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CPW-Fed LTCC Based Broadband Microstrip Antenna for Millimeter-Wave Applications at 60 GHz

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Abstract— *In this paper, a new design of a low-profile and multilayer broadband microstrip antenna is proposed for millimeter-wave applications at 60 GHz. The antenna is a metamaterial inspired structure that consists of a non-uniform octagon shape radiating element on the top of six layers of substrate and a periodic structure at the second layer. The proposed antenna geometry is designed using Low Temperature Co-Fired Ceramic (LTCC) technology for 3D multilayer vertical integration. This antenna achieves 24.16 % of bandwidth ranging from 55.5 GHz to 70 GHz, with a peak gain of 5.1 dBi at 60 GHz. HFSS is used for design and simulation of this LTCC based broadband antenna. Three prototypes are fabricated for measurement and a good agreement of numerical and practical results is obtained which makes this antenna very attractive for the use in future wireless communication systems.*

Keywords— *wideband, microstrip antenna, LTCC, millimeter waves*

I. INTRODUCTION

With the explosive growth of wireless communication systems and new integrated circuit abilities, extending mobile wireless systems to millimeter waves (30 GHz - 300 GHz) is a very active research area [1], [2]. Millimeter waves at 60 GHz are more sensitive to outdoor environmental conditions like rain, gas, dust, vegetation, etc. Due to these hard propagation characteristics, this band requires a unique hardware circuitry where more system design complexities are required to benefit from it [3-5]. The antenna's performance enhancement and design considerations are becoming more significant challenges for facing many stringent requirements of this spectrum. The operation at such frequencies will allow a wideband communication, and consequently much higher data rates compared to the current microwave-based communication systems [6].

Microstrip antennas are extensively used in today's radio communication devices due to their appealing features and advantages such as small size, light weight, low cost and easy integration with planar structures. However, microstrip patch antennas have low gain and a very narrow operating bandwidth that is generally less than 5% [7-9]. In literature, various methods and extensive research efforts have been devoted to this area. In [10] a 9.5 % of bandwidth is obtained using an aperture-coupled microstrip line-fed patch antennas (ACMPAs) where air cavities processed inside the substrate

are used to improve the bandwidth and gain of the antennas. In [11] a low-profile metamaterial-mushroom antenna array consists of a single-layer mushroom radiating structure and a single-layer substrate integrated waveguide (SIW) feeding network exhibiting an impedance bandwidth of 56.3–65.7 GHz. In [12] the artificial magnetic conductors (AMCs) with in-phase reflection characteristics have been investigated, where a 60 GHz CPW-fed patch antenna on multilayer LTCC- and liquid crystal polymer (LCP)-based achieved a bandwidth of about 16% and a peak gain of 5.1 using the LCP substrate. However, the additional fabrication process for the air cavity, substrate integrated waveguide (SIW) cavity, slotted AMC cells and EBG (electromagnetic band gap) surfaces with metallic vias in each unit cell increases circuit complexity and fabrication cost.

In this paper, a low-profile broadband antenna based on Low Temperature Co-Fired Ceramics (LTCC) is proposed. The LTCC technology has been actively studied for millimeter-wave antenna and package solutions. LTCC technology is one of the more suitable technologies for the production of multilayer circuits for vertical 3D integration. It offers an attractive solution for easy, compact and high flexibility for multilayer antennas structures based on vertical integration topology. It offers low conductor and dielectric losses and high design freedom through the high possible number of layers, easy integration, flexible via holes distribution, compactness and excellent high frequency performance [13-17]. However, the proposed antenna based on the LTCC technology is simplified in order to minimize the fabrication cost and to facilitate the manufacturing process.

In the rest of this paper, the antenna geometry and configurations are presented and explained in section 2. The simulation results analysis and discussion are presented in section 3. The manufactured prototypes and their obtained measurement results are also presented and analyzed in this section, while section 4 concludes the paper.

