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Advanced 3D LTCC Passive Components Using Cavity Structures for 60 GHz Gigabit Wireless Systems

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Abstract — **In this paper, a new class of compact cavity-based three dimensional (3D) filters and enhanced-performance antennas is proposed for 60 GHz miniaturized front-ends for multilayer low-temperature co-fired ceramic (LTCC) V-band modules. The low-loss cavity resonator consisting of via fences as sidewalls has been designed to be used as a filter. The probe excitation is employed for the feeding structure and is demonstrated as an attractive option for wideband applications due to its relatively wide bandwidth performance (1.8%) compared to the slot excitation with a $\lambda_g/4$ [1]. Its low loss performance is verified through an insertion loss lower than 0.95 dB over the 3-dB pass band. Plus, an aperture-coupled patch antenna integrated with a soft surface and an underlying stacked cavity below the antenna substrate has been demonstrated on a novel LTCC composite multilayer technology with variable layer dielectric constant as a potential enhanced-performance antenna topology with a higher gain (~7.6 dBi) and a significantly lower backside radiation (at least 5.1 dB) as compared to the use of soft surface only. The proposed compact antenna topology is easily extendable to array configuration for point-to-point applications in short-range indoor wireless personal area networks (WPAN)**

Index Terms — **cavity resonators, low-temperature cofired ceramic (LTCC), V-band, three dimensional (3D) integration, probe excitation, patch antenna, soft surface, composite substrate, mm-wave, WPAN.**

I. INTRODUCTION

The rapid expansion of wireless communications and personal communication networks has led to tremendous demands of miniaturization, portability, low-manufacturing cost and high performance in RF and millimeter-wave (mmW) wireless systems [2]. Especially, the appeal for transmitting multimedia information using high-speed digital data and wideband image signals has motivated the development of 60 GHz wireless communication systems because of their high potential for achieving compactness and wide bandwidth [3]. The 60 GHz front-end module is the foundation of these systems and requires high-performance filters and antennas that can be easily integrated. However, the traditional 2D implementation for the module development is facing various difficulties for a compact passives' integration because they still occupy the highest percentage of the circuit board real estate even after miniaturization due to crosstalk precautions. The multilayer LTCC-based System-on-Package (SOP) approach has emerged as an effective solution because if offers not only a great capability of easy-to-integrate embedded functions by adopting 3D components deployment, but also a real estate efficiency and cost-saving [1].

In this paper, we present for the first time the development of 3D LTCC cavity-based passive components using a novel class of feeding structures as the candidates of choice for the multilayer integration of compact, low-cost wireless gigabit front-end systems to be used in frequency ranges around 60 GHz. Especially, integrated on-package cavity structures are used in the design of the proposed devices to achieve several benefits: 1) relatively high Q and power handling capability compared to planar filter structures 2) less interference from other circuitries utilized in packaging 3) high gain and low backside radiation for the patch antennas. First, the low-loss 3D multilayer cavity resonators, consisting of via fences as side walls, fed by the probe excitation technique have been exploited at 60 GHz (V-band). The probe excitation consisting of the stacked vias is employed for the feeding structure and evaluated in terms of S-parameters and bandwidth. The last developed device is the aperture-coupled microstrip antennas using a soft-surface [4] and one stacked cavity on novel LTCC composite multilayer technology. We further improve the benefits of the soft-surface topology by adding a cavity-based feeding structure on the lower LTCC layers of the integrated module to increase the gain and to reduce the backside radiation. The integrated module's performance is validated in terms of reflection loss (S11) and radiation patterns.

