

Electromagnetic Modeling of an Adaptable Multimode Microwave Applicator for Polymer Processing

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Abstract: Microwaves have been investigated as an attractive alternative (and efficient) energy source to inefficient pressurized ovens for polymer processing. However, industrial use of microwave processing has been impeded by the lack of proper applicator design, modeling, and control/monitoring methods. In this paper, we will briefly talk about conventional multimode applicators, waveguide applicators, and recently developed single-mode applicators. Then we will present the electromagnetic modeling of a novel adaptable multi-feed multimode cylindrical cavity applicator where the spatial distribution of the electric field can be specified *a priori* to accomplish a desired processing task. At the end, the port-to-port coupling analysis will be performed both theoretically and numerically.

Keywords: Electromagnetic Modeling, Adaptable Multimode Applicator, Polymer Processing

1. Introduction

Microwaves have been investigated as an attractive alternative (and efficient) energy source to inefficient pressurized ovens for material processing, including polymers and composites. The observed advantages are volumetric and inside out heating, direct and fast heating, high selectivity, and high controllability. Results have been reported on enhanced polymerization rates [1-2], increased glass transition temperatures of cured epoxy [1], improved interfacial bonding between graphite fiber and polymer matrix [3], and increased mechanical properties of the composites [4]. However, industrial use of microwave has been impeded by the lack of proper applicator design, modeling, and control/monitoring methods. Most existing applicators are for specific applications only and the applicator design has to be performed over and over again for new processes, mostly by trial and error without the assistance of a model. The development of adaptable applicators, which can be configured to accomplish a variety of processing tasks, is very important.

Commonly used applicators for materials processing can be classified into three basic types: waveguide, multimode and single-mode applicators. A waveguide applicator is a hollow conducting pipe with either a rectangular or a circular cross-section. The wave inside a waveguide applicator is fundamentally different from that inside multimode and single-mode applicator. The former is a traveling wave and the latter is a standing wave. Energy from the microwave generator travels through the waveguide and is partially absorbed by the process material. The remainder of the energy is directed to a terminating load. Traveling wave applicators are primarily used for continuous processing

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of high-loss materials; low-loss materials require an excessively long waveguide or a slow processing speed to absorb the necessary energy.

The most popular applicator type is the overmoded or multimode cavity where the electric field distribution is given by the sum of all the modes excited at a particular frequency. The frequent use of multimode cavity applicators is a result of their low cost, simplicity of construction, and adaptability to many different heating loads. This kind of applicator is very versatile in that it can accept a wide range of material loads of different dielectric losses, size and shape [5]. However, that may limit product quality, particularly with regard to the uniformity of temperature distribution in processed materials. Difficulties for multimode cavity analysis of electric field distributions result essentially from coexistence of many resonant modes. By rotating the sample and/or using metal stirrers, it is possible to improve the E-field uniformity and, thus, the heating uniformity inside the multimode applicator [6]. The mode-stirrer is a fan within a multimode cavity designed to change the resonance of multiple modes within a 4MHz band near 2.45 GHz. As the mode-stirrer rotates, the resonant conditions of the cavity change, focusing the energy into different field patterns. The rotation of the fan cycles the cavity through the different resonant modes with a pattern that accepts whatever random heating occurs across the sample. This may improve the heating uniformity to a certain degree, but makes it more difficult to predict the electric field distribution and not suitable for precision materials processing.

The single-mode resonant applicator is designed to support only one resonant mode, therefore resulting in highly localized heating. These applicators can efficiently provide high field strength at mode-specific locations within the cavity since single frequency systems can be tuned for maximum throughput. Although single-mode applicators have a high efficiency relative to multimode and traveling wave applicators, sometimes it is very difficult for them to provide desired uniform heating across a large sample. To obtain uniform heating under these conditions, a technique called mode-switching was developed, in which several modes with complementary heating patterns are alternatively excited [7].

With a fixed frequency microwave power source, mode-switching can be achieved by mechanically adjusting the length of the cavity. This mechanical process slows the response of the system to temperature changes. With a variable frequency power source, modes can be changed by changing frequency. As a result of the instantaneous variable frequency mode switching, not only the speed of the process but also the controllability of the process is much improved [8]. However, variable frequency sources are inherently less efficient than the single frequency versions; the equipment is also very expensive. In our research effort, mode-switching can be obtained by varying the power delivered to multiple ports, hence eliminating the need for mechanical applicator adjustments.

