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RESEARCH ARTICLE

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S-band elliptical–cylindrical cavity resonator for material processing

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Abstract

The development of an elliptical–cylindrical cavity for microwave thermal processing of materials at high electric field strengths is reported. The design methodology based on numerical modeling is validated by experimental measurements. The system can create high-power densities in the heated phases, excellent treatment uniformity, and stable operation without degenerated modes or polarization rotation as suffered by other commonly used circular resonator cavities.

KEYWORDS

elliptical resonator, material processing, microwave heating, resonator cavities

1 | INTRODUCTION

Microwave material processing often requires the creation of a well-defined field pattern that allows for a high degree of homogeneity and elevated power density within the load to provide an effective treatment. Such requirements are usual in microwave chemistry applications,[1] ceramic sintering,[2] ore beneficiation,[3] bio-oil production,[4] among others. The most common solutions for these needs are single-mode resonant cavities of rectangular or circular cross-sections.[5]

Single-mode systems have been used extensively in a broad range of applications including telecommunication systems, particle accelerators, material characterization, and, to a lesser extent, in material processing.[6]

The electric field maxima for a rectangular cavity operating in transverse electric (TE) mode is sensitive to the properties of the material load. Adjustment of a sliding short is commonly used to reposition the maxima of the electric field in the product zone.[5] In circular cavities, transverse magnetic (TM) modes present a more stable field distribution and good treatment uniformities.[7] In particular, the TM_{010} mode is an excellent alternative for treating very small loads at its center. However, for larger loads, cavity size can often become impractically small to keep the desired resonant frequency, and can often even surpass the practical limit (i.e., cavity smaller than product load). This then necessitates the use of use higher-order modes such as, for example, TM_{110} or TM_{210}; however, circular cavities exhibit mode degeneracy (i.e., modes sharing the same resonant frequency), modal polarisation dependency, and mode splitting due to geometry symmetry (i.e., degenerate modes of the same shape orthogonally polarised), which can lead to the excitation of undesired modes in practical applications.[8,9] A range of strategies can be used to minimize the likelihood of unwanted mode excitation, for example, the use of wire meshes or inserts,[9] grooves with lossy loads,[10,11] and surface slits.[12] TM_{0n0} modes go to the other extreme, requiring considerably larger structures and characterized by a sharp decrease in electric field intensity from its center.[8]

In this study, we propose an alternative cavity resonator design with an elliptical cross-section to address these issues. This type of cavity can exhibit distinct high electric fields with zones of varying size, which can be used for input of the microwave energy and the location of the material to be treated. This is shown schematically in Figure 1. This geometry prevents the formation of degenerated low order modes, mode splitting or polarization rotation due to deformation.[5,13–15] A design methodology for a high-electric field system is proposed, tested, and validated experimentally.

2 | DESIGN

2.1 | Product dielectric properties

Characterizing the bulk dielectric properties of the product is the first step in the design and is required to define the required dimensions of the applicator.[12] A two-port transmission waveguide measurement system was developed and built in-house for the room temperature measurements. The system implemented the Newnon-iterative algorithm[16] and was validated against well-known materials samples of PTFE and Nylon 66. The used material for reference testing was granulated copper ore samples of less than 4 mm at a packing density of 1.4 g/cm^3. Measurements showed a dielectric constant of 3.16 ± 0.05, and a loss tangent of 0.038 ± 0.003, averaged from 12 measurements at 2.46 GHz.

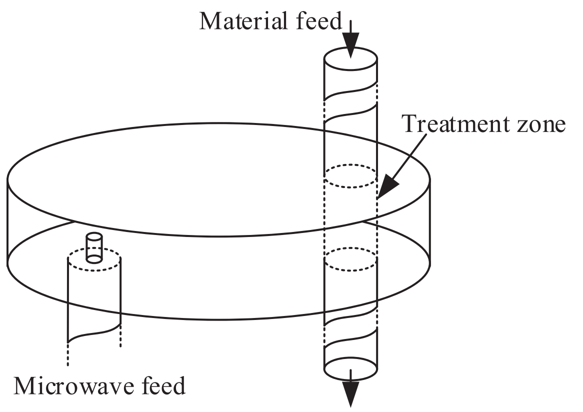

FIGURE 1 Elliptical cylinder applicator conceptual sketch

2.2 | Initial cavity dimensioning

Elliptical waveguide modes can be examined analytically by solving Mathieu's functions.[17] Loaded cavity analysis is considerably more complex making general-purpose numerical techniques essential for practical design.[15] The succession of modes in an elliptical waveguide is a function of its eccentricity.[18] The first four TM modes and the electric field distribution in an elliptical cavity with eccentricity 0.7 are shown in Figure 2, calculated using eigenmode analysis in CST Microwave.[19]

