State-of-the-Art mmWave Antenna Packaging Methodologies

Wonbin Hong

Samsung Electronics

Abstract

Low-Temperature-cofired ceramics (LTCC) antenna packages have been extensively researched and utilized in recent years due to its excellent electrical properties and ease of implementing dense package integration topologies. This paper introduces some of the key research and development activities using LTCC packaging solutions for 60 GHz antennas at Samsung Electronics [1]. The LTCC 60 GHz antenna element topology is presented and its measured results are illustrated. However, despite its excellent performance, the high cost issues incurred with LTCC at millimeter wave (mmWave) frequencies for antenna packages remains one of the key impediments to mass market commercialization of mmWave antennas. To address this matter, for the first time to the author's best knowledge this paper alleviates the high cost of mmWave antenna packaging by devising a novel, broadband antenna package that is wholly based on low-cost, high volume FR4 Printed Circuit Board (PCB). The electrical properties of the FR4 substrate are first characterized to examine its feasibility at 60 GHz. Afterwards a compact multi-layer antenna package which exhibits more than 9 GHz measured bandwidth ($S_{11} \leq -10$ dB) from 57～66 GHz is devised. The measured normalized far-field radiation patterns and radiation efficiency are also presented and discussed.

Ⅰ. Introduction

Wireless ecosystem based on high-data-rate communications using mmWave frequencies is actively being researched across industries and institutions to achieve mass market readiness. Advancements in SiGe and CMOS technologies in recent years have greatly attributed to mitigating the barriers related to commercialization of mmWave radio integrated circuits (ICs). This had led to the emergence of next generation wireless local area networks (WLAN) such as the unlicensed 60 GHz technology through the development of WiGig/IEEE 802.11ad standards. However, the relatively high cost of 60 GHz antenna packages which often exceed the costs of 60 GHz ICs are one of the few critical issues that must be resolved [2].

Low-temperature co-fired ceramics (LTCC) have been widely utilized for mmWave antenna package and RF packaging due to their excellent electrical and thermal properties [3]～[5]. However from a present day commercial standpoint, LTCC is regarded to be relatively expensive prohibiting it from being actively adopted in the consumer electronics industry [6]. Organic PCBs such as liquid crystal polymer (LCP)-based 60 GHz antenna packages have been demonstrated in search of a high performance, low-cost mmWave antenna package solution [7]. In [8], a 60 GHz planar antenna array is designed based on a thermoplastic polymer substrate denoted as ER182 to further enhance the antenna efficiency compared to LTCC. Unfortunately, no specific comments regarding its cost-effectiveness are provided.

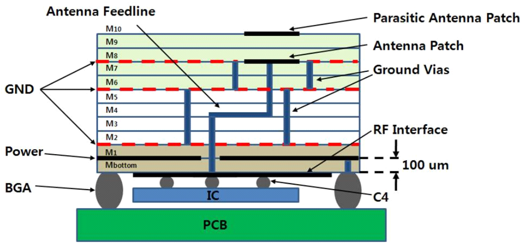
Despite its extremely low cost and abundance, FR4 has been widely regarded to be problematic for commercial mmWave applications within the antenna/RF community. In this paper, the author presents some of the notable mmWave antenna packaging technologies that have been researched and developed at Samsung Electronics in the past few years. Firstly, a 60 GHz antenna packaging solution devised using LTCC is presented along with its simulated and measured results. Building upon this research, a novel, state-of-the-art multilayer mmWave antenna package which is wholly devised and fabricated based on low-cost FR-4 is proposed and presented. The proposed antenna package is expected to be instrumental in resolving the cost-effectiveness issues regarding current 60 GHz radios for commercial applications.

Ⅱ. mmWave LTCC Antenna Package Solution

2-1 LTCC Antenna Element Design

The devised mmWave LTCC antenna package solution consists of a total of 10 LTCC layers as illustrated in [Fig. 1].