In this case, we can tailor the field intensity to achieve high field strength in the regions of the applicator requiring high fields (and hence regions where heating is desirable) and low field intensities in regions where heating is not desired. We will explore multi-port multi-feed applicators where the field spatial distribution can be specified *a priori* to accomplish a desired processing task. Single frequency operation is preferred since the over-all system efficiency is generally higher for such "tuned" systems.

Specifically, in our modeling, we are exciting a cylindrical cavity via two ports to get a TM mode and a TE mode simultaneously. With these separately controllable TM and TE modes, we not only get desired field strength distribution at specific locations inside the cavity, but also have the ability to make heating direction selection; this is particularly useful when anisotropic materials are processed. Taking advantages of TM and TE modes, it is easy for us to get very low port-to-port coupling. This will be shown later in both analytical analysis and numerical results.

2. Adaptable Multimode Applicator

Inside a circular cylindrical cavity, the resonant frequencies for TE and TM modes as functions of cavity height h and radius a can be expressed as [9]:

$$(f)_{npq}^{TE} = \frac{1}{2\pi a \sqrt{\mu\epsilon}} \sqrt{x'_{np}{}^2 + \left(\frac{q\pi a}{h}\right)^2} \quad (1)$$

$$(f)_{npq}^{TM} = \frac{1}{2\pi a \sqrt{\mu\epsilon}} \sqrt{x_{np}{}^2 + \left(\frac{q\pi a}{h}\right)^2} \quad (2)$$

where x_{np} and x'_{np} are tabulated zeros of the Bessel's function and the derivative of the Bessel's function, respectively. Resonant frequency f can be plotted as a function of cavity length in a mode diagram for a fixed radius, as shown in Figure 1.

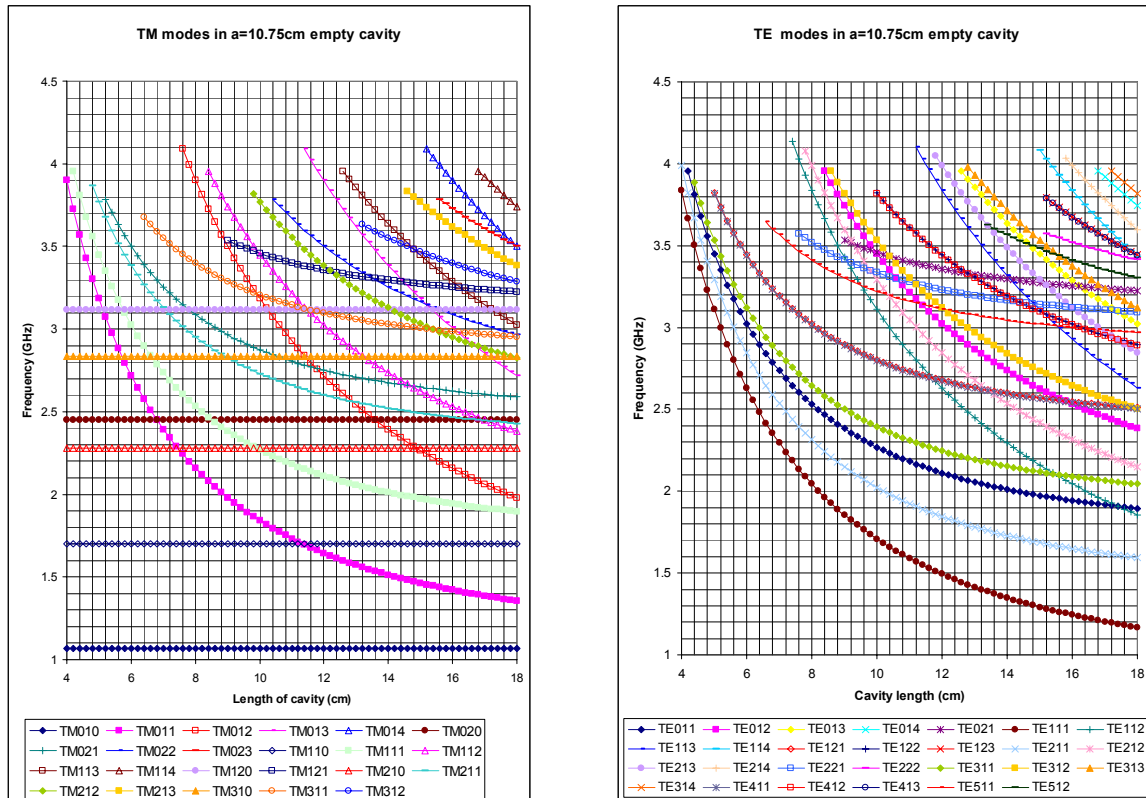


Figure 1. Mode diagrams for a circular cylinder (TM: left, TE: right).