II. CAVITY RESONATOR WITH PROBE EXCITATION

In this section, we propose a 60 GHz (V-band) 3D LTCC cavity resonator fed by the probe excitation technique. It utilizes two arrays of via fences as sidewalls [1] that can be easily integrated into a wireless RF front-end module in LTCC. The design procedure of the cavity on LTCC is well described in [1]. The very mature fabrication capability of LTCC (εr=5.4, $\tan\delta$=0.0019, metal thickness=9μm, substrate layer thickness=100 μm) has allowed for the fabrication of the proposed structure. Fig. 1 illustrates (a) the top view of the feeding structure, (b) the side view of the via-fed cavity resonator. The probe length (PL in Fig. 1 (b)) and the probe position (PP in Fig. 1 (a)) are the dominant design factors to

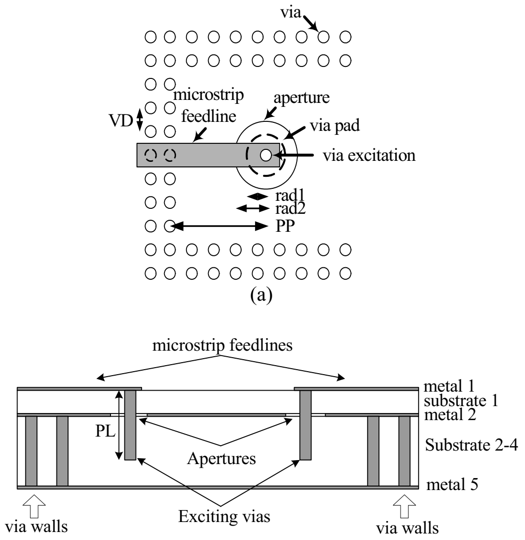


Figure 1. LTCC cavity resonator employing probe excitation: (a) top view of feeding structure (b) sideview of the proposed resonator

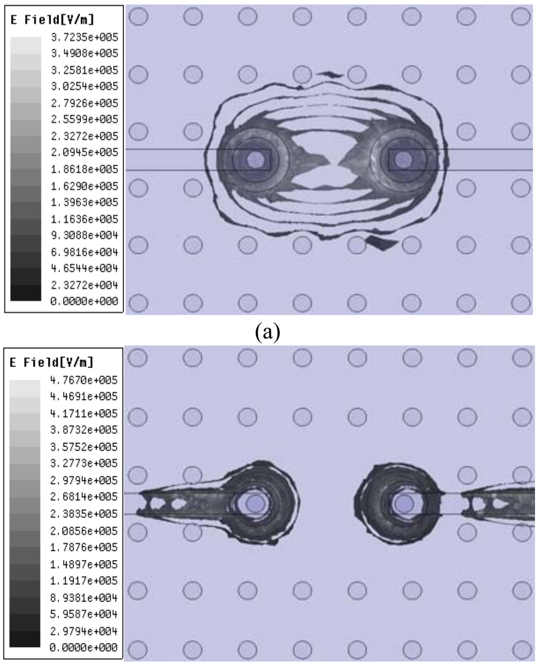


Figure 2. (a) Electric field distribution inside the cavity using probe excitation at resonant frequency (=59.8 GHz) (b) Electric field distribution of the top substrate layer (substrate 1 in Fig. 1 (b)).

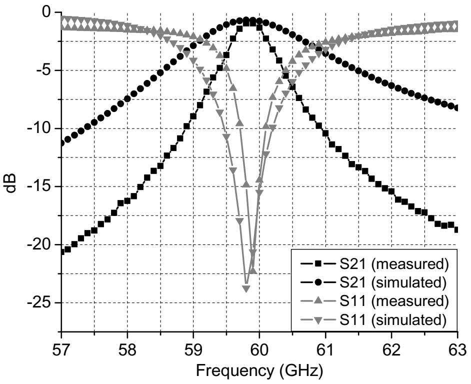
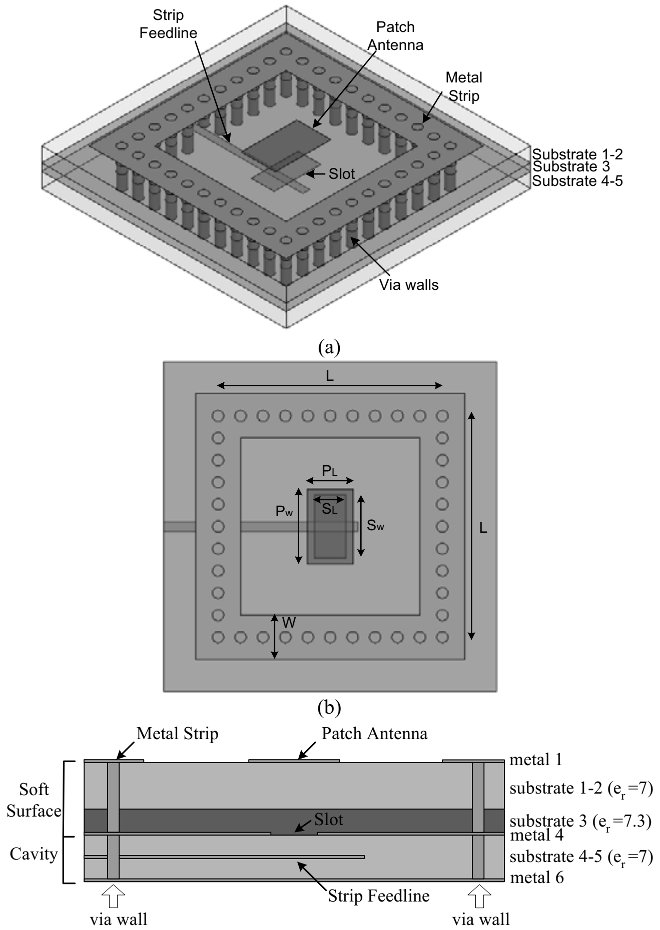


