jet INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2025, VOL. 71, NO. 3, PP. 1-9
Manuscript received June 23, 2025; revised July 2025. doi: 10.24425/ijet.2025.155448

New structure of dielectric resonator with greater separation of higher order modes from fundamental mode

Krzysztof Derzakowski, and Adam Abramowicz

***Abstract*—The paper presents a new dielectric resonator structure that allows to obtain a larger distance between the resonant frequency of TE_{011} mode and higher resonant modes: HE_{111}, TM_{011} and EH_{111}. Obtaining a sufficiently large frequency distance of the higher modes from the basic one allows realization of filters with much better spurious response. The proposed structure is based on a ring dielectric resonator in which the outer edge is flat and cone-shaped regions are cut symmetrically (from the top and bottom) to form the inner edge. To determine the resonant frequencies of the new structure the radial mode matching method has been applied. The proportions of the dimensions of the cut volume of the dielectric resonator were investigated in order to obtain the maximum frequency shift of higher resonant modes from the fundamental one (TE_{011}). The obtained results show that it is possible to achieve a much wider spurious free frequency range than in the structures used so far.**

***Keywords*—dielectric resonator; microwave filters; radial mode matching method; modified cone shaped resonators**

I. Introduction

DIELECTRIC resonators employed in microwave filters and antennas have variety of shapes. The most popular are, easily produced, cylindrical dielectric resonators but they are not the best ones taking into account the distribution of spurious modes. In high-quality microwave filters the mode TE_{011} is quite popular due to possibility to realize a very high-quality factor and a reasonable distance of higher order modes resonant frequencies from the lowest mode resonant frequency. This mode, as the lowest one in typical structures, assures the minimum dimensions of the realized filters. But in general, the cylindrical dielectric resonators have inconvenient distribution of spurious resonant modes, which are usually close to the frequency of operation of the TE_{011} mode [1-2]. Much better distribution of spurious resonant modes can be obtained in ring shaped dielectric resonators or other more complicated shapes [1,3-5]. The following examples of dielectric resonator shapes used in high quality filters limited to axisymmetric structures are commonly used: cylindrical or disc [3-4], ring [1-5], split cylinders (SPDR) and split rings [7, 8], triple layer cylindrical and ring resonators [9,10,11]. These resonators consist of many layers and/or regions of different dielectrics due to support structures. The spurious response of high-quality filters is usually difficult to predict but always related to the distribution of resonant modes in the single resonator structure. The further from the resonant frequency of fundamental TE_{011} mode are frequencies of higher modes the better can be spurious response of the filter.

In order to design a filter, it is necessary to know the parameters of the structure. Therefore, it is necessary to determine the resonant frequency of the used mode but also the resonant frequencies of other (usually higher) modes. The classical paper [1] gives some important directions how to compose disc and ring dielectric resonator structures. It must be also said that separation of modes for optimum conditions in the ring type resonator as in [1] usually cannot be achieved in real structures. The optimal proportions result in difficulties with coupling between resonators and overall size of the filter structure. The Q-factor of the dielectric resonators employed in the filter is a very important factor. The quality factor changes significantly due to mechanical tuning [12]. The couplings between resonators also change due to mechanical tuning [13]. The tunability characteristics of the resonant modes and their quality factors and finally the couplings between resonators and their influence on the resonant frequencies' distribution should be taken into account in the design. It can be stated that due to inter-dependance of listed above parameters the design of filters is quite complicated. The design procedure of high-quality filters requires also high accuracy.

In the case of simple resonator structures like a cylinder or a ring, the calculation of the resonant frequency seems to be is not so complicated, one can even use analytical relationships e.g. in the case of a cylinder placed between two infinite metal plates [18-19]. But the accuracy of analytical formulas is limited to several percent what can be a problem for realization of narrow band filters with relative bandwidths much lower than 1%. Moreover, analytical formulas usually provide results for the TE_{011} mode only. In the case of more complex structures [14-17], more advanced numerical methods should be used, i.e. 3-D electromagnetic simulators e.g. CST [22], QuickWave [23], HFFS [24], the radial mode matching method or the axial mode matching method. The last two methods give the best accuracy of the calculations [3, 20-21].

Krzysztof Derzakowski is with Institute of Radiolectronics and Multimedia Technology, Warsaw University of Technology, Poland (e-mail: Krzysztof.Derzakowski@pw.edu.pl).

Adam Abramowicz is with Institute of Electronic Systems, Warsaw University of Technology, Poland (e-mail: Adam.Abramowicz@pw.edu.pl).

The mode matching method calculations give not only resonant frequencies but also quality factors and mechanical tuning characteristics, thus nearly all needed parameters. Fortunately, in high quality filters the couplings between resonators are very small thus usually have not significant influence on resonant frequencies, quality factors and filter tuning.

There are many publications in the literature describing the analysis of resonant structures by the radial mode matching method [8,11,20-21] as well as the axial mode matching method [2-4]. Unfortunately, most often these works concentrate on structures with a small number of regions and layers. In this work, a method described in [21] is used. The radial mode matching method is more accurate and faster than any of 3D simulators [21] thus is well suited for the vast number of calculations described in the paper.

This article presents the possibility of using the radial mode matching method to determine the resonant frequencies of a dielectric resonator in the form of axially symmetric structures including conical shapes. In order to more accurately represent the lateral surface of the dielectric cone, a previously developed computer program [21] that allowed the division of the calculated structure into 20 regions and 20 layers has been extended to 50 regions and 50 layers.

The influence of the accuracy of the dielectric cone mapping in the mode matching method was analyzed, the influence of the walls of the considered structures was examined, the influence of tuning structures on distribution of modes has been analyzed and, finally, the results of the calculations reveal the possibility to improve spurious response of high-quality filters employing modified ring dielectric resonators.

II. The Basics

The article presents an analysis of the reference structure based on structures investigated in literature Fig.1. The ring dielectric resonator with radius R_c = 8.636 mm, height H_c = 7.62 mm and electric relative permittivity $\varepsilon = 35.74$ was placed symmetrically in a metal cavity with radius R = 12.95 mm and height H = 15.24 mm [5]. By changing the inner radius of the ring the distribution of the modes can be controlled. This structure has rather bad spurious modes distribution for small R_a, but when some changes of geometry are introduced the distribution of spurious modes can be greatly improved.

