^2} + \frac{1}{\lambda_z^2} \tag{2}$$

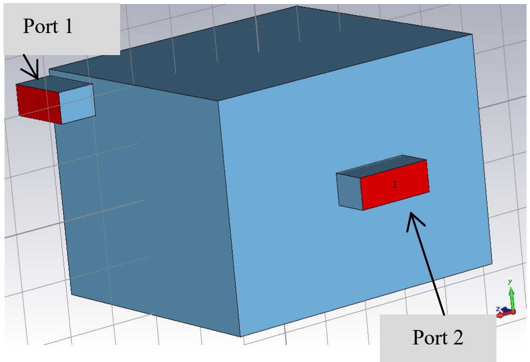
The wavelengths λ_x , λ_y and λ_z in the *x, y* and *z* directions respectively are determined by the linear dimensions L_x, L_y and L_z of the chamber:

$$Lx = l\,\frac{\lambda_x}{2}\,, \qquad Ly = m\frac{\lambda_y}{2}, \qquad Lz = n\,\frac{\lambda_z}{2} \tag{3}$$

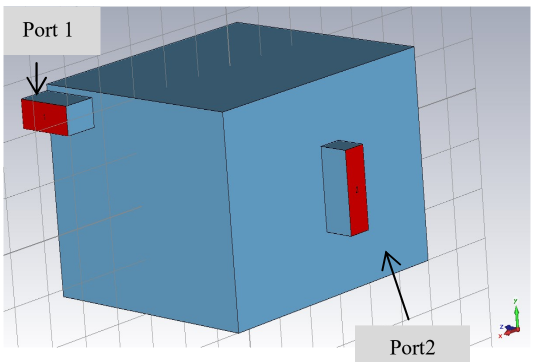
where *l*, *m*, *n* are natural numbers. Three-dimensional standing waves are formed when the oven cavity dimensions match the stimulant frequency and each dimension corresponds to integral multiple of half wavelength of standing wave along the respective plane as shown in Figure 1. The solutions for given (*l, m, n*) are denoted as modes of the resonator. Obviously equation (2) allows more than one possibility to satisfy the same given value of λ. In commercial microwave ovens, the dimensions L_x , L_y and L_z scatter appreciably[14].

3. Model simulation

CST Microwave Studio 2012® commercial software is used to model a two input multimode applicator for coupling two low power sources to applicator chamber. Three-dimensional (3D) multimode applicator geometry created is shown in Figure 3. The applicator dimensions are 310mm x 205mm x 310mm. Rectangular waveguide ports of cross-section 80mm x 28mm is added to the metallic box-like microwave applicator for connecting two low power ($\sim 1kW$) microwave sources operating at 2.45 GHz frequency. The rectangular waveguide ports are operated in the TE_{10} mode.



(a)



(b)

Fig.3. 3-D model of two input multimode applicator with input ports configured (a) in concurrent polarization (b) in crosscurrent polarization.

Microwaves generated from sources pass through the waveguide ports and enter into the applicator. Two wavegude ports can be arranged on the applicator walls in two configurations: (a) in concurrent polarization (b) in crosscurrent polarization as shown in Figure 1. The generators are assumed to provide 1V effective voltage at an excitation frequency of 2.45 GHz.

Applicator walls and waveguide ports are approximated as perfect conductors and the background material of model is set as PEC (Perfect Electric Conductor). The boundary conditions are set as electric field intensity E=0 V/m for all dimensions. Finite integration technique is used in model simulation for transmission parameters. The model is simulated in frequency range of 2.4 to 2.5 GHz with mesh of 10 lines per wavelength. The Design objective of microwave applicator was to generate more heat power and achieve more field uniformity by coupling two low power microwave sources to applicator. The main reason for this improvement is the fact that each feed point couples independently to a different set of modes. The model is simulated for various arrangements of waveguide ports and applicator is optimized to obtain low coupling between the input ports and uniform field distribution inside the applicator chamber.