Figure 3. The comparison between measured and simulated S-parameters of the cavity resonator using probe excitation.

achieve the maximum coupling from the probe to the cavity, influencing the resonator size and performance such as bandwidth and insertion loss. They are investigated with the aid of HFSS. For maximum coupling with the TE_{101} mode in the cavity, the input/ouput probes (exciting vias in Fig. 1 (b)), that couple the energy to/from the microstrip feedlines) descend into the cavity through a circular aperture (aperture in Fig. 1 (a)) etched in the second metal layer (metal 2 in Fig. 1 (b)) up to the location of the maximum electric field at a distance of half of the cavity height. The circular shape has been chosen for the aperture to minimize the possible parasitics from a discontinuity to the circular via pads. The circular aperture size causes capacitive effect to the transition and good impedance matching can be accomplished by adjusting the gap between the via pad and aperture (gap = rad2-rad1 in Fig. 1 (a)). In our design, the excitation probe consists of three vias vertically stacked and penetrates three substrate layers (substrate 1 – 3 in Fig 1 (b)). The length for the probe (PL in Fig. 1 (b)) is determined to achieve the maximum coupling from the probe to the cavity. The size of the via pads is kept to the minimum size allowed by the LTCC design rules to minimize the parasitic effects.

The effect of the probe position (PP in Fig. 1 (a)) is investigated in terms of insertion loss, bandwidth, and input impedance. The probes are initially located at the edge of the cavity, and then move toward the center to achieve the stronger coupling possible. The probe position (PP in Fig. 1 (a)) has been found to be optimum at the location of PP=0.4475 mm ($\approx 0.177\lambda_g$). The effect of the aperture size is also investigated and it is observed from the simulations that the bandwidth gets wider and the insertion loss lower with the decrease of the aperture radius (rad2 in Fig. 1 (a)). The radius of circular aperture (rad 2) is optimized to 0.24 mm ($\approx 0.095\lambda_g$) in the simulation.

The dimension of the cavity composed of the via walls is determined to be 1.95 × 1.276 mm^2 ($\approx 0.77\lambda_g \times 0.5\lambda_g$). The height is determined to 0.3 mm (three substrate layers) to satisfy both the compactness and a relatively high Q value (>350). The width of this cavity is 42 µm smaller than the one using slot excitation with an open stub previously presented in [1]. The resonant frequency shifts down because of the probe perturbation. This perturbation can be characterized with the method of induced dipole moments [5]. In our case, we investigated the probe perturbation effect with the fixed dimensions of cavity by adjusting the probe length in HFSS simulator. The simulated electric field distributions, both inside the cavity and inside its substrate are shown in Fig. 2 (a) and (b) respectively. The efficient containment of the



(a)

(b)

Figure 4. (a) The 3D overview (b) cross-section view (c) cross-section view of a patch antenna with the soft surface and sacked cavity.

electric field and the perfect decoupling less than -50dB between the two feeding structures is observed.

