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RESEARCH ARTICLE

Compact Matryoshka DGS Using Dielectric Resonator

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ABSTRACT In this paper, a compact matryoshka DGS using dielectric resonator (DR) is proposed. Despite the use of dielectric resonators to obtain band-stop frequency response not being a new idea, the proposed compact matryoshka DGS is an original contribution, since only recently the matryoshka geometry was used in DGS applications. Furthermore, a numerical analysis of the positioning of the DR is presented, which makes it possible to determine the region of the DGS for which the minimum resonant frequency is reached, and the resonant frequency range that can be obtained. To the best of the authors' knowledge, this numerical analysis is an unpublished result, even more so, for the matryoshka DGS. The matryoshka geometry was described, including initial design equations. To verify the expected characteristics (miniaturization, selectivity, and resonant frequency tunability), two compact matryoshka DGSs (DGS1 and DGS2) were designed using a high permittivity ceramic (MCT-115) as DR. The obtained numerical and experimental results showed good agreement, and the initial design equations proved to be applicable, which allows new dimensions to be determined for other resonant frequencies, according to the application requirements. Resonant frequencies ranging from the maximum value to 33% (DGS1) and 27% (DGS2) were achieved, depending on the DR position. Considering λ_0 the wavelength in free space, corresponding to the resonant frequency, DGS1 and DGS2 achieved an occupied area of $0.04\lambda_0 \times 0.04\lambda_0$, and $0.05\lambda_0 \times 0.05\lambda_0$, respectively, a good miniaturization. The proposed compact matryoshka DGS may be especially attractive for applications that require a very selective band-stop frequency response. If a wider band-stop is required, the proposed DGS can be cascaded.

INDEX TERMS Defected ground structure, DGS, dielectric resonator, high permittivity ceramic, matryoshka.

I. INTRODUCTION

The use of dielectric resonators to obtain band-stop frequency response is not a new idea [1], [2], [3], [4]. However, the continuous evolution of telecommunications systems, with new frequency response requirements, low cost, reduced volume, among other characteristics, drives the search for new filter configurations that meet these demands [5], [6], [7], [8]. Especially for applications in wireless communications systems, defected ground structures (DGS) have been widely used. In addition to the characteristics already mentioned, they can be easily integrated into other parts of microwave circuits, making them more compact.

A DGS is obtained from a planar transmission line (microstrip, conductor-backed coupled lines, slot-line etc.) from which part of the metallization layer (ground plane)

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is removed. This removed part disturbs the current distribution in the ground plane, causing changes in the transmission line characteristics, such as line capacitance and inductance [9], [10], [11]. Since DGS cells have band-stop properties, many of them have been used in filtering circuits to improve the frequency response [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. Despite the variety of DGS geometries (dumbbell, spiral head, arrowhead-slot, H-shaped, slot-shaped, square open-loop with a slot in middle section, open-loop dumbbell, interdigital etc.), specific frequency response requirements, as well as new applications, impose an ongoing challenge for microwave engineers, demanding new geometries. In this context, a DGS based on the matryoshka geometry (matryoshka DGS) was introduced in [18], Fig. 1. When compared to a dumbbell DGS, the matryoshka DGS showed a reduction in dimensions of approximately 50%, in addition to being more selective. Despite this result being quite interesting, in this paper these two concepts, dielectric resonator and matryoshka geometry, are used to obtain a band-stop filter with even smaller dimensions and more selective frequency response, Fig. 2.

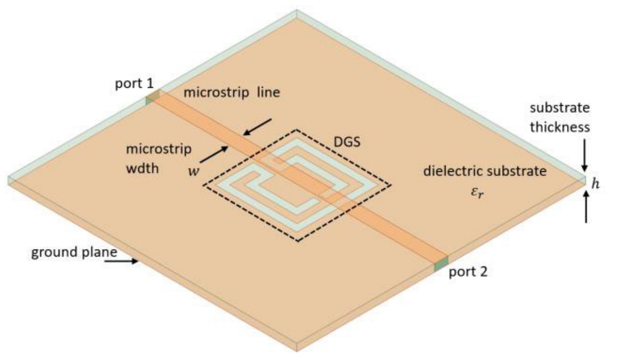

FIGURE 1. Matryoshka DGS geometry.

