A Sensor Using a Matryoshka Geometry Defected Ground Structure

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***Abstract*— A sensor using a Defected Ground Structure (DGS) based on the matryoshka geometry is described. The main idea is to take advantage of the miniaturization and selectivity characteristics of the matryoshka geometry. The proposed DGS sensor geometry is outlined, and initial design equations are presented. A prototype was fabricated and characterized. For the empty sensor, when comparing numerical and measured results, a very good agreement is achieved. Moreover, the resonant frequency determined using the proposed design equations represents a good agreement too. In order to verify the matryoshka DGS sensor sensibility, a mixture of distilled water and isopropyl alcohol was characterized and a calibration curve achieved. Finally, the matryoshka DGS sensor is compared with a dumbbell DGS sensor occupying the same area, confirming the miniaturization and selectivity characteristics of the matryoshka geometry. The achieved results and characteristics instigate the matryoshka DGS sensor research.**

***Index Terms*—DGS, matryoshka, measurements, miniaturization, selectivity, sensors.**

I. INTRODUCTION

Sensors, along with actuators, are one of the most booming technological segments. The growing adoption of Internet of Things, IoT, advances in consumer electronics products, usage of several sensors in smartphones, industry 4.0, automotive industry, and demand for wearables are some drivers of the sensors market [1]. With the increase in quantity and diversity of applications of wireless communication systems, the remote monitoring of several parameters (position, temperature, motion, pollution, flow, among others) has received a great deal of attention. Consequently, the use of sensors, which can measure these parameters, attracts the interest of research groups, especially if these sensors can be integrated into wireless communication systems. Therefore, low-cost, reduced weight and volume are some of the requirements for these sensors. Sensors based on defected ground structures, DGS, meet these requirements and are researched for various applications, from the non-invasive determination of blood glucose level [2] to building material characterization [3].

Basically, a DGS is formed by modifying the ground plane, i.e. removing a certain geometry from its metallization layer [4], Fig. 1. The geometry of the removed part is one of the most flexible parameters in the design of DGS structures, through which its frequency response can be adjusted. By putting the material under test (MUT) in the DGS region, it interacts with the electromagnetic field, thus altering its frequency response, which can be used as a sensor, Fig. 2.

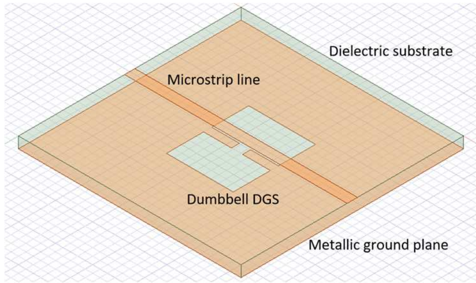


Fig. 1. DGS unit example – Dumbbell geometry.

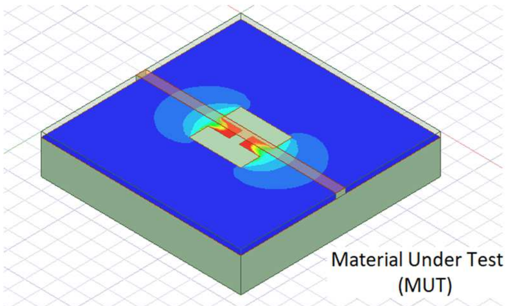
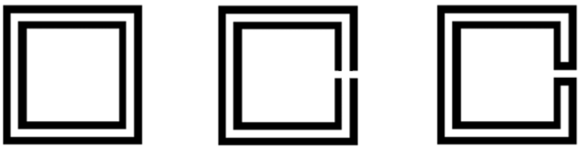


Fig. 2. DGS sensor – Dumbbell geometry.

Despite the variety of DGS geometries (spiral head, arrowhead-slot, H-shaped, shaped slots, a square open-loop with a slot in the middle section, open-loop dumbbell, interdigital DGS etc.) [4], [5], the continuous evolution of the sensors industry, with a seemingly infinite number of sensors being embedded in wireless devices, demands new geometries. In this context, a DGS sensor based on the matryoshka geometry is introduced herein. The main idea is to take advantage of the miniaturization and selectivity characteristics of the matryoshka geometry to obtain a DGS sensor with smaller dimensions and increased selectivity when compared to usual geometries, such as the dumbbell. Initial design equations are presented and a prototype fabricated and characterized, demonstrating good agreement between numerical and measured results. Moreover, the proposed design equations provide very good results for the resonant frequency. Aiming to verify the matryoshka DGS sensor sensibility, a mixture of distilled water and isopropyl alcohol was characterized and a calibration curve achieved. The results obtained make the matryoshka DGS sensor potentially attractive for embedded applications, non-invasive measurements, and wireless sensors network. After this Introduction, the design of the matryoshka DGS sensor is described in Section II. Numerical and measured results are presented in Section III. Conclusions are drawn in Section IV.