II. ANTENNA DESIGN

The geometry of the proposed antenna is presented in Fig. 1. This geometry is designed to achieve a wide bandwidth. To achieve LTCC-based wideband geometry, the first step is to design a conventional microstrip patch antenna to operate in the desired bandwidth. Then, the corners of the radiator

element are truncated to have a non-uniform octagon shape. The antenna is placed on the top of six LTCC layers, having a relative permittivity of 4.11 and loss tangent of 0.008. The antenna is fed using a coplanar waveguide (CPW) structure. This antenna is composed of two grounds; the first ground is printed on the top of the second LTCC layer. This top ground is composed of metallic square patches etched on the top of the bottom substrate. The second ground is placed on the bottom of the first layer. There is no via between the patch and the second ground plane, which helps to reduce the fabrication cost and facilitate the manufacturing process. Note that these periodically integrated patches are a metamaterial inspired surface [20], [21]. However, it is not considered as a metasurface because it not analyzed as a function of phase reflection where a zero-phase of the unit cell must be at the same resonating frequency of the antenna. In our case, the unit cell has a zero-phase degree at around 0.1 THz. Hence, this periodic structure can only be considered as a defected ground surface (DGS) [22].

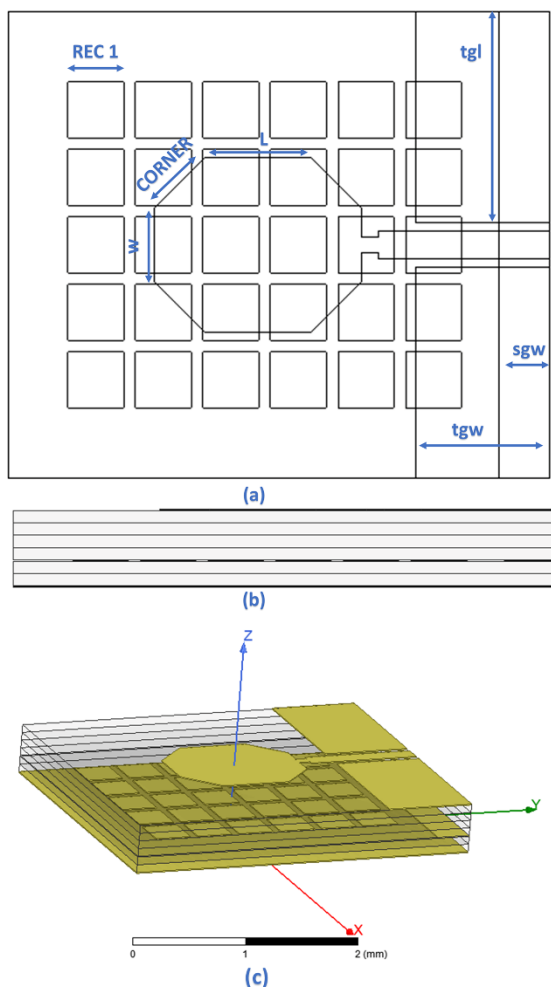


Fig. 1. The antenna geometry, (a) Top view, (b) side view, (c) the designed antenna in High-Frequency Structure Simulator (HFSS).

The antenna dimensions are obtained using an intensive parametric study. First, the considered conventional patch antenna is given a length equal to the half-wavelength at the operating frequency as an initial starting point of the design process. Then, for better accuracy in terms of the resonance frequency, the length of the antenna is adjusted to the other dimensions of the antenna employing a parametric study. To

give more freedom to the optimization process, the radiator was preferred to be octagonal to add another parameter (corner) to the optimization through the parametric study. With the insertion of the periodic square patches' matrix in the antenna substrate, another parametrical study was carried out to keep the desired resonance frequency, which includes the new parameters of this structure, namely the lattice constant, the patch radius, the dimensions and the position of the patches array in Y-axis.

