ASSESMENT OF COAXIAL FILTERS FOR THE INSTALATION OF METALLIC MODE STIRRERS OR TURNTABLES IN MULTIMODE MICROWAVE OVENS

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1. INTRODUCTION

Industrial microwave-heating applicators are often manufactured as multimode cavities with one or multiple magnetrons. This type of cavities creates electric field standing-wave patterns [1] because of multiple mode combinations and this results in multiple cold and hot spots in the processed materials. Uneven electric field distribution may lead to non-uniform temperatures and thermal runaway inside the materials due to different factors such as microwave waveguide location, material dielectric properties, cavity and material geometry, the material location inside the oven and sample movements [2], among others.

There are several techniques that can reduce hot and cold spots within microwave cavities and provide more uniform microwave-heating distributions in multimode cavities, such as the usage of dielectric multilayer structures [3], usage of variable or selected frequencies [4-5] or a combination of phase-delay between two or more sources [6], mainly if solid state generators are employed. But the most extended techniques for increasing uniformity in the electric field pattern are based on the movement of the product, by means of a turntable in domestic ovens or conveyor belt in industrial tunnel applicators, or the time-variant modification of the geometry of the applicator with mode stirrers [2,7].

In the case of turntables or mode stirrers, an external motor produces the movement that is transmitted through a rotary axis that penetrates into the cavity. This also occurs in reverberation chambers, where mode stirrers are commonly used for obtaining open field conditions, but, in that case, working with low power signals. This movement transmission requires that the applicator is open in the zone where the axis go inside it, and that aperture can produce a leakage of microwave radiation.

Figure 1 shows the cross-section scheme of a multimode microwave applicator where the dielectric material is heated. Usually, metallic stirrers are used due to their higher capacity to reflect and disperse electromagnetic fields and, therefore, it might be necessary to employ a metallic axis that can handle the stirrer blades. When torque values are very high then the usage of metallic axes is unavoidable. Unfortunately, this creates a coaxial port in the cavity wall where the metallic axis is introduced and, therefore, coaxial bandstop filters are needed to avoid leakage of microwave radiation in the form of a transversal electric-magnetic (TEM) mode.

Metallic balls can be used both to allow the rotation of the stirrer and to avoid microwave leakage. This metallic bearing balls are placed under a metallic supporting structure and this metallic contact provides, if properly designed, additional electric field shielding. When the metallic bearing balls are, however, contacting the cavity walls without any intermediate bandstop filter, high currents may appear due to the structure movement and, thus, balls and supporting structures might overheat and, finally, degrade.

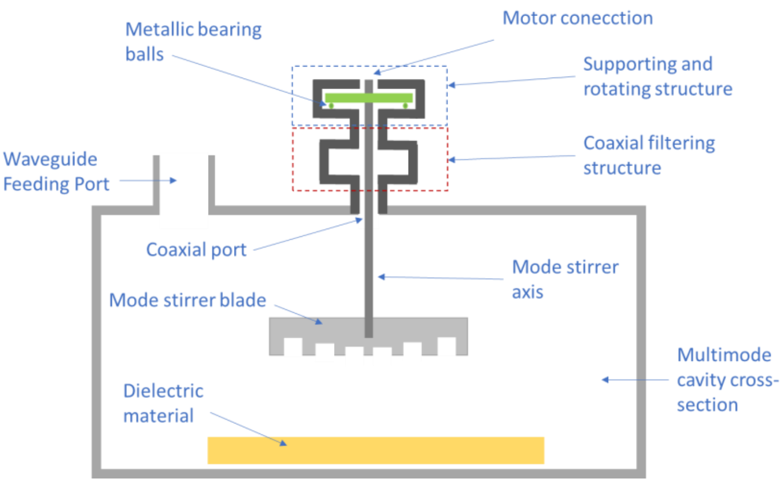

Fig. 1. Cross-section scheme of a microwave multimode cavity with a rotating metallic mode stirrer and coaxial filters to prevent microwave leakage.

Microwave band-stop filters are commonly used in microwave heating applicators. This is the case of corrugated filters at the input and output ports in tunnel applicators, or $\lambda_g/4$ chokes at the oven door (where λ_g is the wavelength at the operation frequency). High-pass filters based on a grid of cut-off waveguides can also be found in oven doors or at air flow input/output. In all these cases, a proper design must be developed to accomplish the EN-55011 standard for electromagnetic compatibility of industrial, scientific and medical (ISM) equipment in Europe.

Microwave heating applications employ narrow-band signals, working at one of the reserved IMS bands, mainly at 433,92 MHz, 915 MHz or 2.45 GHz, and less frequently 5.8 GHz or 24.125 GHz. This leads to design band-stop filters in one of these frequencies. Nevertheless, in the last years a combination of frequencies is being used to improve the heating uniformity in the material. Therefore, in those cases multiband stop-filters must be designed.