II. Matryoshka DGS Sensor Design

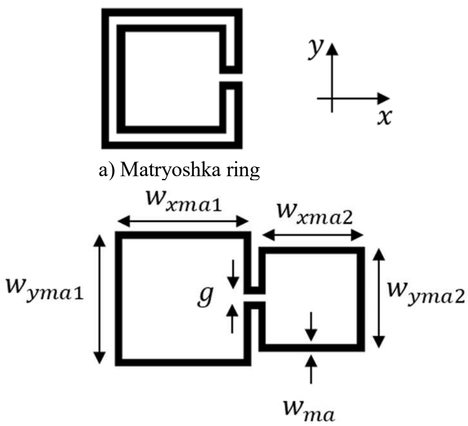
The matryoshka geometry was introduced in [6], [7]. Although it is possible to use a higher number of rings, only one matryoshka ring, composed of two interconnected concentric rings, is considered in this work. In this case, to obtain the matryoshka geometry, initially two concentric rings are designed, Fig. 3(a). Then gaps are inserted at the same position in the rings, Fig. 3(b). Finally, the rings are interconnected, and the matryoshka ring is achieved, Fig. 3(c).



a) Concentric rings | b) Gaps at the same position | c) Interconnected rings

Fig. 3. Step-by-step evolution of the Matryoshka geometry.

The matryoshka geometry is characterized by the interconnection of its concentric rings, increasing its effective length without occupying a larger area which is limited to the outermost ring area, Fig. 4. Frequency selective surfaces, FSS [6]-[8], filters [9] and sensors [10] are examples of applications of the matryoshka geometry and its variations.



b) Expanded matryoshka ring

Fig. 4. Matryoshka geometry – One matryoshka ring, two concentric rings.

Usually, $w_{xma1} = w_{yma1} = w_{ma1}$ and $w_{xma2} = w_{yma2} = w_{ma2}$. Based on previous works [6], [8], as a first approach, considering the empty sensor, i.e. the MUT is air, the resonant frequency can be estimated by:

$$f_{res}(\text{GHz}) = \frac{0.3}{L_{eff}\sqrt{\varepsilon_{reff}}} \tag{1}$$

where

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

and

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

ε_{reff} is the effective dielectric constant for the microstrip line and it can be easily calculated using available software [11]. Note that, differently from [6], [8], where the matryoshka ring is of the patch type and the effective dielectric constant is related to a coplanar waveguide, in this paper the matryoshka ring is of the slot type and the microstrip effective dielectric constant is adopted.

It must be highlighted that (1) – (3) are initial design equations as a first step towards a numerical optimization.

In the proposed DGS sensor, the matryoshka ring is centered under the microstrip line as depicted in Fig. 5. The microstrip width is *w*, the substrate thickness *h*, and its dielectric constant ε_r. The MUT thickness is h_t. It is worth mentioning that in the proposed DGS sensor, similarly to a band pass FSS [12], the matryoshka geometry is etched out of the ground plane metallization.

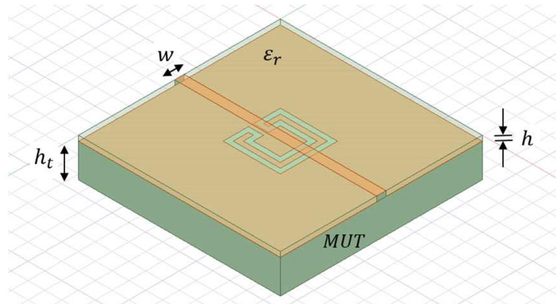


Fig. 5. DGS sensor – Matryoshka geometry.

III. Numerical and Measured Results

In order to verify the characteristics of the proposed DGS sensor, a DGS sensor was designed, fabricated and characterized. Numerical results were obtained using ANSYS Electronics Desktop software [13]. Measured results were acquired at the GTEMA/IFPB microwave measurements laboratory using an Agilent E5071C two-port network analyzer, Fig. 6. Note that the microstrip line is in the bottom side.

