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# Novel 60 GHz DRA topology adapted to the LTCC process

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**Abstract**—This paper presents a novel topology for the conception of millimeter-wave (60 GHz) cylindrical dielectric resonator antenna (DRA) compatible with LTCC (Low Temperature Co-Fired Ceramic) technology. The design process deals with the strategical modification of the shape of the resonator, in order to properly integrate its structure. This technique, compatible with the LTCC process, allows to avoid the use of glues, soldering substances or other mechanical parts which could disturb the antenna properties and to optimize the fabrication process. Moreover, the LTCC technology delivers an additional degree of freedom for the design, since it allows to build non canonical resonator shapes. The developed antenna covers the 57-63 GHz spectrum, being enabled for future 5G applications at the 60 GHz band. The design of the antenna is based on the Theory of Characteristic Modes analysis.

**Index Terms**—5G, LTCC, DRA antenna, TCM, Millimeter wave.

## I. INTRODUCTION

Nowadays, there is a growing interest for the development of antennas which can meet the exigent needs of 5G communications systems. Such systems will deliver higher availability, ultra-low latency and massive capacity for mobile radio networks, as well as a wider bandwidth, thanks to the utilization of the millimeter wave spectrum at frequencies around 28 and 39 GHz and at 60 GHz. Some 5G enabled applications of includes Wireless Gigabit Ethernet, virtual reality, ultra-high definition (UHD) streaming and automotive radar sensors. However, 5G require antennas with high-gain, wide bandwidth, compact footprint and easiness of integration with other in package or on-chip components [1]. In this context, DRA antennas are consolidated as a good and cost-efficient solution which addresses the mentioned requirements. DRA antennas exhibit a reduced sized, light weight, design-construction easiness in several geometries and a wide bandwidth of around 15% [2]. Besides, as compared with microstrip antennas, their associated metallic and dielectric losses are reduced at millimeter-wave frequencies. DRA antennas can be also arranged to conform phased antenna arrays, in order to improve the gain to mitigate the propagation loss in the millimeter-wave band and to assure a high performance in NLOS scenarios.

As a first step to model and design DRA antennas several approaches could be applied. A classical conception deals with the dimensioning of the dielectric resonator by using analytical formulas and then an optimization stage supported

by electromagnetic simulation software. However, this approach is only effective to conceive canonical resonator shapes and also it does not provide a deep insight of the physics underneath the antenna operation. Moreover, the optimization process can be time-consuming and not efficient due to the number of parameters that must be considered

A more appropriate approach for the antenna design consists in the application of the Theory of Characteristic Modes (TCM). This method makes possible to identify and analyze the modal behavior of a resonator and its radiated electromagnetic field distribution, independently of the type of excitation. The main advantage offered by this method is that it provides a better understanding of the resonance and radiation phenomena occurring inside the antenna. Then, by considering the shape, dimensions and material of the resonator, it is possible to adjust the resonance frequency and the characteristic mode that delivers a desired electrical field distribution.

In this context, the technique mentioned above is employed for the conception of a 60 GHz DRA cylindrical antenna in LTCC technology. This technology is characterized by its multilayer flexibility in 3D environments, low losses and high integration and footprint reduction capability for circuits development [3]. However, the construction of a DRA antenna with the LTCC process entails some fabrication problems, especially concerning the resonator placement and fixing in the ground plane. Typically, this procedure is made by using adhesives, soldering substances or other mechanical parts. Nevertheless, its usage can degrade the antenna electrical properties and also could cause misalignments with the feed structure. In order to issue these inconvenients, a new topology, conceived at the same time than the full circuit and with the same LTCC process, is proposed. It consists in the insertion of mechanical dielectric supports, whose location is determined in order to not impact the electrical performance. This physical modification in the resonator shape allows ensuring the mechanical stability and correct positioning of the resonator, while maintaining its original field electrical distribution and radiation properties, leading to a more robust structure. It is found from the literature that there are only few studies about the conception and fabrication of DRA antennas [2-4] in LTCC technology at millimeter wave frequencies, most of them being developed at the 28 GHz band. In [2], a rectangular DRA linear array is designed at 28 GHz by employing a modified feeding structure. Recently,

the research work in [4] presents the conception of an antenna array based on DRA elements, operating at 25.7 GHz. In this case, the resonators were bonded to the ground plane by using a layer of glue Circa with 50 $\mu$ m thickness and  $\epsilon_r = 3$ . The previously mentioned technique impacts the resonance frequency and the antenna impedance bandwidth as well as it leads to alignment issues [5], which could become critical as the antenna operating frequency is increased. In this context, the present research work proposes an innovative approach to design and accurately position the DRA resonator on the ground plane without the use of adhesives or glues, whose performance was validated at 60 GHz with a LTCC ceramic material ESL41020 with  $\epsilon_r = 7.2$ .