In this paper, a very simple band-stop filter in coaxial technology is presented for 2.45 GHz systems that employ metallic axes to avoid this leakage and assure the operation of moving parts, as mode stirrers, inside the applicator. First, the transmission line theory is used for a first-approach theoretical design, whilst the final geometry and performance of the filter is validated by electromagnetic simulation of the structure by means of numerical methods. The theoretical model is validated with CST Microwave Studio simulations.

2. THEORETICAL DESIGN OF BAND-STOP FILTERS IN COAXIAL LINES

Stubs are sections of transmission lines, normally terminated in short-circuit or open-circuit which can be used for designing matching networks or for filtering. A compact band-stop filter can be obtained in coaxial technology with the structure shown in figure 2a, which has the equivalent circuit depicted in figure 2b.

Let us assume without loss of generality the use of lossless conductors and air ($v_{p1} = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = c = 3 \cdot 10^8$ m/s) as dielectric in the coaxial lines. Following the transmission line theory, the impedance at the input of the stub is

$$Z_1 = jZ_{01} \tan(\beta_1 l_1) \quad (1)$$

where $Z_{01} = 60 \cdot \ln \frac{a_1}{b_1}$ is the characteristic impedance of the stub line, $\beta_1 = \frac{2\pi f}{c}$ is its phase constant and l_1 its length.

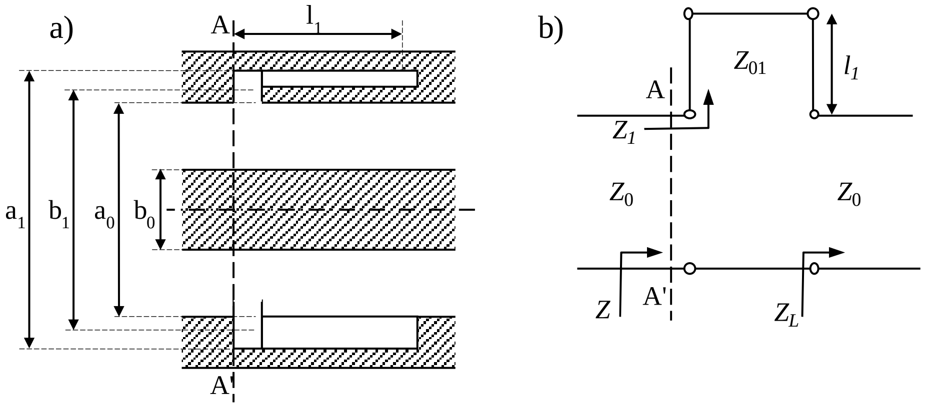

Figure 2. Single short-circuited series stub in a coaxial line: a) axial section of the device, b) equivalent transmission line circuit.

This stub becomes an impedance inverter at a frequency f_0 if we choose $l_1 = \frac{\lambda_1}{4}$, where λ_1 is the wavelength at the operation frequency, that is, $\lambda_1 = \frac{c}{f_0}$.

Since the stub is short-circuited, its input impedance will be in this case

$$Z_1 = jZ_{01} \tan\left(\frac{\pi}{2}\right) \rightarrow \pm\infty \tag{2}$$

and the input impedance at port AA'

$$Z = Z_1 + Z_L = \pm j\infty \tag{3}$$

ideally at the operation frequency (f_0), where Z_L is, in principle, negligible.

If frequency moves up or down from f_0, Z_1 decreases and so Z, allowing the transmission through the filter. Once Z is known, the reflection coefficient at the filter input is obtained by

$$\rho = \frac{Z - Z_0}{Z + Z_0} \tag{4}$$

and the magnitude of the transmission coefficient as

$$|\tau| = \sqrt{1 - |\rho|^2} \tag{5}$$

This filter fits perfectly to microwave heating operation since both filter and microwave sources are narrow band. In fact, even if moving frequency regimes are used (for instance with a solid-state generator) the operation is limited by the definition of the ISM bands as shown in Table 1.

Therefore, it is easy to design a filter for a given band. For instance, for a metal axis of 10 mm in diameter (b_0) moving the stirrer, table 2 shows the design values for the 2.45 GHz band and different attenuation levels obtained at the band limits. In figure 3 the magnitude (dB) of the transmission coefficient obtained for the designs in table 2 is depicted. In this design a_0 has been arbitrary set to 10mm. A 1mm thickness has been chosen for the inner wall and, therefore, $b_1 = a_0 + 1\text{mm}$. The outer wall thickness is irrelevant. The value of a_1 determines the characteristic impedance in the stub Z_{01}, and the ratio between Z_{01} and Z_0 influences the attenuation within the bandwidth, as table2 and figure 3 shows. Thus, a trade-off between diameter of the device and attenuation is necessary.