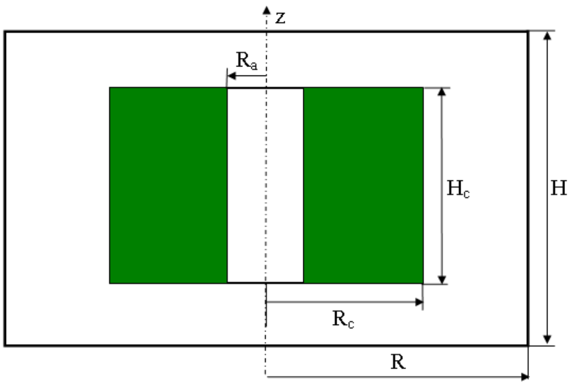

Fig. 1. Basic structure.

The cone-shaped solids at the top and bottom have been removed from this structure as shown in Fig.2.

In order to determine the distance between the resonant frequencies of the higher modes from the basic mode TE_{011}, these frequencies had to be calculated. For this purpose, a previously developed program based on the radial mode matching method was used [21]. As it is known in the radial mode matching method, the structure should be divided into regions along the *r* axis and layers in each region, taking into account changes in material parameters (this time along the *z* axis) This division is shown in Fig. 3.

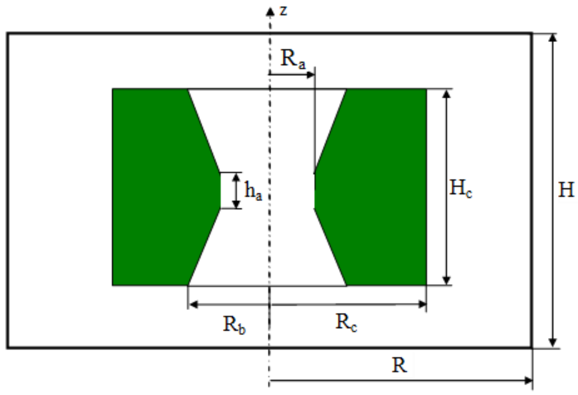

Fig. 2. New dielectric resonator structure.

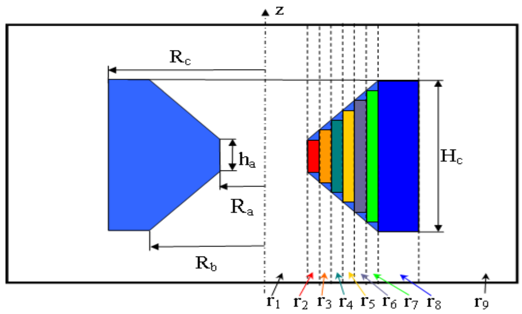

Fig. 3. Division of the structure into regions.

According to the rules of the radial mode matching method, the structure has been divided into N + 2 regions, where the region 1 is the cylinder space in the center (r_1 in Fig. 3), and the N + 2 area is the region between the resonator and the metal cavity (r_9 in Fig. 3). The radii of the regions were determined assuming that the height of the cut cone $(H_c-h_a)/2$ will be divided into N parts (h_N) and that each region will have a height equal to double multiple the value of h_N plus h_a. Hence, the dependence on the radius of a given region is obtained in the form (1):

$$R_i = R_b - (N-i) \cdot h_N \cdot \frac{R_b - R_a}{\frac{H_c - h_a}{2} - \frac{H_c - h_a}{2N}} \tag{1}$$

where: R_i – is a radius of *i* region, N – numbers of regions in a material with high permittivity, $h_N=(H_c-h_a)/2N$.

Examples of region radii and layer heights for N = 7 are given in Table I. It was assumed that the first region would be a cylinder with a radius of $0.2R_c$. The next seven regions are rings with three layers. The second layer is a dielectric with a relative permittivity of 35.74, while the first and third is air. The last, ninth region in the form of a ring consists of only one air layer with a height equal to H.

TABLE I
RADII AND HEIGHTS OF REGIONS AND LAYERS FOR A CONE

No. of a region	Radius [mm]	Height of first and third layer [mm]	Eps of first and third layer	Height of second layer [mm]	Eps of second layer
1	1.7272	3.81	1	7.62	1
2	2.4469	6.9124	1	1.4151	35.74
3	3.1665	6.3954	1	2.4493	35.74
4	3.8862	5.8783	1	3.4834	35.74
5	4.6059	5.3612	1	4.5176	35.74
6	5.3255	4.8441	1	5.5517	35.74
7	6.0452	4.3271	1	6.5859	35.74
8	8.636	3.81	1	7.62	35.74
9	12.95	3.81	1	7.62	1

III. RESULTS OF ANALYSES

This section presents the results of the calculations of the resonant frequency of the proposed dielectric resonator structure. The simulations started with determining the resonant frequencies of various modes for a ring resonator placed in a metal cavity as shown in Fig.1. The inner radius of the ring was changed from a value of 0 to a value of 0.7 of the outer radius.

Fig. 4 shows the resonant frequencies of the first few modes, i.e. TE_{011}, TM_{011}, HE_{111} and EH_{111} as a function of the ratio of the inner ring radius to the outer radius.

Fig. 5 shows the relative spacing of the resonant frequencies of higher modes from the frequency of the TE_{011} mode - R_f as a function of R_a/R_c. The relative spacing R_f is defined by the formula 2.

$$R_f = \frac{f_{mode} - f_{TE011}}{f_{TE011}} \cdot 100\ [\%] \tag{2}$$

where: R_f – the relative difference of frequencies, f_{mode} – the resonant frequency of higher mode, f_{TE011} – the resonant frequency of TE_{011} mode.

The relative change in the resonant frequencies of several types depending on the ratio of the radius of the ring inner radius to the outer radius is shown in Fig. 6, wherein R_r is defined by (3).

$$R_r = \frac{f_{ring} - f_{cylinder}}{f_{cylinder}} \cdot 100\ [\%] \tag{3}$$

where: R_r – the relative frequency tuning, f_{ring} – the resonant frequency of a ring resonator, $f_{cylinder}$ – the resonant frequency of a cylinder resonator.

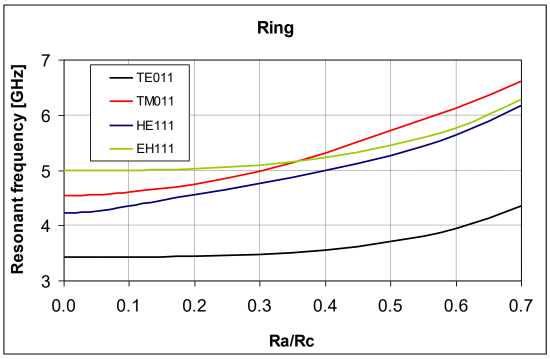

Fig. 4. Resonant frequencies of few modes as a function of R_a/R_c.