## II. DESIGN OF A 60 GHz DIELECTRIC RESONATOR ANTENNA BY USING THE THEORY OF CHARACTERISTIC MODES

### A. Theory of Characteristic Modes

The Theory of Characteristic Modes was first developed by Garbacz and then generalized by Harrington and Mautz [6-7]. It is based on the impedance matrix  $\hat{Z}$ , which associates the current surface density  $J_s$  to the tangential electrical field component to the surface  $S$ . This is expressed by the equation:

$$E_{\text{tan}} = \hat{Z} J_s = (\hat{R} + j\hat{X}) J_s \quad (1)$$

Here  $\hat{R}$  and  $\hat{X}$  are the real and the imaginary parts of the impedance operator respectively. Then, the characteristic modes can be obtained through the resolution of the following eigenvalues problem:

$$\hat{X} J_{s,n} = \lambda_n \hat{R} J_{s,n} \quad (2)$$

In the previous equation,  $\lambda_n$  are the real eigenvalues and  $J_{s,n}$  are the eigenvectors or characteristic modes, which correspond to the currents on the structure. They depend of the dimensions and shape of the resonator and are independent of the type of excitation utilized. This information is useful to characterize the antenna modal behavior as well as its radiating properties.

### B. Antenna design by using the Theory of Characteristic Modes.

The antenna design process was performed by using the electromagnetic simulation software FEKO and HFSS. FEKO was employed for the antenna modal analysis and to assess the electromagnetic field distribution. On the other hand, HFSS was utilized for the simulation of the whole antenna structure, including the feeding mechanism. Both tools allow optimizing the resonant frequency and the bandwidth, as well as the antenna radiation diagram.

To illustrate the procedure, a cylindrical DRA operating at 60 GHz was simulated by using the LTCC substrate ESL41020, with  $\epsilon_r = 7.2$ . The layers' thickness is 90 $\mu$ m after firing, so the resonator height must be chosen as a multiple

of the individual layer thickness. Hence, the radius and the resonator height are the two parameters that can be modified to tune the resonance frequency. In order to ease the fabrication and to assure a good aspect ratio, a height of 540 $\mu$ m (6 layers) was initially chosen. Fig. 1 depicts the resonator structure modeled in FEKO. This software allows verifying the eigenvalues' curves in function of the frequency and the electrical field distribution of the resonating modes inside the resonator. After comparing the different modes, it was seen that the mode  $HE_{11}$  exhibits a radiation maximum in the Z direction and an important concentration of electrical field on the superior and inferior resonator surfaces. For this reason, this mode was elected to conceive the antenna. Subsequently, the radius value must be modified in such a way that the  $HE_{11}$  eigenvalue curve cuts by 0 at 60 GHz. The radius value obtained by following this procedure is  $r=1.28$ mm. Fig. 2 presents the aforementioned curve. Moreover, Fig. 3 shows the transversal and superior face view of the electric field distribution for the cited mode.

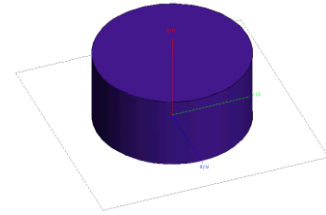


Fig. 1. DRA resonator scheme in FEKO.