Table 1. Main ISM bands for heating applications

Central frequency (MHz)	Lower limit (MHz)	Upper limit (MHz)
433,92	433,05	434,79
915	902	928
2450	2400	2500
5800	5725	5875

Table 2. Geometry values for a stub band-stop filter and attenuation at 2.45GHz band.

l1 (mm)	a_0 (mm)	b_1 (mm)	Z_{01}/Z_0	a_1 (mm)	Atten. (dB) at 2.4/2.5GHz
30.6	20	22	0.5	31.1	17.9
30.6	20	22	1	44	23.9
30.6	20	22	2	88	29.9

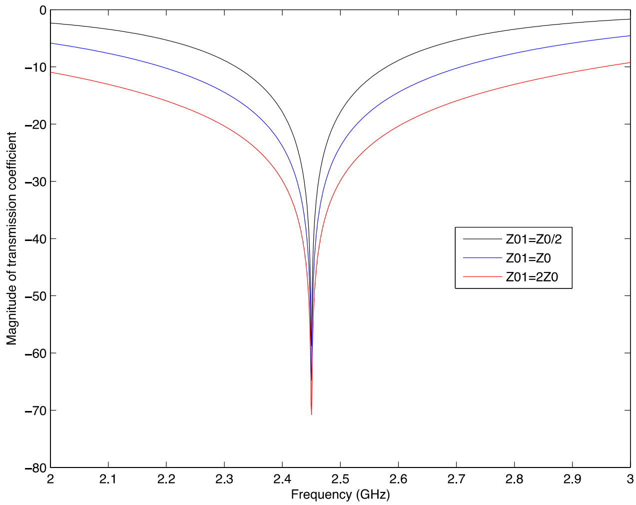

Figure 2. Response of the stub filter at 2.45GHz for different Z_{01}/Z_0 ratios.

Another option for increasing the attenuation in the band is concatenating N series stubs, thus obtaining $|\tau_{total}|(\text{dB}) = N|\tau|$. In this case, the device will be approximately N times longer than a single one.

3. SIMULATION SETUP

Simulations were carried out in CST Studio Suit 2020 from Dassault Systems [8] in a DESKTOP-6876203 ThinkStation with i9-990K Intel(R) Core CPU, a clock frequency of 3.6 GHz and 64 GBytes of RAM memory. Windows 10 Pro 64-bit operative system was used.

Figure 3 shows the two different structures simulated in CST Microwave Studio. Figure 3a shows the usage of metallic bearing balls and metallic supporting structures to allow the rotation of the mode stirrer axis. Figure 3b shows the cross section of the coaxial filter with the 2 coaxial ports and the coaxial stub. All simulations ranged from 2 to 3 GHz and the Time Domain Simulation solver was used.

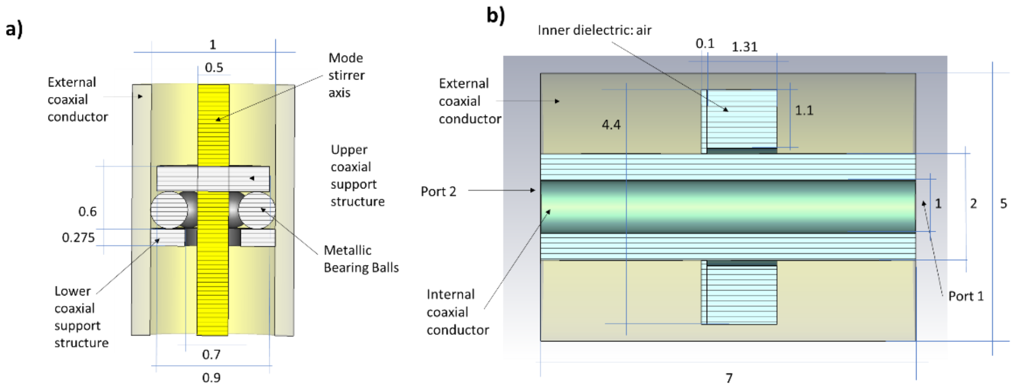

Figure 3. a) metallic bearing balls and metallic supporting structures to allow the rotation of the mode stirrer axis, b) Cross section of the coaxial filter simulated in CST Microwave Studio. Dimensions in cm.