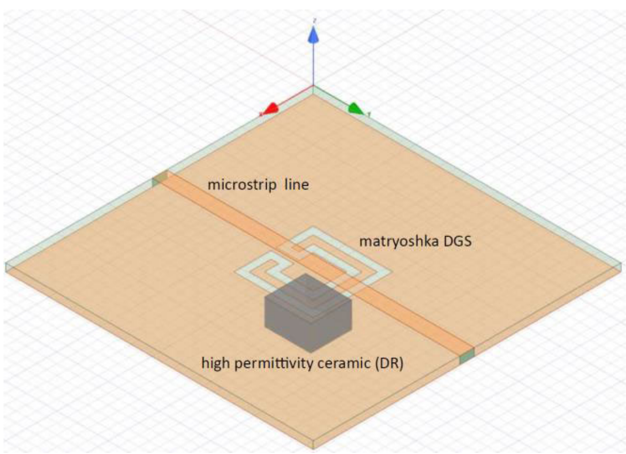

FIGURE 2. Matryoshka DGS with dielectric resonator (DR).

In addition to the matryoshka geometry, which has only recently been employed in DGS, the proper location of the dielectric resonator is discussed in this paper. In this way, it is possible to identify the location of the dielectric resonator that allows not only the lowest resonant frequency, but also intermediate resonant frequencies, which can be very useful if a tuning process is necessary. It should also be noted that this paper presents results for only one cell of the proposed DGS. Frequency responses with a wider rejection band can be obtained by using cells from the proposed DGS in cascade.

After this Introduction, this paper is organized as follows: in Section II, the matryoshka geometry is detailed, including initial design equations, as well as the MCT-115 high permittivity ceramic, which is used as the DR, is described. Section III presents numerical and experimental results. The two DGSs designed, fabricated, and characterized are described. The DR position and its influence on the resonant frequency is numerically analyzed. Frequency response comparisons for compact matryoshka DGS, matryoshka DGS and dumbbell DGS are also presented in this section. Finally, a brief conclusion is given in Section IV.

II. PROPOSED MATRYOSHKA DGS DESIGN

The matryoshka geometry was introduced in [19]. Essentially, it is composed of concentric and interconnected rings, Fig. 3. As the rings are interconnected, the effective length of the matryoshka ring increases, without increasing the occupied area, limited to the area of the outmost concentric ring. This characteristic, when applied to frequency selective surfaces [19], [20] and filters [18], gives to matryoshka geometry a multi-resonance and more selective frequency response, as well as miniaturized dimensions. Although it is possible to use more than two concentric rings forming the matryoshka ring, in this work only two concentric rings will be considered.

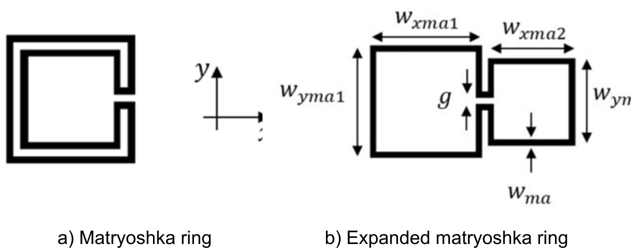

FIGURE 3. Matryoshka geometry.

Usually, $w_{xma1} = w_{yma1} = w_{ma1}$ and $w_{xma2} = w_{yma2} = w_{ma2}$. As a first approach, the resonant frequency can be estimated by [18]:

$$f_{res}(GHz) = \frac{0.3}{L_{efe}\sqrt{\varepsilon_{refe}}}, \tag{1}$$

with,

$$L_{efe} = 3 \times \left(w_{ma1-avg} + w_{ma2-avg}\right). \tag{2}$$

and,

$$w_{mai-avg} = w_{mai} - w_{ma}, \; i = 1, 2. \tag{3}$$

ε_{reff} is the effective dielectric constant for the microstrip line with width w, substrate thickness h, and dielectric constant ε_r.

It should be noted that two different widths are considered: one for the DGS (w_{ma}) and another for the microstrip (w).

L_{efe} is the effective average length of the matryoshka ring. $w_{mai-avg}$ is the average side length of the *i-th* ($i = 1, 2$) concentric ring.