According to the process requirements, the fourth mode was considered as a desirable field distribution presenting two distinct and highly concentrated field zones. An initial eccentricity of 0.7 was selected under the premise that modal frequencies can be spaced out.[15] An estimation of the cavity size can be realized from the analytical solution of Matthieu's functions or directly by numerical eigenmode analysis. Using the former (e.g., evaluating the polynomials presented in Komarov and Colleagues[15,18]) an empty cavity size was determined resulting in a 112 × 80 mm elliptical cross-section.

The resonant frequencies of these TM modes are independent of the cavity height. The selection of height comes from avoiding longitudinal TE modes that might enter the operational band and complying with required

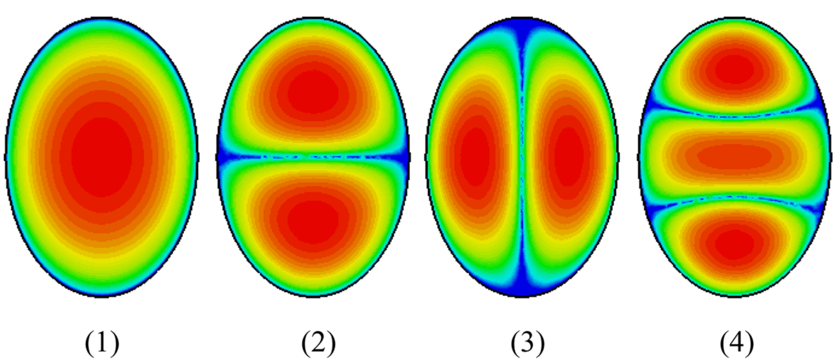

FIGURE 2 First four TM modes electric field distribution of an empty elliptical cylinder resonator with eccentricity $e = 0.7$. TM, transverse magnetic.

processing conditions. In this case, the latter was the limiting factor, requiring a height of 50 mm to achieve the required power loss density within the sample.

2.3 | Material feeding

Only relatively small cylindrical loads can be uniformly treated with this type of construction.[15,20] The material feed tube size was chosen to act as a self-choking microwave element (i.e., small enough to prevent microwave leakage). The tube can be considered as a dielectrically filled circular waveguide in which the cut-off frequency of the dominant mode in Hz is given by[8]

$$f_c = \frac{1.841}{2\pi a\sqrt{\mu\varepsilon}}, \tag{1}$$

where a is the tube radius in m, μ the magnetic permeability in H/m, and ε the electrical permittivity in F/m of the filling material. The attenuation of the fundamental mode due to being below a cut-off frequency can be estimated by evaluating the propagation constant of the filled waveguide, resulting in an attenuation per tube length of

$$\alpha(\mathrm{dB/cm}) = \frac{1}{100} Re\left[2\pi\sqrt{\mu\varepsilon}\sqrt{\left(\frac{1.841}{2\pi a\sqrt{\mu\varepsilon}}\right)^2 - f^2}\right] \frac{20}{\ln 10}, \tag{2}$$

where f is the operation frequency Hz. The waveguide acts as a high-pass filter in which the operating frequency should be smaller than the cut-off frequency to avoid propagation resulting in $a < 20$ mm. For the prototype, a radius of 10 mm and tube length of at least 6 cm was selected to ensure over 80 dB of attenuation. Also, a 1.7 mm thick PTFE tube was used as lining for containment of the product, generally used as a carrying capsule to move the product through the resonator.

2.4 | Loaded cavity

The use of analytical methods cannot be easily applied to loaded cavities making general-purpose numerical methods key to study such structures. Eigenmode and time-domain full electromagnetic simulations were done using CST Microwave.[19] Results were cross-validated by frequency-domain simulations using COMSOL Multiphysics[21] and experimental measurements.

An automatized iterative parametric swept design procedure was implemented. Initially, the sample was set in one of the maximums obtained from the eigenmode analysis of the empty cavity. Then, the ellipse semi-axis size and eccentricity were modified to bring the resonance to the central operating frequency of 2.46 GHz and provide a modal frequency separation of at least 50 MHz (i.e., separation between the desired and adjacent modes). The field distribution is analyzed, and the sample is repositioned in the new maximum position if needed. This is iterated until the goals for resonance frequency, modal frequency separation and sample positioning in the maximum are all met within specified tolerances, which for the case of study were set to ± 5 MHz, >50 MHz and ± 0.5 mm, respectively. This resulted in a loaded cavity with an eccentricity of 0.73 and an elliptical cross section of 102×70 mm. Eigenmode analysis of the structure showed a resonant frequency of 2462.8 MHz with sample center and maximum at 74.4 mm from the cavity center.