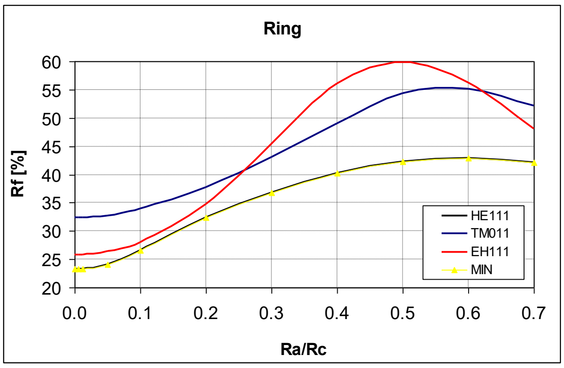

Fig. 5. The relative difference of the resonant frequency of higher modes to the TE_{011} mode as a function of R_a/R_c.

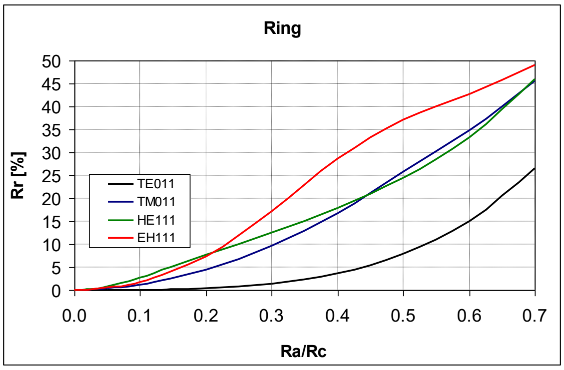

Fig. 6. Relative resonant frequency tuning of several modes vs. the R_a/R_c ratio.

Fig. 4 shows that the resonant frequencies increase with the increase of the ring inner radius. The resonant frequency spacing of the higher modes from the mode TE_{011} is different for different modes (Fig.5). The mode closest to TE_{011} is HE_{111}. The largest relative distance of this mode is obtained for R_a = $0.6R_c$ and it amounts to 43%. Fig. 6 shows the relative change in the resonant frequencies of several modes of the dielectric ring resonator in relation to these frequencies of the dielectric cylinder, taking the ratio R_a to R_c as the parameter.

The obtained results are consistent with the results presented in the literature [1-4]. This confirms the correct operation of the previously developed program. These results also served as a basis for comparisons with the results obtained for the new proposed structure.

It is shown in [5] that in a structure with additional air cylinders at the bottom and top of the structure with radii larger than the inner radius of the ring a greater distance between the following modes and basic mode can be obtained. For this reason, a new structure has been proposed in which there are cone shaped inner walls of the modified ring as shown in Fig. 2.

The proposed structure was analyzed in order to obtain the maximum distance of the closest higher mode from the basic one. The influence of different parameters (radii, heights) and their mutual relations were investigated. Examples of calculations are presented in the several following figures.

Figs. 7, 12 and 18 show the values of the resonant frequencies of the first four modes of the structure under investigation depending on the R_b / R_c ratio for $h_a = 0.05H_c$ for three different values of the internal structure radius R_a. It can be seen from

Fig.7 that the mode HE_{111} is the closest to the TE_{011} mode for all R_b/R_c values. For the radius $R_a = 0.2R_c$ (Fig.12) also the HE_{111} mode is closest to the TE_{011} mode up to R_b/R_c=0.5, however, above the R_b/R_c=0.5 value, the EH_{111} mode becomes closer to the basic one. A similar behavior can also be observed in Fig.18, where the influence of the mode EH_{111} starts with R_b/R_c greater than $0.7R_c$.

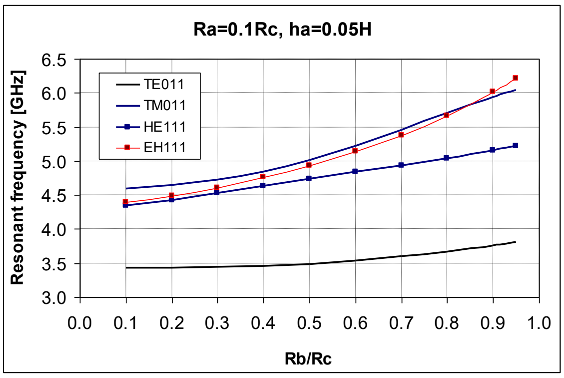

Fig. 7. Resonant frequencies of lowest modes as a function of R_b/R_c for propose structure for $R_a = 0.1R_c$ and h_a=$0.05H_c$.

Figs. 8-10, 13-16 and 19-21 show the relative frequency distance of the modes TM_{011}, HE_{111} and EH_{111} from the mode TE_{011} as a function of the R_b/R_c ratio for different values of h_a and R_a.

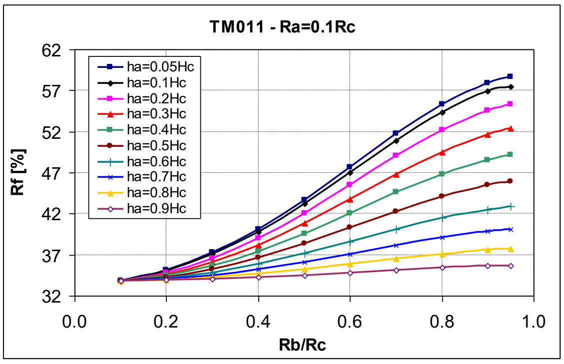

Fig. 8. Relative difference in the resonant frequency of mode TM_{011} to mode TE_{011} for the proposed structure for $R_a = 0.1R_c$ and several h_a values vs the R_b/R_c ratio.

As can be seen in Figs. 8. 13, 18, the distance of the TM_{011} mode from the basic mode increases with the increase of the R_b/R_c ratio. In addition, greater separation of the mode TM_{011} from TE_{011} is achieved for lower h_a values. For different R_a values, this mode behaves essentially in the same way.

Fig.9 shows that the relative distance of the HE_{111} mode from the TE_{011} mode increases with the increase of the R_b/R_c ratio, then it stabilizes and starts to decrease slightly. This tendency is more visible for lower h_a values.

