A 60 GHz Millimeter-wave Antenna Array for 3D Antenna-in-Package Applications

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ABSTRACT This paper presents a 60 GHz millimeter-wave (mm-wave) antenna array using standard printed circuit board (PCB) for 3D Antenna-in-package (AiP) implementation. The array consists of a 4 microstrip patch elements, differentially fed with an open stub matching feed network to enable 3D integration. The 1×4 finite antenna array with ball grid array (BGA) and silicon (Si) interposer operates from 58.46 to 62.14 GHz with 3.6 GHz instantaneous bandwidth, low mutual coupling of about <-25 dB and achieves a realized gain of about 10.51 dBi. The array is capable of scanning down to ±45° and provides low cross polarization levels of -40 dB. The fabricated multilayer 1×4 array consists of two substrates and one bondply layer with antennas, via-to-open stub matching network, and a differential to single-ended corporate feed network for the measurement. A prototype with a differential to single-ended corporate feed network was fabricated and tested showing a gain of about 10.02 dBi at the operating frequency with ≥90% radiation efficiency. Such a gain and efficiency make the presented design a leading candidate for 3D AiP applications.

INDEX TERMS Antenna arrays, Electronics packaging, Millimeter-wave communication, PCB, System integration, 60 GHz

I. INTRODUCTION

THE need for fast data processing and high data rates is increasing exponentially and exceed the limits of current available technologies. Currently, the radio frequency (RF) spectrum (<6 GHz) is highly congested with limited resources and degradation in the quality of services [1-2]. To overcome this problem, radio applications are moving towards millimeter-wave (mm-wave) spectrum for wider bandwidth and high speed communications. In particular, mm-wave bands are attractive for mobile communications, WiGig applications, short-range and long-range satellite communications, and future autonomous and vehicular communications [3-5].

However, mm-wave systems suffer from high penetration loss, high path loss, and attenuation due to rain and severe weather conditions and are associated with fabrication errors due to their smaller sizes. The large pathloss can be overcome by utilizing high gain antenna arrays and by performing beamforming techniques. Notably, the most widely implemented mm-wave antennas are either a dipole, a patch, a grid or a loop antenna. These antennas are simple to design and are of small size, which make them ideal candidates for system-on-chip (SoC)/system-in-package (SiP) integration [6-8].

On-chip antennas suffer from high losses and surface mode excitation due to the proximity between the antennas and the Si substrate. Further the high relative permittivity ε_r and low resistivity of Si substrates suppress the gain and the efficiency of the antennas [6]. High cost and low yield of the SoC drives the designers towards a system-in-package (SiP) approach where antennas and other integrated circuits (IC) components are integrated together on the same package. However, the SiP requires the usage of bond wires which are lossy and lead to path loss at such higher frequencies. Recently, a low loss 3D integrated method to interconnect heterogeneously stacked ICs within a SiP was presented in [9-10]. Instead of using lossy bond wires, Through Silicon Via (TSV) structures were employed to enable 3D vertically stacked ICs. This resulted in significant size reduction and higher efficiency as compared to the traditional 2D SiP implementation. Concur-
rently, the potential of this novel 3D SiP method cannot be realized without a low profile, highly efficient antenna that can be vertically integrated on the package.

The implementation of mm-wave antennas has so far been challenging due to the high losses, expensive fabrication processes, and inaccuracies at such high frequencies. Mm-wave antenna arrays fabricated using low-temperature cofired ceramic (LTCC) process has been widely studied [11-13]. A simple and easy fabrication method is using printed circuit board (PCB). In [14], substrate-integrated waveguide (SIW) slot antennas with multi-layer circular patch array printed on a discontinuous dielectric substrate were designed using PCB. However, the requirement for an additional fabrication process and the high risk of structure deformation present significant limitations. An organic package with multi-layer phased antenna array designed using air cavity technology was presented in [15]. However, the introduction of the air cavities leads to fabrication challenges and also increases the risk of delamination during bonding or soldering at high temperatures. In [16], a PCB-based aperture coupled phased array with additional reflector to improve front-to-back ratio >10 dB was designed. The reflector requires additional substrate layer below the feed network, and hence the package suffers from increased thickness. Further, the antenna design requires specials vias (viz. blind vias) which increases the design complexity. We note that PCB fabrication requires stringent design rules such as trace widths >5 mil, conductor spacing >5 mil, and copper-to-edge clearance >5 mil.