Typically, the parametrical study permits more than three-dimensional parameters to be varied while the other parameters are fixed in a constant value. However, by treating only one or two variables parametrically, it is possible to explore the structure more effectively and permits to better analyze the antenna behavior. When a large number of parameters have to be explored, a sensitivity analysis of the parameters is applied to effectively guide the optimization by moving form parameters with a significant effect to those with a weaker effect. This study is repeated until achievement of a configuration that satisfies the design needs in terms of antenna performance such as impedance matching, gain, etc. The proposed structure is simplified to minimize the fabrication cost, by reducing of the total module size without the use of integrated cavities, vias, and other complex structures such as EBG Structures. The antenna geometry has been developed respecting the LTCC technology design rules [23]. The single LTCC layer thickness is $75 \mu\text{m}$ for each tape after firing. The used conductor for the metal layers is gold having a thickness of $6 \mu\text{m}$. Four layers are used to compose the top substrate and two LTCC layers in the bottom substrate, giving a height of $300 \mu\text{m}$ for the top substrate and $150 \mu\text{m}$ for the bottom substrate. Table 1 shows the values of the rest parameters.

TABLE I. ANTENNA PARAMETERS

Parameter	Value (μm)	
Radiating element layer	L	630
	w	441
	tgl	1246
	tgw	792
	$corner$	420
Periodic structure layer	sgw	300
	$REC 1$	330
	$Lattice\ constant$	400

III. RESULTS AND DISCUSSION

The proposed antenna is designed simulated using High-Frequency Structure Simulator (HFSS), which is based on finite element modeling (FEM). Fig. 2 shows the surface current distribution in logarithmic scale at the top and the middle metal layers. The current distribution is maximum at the edges of the antenna and minimum at the center of the antenna. The current distribution on the periodic square patches is maximum at the bottom of the antenna and minimum outside this region. Therefore, the number of these periodic patches is chosen to be 5×6 elements to provide an adequate space for current distributions. Note that a relatively large number of elements only slightly improves antenna performance where the manufacturing of the antenna becomes more complex.

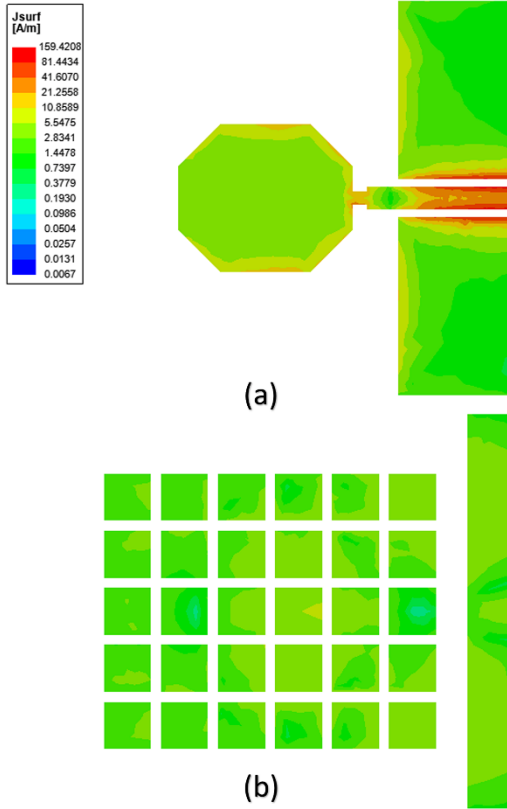


Fig. 2. Logarithmic scale of the surface current distribution at the top and the middle metal layers.

The antenna input impedance is examined to ensure that the maximum power is transferred from the radio frequency (RF) circuitry to the antenna with negligible amount being reflected back. Fig. 3 shows the curves of the real and the imaginary parts of the input impedance of this proposed antenna structure. An antenna with zero reactance and real input impedance is considered to be resonant at the corresponding frequency. The imaginary part of the input impedance represents the power that is stored in the near field of the radiator. This power is not considered as a radiated power. According to the reactance curve, a zero imaginary part is obtained at 60 GHz. The antenna input resistance is around 50 ohms, which means the power that arrives at the antenna is radiated away. These simulation results of the input impedance show a good impedance matching at the considered frequency spectrum.

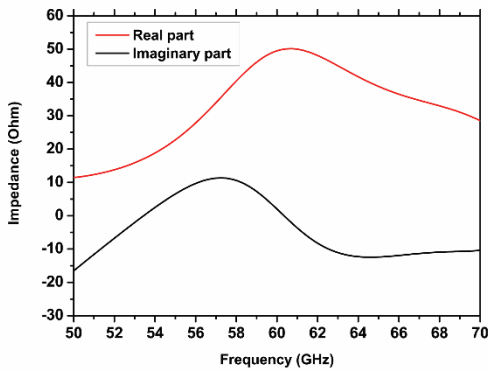


Fig. 3. The antenna input impedance; real and imaginary parts.

