Electromagnetic Modeling of an Adaptable Multimode Microwave Applicator for Polymer Processing

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Abstract—**This paper presents 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. The electric field intensity inside the cavity can be tailored by just varying the power delivered to each port, and the mode-switching can be realized without mechanically adjusting the cavity dimensions. An orthogonal feeding mechanism is developed to reduce the cross coupling between the ports. Numerical simulations are performed for the cavity applicator to verify the theoretical analysis.**

Index Terms—**Electromagnetic modeling, adaptable multimode applicator, orthogonal feeding.**

I. INTRODUCTION

MICROWAVES have been investigated as an attractive and efficient alternative energy source compared to inefficient pressurized ovens for material processing, including polymers and composites. The observed advantages are volumetric 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 fibers and the polymer matrix [3], and increased mechanical properties of the composites [4]. However, industrial use of microwave processing 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 therefore 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 material being processed. The remainder of the energy is directed to a terminating load. Traveling wave applicators are primarily used for continuous processing of high-loss materials; low-loss materials require an excessively long waveguide or a long processing period 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 4 MHz 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 material 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

heat along a preferred direction; this is particularly useful when anisotropic materials are processed. Taking advantages of TM and TE modes, it is easy for us to get low port-to-port coupling, especially when a lossy load is present. This will be shown later in both theoretical analysis and numerical results.

II. 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]:

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

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

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 Fig. 1.
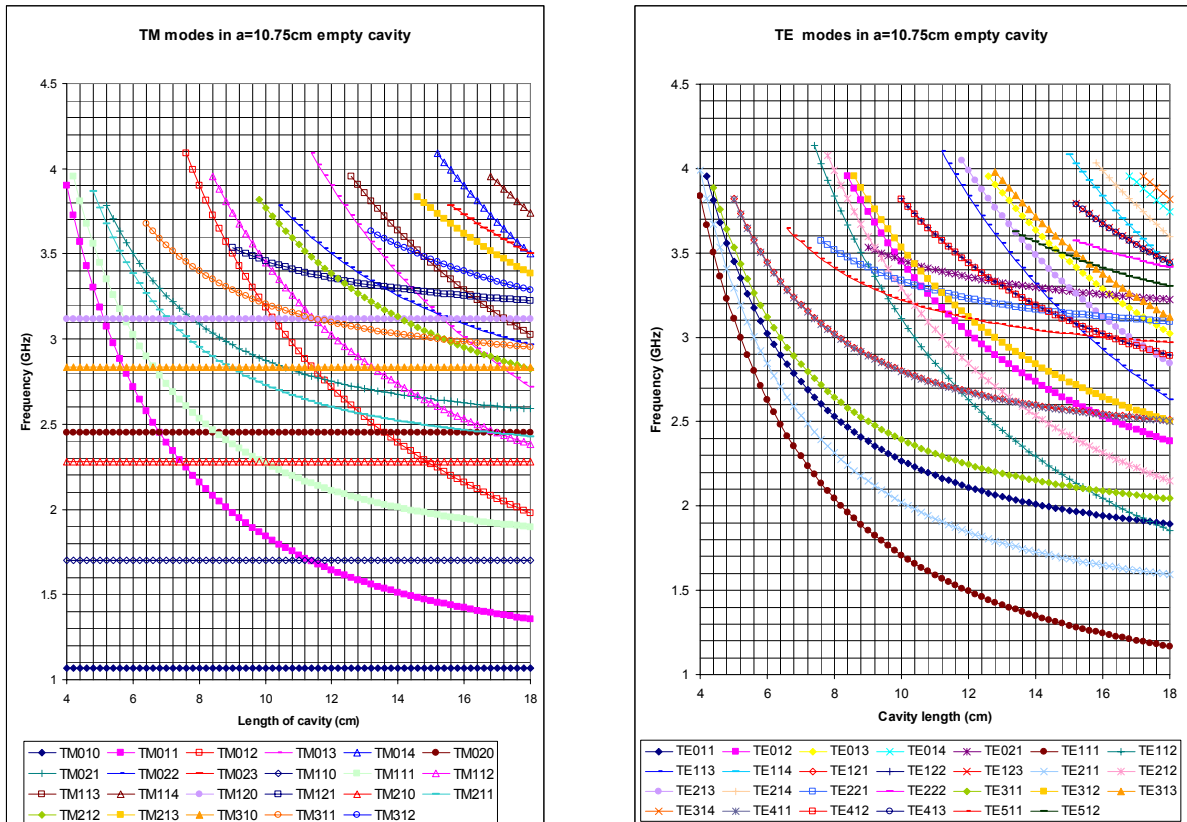