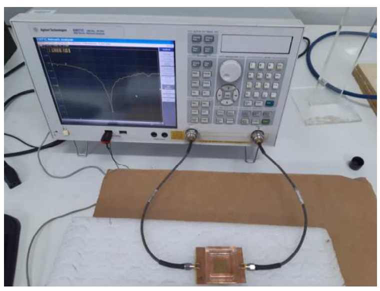
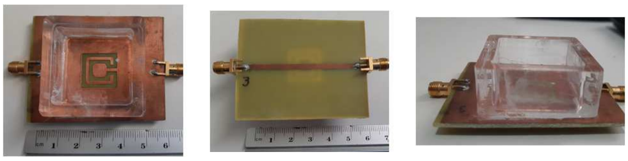


Fig. 6. Measurement setup.

The DGS sensor was fabricated using a low-cost fiber-glass FR-4 substrate (ε_r = 4.4, $tan\delta$ = 0.02, thickness h = 1.6 mm) with a microstrip line width w = 2.8 mm. An acrylic cell (30 mm × 30 mm × 15 mm) has been placed over the DGS, which is filled with the MUT (liquid), Fig. 7. The matryoshka geometry dimensions are summarized in Table I.



a) DGS view b) Microstrip view c) Side view

Fig. 7. Fabricated matryoshka DGS sensor.

TABLE I. MATRYOSHKA GEOMETRY DIMENSIONS

w_{ma1}	w_{ma2}	w_{ma}	g
15.5 mm	9.5 mm	1.5 mm	1.0 mm

As a first step, the empty DGS sensor was characterized. The obtained results are presented in Fig. 8, demonstrating good agreement between numerical and measured results. The numerical resonant frequency (2.39 GHz) is slightly less than the measured one (2.48 GHz), with an error difference of 3.76 %, which can be attributed to the manufacturing process so that after corrosion, the dimensions were somewhat smaller when compared to the design values. Furthermore, the resonant frequency calculated using (1) – (3) is 2.32 GHz, which presents a very good result as a first approach.

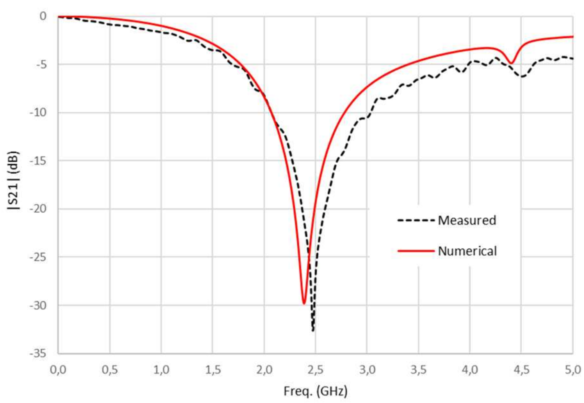


Fig. 8. Empty (air) DGS sensor – Frequency response.

To verify the proposed DGS sensor sensibility, an acrylic cell was filled with a liquid mixture of distilled water (ε_r = 80.1) and isopropyl alcohol (ε_r = 19.9) [14]. The distilled water and isopropyl alcohol were mixed in fractions of 10 %, i.e. 100 % distilled water and 0 % isopropyl alcohol, 90 % distilled water and 10 % isopropyl alcohol, and so on up to 0 % distilled water and 100 % isopropyl alcohol. The obtained frequency responses are shown in Fig. 9, and it is possible to observe that the resonant frequency decreases monotonically as the distilled water contents increases. The resonant frequency as a function of the distilled water contents is presented in Fig. 10, which can be seen as a calibration curve.

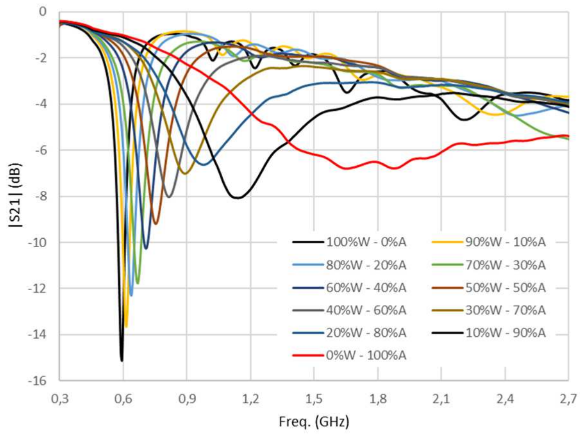


Fig. 9. DGS sensor – Frequency response for different distilled water (isopropyl alcohol) contents.