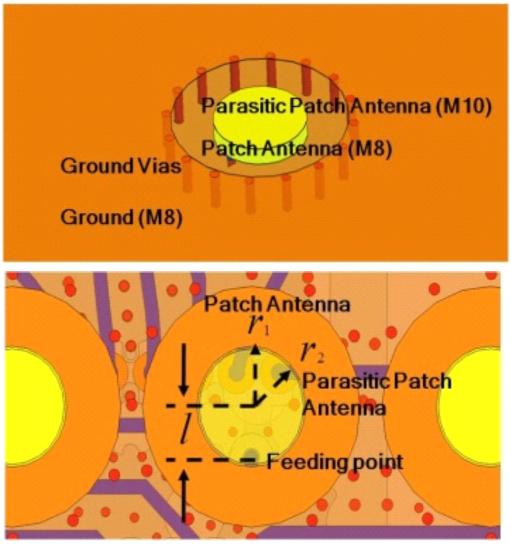
The top 4 layers are allocated for the antenna element topology. The next 4 layers stacked below are allocated for the antenna array feed lines. The bottom 2 layers are intended for auxiliary functions such as the power distributed networks (PDN) and low speed, high speed interfaces. Each LTCC layer have a fired thickness of 100 um, permittivity of 5.8 and loss tangent of 0.004.



[Fig. 1] mmWave LTCC antenna package topology.

Designing a compact broadband antenna at mmWave frequencies is a challenge in itself. At mmWave frequencies, antenna design parameters such as antenna dimension, feeding location, line width etc. must be designed within tens of um-level accuracy to ensure sufficient antenna performance. In addition, for commercial application scenarios, various factors such as fabrication accuracy limit, ease of fabrication, possibility of high-volume production, and fabrication yield must be thoroughly considered. As a result, these factors often become practical limitations during the actual design process. The mmWave antenna element topology designed to cover the 57~66 GHz band is illustrated in [Fig. 2].

A stacked circular patch antenna topology is designed due to its relative simplicity, omnidirectional radiation pattern and broad bandwidth. The driven patch antenna is situated in M8 and is directly fed by a signal Via. The parasitic patch antenna, located in the M10 is capacitively coupled by the driven patch antenna. The parasitic patch element is designed to resonate in close vicinity to the resonance created by the driven patch element. Both patch elements are designed in a circular topology for two main reasons: 1. To limit the number of design parameters, 2. To maximize fabrication yield

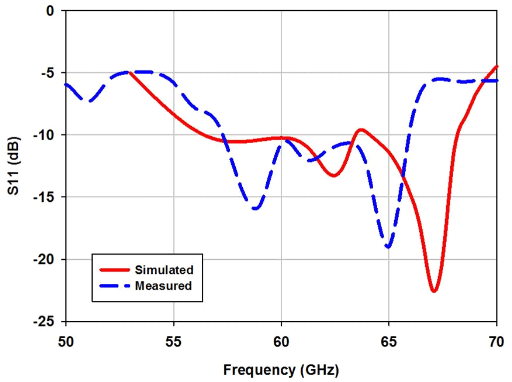


[Fig. 2] mmWave LTCC antenna element design topology.

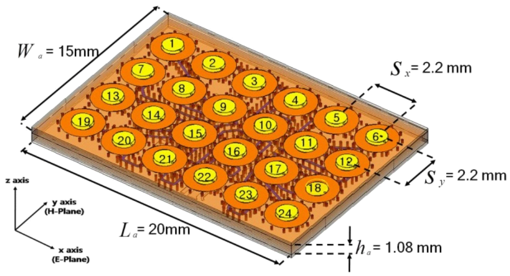
during production. The radii r_1 and r_2 are further modified using Ansoft HFSS so that the two resonances created by each respective patch elements are merged to exhibit the desired broadband behavior. The finalized radii are determined to be r_1 = 520 um and r_2 = 480 um respectively. The input impedance of the antenna is matched to 50 Ohms by offsetting the feed location of the signal Via from the center of the driven patch antenna by an optimized distance of l = 360 um. The simulated and measured *S*-parameters of the designed LTCC antenna element are presented in [Fig. 3].

2-2 LTCC mmWave Antenna Array Design

The devised LTCC mmWave antenna is further expanded into a phased array configuration for beam-steering applications as illustrated in [Fig. 4]. The presented LTCC mmWave antenna array consists of 24 LTCC antenna elements with equal number of ports situated on a 20 mm (L_a) × 15 mm (W_a) ×v1.02 mm



[Fig. 3] S_{11} amplitude of the mmWave LTCC antenna element design topology.



[Fig. 4] 24-element mmWave LTCC antenna array.