The S-parameter data from both simulations and measurements are shown in Fig. 3. The measured insertion loss of 0.95 dB is slightly larger than the simulated value 0.67 dB but the measured bandwidth of 1.8 % is narrower than the predicted value 3.74 %. This difference has been investigated in the simulations, and it has been observed that a change in the external coupling caused by a slightly misaligned probe position and a misallocated probe position (PP in Fig. 1(a)) could be major factors to affect the electromagnetic performance, especially narrow bandwidth. It is observed that the coupling factor is decreased as the feeding point moves to the center of the cavity. No significant frequency shift in the operating frequencies of 59.8 GHz has been observed.

III. ANTENNA USING A SOFT-SURFACE AND STACKED CAVITY

An aperture-coupled microstrip patch antenna integrated with a soft surface [4] and a vertically stacked cavity has been demonstrated on LTCC multilayer technology as an effective solution for high gain and low-backside radiation. The 3-D overview, top view and cross-section view of this fully integrated topology are shown in Fig. 4 (a), (b) and (c), respectively. The antenna is implemented into 5 LTCC substrate layers (layer thickness = 117 μm) and 6 metal layers (metal layer thickness = 9 μm). The utilized LTCC is a novel composite material of high dielectric constant (ε_r~7.3) in the middle layer (substrate 3 in Fig. 4 (c)) and slightly low dielectric constant (ε_r~7.1) in the rest of the layers (Substrate 1-2 and 4-5 in Fig. 4 (c)). A 50Ω strip-line is utilized to excite the microstrip patch antenna (metal 1) through the coupling aperture etched on the top metal layer (metal 4) of the cavity as shown in Fig. 4 (c). In order to realize the magnetic coupling by maximizing magnetic currents, the slot line is terminated with a $\lambda_g/4$ open stub beyond the slot. The probe feed could not be used for the feeding structure because the size of the patch at the operating frequency of 61.5 GHz is too small to be connected to a probe via according to the LTCC design rules. The patch antenna is surrounded by a soft surface structure that consists of a square ring of metal strips that are short-circuited to the ground plane (metal 4 in Fig. 4 (c)) for the suppression of outward propagating surface waves [4]. Then, the cavity (Fig.4 (c)) that is realized utilizing the vertically extended via fences of the "soft-surface" as its sidewalls is stacked right underneath the antenna substrate layers (substrate 4-5 in Fig. 4 (c)) to improve the gain and to reduce backside radiation. The operating frequency is chosen to be 61.5 GHz. The optimized size ($P_L \times P_W$) of patch is 0.54×0.88 mm^2 with the rectangular coupling slot ($S_L \times S_W = 0.36 \times 0.74$ mm^2). The size (L×L) of the square ring of metal strip and the cavity is optimized to be 2.6×2.6 mm^2 to achieve the maximum gain [4]. The width of the metal strip (W) is found to be 0.52 mm to serve as an open circuit for the TM_{10} mode of the antenna, alleviating the surface current flowing outward (transversely to the via walls of the soft surface). The ground planes are implemented on metal 4 and 6. We achieved the significant miniaturization on the ground planes because their size excluding the feeding lines is the same as that of the soft surface (≈ 3.12×3.12 mm^2). In addition, the underlying cavity is used as a dual-mode filter to separate