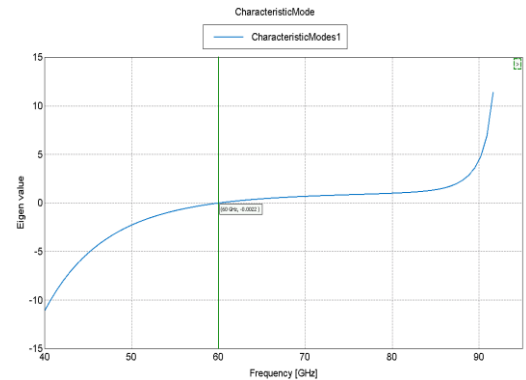


Fig. 2. Eigenvalues vs frequency curve for the  $HE_{11}$  mode

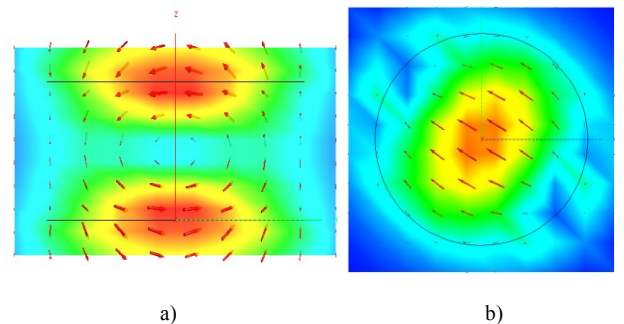


Fig. 3. Electrical field distribution for the  $HE_{11}$  mode a) Transversal view b) Superior view.

### C. Description of the novel DRA topology adapted to the LTCC process.

The electromagnetic simulation of the antenna, including the excitation structure, was carried out in HFSS, by considering the resonator dimensions as found previously. Initially, the resonator was placed on the top face of a square ground plane. Then, a coplanar structure with a 50-ohm transmission line ending up in a dipole was used as feeding mechanism. It allows to excite the  $HE_{11}$  mode in a convenient way and to assure a good radiation efficiency. As reported in [8], the antenna gain is influenced by the diffraction phenomena at the ground plane edges, due to the presence of side lobes directing towards them. In consequence, the maximum antenna gain depends of the ground plane size in a periodic way. Therefore, it is necessary to adjust carefully its dimension in order to maximize the antenna efficiency. The antenna exhibits a linear polarization, with a maximum gain in the Z direction.

The antenna fabrication in its actual state implies certain difficulties, such as the fact that the dielectric resonator needs to be fixed to the metallic ground plane. This action could be made by employing adhesives or soldering substances. However, this can degrade the antenna performance due to the presence of an external agent between the resonator and the feed mechanism that perturbs the coupling between both structures. Moreover, there exists an alignment problem, since the resonator needs to be placed in an exact position upon the feed dipole. The latter becomes more important at the 60 GHz band, due to the reduced dimensions of the antenna structures. Then, if a misalignment is present, it can provoke efficiency problems to excite the desired resonant mode.

As an alternative to solve the cited problematic, a novel DRA topology is proposed. It consists in the insertion of two triangular-shaped dielectric supports at each side of the resonator, resembling its final structure to a butterfly. By observing the resonator field distributions depicted on Fig. 3, it is noticed that the electrical field distribution is concentrated on the central region of the resonator and there is no field presence on two regions on the periphery. For this reason, the proposed modification does not affect the original field distribution in a great extent. Then, the principle is to insert a pair of dielectric supports connected to the DRA antenna at these regions. Fig. 4 depicts the novel structure as well as the superior view of the electrical field distribution.

Fig. 5 details the total DRA structure modeled in HFSS with the proposed modification. The ground plane is enlarged in order to facilitate the measurement. The dimensions of the total structure are: length=15mm, width=12mm and height=0.9mm. Fig. 6 presents the electromagnetic simulation results of the reflection coefficient. The antenna operation frequency is placed around 60 GHz and the 10-dB bandwidth is of 18.6 GHz, comprised between 52.2 and 71 GHz. The obtained bandwidth covers the 5G standard band for 60 GHz applications, comprised between 57 and 63 GHz.