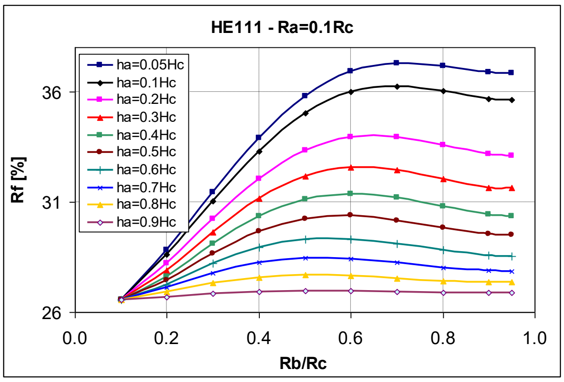

Fig. 9. Relative difference in the resonant frequency of mode HE_{111} to mode TE_{011} in the proposed structure for $R_a = 0.1R_c$ and several h_a values vs the R_b/R_c ratio.

For higher R_a values (Figs.14, 19), the relative difference between the resonant frequencies of the HE_{111} mode and the TE_{011} mode increases in the entire R_b/R_c variability range.

When analyzing the graphs in Figs.10, 15, 20, it should be stated that the dependence of the relative distance of the EH_{111} mode from the TE_{011} mode as a function of R_b/R_c is different for each R_a value.

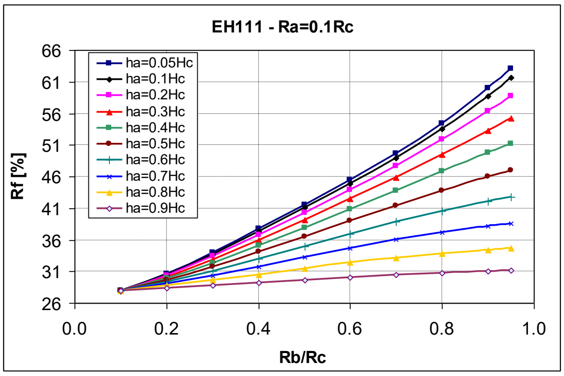

Fig. 10. Relative difference of the resonant frequency of mode EH_{011} to mode TE_{011} in the proposed structure for $R_a = 0.1R_c$ and few h_a values as a function of the R_b/R_c ratio.

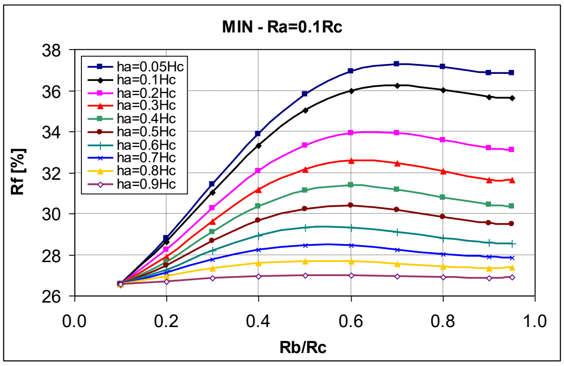

Fig. 11. Minimal relative difference in the resonant frequency of higher mode to mode TE_{011} in the proposed structure for $R_a = 0.1R_c$ and several h_a values vs the R_b/R_c ratio.

The relative minimum frequency separation of higher modes from TE_{011} mode for R_a=0.1R_c is determined by HE_{111} mode over the whole R_b/R_c range (see. Fig.11). The maximum distance of the higher mode from the basic mode occurs for the structure with h_a=0.05H_c and R_b/R_c=0.7 and reaches 37.29%.

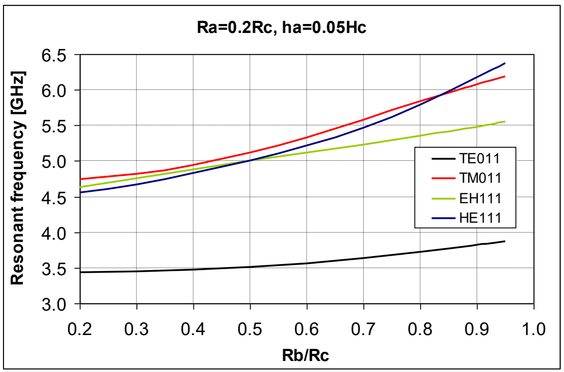

Fig. 12. Resonant frequencies of few modes as a function of R_b/R_c in the propose structure for R_a = 0.2R_c and h_a=0.05H_c.

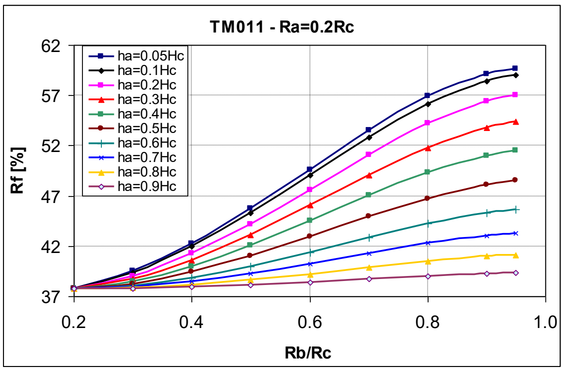

Fig. 13. Relative difference in the resonant frequency of mode TM_{011} to mode TE_{011} in the proposed structure for R_a = 0.2R_c and several h_a values vs the R_b/R_c ratio.

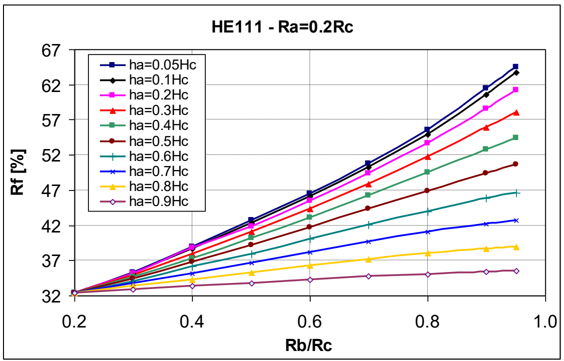

Fig. 14. Relative difference of the resonant frequency of mode HE_{111} to mode TE_{011} in the proposed structure for R_a = 0.2R_c and several h_a values as a function of the R_b/R_c ratio.

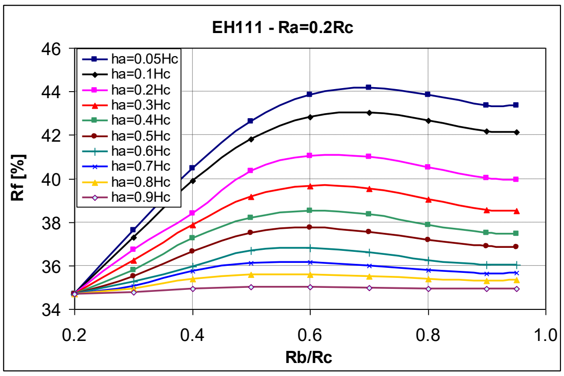

Fig. 15. Relative difference of the resonant frequency of mode EH_{011} to mode TE_{011} in the proposed structure for R_a = 0.2R_c and several h_a values as a function of the R_b/R_c ratio.