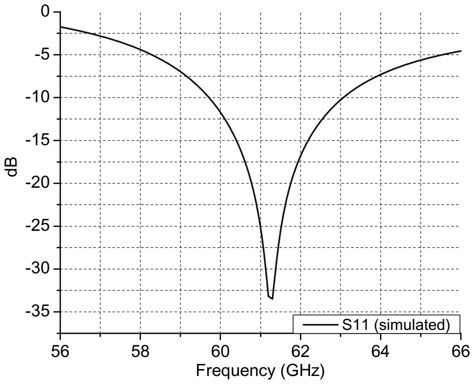
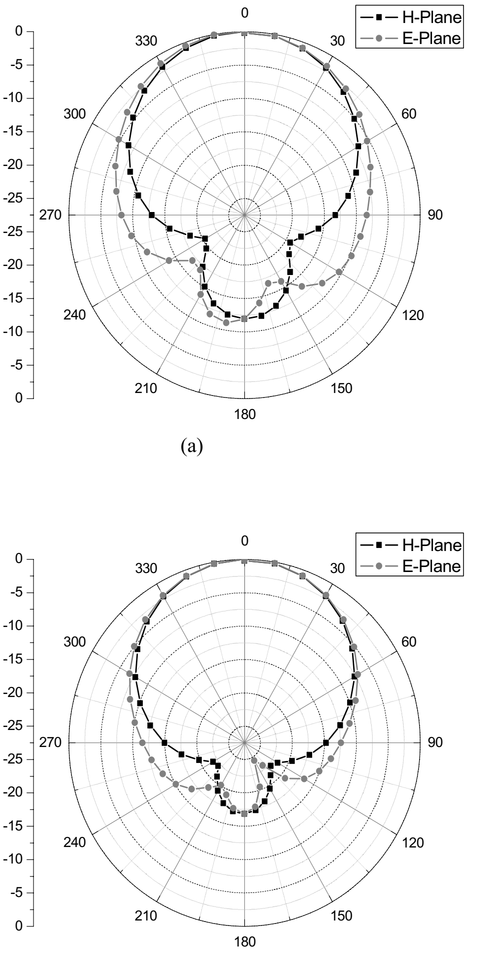


Figure 5. Simulated S-parameters of the dual-mode cavity BPF.



(a)

(b)

Figure 6. (a) The 3D overview (b) cross-section view (c) cross-section view of a patch antenna with the soft surface and sacked cavity.

TM_{10} mode whose phase and amplitude contain the information transmitted through short-range indoor WPAN.

The full antenna structure is analyzed with the aid of a FEM-based full-wave simulator (HFSS). The simulated result for the return loss is shown in Fig. 5. Its excellent impedance matching property is observed around the design frequency. From our investigation on the impedance performance, It is noted that the soft-surface structure vertically stacked by the cavity does not provide significant effect on the bandwidth of the patch with the soft surface only. The radiation patterns simulated in E and H planes of patch antennas with the soft surface only and with the soft surface/stacked cavity are shown and compared in Figs. 6 (a) and (b), respectively. It is confirmed that the back radiation is significantly reduced by about 5.1 dB by stacking the cavity to the patch antenna with the soft surface. The simulated gain at the broadside direction for at the operating frequency of 61.5 GHz is also investigated for both cases. A 7.6 dBi gain is obtained from the patch with the soft surface/stacked cavity which is 2.4 dB improvement compared to the one with the soft surface. In addition, the simulated half-power beamwidth at the operating frequency for the patch antenna with the soft-surface/stacked cavity is observed around 68°, almost 6° narrower than the one with soft-surface only.

IV. CONCLUSION

In this work, we presented the development of a new class of advanced 3D compact cavity-based passive components, such as filters and enhanced-performance antennas, for 60 GHz compact front-ends to be integrated into the 3D LTCC V-band modules. The 3D integrated cavity resonators composed of via walls have been successfully demonstrated with excellent performance using LTCC technology at 60 GHz. The probe excitation has been studied and demonstrated as an attractive option of wideband applications due to its relatively wide bandwidth performance (1.8%) in comparison to traditional slot/stub excitation approaches. Also, the low loss performance of the proposed structure is verified through an insertion loss lower than 0.95 dB over the 3-dB pass band. A patch antenna integrated with a soft surface and a stacked cavity, operating as a dual-mode filter, has been investigated on LTCC composite multilayer technology. The underlying cavity is used as a dual-mode filter to separate TM_{10} mode. By stacking the cavity underneath the antenna substrate, a higher gain and a significant reduction of the backside radiation (by at least 5.1 dB), without compromising the bandwidth performance, is observed as compared to the patch antenna with the soft surface only. The compact antenna with a surrounding soft surface and a stacked cavity can be easily integrated into 3D 60 GHz modules. An antenna array using the proposed antenna as a unit cell will be investigated to achieve the higher gain and directivity for point-to-point applications in short-range indoor WPAN and results will be presented at the conference.

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