With this in mind, we introduce a simple mm-wave PCB-based patch antenna array with low loss and high efficiency to interconnect heterogeneously integrated stacked circuits in a 3D SiP, as depicted in Fig.1. The array is designed to operate at 60 GHz using a 4-element patch array. In [10], an initial design of the array without ball grid array (BGA) was presented with only simulations. In this paper, we extend the work in [10] to include a standard PCB multilayer array design considering BGAs and Si interposer and for the measurement purpose alone, we fabricated an array prototype with corporate feeding network for testing and characterization using a single end launch connector. The paper is organized as follows. In Section II, we present the design and simulation results of the mm-wave antenna array stack-up. Then, fabricated and measured results of the fabricated prototype with a differential to single-ended corporate feed network are presented in Section III.

II. DESIGN OF A 60 GHZ MULTILAYER ANTENNA ARRAY

A. GEOMETRY OF THE ARRAY STACK-UP

In this section, we present the design of finite mm-wave patch antenna array operating at 60 GHz using a simple PCB design. Fig. 2 shows the infinite array’s antenna element of 3D Antenna-in-Package (AiP) that consists of the antenna array, ball grid array (BGA), and Si interposer. In this paper, we only show the design and implementation of the antenna array. The choice of PCB implementation avoids the losses
associated with the Si substrate. The overall dimensions of the stack-up are 9.6mm × 2.8mm × 0.568mm (L × W × h). The multilayer phased antenna array is comprised of 4 patch antenna elements designed on Isola tachyon substrate with dielectric constant $\epsilon_r = 3.02$, thickness 0.13 mm, and dielectric loss tangent $\tan\delta = 0.0021$.

The patch elements with $L_{\text{patch}} = 1.28$ mm and $W_{\text{patch}} = 2$ mm are differentially fed from the Si interposer by using through-hole vias, a feed network, and BGAs. Further, no balun is required since the antenna elements are excited in the differential mode from the Si interposer [9, 10]. Fig. 3 shows the antenna element of the designed infinite antenna array. A 50Ω impedance matching feed network is designed on a separate Isola tachyon substrate with thickness 0.13 mm and serves as a transition between the Si interposer and the through-hole vias feeding the antenna aperture. A prepreg layer of thickness 0.038 mm and the dielectric constant same as the core material is used for bonding the two core substrates. The feeding network consists of a 50Ω transmission line and compact open stubs on both sides. The multi-layer design adds additional capacitance to the feeding network, therefore an open stub that acts as an inductance is added on both the sides of the transmission line. The optimized length and width of the stubs are $L_{\text{stub}} = 0.42$ mm and $W_{\text{stub}} = 0.13$ mm. We note that, in this analysis, BGAs of 0.1 mm diameter are used as an integrating component between the multilayer antenna array and Si interposer.

**B. SIMULATED RESULTS**

An infinite array simulation with the designed antenna elements was carried out to optimize the array operation at 60GHz, using Ansys HFSS software. Fig. 4 illustrates that increasing the length of the open stubs increases the reactance of the antenna’s input impedance. Fig. 5 depicts the simulated active S11<-10 dB showing a good matching to 50Ω across 57.97-62.18 GHz. The bandwidth of the antenna can be further improved by increasing the thickness of the substrate and choosing a low dielectric constant material. The realized
gain of designed antenna element is compared to a similar single layer traditional patch antenna element without BGA and Si interposer, as illustrated in Fig. 6. The theoretical gain of the antenna element was estimated using the antenna’s effective aperture by [17]

\[ G = \frac{4\pi A_e}{\lambda^2} \]  

(1)

where \( A_e \) is the effective aperture of the antenna, \( \lambda \) is the operating wavelength. Notably, the addition of BGA and Si interposer to the antenna element only accounts for a 0.23 dBi loss.

A 1 \( \times \) 4 array with 4 patch antenna elements was designed as shown in Fig. 7. The spacing between the patches are maintained at a distance of 0.48\( \lambda \). The dimensions of the open stubs are optimized for 50\( \Omega \) impedance matching. The optimized 1 \( \times \) 4 finite array was simulated. Fig. 8 shows that the array operates from 58.46 to 62.14 GHz with low mutual coupling of <-25 dB between the adjacent elements. Notably, the designed differential feed array provides good isolation by maintaining a center-to-center element spacing of 0.48\( \lambda \), without using any additional isolation improvement technique.