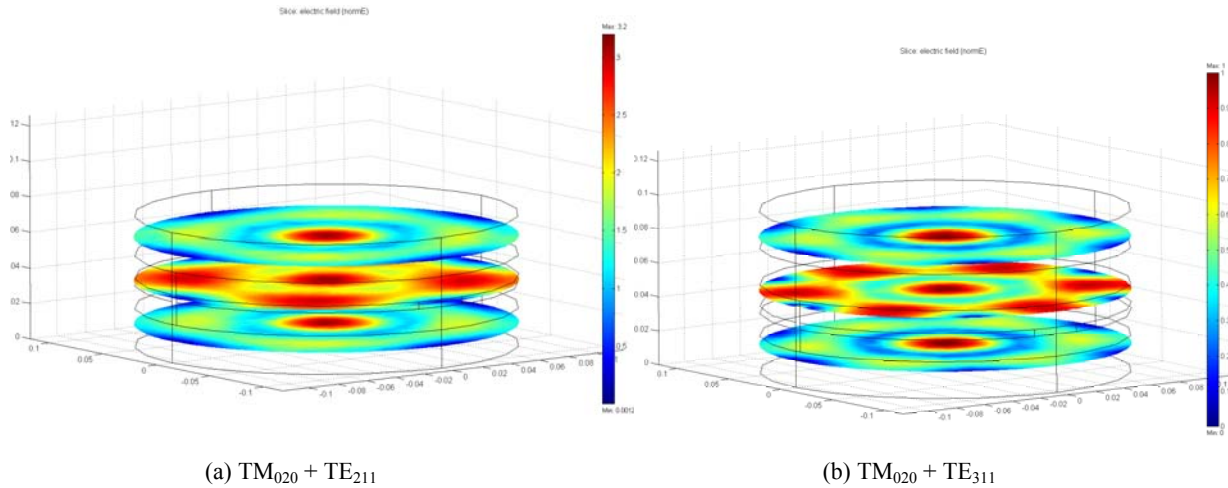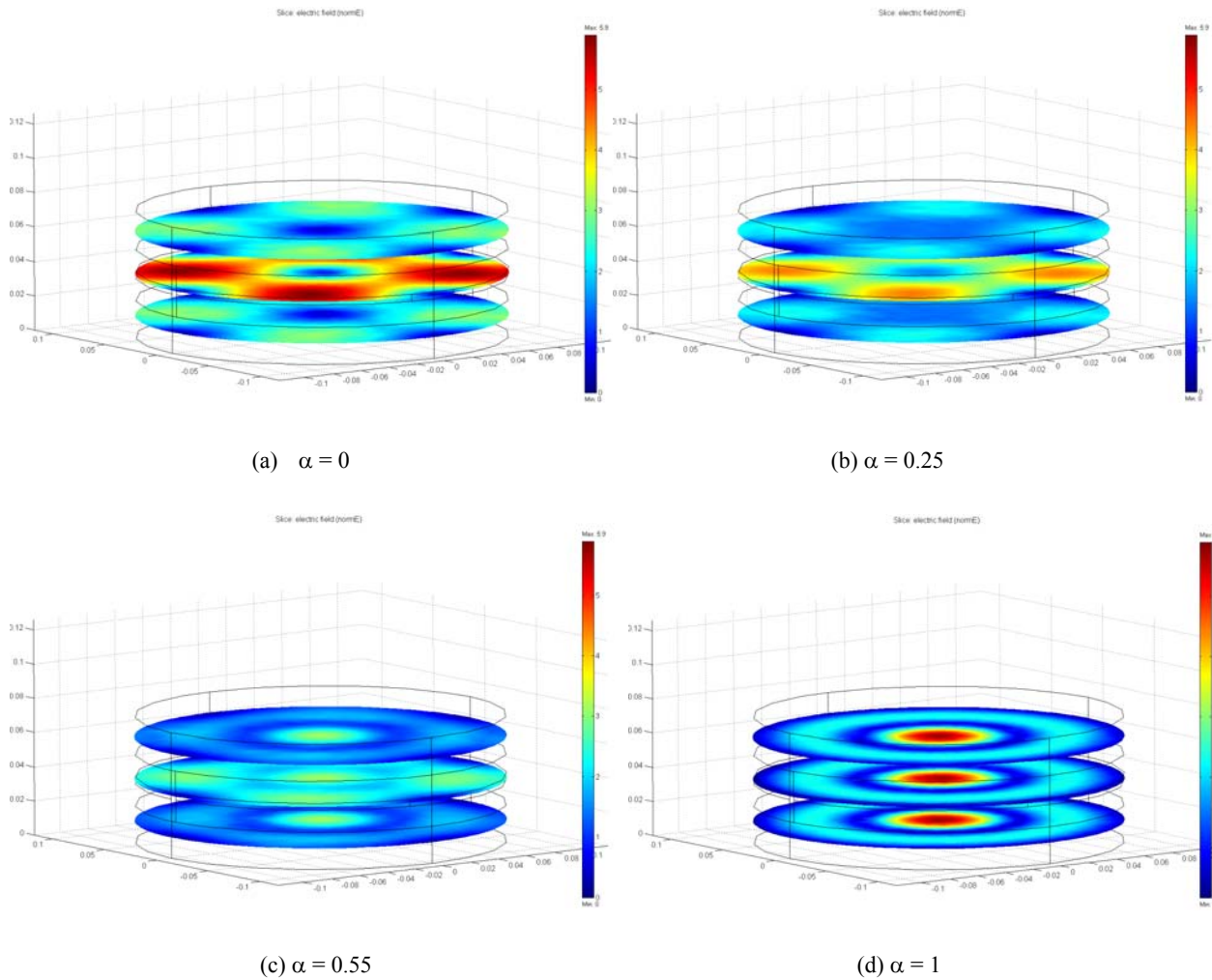Figure 1. Mode diagrams for a circular cylinder (TM: left, TE: right).

