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Finding Resonant Frequencies for High Loss Dielectrics in Cylindrical Cavities

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***Abstract*—This paper proposes the use of APM (Argument Principle Method) method to find all complex resonant frequencies in a three layer cylindrical cavity. APM guarantees that no root is lost and frequencies can be associated with the resonant mode. The roots can be used to find permittivity of a material inside a cavity.**

***Index Terms*—Electromagnetic modeling, resonant cavities, complex resonant frequency, high loss permittivity measurements.**

I. Introduction

When numerical methods are used to find the complex resonant frequency of structures, it is easy to find wrong solutions, in the meaning that the found solution is the solution of another higher or lower mode than the mode that we were interested in. This problem arises especially when using gradient methods to find the roots and several solutions are possible. This implies that initial information must be known, and this is used as the starting point (seed) for the gradient method to find the root.

When the function to find the resonant frequency does not have an analytic expression, the use of the gradient method is preferred to find the roots. This usually happens when applying the resonant condition [1] to a set of equations obtained after using Mode Matching or Circuit Method [2], and a good seed value is required.. The seed can be provided by either (i) the perturbation technique [3], or (ii) by other alternatives methods that provides less accuracy but good enough seed (like Dielectric Dielectric-Loaded Airline [4] or Open Open-Ended Coaxial Probe

[5], depending on the sample mechanical capabilities or expected losses) or (iii) by the solution of a simpler cavity model, that is close to the real set-up but with analytical solution.

It is this last case the one that is proposed in this letter for a cylindrical cavity with three dielectric layers. This cavity, shown in figure 1, is a simplification of a cavity including a dielectric in the center (ε_{r1}), a tube that surrounds the material (ε_{r2}) and all introduced through an insertion hole from the top of the cavity [6,7]. For the typical cavity dimensions used for dielectric characterization, the first TM_{0np} modes (ordered in increasing frequencies) are TM_{010}, TM_{011} and TM_{020}. The first resonant mode is usually the most interesting but, for some applications, especially for the measurement of high-loss dielectrics, the TM_{020} mode may be preferred from the point of view of measurements because it presents a higher *Q*-factor. However, this mode is problematic from a numerical point of view, since its associated root is, sometimes, wrongly found and then the solution for TM_{011} mode is achieved instead. It is in this frame where the method proposed in this paper gives the solution.

II. Theory

Figure 1 shows the geometry of a cylindrical cavity to be analyzed in order to obtain the resonant frequencies. The cavity has three dielectric materials, with relative permittivities ε_{r1}, ε_{r2} and ε_{r3}, and external radii a, b and R, respectively.

The full-wave analysis of the TM_{0np} resonant modes and resonant frequencies is a well-known problem [8,9] and is based on the expression of the electromagnetic fields in each region (region 1, with $0 \leq r \leq a$, region 2, with $a \leq r \leq b$ and region 3, with $b \leq r \leq R$):

$$
\begin{aligned}
E_{zi} &= B_i \cdot \left[\mathrm{J}_0\left(k_{ci} r\right) + \alpha_i \cdot \mathrm{Y}_0\left(k_{ci} r\right) \right] \cdot 2 \cdot \cosh\left(\gamma \cdot z\right) \\
E_{ri} &= -B_i \cdot \frac{\gamma}{k_{ci}} \cdot \left[\mathrm{J}_1\left(k_{ci} r\right) + \alpha_i \cdot \mathrm{Y}_1\left(k_{ci} r\right) \right] \cdot 2 \cdot \sinh\left(\gamma \cdot z\right) \\
H_{\varphi i} &= B_i \cdot \frac{j\omega\varepsilon_i}{k_{ci}} \cdot \left[\mathrm{J}_1\left(k_{ci} r\right) + \alpha_i \cdot \mathrm{Y}_1\left(k_{ci} r\right) \right] \cdot 2 \cdot \cosh\left(\gamma \cdot z\right)
\end{aligned}
\tag{1}
$$

where i=1,2,3 represents each region, $J_n(x)$ and $Y_n(x)$ are the Bessel functions of the first and second kind and order n, k_{ci}, are the cut-off wavenumbers in each region, γ is the propagation constant, which is common for all the regions, α_i are the coefficients for the Bessel functions of the second kind to accomplish the boundary conditions, as well as coefficients B_i.