For a structure with R_a=0.2R_c, (Fig.16) the relative minimum distance between frequencies of higher mode and TE_{011} mode begins to be influenced by the mode EH_{111} for the ratio R_b/R_c greater than 0.5 for h_a = 0.05 H_c. The maximum distance of the higher mode from the TE_{011} mode occurs for the structure with h_a=0.05H_c and R_b/R_c=0.7 and reaches 44.16%.

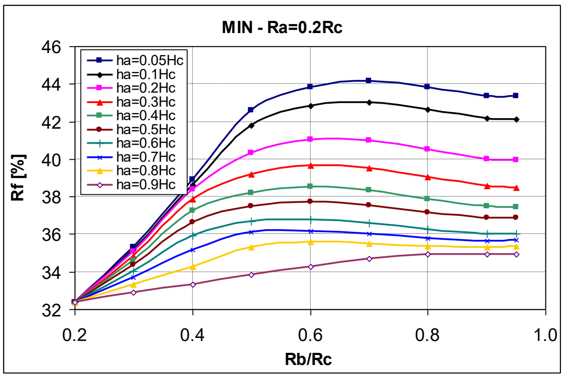

Fig. 16. Minimal relative difference of the resonant frequency of higher mode to mode TE_{011} in the proposed structure for R_a = 0.2R_c and several h_a values vs the R_b/R_c ratio.

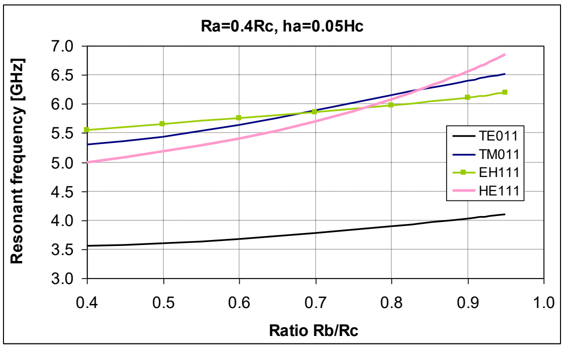

Fig. 17. Resonant frequencies of few modes as a function of R_b/R_c in propose structure for R_a = 0.4R_c and h_a=0.05H_c.

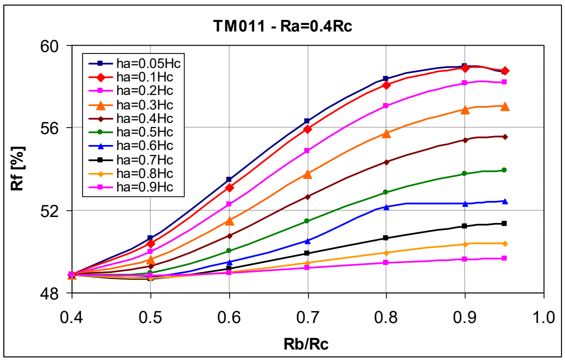

Fig. 18. Relative difference of the resonant frequency of mode TM_{011} to mode TE_{011} in the proposed structure for $R_a = 0.4R_c$ and several h_a values vs the R_b/R_c ratio.

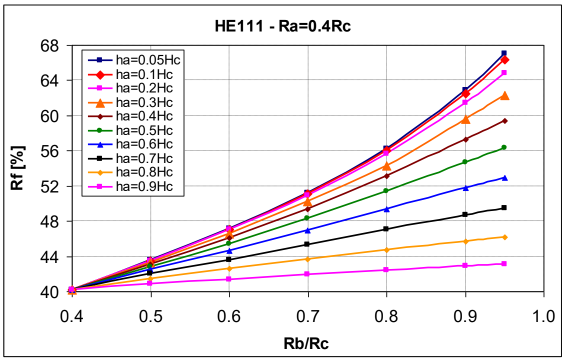

Fig. 19. Relative difference of the resonant frequency of mode HE_{111} to mode TE_{011} in the proposed structure for $R_a = 0.4R_c$ and several h_a values as a function of the R_b/R_c ratio.

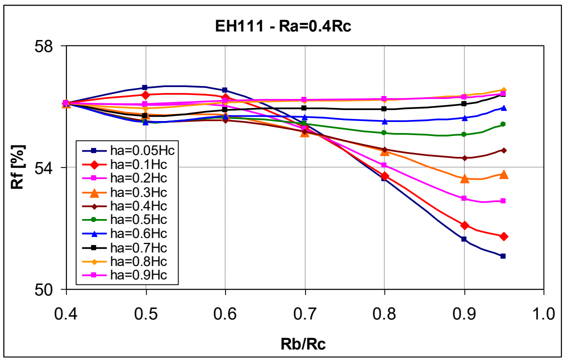

Fig. 20. Relative difference of the resonant frequency of mode EH_{011} to mode TE_{011} in the proposed structure for $R_a = 0.4R_c$ and several h_a values.

For a structure with R_a=0.4R_c (Fig.21), the relative minimum frequency spacing of the higher order from the TE_{011} mode also depends on the EH_{111} mode for the larger R_b/R_c ratio. In this case, the maximum distance of the higher mode from the TE_{011} mode occurs for the structure with h_a=0.3H_c and R_b/R_c=0.8 and is equal to 54.29%.

In the case of structures with a higher R_a, for higher h_a values, the EH_{111} mode begins to matter, which causes that the minimum distance of the higher mode from the TE_{011} mode begins to decrease.

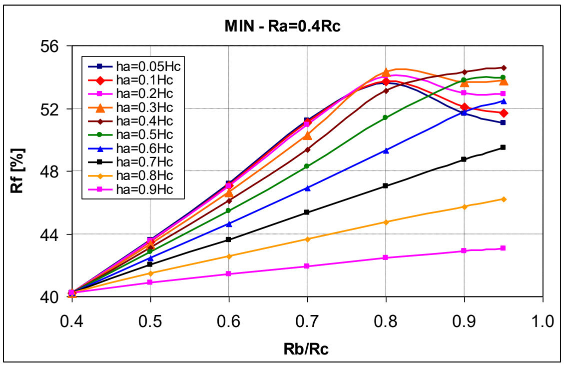

Fig. 21. Minimal relative difference of the resonant frequency of higher mode to mode TE_{011} in the proposed structure for $R_a = 0.4R_c$ and several h_a values.