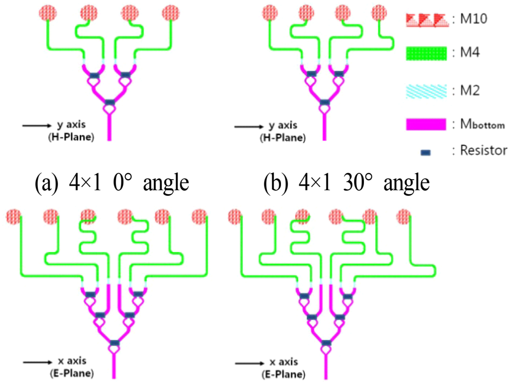
(h_a) LTCC substrate. The spacing between each antennas elements and array configuration are determined based on four criterions: 1. Maximized scan angle in the x and y direction of the horizontal radiation plane. 2. Suppression of grating lobes. 3. Maintain high levels of isolation (S_{21}) between adjacent antenna elements. 4. Compact antenna array footprint confined within the aforementioned substrate size. The antennas are arranged in a 4×6 layout for versatility in beam tilt in both axes. Full-wave simulations are extensively used to optimize the antenna spacings S_x and S_y while keeping the antenna array dimension relatively compact. The finalized dimensions for both S_x and S_y are 2:2 mm.

In reality, measuring the radiation performance of the proposed antenna array with 24 individual ports is extremely cumbersome due to the extensive number of measurement equipments and complexity of the measurement procedure. To verify the performance of the antenna array such as radiation pattern, beam tilts, gain in a conventional measurement environment, the antenna array is subdivided into two separate 4×1 and 1×6 array layouts. The 4×1 array is intended to be utilized to examine the antenna array performance along the y axis. Likewise, the 1×6 array is designed to examine the antenna array performance along the x axis. Four different arrays are designed and fabricated based on the desired beam tilt angles. The devised beam tilt angles for each antenna arrays configurations are summarized in <Table 1>.

For each beam-tilt angles, Wilkinson power dividers are designed as feed networks. 100 Ohm thin film resistors manufactured by Vishay [9] are implemented on the Wilkinson power dividers using surface mount technology (SMT). The topologies of the 4×1 and 1×6 arrays designed for their respective beam tilt angles are presented in [Fig. 5]. In addition, the co-polarized simulated and measured far-field radiation patterns at the plane of interest of the four 4×1 and 1×6 arrays are

<Table 1> Summary of the beam tilt configurations for mmWave LTCC antenna.

Antenna array	Simulated beam tilt	Measured beam tilt
4×1	0°	0°
4×1	30°	26°
1×6	0°	0°
1×6	40°	40°

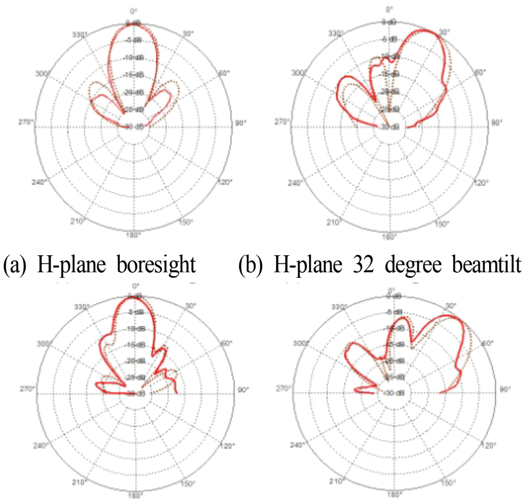


(a) 4×1 0° angle (b) 4×1 30° angle

(c) 1×6 0° angle (d) 1×6 40° angle

[Fig. 5] mmWave LTCC antenna array configurations for each corresponding beam tilt angles.

plotted in [Fig. 6]. The coherence between the simulated and measured far-field radiation patterns ascertain the intended functionality of the 24 element antenna array. The discrepancies between the simulated and


(a) H-plane boresight (b) H-plane 32 degree beamtilt

(c) E-plane boresight (d) E-plane 40 degree beamtilt

[Fig. 6] Measured and simulated mmWave LTCC antenna array far-field radiation patterns.