4. Simulation results and discussion

The port to port coupling from port 1 to port 2 and from port 2 to port1 is called cross coupling and is indicated by scattering parameters S_{21} and S_{12} respectively. Figure 4 shows scattering parameter in the range of 2450±50 MHz for input ports configured in concurrent polarization. Figure 5 shows scattering parameter in range of 2450±50 MHz for input ports configured in crosscurrent polarization. As evident from the two graphs; concurrent polarization of input ports resulted in higher coupling than crosscurrent polarization of the two input waveguide ports and is therefore not preferred.

Two microwave sources connected to applicator cavity can fluctuate in the frequency range of 2450±50 MHz. Crosscurrent polarization of the two input waveguide ports provides low coupling in this frequency range and is more suitable. The low coupling means less returned wave between ports and therefore less risk for microwave sources to be damaged by cross coupling.

Simulation is carried out for different arrangements of waveguide ports and applicator is optimized. Results show that a minimum port to port coupling of -52 dB is achieved with two input ports arranged on adjacent face and in crosscurrent configuration.

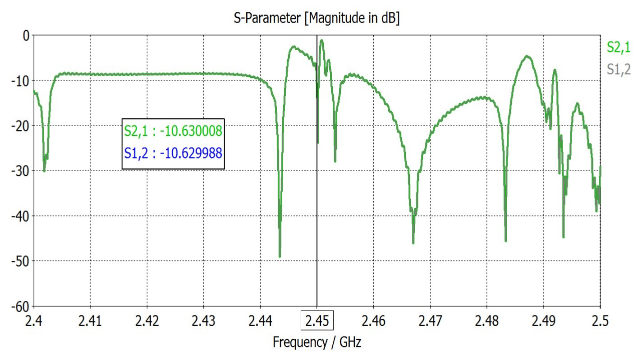


Fig.4. Cross coupling in range of 2450±50 MHz for input ports configured in concurrent polarization.

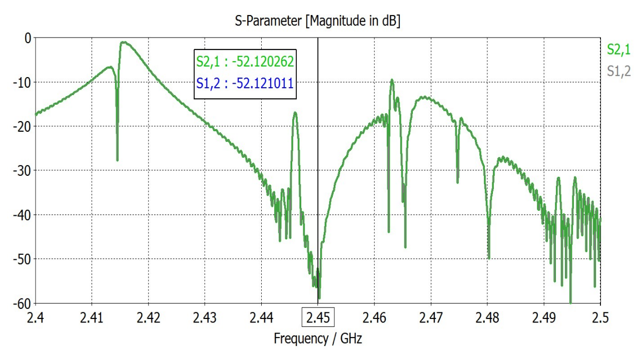


Fig.5. Cross coupling in range of 2450±50 MHz for input ports configured in crosscurrent polarization.

Figure 6 shows simulated electric field distribution inside the empty microwave cavity with waveguide port arrangement with uniform field distribution. The electric field distribution shows the high field regions spread uniformly throughout the cavity. For optimum cavity design we will have to consider the microwave power absorption by the sample placed inside the cavity.

The E-field inside the empty microwave cavity is modified when cavity is loaded with a wood sample as shown in (Figure 7). The size of sample is 50.8mm x 50.8mm x 50.8mm and it is located at the centre of cavity.

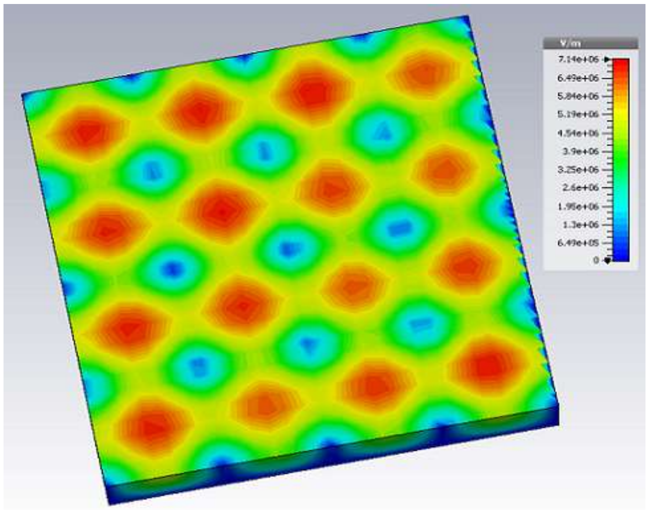


Fig.6. Electric field of cross section plane of empty microwave cavity.