Note that (1) is similar to the equation for calculating the resonant frequency of a loop-type FSS, for which resonance occurs when the effective length of the loop, herein given by (2), is approximately one wavelength long [21]. Furthermore, it must be highlighted that (1)–(3) are initial design equations, and, if necessary, the obtained values can be used as a first approach for a numerical optimization. Finally, it is worth mentioning that in a matryoshka DGS, similarly to a band-pass FSS [22], this matryoshka geometry is detached from ground plane metallization.

Magnesium Calcium Titanate, MCT [23], is one of the ceramic materials that is not characterized for resonator applications, but for bulk, miscellaneous shapes, or substrates. Typical applications include patch antenna substrates, matching structures for circulators and isolators. MCT series presents dielectric constant ranging from 18 to 140. In this work, the MCT-115 ($\varepsilon_r = 115$) is used.

III. NUMERICAL AND MEASURED RESULTS

In order to verify the expected characteristics (miniaturization, selectivity and resonant frequency tunability), two matryoshka DGSs were designed, fabricated and characterized, using a low-cost fiber-glass FR-4 substrate ($\varepsilon_r = 4.4$, loss tangent $tg\,(\delta) = 0.02$), with overall dimensions of 60mm $\times$ 60mm $\times$ 1.6mm. The microstrip width is $w = 2.8$mm. Table 1 presents the matryoshka DGS dimensions. The MCT-115 has 8mm $\times$ 9mm $\times$ 5mm. Numerical results were obtained using ANSYS HFSS software, and the simulated geometry is illustrated in Fig. 4. Lumped ports were used as excitation, and the radiation box has $75mm \times 75\ mm \times 18\ mm$.

TABLE 1. Matryoshka DGS dimensions.

	w_{ma1}	w_{ma2}	w_{ma}	g
$DGS1$	15.5 mm	9.5 mm	1.5 mm	1.0 mm
$DGS2$	12.5 mm	6.5 mm	1.5 mm	1.0 mm

Measured results were acquired at the GTEMA/IFPB microwave measurements laboratory, using an Agilent E5071C two ports network analyzer, Fig. 5.

Once the matryoshka DGS has been designed, the next step is to determine the appropriate position of the dielectric resonator (DR) to obtain a certain frequency response. Comparing with the matryoshka DGS without the resonator, one wants, for example, to know the position that produces the smallest resonant frequency. As a first step, the DR is positioned at the center of the matryoshka DGS ($dpx = dpy = 0.0$mm), Fig. 6. Next, it is displaced over the matryoshka DGS, varying the resonant frequency until the desired value

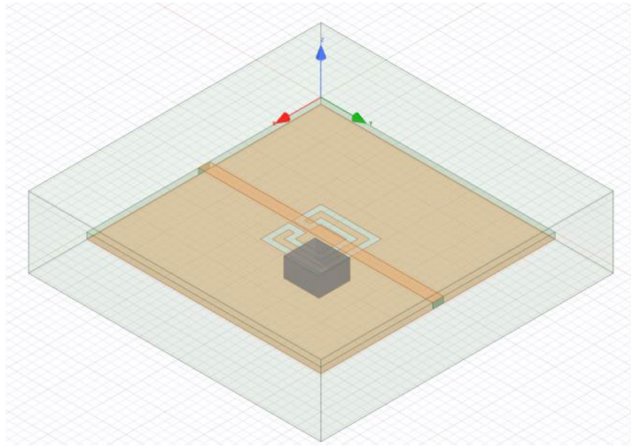

FIGURE 4. Simulated geometry.

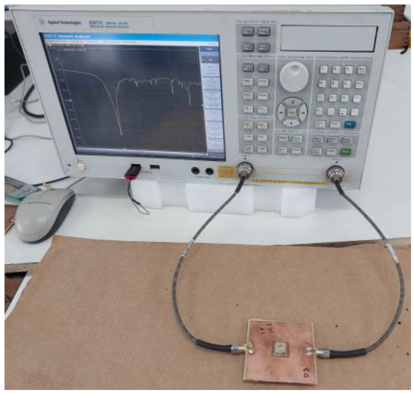

FIGURE 5. Measurements setup.