Dielectric resonators are often used in microwave filters. In this case, the possibility of a slight re-tuning of the resonant frequency of the resonator is often necessary. For this reason, such a possibility was investigated by using a metal tuning cylinder placed on one of the plates of the metal cavity, as in Fig. 22. The influence of the height h_m and the radius R_m of the cylinder on the relative distance of the higher modes from the TE_{011} one and the related frequency change of the basic and higher mode. Selected results are presented in the following figures.

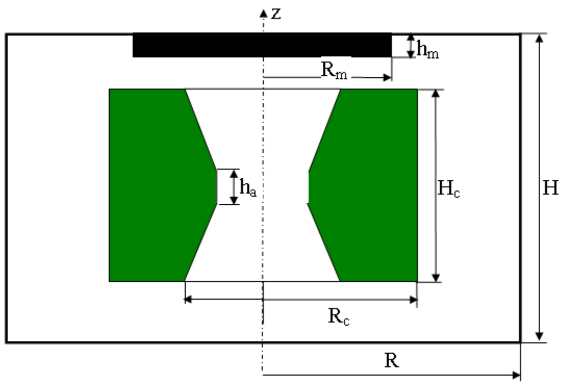

Fig. 22. Analyzed structure with a metal tuning cylinder.

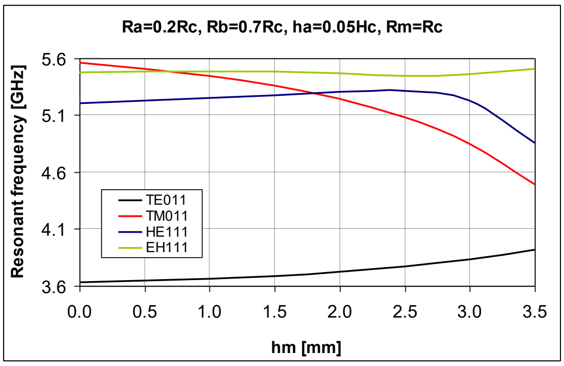

Fig. 23. Resonant frequency of few modes as a function of the height of the metal tuning cylinder for the proposed structure for a radius of this cylinder R_m=R_c.

Fig. 23 shows the resonant frequencies of several modes as a function of the height of the tuning cylinder h_m for its radius equal to the radius of the resonator R_c.

Figs. 24-27 show the dependence of the relative distance of higher modes on the TE_{011} mode and the minimum distance of the higher mode from the basic one as a function of the thickness of the tuning cylinder for different radii of this cylinder. As can be seen, by varying the thickness of the tuning cylinder, the spacing of the higher modes from the TE_{011} mode can be controlled. As the thickness of the cylinder increases, the mode separation decreases. The value of this separation also depends on the radius of the metal cylinder. More precisely it is presented in Figs. 29-31.

As the radius of the tuning cylinder R_m increases, the relative separation of the higher modes from the TE_{011} mode decreases, reaching a minimum value for R_m of about R_c, and then increases slightly. These changes are substantial and important for practical applications. In the case of using a dielectric resonator as a filter element, a re-tuning of a few percent seems to be sufficient, which can be achieved with a tuning cylinder with a small radius [12].

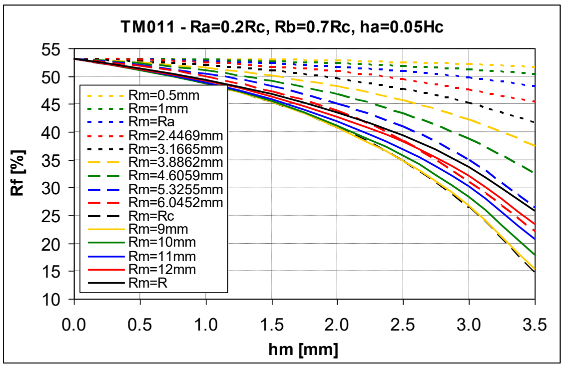

Fig. 24. Relative difference of the resonant frequency of mode TM_{011} to mode TE_{011} as a function of the height of the metal tuning cylinder in the proposed structure for different radii of this cylinder.

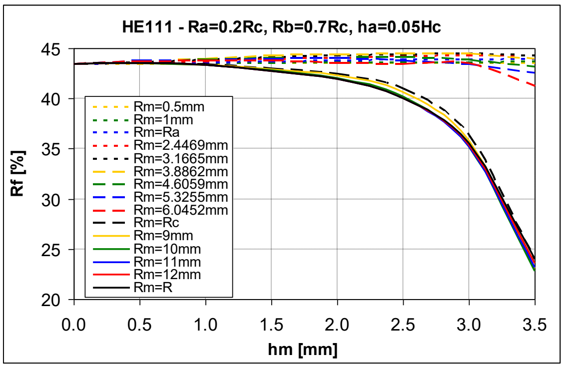

Fig. 25. Relative difference of the resonant frequency of mode HE_{111} to mode TE_{011} as a function of the height of the metal tuning cylinder in the proposed structure for different radii of this cylinder.

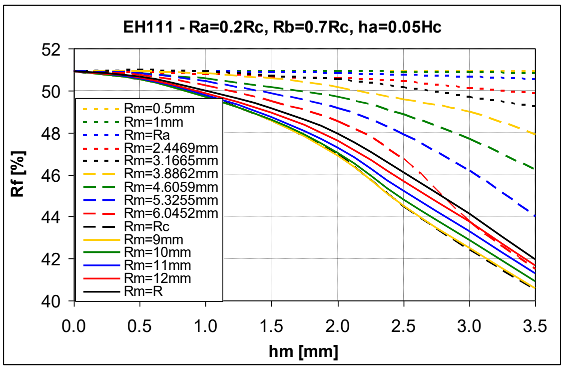

Fig. 26. Relative difference of the resonant frequency of mode EH_{111} to mode TE_{011} as a function of the height of the metal tuning cylinder in the proposed structure for different radii of this cylinder.