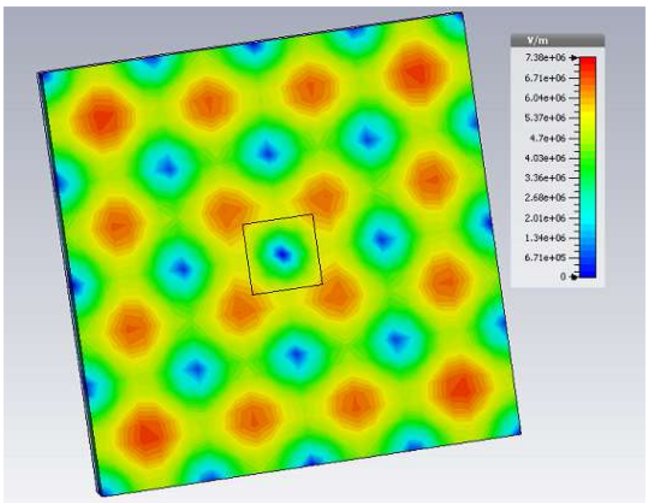


Fig.7. Electric field of cross section plane of modelled microwave cavity with wood sample inside.

As the waves are absorbed and transmitted through the wood sample the field is more concentrated towards the sample. The dielectric constant of the wood sample is taken as $\varepsilon_r = 2.1\text{-j}0.25$.

Inside the sample electric field concentrated more at the edges of the sample and attenuated in radial direction to the center of the sample (Figure 8). Load inside the cavity play a major role in microwave distribution.

Figure 9 shows energy density in the empty oven and Figure 10 shows energy density inside loaded cavity which shows a concentration of energy inwards the sample indicating condition for uniform heating of the sample.

The power loss density graphs in Figures 11-13 show the pattern of microwave absorption inside the wood sample which shows uniform power loss across the xz, yz, and xy cross-section planes. Microwave power is absorbed uniformly from core to the outer periphery of the sample. The oven design seems to work optimally for the uniform heating of sample and low port to port coupling. Further uniformity can be improved by adding the rotating tray to provide radial movement to the sample.

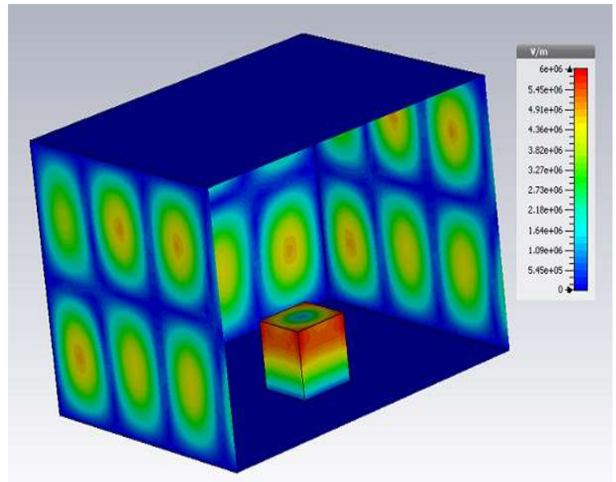


Fig.8. Electric field distribution inside the wood sample placed in the microwave cavity.

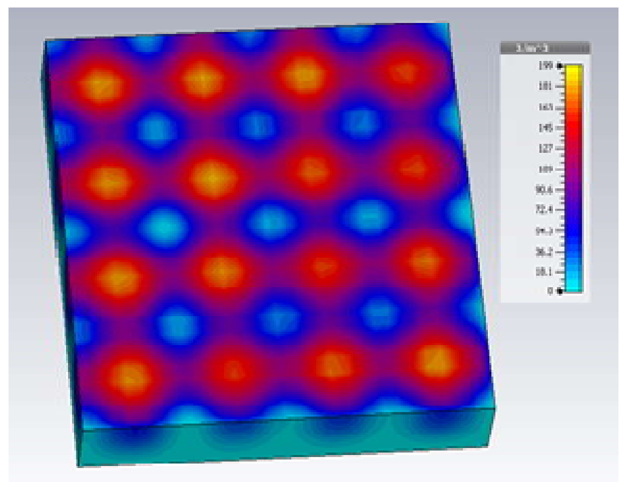


Fig.9. Energy density of cross section plane at y = 5.1cm from the bottom inside empty microwave cavity