(a) $TM_{020} + TE_{211}$

(b) $TM_{020} + TE_{311}$

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

(a) $\alpha = 0$

(b) $\alpha = 0.25$

(c) $\alpha = 0.55$

(d) $\alpha = 1$

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

Typically, inside the cavity, TM modes are excited with a coaxial probe while TE modes are excited with sidewall-mounted loops. Although these are useful methods for feeding, they may not lead to sufficient decoupling of the two

ports. If the feeds are ideally 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. Our cavity design has two feed ports. 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 2.45 GHz, and thus get different electric field distribution inside the cavity. When the radius a = 10.75 cm and height h = 7.34 cm, we can get the combination of TM_{020} and TE_{211}, which is shown in Fig. 2(a); while a = 10.75 cm and h = 9.50 cm, the combination of TM_{020} and TE_{311} is shown in Fig. 2(b). For both cases, we have an axisymmetric electric field 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 Fig. 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 [10] were performed for different α, which

means different relative power delivered to each port. Fig. 3 illustrates the field distribution for each α, where (c) is the same as that in Fig. 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.

III. 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:

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

For TE_{211} mode, we have:

$$
\begin{aligned}
&E_\rho = -\frac{1}{\rho}\frac{\partial \psi_{211}}{\partial \phi} = \frac{2}{\rho}J_2(\frac{3.054}{a}\rho)\sin(2\phi)\sin(\frac{\pi z}{h}) \\
&E_\phi = \frac{\partial \psi_{211}}{\partial \rho} = \cos(2\phi)\sin(\frac{\pi z}{h})\left[J_1(\frac{3.054}{a}\rho) - \frac{2a}{3.054\rho}J_2(\frac{3.054}{a}\rho)\right] \\
&E_z = 0 \\
&H_\rho = \frac{1}{j\omega\mu}\frac{\partial^2 \psi_{211}}{\partial \rho \partial z} = \frac{\pi/h}{j\omega\mu}\cos(2\phi)\cos(\frac{\pi z}{h})\left[J_1(\frac{3.054}{a}\rho) - \frac{2a}{3.054\rho}J_2(\frac{3.054}{a}\rho)\right] \\
&H_\phi = \frac{1}{j\omega\mu}\frac{1}{\rho}\frac{\partial^2 \psi_{211}}{\partial \phi \partial z} = -\frac{2\pi/h}{j\omega\mu\rho}\sin(2\phi)\cos(\frac{\pi z}{h})J_2(\frac{3.054}{a}\rho) \\
&H_z = \frac{1}{j\omega\mu}(\frac{\partial^2 \psi_{211}}{\partial z^2} + k^2\psi_{211}) = \frac{1}{j\omega\mu}(\omega^2\mu\varepsilon - \left(\frac{\pi}{h}\right)^2)J_2(\frac{3.054}{h}\rho)\cos(2\phi)\sin(\frac{\pi z}{h}).
\end{aligned}
$$

$$(4)$$

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 seen that with these two specific modes, we can

have very low port-to-port coupling, which is essential for achieving improved efficiency.