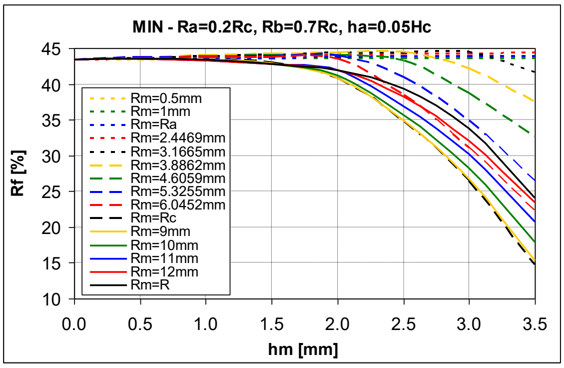

Fig. 27. Minimal relative difference of the resonant frequency of higher mode to mode TE_{011} as a function of the height of the metal tuning cylinder in the proposed structure for different radii of this cylinder.

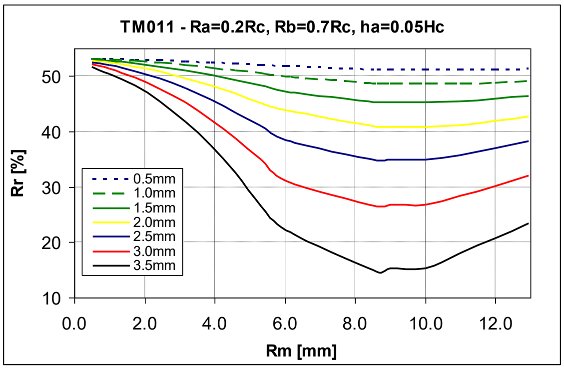

Fig. 28. Relative difference of the resonant frequency of mode TM_{011} to mode TE_{011} as a function of the radius of the metal tuning cylinder in the proposed structure for different height of this cylinder.

When analyzing the results presented in Fig. 13 and 14, it should be stated that in the case of the resonator structure with the conical cut, the number of waveguide modes taken into account should be slightly greater than for simpler structures. It seems that 10 to 15 of these modes should be included in this case.

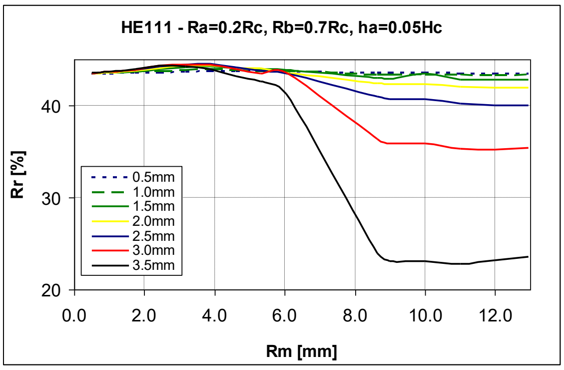

Fig. 29. Relative difference of the resonant frequency of mode HE_{111} to mode TE_{011} as a function of the radius of the metal tuning cylinder in the proposed structure for different height of this cylinder.

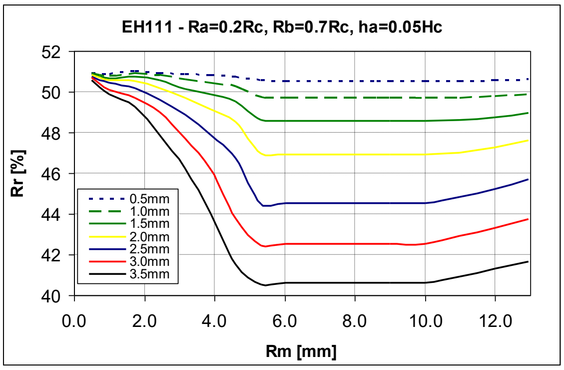

Fig. 30. Relative difference of the resonant frequency of mode EH_{111} to mode TE_{011} as a function of the radius of the metal tuning cylinder in the proposed structure for different heights of this cylinder.

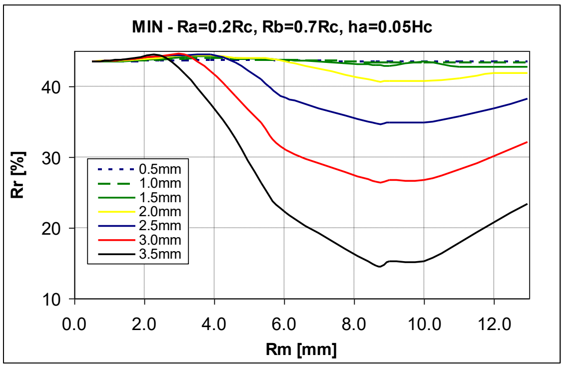

Fig. 31. Minimal relative difference of the resonant frequency of higher mode to mode TE_{011} as a function of the radius of the metal tuning cylinder in the proposed structure for different heights of this cylinder.

TABLE II
COMPARISON OF DIFFERENT STRUCTURES

No.	Structure	Max mode separation [%]
1	Cylinder [4]	23.24
2	Ring [4] R_a=0.6R_c	42.86
3	Modified Ring [5] R_a=0.6R_c	48.74
6	Proposed structure	54.23

CONCLUSION

The paper presents an analysis of the new dielectric resonator structure. The radial mode matching method has been used to determine the resonant frequencies of a dielectric resonator in the shape of a truncated cone. The results of calculations for different ratios of the radius of the upper to the lower base of the cone are presented. The influence of mapping the shape of the resonator with conical shape in the discussed method through the cylinders and rings (regions) on resonant frequencies and their accuracy were analyzed. On this basis one can state that it was sufficient to divide the cone into 40 regions. The minimum number of waveguide modes considered in the solution was also estimated. It was found that this number should not be lower than 10. The results of the calculations were compared with the results obtained with the use of the commercial 3D electromagnetic simulator QuickWave. The differences in the results were really small. Based on the presented results, it can be concluded that the radial mode of matching method is fully useful for the analysis of a cone-shaped dielectric resonators and can be used to accurately predict resonant frequencies as well as to optimize cone dielectric resonator structures. Modification of the ring shaped dielectric resonator with the conical cut produces better spurious frequencies distribution thus it can be used to realize dielectric resonator filters with wider spurious free frequency band.

The proposed resonator shape is quite well fitted to the present technology of firing dielectrics. Moreover, the proposed resonator structure can be easily realized through the additive manufacturing [25] when this technology overcome the problems related to high permittivity dielectrics.