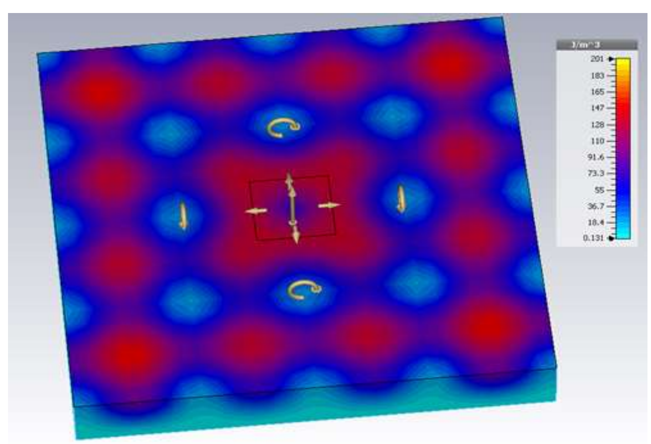


Fig.10. Energy density of cross section plane at y = 5.1cm from the bottom inside the microwave cavity with wood sample inside.

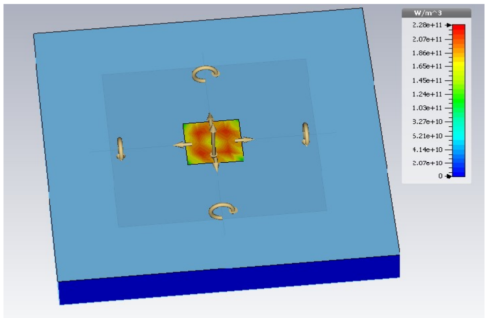


Fig.11. Power loss density absorbed into the wooden sample of xz cross section plane at y = 5.1cm from the bottom.

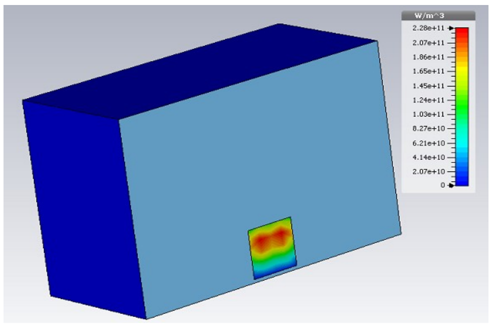


Fig.12. Power loss density absorbed into the wooden sample of yz cross section plane.

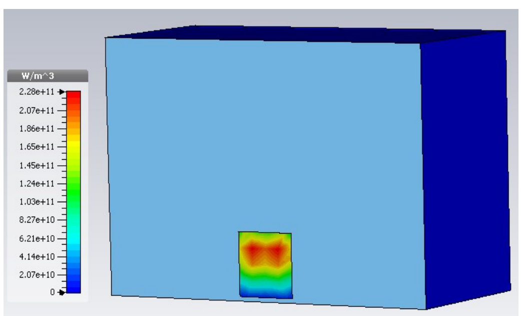


Fig.13. Power loss density absorbed into the wooden sample of xy cross section plane.

5. Conclusions

(i) The basic operation of a generic resonant cavity and mode excitation in a cavity are explained.
(ii) Model of two input multimode applicator is presented. Two inputs allow coupling two low power sources to applicator chamber.
(iii) Two inputs provide operational redundancy and eliminate the need of a single high power source.
(iv) Arrangements of input waveguide ports determine the field distribution inside the applicator.
(v) Minimum port to port coupling of -52 dB is achieved with two input ports arranged on adjacent face and in crosscurrent configuration.
(vi) The electric field distribution in the empty cavity and cavity loaded with wood sample is well uniform.
(vii) Energy density and power loss density graphs show uniform microwave absorption inside the sample.
(viii) Simulated results show that the microwave applicator design is optimum for low port to port coupling and uniform microwave power absorption.

6. References

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