Fig. 4 shows the obtained reflection coefficient of the proposed antenna as a result of simulation. As it is observed in this figure, the obtained S_{11} is about -51 dB with a single resonance frequency at 60 GHz. The obtained bandwidth based on the -10 dB criterion of the reflection coefficient is 14.5 GHz ranging from 55.5 GHz to 70 GHz. According to these results, the antenna offers a good impedance matching with a wide bandwidth. This wide bandwidth, equivalent to 24.16 %, allows this multi-layer antenna to largely surpass the requirement of 11.66 % of the bandwidth of 60 GHz spectrum and to cover the entire unlicensed spectrum [24].

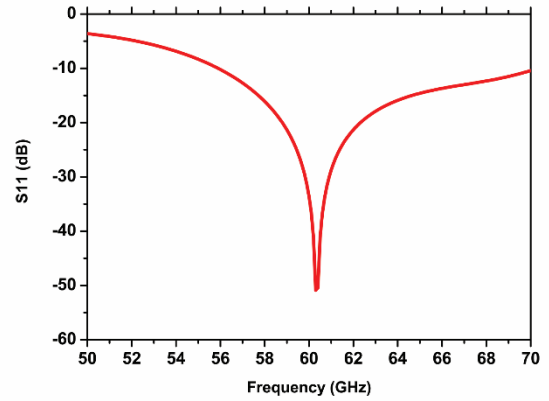


Fig. 4. Antennas reflexion coefficient.

Fig. 5 shows a parametrical variation of RECT1 parameter. According to these curves, the change in the dimensions of the patches has an influence in terms of resonant frequency and S_{11} magnitude. Decreasing the dimensions of the patch results in a transition to a higher resonant frequency. It is also observed that a good precision in terms of resonance frequency can be obtained by choosing $RECT1 = 170 \mu\text{m}$. However, this dimension reduces the space between the patches to less than $65 \mu\text{m}$, which may not be achieved in practical designs due to manufacturing tolerances. Note that the larger the space between two patch elements, the more precision can be obtained. According to these graphs, the dimension of the integrated patches is chosen in order to have deeper S_{11} at the resonance frequency.

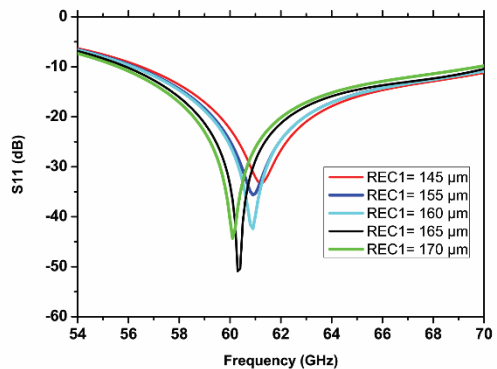


Fig. 5. The reflexion coefficient curves of parametric variation of RECT1.

Fig. 6 shows the plots of gain at 60 GHz in E-plane for $\Phi = 90$ and H-plane for $\Phi = 0$. According to these curves, the maximum radiation is obtained at $\Theta = 0$ in both E plane and H plane having a peak gain of 5.1 dBi. Fig. 7 shows the obtained simulation plots of gain as a function of frequency in

the used software program. The antenna has a gain of 5.10 dBi at 60 GHz. It is also observed that the antenna exhibits a gain reduction as the frequency increases. This obtained gain is acceptable for a single antenna at this range of spectrum where the size must be scaled to the wavelength, which leads to a reduction in the radiating element dimensions.

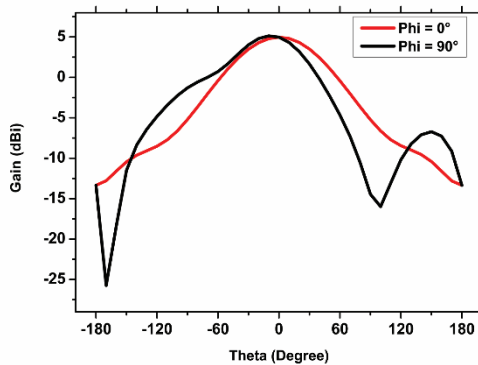


Fig. 6. The plots of gain at 60 GHz; in E-plane for Phi = 90 and H-plane for Phi = 0.