The propagation constant γ is known because equation (1) is the result of applying boundary condition at z=0 and z=h to the TM_{0n} modes in the cylindrical waveguide. So:

$$
\gamma = j \cdot p \cdot \pi / h \quad ; \quad p = 0,1,2,... \tag{2}
$$

where coefficient p represents the z variations of the field. Additionally, the relationship between the k_{ci} and γ is:

$$
k_{ci}^2 = k_i^2 + \gamma^2 = \omega^2 \mu_0 \varepsilon_0 \varepsilon_{ri} + \gamma^2 \tag{3}
$$

By applying the boundary conditions between the dielectric materials, we find that the resonant frequencies are those that solve the following equation (in terms of k_{c2}):

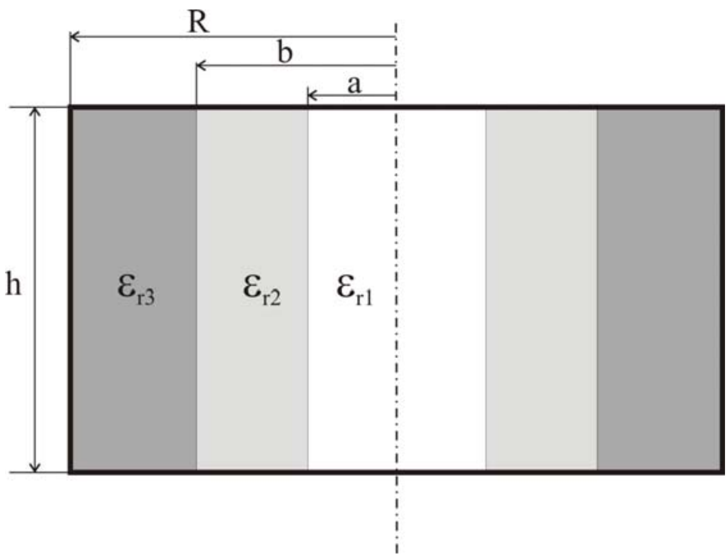

Fig. 1. Cylindrical cavity coaxially-filled with three dielectrics and PEC walls.

	Using (4) with APM Method		Circuit method [2]	
	f_r [GHz]	Q	f_r [GHz]	Q
TM_{010}	3.22129	1887.66	3.22129	1887.66
TM_{011}	6.65684	5060.96	6.65680	5062.31
TM_{020}	7.14823	3054.51	7.14823	3054.51

Table I.-Resonant frequencies for $\varepsilon_{r1}=5\cdot(1-j\cdot10^{-3})$

	Using (4) with APM Method		Circuit method [2]	
	f_r [GHz]	Q	f_r [GHz]	Q
TM_{010}	3.21902	20.19	3.21902	20.19
TM_{011}	6.65535	54.60	6.65510	54.62
TM_{020}	7.13949	31.22	7.13949	31.22

Table II.-Resonant frequencies for $\varepsilon_{r1}=5\cdot(1-j\cdot10^{-1})$

	TM_{010}		TM_{011}		TM_{020}	
ε_{r1}	f_r [GHz]	Q	f_r [GHz]	Q	f_r [GHz]	Q
$5\cdot(1-j\cdot10^{-3})$	3.2815	2000	6.7111	5179	7.2127	2949
$5\cdot(1-j\cdot10^{-1})$	3.2794	21.8	6.7101	57.1	7.2043	30.5