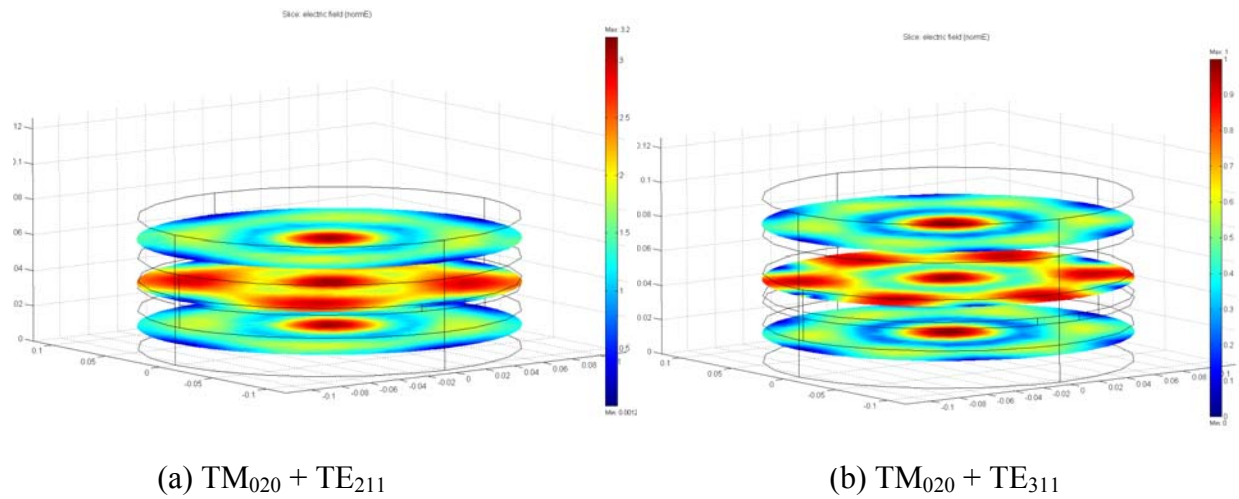
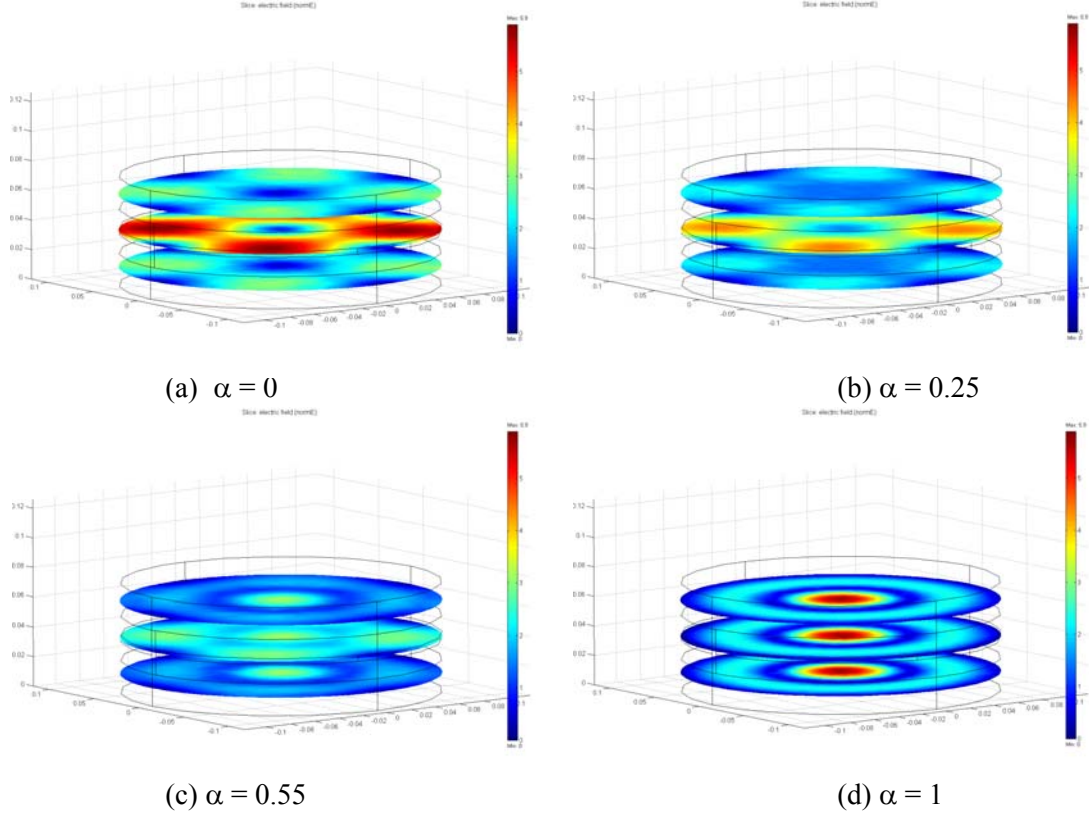