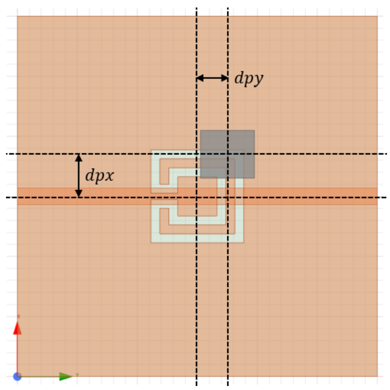

FIGURE 6. Matryoshka DGS with DR, bottom view.

is reached. To exemplify this procedure, consider the DGS1, with dpx and dpy ranging from -12 mm to +12 mm. For the different DR positions, i.e. for different dpx and dpy values, resonant frequencies vary from a minimum value, where the interaction of the DR with the DGS electromagnetic fields is stronger, to a maximum value, when the DR has a weak interaction with the DGS. The obtained resonant frequencies are shown in Fig. 7, with resonant frequencies from 0.74 GHz

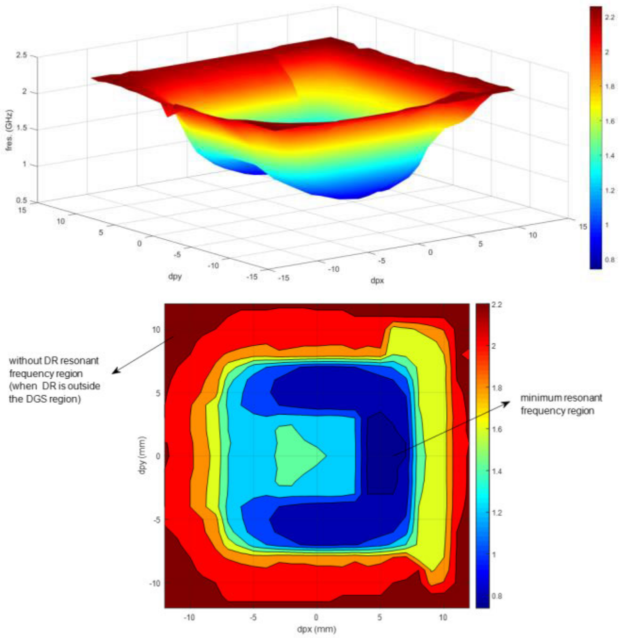

FIGURE 7. Resonant frequencies for different DR positions (DGS 1).

(minimum resonant frequency region) to 2.24 GHz (without DR resonant frequency region, when the DR is outside the DGS region). So, in addition to reducing the resonant frequency to 33% of its initial value, it is also possible to adjust the resonant frequency to intermediate values, between the minimum (0.74 GHz) and the maximum (2.24 GHz).

DGS1 and DGS2 were fabricated, Fig. 8, with measured and numerical results presented in Figs. 9 and 10. Three situations were considered: without DR, center ($dpx = dpy =$ 0.0mm), and corner ($dpx = 0.5 \times (w_{ma1} - 7.5)$, $dpy = 0.5 \times (w_{ma1} - 8.5)$). When compared to measured ones, numerical results present a good agreement, confirming the expected results. Some discrepancies, especially after the resonant frequency, can be attributed to the fact that the DR is not really fixed over the DGS. Tables 2-7 summarize the obtained results. It should also be noted that the resonant frequency values calculated by (1)-(3), for the DGS matryoshka without the DR, Table 2, showed good agreement, when compared to the measured values.

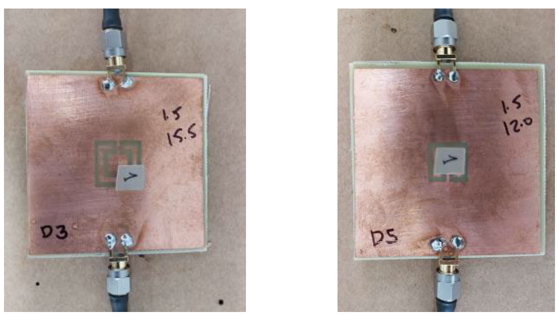

FIGURE 8. Fabricated matryoshka DGS with DR, bottom view.

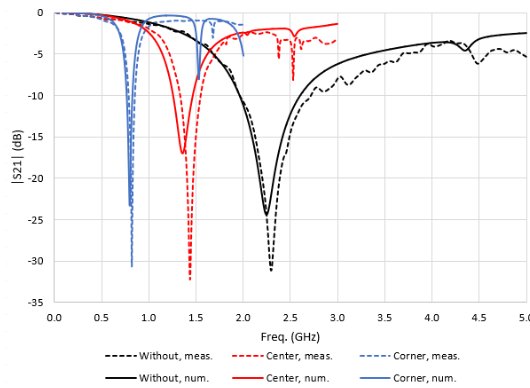

FIGURE 9. Matryoshka DGS1 with DR, frequency response.