The 3D radiation pattern is illustrated in Fig. 8 in order to verify the stability of the radiation at the considered frequency bandwidth. The shown figure illustrates the produced radiations pattern at 56 GHz, 60 GHz and 66 GHz. According to this figure, this antenna has another important factor of performance in terms of stability of the radiation pattern.

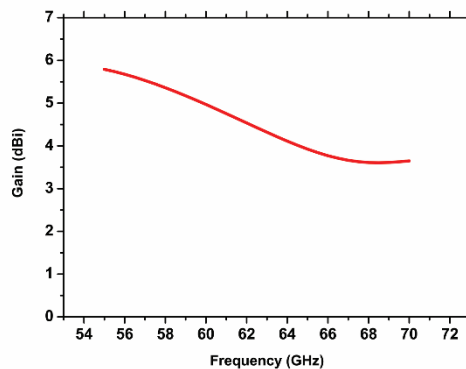


Fig. 7. The antenna gain variation as a function of frequency.

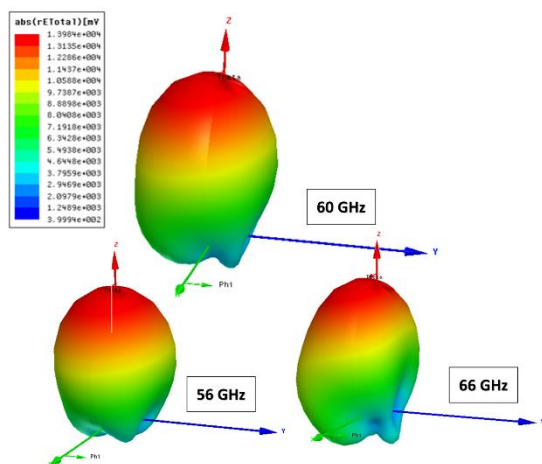


Fig. 8. 3D radiation pattern at different frequencies.

Fig. 9 shows the antennas manufacturing and measurement. Fig. 10 shows the manufactured prototype (Three prototypes are manufactured and only prototype three is shown for briefness). The prototypes of the proposed antenna are manufactured based on LTCC multilayer technology which consists of assembling many individual ceramic layers, the manufacturing is performed using ESL41111-G tape with a dielectric permittivity of 4.11 and a layer thickness of 75 ± 5 after firing, fired shrinkage of $15 \pm 1\%$ in X and Y directions and $16 \pm 2\%$ in the Z direction. After preparing the individual ceramic layers and printing the conductive tracks, the ceramic layers are stacked onto each other to form the circuit. The laminating pressure is 21 MPa at 70°C and the firing temperature is 850°C . The S-parameters are measured with Rohde & Schwarz ZVA67 Vector Network Analyzers. The obtained results of the three prototypes are illustrated in Fig. 11. These realized prototypes show a very small shift in terms of the resonance frequency. A good impedance matching is obtained in all tested prototypes where the obtained S_{11} is close to -50 dB in the first prototype, close to -30 dB in the second prototype and close to -40 dB in the third prototype. In terms of bandwidth, the manufactured prototypes show a wide bandwidth that looks larger in comparison to this of the simulation result. This can be justified by the previously indicated tolerances, and the tolerances in the printed metal layers, see Fig. 11, and the tolerances of layer misalignment in LTCC manufacturing. The influences of these process tolerances become more important at high frequencies as more as the dimensions of the antenna are reduced.

These obtained results of our antenna are compared to recent similar works in Table 2. The proposed antenna has a higher gain at 60 GHz with a lower gain variation over the considered bandwidth. Moreover, the antenna has a higher bandwidth compared to other antennas. In terms of reflection coefficient, the proposed antenna has a deeper value of S_{11} . In [25], three AMC based antennas are proposed, our antenna can be compared to this antenna when we consider the periodic structure as an artificial magnetic conductor with a zero phase of the unit cell at around 0.1 THz, showing that the use of zero-phase reflection at higher frequency leads to better performance than a zero-phase reflection at the resonant frequency.