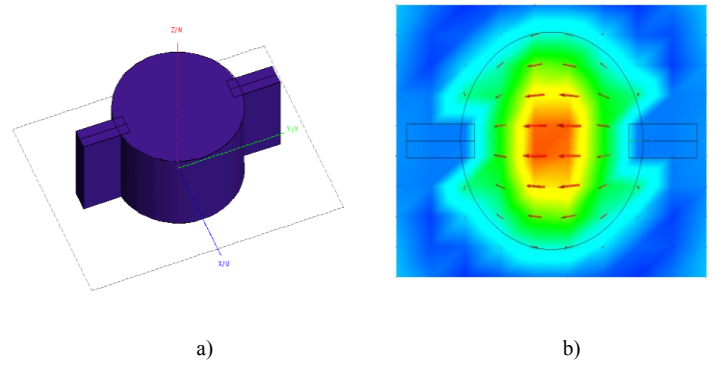


Fig. 4. Novel DRA resonator scheme in FEKO and its associated electrical field distribution a) Resonator scheme b) Electrical field superior view

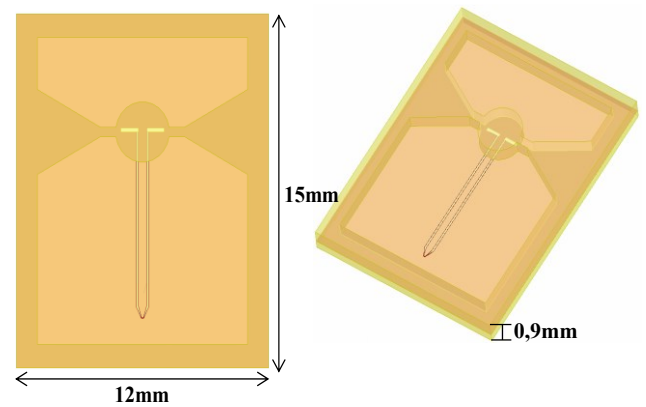


Fig. 5. 60 GHz cylindrical DRA novel topology

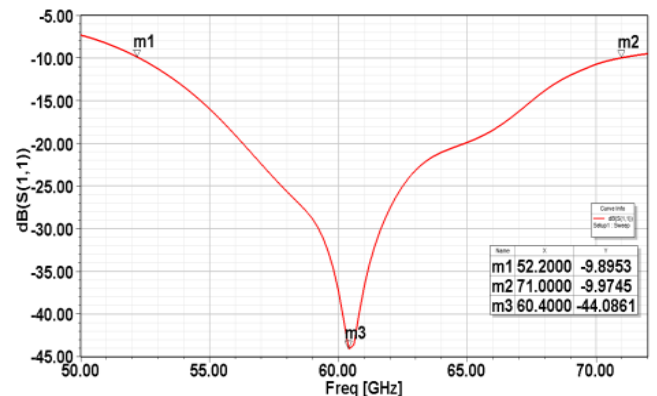


Fig. 6. Electromagnetic simulation result.

### III. LTCC GENERALITIES AND FABRICATION PROCEDURE

The LTCC technology consists in the stacking of several substrate layers, where each one of them has passed through several standard planar processes. The substrate tapes are drilled, screen-printed and cut separately. Subsequently, they are stacked, laminated and co-fired at temperatures close to 900 °C, to finally obtain a homogeneous structure [9]. Fig. 7 describes the fabrication process of a LTCC circuit.

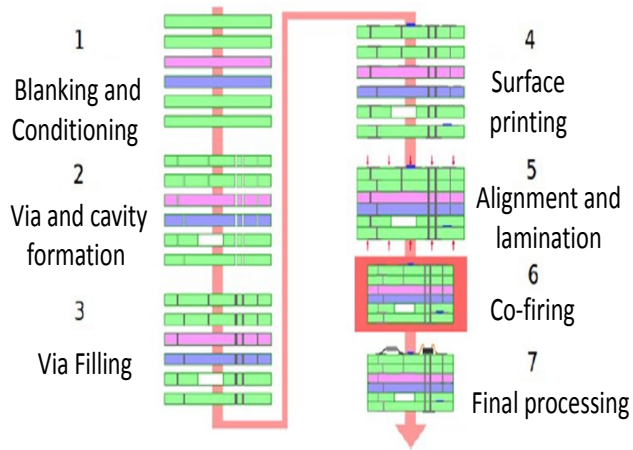


Fig. 7. Fabrication process of a circuit in LTCC technology [10].