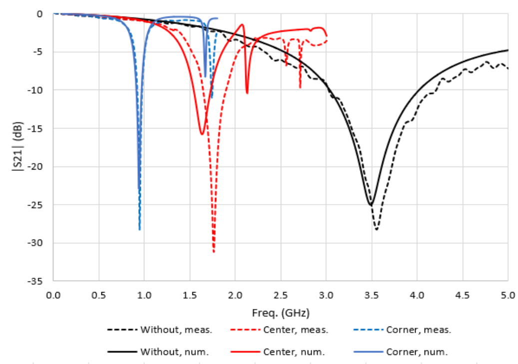

FIGURE 10. Matryoshka DGS2 with DR, frequency response.

TABLE 2. Matryoshka DGS resonant frequencies without DR.

	$f_{res.}$ meas.	$f_{res.}$ num.	$f_{res.}$ calc.	$dif.\% \left(\frac{calc.}{meas.}\right)$	$dif.\% \left(\frac{num.}{meas.}\right)$
DGS1	2.30 GHz	2.25 GHz	2.49 GHz	8.26%	−2.17%
DGS2	3.55 GHz	3.49 GHz	3.42 GHz	−3.64%	−1.69%

TABLE 3. Matryoshka DGS resonant frequencies DR in the center position.

	$f_{res.}$ meas.	$f_{res.}$ num.	$dif.\% \left(\frac{num.}{meas.}\right)$
DGS1	1.43 GHz	1.36 GHz	−4.90%
DGS2	1.76 GHz	1.64 GHz	−6.82%

TABLE 4. Matryoshka DGS resonant frequencies DR in the corner position.

	$f_{res.}$ meas.	$f_{res.}$ num.	$dif.\% \left(\frac{num.}{meas.}\right)$
DGS1	0.82 GHz	0.80 GHz	−2.44%
DGS2	0.95 GHz	0.95 GHz	0.00%

Aiming to illustrate the miniaturization properties of the proposed matryoshka DGS, two dumbbell DGSs [24], occupying the same matryoshka DGS area, are considered.

TABLE 5. Matryoshka DGS bandwidth without DR.

	$BW_{meas.}$ $-3\ dB$	$BW_{num.}$ $-3\ dB$	$BW_{meas.}$ $-10\ dB$	$BW_{num.}$ $-10\ dB$	$dif.\%$ $-3\ dB$ $\left(\frac{num.}{meas.}\right)$	$dif.\%$ $-10\ dB$ $\left(\frac{num.}{meas.}\right)$
$DGS1$	–	–	0.75 GHz	0.63 GHz	–	−16.00%
$DGS2$	–	–	1.18 GHz	0.97 GHz	–	−17.80%

TABLE 6. Matryoshka DGS bandwidth DR in the center position.

	$BW_{meas.}$ $-3\ dB$	$BW_{num.}$ $-3\ dB$	$BW_{meas.}$ $-10\ dB$	$BW_{num.}$ $-10\ dB$	$dif.\%$ $-3\ dB$ $\left(\frac{num.}{meas.}\right)$	$dif.\%$ $-10\ dB$ $\left(\frac{num.}{meas.}\right)$
$DGS1$	0.74 GHz	0.77 GHz	0.22 GHz	0.19 GHz	4.05%	−13.63%
$DGS2$	–	0.63 GHz	0.24 GHz	0.17 GHz	–	−29,17%

TABLE 7. Matryoshka DGS bandwidth DR in the corner position.

	$BW_{meas.}$ $-3\ dB$	$BW_{num.}$ $-3\ dB$	$BW_{meas.}$ $-10\ dB$	$BW_{num.}$ $-10\ dB$	$dif.\%$ $-3\ dB$ $\left(\frac{num.}{meas.}\right)$	$dif.\%$ $-10\ dB$ $\left(\frac{num.}{meas.}\right)$
$DGS1$	0.21 GHz	0.19 GHz	0.06 Hz	0.06 GHz	−9.52%	0.00%
$DGS2$	0.17 GHz	0.17 GHz	0.05GHz	0.05 GHz	0.00%	0.00%

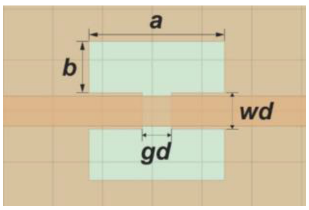

FIGURE 11. Dumbbell DGS geometry.