2.5 | Microwave feeding

A variable penetration grounded probe (inner probe) with an adjustable impedance matching step (outer probe) was designed to couple the microwaves to the cavity, as shown in Figure 3A. By being grounded to the enclosure, it is possible to adjust the penetration of the inner and outer probe sections externally, without disassembling the applicator, to allow for active tuning of the resonance frequency with different materials. The probe was fed from a TE_{10} WR340 rectangular waveguide with forced air circulation which served to cool the probe. In addition, the use of filleted ends on both inner and outer probes served to prevent arcing during higher-power operation. The probe was fitted in symmetry opposing the material load, allowing the excitation of the required TM mode, as shown in Figures 1 and 3B.

3 | RESULTS

The system performance was analyzed using CST Microwave[19] and COMSOL Multiphysics.[21] The electric field and power loss density distributions, shown in Figure 4, show a uniform distribution across the product, with a power uniformity index[22] (PUI) of 0.17, and an average power loss density in the bulk of 3.5×10^8 W/m^3 for a 6 kW input power.

The fabricated prototype showed a good agreement with simulations as seen in Figure 5A, with a 90% bandwidth of 9 MHz for both simulations and 8 MHz for the experimental measurement. A Quality factor of 234 was measured, while simulated quality factors of 198 and

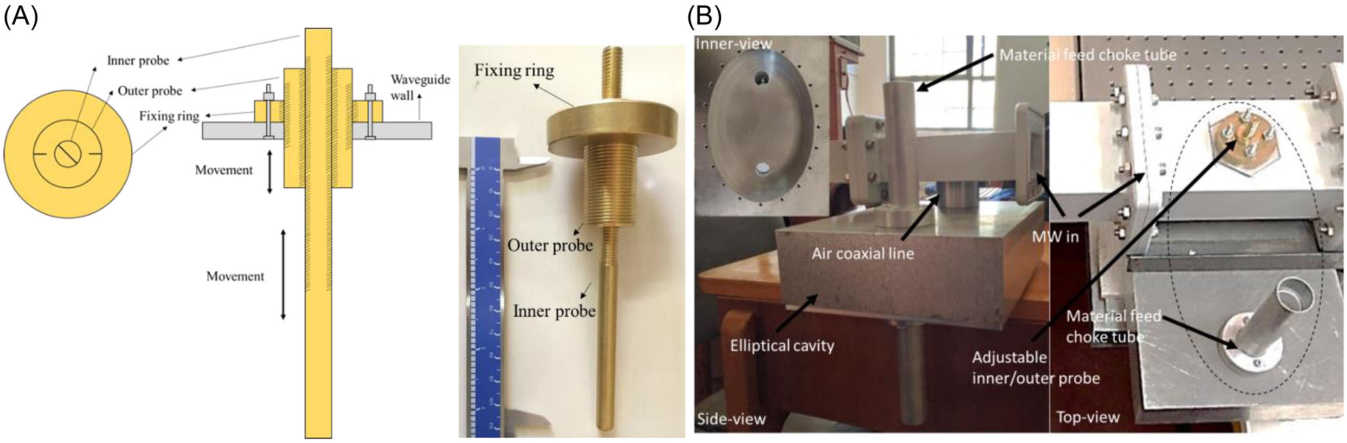

FIGURE 3 (A) Adjustable probe sketch, fabricated prototype and (B) inner view of fabricated cavity, side and top view of the system

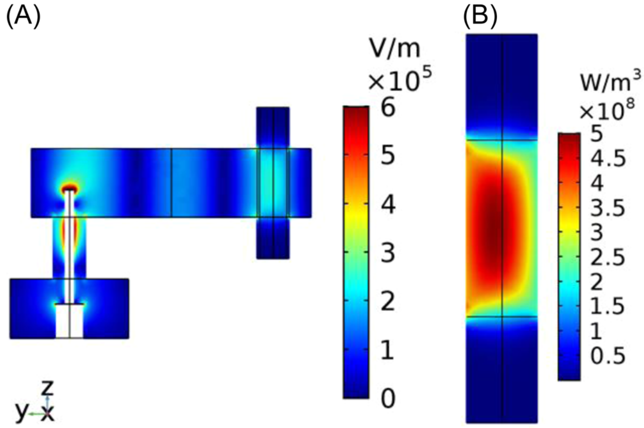

FIGURE 4 (A) Electric field and (B) power loss density distributions, simulated with COMSOL Multiphysics at 2.46 GHz

196 were obtained with COMSOL and CST respectively. The stability of treatment with product properties change is illustrated by the minimal variation of PUI upon changing values of the product dielectric constant shown in Figure 5B. Nonetheless, large variation of properties does require the need to actively retune the resonant frequency by varying the probe penetration to maintain stable power delivery to the product.