In this work, the tape ESL41020 from Ferro is used. According to the manufacturer, the relative permittivity is 7.2 to 8.2 in the range up to 18 GHz, and the loss tangent is given to be inferior of 0.5 % from ring resonator measurements. From cavity resonator measurements, performed at XLIM, it was found a relative permittivity of 7.27 and a loss tangent of  $4.98 \times 10^{-3}$  at 15 GHz, at an ambient temperature of 20°C. ESL803 gold paste is used to screen print the 6  $\mu\text{m}$  thick metallized layer where the ground plane and the dipole structure are realized. The DRA antenna is built on ten LTCC substrate layers, where the three first layers are used to provide a mechanical stability. The antenna feed structure is screen printed on top of the fourth layer, as can be seen in Fig. 8. The DRA resonator is built on layers five to ten by doing cutouts using a Nd:YAG laser equipment, as shown on Fig. 9. It follows that the DRA is 540  $\mu\text{m}$  thick after firing. To protect the DRA shape and the surrounding cavities during lamination, pieces of fugitive tape (ESL49000) are cut in the same shapes as the cavities and placed into them, layer by layer, during the stacking procedure, as presented in Fig 10.

In this early stage of prototyping, the antenna is to be measured in a probe station. The GSG probes from Picoprobe have a 150  $\mu\text{m}$  pitch, which leads to a need of coplanar probe pad dimensions that are smaller than we can achieve by screen printing (signal line width of 100  $\mu\text{m}$  width and gaps size of 30  $\mu\text{m}$ ). To provide this, a post-fire laser ablation is used to realize the coplanar tapered end. The final antenna structure can be seen in Fig. 11. After firing the resulting antennas all showed some ground plane voids. These voids may come from air trapped between some of the LTCC layers or from air trapped underneath the screen-printed gold on layer four. Further research needs to be done to find the reason why they appear and how to eliminate them.

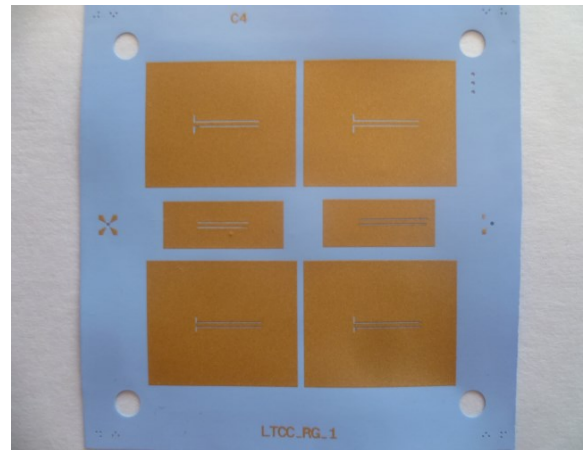


Fig. 8. ESL803 screen printed on tape layer four. Four antennas and two test lines (the one to the right is erroneous) are placed on the same 2" by 2" substrate.

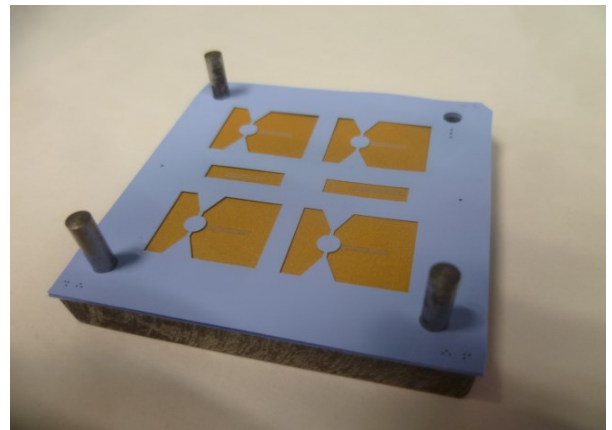


Fig. 9. Stacking procedure. Here, layer five is placed on layer four on the satcking support. The cavity cutouts will shape the DRA resonator