Table III.-Resonant frequencies with insertion hole using Circuit Method

$$f(k_{c2}) = \frac{k_{c2}}{\varepsilon_2 k_{c1} k_{c3}} \cdot \left[D \cdot \mathrm{J}_0(k_{c2}b) + N \cdot \mathrm{Y}_0(k_{c2}b)\right] \cdot A_1 + \\ + \frac{-1}{\varepsilon_3 k_{c1}} \cdot \left[D \cdot \mathrm{J}_1(k_{c2}b) + N \cdot \mathrm{Y}_1(k_{c2}b)\right] \cdot A_2 = 0 \tag{4}$$

where:

$$\begin{aligned} A_1 &= \mathrm{J}_1(k_{c3}b)\cdot \mathrm{Y}_0(k_{c3}R) - \mathrm{J}_0(k_{c3}R)\cdot \mathrm{Y}_1(k_{c3}b) \\ A_2 &= \mathrm{J}_0(k_{c3}b)\cdot \mathrm{Y}_0(k_{c3}R) - \mathrm{J}_0(k_{c3}R)\cdot \mathrm{Y}_0(k_{c3}b) \\ N &= \begin{cases} \varepsilon_1 \cdot k_{c2} \cdot \mathrm{J}_0(k_{c2}a)\cdot \mathrm{J}_1(k_{c1}a) + \\ + (-\varepsilon_2)\cdot k_{c1} \cdot \mathrm{J}_0(k_{c1}a)\cdot \mathrm{J}_1(k_{c2}a) \end{cases} \\ D &= \begin{cases} \varepsilon_2 \cdot k_{c1} \cdot \mathrm{J}_0(k_{c1}a)\cdot \mathrm{Y}_1(k_{c2}a) + \\ + (-\varepsilon_1)\cdot k_{c2} \cdot \mathrm{Y}_0(k_{c2}a)\cdot \mathrm{J}_1(k_{c1}a) \end{cases} \end{aligned} \tag{5}$$

and:

$$\begin{gathered} k_{c1}^2 = \varepsilon_{r1}\cdot k_0^2 + \gamma^2 \quad k_{c2}^2 = \varepsilon_{r2}\cdot k_0^2 + \gamma^2 \\ k_{c3}^2 = \varepsilon_{r3}\cdot k_0^2 + \gamma^2 \\ k_0^2 = \omega^2 \mu_0 \varepsilon_0 \quad ; \quad \gamma^2 = -\left(\frac{p\cdot\pi}{h}\right)^2 \end{gathered} \tag{6}$$

Then the solutions of equation (4) will yield to the complex resonant frequencies for modes TM_{0np}.This equation is usually solved by methods based on the gradient procedure which have two important drawbacks: they need a good starting point (seed) to achieve the desired solution, and there is no guarantee that the obtained solution is the proper one.

Since the explicit equation is known, the APM method, based on the Cauchy Integral, is used to overcome this problem. This method has been proposed previously, originally in [10], and then successfully used for electromagnetic purposes in [11, 12, 13].

In order to apply the APM method successfully to (4), some precautions must be taken to: (i) ensuring that the function is even for the variables k_{c1} and k_{c3} (to facilitate the integration process in the complex plane avoiding branch lines) and (ii) preventing poles in the area to find the roots. These conditions/requirements are accomplished in (4). Then it is possible to apply APM method to (4) to find the resonant frequency, using as variable to be solved the cut-off number k_{c2} in the center material (region 2), because is the one that satisfies precaution (i) stated above. It is clear that once k_{c2} is obtained, the resonant frequency is easily obtained from (6).

The poles that appear in (4) can be avoided by applying the integration strategy showed in [11] and [13].

III. METHOD VALIDATION

As an example of the use of the proposed method, and the problems previously stated, let’s assume the cylindrical cavity shown in Fig. 1 with a=5 mm, b=6 mm, $R=28$ mm, $h=25$ mm, and materials with permittivities $\varepsilon_{r3}=1$, $\varepsilon_{r2}=2-j\cdot 10^{-3}$ and ε_{r1} (material in the center).

Table I shows the resonance frequencies and Q-factors obtained analytically from (4) with APM method and values numerically computed using the circuit analysis in [2] for the first three TM_{0np} modes when $\varepsilon_{r1}=5\cdot(1-j\cdot 10^{-3})$. Both methods offer the same results, as expected, and it also validates the circuit method. The remarkable difference is that the values obtained by the analytical method with APM are direct and no roots are lost, while the numerical procedure does not always provide the appropriate root, as shown in the next paragraphs, where figures 2 and 3 are explained to obtain a seed for the circuit method.