Further, the scanning performance of the 1 \( \times \) 4 finite antenna array was analyzed by including progressive phase shifts between the elements. The phase shifts between the elements were calculated using (2)

\[ \Delta \phi = kdsin\theta \]  

(2)

where \( k = \frac{2\pi}{\lambda} \), \( \lambda \) is the operating wavelength, 
\( d \) is the antenna element’s spacing, and \( \theta \) is the scan angle.

Fig. 9 shows that the antenna array can scan down to \( \pm 45^0 \) in E plane (YZ plane) with a scan loss of about 2.29 dBi. As expected, the realized gain reduces by a \( \cos(\theta) \) factor. Notably, the designed array achieves a total gain of 10.51 dBi at boresight in both E (YZ plane) and H plane (XZ plane), as displayed in Fig. 10. Since the antenna elements are designed using infinite array boundary conditions, the designed array

![FIGURE 8. S parameters (dB) of the 1 \( \times \) 4 fully integrated antenna array.](image)

![FIGURE 9. Scanning performance of a 1 \( \times \) 4 patch array at 60 GHz for angles: \(-45^0\) to \(+45^0\).](image)

![FIGURE 10. Simulated radiation pattern of 1 \( \times \) 4 array at 60 GHz.](image)

![FIGURE 11. Simulated gain and radiation efficiency vs frequency of the 1 \( \times \) 4 array.](image)
can be easily extended to larger number of elements for higher gain. Therefore, the designed array with high gain and ±45° beam scanning has a capacity to compensate pathloss.

Fig. 10 also demonstrates that the antenna array provides sidelobe level of 14 dB. The designed via feed array provides a front-to-back ratio of >17 dB at 60 GHz, whereas an aperture-coupled antennas require additional reflector for improving the front-to-back ratio [16]. Additionally, the simulated antenna array provides low cross polarization levels of a -40 dB in E plane and -50 dB in H plane with ≥90% radiation efficiency at the operating frequency, as shown in Fig. 11. Indeed, the differential feed from Si interposer provides polarization purity and radiation symmetry.

III. DESIGN VALIDATION OF THE 1×4 ARRAY WITH CORPORATE FEED NETWORK

A 60 GHz multilayer 1×4 antenna array was fabricated and measured to validate the designed 3D AiP approach. For the measurement purpose, we developed a differential to single-ended corporate feed network to excite all the 4 patches at boresight, as shown in Fig. 12(a). The designed feed network provides 0° and 180° phase outputs to excite the differential patches along with optimized open stubs (Lstub=0.35 mm, Wstub=0.24 mm) for 50Ω impedance matching (see Fig. 12(b)). Fig. 12(c) shows that the patch elements and feed network are designed on separate Isola Tachyon substrate with thickness 0.25 mm, dielectric constant εr=3.02, and dielectric loss tangent tanδ=0.0021. A prepreg material of dielectric constant εr=3.02 and thickness 0.038 mm (1.5 mil) is used as a bonding material between these two substrates. A ground plane with 35 μm of copper was created on the top layer for a 1.85mm connector’s ground connection. The connector’s ground is connected to the antenna’s ground plane by using through-hole vias with diameter 0.2 mm and pitch spacing of 1 mm on both the sides.

The fabricated multilayer antenna array is measured using a 1.85mm end launch connector. The top and bottom view of the fabricated prototype are shown in Fig. 13 (a) and (b), respectively. The antenna array is connected to 1mm measuring cable using a 1.85mm to 1mm adapter. Fig. 14 shows the simulated and measured S11 of the array with corporate feed network. Notably, the simulation shows that the array with differential feed network operates from 57.6 to 63 GHz. Conversely, the array without differential feed network operates from 58.46-62.14 GHz (3.6 GHz impedance
FIGURE 15. Measurement setup of the 60 GHz antenna array.

FIGURE 16. Measured and simulated radiation pattern of the 1 × 4 array with differential corporate feed network at 60 GHz in E plane.

FIGURE 17. Measured and simulated radiation pattern of the 1 × 4 array with differential corporate feed network at 60 GHz in H plane.

FIGURE 18. Measured gain and radiation efficiency of 1 × 4 array with differential corporate feed network.

bandwidth). The measured S11 shows that it operates from 59.3 to 65 GHz. Discrepancies between the simulated and the measured results are due to fabrication errors, the presence of 1.85mm connectors and adapter used for the measurement. Nevertheless, the designed antenna array with differential feed network provides a bandwidth of about >5 GHz.