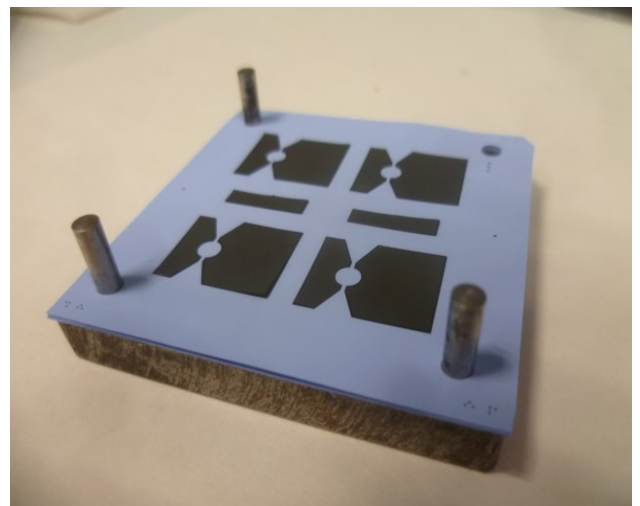


Fig. 10. Fugitive tape placed in the cavities, layer by layer to protect the DRA resonator from being deformed during the following lamination step.



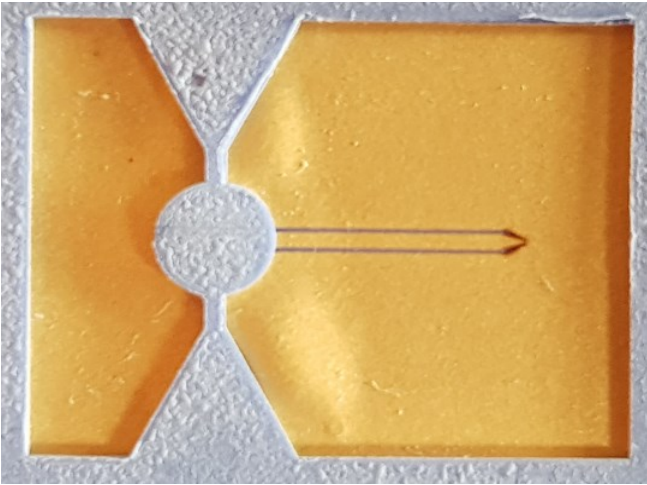


Fig. 11. Final DRA antenna structure.

#### IV. MEASUREMENT RESULTS

Fig. 12 shows the experimental results of the reflection coefficient for the fabricated antenna. The antenna resonance frequency is located around 58.2 GHz and the 10-dB bandwidth is of 6.64 GHz, comprised between 53.43 and 60.07 GHz. There is a frequency shift of 3% as compared with the simulation results, mainly induced by the dispersion of the permittivity, whose value must be characterized at the 60 GHz band. Moreover, the bandwidth reduction could be associated to some imperfections in the fabrication process regarding the resonator radius and the dimensions of the feed mechanism, including the presence of some voids in the ground plane surface. However, despite the frequency shift the obtained bandwidth is higher than 6 GHz, value that meets the requirement for 5G applications at the 60 GHz band. The aforementioned issues will be addressed for the next fabrication run.

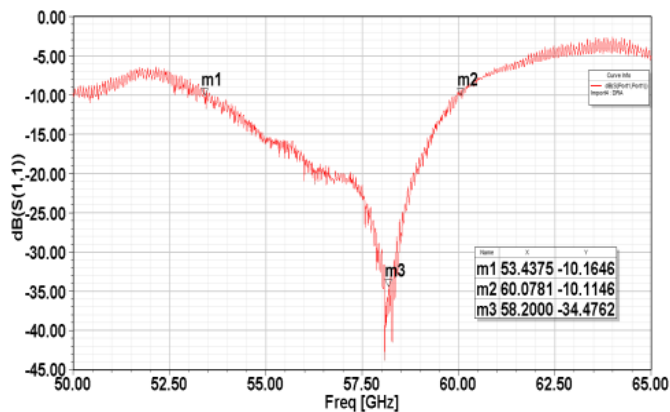


Fig. 12. Experimental simulation result.

#### V. CONCLUSIONS

This paper presents a novel topology for the design of a cylindrical DRA at 60 GHz compatible with the LTCC process. Through the proposed physical modification on the

resonator shape, supported by a modal analysis of the field distributions, it was obtained a stable mechanical fixing of the resonator on the ground plane and a precise alignment upon the feed structure, crucial for 60 GHz applications. The experimental measurements demonstrate the potential of the proposed topology to meet the requirements imposed by the 5G standard at the 60 GHz band. In the next fabrication run the manufacturing process will be refined to solve the physical problems on the antenna structure and the ceramic material electrical properties will be characterized at the antenna operation band.

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