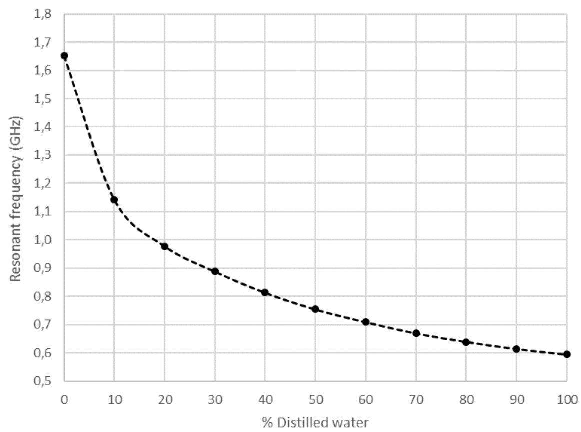


Fig. 10. Resonant frequency as a function of the distilled water contents.

Aiming to verify the proposed DGS sensor miniaturization properties, Fig. 11 compares frequency responses of the proposed DGS sensor with those of a dumbbell DGS sensor occupying the same area, dumbbell 1, and with a second dumbbell DGS sensor with the same resonant frequency, dumbbell 2. In this case, the empty DGS sensors are considered.

The dumbbell 1 DGS sensor presents a resonant frequency of 4.34 GHz, 81.6 % larger than that of the matryoshka DGS sensor. Furthermore, considering -10 dB as a reference level, the dumbbell DGS sensor has a bandwidth of 3.54 GHz, much larger than that of the matryoshka DGS sensor which is 0.70 GHz.

The dumbbell 2 DGS sensor occupies an area of $32.8\,mm \times 15.5\,mm = 508.40\,mm^2$, 111.6 % larger than that occupied by the matryoshka DGS sensor, $15.5\,mm \times 15.5\,mm = 240.25\,mm^2$.

Thus, the characteristics of miniaturization and improved selectivity of the matryoshka DGS sensor are confirmed.

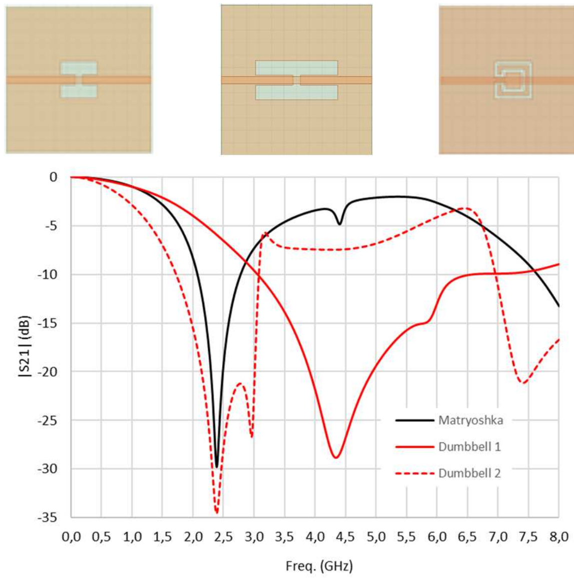


Fig. 11. Comparing matryoshka and dumbbell DGS sensors.

IV. Conclusions

In this paper, a DGS sensor based on the matryoshka geometry was described. This DGS sensor geometry provides miniaturization and increased selectivity, which are interesting features previously observed in FSS and filter applications. The resonant frequency determined using the proposed DGS sensor design equations (2.32 GHz) presented a good agreement when compared with numerical (2.39 GHz) and measured results (2.48 GHz).

In order to verify the proposed DGS sensibility, a liquid mixture of distilled water (ε_r = 80.1) and isopropyl alcohol (ε_r = 19.9) with fractions of 10 % steps was characterized. The achieved calibration curve indicates the applicability of the proposed DGS sensor.

Finally, the matryoshka and equivalent dumbbell DGS sensors were compared, confirming that the matryoshka DSG sensor occupies a reduced area, shows a smaller resonant frequency and better selectivity – important characteristics for a sensor.

The matryoshka DGS sensor features instigate new investigations, for example, increasing the number of matryoshka rings, as well as compiling calibration curves for other materials.

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