In practice, the microwave power is delivered into the cylindrical cavity by rectangular waveguides (for this work, WR-284) via iris-coupling (shown in Fig. 4 as meshed geometry in FEMLAB). The dominant mode inside the

waveguide is TE_{10} mode. The dimensions of the irises need to be determined so that the S_{11}, S_{21}, S_{22}, and S_{12} are minimized. Under these conditions, the maximum power is delivered to the load for processing. Fig. 5 and Fig. 6 show the simulated S-parameters for this empty two-port-feed cavity, where we call the TE-port as port 1 and TM-port as port 2. The resonant frequency shifted down a little bit from 2.45 GHz due to the existence of the irises. After the lossy epoxy samples are loaded inside the cavity, the S_{21} and S_{12} are expected to be even smaller. This multimode applicator is primarily designed for the processing of epoxy resins DGEBA/DDS mixture. The ε_r' and ε_r'' as a function of temperature and extent-of-cure are measured at MSU using perturbation technique with single-mode cavity, and are shown in Fig. 7. More information about DGEBA/DDS to be processed with this cavity applicator can be found in [11]. Since the complex permittivity of DGEBA/DDS varies as a function of temperature and extent-of-cure during microwave heating, the S_{11} and S_{22} are expected to vary significantly due to the loaded epoxy sample. In practice, in order to adjust the reflection coefficients at the

two ports, a brass plunger can be introduced lying very close to each coupling iris [12], so that the S_{11} and S_{22} can be retuned in real-time.
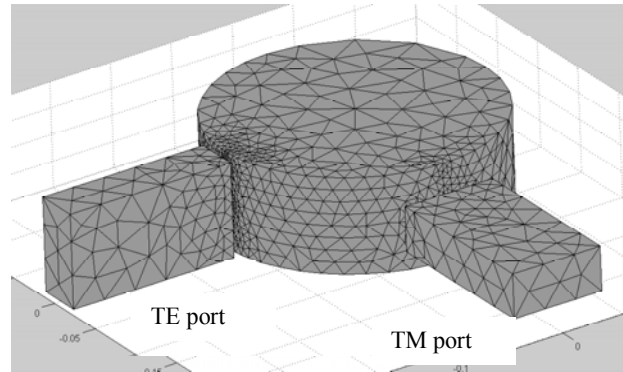

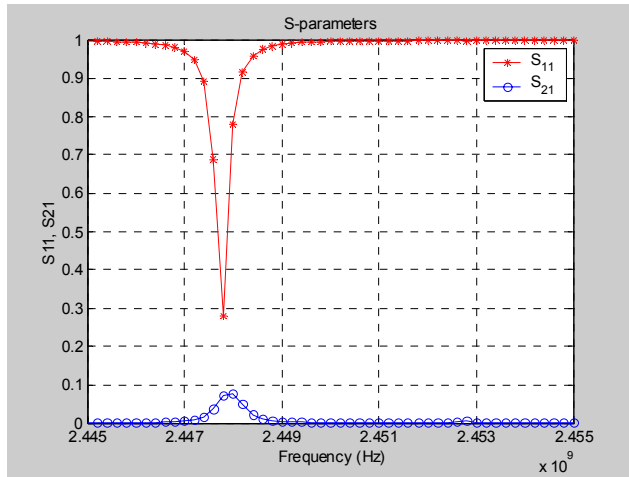Figure 4. Cavity fed with waveguides via irises.

Figure 5. TE mode (S_{11} and S_{21}) for the two-port cavity.
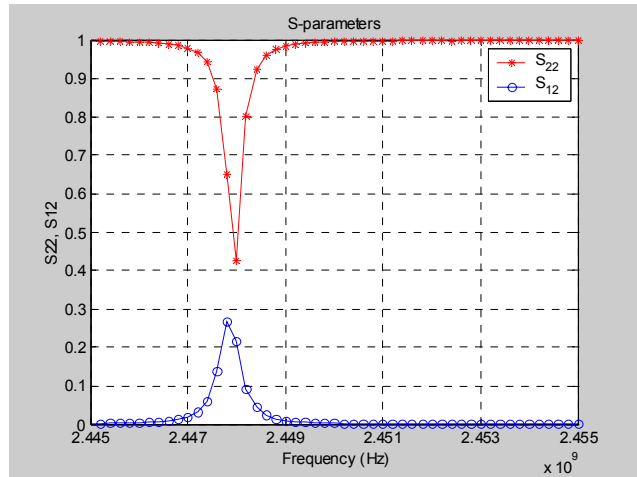