Measured Co polarization
Simulated Co polarization

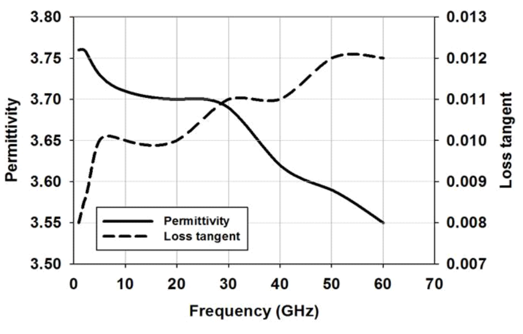
measured results can mostly be attributed to the non-ideal measurement environment. At mmWave frequencies, measurement equipments such as RF probes, chuck and cables tend to be electrically large compared to wavelength, causing various edge diffractions and scattering which contributes to pattern distortions. Additional measures are being thoroughly considered to further improve the measurement accuracy at mmWave frequencies.

Ⅲ. mmWave FR-4 Antenna Package Solution

As mentioned earlier, while LTCC packaging solutions offer excellent electrical characteristics at mm Wave frequencies, it relatively high fabrication cost has widely been deemed to be problematic from a commercial standpoint. In this section, a novel mmWave antenna package which is wholly devised using low-cost FR-4 substrates is presented.

3-1 FR-4 Characterization and Antenna Package

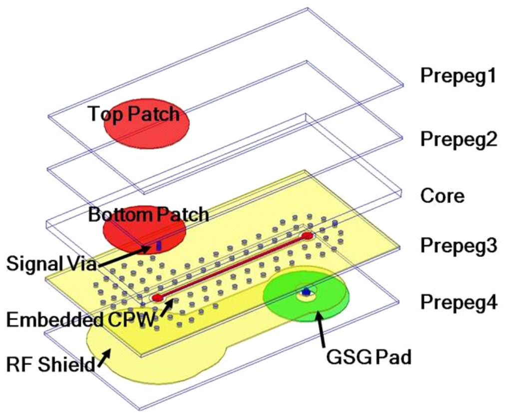
Material properties of the FR-4 substrate at the 60 GHz frequency band are first thoroughly studied prior to designing the antenna package. Cavity resonance method proposed in [10] is repeated to extract the permittivity and loss tangent as a function of frequency from 1 GHz to 66 GHz respectively as presented in [Fig. 7]. As expected, the loss tangent is several orders higher in magnitude compared to that of LTCC used in the previous section of this paper. Nonetheless, it is determined feasible to alleviate the potential performance degradation of the antenna package based on FR-4 to a certain extent through design efforts such as minimized impedance mismatch in transitions and short antenna feedlines with minimum radiation loss. In addition, the relatively lower permittivity of the FR-4 is advantageous for radiation efficiency improvement.



[Fig. 7] Measured permittivity and loss tangent of the FR-4 substrate.

3-2 Antenna Package Design

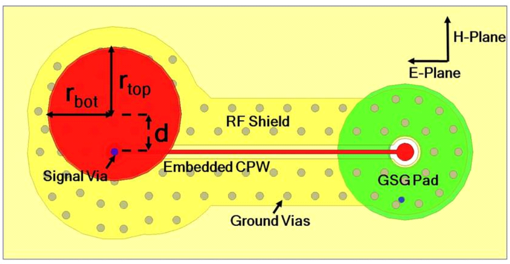
The devised FR-4 based mmWave antenna package is illustrated in [Fig. 8] in an exploded view. The antenna package consists of one core substrate and four prepreg substrates. The thickness of the core and prepregs are 150 um and 50 um respectively. Metallized layers are inserted on the surfaces of each substrates with the exception of Prepreg 2 using gold and copper



[Fig. 8] Exploded view of the mmWave FR-4 antenna package.

materials. The top circular patch antenna is first implemented on the top exposed metal layer of Prepreg 1. The bottom circular patch antenna is located on the metal layer of the core substrate. Similar to the devised mmWave LTCC antenna element, the bottom circular patch antenna is excited through an off-centered signal via feed which has a diameter of 80 um. The top circular patch antenna parasitically couples to the bottom circular patch antenna to create a secondary resonance frequency to enhance the antenna bandwidth. The signal via feed is vertically connected to the embedded co-planar waveguide (CPW), which serves as the antenna feedline located on the metal layer of Prepreg 3. Buried ground vias surround the embedded CPW to suppress undesired signal cross-talks. In addition, RF shield is implemented on the embedded metal layer of Prepreg 4 to minimize potential detuning effects caused by external RF components for possible integration scenarios. A 250 um-pitch ground-signal-ground (GSG) contact pad is designed on the bottom exposed metal layer of Prepreg 4 for measurement and assembly with the radio IC in the future. The total dimension of the antenna package is 2.6 mm×5.2 mm×0.404 mm.