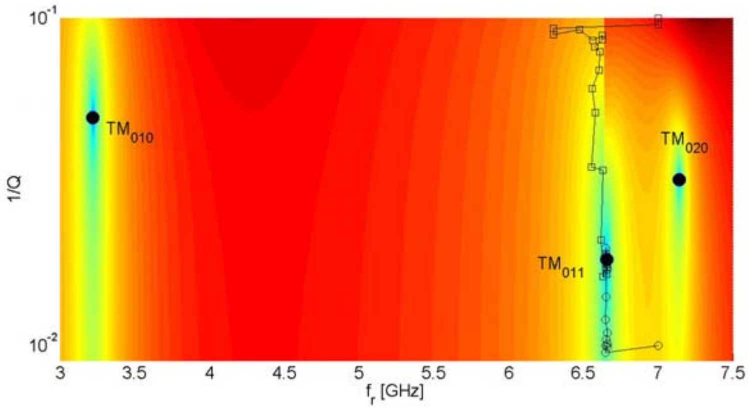

Fig. 2. 2-D figure with the location of the first 3 TM resonant modes for the analyzed cavity shown in figure 1 and permittivity ε_{r1}=5·(1-j·10^{-1})

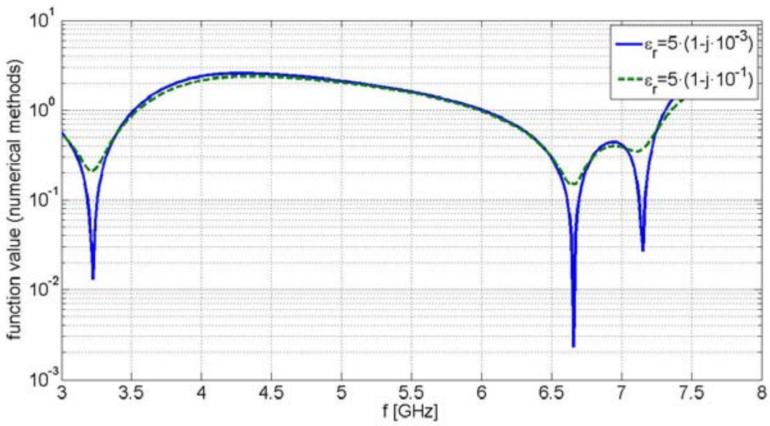

Fig. 3. Magnitude of the resonant condition for the analyzed cavity shown in figure 1 for two dielectrics with different losses

Figure 2 shows a 2D image of the problem to be solved by circuit analysis [2] (applying the resonant condition described in [1]) with the location of the zeros that are the complex resonant frequencies for the high loss dielectric case, i.e. ε_{r1}=5·(1-j·10^{-1}). It is clear that the zeros are the complex resonant frequencies, defined as $\Omega = f_r \cdot \left(1 + j/(2 \cdot Q)\right)$, where the real part is the resonant frequency and the imaginary part is related with the Q-factor as shown in [14]. These 3 zeros are those shown in table II. A similar surface can be plotted for the 3 zeros of table I.

Figure 3 shows in green and dash a cut of figure 2 when Q=1000 (as a starting seed), where is quite clear that the resonant modes are not easily located. In blue and continuous line is the same but for low loss dielectric (ε_{r1}=5·(1-j·10^{-3})) where for the same seed (Q=1000) the resonant frequencies are clearly present in the three peaks. These curves are very useful to find a good seed (by inspection) when gradient methods are used, as it happens when circuit method [2] is used.

So, and coming back to the results in table I, an inaccurate seed in the gradient method may yield to an incorrect solution. For example, if we are interested in the TM_{011} mode, when a seed of f=6.80 GHz and Q=1000 is used in the gradient method, the solution is the mode TM_{020}. Even the starting values f=6.80 GHz and Q=5000 (very near to the good solution of TM_{011}) yield the solution of the mode TM_{020} in the gradient method. This happens because both modes are really close. Only a very good seed as f=6.65 GHz and Q=1000 provides the correct solution for mode TM_{011} (f=6.65684 GHz, Q=5060.96).