Figure 2. Electric field distributions for different combination of TM and TE modes.

This design will include two feed ports. The feed structure will not be coaxial (for TM modes) and loop (for TE modes). Although these are useful methods for feeding, as well as being typical, they may not lead to sufficient decoupling of the two ports. If the feeds are orthogonal, the mutual coupling between ports is zero (e.g. $S_{21} = 0 = S_{12}$). This is a desirable condition since a non-zero transmission term indicates that power from one port will exit the cavity through the other port doing no significant heating of the polymer. The feed mechanism chosen, to minimize mode cross-coupling, are an axial slot (to excite a TE mode) and an azimuthal slot (to excite a TM mode). These slots are electrically very narrow to avoid mode cross-coupling.

By observing the mode diagrams, it is seen that when the cavity height is adjusted, we can have different combinations of TM and TE modes resonant at 2.45GHz, and thus get different electric field distribution inside the cavity. When the radius $a = 10.75\text{cm}$ and height $h = 7.34\text{cm}$, we can get the combination of TM_{020} and TE_{211} , which is shown in Figure 2(a); while $a = 10.75\text{cm}$ and $h = 9.50\text{cm}$, the combination of TM_{020} and TE_{311} is shown in Figure 2(b). For both cases, we have a bulls-eye heating pattern (TM_{020}) at the center as well as some distributed spots (TE_{211} or TE_{311}) around it. TM mode has the electric fields along the central axis of the cylinder, which is best suited for heating rods and cylinders located along the axis of the cylinder; TE mode has the electric fields parallel to the bottom plate of the applicator, which is best suited for heating flat panels or disks.

For each combination of TM and TE mode with fixed cavity height, by varying the power delivered to each port, mode-switching can be obtained at a single frequency without mechanically adjustment of the cavity dimensions. This transition can be shown in figure 3 for the combination of TM_{020} and TE_{211} case. To investigate the curing field for simultaneous mode excitation, a parameter α is introduced. A pure TE mode excitation has $\alpha = 0$ while a pure TM mode excitation is given by $\alpha = 1$. The cavity model was verified for these two cases using the appropriate slot excitation methods. The numerical simulations using COMSOL's FEMLAB code were performed for different α , which means different relative power delivered to each port. Figure 3 shows the field distribution for each α , where (c) is the same as that in figure 2(a) but with different scale. It was determined that $\alpha = 0.55$ yielded the most uniform curing field in the center plane of the applicator. A uniform field is desirable since that will allow the curing of the largest diameter part.


 Figure 3. Parametric study on the weighting factor α for the combination of the two modes.