The top view of the mmWave antenna package is presented in [Fig. 9] with the substrates and metal layers overlapped for better understanding. The antenna

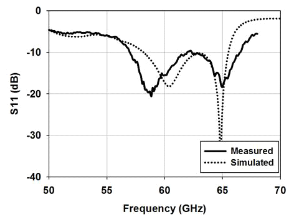


[Fig. 9] Top view of the mmWave FR-4 antenna package.

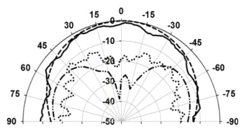
package is simulated and its design parameters are op-timized using Ansoft HFSS. The finalized radii of the top and bottom circular patch antennas are r_{top} = 700 um and r_{bot} = 670 um respectively. The location of the signal via in respect to the center of the bottom circular patch antenna is adjusted to d = 410 um. The width of the signal line in the embedded CPW antenna feedline is 40 um. The edge-to-edge gap from the signal line to the signal ground of the embedded CPW is 60 um. This embedded CPW configuration returns an impedance of approximately 42.5 Ohm at 60 GHz. Additional improvement of the impedance is determined to be difficult mainly due to the limited resolution of the electroplating process of the FR-4 material.

3-3 Measurement

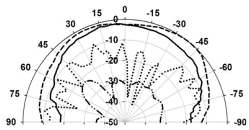
[Fig. 10] presents the simulated and measured results of the fabricated mmWave antenna package. The antenna package is placed on a wafer probe station and the



(a) S_{11} amplitude



(b) Normalized far-field radiation pattern: E-plane



(c) Normalized far-field radiation pattern: H-plane

[Fig. 10] Performance of the mmWave FR-4 antenna package. (Solid: Measured Co-pol. Dash: Simu- lated Co-pol. Dot: Measured Cross-pol. Dash-Dot- Dot: Simulated Cross-pol.)

return loss is measured using Cascade Microtech GSG RF probe. The mmWave antenna package exhibits more than 9 GHz of −10 dB bandwidth from 57～66 GHz. The normalized far-field radiation patterns are measured using a custom-designed measurement jig which incorporates the wafer probe station. A V-band standard gain horn antenna is used to transmit continuous waveform (CW) signals from 57～66 GHz. Small variations between the simulated and measured E-plane and H-plane co-pols are observed. The deviations between the simulated and measured cross-pols can be mostly attributed to unwanted scattering and backscattering of the measurement environment, which is difficult to take into account during the simulation process. Nonetheless, the co- and cross-pols in both planes exhibit more than 10 dB differences. The average measured gain obtained every 0.5 GHz interval from 57～66 GHz is calculated o be 4.9 dBi, indicating an average radiation efficiency of 84.7 %.

Ⅳ. Conclusions

This paper summarizes some of the recent key research accomplishments in the field of mmWave antenna packaging solutions at Samsung Electronics. Firstly, a 10-layer LTCC mmWave antenna element has been presented and discussed. The stacked circular patch antenna topology is confirmed to operate from 57～66 GHz with less than −10 dB S_{11} amplitudes. The antenna element package configuration is further expanded into a 24-element antenna array package for phased array scenarios. To mitigate the cost-limitations of LTCC, a new, state-of-the art mmWave antenna package solution involving full utilization of low-cost, mass producible FR-4 substrates is presented and proposed. Simulated and measurement results confirm the antenna package to feature more than 9 GHz of −10 dB band- width while exhibiting an average radiation efficiency of more than 84 %.

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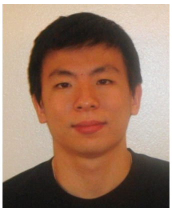
Wonbin Hong



received the B.S. degree in electrical engineering from Purdue University, West Lafayette, in 2004. He received the M.S. degree and Ph.D in electrical engineering from the University of Michigan, Ann Arbor in 2005 and 2009 respectively.
He is currently a senior engineer at Samsung Electronics, DMC R&D Center. His current research involves the development and characterization of microwave and millimeter-wave front-end circuits and miniaturized antennas. Dr. Hong was the recipient of the Samsung Scholarship for Graduate Studies.