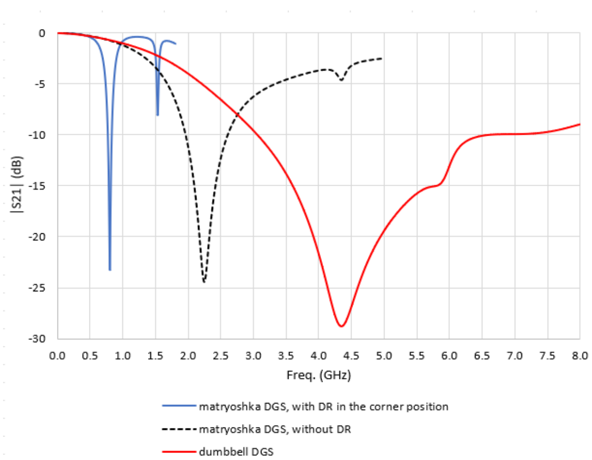

FIGURE 12. DGS1 versus dumbbell DGS (a = 15.5 mm, b = 5.75 mm, wd = 4.0 mm, gd = 3.0 mm).

The dumbbell DGS geometry is depicted in Fig. 11. Numerical results for the frequency responses are presented in Figs. 12 and 13, for which it is evident both the reduction in the resonant frequency and the greater selectivity of the matryoshka DGS with the dielectric resonator.

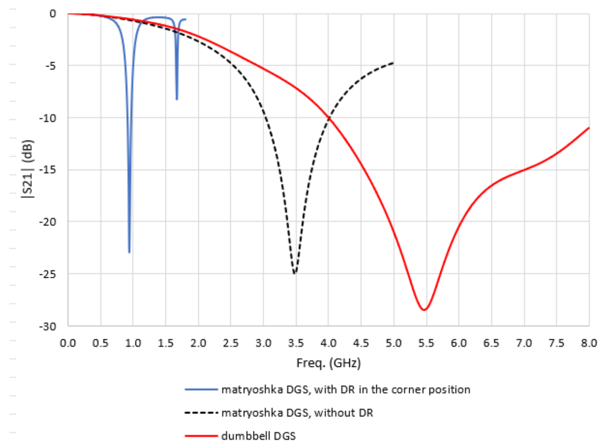

FIGURE 13. DGS2 versus dumbbell DGS (a = 12.5 mm, b = 4.25 mm, wd = 4.0 mm, gd = 3.0 mm).

IV. CONCLUSION

In this paper, a compact matryoshka DGS using dielectric resonator is introduced. The matryoshka geometry was described, including initial design equations. This DGS geometry keeps the reduction of the resonant frequency and selectivity, interesting features previously observed in FSS and filter applications. With the inclusion of the dielectric resonator, it becomes possible to obtain an even more compact and selective DGS.

The use of the dielectric resonator in a matryoshka DGS is an original contribution, since only recently the matryoshka geometry was used in DGS. Another important contribution is the numerical analysis of the location of the dielectric resonator, which allowed for determining the region of minimum resonant frequency. Furthermore, it was found that, depending on the position of the dielectric resonator, it was possible to vary the resonant frequency up to 27% of the maximum value, an important feature when a tuning process is necessary.

Two matryoshka DGS, DGS1 and DGS2, using a high permittivity ceramic MCT-115 as dielectric resonator, were fabricated and characterized, with numerical and experimental results showing good agreement. The initial design equations proved to be applicable, which allows new dimensions to be determined for other resonant frequencies, according to the application requirements. Considering λ_0 the wavelength in free space, corresponding to the resonant frequency, DGS1 and DGS2 reaching an occupied area of $0.04\lambda_0 \times 0.04\lambda_0$, and $0.05\lambda_0 \times 0.05\lambda_0$, respectively, a good miniaturization.