4. RESULTS AND DISCUSSION

Figure 4 shows the attenuation provided by the simulation of the simple structure depicted in figure 3a) whereas Figure 5 shows the current values in a static situation of Figure 3a). It can be observed that although this structure can provide more than 50 dB attenuation values at 2.45 GHz, current values are high even at static conditions (without the rotation of bearing balls) and low power excitation (1 Watt). This indicates that when the structure rotates, higher currents can be observed and overheating can be produced.

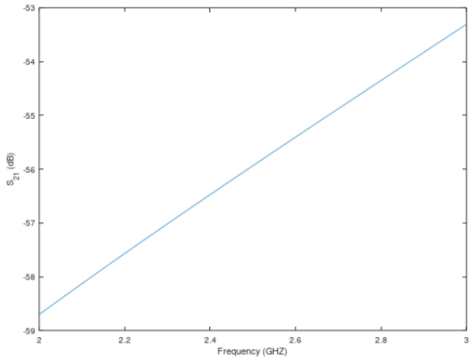

Figure 4. Attenuation provided by structure in Figure 3a) in static conditions.

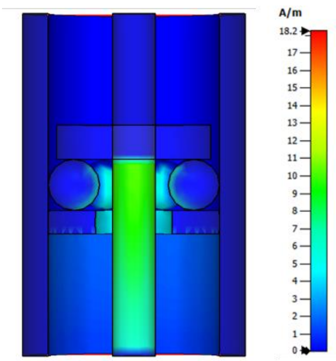

Figure 5. Current density (A/m) in static conditions for structure in Figure 3a).

Figure 6 shows the validation of the theoretical results of a stub design considering ($Z_{01}=Z_0/2$) and its equivalent CST design depicted in Figure 3b). It can be observed how both designs are fully in agreement with slight frequency deviations. The stub filter is able to provide attenuations bigger than 18 dB in the 2.4-2.5 GHz band.

Finally, Figure 7 shows the electric field distribution inside the stub when port 1 is excited at 2.45 GHz. As it can be observed, the electric field is highly attenuated inside this structure and, therefore, it would avoid high currents in the bearing balls of Figure 3a)

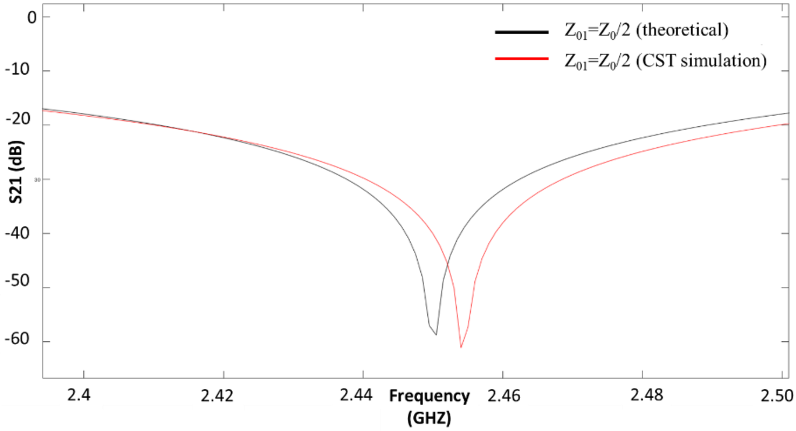

Figure 6. Validation of theoretical design and CST design of single coaxial stub.

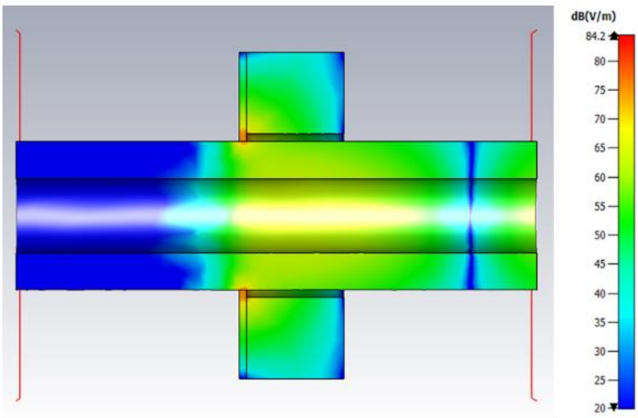

Figure 7. Magnitude of the electric field at 2.45 GHz for the CST design of single coaxial stub in Figure 3b).

5. CONCLUSIONS

Very simple cylindrical structures can be employed to introduce metallic axis inside multimode microwave cavities that allow the rotation of metallic mode stirrers or turntables. The usage of metallic bearing balls can provide very high attenuation levels, but important current values can be perceived even at static conditions when no rotation is employed.

The introduction of a single coaxial stub can provide additional attenuation levels (higher than 18 dB) reducing the electric field and current values at the metallic rotation station structure.

Theoretical and simulation results show very similar behaviors and attenuation levels.

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