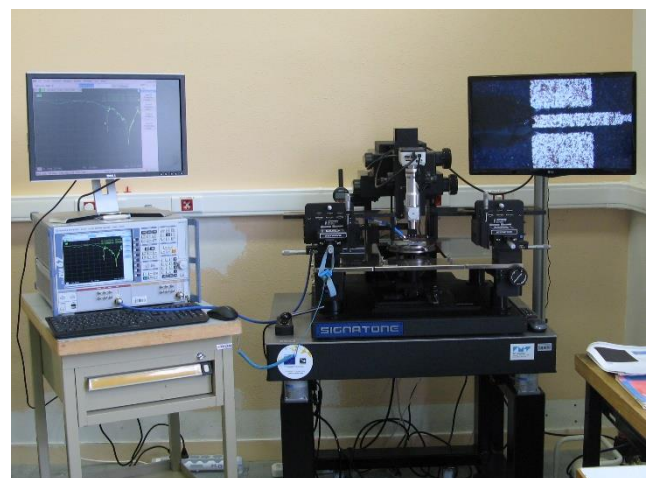


Fig. 9. Prototype under measurement.

TABLE II. ANTENNA PARAMETERS

Antenna	Technology	Center Frequency (GHz)	S11 (dB)	BW (GHz)	BW	GAIN (dBi) at 60 GHz	Gain variation	Year
Proposed antenna	LTCC	60	-51.70	14.5	24.16 %	5.10	2.15	-
[12]	LCP	60	-31	10	16.6%	5.10	1.9	2016
	LTCC	60	27	10	16.6%	4.9	2.6	
[25]	LTCC AMC1	60	-29	13.3	22.1%	4.8	2.6	2019
	LTCC AMC2	60	-36	13.7	22.7%	4.4	-	
	LTCC AMC3	60	-23	8.6	13.7%	4.8	-	

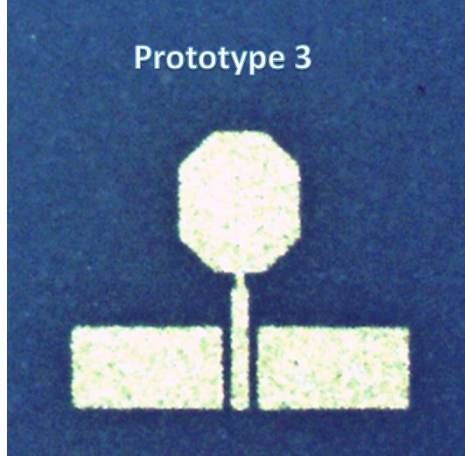


Fig. 10. LTCC based manufactured prototypes; only prototype three is shown for brevity.

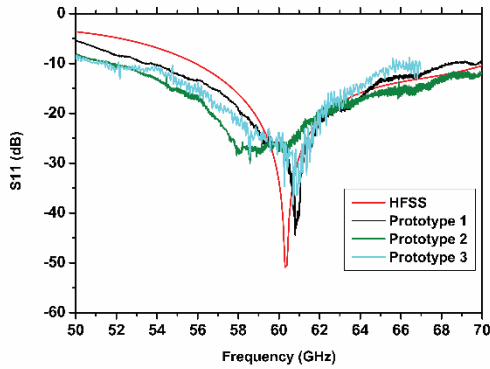


Fig. 11. Comparison of S11 simulation results and measurement of prototypes 1, 2 and 3.

IV. CONCLUSION

This work presents a design of 60 GHz band antenna based on LTCC technology, with a bandwidth of more than 26% centered at 60 GHz and stable radiation over the considered bandwidth. The proposed antenna offers a good impedance matching with an adequate gain. The obtained results have been verified using HFSS software and three prototypes are manufactured for measurement purposes. A good agreement between simulation and measurement results was obtained. These antenna performances make it attractive for use in practical devices in future wireless communications and to support many other 60 GHz applications needs.

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