When compared to the dumbbell DGS and the matryoshka DGS without the dielectric resonator, it is evident that the compact matryoshka DGS proposed in this paper, in addition to presenting good miniaturization, is much more selective. These features make the compact matryoshka DGS especially attractive for applications such as suppression of undesired harmonics, e.g. in mixer and filter circuits, or undesired resonances in planar antennas.

In conclusion, it should be noted that this paper does not intend to exhaust all design issues of the proposed compact matryoshka DGS. In fact, what is being presented is a concept. For example, the minimum DR dimensions have not been optimized and it is an open issue. However, the proposed compact matryoshka DGS concept is clearly described. In addition, aiming at a specific application, the procedures for subsequent optimization are indicated.

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REFERENCES

[1] P. Guillon, S. Mekerta, and Y. Garault, ''A dielectric resonator bandstop filter,'' in *IEEE MTT-S Int. Microwave Symp. Dig.*, Jun. 1981, pp. 170–173, doi: 10.1109/MWSYM.1981.1129858.

[2] A. Abramowicz, ''MIC realization of dielectric resonator elliptic filters,'' in *Proc. 19th Eur. Microwave Conf.*, Sep. 1989, pp. 495–500, doi: 10.1109/EUMA.1989.334018.

[3] R. V. Snyder, S. Shin, and K. Keck, ''Bandstop filter design using evanescent mode resonators,'' in *IEEE MTT-S Int. Microwave Symp. Dig.*, Philadelphia, PA, USA, Jun. 2003, pp. 1073–1076, doi: 10.1109/MWSYM.2003.1212554.

[4] H. Uchida, H. Kamino, K. Totani, N. Yoneda, M. Miyazaki, Y. Konishi, S. Makino, J. Hirokawa, and M. Ando, ''Dual-band-rejection filter for distortion reduction in RF transmitters,'' *IEEE Trans. Microwave Theory Techn.*, vol. 52, no. 11, pp. 2550–2556, Nov. 2004, doi: 10.1109/TMTT.2004.837161.

[5] H. Bohra and G. Prajapati, ''Microstrip filters: A review of different filter designs used in ultrawide band technology,'' *Makara J. Technol.*, vol. 24, no. 2, p. 79, Sep. 2020, doi: 10.7454/mst.v24i2.3903.

[6] W. Fu, Z.-M. Li, J.-W. Chcng, and X. Qiu, ''A review of microwave filter designs based on CMRC,'' in *IEEE MTT-S Int. Microwave Symp. Dig.*, Shanghai, China, Sep. 2020, pp. 1–3, doi: 10.1109/IWS49314.2020.9360131.

[7] K. Bi, X. Wang, Y. Hao, M. Lei, G. Dong, and J. Zhou, ''Wideband slot-coupled dielectric resonator-based filter,'' *J. Alloys Compounds*, vol. 785, pp. 1264–1269, May 2019, doi: 10.1016/j.jallcom.2019.01.286.

[8] B. Ragavi., S. Sharmila, J. Dharani, and K. Deepthika, ''Design of dielectric coupled line resonator with defector ground structure for microwave frequency with double band pass filter,'' in *Proc. Int. Conf. Comput. Commun. Informat. (ICCCI)*, Coimbatore, India, Jan. 2023, pp. 1–6, doi: 10.1109/ICCCI56745.2023.10128197.

[9] M. K. Khandelwal, B. K. Kanaujia, and S. Kumar, ''Defected ground structure: Fundamentals, analysis, and applications in modern wireless trends,'' *Int. J. Antennas Propag.*, vol. 2017, pp. 1–22, Feb. 2017, doi: 10.1155/2017/2018527.

[10] C. Garg and M. Kaur, ''A review of defected ground structure (DGS) in microwave design,'' *Int. J. Innov. Res. Electr. Electron. Instrum. Control Eng.*, vol. 2, no. 3, pp. 1–6, Mar. 2014.

[11] L. H. Weng, Y. C. Guo, X. W. Shi, and X. Chen, ''An overview on defected ground structure,'' *Prog. Electromagn. Res. B*, vol. 7, pp. 173–189, 2008.

[12] A. Fernández-Prieto, V. dos Santos, J. Martel, J. L. M. del Río, F. Mesa, O. Quevedo-Teruel, R. R. Boix, and F. Medina, ''Glide symmetry applied to the design of common-mode rejection filters based on complementary split-ring resonators,'' *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 70, no. 6, pp. 1911–1915, Jun. 2023, doi: 10.1109/TCSII.2023.3235340.