To further understand the differences in using an elliptical cavity over more conventional designs, a comparison was made between it and a circular TM_{210} and rectangular WR340 TE_{103} cavity resonators with aluminum walls and using a load with complex electrical permittivity of $\varepsilon_r = 3 - 0.1j$. All cases were simulated using COMSOL. The circular applicator presented virtually the same performance as the elliptical but with mode degeneracy, modal polarization dependency and splitting due to its rotational symmetry. The rectangular resonator, on the other hand, presented a 35% lower average power loss density within the sample as the elliptical one creates a focusing effect in the sample, as can be seen in Figure 6; 20% lower empty quality factor; and larger field deformation with change of sample permittivity (e.g., upon doubling dielectric constant from 3 to 6, a displacement in maximum position of 2.2 mm is seen in the elliptical while a 3.3 mm is seen for the

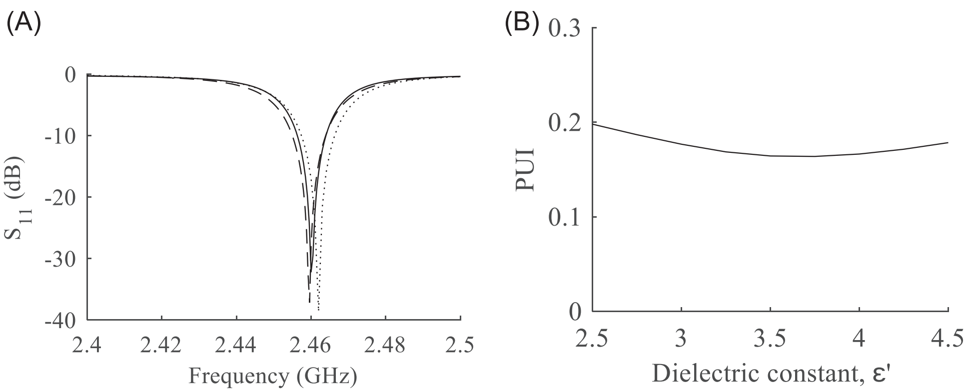

FIGURE 5 (A) Experimental (solid line) CST simulated (dash line) and COMSOL simulated (dot line) reflection coefficient magnitude (dB). (B) Power uniformity index with the change of product dielectric constant simulated with COMSOL at 2.46 GHz.

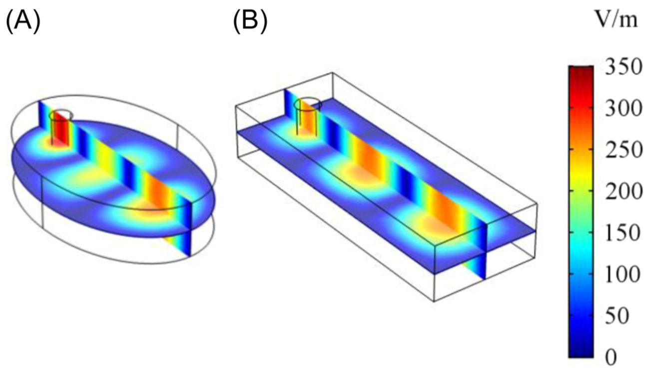

FIGURE 6 Electric field distribution simulated at 2.46 GHz for (A) elliptical and (B) rectangular applicators

rectangular), and the same PUI of 0.11, without mode degeneracy.

4 | CONCLUSIONS

A design methodology was provided for an elliptical cavity resonator for thermal treatment of materials, which can perform similarly or better than conventional technologies, without suffering from problems such as the apparition of degenerated modes or polarization rotation. The developed cavity can provide very high-power densities and a uniform, reliable and repeatable treatment when highly precise processing is required as it avoids any excitation of unwanted modes. The design and evaluation approach was confirmed by cross-comparison between two numerical methods and validated using experimental measurements with a reference test material.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request

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