Fig. 15 shows pattern measurement setup using a mm-wave anechoic chamber. The normalized simulated and measured radiation patterns of the fabricated array in the E and H plane are shown in Fig. 16 and Fig. 17, respectively. Simulations show that the realized gain with differential feed network is about 10.47 dBi in the E plane and 10.41 dBi in the H plane. Conversely, the realized gain without feed network is 10.51 dBi in both E and H planes. The measured gain with differential feed network in the E and H planes is 9.34 dBi and 10.02 dBi, respectively. Even here, the ∼1 dB discrepancy between simulation and measurement is due the use of 1.85mm connectors and adapter.

The aperture efficiency of the antenna array can be estimated using the formula

\[ \epsilon_{Ae} = \frac{G\lambda^2}{4\pi A_e} \]  

where G is the gain of the antenna array, and \( A_e \) is the effective area of the antenna array [22]. The aperture efficiency of the antenna array without feed network in Fig. 7 is 81% at 60 GHz. Fig. 18 shows that the designed 1 × 4 antenna array operates with ≥90% radiation efficiency at the operating frequency. The implemented array provides low loss and high efficiency which makes it suitable for mm-wave 3D AiP applications.

Table I compares the different 60 GHz millimeter-wave in-package antennas and their fabrication process. It clearly indicates that the designed antenna array provides high efficiency, low mutual coupling, good gain, low profile, simple in structure. Further, it does not require any special vias such as blind or buried vias, thus reducing the design complexity.
TABLE 1. Comparison between various 60 GHz mm-wave antennas for antenna-in-package applications

| Resonant frequency | Antenna type/ Number of layers | Total Dimension of the fabricated prototype | Operating bandwidth | Gain (dBi) | Efficiency | Mutual coupling (dB) | Fabrication process |
|--------------------|-------------------------------|---------------------------------------------|---------------------|-----------|-----------|---------------------|-------------------|
| [12] 60 GHz        | 4 multidiagonal horn antenna  | 6mm×6mm×1.5mm                               | 57-66 GHz           | 6.3 dBi   | 85%       | <25 dB              | LTCC              |
| [13] 60 GHz        | 4×6 patch array/ 10 layers    | 20mm×15mm×1.02mm                             | 57-66 GHz           | 14.5 dBi  | NA        | NA                 | LTCC              |
| [18] 62 GHz        | 4×4 patch array/ 5 layers     | 14mm×14mm×0.925mm                            | 57.2-64.5 GHz       | 4.5-7.5 dBi (Each element gain) | 18.1 dBi (Sim.) | 89.6%              | <20 dB            | Standard PCB      |
| [19] 60 GHz        | 1 element patch/ 4 layers     | 11mm×11mm                                   | 57-66 GHz           | >6 dBi    | 78%       | NA                 | HTCC              |
| [20] 60 GHz        | 4×16 patch array/ 3 layers    | 50mm×41mm×0.478mm (with feed network)        | 57-65 GHz           | 20.8 dBi  | NA        | <18 dB             | Standard PCB      |
| [21] 60 GHz        | 5×5 patch array               | 15mm×15mm                                   | 57.6-61.2 GHz       | 18.5 dBi  | 85%       | <19 dB             | Standard PCB      |
| [23] 60 GHz        | 4×4 patch array/ 18 layers    | 14.4mm×15mm×1.8mm                           | 56.25-63.25 GHz     | 17 dBi    | NA        | <25 dB (soft- surface structures) | LTCC |
| This work          | 60 GHz                        | 1×4 patch array/ 3 layers                    | 12.8mm×10.87mm×0.597mm (with feed network) | 10.47 dBi (sim.) 10.02 dBi (meas.) | ≥90%       | <25 dB             | Standard PCB      |

IV. CONCLUSION

This paper presented a 60 GHz mm-wave antenna array for 3D AiP applications. The designed antenna array consists of a differentially fed patch antenna elements with a via-to-open stub matching feed network. The designed antenna array with BGA and Si interposer provides a gain of 10.51 dBi with ≥ 90% radiation efficiency. The fabricated array with differential to single-ended corporate feed network operates from 59.3 to 65 GHz with a measured gain of 10.02 dBi. Notably, the antenna array can be fabricated independently and combined using traditional BGA packaging technology, thus making it an ideal candidate for antenna-in-package integration.

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