[13] Y. Liu, L. Liu, C. Liang, and I. Majid, ''Compact planar tunable filter with constant absolute bandwidth and wide-frequency tuning range using DGS coupling structure,'' *IEEE Access*, vol. 9, pp. 157259–157266, 2021.

[14] B. A. Mouris, A. Fernández-Prieto, R. Thobaben, J. Martel, F. Mesa, and O. Quevedo-Teruel, ''Glide symmetry to improve the bandgap operation of periodic microstrip defected ground structures,'' in *Proc. 50th Eur. Microwave Conf. (EuMC)*, Utrecht, Netherlands, Jan. 2021, pp. 483–486, doi: 10.23919/EuMC48046.2021.9337947.

[15] C. Liu, Y. Rao, J. Zhou, and X. Luo, ''Compact dual-band bandpass filter with wide stopband using hybrid microstrip/DGS,'' in *IEEE MTT-S Int. Microwave Symp. Dig.*, Peru, Nov. 2021, pp. 82–84, doi: 10.1109/IMFW49589.2021.9642349.

[16] Y. Rao, H. J. Qian, B. Yang, R. Gómez-García, and X. Luo, ''Dual-band bandpass filter and filtering power divider with ultra-wide upper stopband using hybrid microstrip/DGS dual-resonance cells,'' *IEEE Access*, vol. 8, pp. 23624–23637, 2020.

[17] N. Ismail, S. M. Ulfah, I. Lindra, A. S. Awalluddin, I. Nuraida, and M. A. Ramdhani, ''Microstrip hairpin bandpass filter for radar S-band with dumbbell-DGS,'' in *Proc. IEEE 5th Int. Conf. Wireless Telematics (ICWT)*, Yogyakarta, Indonesia, Jul. 2019, pp. 1–4, doi: 10.1109/ICWT47785.2019.8978257.

[18] A. G. Neto, J. C. E. Silva, I. B. G. Coutinho, S. S. C. Filho, D. A. Santos, and B. L. C. D. Albuquerque, ''A defected ground structure based on matryoshka geometry,'' *J. Microwave, Optoelectronics Electromagn. Appl.*, vol. 21, no. 2, pp. 284–293, Jun. 2022, doi: 10.1590/2179-10742022v21i2256115.

[19] A. G. Neto, A. G. Dassunção, J. C. E. Silva, A. N. D. Silva, H. D. P. A. Ferreira, and I. S. S. Lima, ''A proposed geometry for multi-resonant frequency selective surfaces,'' in *Proc. 44th Eur. Microwave Conf.*, Oct. 2014, pp. 897–900, doi: 10.1109/EuMC.2014.6986580.

[20] V. Bhope and A. R. Harish, ''Polarization insensitive miniaturized multiband FSS using matryoshka elements,'' in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting (AP-S/URSI)*, Denver, CO, USA, Jul. 2022, pp. 1890–1891, doi: 10.1109/AP-S/USNC-URSI47032.2022.9887292.

[21] B. A. Munk, ''Estimating the resonant frequency of a single periodic surface: The concept ε_{eff},'' in *Frequency Selective Surfaces: Theory and Design*. Hoboken, NJ, USA: Wiley, 2000, p. 393.

[22] A. G. Neto, J. C. E. Silva, A. J. René Serres, M. D. O. Alencar, I. B. G. Coutinho, and T. D. S. Evangelista, ''Dual-band band-pass frequency selective surface based on the matryoshka geometry with angular stability and polarization independence,'' in *Proc. 14th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2020, pp. 1–4, doi: 10.23919/EuCAP48036.2020.9135542.

[23] Trans-Tech. *Products for RF/Microwave Applications*. Accessed: Aug. 5, 2023. [Online]. Available: https://datasheet.octopart.com/SR9000SPQ0472AY-Trans-Tech-datasheet-8861441.pdf

[24] F.-R. Yang, K.-P. Ma, Y. Qian, and T. Itoh, ''A uniplanar compact photonic-bandgap (UC-PBG) structure and its applications for microwave circuit,'' *IEEE Trans. Microwave Theory Techn.*, vol. 47, no. 8, pp. 1509–1514, Aug. 1999, doi: 10.1109/22.780402.

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