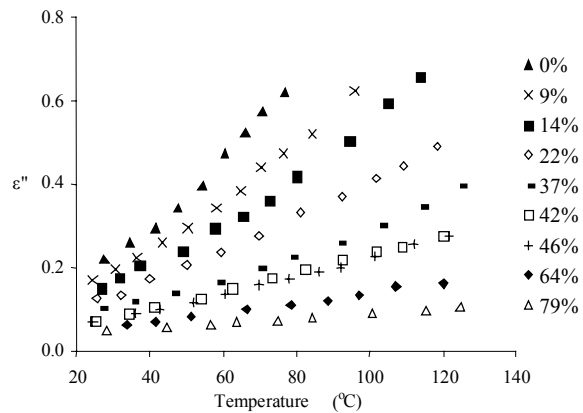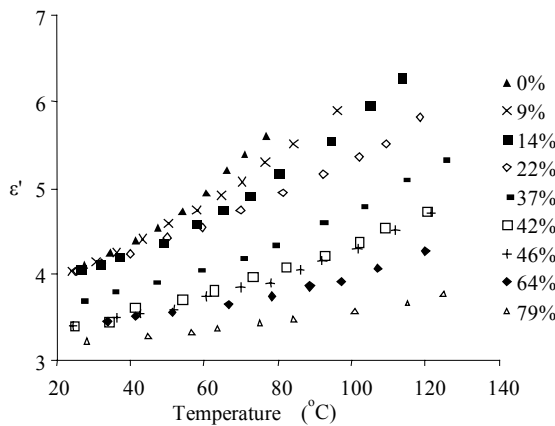Figure 6. TM mode (S_{22} and S_{12}) for the two-port cavity.

Figure 7. Dielectric properties of DGEBA/DDS as a function of temperature and extent-of-cure measured at MSU.
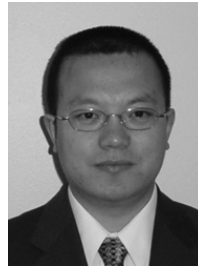
IV. Conclusion

In this paper, we have presented the electromagnetic modeling of an adaptable multimode microwave cavity applicator for polymer processing. It is shown that the mode-switching can be realized by just varying the power delivered to each port, without mechanically adjustment of the cavity dimensions. An orthogonal feeding mechanism is developed to reduce the cross coupling between the ports. The feed network that consists of coax-to-waveguide transition followed by iris-coupled cavity is being implemented. Experiments will be carried out to verify the model and develop control strategies.

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Rensheng Sun was born in Heilongjiang, China, in 1975. He received the B.E. degree from Tsinghua University, Beijing, China, and the M.S. degree from Villanova University, Villanova, PA, both in electrical engineering, in 1999 and 2002, respectively. He is currently working toward the Ph.D. degree in electrical engineering at Michigan State University, East Lansing. His current research interests include computational electromagnetics, numerical modeling on microwave processing of materials, and multimode cavity design. He is a student member of IEEE and a member of Eta Kappa Nu and Tau Beta Pi.

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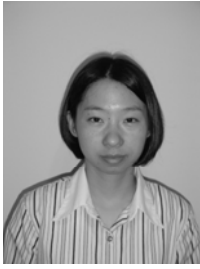
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Martin C. Hawley is currently professor and chairperson of the department of Chemical Engineering and Materials Science at Michigan State University. He teaches and has developed graduate and undergraduate courses in chemical kinetics and chemical reactor design; applied mathematics; process design, economics and optimization. Present research is concerned with chemicals from biomass; free radical production in microwave plasmas; electromagnetic coupling and measurements for materials processing; and basic reaction and transport studies in thick-section composites. Dr. Hawley consults for industry and government in areas of computer simulation, chemical reactor design, process design, and materials processing.

He has developed text materials and taught courses to students in international education programs on project engineering and management. Professor Hawley holds six patents and has published over 200 articles and books.

The Mid-Michigan Section of AIChE named Dr. Hawley "Chemical Engineer of the Year" for 1975 and 1976 for his overall contributions to the Chemical Engineering profession. In 1982 he was honored by Michigan State University with a Distinguished Faculty Award.