REFERENCES

[1] Y. Kobayashi, M. Miura, "Optimum design of shielded dielectric rod and ring resonators for obtaining the best mode separation"; in Proc. IEEE MTT International Microwave Symposium, San Francisco 1984. https://doi.org/10.1109/MWSYM.1984.1131732

[2] K. A. Zaki, A. Atia, "Modes in dielectric loaded waveguide and resonators"; IEEE Trans. on Microwave Theory and Techniques, Vol. 31, No. 12, pp. 1039-1045, Dec. 1983. https://doi.org/10.1109/TMTT.1983.1131658

[3] S. W. Cheng, K. A. Zaki, "Dielectric ring resonator loaded in waveguide and on substrate"; IEEE Trans. on Microwave Theory and Techniques, vol. 39, vo. 12, pp. 2069-2076, Dec. 1991. https://doi.org/10.1109/22.106548

[4] H. C. Chang, K. A. Zaki, "Unloaded Q's of axially asymmetric modes of dielectric resonators"; in Proc. IEEE MTT International Microwave Symposium, Long Beach, 1989. https://doi.org/10.1109/MWSYM.1989.1031849

[5] K. V. Srivastava, V. V. Mishra, A. Biswas, "A modified ring dielectric resonator with improved mode separation and its tunability characteristics in MIC environment"; IEEE Trans. on Microwave Theory and Techniques, Vol. 53, No. 6, pp. 1960-1967, June 2005. https://doi.org/ 10.1109/TMTT.2005.848837

[6] J. K. Plourde and C .L. Ren, "Application of dielectric resonators in microwave components"; IEEE Trans. on Microwave Theory and Techniques, Vol. 29, No. 8, pp. 754-770, Aug 1981. https://doi.org/10.1109/TMTT.1981.1130444

[7] G. Lin, A. Coillet, Y. K. Chembo, "Nonlinear photonics with high-Q whispering gallery-mode resonators"; Advances in Optics Photonics, vol. 9, no. 4, pp. 828–890, Dec 2017. https://doi.org/10.1364/AOP.9.000828

[8] J. Krupka, “Precise measurements of the complex permittivity of dielectric materials at microwave frequencies”, Materials Chemistry and Physics, vol. 79, no.2-3, pp. 195-198, April 2003. https://doi.org/10.1016/S0254-0584(02)00257-2

[9] A. Can Gungor, M. Olszewska-Placha, M. Celuch, J. Smajic, J. Leuthold, “Advanced modelling techniques for resonator based dielectric and semiconductor materials characterization”, MPDI Applied Sciences, vol.10, 8533, Nov 2020. https://doi.org/10.3390/app10238533

[10] R. Saliminejad, M. R. Ghafourifard, “A novel and accurate method for designing dielectric resonator filter”, Progress in Electromagnetics Research B, Vol. 8, pp. 293–306, 2008. http://dx.doi.org/10.2528/PIERB08070602

[11] J. Krupka, A. Abramowicz, K. Derzakowski, “Design and realization of high–Q triple dielectric resonator filters with wide tuning range”, in Proc. 29th European Microwave Conf., pp. 103–106, Munich, Oct. 1999. http://dx.doi.org/10.1109/MMM.2009.933591

[12] Sz. Maj, J. Modelski, A. Abramowicz, “Computer-Aided Design of Mechanical Tuning Structures of a Dielectric Resonator on Microstrip Substrate”, in Proc. 17th European Microwave Conf., pp. 859–864, Rome, Sept 1987. http://dx.doi.org/10.1109/EUMA.1987.333764

[13] A. Abramowicz, J. Modelski, “Design of Intermediate-Bandwidth Dielectric Resonator Filters”, in Proc. 22nd European Microwave Conf., pp. 1325-1330, Helsinki, Aug. 1992. https://doi.org/10.1109/EUMA.1992.335888

[14] S. B. Cohn, “Microwave bandpass filters containing high-Q dielectric resonators”, IEEE Trans. on Microwave Theory and Techniques., vol. 16, pp. 218 –227, Apr 1968. https://doi.org/10.1109/TMTT.1968.1126654

[15] S. K. K. Dash, T. Khan, A. De, “Modelling of dielectric resonator antennas using numerical methods: a review", Journal of Microwave Power and Electromagnetic Energy, vol. 50, no. 4, pp. 269-293, Jan. 2017. https://doi.org/10.1080/08327823.2016.1260677

[16] H. Twu Chen, Y. T. Cheng, S. Y. Ke, „Probe-fed section-spherical dielectric resonator antennas”. in Proc. of the IEEE Asia Pacific Microwave Conference, vol. 2, pp. 359-362, Nov. 1999. https://doi.org/10.1109/APMC.1999.829875

[17] P. Abdulla, A. Chakraborty, “Rectangular waveguide-fed hemispherical dielectric resonator antenna” Progress in Electromagnetics Research.83: pp. 225-244, Jan. 2008. http://dx.doi.org/10.2528/PIER08050701

[18] T. Itoh, R. Rudokas, “New method for computing the resonant frequencies of dielectric resonators”, IEEE Trans. on Microwave Theory and Techniques,. Vol. 25. No. 1, pp.52-54, Jan. 1979. https://doi.org/10.1109/ TMTT.1977.1129030

[19] M. W. Pospieszalski, “Cylindrical dielectric resonators and their applications on TEM-line microwave circuits”, IEEE Trans. on Microwave Theory and Techniques, Vol. 27, No. 3, pp.233-238, March 1979. https://doi.org/10.1109/TMTT.1979.1129599

[20] J. Krupka, K. Derzakowski, J. G. Hartnett, “Measurements of the complex permittivity and the complex permeability of low and medium loss isotropic and uniaxially anisotropic metamaterials at microwave frequencies”, Measurement Science and Technology, vol. 20, Issue 10, pp.1004-1008, Oct. 2009. http://dx.doi.org/10.1088/0957-0233/20/10/105702

[21] K. Derzakowski, “Full wave analysis of multilayered cylindrical resonator containing uniaxial anisotropic media”, Progress in Electromagnetics Research M, vol. 101, pp. 101-115, 2021. http://dx.doi.org/10.2528/ PIERM20120804

[22] https://www.ansys.com/products/electronics/ansys-hfss - Ansys HFSS|3D High Frequency Simulation Software

[23] https://www.qwed.com.pl/ quickwave.html - QuickWave Software for electromagnetic design and simulations based on conformal FDTD method

[24] https://www.3ds.com/products/simulia/cst-studio-suite - CST Studio Suite

[25] K. S. P. Hehenberger, S. Caizzone, A. G. Yarovoy, “Additive Manufacturing of Linear Continuous Permittivity Profiles and Their Application to Cylindrical Dielectric Resonator Antennas”, IEEE open Journal of Antennas and Propagation, vol. 4, pp.373-382, March 2023. https://doi.org/10.1109/OJAP.2023.3258147