For lossy materials things are even worst for higher modes. To illustrate this, let's use figure 3 again, and paying attention to the green and dashed curve obtained for $\varepsilon_{r1}=5\cdot(1-j\cdot 10^{-1})$, also assuming Q=1000 for initial seed. Now the curve exhibits where the modes TM_{010} and TM_{011} are, but the TM_{020} mode has almost disappeared.

The correct resonant frequency and Q-factor values, using (4) with APM and the circuit method in [2] are shown in Table II. The resonant frequency has hardly changed from the values with low losses, but the Q-factor is low (from 20 to 55 depending on the mode).

In this case an extremely good seed is necessary to find the complex resonant frequency of TM_{020} mode. For instance, even a seed of f=7.00 GHz and Q=100 provides a wrong solution and yields to the TM_{011} mode complex resonance frequency. The same happens for a seed of f=7.00 GHz and Q=10. Only a very good seed as f=7.14 GHz and Q=100 provides the good solution for the mode TM_{020} (f=7.13949 GHz, Q=31.22). This is shown in Fig. 2, with solid lines and "**o**" or "□", showing how, even with a supposed good seed for TM_{020}, the algorithm gives the solution TM_{011}.

For the TM_{010} mode, it is worth mentioning that in both cases (for $\varepsilon_{r1}=5\cdot(1-j\cdot 10^{-3})$ and $\varepsilon_{r1}=5\cdot(1-j\cdot 10^{-1})$ the gradient method provides good results because it is quite far away from the other modes.

Finally, the resonant values for all the 3 modes with insertion hole, with the seeds obtained with the theory showed in this paper, are shown in Table III. Of course these values are only calculated with the circuit method in [1], because there is no analytical expression for this problem. Although the APM method can be applied to the formulation of the circuit method, it implies a large computation problem. So, it was not applied here and the seeds previously obtained with the APM method in the ideal case (cavity without insertion hole) were used instead.

Fig. 4. Cylindrical cavity used to measure a ROD of dielectric material (h=40 mm; R=51.917 mm; b=6.325 mm; a=6.250 mm; $\varepsilon_{r2}=\varepsilon_{r3}=1$)

To finish the validation, a dielectric sample has been measured in a cylindrical cavity with an upper insertion hole, as shown in figure 4. The cavity dimensions are in the same figure, and the resonant frequencies measured for a dielectric sample are $f_r=2.10076$ *GHz* and $Q=149.5$ (mode TM_{010}), $f_r=4.29202$ *GHz* and $Q=504.1$ (mode TM_{011}) and $f_r=4.56161$ *GHz* and $Q=74$ (mode TM_{020}).

These 3 measurements give a seed, using the procedure described in this paper, of $\varepsilon_{r1}=2.851$ (mode TM_{010}), $\varepsilon_{r1}=2.821$ (mode TM_{011}) and $\varepsilon_{r1}=2.825$ (mode TM_{020}).

Then, and following the procedure described above, these values are used as seed for the Circuit Model, that takes into account the insertion hole, giving a permittivity of $\varepsilon_{r1}= 2.947\text{-}j\cdot 0.121$ (mode TM_{010}), $\varepsilon_{r1}= 2.983\text{-}j\cdot 0.125$ (mode TM_{011}) and $\varepsilon_{r1}= 2.919\text{-}j\cdot 0.125$ (mode TM_{020}). It is important to note that a bad selection of the seed gives bad results. For example, a bad selection of the seed in the second mode (TM_{011}) gives the permittivity value of $\varepsilon_{r1}=4.176$., that clearly is a wrong value.

	Measurements			
Mode	f_r [GHz]	Q	ε_r (seed)	ε_r (using circuit method [2])
TM_{010}	2.10076	149.5	2.851	2.947-j·0.121
TM_{011}	4.29202	504.1	2.821	2.983-j·0.125
TM_{020}	4.56161	74	2.825	2.919-j·0.125

Table IV.-Measured values for the cavity shown in figure 4.

All these values are summarized in table IV.

IV. Conclusion

The problem of finding the proper complex resonant frequency when higher resonant modes are desired implies, when gradient methods are used to apply the resonant conditions, very good seed. This seed sometimes is not available, then the proposed technique based on the APM method provides good seeds as has been proved and ensures that the proper modes are used.

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