3. Port-to-Port Coupling Analysis

As mentioned above, the mutual coupling between the two ports is a very important factor that influences the performance of the applicator. To get better performance, we wish to get lowest possible coupling in order to avoid the energy leakage through the ports. In a homogeneous, source-free cylindrical cavity with perfectly conducting walls, the electromagnetic fields inside the cavity can be derived from Maxwell's equations and boundary conditions [9]. For TM_{020} mode, we can get:

$$\begin{aligned}
 E_\rho &= 0 & E_\phi &= 0 \\
 E_z &= \frac{k^2}{j\omega\epsilon} J_0\left(\frac{5.52\rho}{a}\right) = -j\omega\mu J_0\left(\frac{5.52\rho}{a}\right) \\
 H_\rho &= 0 & H_z &= 0 \\
 H_\phi &= -\frac{\partial \psi_{020}^{TM}}{\partial \rho} = \frac{5.52}{a} J_1\left(\frac{5.52\rho}{a}\right)
 \end{aligned} \tag{3}$$

For TE_{211} mode, we have:

$$\begin{aligned}
 E_\rho &= -\frac{1}{\rho} \frac{\partial \psi_{211}}{\partial \phi} = \frac{2}{\rho} J_2\left(\frac{3.054}{a}\rho\right) \sin(2\phi) \sin\left(\frac{\pi z}{h}\right) \\
 E_\phi &= \frac{\partial \psi_{211}}{\partial \rho} = \cos(2\phi) \sin\left(\frac{\pi z}{h}\right) \left[J_1\left(\frac{3.054}{a}\rho\right) - \frac{2a}{3.054\rho} J_2\left(\frac{3.054}{a}\rho\right) \right] \\
 E_z &= 0
 \end{aligned} \tag{4}$$

$$H_\rho = \frac{1}{j\omega\mu} \frac{\partial^2 \psi_{211}}{\partial \rho \partial z} = \frac{\pi/h}{j\omega\mu} \cos(2\phi) \cos\left(\frac{\pi z}{h}\right) \left[J_1\left(\frac{3.054}{a} \rho\right) - \frac{2a}{3.054\rho} J_2\left(\frac{3.054}{a} \rho\right) \right]$$

$$H_\phi = \frac{1}{j\omega\mu} \frac{1}{\rho} \frac{\partial^2 \psi_{211}}{\partial \phi \partial z} = -\frac{2\pi/h}{j\omega\mu\rho} \sin(2\phi) \cos\left(\frac{\pi z}{h}\right) J_2\left(\frac{3.054}{a} \rho\right)$$

$$H_z = \frac{1}{j\omega\mu} \left(\frac{\partial^2 \psi_{211}}{\partial z^2} + k^2 \psi_{211} \right) = \frac{1}{j\omega\mu} \left(\omega^2 \mu \epsilon - \left(\frac{\pi}{h} \right)^2 \right) J_2\left(\frac{3.054}{h} \rho\right) \cos(2\phi) \sin\left(\frac{\pi z}{h}\right)$$

Considering the field generated by azimuthal slot for TM_{020} mode, E_ρ and E_ϕ are zero, and E_z is very difficult to be coupled out through the axial slot; similarly, for the field generated by axial slot for TE_{211} mode, E_z is zero and it is very difficult for E_ρ and E_ϕ to be coupled out through the azimuthal slot. So it is clear that with these two specific modes, we can have very low port-to-port coupling, which is very essential to get better efficiency. Figure 4 shows the simulated S-parameters for this two-port-feed cavity. It is seen S_{21} is very small. When the lossy materials are loaded in practice, S_{21} is expected to be even smaller.

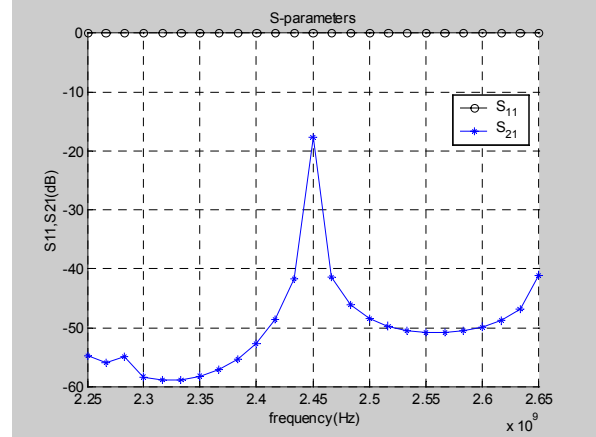


Fig. 4. S-parameters for the cavity.

4. Closing Remarks

In this paper, we have presented the electromagnetic modeling of an adaptable multimode microwave cavity applicator for polymer processing. Currently, the feed network which consists of coax-to-waveguide transition followed by aperture-coupled cavity is being modeled.

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